ANALYSIS OF BUILDING PEAK COOLING LOAD CALCULATION METHODS FOR COMMERCIAL BUILDINGS IN THE UNITED STATES

A Dissertation

By

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ABSTRACT

This study aims to provide valid comparisons of the peak cooling load methods that were published in the ASHRAE Handbook of Fundamentals, including the Heat Balance Method (HBM), the Radiant Time Series Method (RTSM), the Transfer Function Method (TFM), the Total Equivalent Temperature Difference/ Time Averaging Method (TETD/TA), and the Cooling Load Temperature Difference/Solar Cooling Load /Cooling Load Factor Method (CLTD/SCL/CLF), and propose a new procedure that could be adopted to update the SCL tables in the CLTD/SCL/CLF Method to make the results more accurate.

To accomplish the peak cooling load method comparisons, three steps were taken.

First, survey and phone interviews were performed on selected field professionals after an IRB approval was obtained. The results showed that the CLTD/SCL/CLF Method was the most popular method used by the HVAC design engineers in the field due to the reduced complexity of applying the method while still providing an acceptable cooling load prediction accuracy, compared to the other methods.

Next, a base-case comparison analysis was performed using the published data provided with the ASHRAE RP-1117 report. The current study successfully reproduced the HBM results in the RP-1117 report. However, the RTSM cooling load calculation showed an over-prediction compared to the RTSM results in the report. In addition, analyses of the TFM, the TETD/TA Method and the CLTD/SCL/CLF Method were compared to the base-case cooling load. The comparisons showed the HBM provided the most accurate analysis compared to the measured data from the RP-1117 research

project, and the RTSM performed the best among the simplified methods. The TFM estimated a value very close to the peak cooling load value compared to the RTSM. The CLTD/SCL/CLF Method behaved the worst among all methods.

Finally, additional case studies were analyzed to further study the impact of fenestration area and glazing type on the peak cooling load. In these additional comparisons, the HBM was regarded as the baseline for comparison task. Beside the base case, fifteen additional cases were analyzed by assigning different window areas and glazing types. The results of the additional tests showed the RTSM performed well followed by the TFM. The TETD/TA Method behaved somewhere in between the TFM and CLTD/SCL/CLF Method. In a similar fashion as the base-case comparisons, the CLTD/SCL/CLF Method performed the worst among all methods.

Based in part on the results of the survey and interview as well as the comparisons, updates to the SCL tables in the CLTD/SCL/CLF Method were developed that allowed the CLTD/SCL/CLF Method to be more accurate when compared to the HBM. The new updated SCL tables were calculated based on the SHGC fenestration heat gain model instead of the SC and DSA glass coefficients. Three examples were provided that showed the improved analysis with the updated SCL tables. All of the results showed an improved peak cooling load estimation.

DEDICATION

To my dearest husband and beloved parents

ACKNOWLEDGEMENTS

My dissertation would never have been accomplished without the help and support from multiple people. First, I would like to gratefully thank my research co-chair, Professor Jeff Haberl, for his great support and guidance during my doctoral studies at Texas A&M University. His encouragement inspired me to overcome many difficulties that I faced during my study. I would also like to express my gratitude to my co-chair, Professor Juan-Carlos Baltazar. He devoted his time to guiding me through the complex equations at each step of my research, and he helped me with numerical coding issues. He also patiently listened to my ideas and brought me new insights and suggestions.

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Last but not least, I want to express my sincerely gratitude to my dearest husband and beloved parents. My husband was my motivation that kept me going when I felt frustrated. He was always positive and supportive and is the sunshine in my life. I also want to thank my parents who gave me their unconditional love and were always on my side whenever I needed them.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

1.1 Background

Today, buildings consume a large portion of the total United States energy use. A recent study by Lawrence Livermore National Laboratory (LLNL, 2014) showed that the total United States (U.S.) energy use in 2014 was approximately 98.3 Quads (1 Quad = 10^{15} Btu, QBtu). In the LLNL study, the three main energy end-use sectors included: buildings (residential + commercial), industrial and transportation, which consumed 20.73 QBtu (28.6%), 24.7 QBtu (34.1%) and 27.1 QBtu (37.3%), respectively.

In the LLNL 2014 study, the buildings sector (i.e., residential + commercial) accounted for 20.73 QBtu or about one third of the end-use energy use in the U.S. in 2014. However, if the energy waste from the electricity production is considered and the waste from this sector is proportioned according to the end-use, the buildings sector was responsible for 40.3 QBtu of total U.S. source energy consumption. Therefore, buildings represent 41% of total U.S. source energy use. Clearly, designing more energy efficient buildings will have a major impact on reducing future U.S. source energy use.

The building industry has responded to this need with efforts to improve commercial building energy efficiency in the past 39 years since the 1973 oil embargo. The first commercial building energy standard, ASHRAE Standard 90-1975, was published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as a direct response to the 1973 energy crisis (Skalko, 2012). Since then, a series of new, more stringent energy codes were published, including: the 1977 Model Energy Code (MEC), ASHRAE Standard 90A-1980, ASHRAE Standard 90B-1975, the 1983-1986 MEC, the 1988 MEC, ASHRAE Standard 90.1-1989, the 1992 MEC, the 1995 MEC, ASHRAE Standard 90.1-1999, the 2003 IECC, the 2004 IECC, ASHRAE Standard 90.1-2004, the 2006 IECC, ASHRAE Standard 90.1-2007, the 2009 IECC, ASHRAE Standard 90.1-2010 and the 2012 IECC. Presently, there are several published standards and guidelines for building designs, including: the minimum standards for energy efficiency – ASHRAE Standard 90.1-2013 (ASHRAE, 2013b) and the 2015 International Energy Conservation Code (ICC, 2015a); ASHRAE's Advanced Energy Design Guides (30% AEDG[1] and 50% AEDG[2]); and high-performance green building standards - ASHRAE Standard 189.1-2014 (ASHRAE, 2014) and the 2015 International Green Construction Code - IGCC (ICC, 2015b).

As a result of increasing energy prices, environmental concerns and improved building energy standards, there is an increasing effort to analyze, design and construct new high performance buildings that will be affordable, consume less energy, look appealing, and provide acceptable indoor air conditions. However, in many cities in the U.S. developers are asked to try to reuse some portion of an existing structure, or add-on to an existing structure without really knowing how that previous building was designed, especially the HVAC system. Often, older buildings have existing HVAC systems that are significantly over-sized, which makes them inefficient for meeting the heating and

[1] The 30% AEDG include: small hospital and healthcare facilities (ASHRAE,2009a), highway lodging (ASHRAE, 2009b), small warehouses and self-storage buildings (ASHRAE, 2008a), K-12 school buildings (ASHRAE, 2008b), small retail buildings (ASHRAE, 2008c), and small office buildings (ASHRAE, 2004).
[2] The 50% AEDG include: large hospitals (ASHRAE, 2012), K-12 school buildings (ASHRAE, 2011b), small to medium office buildings (ASHRAE, 2011c), and medium to big box retail buildings (ASHRAE, 2011d).

cooling loads they must supply. In some cases, the thermal mass of these older buildings has never been adequately taken into account during the design process, which may have led to the significant over-sizing errors in the thermal load calculations. Furthermore, efforts to develop net-zero buildings, for example, the Research Support Facility (RSF) designed by National Renewable Energy Laboratory (NREL) are adding another layer of efficiency requirements to building design. Finally, many characteristics are not easily incorporated into the peak load design calculation, such as natural ventilation, underfloor air distribution, radiant slabs, etc.

Currently, several peak load cooling calculation methods are in use, including: the Total Equivalent Temperature Difference/ Time Averaging (TETD/TA) Method, the Heat Balance Method (HBM), the Transfer Function Method (TFM), the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM). Since 2001, detailed descriptions of the TFM, the TETD/TA Method and the CLTD/SCL/CLF Method have been removed from ASHRAE Handbook of Fundamentals with only the HBM and the RTSM remaining. At the 2016 ASHRAE winter conference, in one of the seminar presentations, Professor Jeffrey Spitler provided an overview of how ASHRAE Technical Committee TC 4.1 decided to replace the previous three simplified methods with only the RTSM (Spitler, 2016). In this presentation, it was explained that TC 4.1 had received numerous complaints from ASHRAE members about how confusing it was to have all three methods included in one Handbook. As a result, TC 4.1 decided to replace the discussion of the three methods with only one discussion about the RTSM and only brief summaries about the other methods.

However, no clear comprehensive comparative studies have been found to clarify the differences that arise when calculating the peak cooling load with all the different methods. Therefore, whether the RTSM can actually replace all previous methods used by architects and engineers, and perform a reasonable prediction of peak cooling loads remains to be seen.

As of result of these issues, there is a need for a better understanding of how effective the existing peak cooling load calculation methods are for commercial building design in the U.S., including current methods in the ASHRAE Handbook compared with the previously published methods, and how/whether those methods are being used effectively by engineers.

1.2 Purpose and Objectives

The purpose of the current study is to analyze and compare building peak cooling load calculation methods, and to determine how effectively those methods are being used by architects and engineers. The long-term goal of this work is to improve the use of peak cooling load predictions that are used by architects and engineers to size HVAC systems in commercial buildings.

The following objectives were accomplished:

- A literature review of the existing peak cooling load calculation methods for commercial buildings in the U.S.,

- A survey and interview of field professionals to determine what methods are used today in the HVAC design,
- The selection of a representative case-study building for comparing the peak cooling load methods,
- The application of the peak cooling load design methods to the case study building,
- A search to investigate the possible shortcomings of today's peak cooling load design methods,
- The development of recommendations regarding peak cooling load design methods.

1.3 Significance and Limitations of the Study

This study is significant because of the following:

- It provides a thorough literature review on the history of peak cooling load design methods;
- It provides a comprehensive document of all peak cooling load methodologies that were included in the ASHRAE Handbook of Fundamentals from 1967-2013;
- It compares all peak cooling load design methods in use in the U.S., including: the HBM; the RTSM; the TFM; the TETD/TA Method; and the CLTD/SCL/CLF Method.
- It proposes and documents new SCL table updates for the CLTD/SCL/CLF Method based on the ASHRAE RTSM Spreadsheet Tool.

The current study has the following limitations:

- The study focuses only on the building envelope peak cooling loads only, and does not cover cooling loads coming from internal heat gains, HVAC system and plant;
- Only sensible peak cooling loads are studied, which does not cover the latent cooling loads;
- The pool of participants for the survey and interview was drawn from a limited group of participants;
- Peak cooling load methods not published in the ASHRAE Handbook of Fundamentals were not analyzed or compared in this study.

1.4 Organization of the Dissertation

This dissertation is organized as follows:

In Chapter I, the study background is provided as well as the study purpose and objectives, followed by the study significance and the limitations.

In Chapter II, a comprehensive literature review was performed, covering the history of related science and the peak cooling load calculation methods. The first section tracks the early science development that lead to dynamic heat transfer analysis methods, including: gas laws, heat transfer and thermodynamics. The second section reviews the history of the major peak heating and cooling load calculation methods in four different periods: Pre-1945, 1946-1969, 1970-1989, and 1990-Present. It also summaries the five existing peak cooling load design calculation methods, which are the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging Method

(TETD/TA), the Transfer Function Method (TFM), the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor Method (CLTD/SCL/CLF), and the Radiant Time Series Method (RTSM). In the last section, previous comparisons related to this work are reviewed.

In Chapter III, the research methodology is presented, including: the procedure used to survey and interview field professionals; the comparison analysis procedure of the peak cooling load design calculation methods; and a proposed improved peak cooling load design methodology.

In Chapter IV, the study results are shown. In Part I, the survey and interview results are shown. Part II provides the results of the base-case analysis comparison of the peak cooling load design methods. Finally, additional case studies are presented for all methods in Part III, followed by a summary of the findings.

In Chapter V, the proposed new SCL table updates for the CLTD/SCL/CLF Method are developed.

Finally in Chapter VI, result summary and conclusions are provided from the study and the potential future work is discussed.

CHAPTER II

LITERATURE REVIEW*

2.1 Overview

Currently, there is an increasing interest in the HVAC community to analyze, design and construct new high performance buildings that will consume less energy, look appealing, and provide acceptable indoor air conditions. However, in many cities in the U.S. developers are asked to try to reuse some portion of an existing structure, or add-on to an existing structure without really knowing how that previous building was designed, especially the HVAC systems. Often, older buildings have existing HVAC systems that are significantly over or under sized, which makes them inappropriate for meeting the heating/cooling loads they must supply. In some cases, the thermal mass of these older buildings has never been adequately taken into account during the HVAC design process, which may have led to large errors in the thermal load sizing calculations that produces inefficient, oversized systems.

Although there have been a number of previous papers that have presented historical discussions of the origins of computer simulation programs, few if any studies have provided an historical analysis of peak heating and cooling load calculation methods that covered periods before computerized simulations came into use (Feldman and Merrian, 1979; Kusuda, 1985; Stamper,1995; Sowell and Hittle, 1995; Shavit, 1995).

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*Part of this chapter is reprinted from *Peak Heating/Cooling Load Design Methods: How We Got to Where We Are Today*. Mao, C., Haberl, J.S. and Baltazar, J.C., 2013, Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28. Copyright 2013 by original authors.

2.2 History of Science Related to Peak Load Calculation

The development of peak heating and cooling load calculations, and annual building energy use calculation methods could not have been performed without a solid foundation based on the related sciences. Therefore, a brief review of the previous sciences and engineering practices from the 1700s to the 1900s is provided, including[3]: gas laws, heat transfer, and thermodynamics.

2.2.1 Gas Laws

The development of the science of the behavior of gasses, such as moist air, was important for sizing building heating and cooling systems. The earliest studies of gas laws began in the 17th century first with experiments that defined temperature, pressure and volume relationships, followed shortly thereafter with a better understanding of partial gas pressures, molecules and eventually atoms. One of the earliest studies was performed by the British scientist and philosopher, Robert Boyle (1627-1691), who performed experiments with an air vacuum pump to observe the effects of reducing air pressure, which was reported in his book "*New Experiments Physico-Mechanicall, Touching the Spring of the Air, and its Effects*" in 1660 (West, 2005; Donaldson et al., 1994); Two years later, he published his results, which demonstrated that the product of gas pressure and volume was constant at a given temperature; now referred to as "Boyle's Law". Robert Boyle is usually credited with being the first to research gas properties through observations based on experiments (Donaldson et al., 1994).

[3] Adapted from Mao et al. (2012, 2013).

One hundred years later, in 1787, Jacques Charles (1746-1823), the French chemist and physicist, formulated Charles' Law (Acott, 1999; Donaldson et al., 1994), which stated that the gas volume was proportional to the gas temperature at a given gas pressure. However, Charles' Law was not published until 1802 when it was cited by Joseph Louis Gay-Lussac (Elena and Manuela, 2006), a French chemist and physicist. Gay-Lussac's Law showed the relationship between gas pressure and temperature at a constant gas volume. A combined gas law that considered gas pressure, temperature and volume was later derived by combining Boyle's Law and Charles' Law (Sandfort, 1962; cited in Donaldson et al., 1994).

In 1801, the English chemist, meteorologist and physicist, John Dalton (1766-1844), introduced the concept of “partial pressure” (Woo and Yeo, 1995; Donaldson et al., 1994), which proposed that the summation of the partial pressures of each gas component was equal to the total pressure of mixture. This later became known as "Dalton's Law". Eight years later, in 1809, Joseph Louis Gay-Lussac developed another law about the conservation of gas volumes in chemical reactions at the same temperature and pressure (Elena and Manuela, 2006). In 1811, based on Gay-Lussac's data, Amedeo Avogadro (1776-1856) proposed Avogadro's Law, which was the first to suggest that "molecules" should be differentiated from “atoms” (Elena and Manuela, 2006), which helped to further understand gaseous mixture. Avogadro's Law also stated that gases with equal volumes at the same temperature and pressure had equal numbers of molecules (Hirang, 2008-2009). Eventually, all these discoveries lead to the Ideal Gas Law that formed the basis of today’s thermodynamic principles for moist air.

2.2.2 Heat Transfer

Heat transfer, the discipline that studies the process of transferring heat from one object to another, is composed of three important fields: conduction, convection and radiation. The earliest theories of heat transfer began with Isaac Newton (1642-1727) who published "Newton's Law of Cooling" in 1701 that first introduced the term "heat transfer coefficient" (Bergles, 1988). Newton proposed a proportional relationship between the cooling rate and the temperature difference of two surfaces based on his early experiments. His Law of Cooling was considered the beginning of convective heat transfer studies. The three modes of heat transfer: conduction, convection and radiation, were not separately distinguished until 1757 by Joseph Black (1728-1799), who also introduced the term "Latent Heat" (Cheng and Fujii, 1988).

In 1807, the theory of heat conduction was first formulated by Joseph Fourier (1768-1830) through the use of partial differential equations that described the transient process (Narasimhan, 1999). Fifteen years later, in 1822, Fourier's Law of Heat Conduction was formally proposed in his published paper "*The Analytic Theory of Heat*" (Donaldson et al., 1994). In the beginning of the 19th century, the earliest work on radiation heat transfer started with the recognition of "invisible light" by William Herschel in 1800 (Backman and Harman, 2011; Donaldson et al., 1994). It was not until sixty years later, in 1860, that Kirchhoff's law of radiation was formulated by Gustav Kirchhoff (l824-1887) (Mätzler, 2012), which gave us an equation to calculate the radiative heat transfer process at the surface of a material. Shortly after this, Stefan's Law was proposed in 1879, based on experiments performed by Joseph Stefan (1835-1893), which stated that there was a proportional relation between radiation and the fourth power of surface temperature. Then, five years later, in 1884, Ludwig Boltzmann (1844-1906) provided a derivation of a fourth power radiative heat transfer law (Carter, 2004). Stefan and Boltzmann's work were later combined and are now referred to as the "Stefan-Boltzmann Law", which includes the Stefan-Boltzmann constant for performing the radiative heat transfer calculation. In summary, these heat transfer discoveries provided the basic theories and equations that were needed to calculate dynamic building peak load calculations as well as annual energy use calculations.

2.2.3 Thermodynamics

Thermodynamics is a discipline that combines the concepts of heat, work and energy, including: the First, Second and Third Law of Thermodynamics. The science of thermodynamics developed gradually alongside the development of gas laws and heat transfer in the 19th century (Cheng and Fujii, 1988). Beginning in 1824, Sadi Carnot (1796-1832), also known as the "Father of Thermodynamics", proposed the Carnot cycle, which was published in his "*Reflections on the Motive Power of Fire and on Machines Filled to Develop That Power*" (Donaldson et al., 1994); this paper marked the birth of the science of thermodynamics and established the foundation for the First and Second Law of Thermodynamics. The First Law of Thermodynamics – the Conservation of Energy was first introduced in 1842 by Robert Mayer (1814-1878) who proposed that heat was a form of energy (Cheng and Fujii, 1988; Donaldson et al., 1994). One year later, the equivalence of heat and mechanical work was demonstrated by James Prescott Joule (1818-1889)[4] (Donaldson et al., 1994).

In 1847, an energy conservation formula was first proposed by Hermann von Helmholtz (1821-1894) (Donaldson et al., 1994). This led to the development of the Second Law of Thermodynamics, which was presented by Rudolf J. Clausius (1822-1888) in 1850 when be introduced the term "entropy", which was based on Helmholtz and Carnot's work (Powers, 2012; Donaldson et al., 1994). The Third Law of Thermodynamics was not proposed until 1906 by the physical chemist, Walther Hermann Nernst (1864-1941), which stated that the entropy of a system was zero if the temperature was absolute zero (Javadi, n.d.). These three Laws of Thermodynamics helped consolidate the concepts of heat, work and energy into calculations of a single subject or system of equations, which together with the science of gas laws and heat transfer became the foundations of building peak heating and cooling load calculations and annual energy use calculations.

2.3 Peak Load Calculation Methods

Building peak load calculation methods, which include peak heating and cooling load calculations, are used for sizing HVAC equipment in order to provide adequate heating or cooling when extreme weather conditions occur. This section reviews the history of the major peak heating and cooling load methods in four different periods: Pre 1945, 1946-1969, 1970-1989, and 1990-Present.

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[4] The S.I. energy unit was named after James Prescott Joule.

2.3.1 Pre 1945

The birth of most engineering methods is often inspired by the need to solve problems that were relevant and practical for a given period. Prior the development of standardized peak load calculation methods, most engineers tried to design building HVAC systems by relying on manufacturer's literature for a specific system, a few available textbooks, even fewer handbooks or guidebooks.

The earliest heating and ventilating design developments started in the nineteenth century. Unfortunately, engineers had to design systems with rules-of-thumb or approximate design methods because useful textbooks or guidebooks that were based on first principles were in scarce supply. As early as in 1834, Dr. Boswell Reid redesigned the heating and ventilating system for British House of Commons using a chimney to induce air flow through the building[5], as shown in Figure 2.1, with a water spray cooling and steam heating system (Donaldson et al., 1994). This was probably one of the first successful applications of purposeful "fresh air" into a public space, with evaporative cooling and/or heating applied to the air under manual controls.

[5] This is because reliable air-handling units were not available.

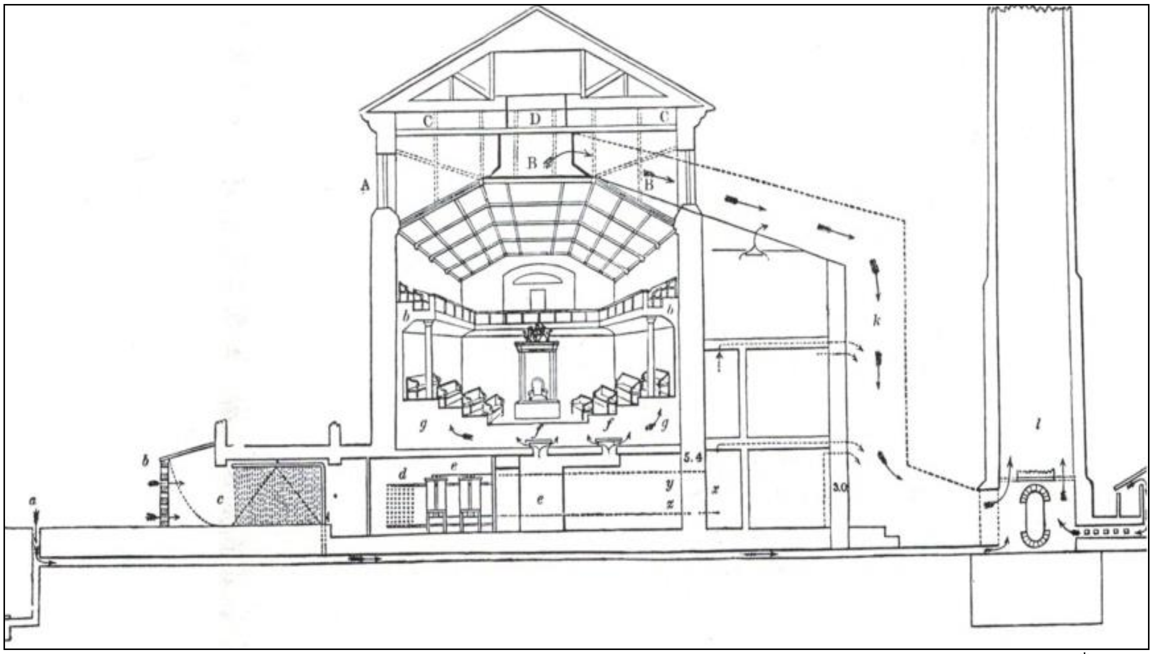

Figure 2.1: British House of Commons (Donaldson et al., 1994; with permission*)

About the same time, Eugéne Péclet, a French physicist and a heat engineer, was probably the first to introduce heat transfer calculations by publishing his textbook "*Traité De La Chaleur*" (Treatise on Heating) in 1844 (Donaldson et al., 1994; Nicholls, 1922). His work involved many aspects of heating applications, including furnaces, boilers, distillation and so forth (Pittsburgh, 1922). By calculating the CO_2 change, he suggested a desired fresh air quantity to keep the air fresh at a minimum cost. He recommended ventilation control when realizing the "hotness" feeling depending on not only the indoor temperature but also the forced ventilation that were cut-off previously. Unfortunately, few engineers and architects were aware of Péclet's work since it was written only in French and was not translated until many years after it was published. In

*Reprinted from *Heat & Cold: Mastering the Great Indoors*, Donaldson B., Nagengast, B. and Meckler G, 1994, Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Copyright 1994 by ASHRAE.

1904, some of Péclet's work was finally translated into English by Charles Paulding (Paulding, 1904).

In 1855, Robert Briggs designed and installed a heating and ventilation system for the U.S. House of Representatives (Donaldson et al., 1994), shown in Figure 2.2.

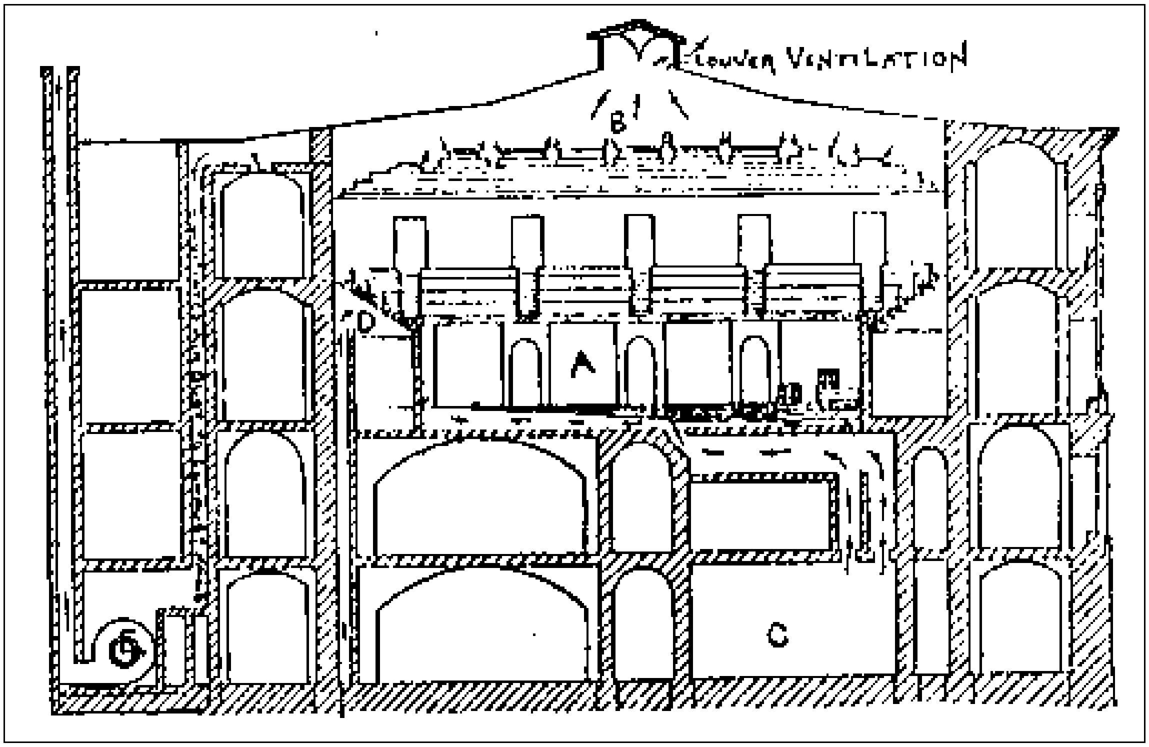

Figure 2.2: U.S. Capitol (Donaldson et al., 1994; with permission*)

His system used indirect steam heaters (i.e., underfloor radiators), a chimney[6], and subterranean airways for each wing. Engineers at that time could only count on the knowledge gained from their own practical design experience, which was often limited.

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[6] Originally, which was later replaced with a large fan.

In the U.S., useful textbooks that contained design tables and equations did not start to appear until twenty to thirty years later.

In 1884, Frank E. Kidder introduced the first version of his book "*Architect's and Builder's Handbook*" (Kidder, 1906). This book was oriented towards architects and mostly contained information from manufacturer's literature regarding the sizing of steam radiators by the determination of the room size and boiler size. Although a heat loss calculation method was included, it was described using words instead of equations. In addition, thermal mass was not considered in the HVAC system design, since all tabulated heat transfer coefficients were for steady-state calculations.

Shortly after, in 1894, a professor of the Technical University of Berlin, Hermann Rietschel published a German textbook called "*Lüftungs-und Heizungs-Anlagen*"[7] (Ventilation and Heating Systems) that was later translated into English version by C.W. Brabbee in 1927 (Rietschel and Brabbee, 1927). This book is widely recognized as Europe's first scientifically-based text on heating and ventilating. It contained relatively complete information about how to calculate heat transfer, including equations that are still in use today. It also described how to size steam systems, piping, etc., and it even provided a detailed solution to the dynamic heat transfer calculation in a single slab of wall material as well as steady-state heat loss calculations for walls, roofs, windows and ventilation. The book also included tables of useful heat transfer coefficients as well as charts and graphs with plotted properties of moist air (Usemann, 1995). Unfortunately, no formulas for moist air were included.

[7] Private communication with Mr. Bernard Nagengast.

Shortly after, in 1896, Rolla Carpenter, a professor at Cornell University, published the first version of his textbook named *Heating and Ventilating Buildings* (Carpenter, 1896). This book included theory and applications of heating and ventilating apparatus by Thomas Tredgold (1836), Charles Hood (1855), and Eugéne Péclet (1850). It also included tables of materials, properties of air and math equations, which makes it equivalent to one of today's engineering handbook.

Around the same period, in the 1890s, Alfred R. Wolff, a well-known heating and ventilating design engineer in the U.S., published his "heat transfer coefficient" chart that was derived from the previous work by Eugéne Péclet and Thomas Box. It included a graph that showed the heat loss per unit area for windows, doors and walls and ceilings of varying thickness (Wolff, 1894; cited in Donaldson et al., 1994). Wolff was regarded as one of the first U.S. engineers to use "heat transfer coefficients", and his chart that showed "varying thickness" was probably the first published graph that estimated the dynamic effect of thermal mass, shown in Figure 2.3. Wolff was the best known as the designer of the air-conditioning system[8] for the Board Room of the New York Stock Exchange[9] in 1903, which is regarded as one of the earliest commercial air-conditioning systems to be designed and operated for comfort in the U.S. (Donaldson et al., 1994).

[8] Alfred Wolff consulted Henry Torrance of the Carbondale Machine Company for this design (Donaldson et al., 1994).
[9] Two years later, in 1905, Stuart Cramer first used the term "air conditioning" for treating air in textile mills in N.C., which became widely adapted as the terminology that described artificial cooling system (Donaldson et al., 1994).

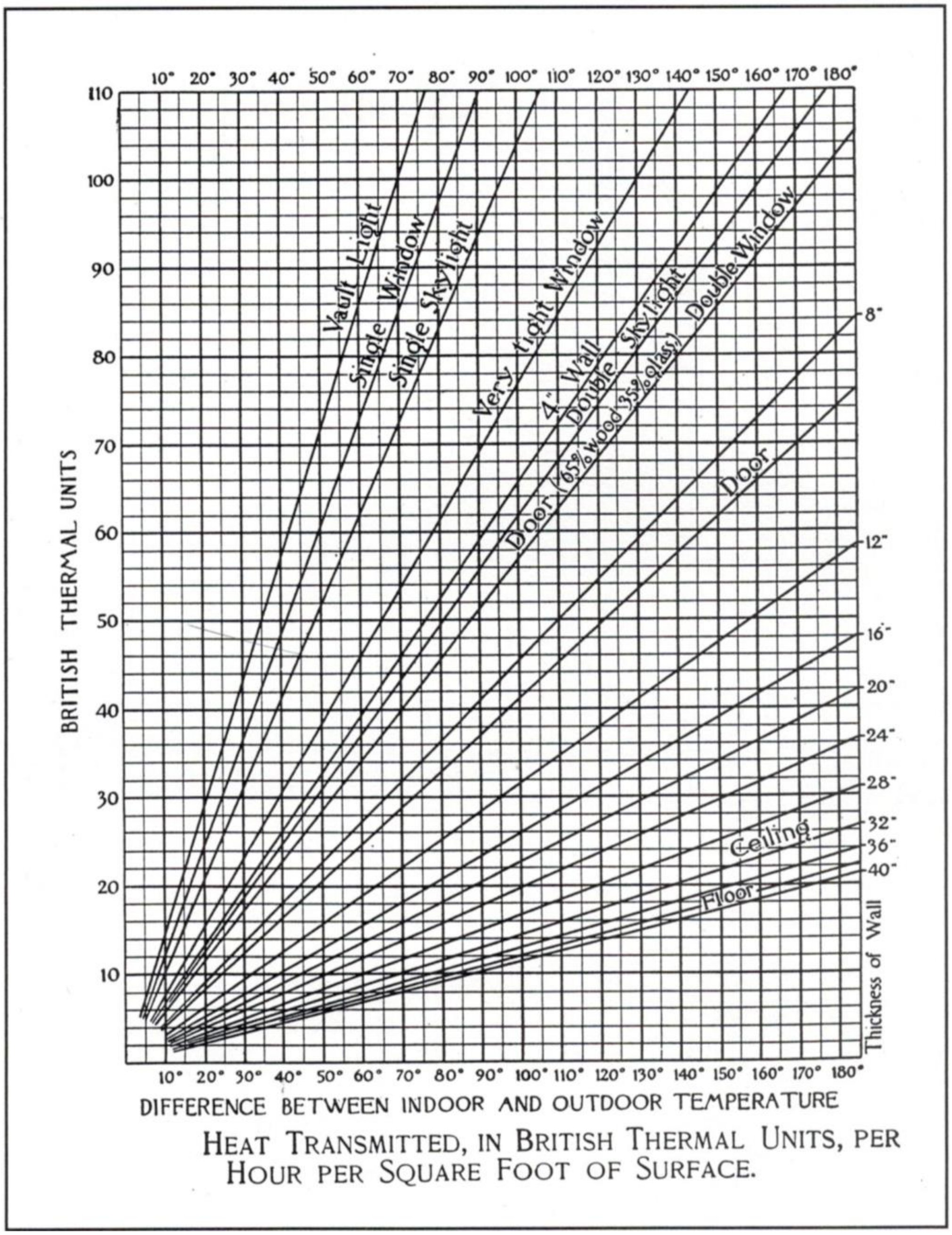

Figure 2.3: Wolff's Graph (Donaldson et al., 1994; with permission*)

*Reprinted from *Heat & Cold: Mastering the Great Indoors*, Donaldson B., Nagengast, B. and Meckler G, 1994, Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Copyright 1994 by ASHRAE.

Stepping into the 20th century, new peak cooling load methods began to be developed during the 1900 to 1945 period, including: the psychrometric chart and the governing equations for moist air (Carrier, 1911), the sol-air temperature method (Mackey and Wright, 1944) and the thermal network method (Paschkis, 1942). In 1902, a young engineer at the Buffalo Forge company, named Willis Carrier designed his first ventilation system with cooling coils for the Sackett and Wilhelms Company, in Brooklyn, N.Y. (Donaldson et al., 1994). Unfortunately, the system was not successful, because, although it could cool the air stream, it could not control the humidity inside the building. After studying the failure, Carrier determined that a spray-type air washer using chilled water could be used to control temperature and humidity[10].

In 1906, Carrier developed a complete working system and applied for a patent for an "apparatus for treating air", which allowed him to control the absolute humidity of the air stream exiting the chilled water spray (Donaldson et al., 1994). Two years later, in 1908, Carrier published his first psychrometric chart based on his psychrometric formulas[11] (Donaldson et al., 1994), shown in Figure 2.4.

[10] Information was retrieved from: http://en.wikipedia.org/wiki/Willis_Carrier
[11] Carrier's psychrometric chart was later formally published in 1911 in ASME (Carrier, 1911).

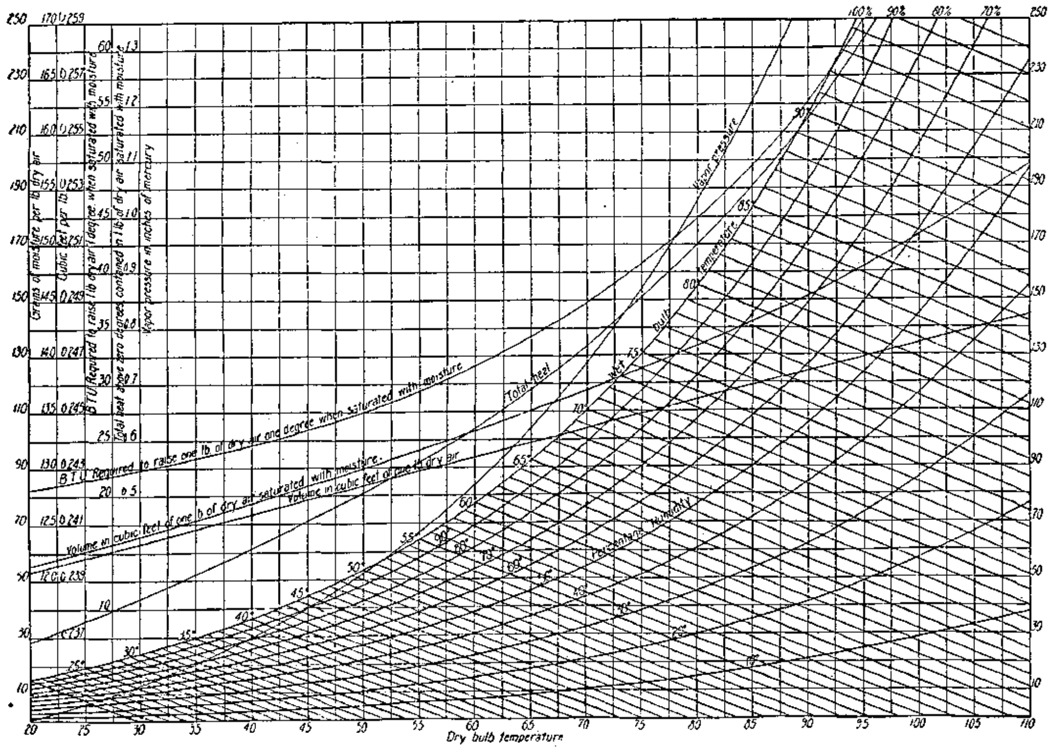

Figure 2.4: First Psychrometric Chart (Carrier, 1911; with permission*)

In 1928, Carrier designed the mechanical system for the Milam Building in San Antonio, Texas, which was the first high-rise, air-conditioned office building in U.S. (ASME, 1991), shown in Figure 2.5. In the Milam building two centrifugal refrigeration units, developed by the Carrier Company, were used as the cooling system. Unfortunately, the radiant heat that was supposed to be absorbed by the heavy exterior construction was not well understood. This resulted in the HVAC system not working as planned due to an unexpected asymmetric East-West cooling load. To remedy this,

* Reprinted from *Rational Psychrometric Formulae*, Carrier, W.H., 1911, ASME Transactions, 33, 1005-1053. Copyright 1911 by ASME.

venetian blinds, cloth window shades and duct dampers were installed and manually operated to solve morning or afternoon overheating problems (ASME, 1991).

In 1914, the Buffalo Forge Engineer's Handbook was published, which was recognized as the first comprehensive U.S. manufacturer's handbook for heating and ventilating (Carrier, 1914). It contained detailed equations for heat loss calculations for walls, roofs, windows and ventilation, including tables of useful coefficients as well as Carrier's psychrometric chart, which was the first time that a psychrometric chart was introduced in a handbook. Eight years later, in 1922, ASHVE published its first guide book, "*The American Society of Heating and Ventilating Engineers Guide*", which also had basic heat loss formula, unfortunately which were presented as "word formulas" (ASHVE, 1922).

During this period, several other useful textbooks appeared. In 1918, John R. Allen et al. published the first edition of their book "*Heating and Ventilation*" that provided detailed heat loss calculation methods that also included tables of useful coefficients and equations (Allen et al., 1931).

Shortly after Allen et al.'s book was published, Charles Merrick Gay together with Charles De Van Fawcett published their first textbook in 1935, which contained detailed equation-based calculations for heat loss and a very terse advice about how to calculate summertime heat gain[12] (Gay and Fawcett, 1937). One year later, the TRANE Company published its first design manual, which provided a load estimate sheet for engineers to

[12] In the book, they recommended the use of a rule-of-thumb method: "add 25°F to the dry bulb temperature difference for heat transmission calculation".

use (TRANE, 1938). This design manual used tabulated "solar temperature differences" and also included instructions for using the TRANE air - conditioning slide ruler[13].

Figure 2.5: The Milam Building (ASME, 1991; with permission*)

[13] This slide ruler was for use with the TRANE psychrometric chart. Interestingly, the TRANE heat transfer tables were listed according to the color of the wall, versus thermal mass characteristics.

*Reprinted from *The Milam Building, San Antonio, Texas: A National Mechanical Engineering Heritage Site. New York: ASME Book No. HH9106*. Copyright 1991 by National Mechanical Engineering Heritage.

Several important papers were also published during this period in Europe and in the U.S. In 1925 in Europe, the Response Factor Method was first introduced for transient flow calculation by André Nessi and Léon Nisolle in France (Nessi and Nisolle, 1925). In 1939 in the U.S., Alford et al. published a paper on the heat storage/heat transfer through walls driven by temperature and solar intensity in the ASHVE Transactions. Their paper provided a detailed solution to the differential equation in the form of a decrement factor and a time delay (Alford et al., 1939). Three years later, in 1942, the thermal R/C network method was first published by Victor Paschkis to calculate the dynamic heat transfer through building walls (Paschkis, 1942). Later in 1944, C.O. Mackey and L.T. Wright Jr. used a modified version of Alford et al.'s equations and proposed the "sol-air temperature method" (Mackey and Wright, 1944). Using the sol-air temperature method, the inside surface temperature of building material can be calculated using a daily average sol-air temperature, a constant indoor temperature, a decrement factor and a time lag for homogeneous walls shown in Figure 2.6. In the same year, in 1944, John G. Linvill and John J. Hess Jr. published their article "Studying Thermal Behavior of Houses", which was an undergraduate student project at M.I.T. Their article showed how the thermal R/C network method could be used to simulate the dynamic heat transfer of an entire house (Linvill and Hess, 1944).

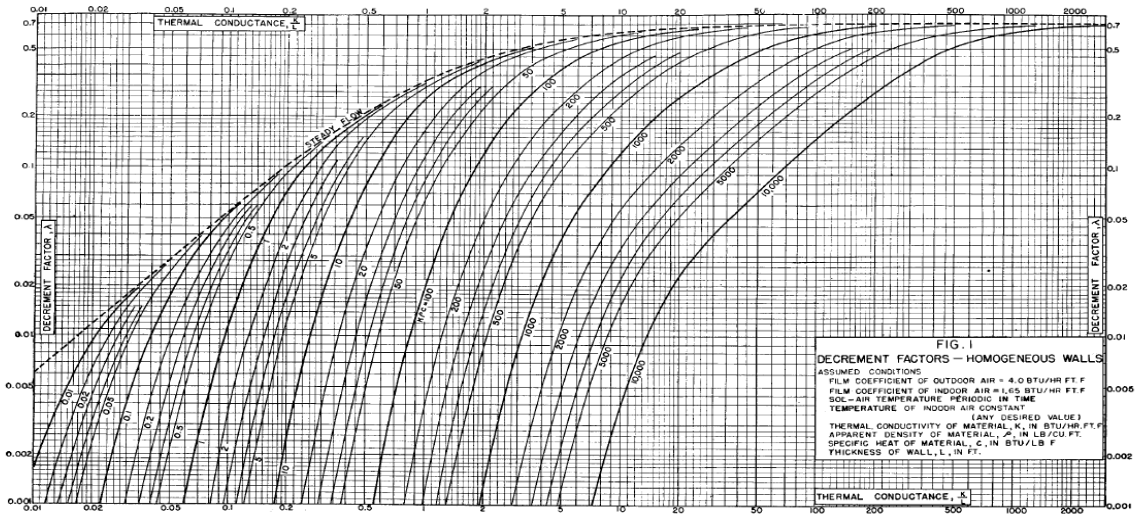

Figure 2.6: Decrement Factor Graph (Mackey and Wright, 1944; with permission*)

In summary, during the period prior to 1945, there were at best inconsistent methods for calculating peak heating and cooling loads. Some methods contained the seeds of the dynamic heat transfer calculations used today, others were rough estimation. These methods appeared in textbooks, handbooks, guidebooks and manufacturer's literature published during this period. However, during this same period, the foundation was laid for today's modern methods, which began with sol-air temperatures, decrement factors and the use of a thermal R/C network to calculate dynamic building heat gain/loss.

2.3.2 1946-1969

Most of the manual peak cooling calculation methods used today in the U.S. were proposed during the 1946-1969 period. In 1948, as a design engineer at Carrier

* Reprinted from Periodic Heat Flow – Homogeneous Walls or Roofs, Mackey, C.O. and Wright, L.T., Jr. 1944, ASHVE Journal, 16(9), 546-555. Copyright 1944 by ASHRAE.

Corporation, James P. Stewart was the first to outline Equivalent Temperature Differentials (ETD), which were based on Mackey and Wright's earlier work (Stewart, 1948), that was intended to be an easy-to-use tabulated design method that would estimate the dynamic heat gains through the walls and roofs. Stewart's ETD tables were generated under specific conditions: 1) July at 40° N Latitude; 2) maximum and minimum outdoor temperatures of 95 °F and 75 °F; and 3) a room temperature of 80 °F. If the temperature difference between the outdoor maximum design temperature and the room temperature were larger (or smaller) than 15 °F, it was suggested to use the published ETD and add (or subtract) the difference (Stewart, 1948). The ETD tables were adopted for use in the *1951 ASHVE Guide* and *1961 ASHRAE Guide and Data Book* (ASHVE, 1951; ASHRAE, 1961). Total Equivalent Temperature Difference/ Time Averaging Method (TETD/TA) were later tabulated in the *1967 ASHRAE Handbook of Fundamentals* (ASHRAE, 1967) by adding the Time Averaging (TA) Procedure and suggesting that the method was suitable for calculating extended hourly profiles only if the radiant heat gain components were averaged over the representative period for all the thermal mass of the building. Unfortunately, judging the amount of thermal mass in a building was a difficult job for an average engineer, which ultimately made the method useful only in the hands of an experienced engineer. Appendix G details the TETD/TA Method calculations.

In 1955, a new edition of Gay and Fawcett's textbook was published that included a new author, William McGuinness who was a professor of Architecture at the Pratt Institute of Technology (Gay et al., 1955). This new edition included a revised procedure for air-conditioning design, as well as improved data for calculating heat gains, which referenced the ETD tables in the *1951 ASHVE Guide*[14]. So, by the mid-1950s either the direct use of Mackey and Wright's sol-air temperature equations or the TETD/TA Method provided designers with an improved manual method to calculate the impact of thermal mass on the dynamic heat gain.

In the mid-1950, W.R. Brisken, S.G. Reque and P.R. Hill laid the foundations of today's thermal Response Factor Method (RFM), based on Nessi and Nisolle's 1925 work. In 1956, Brisken and Reque published their heat load calculations using the RFM (Brisken and Reque, 1956). In this method, they proposed using "square waves" to represent a time-varying "curve" of dynamic temperature response. One year later, Hill developed a more accurate "unit triangle" method for calculating the time-varying 1-D surface temperature (Hill, 1957). Based on these works, in 1967, Gintas Mitalas and Don Stephenson developed the thermal Response Factor Method (RFM), which allowed for the solution to the dynamic heat transfer problem without having the knowledge of how to solve a separate differential equation for each new wall type (Mitalas and Stephenson, 1967; Stephenson and Mitalas, 1967). Later, this method became part of the Transfer Function Method that is also called the Weighting Factor Method (Mitalas, 1972; ASHRAE, 1981).

Beginning in the 1940s, several authors investigated the use of thermal R/C network models for analyzing dynamic heat transfer (Paschkis, 1942; Buchberg, 1955; Nottage and Parmelee, 1954). As previously mentioned, although the first thermal R/C network

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[14] Gay et al.'s book cited the 1951 ASHVE Guide as the source of the ETD tables, which were based on Mackey and Wright's 1944 sol-air equation.

method appeared in 1942, Harry Buchberg developed a complete R/C thermal network for a house model using heat balance calculations in an analog computer in 1958. This project was an ASHRAE - sponsored project and is regarded as the first time that the Heat Balance Method and the thermal network method were used together in an analog building simulation (Buchberg, 1958), shown in Figure 2.7.

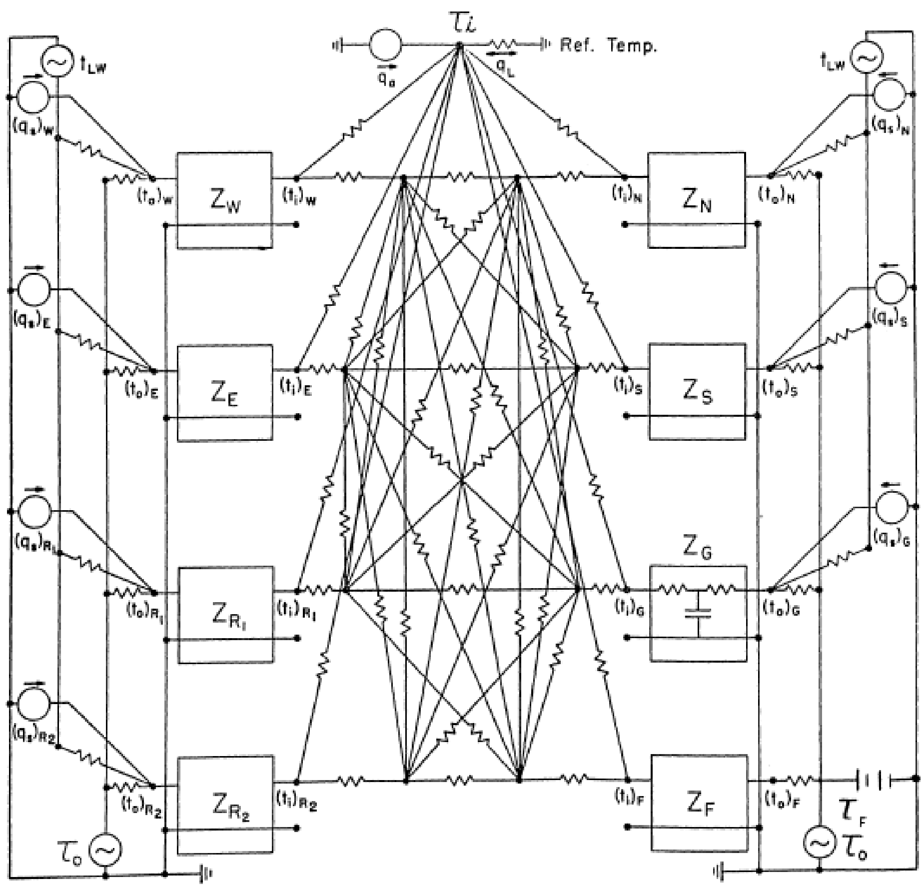

Figure 2.7: Thermal Network for a Test House (Buchberg, 1958; with permission*)

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* Reprinted from Cooling Load from Thermal Network Solutions, Buchberg, H., 1958, ASHRAE Transactions, 64, 111-128. Copyright 1944 by ASHRAE.

The Heat Balance Method was later included in the *1981 ASHRAE Handbook* along with the Weighting Factor Method (WFM) as building annual energy use calculation methods (ASHRAE, 1981).

The guide books during the 1946 to 1969 period included: the *1951 ASHVE Guide* (ASHVE, 1951), the *1955 TRANE Air Conditioning Manual* (TRANE, 1955), the *1960 Carrier Handbook of Air Conditioning System Design* (Carrier, 1960), several *ASHRAE Guide and Data Book* (ASHRAE, 1961, 1963, 1965), and the first version of *ASHRAE Handbook* (ASHRAE, 1967). In these handbooks, thermal mass was considered either using sol-air temperature calculations or the TETD/TA Method.

Besides the methods discussed above, two other widely used methods were developed about this time to solve the time-varying heat transfer problems: the Finite Difference/Finite Element Method (FDM/FEM) and the admittance method. The FDM/FEM was introduced in 1960 (Clough, 1960; Forsythe and Wasow, 1960) in the form of equations that could be directly used in computer algorithms. The admittance method was originally developed in the U.K. by A.G. Loudon in 1968 (Loudon, 1968). The concept of "Thermal Admittance" was first introduced in the U.K. in the *Institution of Heating and Ventilating Engineers Guide* (IHVE) in 1970 (Goulart, 2004) to measure the ability of building components to smooth-out the temperature swings within a 24-hour cycle. This method was later adopted by the Charted Institution of Building Services Engineers (CIBSE) and is now widely used in the U.K.

During 1946-1969 period, the first edition of ASHRAE Handbook appeared, which adopted the available peak heating and cooling load methods from important published papers. In addition, during this period, several of the popular textbooks and manufacturer's literature were updated to reflect the new methods as well. In summary, steady-state peak heating calculation methods matured and time-varying cooling load calculation methods that considered ambient temperature and solar radiation became available for designers to use.

2.3.3 1970-1989

Peak cooling load methods continued to develop during the period 1970-1989. In 1972, the ASHRAE Task Group on Energy Requirements (TGER) first introduced the Transfer Function Method (TFM) for peak cooling load calculation, which was based on Mitalas and Stephenson's earlier work (ASHRAE, 1972) and is considered the first, wide-spread, computer-oriented method for solving dynamic heat transfer problems in buildings in the U.S. (Mitalas, 1972). It utilized Conduction Transfer Function coefficients and sol-air temperatures to calculate the dynamic conduction heat gains from walls and roofs. By applying weighting factors, heat gains from all surfaces could then be converted into the room cooling load. Appendix F introduces the detailed calculation procedure of TFM.

However, even as new computer-based methods were being developed, manual, tabulated methods continued to be updated and used because many engineers could not justify the time and expense required by the computer methods. One such method, based on the principles of TFM, is the Cooling Load Temperature Difference/Cooling Load Factor Method (CLTD/CLF), which was developed by William Rudoy and Fernando

Duran in 1974 at University of Pittsburgh (Rudoy and Duran, 1974). It included tabulated results of controlled-variable tests summarized in ASHRAE research project RP-138 for cooling load calculations. The CLTD/CLF Method attempted to simplify the two-step TFM and TETD/TA Method into a single-step technique, which was later published in the *1977 ASHRAE Handbook of Fundamentals* (ASHRAE, 1977). Eleven years later, in 1988, the CLTD/CLF Method was modified by Prof. Edward Sowell at California State University who ran 200,640 simulations to provide new tabulated values (Sowell, 1988). That same year, Steven Harries and Faye McQuiston proposed additional Conduction Transfer Function (CTF) coefficients to cover more roof and wall construction groups in ASHRAE research project RP-472 at Oklahoma State University (Harries and McQuiston, 1988).

In summary, during the 1970 to 1989 period, peak heating load calculation methods remain unchanged while major advances were made in peak cooling load calculation methods, which are still taught in today's textbooks, but no longer exist in the current *2013 ASHRAE Handbook of Fundamentals* (ASHRAE, 2013a)[15].

2.3.4 1990-Present

In 1993, Jeffery Spitler et al. at Oklahoma State University updated the CLTD/CLF Method to become the CLTD/SCL/CLF Method by introducing the term "Solar Cooling Load (SCL)" for an improved solar heat gain calculation through fenestration (Spitler et al., 1993). Using Spitler et al.'s method, tables of CLTD, SCL and CLF were generated

[15] For non-residential buildings, the Heat Balance Method and Radiant Time Series Method are included in Chapter 18 for peak cooling load calculations methods in the 2013 ASHRAE Handbook of Fundamentals.

based on the TFM. Once the cooling load was obtained by the TFM, the values of CLTD, SCL, and CLF could then be calculated by dividing the surface area and overall U-factor for the tabulated wall and roof combination groups. This new CLTD/SCL/CLF Method was later incorporated into the *1993 ASHRAE Handbook of Fundamentals* (ASHRAE, 1993). Appendix H details the cooling load calculation procedure for this method.

The most current cooling load calculation method is the Radiant Time Series Method (RTSM) that Spitler et al. developed in 1997, which is an improvement over all previous methods (Spitler el al., 1997). In response to research proposed by ASHRAE Technical Committee TC 4.1, the RTSM was derived directly from, but is simpler than, the Heat Balance Method. In the RTSM, the 1-D time-varying conduction is calculated using 24-term response factors. The RTSM converts the radiant portion of hourly heat gain to hourly cooling loads using radiant time factors. The accuracy of the RTSM is similar to that of the TFM if custom weighting factors and custom conduction transfer functions were used for all components in a building.

In 1997, Curtis Pedersen et al. at the University of Illinois further developed the HBM using a model with twelve surfaces. Their published work included a complete description of the mathematical calculations for the heat balance process. (Pedersen et al., 1997). Finally, in 2001, the ASHRAE building load calculation toolkit (LOADS Toolkits) was developed by Professor Pedersen (Pedersen, et al., 2001), which provided FORTRAN source codes for the heat balance calculations. The HBM procedure is explained in detail in Appendix D.

For residential load calculations, the Residential Heat Balance (RHB) and the Residential Load Factor (RLF) methods were developed by Charles Barnaby in 2004 (Barnaby et al., 2004). In a similar fashion as the RTSM and LOADS Toolkit, the RHB method was developed to be a computer algorithm, which was also coded using FORTRAN, while the RLF method was developed to be a simplified method that could be used manually or with a spreadsheet.

In 2000, an extensive analysis was developed that compared peak cooling load calculation methods in the U.S. and the U.K. by Simon Rees at Oklahoma State University (Rees et al., 2000). This analysis concluded that the cooling load calculation methods in the U.S. and U.K. have the possibility of converging in the future.

In 2006, a spreadsheet tool was proposed by TC 4.1 volunteers to generate the custom CLTD and CLF tables using the RTSM[16] (Bruning, 2016). In this spreadsheet, for the window cooling load calculation, a window CLF table was used to combine the cooling load from both conduction and solar heat gains, which eliminated the SCL tables. However, this tool was never published by ASHRAE.

Finally in 2007, the RTSM was improved by Nigusse at Oklahoma State University (Nigusse, 2007; Nigusse and Spitler, 2010). The original RTSM uses Periodic Response Factors (PRFs) to calculate heat gains through opaque surfaces, while the improved RTSM introduced Conduction Time Series Factors (CTSFs), which are a set of dimensionless factors, to perform the calculations. In the improved method, the window solar heat gains are determined by a solar heat gain coefficient (SHGC) instead of the

[16] Personal communication with Mr. Steve Bruning in January 2016.

original shading coefficient (SC). Appendix E distinguishes the two versions of RTSM and details the cooling load calculation procedure.

2.4 Peak Cooling Load Calculation Method Comparisons

Only a few studies have shown comparisons among the five most common methods used in U.S. for calculating peak design cooling load. This section reviews the previous studies that are related to peak cooling load design methods.

2.4.1 Comparisons among the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method

Among all the ASHRAE Handbook of Fundamentals, only the 1993 and 1997 versions covered the total sensible cooling load comparisons of the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method using the same one-story office building example, located at 40° N latitude, shown in Figure 2.8 and Figure 2.9.

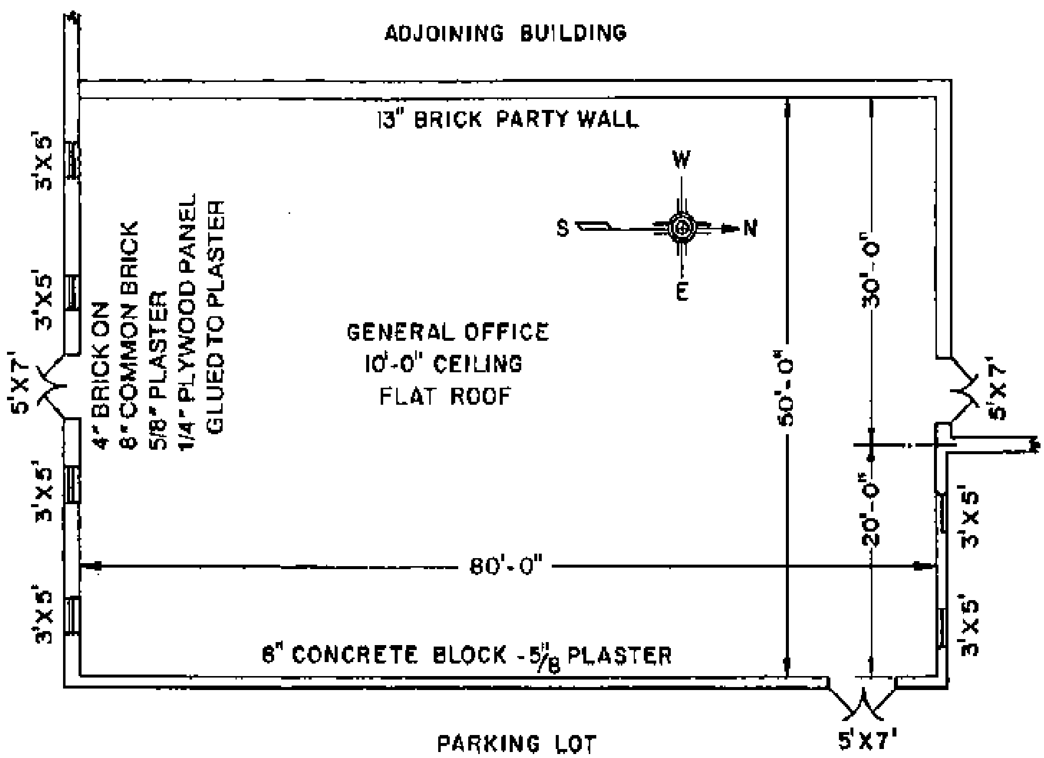

Figure 2.8: ASHRAE Example Office Building (ASHRAE, 1993; ASHRAE, 1997; with permission*)

In the previous comparison, the TFM and the TETD/TA Methods had similar dynamic cooling load profiles with the same peak time (at 4 P.M.) but they had different peak cooling load values. The TETD/TA over-predicted by 13% when compared to the TFM. Whereas, the CLTD/SCL/CLF Method presented a slightly different profile pattern in the middle of the TETD/TA and the TFM, but over-predicted by 19.8% when compared to the TFM.

However, errors found in the calculated sol-air temperatures for the TFM in the *1997 ASHRAE Handbook of Fundamentals* were reported by Al-Rabghi and Al-Johani (Al-

*Reprinted from *ASHRAE Handbook of Fundamentals*, 1993, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Copyright 1993 by ASHRAE.

Rabghi and Al-Johani, 1997). Therefore, a review of *1993 and 1997 ASHRAE Handbook of Fundamentals* was also performed in this study to further check the calculations. In this review, it was found that the sol-air temperatures of the south wall had issues with both the TFM and the TETD/TA Method, which are plotted in Figure 2.10. Without actual measurements, the sol-air temperatures were calculated based on the ASHRAE clear-sky model. As shown in Figure 2.10, the red line represents the corrected sol-air temperatures that were calculated in this study for south wall. The black and green lines represent the sol-air temperatures published in *1993 and 1997 ASHRAE Handbook of Fundamentals* for the TFM and the TETD/TA Method, respectively. In Figure 2.10, two abnormal peaks in the morning are clearly shown.

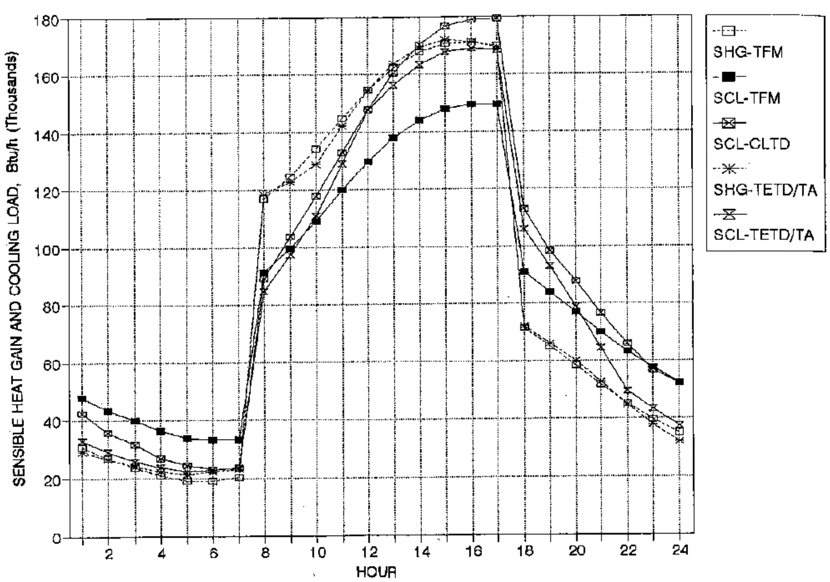

Figure 2.9: Sensible Heat Gain and Cooling Load Comparisons among the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method[17] (ASHRAE, 1993; ASHRAE, 1997; with permission*)

[17] SHG: Sensible Heat Gains; SCL: Sensible Cooling Load.

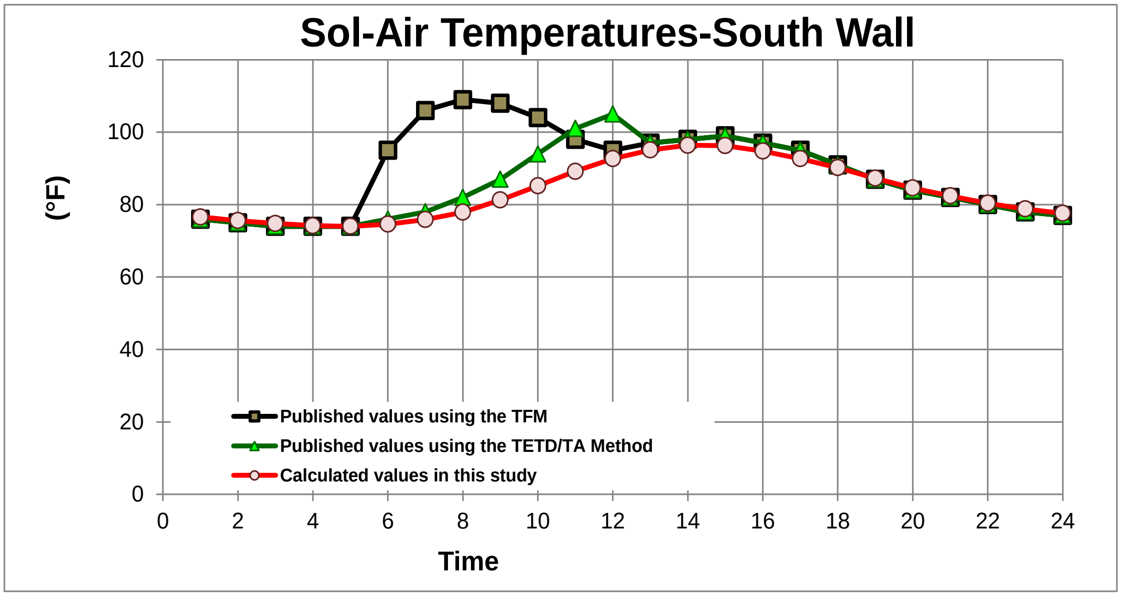

Figure 2.10: Sol-Air Temperature Check for South Wall[18] (ASHRAE, 1993; ASHRAE, 1997)

In the ASHRAE literature, the sol-air temperature calculations are the foundation of space cooling load calculations, which are usually derived from exterior solar intensities that can be estimated from ASHRAE clear-sky model. This implies that the original solar intensities on the exterior south wall may have been wrongly calculated. Therefore, the cooling load results published by *1993 and 1997 ASHRAE Handbook of Fundamentals* were determined to be not reliable, which calls into question the previous comparisons of the three methods.

Joudi and Al-badree also compared the cooling load estimated by these three methods against the measured data in 2005 (Joudi and Al-badree, 2005). To accomplish this, they set up a test room in Baqubah, Iraq, with 33.3°N latitude and 44.1° E

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[*]Reprinted from *ASHRAE Handbook of Fundamentals*, 1993, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Copyright 1993 by ASHRAE.

[18] The data used for plotting was from *1993 and 1997 ASHRAE Handbook of Fundamentals*.

longitude. The building had a medium weight with an air-conditioning unit installed to control indoor dry bulb indoor temperatures to be constant at 26°C (78.8° F). The hourly outdoor dry bulb temperatures, indoor dry bulb temperatures and air velocities were measured for May 21st, June 21st, July 21st, August 21st, and September 21st in 2004. The peak cooling load estimations were then performed for the design days using the TFM, the TETD/TA Method, the CLTD/SCL/CLF Method. Their study showed a large difference between the measured and predicted cooling load for all three methods, which were 36%, 33% and 40 % percent differences for the CLTD/SCL/CLF Method, the TFM, and the TETD/TA Method, respectively. These comparisons were performed using one type of building construction. In general, although this study had very different results, it is viewed as an important reference rather than a final conclusion for three method comparisons.

2.4.2 Comparisons among the HBM, the RTSM, and the Admittance Method

A comparison of cooling load calculation procedures published by ASHRAE/CIBSE was also performed in ASHRAE Project RP-942, which resulted in four papers (Spitler and Rees, 1998; Rees et al., 1998; Rees and Spitler, 1999; Rees et al., 2000). The focus of this project compared the HBM, the RTSM and the admittance method.

In general, European countries use the admittance method for peak cooling load calculations. It was first developed by A.G. Loudon (Loudon, 1968) at the Building Research Station to calculate summertime temperatures in buildings, and later adopted by the CIBSE in Guide A (originally, named IHVE Guide) in 1970. In the admittance method, instead of just referencing the zone air temperature, the admittance method relies on two nodes inside the building: the zone air temperature node and the environmental temperature node, where the “environmental temperature node” is a hypothetical node that was introduced by Loudon to take account of the effects of the mean radiant temperature (MRT) on heat losses because the heat is transferred to the surfaces of exposed panels by long-wave radiation from other room surfaces as well as by convection from air. CIBSE also published a so called “cyclic” model to predict dynamic heating and cooling loads of buildings (CIBSE, 2006). This cyclic model includes both a steady-state and a fluctuation model, which assumes that all fluctuations are sine waves with a period of 24 hours.

Spitler and Rees performed a quantitative comparison of the North American and U.K. cooling load calculation procedures in 1998 (Spitler and Rees, 1998). The comparison detailed all parameters and calculation tools that were used. In the same year, Rees et al. published the results of the comparison of these three methods (Rees et al., 1998). In their comparison over 7,000 combinations of tests were performed. Compared to the HBM, they found that the RTSM significantly over-predicted the peak cooling loads under the condition of large amounts of single-pane glazing, which reached as high as a 37% difference. For other cases, the RTSM was generally well behaved. The study also showed the admittance method over-predicted the peak cooling load for heavy-weight cases, but under-predicted the peak cooling load for light weight cases. One year later, in 1999, Rees and Spitler proposed a diagnostic test procedure for building loads (Rees and Spitler, 1999). In this study, several tests were performed using the HBM, the RTSM and the admittance method to diagnose problems, errors, and deficiencies in the models used in the methods.

In the published results, a qualitative comparison of the HBM, the RTSM and the admittance method was presented by Rees et al. (Rees et al., 2000). In the comparison, the different nodal networks were compared as well as the calculation procedure flow charts. Rees et al. showed the HBM approach was the most detailed method to simulate the physical heat transfer process. In addition, Rees et al. showed both the RTSM and the admittance method use a two-step procedure. In the first step of the RTSM, all types of heat gains were calculated and then converted to a cooling load in the second step. In contrast, they showed the admittance method calculated the steady-state components first and then considered the fluctuating components of the loads.

2.4.3 Comparisons among the HBM, the RTSM, the TFM and the TETD/TA Method

Since in the *2001 ASHRAE Handbook of Fundamentals*, detailed information about the TFM, the TETD/TA Method and the CLTD/SCL/CLF Method have been removed. Only the HBM and the RTSM remain in current edition of the Handbook of Fundamentals. In the last section of Chapter 29 in the *2001 ASHRAE Handbook of Fundamentals*, a simple comparison between the HBM, the RTSM, the TFM, and the TETD/TA Method was presented using the example previously included in the *1997 ASHRAE Handbook of Fundamentals*, shown in Figure 2.11. However, the calculation errors in the sol-air temperatures for the south wall of the example that were demonstrated in Section 2.4.1 in this study, remained in the printed text. Therefore, the comparison in the *2001 ASHRAE Handbook* may not be the most accurate.

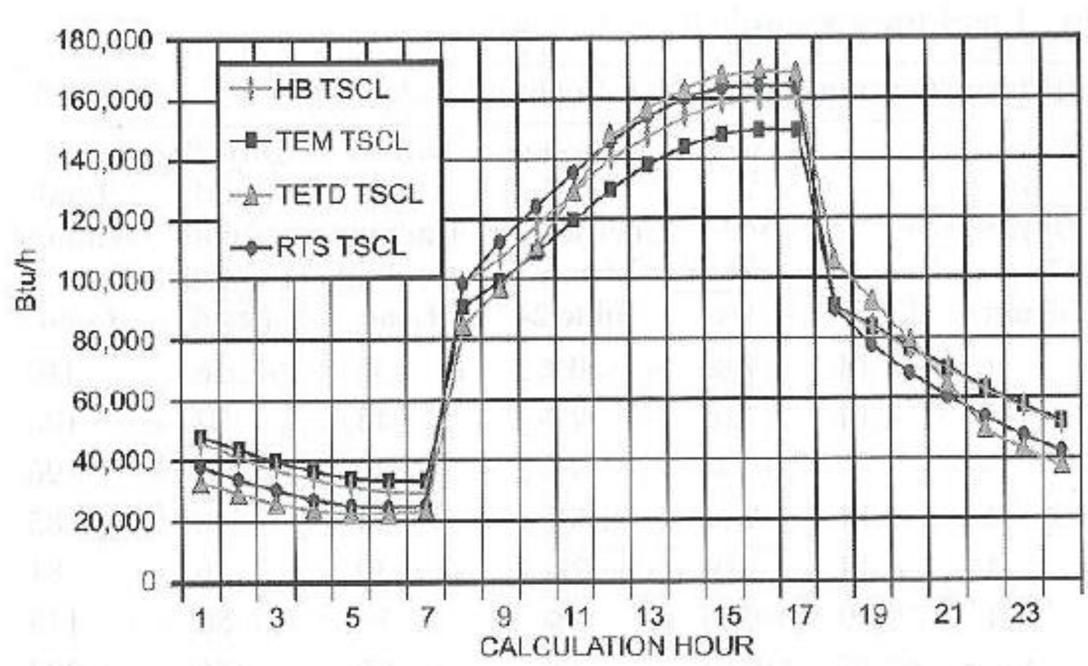

Figure 2.11: Total Sensible Cooling Load (TSCL) Comparisons of the HBM, the RTSM, the TFM, and the TETD/TA Method[19] (ASHRAE, 2001; with permission[*]).

2.5 Summary

Prior to the 1944 sol-air temperature method developed by Mackey and Wright (1944) and the ETD tables by Stewart (1948), there were no widely-used design methods for calculating time-varying peak cooling loads in the U.S. To design building HVAC systems during this period, engineers and architects had to refer to manufacturer's

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[19] The TEM in the data label table is a typo. It was supposed to be TFM representing the Transfer Function Method. The example building is the same as the one used in the *1993 and 1997 ASHRAE HOF*.

[*] Reprinted from *ASHRAE Handbook of Fundamentals*, 2001, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Copyright 2001 by ASHRAE.

literature, textbooks, guidebooks or their own experiences, which varied widely. The earliest textbooks include: Eugéne Péclet (1844), Hermann Rietschel (1894), Rolla Carpenter (1896), Charles Paulding (1904), Frank Kidder (1906), John Allen (1935), Charles Merrick Gay and Charles De Van Fawcett (1937). In addition, manufacturers like Trane and Carrier developed and used their own methods, which were eventually published (TRANE, 1938; Carrier, 1914). Interestingly, prior to 1944, building peak heating load calculation methods primarily used "word formulas" to describe the calculation procedure, which may be due in part to the difficulty and expense of type-setting the complex formula in the published text. In the U.S., building peak cooling load calculations began with the decrement factor by Alford et al. in 1939, which provided the foundation for the sol-air temperature method later developed by Mackey and Wright in 1944.

In 1948, Stewart developed the Equivalent Temperature Differentials table from the sol-air temperature equations of Mackey and Wright, which resulted in the ETD tables published in the *1951 ASHVE Guide* and *1961 ASHRAE Guide and Data Book*. The ETD tables were the foundation of TETD/TA Method later introduced in *1967 ASHRAE Handbook of Fundamentals*.

The thermal response factor method was introduced by Mitalas and Stephenson in 1967, based on the previous work done by Nessi and Nisolle (1925), Hill (1957), and Brisken and Reque (1956). In 1958, the heat balance and thermal network methods were demonstrated by Buchberg (1958) for simulating a house on an analog computer as part of an ASHRAE sponsored research project. In 1972, ASHRAE Task Group published the TFM for calculating dynamic heat transfer, which laid the basis for the CLTD/CLF Method that was later modified by Sowell (1988), Harries (1988), McQuiston (1988), and Spitler (1993) to become the CLTD/SCL/CLF Method.

In 1993, Spitler et al. published the RTSM for dynamic peak cooling load calculations. The RTSM served as a foundation for the residential RHB and RLF methods developed by Barnaby in 2004. Finally, ASHRAE released its LOADS Toolkit, developed by Professor Curtis Pedersen at the University of Illinois, which included FORTRAN code for the HBM in 2001. Today, all five methods (i.e., TETD/TA Method, TFM, CLTD/SCL/CLF Method, RTSM, HBM) remain in use in the industry. However, only the HBM and RTSM are referenced in the ASHRAE Handbook of Fundamentals since the 2001 edition.

Also, several studies were reviewed that compared the existing methods, including: comparisons of the TFM, the TETD/TA and the CLTD/SCL/CLF; comparisons of the HBM, the RTSM, and the admittance method; and comparisons of the HBM, the RTSM, the TFM, and the TETD/TA Method. However, mistakes related to sol-air temperature calculations were discovered by Al-Rabghi and Al-Johani as well as the current study. Therefore, the comparison results may not be as reliable as once thought. In addition, in the ASHRAE Handbook comparisons, the shown example was one building configuration in one climate. No other cases were identified that presented results for different climates. Therefore, there is a need to revisit and compare all five peak cooling load methods.

CHAPTER III

METHODOLOGY

3.1 Overview

This Chapter presents details about the research methodology used for the current study, which is shown in Figure 3.1. The methodology used in the current study is composed of four tasks: a survey and interview; the RP-1117 base-case comparison; the additional case-study comparison; and the proposed modifications to the CLTD/SCL/CLF Method.

The survey and interview were performed to better understand the actual peak cooling load design process used in the HVAC field. By surveying and interviewing the HVAC field professionals, the use of the HBM, the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method were reviewed, as well as the pros and cons of each methodology.

Next, a quantitative analysis was performed to thoroughly compare the current five methods using selected data from the published case studies from the ASHRAE RP-1117 report. Base-case comparisons were then performed using as-built building information in the report. In addition, an extended analysis of the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method was performed. Furthermore, in order to study fenestration heat gain impacts on the space sensible cooling loads predicted by the five methods, fifteen additional study cases were designed and analyzed. Finally, an update to the SCL tables was proposed to modify the CLTD/SCL/CLF Method, since the fenestration heat gain model in the CLTD/SCL/CLF Method is out-of-date compared to the RTSM.

3.2 Survey and Interview

The survey and interview process is shown in Figure 3.2. To begin with, a potential participant list was obtained from the ASHRAE Houston Chapter. All candidates were building design professionals who were active in the design field. Next, research questions were developed for the survey form and the phone interview. The whole process consisted of two parts: a written survey; and a phone interview. The written survey form was intended to be a quick way to obtain a basic set of information. The phone interview was designed to obtain additional details about the questions in the written survey.

Before the survey was conducted, an approval from Institutional Review Board (IRB) was obtained. The IRB submission included:

- Contact list;
- Designed survey form;
- Designed interview questions;
- Consent information sheet;
- Recruitment email.

The approval letters are shown in Appendix A.

Once the IRB approval was received, a recruitment email was sent to each potential candidate in the list. If the candidates were willing to participate in the study, the one-page written survey form was sent to obtain the general survey information. After the survey was performed, the participants were asked whether they were willing to participate in a phone interview. If they answered yes, a 15-minute phone interview was scheduled and the design interview questions were presented. The survey and interview results were analyzed in the final step.

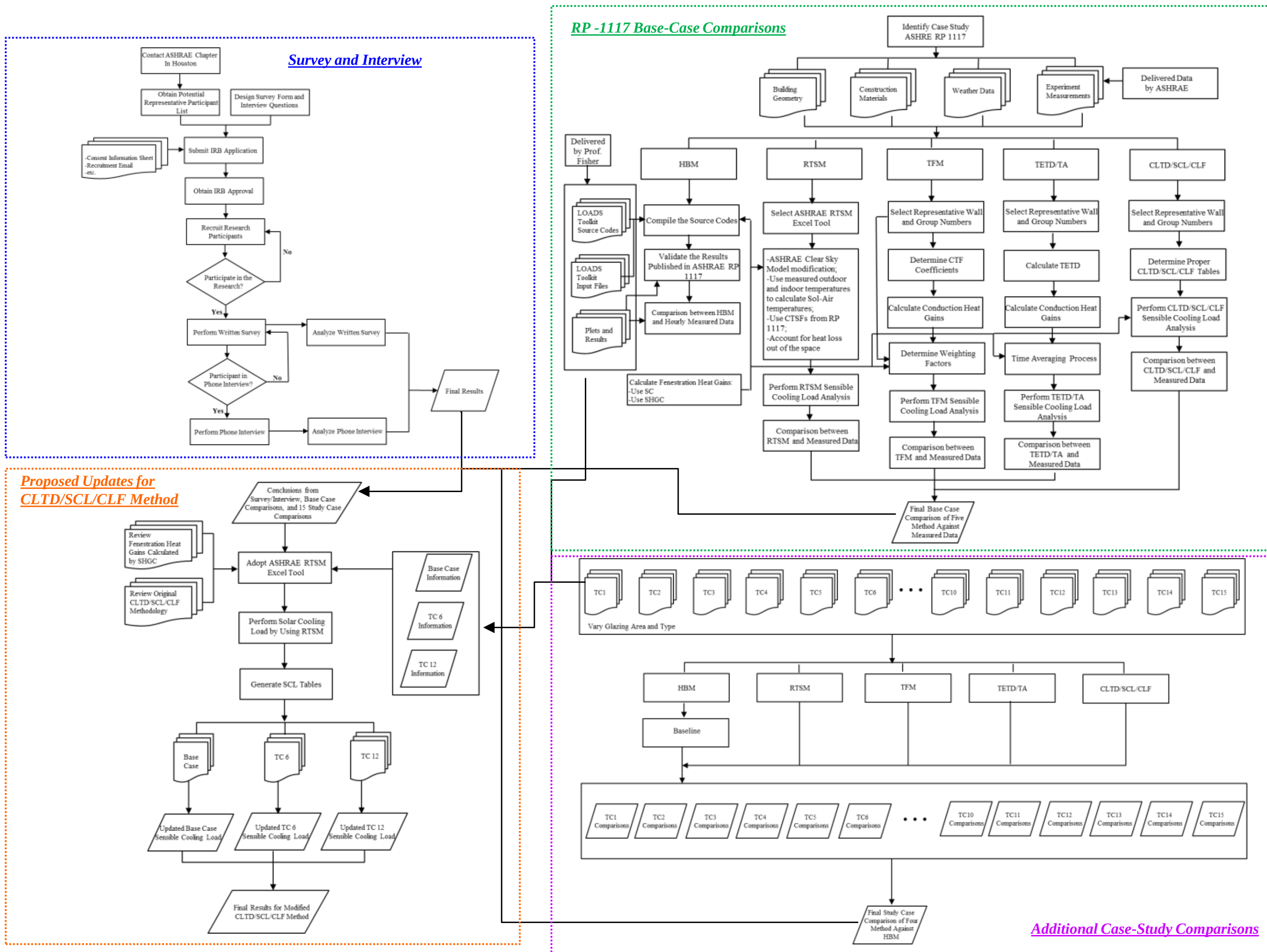

Figure 3.1: Overview of Research Methodology

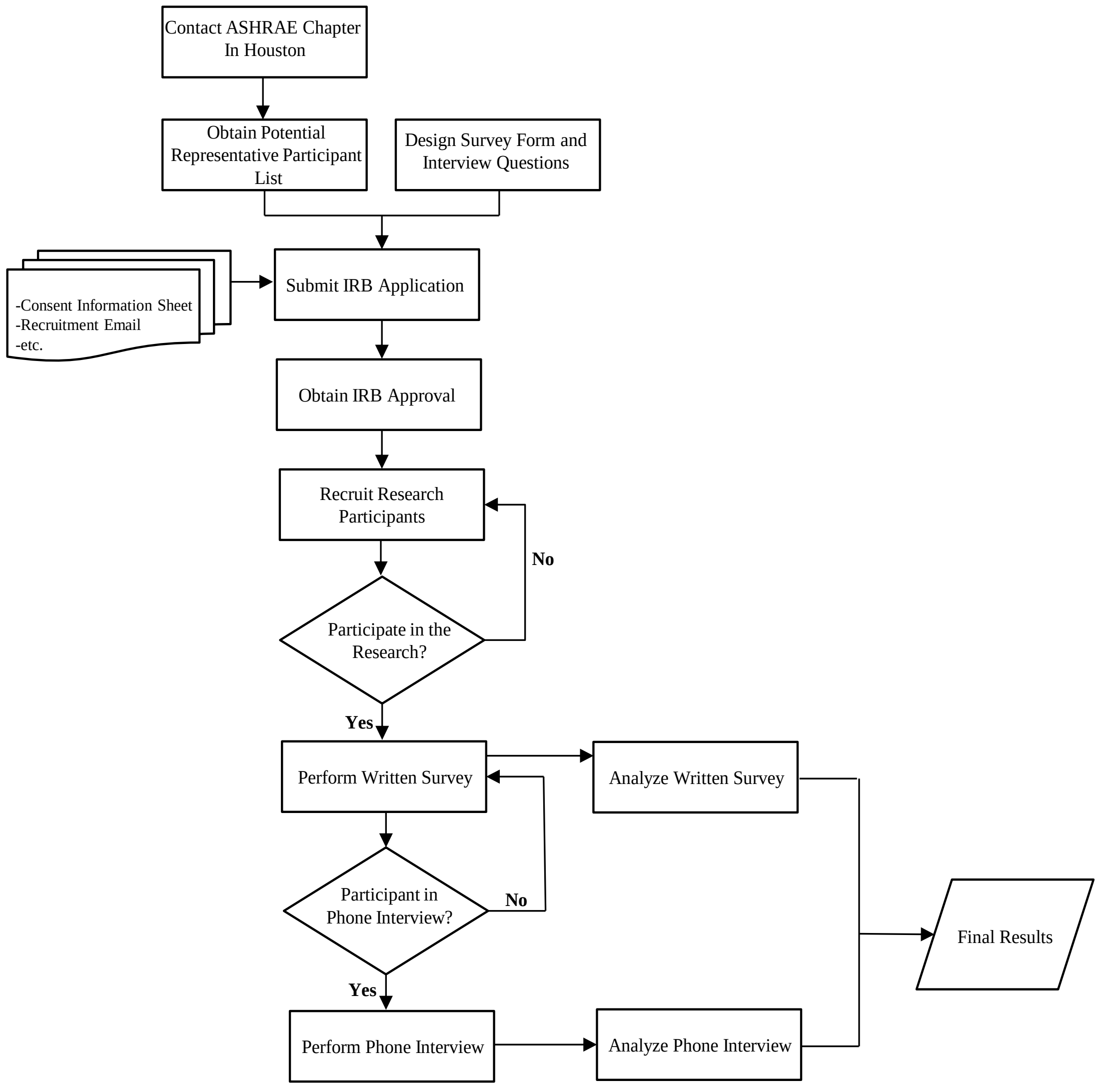

Figure 3.2: Survey and Interview Process

3.3 Analysis and Comparison of Peak Cooling Load Design Methods Using the RP-1117 Data

The analysis and comparison of peak cooling load design methods is the core of this study. It included a base-case and additional study-case analyses comparisons. Both studies compared the sensible peak cooling load predicted by the HBM, the RTSM, the

TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method. In both analyses, only the building envelope load was studied, which did not cover the effects of internal heat gains, different HVAC system configuration, and plant. In all cases, one simplified case-study building in the RP-1117 project was used to help identify differences in the specific envelope components of the peak cooling load.

3.3.1 RP-1117 Base-Case Analysis and Comparisons of Cooling Load Methods

The base-case study uses the published data from the ASHRAE RP-1117 report and additional data provided by contacting authors of RP-1117 report (Fisher, 2015). The analysis and comparison procedure is shown in Figure 3.3.

3.3.1.1 HBM Validation Analysis

Since the ASHRAE RP-1117 project adopted the ASHRAE LOADS Toolkit as the primary tool to perform the HBM analysis, it was determined that it was necessary to verify the published simulation results in this report. Unfortunately, the first attempt to replicate the analysis failed when using the published ASHRAE LOADS Toolkit CD and associated source codes. So the author of RP-1117 report was contacted and a separate FORTRAN code and data files used in the RP-1117 were provided (Fisher, 2015).

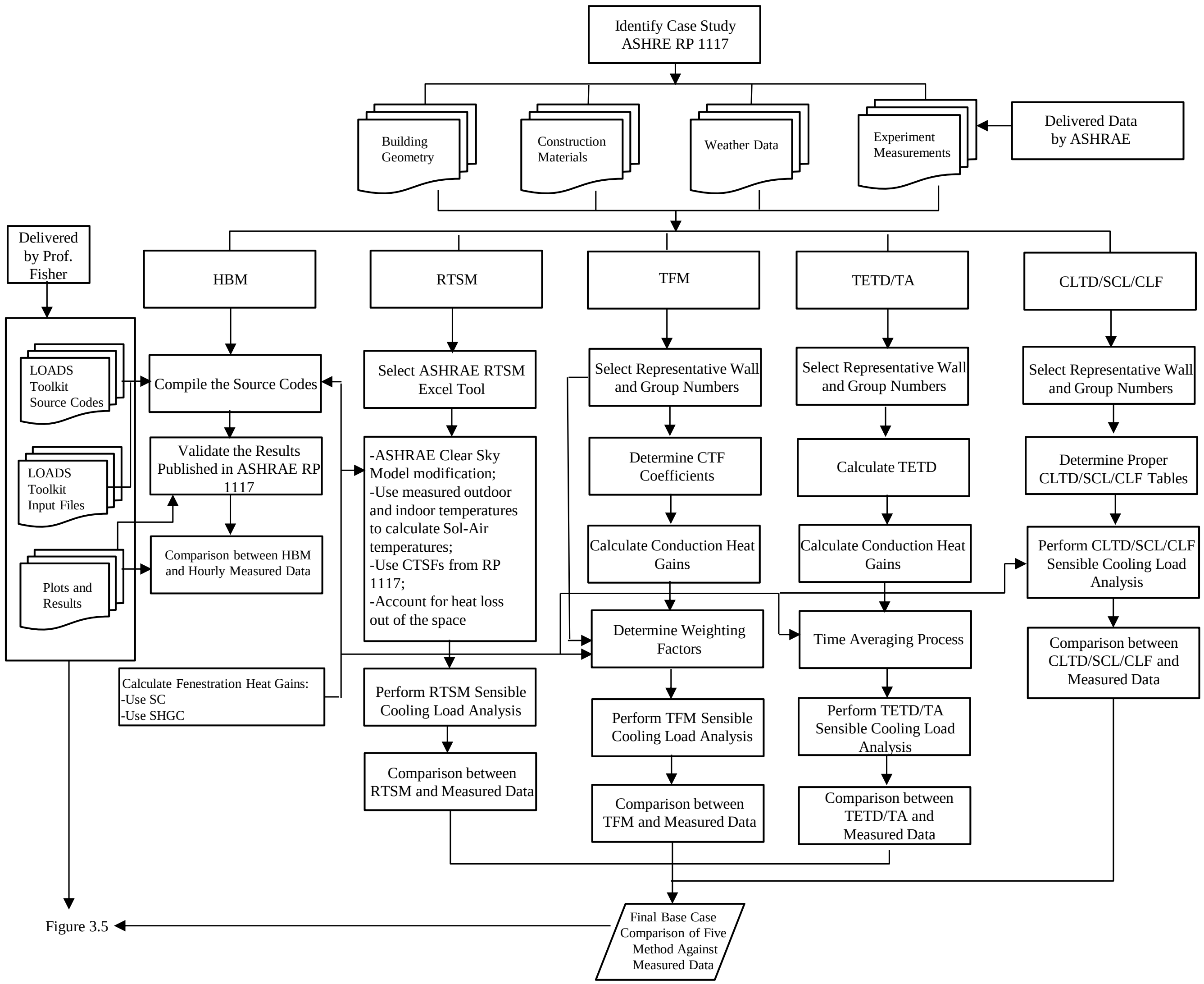

Figure 3.3: Base Case Analysis and Comparison Process

Once these were successfully compiled, the analysis was repeated and the results of the RP-1117 report were reproduced.

In reviewing the HBM source codes, it was also found that the ASHRAE clear-sky model had differences with the published models, which are the 1967 ASHRAE clear-sky model (ASHRAE, 1967-2005) and 2009 clear-sky model (ASHRAE, 2009-2013). The 1967 ASHRAE clear-sky model utilizes A, B, C coefficients and has two sets of numbers have been found, which are shown in Table B.1 and Table B.2 in Appendix B. The 2009 ASHRAE clear-sky model uses a different algorithm that is shown in Section B.2.2 in Appendix B.

In addition, prior to the analysis, it was found that the published measured sensible peak cooling load data was provided with 15-min interval. In order to compare the measurements against other methods that provided the hourly sensible cooling load only, the 15-min data was converted into hourly data.

3.3.1.2 RTSM Analysis

ASHRAE published a spreadsheet tool to perform the RTSM analysis (Spitler, 2009), which was adopted as the primary tool in this study. However, to adapt the tool for the current study, several modifications were made to use actual measured indoor, outdoor temperatures rather than the temperatures from peak design conditions that are provided with the tool. Originally, the RTSM Visual Basic for Application (VBA) source codes uses the 1967 ASHRAE clear-sky model with the second sets of coefficients. Therefore, to be consistent with the HBM used in RP-1117, the first sets of values were used in this study. In the RP-1117 report, the solar heat loss was calculated and subtracted from the total solar heat gains, which was also included in the spreadsheet tool. Finally, the sensible cooling load was estimated from this RTSM Spreadsheet Tool and compared to the hourly measured data.

3.3.1.3 TFM Analysis

The accuracy of the TFM depends significantly on the how well representative wall and roof group numbers that are selected by the peak load designer match the building being studied. Using the building geometry and construction material layers defined in the RP-1117 report, the proper group combinations were chosen for this study, as well as the published default tables by ASHRAE so the Conduction Transfer Function coefficients could be determined (ASHRAE, 1997). Next, the conduction heat gains were calculated.

During this process, it was also noticed that the last published version of TFM still recommended using the Shading Coefficient (SC) to calculate fenestration heat gains (ASHRAE, 1997). Starting from the 2001 ASHRAE Handbook of Fundamentals, the TFM was eliminated from the Handbook and replaced with the HBM and the RTSM peak cooling load calculation methods. As the RTSM was developed, the fenestration model was updated to use the new angular Solar Heat Gain Coefficients (SHGC) instead of the older SC method. A comparison of the two fenestration models is provided in Appendix C. In this study, the most recent SHGC fenestration heat gain model was used in the TFM analysis, which could provide more precise estimation for solar heat gains coming into the space.

After all the heat gains were calculated, the next step was to determine the corresponding weighting factors, which were obtained through TFMTAB.EXE (McQuiston and Spitler, 1992). The software is shown in Appendix F. Finally, the sensible cooling load using the TFM was analyzed. The comparisons between the TFM and measured data were then performed.

3.3.1.4 TETD/TA Method Analysis

In the same fashion as the TFM, once the wall and group combination group numbers were determined, the hourly TETD was calculated using the corresponding time lag and decrement factor (ASHRAE, 1997). The conduction heat gains were then calculated by multiplying TETD by the UA. Next, the time averaging process was performed. Finally, the sensible cooling predicted by the TETD/TA Method was calculated and the comparison was made against measured cooling load.

3.3.1.5 CLTD/SCL/CLF Method Analysis

Similarly, the wall and roof group numbers were selected for the CLTD/SCL/CLF Method. The best selection was made to better represent the current case study. The CLTD and SCL tables for the correct latitude and month were generated by CLTDTAB. EXE program (McQuiston and Spitler, 1992). Additional details are provided in

Appendix H. Finally, the sensible cooling load using CLTD/SCL/CLF Method was calculated and the comparison was made against the measured data.

3.3.1.6 Comparison of All Methods Against the Measured Data

With all individual peak cooling load estimated, the final comparisons between the HBM, the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method were performed.

3.3.2 Additional Case-Study Analysis and Comparisons of the Cooling Load Methods

To further understand the influence of glazing area on the sensible peak cooling load estimation by all five methods, fifteen additional test cases were used in the comparison. The procedure is shown in Figure 3.4, starting with the entry of all information for each case for the HBM, the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method. In all comparisons, the sensible peak cooling load by the HBM was regarded as the baseline to be compared against.

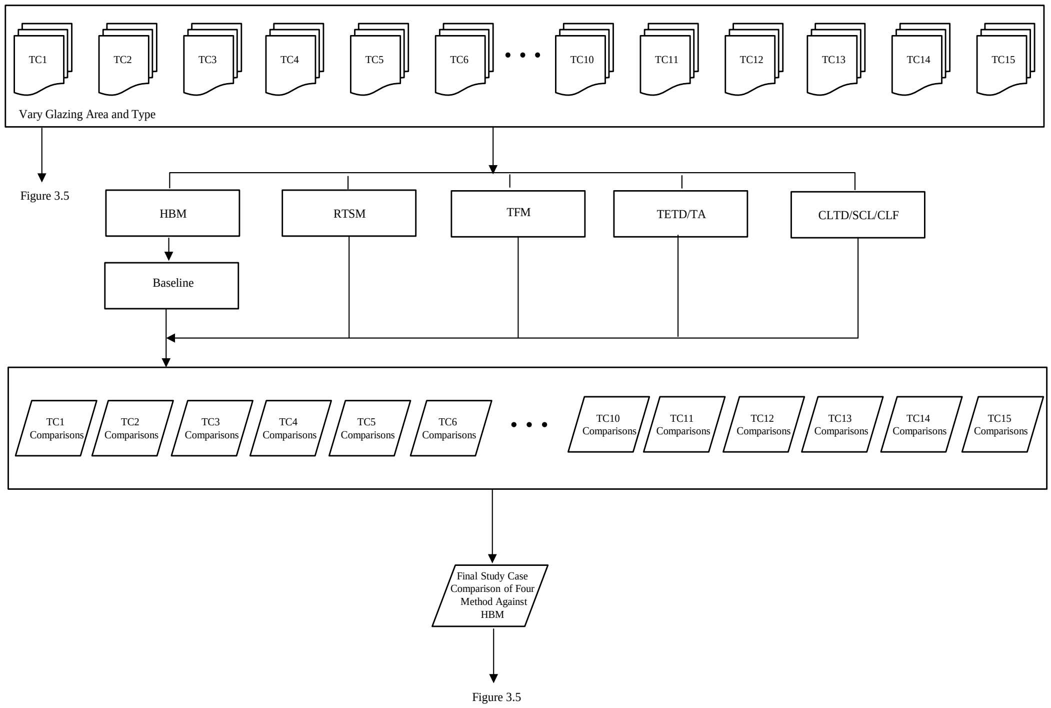

Figure 3.4: Study Case Analysis and Comparison Process

3.4 Proposed Analysis to Update the SCL Tables for the CLTD/SCL/CLF Method

In the current study, a proposed procedure to update the SCL tables for the CLTD/SCL/CLF Method is presented, as shown in Figure 3.5. The motivation for this was from the survey and interview results as well as the comparison results, which showed that the CLTD/SCL/CLF Method was still in use more than any of the other methods. But, it performed the worst in predicting peak cooling loads among all the methods. The comparison showed the RTSM was the most recommended method among all the simplified methods, and the HBM was the most accurate method of all the methods. However, the HBM did not provide a detailed breakdown for the peak cooling load components that was provided by the RTSM. Therefore, the generation of the new SCL tables was based on the RTSM.

As previously mentioned in the Section 2.3.4, in 2006, a spreadsheet tool was proposed by TC 4.1 volunteers to generate the custom CLTD and CLF tables using the RTSM (Bruning, 2016). In this tool, for the window cooling load calculation, a window CLF table was used to combine the cooling load from both conduction and solar heat gains, which eliminated the SCL tables.

Differently, the current study approach focuses on updating the SCL tables only to improve the accuracy of the CLTD/SCL/CLF Method. This is because the solar cooling load calculation by ASHRAE CLTD/SCL/CLF Method uses the published SCL tables and the Shading Coefficient (SC) instead of the Solar Heat Gain Coefficient (SHGC) method. Therefore, there is a need to update the SCL tables to reflect the more accurate values from the SHGC fenestration heat gain model. To accomplish this, a new term called "$SCL_{Modified}$" was derived from the fenestration solar heat gain calculation using the RTSM principles. This resulted in a new equation to calculate the solar cooling load by multiplying the $SCL_{Modified}$ by window area time the product of the normal SHGC and the Interior Attenuation Coefficients (IAC). The modified SCL tables were then updated using the same format of the original SCL tables. An example of how to use the potential ways to generate the SCL tables was also provided.

In this analysis, three representative cases were chosen, which included a base case (single-pane clear glazing), a TC6 case (double-pane clear glazing), and a TC12 case (triple-pane clear glazing). To accomplish this analysis, all information was loaded into the ASHRAE RTSM Spreadsheet Tool. Next, in the same fashion as the original SCL tables, all nine orientations of the windows were analyzed, including N, NE, E, SE, S, SW, W, NW, and Horizontal. The solar cooling load from both the beam and diffuse solar heat gains were then calculated with the RTSM tool. The SCL was next determined by dividing the hourly sensible cooling load by the surface area and normal SHGC. Finally, the new SCL numbers replaced the old SCL values and the modified sensible cooling load results were obtained.

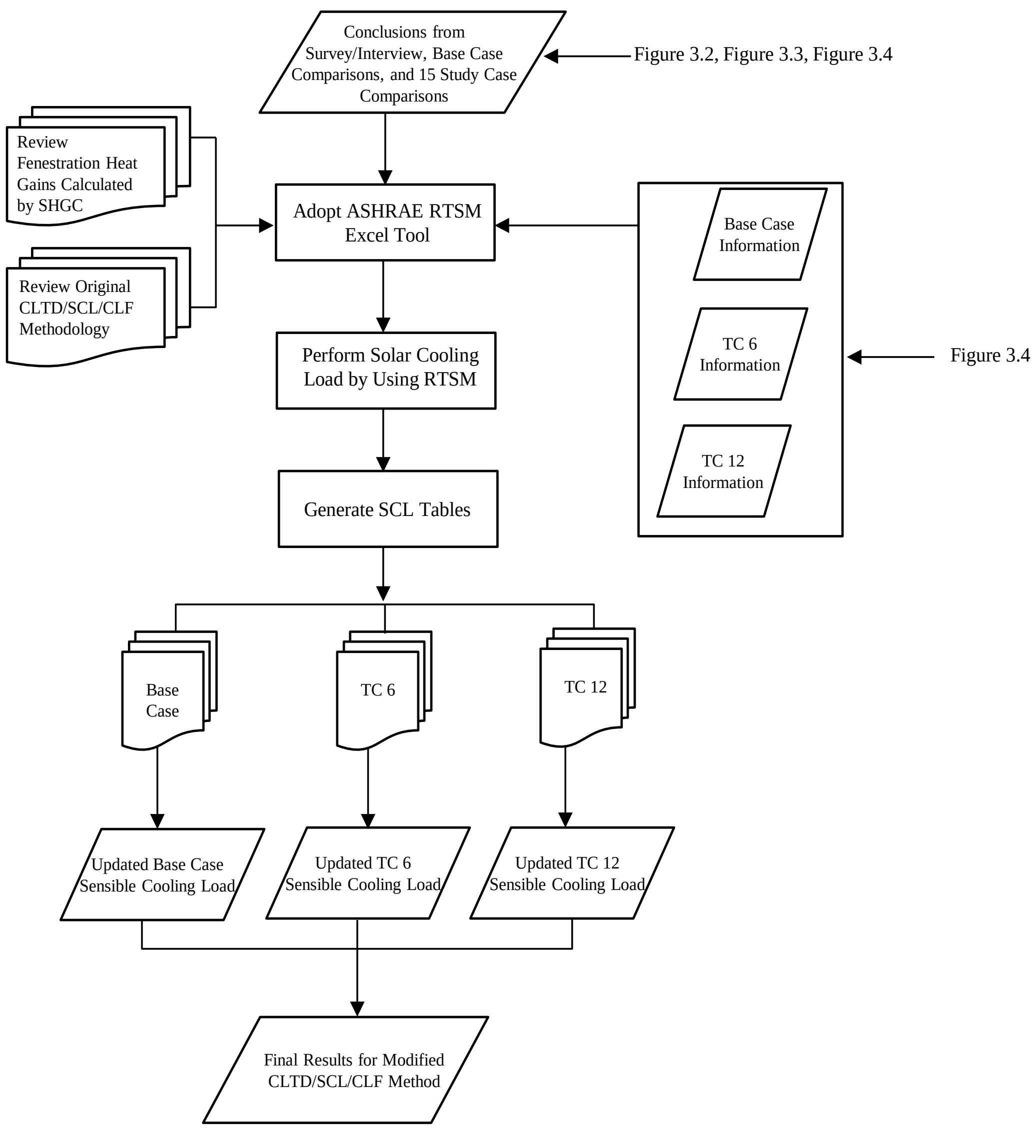

Figure 3.5: Procedure of CLTD/SCL/CLF Method Updates

CHAPTER IV

RESULTS OF THE STUDY

This chapter includes three parts of the results:

-Part I Results of survey and interview;

-Part II Base-case analysis and comparison of peak cooling load design methods;

- Part III Additional case-study comparison of the peak cooling load design methods.

4.1 Part I: Results of Survey and Interview

4.1.1 Overview

This section presents the results of a survey and interview process regarding the use of building peak cooling load calculation methods in the design of today's commercial buildings. After the IRB approval[20], the procedures used in the survey and interview process were conducted in two phases. In Phase One, the selected candidates were asked to fill-out a one-page survey form to gather general information about the participants, such as: their knowledge background; types of buildings they have designed; the methods that were used to design the buildings, etc. In Phase Two, if the candidates were willing to continue, a 15-minute phone interview was scheduled to discuss the advantages and disadvantages of the different peak cooling load design methods and the tools that are being used in the field with each participant.

Originally, thirty-one candidates were selected, who were representative of HVAC design professionals in the U.S. These candidates were invited to participate in the study

[20] The IRB approval letters are shown in Appendix A.

through the ASHRAE Chapter in Houston, TX. Eleven candidates agreed to participate in the survey study (Phase One) and nine candidates agreed to perform both the survey and interview (Phase One + Phase Two). The name of candidates were coded as Selected Field Professional (SFP) and kept confidential, in compliance with IRB requirements.

4.1.2 Survey Results

The pre-designed one-page survey was sent to each SFP candidate through the recruitment email (shown in Figure 4.1), which contained eight questions.

<u>4.1.2.1 Questions 1-3: SFP Knowledge Background</u>

Questions 1-3 were designed to acquire information about the participants' knowledge background. Nine out of eleven participants had a general engineering background, and the remaining had an architectural engineering background. The years of experience in designing actual building or HVAC systems ranged from 4 to 42 years. Ten out of eleven participants have PE licenses. Two out of ten not only have PE licenses, but also have LEED/Certified Commission Authority certificates. One participant does not have a PE license.

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: ______________________________

1. What is your background?

   ☐ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify______________________________

2. How many years have you designed actual buildings/HVAC systems?__________________

3. Do you have any professional licenses?

   ☐ PE; ☐ Other, please specify______________________________

4. Type and numbers of building designed?

   ___Residential, single family ___Residential, multi-family ___K-12 schools ___Office building

   ___Retail ___Hospital ___Warehouse ___Hotel ___Restaurant ___Museum

   ___Institution ___Other, please specify______________________________

5. Where is the building location(s): City:_______________; State:_______________

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☐ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☐ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☐ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☐ Elite Software

   ☐ Spreadsheet ☐ Other, please specify______________________________

IRB NUMBER: IRB2014-0295D
IRB APPROVAL DATE: 03/23/2015
IRB EXPIRATION DATE: 01/01/2016

Figure 4.1: Designed Survey Form

Table 4.1: Building Types, Number, and Locations.

	SFP 1	SFP 2	SFP 3	SFP 4	SFP 5	SFP 6	SFP 7	SFP 8	SFP 9	SFP 10	SFP 11
Residential (Single Family)			2	X					2	X	X
Residential (Multi-Family)		X	5					1	1	X	X
K-12 Schools	1	X		X	2	10	20+	1			X
Office	5	X	50	X	5	40	20+	12	100+	X	X
Retail		X		X		60	100+		3		X
Hospital	8	X							109		X
Warehouse		X				40	20+	1	3		X
Hotel		X	3				20+				X
Restaurant		X		X		60	20+		5		X
Museum	3	X							2		X
Institution	12	X		X	20+						X
Other		X Refrigeration; Laboratory; Church					(100+) office build-outs; clinics; industrial	(3) Laboratories; (3) Corporate Amenities Buildings	(1) Medical office; (2) Laboratory; (5) Banks; (2) Churches	X Fire station; Police station	X (Over 2000 projects)
Locations	Vary	TX	World	CA	TX	TX,LA, CO,AZ	Vary	TX, MX	TX	TX, MA, IN, IL	US, Thailand, Germany, England, Panama, Brazil

4.1.2.2 Questions 4-5: Types, Numbers, and the Locations of Buildings

The purpose of these two questions was to gather the information about the building types, number of buildings and building locations that the participants have designed. The answers varied significantly from one participant to the next, as shown in Table 4.1.

All participants had experience designing buildings and HVAC systems. Especially, SFP 6, SFP 7, and SFP 9 who showed extensive design experience. Unfortunately, SFP 2, SFP 4, SFP 10 and SFP 11 only indicated the building types rather than the number of each type of building. The building locations cover US locations as well as other international countries.

4.1.2.3 Questions 6-7: Peak Load Design Methods That Have Been Used or Are Being Used

Those two questions were intended to determine what design methods the participants knew about, and/or were/being in use. The first question revealed how many methods each participant was familiar with. The second question inquired about which methods the participants were using.

Nine out of eleven participants had used the CLTD/SCL/CLF Method, and four people were continuing to use it. Five of the participants indicated that they had used the RTSM, and only three were currently using the method. Four out of the eleven participants had used the TETD/TA Method and three were currently using it. Three of the participants had used the HBM. Two were currently using it. Finally, only one of the participants indicated that he had used TFM. None of the participants were currently using the method.

The results showed most SFPs were familiar with the CLTD/SCL/CLF Method, the RTSM, and the TETD/TA Method. It was also found that the CLTD/SCL/CLF Method was the most popular method that is currently being used (four participants), followed by the TETD/TA Method (three participants), the RTSM (three participants) and HBM (two participants).

4.1.2.4 Question 8: Software Used in the Peak Load Design Process

From the survey results, ten out of the eleven participants are using the TRACE software (Trane, 2010), which contains the TETD/TA Method, the CLTD/SCL/CLF

Method, and the RTSM. Five participants use Elite Software (Elite Software, 2016). Three participants used spreadsheets that they had prepared. One participant uses the HAP software (Carrier, 2003). There are also participants using building energy simulation software to perform peak load calculations. Two of these participants used eQuest (James J. Hirsch & Associates, 2010). One used DOE-2 (Winkelmann et al., 1993) and the other chose to use the Ener-Win software (Degelman and Soebarto, 1995).

4.1.3 Interview Results

The purpose of the interview process was to have an opportunity to talk to the SFPs to further understand the advantages and disadvantages of the methods that they are using and the design issues and difficulties that they were facing and coping with.

A phone interview was scheduled with each SFP who was willing to participate. Among the eleven, nine SFPs agreed to be interviewed. The phone interview was conducted in a quiet conference room at the Energy Systems Laboratory. Each phone interview lasted approximately 15 minutes. During the interview, pre-designed questions were used, as shown in Figure 4.2. The answers from the participating SFPs were manually transcribed. Once each phone interview was finished, a summary of all answers was drafted. The draft summaries were sent to each SFP for review. The interview results were then finalized after the comments were received from the participating SFPs. One of the nine SFPs did not provide comments on the draft summaries.

Interview Questions

1. What kinds of building do you primarily design?
   Probe: What information do you gather to start the design process?
2. What aspects of HVAC design are you most familiar with?
   Probe: What is the step-by-step process to design HVAC system based on your experience?
3. What do you use to size HVAC system?
   Probe: How do you calculate peak heating and cooling loads for a commercial building?
4. What are the pros and cons for the current peak heating and cooling methods?
   Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?
5. How did you learn HVAC system sizing design methods?
   Probe: -Was it in college or on the job?
   -How long did it take for you to master the methods?
6. Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?
   Probe: -Why do you think about this?
   -Are you aware of any other methods?
7. What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?
   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?
8. What do you think is the future trend of peak heating and cooling methods?
   Probe: How important do you think they play a role in design commercial buildings today?
9. Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?

Figure 4.2: Designed Interview Questions

4.1.3.1 Question 1: The Primarily Designed Building Type

The purpose of this question was to understand the building types that SFPs are familiar with and have experience in designing. Four out of the nine SFPs primarily design commercial buildings. Three of the nine participants indicated designing office buildings only. One mentioned designing fire and police stations. The last SFP did not mention the specific building types they had designed, but did mention that over 2,000 projects had been designed.

4.1.3.2 Question 2: The Aspects of HVAC Design and Step-by-Step Design Process

The main focus of this question was to explore the actual design process used in the industry when engineers design a building. Despite differences in the details, all SFPs provided similar design procedures as follows:

1) The building owner brings a description and requirement to the responsible architect(s).
2) The architect(s) prepare the conceptual design and send the building plans to the engineers, such as the building envelope information.
3) The engineers perform load calculations, select system types, decide system layout, and design the electrical, plumbing, fire protection, etc.
4) Finally, the engineers prepare all related documents, specifications, and notes.

From this general procedure, it was clear that one of the engineer's major duties was to perform the peak heating and cooling load calculations, after the architect had performed the preliminary design of the building.

4.1.3.3 Question 3: Tools and Methodology Used in the Peak Load Design Process

The primary tools mentioned in the interview include the TRACE, IES, HAP, and Elite software, which were used to perform the load calculations. The calculation methodologies used by the tools included the CLTD/SCL/CLF Method, the TETD/TA Method, the HBM, and finally the RTSM. The TFM was not mentioned by any of the nine SFPs.

4.1.3.4 Question 4: The Advantages and Disadvantages of the Peak Load Design Methods

Five out of the nine SFPs said they used the CLTD/SCL/CLF Method because it is user friendly and easy-to-use as well as the fact that it provides a detailed breakdown of each cooling load component. However, one SFP mentioned the CLTD/SCL/CLF was their least favorite method because it was too simplified and contained too many assumptions about the CLTD/SCL/CLF tables.

Three out of the nine SFPs discussed the RTSM. Two of the SFPs gave very different views. One said the RTSM would be used when designing LEED building and the other said RTSM was rarely used even though it is a more accurate method compared to others. The last SFP claimed the RTSM was their favorite method, because it was derived from the HBM. This SFP said that for a typical building, the RTSM results were very close to results from the HBM.

4.1.3.5 Question 5: How was the Method/Tool Learned

Most of the SFPs learned the original methodologies in school, but mastered the software at work.

4.1.3.6 Question 6: Whether the Current Tools/Methods are Good Enough for Designing Today's Commercial Buildings in the U.S.

All SFPs said yes to this question. One SFP suggested that sometimes they needed to change the design inputs when using the tools to better match a particular building.

4.1.3.7 Question 7: Building Features that are not Covered in the Current Methods

All SFPs indicated that the typical features found in today's building are all covered in the current methods. However, some high-performance features were not covered, including: double-skin façades, renewable energy systems, chilled beams, radiant floor slabs, and comfort control.

4.1.3.8 Question 8: Future Trend of Peak Load Design Method

All the SFPs agreed that simulation will be used more and more in the future and the manual calculation would be performed only as a quick check. Two SFPs think that the Building Information Modeling (BIM) software, such as Revit, will be the future tool that can integrate the architectural design with load calculation.

4.1.3.9 Question 9: Other Issues/Challenges

Each SFP has their own opinions about this question according to their working experience, including:

1) More attention should be given to controls and equipment efficiency;
2) Cooperation with architects during the design process was important ;
3) Challenges in peak load diversities and non-well mixed spaces;
4) Changes in climate zone definitions and building codes;
5) Humidity control during the design process;
6) Quality input data for the simulation.

4.1.4 Summary of Survey and Interview Analysis

In summary, the survey and interview of the Selected Field Professionals (SFPs) showed that the CLTD/SCL/CLF Method was still widely used today. This method is implemented in the TRACE software and is felt to be user friendly. The HBM was felt to be the most accurate method. However, it has no breakdown for each cooling load component and it has complexities that make it difficult to use. Among the current study pool, only three SFPs mentioned the RTSM, which was the only simplified method contained in the current ASHRAE Handbook of Fundamentals (ASHRAE, 2013a). However, two of the SFPs rarely used this method since other easy-to-use methods were still available and continued to perform well for them. The TETD/TA Method was still used during the peak load design phase. However, none of the SFPs used the TFM for their designs.

4.2 Part II: Base-Case Analysis and Comparison of Peak Cooling Load Design Methods

4.2.1 Overview

This section presents a comparison of the five peak cooling load calculation methods for the selected base case study. The current five peak load design methods are: the Heat Balance Method (HBM); the Radiant Time Series Method (RTSM); the Transfer Function Method (TFM); the Total Equivalent temperature Difference/Time Averaging Method (TETD/TA); and the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor Method (CLTD/SCL/CLF).

For a typical building, all types of heat gains can enter a space. The convective heat gains directly impact the cooling load, while, the radiative heat gains are first absorbed by the interior structures and then convected to the zone air in the space after a time delay, as shown in Figure 4.3.

The HBM is considered the most accurate method among all the methods. As a one-step method, it utilizes an iterative procedure to perform the heat balance calculations on each interior and exterior surface. Due to its complexity, the users need to rely on software to run a peak cooling load analysis with the HBM.

The other four methods are simplified methods. The CLTD/SCL/CLF Method was developed as a manual one-step calculation procedure. The CLTD is used to calculate the space cooling load from conduction heat gains through external surfaces, including walls, roofs, and windows. The SCL are applied to obtain the space cooling load from the solar heat gains through the fenestration. The CLF is only used when internal heat gains are involved.

The RTSM, the TFM and the TETD/TA Method are all two-step methods. They all use the concept of sol-air temperatures to combine the solar radiation effects on the external surfaces together with the one-dimensional heat conduction process. The differences among them are the way they calculate the conduction heat gains through the exterior opaque surfaces and the procedure to convert the heat gains into the space cooling loads. As shown in Figure 4.3, the conduction heat gains for opaque surfaces can be determined using the Periodic Response Factors (PRFs)/Conduction Time Series Factors (CTSFs) of the RTSM, Conduction Transfer Functions (CTFs) of the TFM, or Total Equivalent Temperature Difference (TETD) of the TETD/TA Method. In order to calculate the space cooling load, the RTSM simply applies Radiant Time Factors (RTFs) to the radiative heat gains, while the TFM uses Room Transfer Functions (also named Weighting Factors) to calculate the space cooling load. The TETD/TA Method averages all the heat gains according to a selected time period that is subjective by designers.

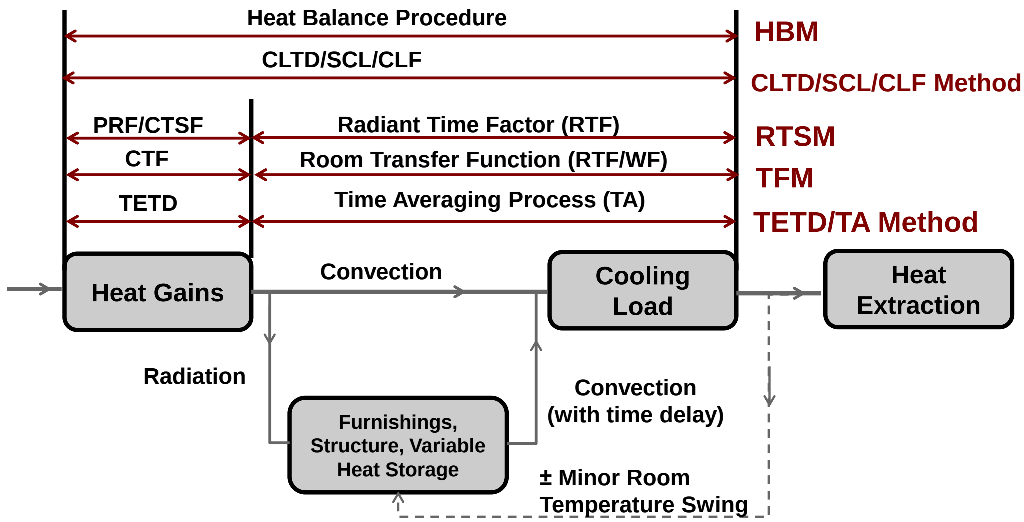

Figure 4.3: Peak Cooling Load Design Method Comparison (Adapted from ASHRAE Handbook of Fundamentals)

4.2.2 Selection of the Case Study Site

In order to test the peak cooling load methods, it is necessary to either construct a test bench with needed instruments or search for a previously published case study with measured cooling load data. Unfortunately, considering the cost and time efforts, constructing a new test bench facility was not an option. Therefore, it was necessary to look for a suitable commercial building that had already been built.

Several complications were encountered during the case selection process:

- Typical commercial buildings do not have sub-metering. Therefore, it is difficult to separate the measured building envelope load and measured HVAC system load from the total energy consumptions. This was a major concern. For a typical building, the measured energy consumption is obtained through the utility offices. The energy consumption in the utility bills usually reflects the combined building envelope and system loads, which may result in an inaccurate validation process. Therefore, more time and costs were needed to obtain the measured data just for building envelope load.

- Typical commercial buildings are too complex. Since the current study focuses on space cooling loads estimated by different load calculation methodologies, the result discrepancies were expected to come from the methodologies only. Unfortunately, the complexity of the most buildings introduces unwanted factors that can influence cooling load differences beyond the intended measurement range. Therefore, a simple building was desired for this study.
- Typical commercial buildings include high-performance features to lower the energy consumption and costs. Unfortunately, the current published methods cannot model certain high-performance features that are implemented in such buildings and become part of the building envelope, including: PV panels serving as building wall and roof materials; active windows; double envelope façades; phase-change materials; and ground-coupling features.

After careful consideration, the published data used in ASHRAE RP-1117 project (Fisher and Spitler, 2002) was selected to avoid the complications mentioned above. The test site in the RP-1117 study is located in Stillwater, Oklahoma. At the site, two, two-story buildings are used in the experiments, with the HVAC system installed in the first floor of each building. The room on the second floor is the target to be tested, where the cooling load analysis was performed. One building is a heavy-weight construction and the other building is a light-weight construction. This case study was chosen so that the difference in the cooling loads would reflect the thermal mass differences between the two buildings. In each building, single-pane clear glass windows (6.45 m^2) were mounted on each side of the south and west walls, which represented the worst types of windows.

Several test cell configurations were studied in the ASHRAE RP-1117 report, including: a base configuration; a drop ceiling; carpet; blinds; furniture; and different office configurations. For each test cell configuration, base and tuned models[21] were developed. Since the duplication of all previous tests was not the intention of the current study, only the tuned configuration of both heavy-weight and light-weighted building cases was selected for cooling load design method comparisons.

The tuned model used the measured global horizontal solar radiation to calculate the direct normal solar radiation, compared to the base model, which utilized the 1967 ASHRAE clear-sky model[22] that calculates normal direct solar radiation by using A and B coefficients, shown in Appendix B.

In the tuned model, the direct normal solar radiation E_{DN} is given by (Fisher and Spitler, 2002),

[21] Tuned models were established using measured outside dry bulb temperatures, indoor dry-bulb temperatures and global horizontal solar radiation. More details can be found in ASHRAE RP-1117 report.

[22] Appendix B details the 1967 ASHRAE Clear-Sky Model.

$$E_{DN} = \frac{E_{TH}}{C + \cos\theta_z} \quad (4.1)$$

where,

E_{TH} : measured global horizontal solar radiation, W/m^2;

C : ASHRAE clear-sky model coefficients;

$\cos\theta_z$: cosine of solar zenith angle (θ_z).

The model used the following measured weather (Figure 4.4):

- Outdoor air temperatures (°C), Tdb;
- Indoor air temperatures (°C), Tin-Heavy and Tin-Light;
- Global solar radiation (W/m^2);
- Wind speed (m/s) and wind direction (degree).

The original data represented data averaged over a 5-min period. Therefore, in order to simulate the hourly cooling load, the data was converted to a one-hour interval, as shown in Figure 4.4. Besides the measurements mentioned above, the room supply temperature, room return temperature and system volumetric flow rate were measured to calculate the cooling loads.

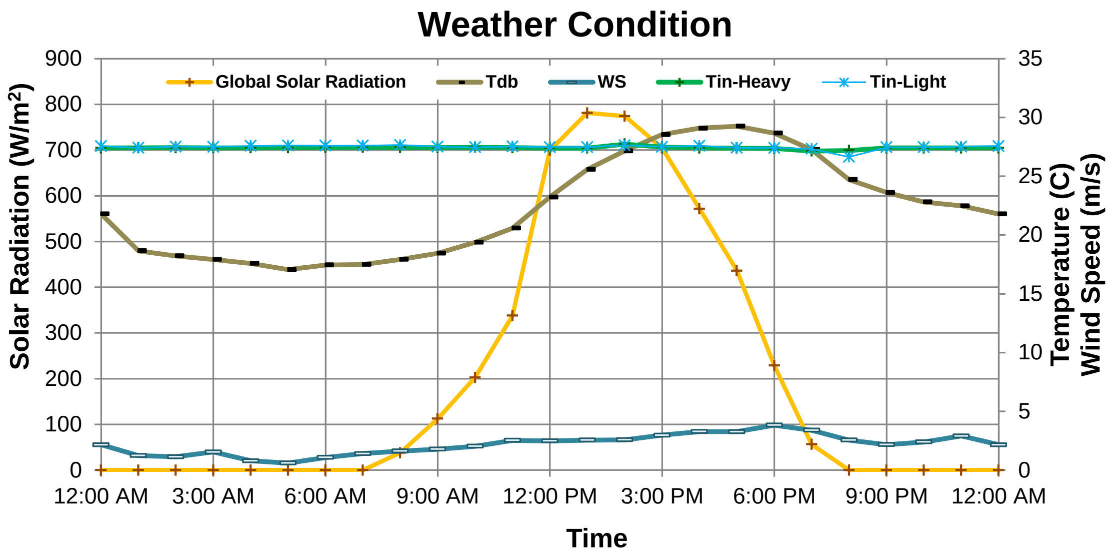

Figure 4.4: Measured Weather Data on September 22nd, 2001, in Stillwater, OK.

4.2.3 Heat Balance Method Verification

This section presents the validation of the space cooling loads predicted by the Heat Balance Method (HBM) that were published in ASHRAE RP-1117 report (Fisher and Spitler, 2002). Details about the heat balance algorithms are provided in Appendix D. Two modeling tools that used for the heat balance algorithms were available for use during the ASHRAE RP-1117 project period, which were the HBFORT program (Pedersen et al., 1998) and the ASHRAE LOADS Toolkit (Pedersen et al., 2001). The LOADS Toolkit was the primary tool selected by ASHRAE RP-1117 report.

4.2.3.1 ASHRAE LOADS Toolkit Review

The LOADS Toolkit CD was originally distributed by ASHRAE in 2001. The CD includes source code written in FORTRAN 90. To be able to run the LOADS Toolkit, the following files are needed,

- The executable: SuccessiveSub.exe
- The input file: in.idf
- The object definition file: Toolkit.idd

The executable file provided by the RP-1117 report was generated by a FORTRAN compiler that used FORTRAN source code with all FORTRAN libraries. To run this, one needs to make sure all the above files are in the same folder. Running the .exe file gives the following output files:

- Audit.out
- Toolkit.out
- Toolkit.err

where the cooling load calculation results are contained in the Toolkit.out file.

4.2.3.1.1 Outside Surface Heat Balance

Three heat transfer processes are engaged in the outside surface heat balance calculations, which include: the outside air convection; the absorbed incident solar; and the long-wave radiation exchange.

(1) <u>Convection heat exchange with outside air.</u>

Outside air flow over the exterior building surfaces contributes to convection heat transfer, which is given by,

$$q''_{conv} = h_c (T_{so} - T_{air}) \tag{4.2}$$

where,

h_c : outside surface convection heat transfer coefficient, W/m^2-K;

T_{so} : outside surface temperature, K;

T_{air} : outside air temperature, K.

Four models were documented in the ASHRAE LOADS Toolkit Manual for determining the h_c (Pedersen et al., 2001): the BLAST model (Walton, 1981; cited by Pedersen et al., 2001), the TARP model (Walton, 1983; cited by Pedersen et al., 2001), the MoWiTT model (Yazdanian and Klems, 1994; cited by Pedersen et al., 2001), and the DOE 2 model (LBL, 1994; cited by Pedersen et al., 2001), shown in Table 4.2. The BLAST and TARP models separate the convection heat transfer coefficient into forced and natural convection components. However, the method of calculating the modified wind speed was different. The DOE 2 model depends on both natural and surface convective heat transfer coefficients. The MoWiTT model was primarily selected by ASHRAE RP-1117 report, which was based on the Mobile Window Thermal Test measurements.

(2) Long wave radiation exchange with the air and surroundings

Long wave radiation that accounts for thermal radiation exchange with surrounding surfaces is expressed as:

$$q''_{LWR} = \varepsilon\sigma[(T_o^4 - T_{so}^4) + F_{sky}(T_{sky}^4 - T_o^4) + F_g(T_g^4 - T_o^4)] \quad (4.3)$$

where,

ε : long wave emittance of the surface, dimensionless;

σ : Stefan-Boltzmann constant, 5.670367 x 10^{-8} W/m^2-K^4;

T_o : outside air temperature, K;

T_{so} : outside face temperature, K;

F_{sky} : view factor of wall surface to surrounding sky, dimensionless;

T_{sky} : sky temperature, K;

F_g : view factor of wall surface to surrounding ground surfaces, dimensionless;

T_g : ground surface temperature, K.

(3) Absorbed incident solar radiation

The calculations of incident solar radiation are detailed in Appendix B. ASHRAE LOADS Toolkit follows the 1967 ASHRAE clear-sky model calculation algorithms, following Equations (B.1-B14).

Table 4.2: Outside Convective Models[23] (Adapted from Pedersen et al., 2001)

Model Name	Surface Exterior Convective Heat Transfer Coefficent h_c (W/m^{2}K)	Natural Convecctive Heat Trasnfer Coefficeint h_n (W/m^{2}K)	Forced Convective Heat Transfer Coefficient h_f (W/m^{2}K)
BLAST Model	$h_c = h_n + h_f$	$h_n = 9.482 \cdot \frac{\sqrt[3]{\lvert\Delta T\rvert}}{7.238 - \lvert\cos\phi\rvert}$ *upward heat flow* $h_n = 1.810 \cdot \frac{\sqrt[3]{\lvert\Delta T\rvert}}{1.382 + \lvert\cos\phi\rvert}$ *downward heat flow*	$h_f = 2.537 \cdot W_f \cdot R_f \sqrt{\frac{P \cdot V_{az}}{A}}$ $V_{az} = V_o \cdot (z/9.14)^{1/\alpha}$
TARP Model	$h_c = h_n + h_f$	$h_n = 9.482 \cdot \frac{\sqrt[3]{\lvert\Delta T\rvert}}{7.238 - \lvert\cos\phi\rvert}$ *upward heat flow* $h_n = 1.810 \cdot \frac{\sqrt[3]{\lvert\Delta T\rvert}}{1.382 + \lvert\cos\phi\rvert}$ *downward heat flow*	$h_f = 2.537 \cdot W_f \cdot R_f \sqrt{\frac{P \cdot V_{az}}{A}}$ $V_{az} = V_o \cdot \beta \cdot \left(\frac{z}{z_o}\right)^{\alpha}$
MoWiT T Model	$h_c = \sqrt{\left[C_t (\Delta T)^{1/3}\right]^2 + \left[a V_o{}^b\right]^2}$	-	-
DOE 2 Model	$h_c = h_n + R_f (h_{c,glass} - h_n)$ $h_{c,glass} = \sqrt{h_n{}^2 + (a \cdot V_o{}^b)^2}$	$h_n = 9.482 \cdot \frac{\sqrt[3]{\lvert\Delta T\rvert}}{7.238 - \lvert\cos\phi\rvert}$ *upward heat flow* $h_n = 1.810 \cdot \frac{\sqrt[3]{\lvert\Delta T\rvert}}{1.382 + \lvert\cos\phi\rvert}$ *downward heat flow*	-

4.2.3.1.2 Wall Conduction Process

The building wall conduction process is modeled as a one-dimensional transient conduction heat transfer, which can be solved using any one of several different methods, including: numerical finite difference methods, numerical finite element methods, transform methods, and time series methods (Pedersen et al., 2001). Among the transform methods, the Laplace and State Space methods are available for determining the Conduction Transfer Functions (CTFs). ASHRAE LOADS Toolkit selected the State Space method in its modules. Further information about the equations used for the heat conduction fluxes is contained in Appendix D.

[23] The nomenclatures can be found in ASHRAE LOADS Toolkit Manual (Pedersen et al., 2001).

4.2.3.1.3 Inside Surface Heat Balance

(1) Interior convection heat flux

This convection process is governed by the temperature difference between the inside surface and the mean zone air temperatures. The convection heat flux is calculated by,

$$q''_{conv} = h_{ci}(T_{surf} - T_a) \tag{4.4}$$

where,

h_{ci}: convection heat transfer coefficient, W/m^2-K;

T_{surf} : inside surface temperature, K;

T_a : mean zone air temperature, K.

The h_{ci} can be determined by either ASHRAE default values or the TARP method (Pedersen et al., 2001).

(2) Zone long wave radiation exchange

The ASHRAE LOADS Toolkit utilizes the Mean Radiant Temperature (MRT) concept to model the zone long wave radiation exchange. To do this, it assumes a fictitious surface to engage in the heat exchange process. The zone long wave radiation can then be calculated by,

$$q''_{LWX} = \sigma F_{MRT_i}(T_i^4 - T_{MRT_i}^4) \tag{4.5}$$

$$F_{MRT_i} = \frac{1}{\frac{1-\varepsilon_i}{\varepsilon_i} + 1 + \frac{A_i(1-\varepsilon_{MRT_i})}{A_{MRT_i}\varepsilon_{MRT_i}}} \tag{4.6}$$

where,

$$A_{MRT_i} = \sum_{j \neq 1}^{N} A_j \tag{4.7}$$

$$\varepsilon_{MRT_i} = \sum_{j \neq 1}^{N} \frac{A_j \varepsilon_j}{A_{MRT_i}} \tag{4.8}$$

σ : Stefan-Boltzmann constant, 5.670367 x 10^{-8} W/m^2-K^4;

F_{MRT_i} : the radiation interchange factor to the fictitious surface, dimensionless;

T_i : inside face temperature, K;

T_{MRT_i} : mean radiant temperature of the fictitious surface, K;

ε_i : long wave emittance of the interior surface, dimensionless;

A_i : interior surface area, m^2;

A_{MRT_i} : sum of all interior surface areas, m^2;

ε_{MRT_i} : long wave emittance of the fictitious surface, dimensionless.

Other zone formulation models are mentioned in the ASHRAE LOADS Toolkit manual, such as the Exact model and the Davies Star model (Pedersen et al., 2001). However, only the MRT model was programmed in to the source code module.

(3) Transmitted solar radiation flux

The fenestration heat flow chart is detailed in Appendix C. The LOADS Toolkit uses an incidence angle-based SHGC, transmittance and absorptance to perform these calculations. The transmitted solar heat gain is then determined by multiplying the proper angular transmittance for beam and diffuse solar radiation. The inwarding flux of absorbed solar heat gain is calculated as the angular (SHCG minus transmittance) times the beam and diffuse solar radiation.

(4) Heat exchange from internal heat gains

The detailed internal heat gain calculations are contained in Appendix E, including: occupants, lighting, and equipment heat gains.

4.2.3.1.4 Air Heat Balance

The air heat balance equation balances the convection from the surfaces, the convective portion of internal heat gains, the sensible loads due to infiltration and ventilation, and finally the load transferred from/to the HVAC system (also called the zone cooling load).

Two methods are provided by the LOADS Toolkit to calculate the infiltration heat gain load, which are: the simple air changes per hour (ACH) method, and the modified ACH methods. The difference is that the second method considers the exterior wind speed. The simple ACH method uses the following equation:

$$q_{Infil} = ACH \cdot V \cdot \frac{hr}{3600s} \cdot C_{p,air} \cdot \rho_{air} \cdot (T_{a,out} - T_{a,in}) \,, \tag{4.9}$$

where,

V : zone volume, m^3;

$C_{p,air}$: specific heat of air, J/kg-K;

ρ_{air} : air density, kg/m^3;

$T_{a,out}$: outside air temperature, K;

$T_{a,in}$: inside zone air temperature, K.

The modified ACH method gives,

$$q_{Infil} = ACH \cdot V \cdot \frac{hr}{3600s} \cdot [A + B \cdot (T_{a,out} - T_{a,in}) + C \cdot \dot{V} + D\dot{V}^2] \tag{4.10}$$

where,

$\dot{V}$: wind speed, m/s;

A, B, C, D: coefficients in the equation.

The A, B, C, D coefficients are needed by the ASHRAE LOADS Toolkit. The BLAST infiltration method gives values of A=0.606, B=0.03636, C=0.1177, and D=0, which are based on a wind speed of 7.5 mph (Pedersen et al., 2001; Bowri et al., 2009).

4.2.3.2 Validation Procedure

As mentioned previously, the study cases published in the ASHRAE RP-1117 report were chosen as the case studies in the current study. Therefore, the validation of the

ASHRAE RP-1117 report data was an important step before further work could proceed. To accomplish this, two methods were used to gather the information used in the RP-1117. First, the measured data and RP-1117 report were obtained from ASHRAE[24]. The measured data files included both outdoor and indoor conditions (Table 4.3). However, the measured system volumetric flow rate was missing in all data files, which caused a problem with calculating the measured cooling load information.

Second, additional detailed information was obtained from the author of RP-1117 (Fisher, 2015), including all measured data and all source codes of the HBM that were used for the LOADS Toolkit in the RP-1117. There were some differences that were observed between the LOADS Toolkit source code from the published ASHRAE CD (Version 1) and the source codes provided by RP-1117 author (Version 2), as shown in Table 4.4.

Table 4.3: Data Files Included in the ASHRAE RP-1117 Project

File No.	**File Name**
1	measured data_basecase.xls
2	measured data_blind.xls
3	measured data_carpet.xls
4	measured data_drpclng.xls
5	measured data_furniture.xls
6	measured data_office.xls
7	RP-1117 Final Report.doc
8	RP-1117 Paper 1_Exp New.doc
9	RP-1117 Paper 2_HBM new.doc
10	RP-1117 Paper 3_RTSM New.doc

[24] Donna Daniel who is the research coordinator of ASHRAE and Michael Vaughn who is the manager of Research & Technical Services of ASHRAE helped deliver the documents.

Table 4.4: HB LOADS Toolkit Source Code Comparisons

No.	Source Code Version 1	Source Code Version 2	Comments
1	N/A	BlindEplus.f90	PUBLIC EplusBlind PRIVATE ManageOpticalCalculations PRIVATE CalcFenestrationProperties PRIVATE GetBlindData PRIVATE InitBlindData PRIVATE AngOptProp PRIVATE ProfileAngle PRIVATE CalcWindowBlindProperties PRIVATE BlindOpticsDiffuse PRIVATE BlindOpticsBeam PRIVATE ViewFac PRIVATE InvertMatrix PRIVATE LUDCMP PRIVATE LUBKSB PRIVATE DiffuseAverage
2	N/A	BlindGlsim.f90	PUBLIC GlsimBlind PRIVATE GetBlindData PRIVATE ProfileAngle PRIVATE DirectTrans PRIVATE DiffuseTrans PRIVATE AngOptProp PRIVATE Interaction PRIVATE DirectGlazing PRIVATE DiffuseGlazing PRIVATE DirReflDiff PRIVATE DirReflSpec PRIVATE DiffRefl
3	N/A	BlindParmelee.f90	PUBLIC ParmeleeBlind PRIVATE GetBlindData PRIVATE AngOptProp PRIVATE ProfileAngle PRIVATE DirectDiffuseBlindCalc PRIVATE DirectSpecularBlindCalc PRIVATE SkyDiffuseBlindCalc PRIVATE GroundDiffuseBlindCalc PRIVATE ConfigurationFactor PRIVATE CosIncidentAngle PRIVATE Interaction
4	CTFMod.f90	CTFMod.f90	
5	N/A	DataConversions.f90	Conversion for Conduction Transfer Functions
6	EnvrnSurfTemperatureMod.f90	EnvrnSurfTemperatureMod.f90	

Table 4.4 Continued

No.	Source Code Version 1	Source Code Version 2	Comments
7	ExteriorConvectionMod.f90	ExteriorConvectionMod.f90	
8	ExteriorLWRadiationMod.f90	ExteriorLWRadiationMod.f90	
9	N/A	General.f90	PUBLIC SolveRegulaFalsi PUBLIC POLYF PUBLIC InterpSw PUBLIC InterpBlind PUBLIC InterpSlatAng PUBLIC InterpProfAng PUBLIC InterpProfSlatAng PUBLIC BlindBeamBeamTrans PUBLIC POLY1F ! Not currently used in EnergyPlus (Dec 2001) PUBLIC POLY2F ! Not currently used in EnergyPlus (Dec 2001)
10	GroundTemperatureMod.f90	GroundTemperatureMod.f90	
11	InfiltrationVentilationMod.f90	InfiltrationVentilationMod.f90	
12	InputProcessor.f90	InputProcessor.f90	1). Add SUBROUTINE ShowContinueError(Message,Unit1,Unit2) 2). Add SUBROUTINE ShowContinueError(Message,OutUnit1,OutUnit2
13	InteriorConvectionMod.f90	InteriorConvectionMod.f90	1). Add SUBROUTINE CalculateHcInCeilingDiffuser
14	InternalGainsMod.f90	InternalGainsMod.f90	
15	IRViewsToGroundAndSky.f90	IRViewsToGroundAndSky.f90	
16	PsychrometricsMod.f90	PsychrometricsMod.f90	
17	RadiativeGainsDistributionMod.f90	RadiativeGainsDistributionMod.f90	1). SUBROUTINE DetailedRadGainsDistribs 2). SUBROUTINE GetBeamRadDistribInput
18	ShadingMod.f90	ShadingMod.f90	
19	SkyRadiationMod.f90	SkyRadiationMod.f90	1). SUBROUTINE MeasuredSkyModel 2). SUBROUTINE EPlusClearSkyModel
20	SkyTemperatureModelsMod.f90	SkyTemperatureModelsMod.f90	1).Add USE PsychrometricsMod, ONLY : SATPRESS
21	SolarPosition.f90	SolarPosition.f90	1).Add SUBROUTINE EplusDeclinationAndTime 2).Add SUBROUTINE JulianDay
22	SolarViewsToGroundAndSky.f90	SolarViewsToGroundAndSky.f90	1).Add SUBROUTINE AnisoSkyViewFactors
23	SuccessiveSubstitutionSolution.f90	SuccessiveSubstitutionSolution_Baseline Model.f90	1). Add SUBROUTINE GetWindInput
24	Toolkit.f90	Toolkit.f90	
25	UtilityMod.f90	UtilityMod.f90	
26	ViewFactorMod.f90	ViewFactorMod.f90	
27	Windows.f90	Windows.f90	
28	ZoneLWRadiationMod.f90	ZoneLWRadiationMod.f90	

All source codes were loaded into the Eclipse FORTRAN compiler (The Elipse Foundation, 2016), which was used to compile, link, and generate the executable file. In this way, the input files for heavy-weight and light-weight building cases were run by the two executable files that were compiled using two sets of source codes, which allowed for the cooling load differences as shown in Figure 4.5 and Figure 4.8. Figure 4.5 and Figure 4.8 show the comparisons of cooling load calculated by the executable files generated by compiling source code Versions 1 and 2 for heavy-weight and light-weight building cases. The graphs clearly showed the results from source code version 2 were offset, when compared to Version 1. The largest offset was observed to be from 7:00 a.m. to 4:00 p.m., with an inverse offset from 4:00 p.m. to 5 p.m.

Using the source code (Version 1) contained in the ASHRAE LOADS Toolkit CD failed to replicate the cooling load results in the ASHRAE RP-1117 report as shown in Figure 4.6 and Figure 4.9. The graphs clearly showed the two results were not matching, with an R^2 equaling to 0.9668 and 0.9681 for heavy-weight and light-weight building cases, respectively.

However, the source code (Version 2) successfully calculated the same cooling load results as shown in Figure 4.7 and Figure 4.10, which showed the cooling load matched with the published results in the ASHRAE RP-1117 report, with an R^2 equal to 1. Therefore, the published results performed by HBM are considered validated and ready to be used in the further cooling load comparisons.

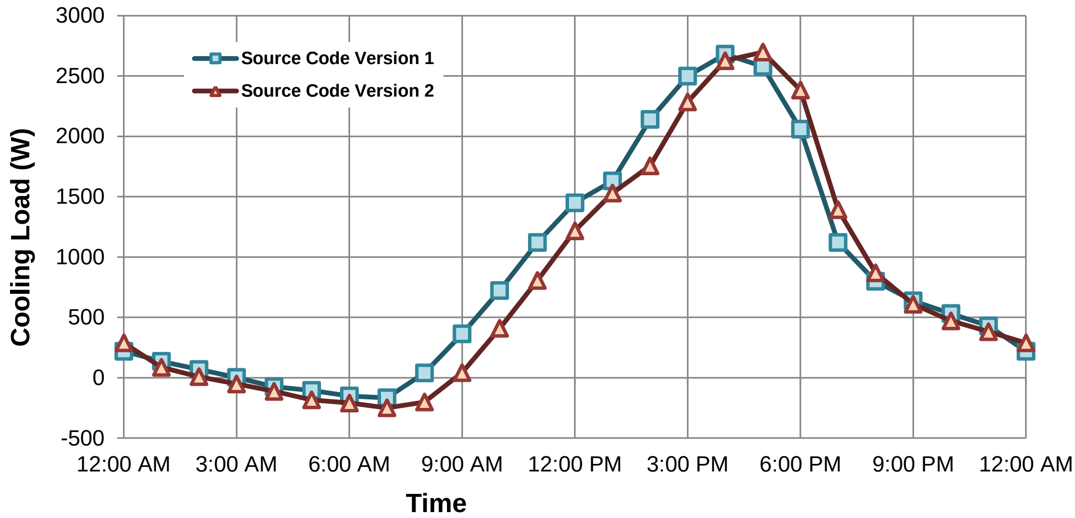

Figure 4.5: Cooling Load Predicted by The ASHRAE LOADS Toolkit Comparisons for Heavy-Weight Building Case Using Two Different Source Codes.

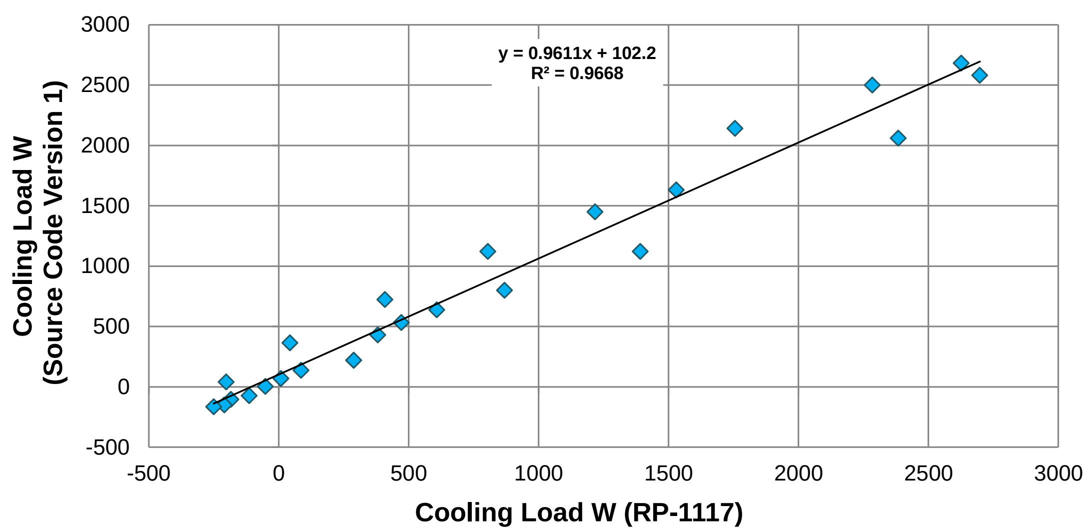

Figure 4.6: Cooling Load Using Source Codes (Version 1) from the ASHRAE LOADS Toolkit CD Compared to the Published Results in ASHRAE RP-1117 Report for Heavy-Weight Building Case.

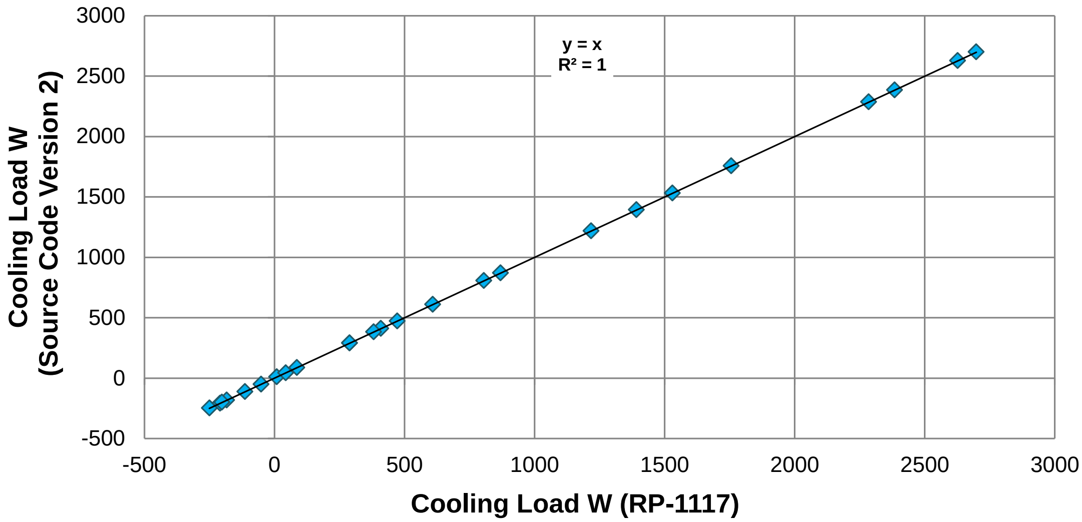

Figure 4.7: Cooling Load Using Source Codes (Version 2) Compared to the Published Results in the ASHRAE RP-1117 Report for Heavy-Weight Building Case.

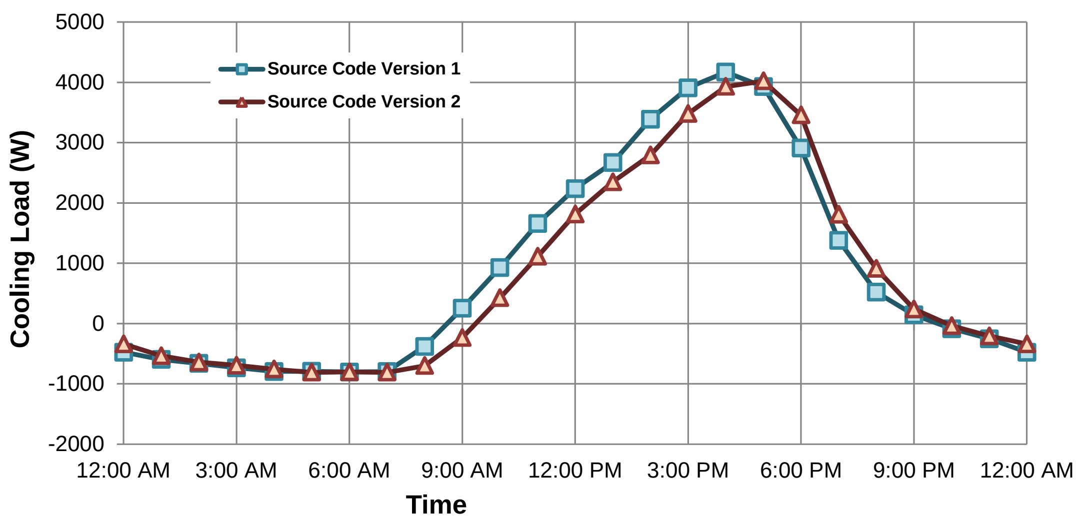

Figure 4.8: Cooling Load Predicted by the ASHRAE LOADS Toolkit Comparisons for Light-Weight Building Case Using Two Different Source Codes.

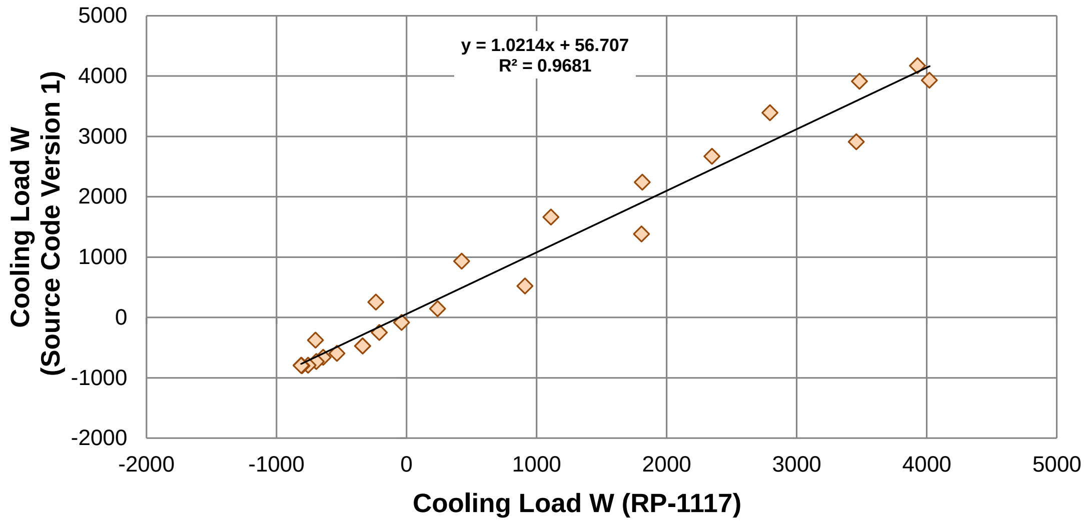

Figure 4.9: Cooling Load Using Source Codes (Version 1) from the ASHRAE LOADS Toolkit CD compared to the Published Results in ASHRAE RP-1117 Report for Light-Weight Building Case.

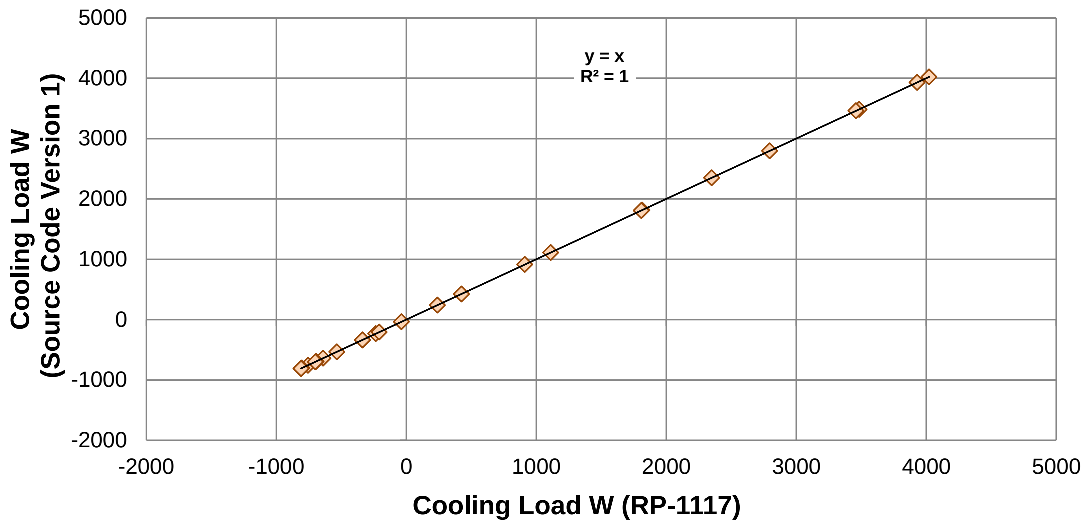

Figure 4.10: Cooling Load Using Source Codes (Version 2) Compared to the Published Results in ASHRAE RP-1117 Report for Light-Weight Building Case.

4.2.3.3 Comparison between the HBM and Measured Data

Figure 4.11 shows the comparisons of the cooling loads of the HBM simulation versus the measured data. Due to the thermal mass effects, the peak values of both the HBM simulated cooling load and the measured data for the heavy-weight building case were reduced, compared to the light weight building case. During the night time, the heavy-weight building retained the heat longer than the light-weight building. No time delay of the peak cooling load was observed because the solar heat gains through the windows dominated the heat gain. Both the heavy-weight and light-weight buildings had the same type of window glazing. Compared the measured data, the peak cooling load predicted by HBM showed 1.83% and 5.15% differences for heavy-weight and light-weight buildings, respectively. All peaks occurred at 5:00 p.m.

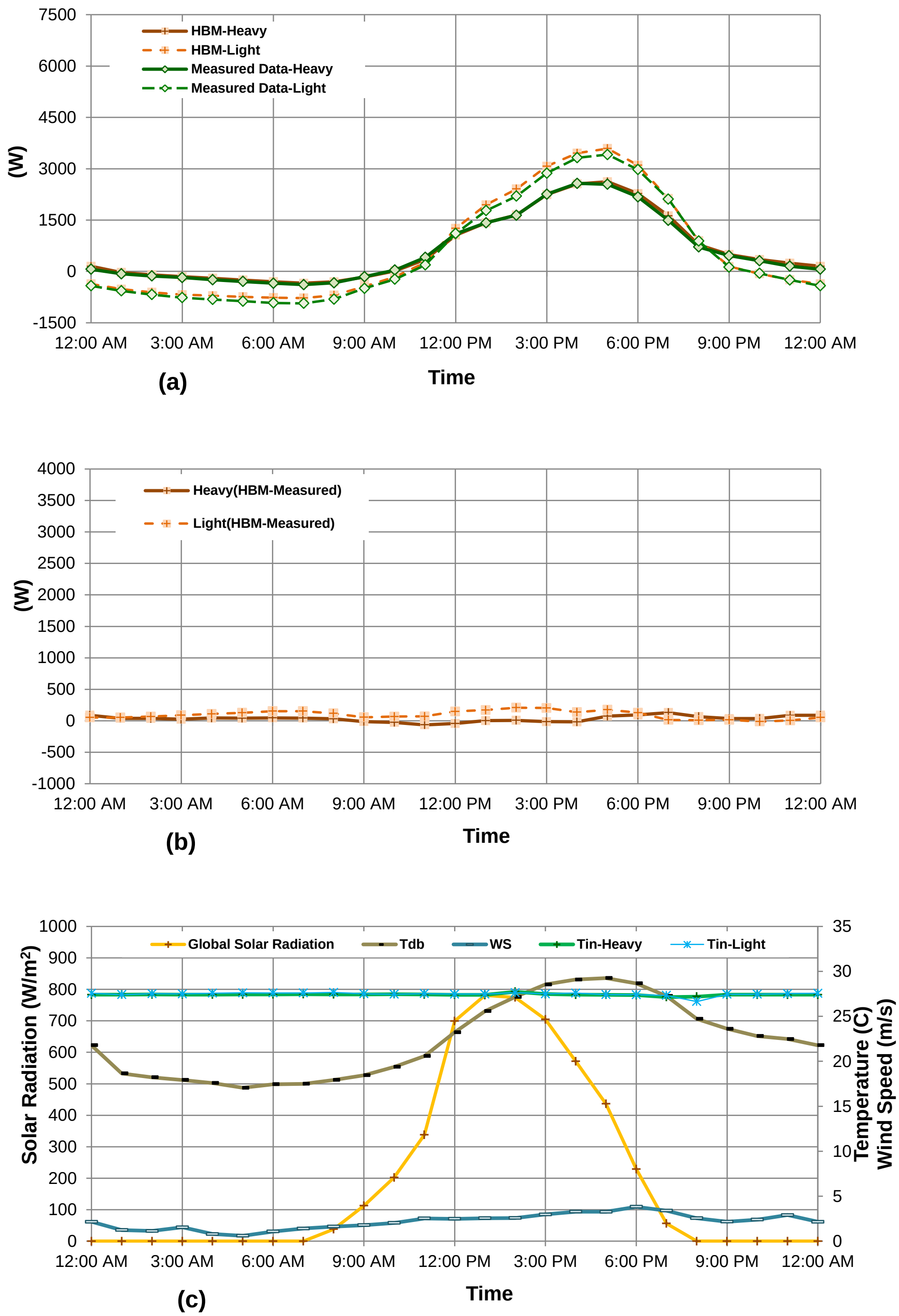

Figure 4.11: HBM versus Measured Data: (a) Cooling Load Comparisons between HBM and Measured Data for Heavy-Weight and Light-Weight Buildings; (b) Cooling Load Differences between HBM and Measured Data for Heavy-Weight and Light-Weight Buildings; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

4.2.4 Radiant Time Series Method

The Radiant Time Series Method (RTSM) can be applied using the ASHRAE LOADS Toolkit (Pedersen et al., 2001) or the ASHRAE RTSM spreadsheet tool (Spitler, 2009), shown in Table 4.5. The 2009 ASHRAE RTSM spreadsheet tool was adopted in this process to predict the cooling loads of the selected study cases. The RTSM procedure is detailed in Appendix E.

The ASHRAE RTSM spreadsheet tool consists of several individual spreadsheets, covering the calculations of solar, Conduction Time Series Factors (CTSFs), Radiant Time Factors (RTFs), and contains an example of a whole-room application.

Table 4.5: Tools for RTSM Simulation

	ASHRAE LOADS Toolkit	**ASHRAE RTSM Spreadsheet**
File Names	-Source codes; -in. idf; -ToolkitTest.idd; -Toolkit.err; -RadiantTimeSeries.exe; -audit.out; -RTSoutput.put	-Weather stations; - 7-1-solar.xls; - 7-3_tabulated_CTSF.xls; - 7-4_generate_CTSF.xls; - 7-6 RTF_tabulated.xls; - B-1_RTSM.xls; - C-1_CTFSgen.xls; - C-2_RTFgen.xls; - D-1-solar.xls; - Example 7.1 Compute CTSF.xls; - Example 7.1 Conduction.xls; - Example 7.2 Window.xls; - Example 7.3 RTF generation.xls; - Example 7.4 ClgLoad from Heat Gain.xls; - Example 8.1 Compute CTSF.xls; - Example 8.1 Compute RTF.xls; - Example 8.1 Conduction HG.xls; - Example 8.1 solar.xls;

4.2.4.1 Weather Data File Review

Since the default weather information that is provided with RTSM spreadsheet tool does not include the Stillwater, OK, weather data additional was added manually. The input information consisted of latitude, longitude, elevation, monthly design dry bulb and mean coincident wet bulb temperatures, and mean daily temperature range.

While reading through the weather condition data published in *2009 ASHRAE Handbook of Fundamentals*, it was noticed that at the bottom of the data sheet, a section named “clear-sky solar irradiance” was added, compared to previous weather data. This yielded the values of beam and diffuse optical depth and default radiation that are needed in the 2009 ASHRAE clear- sky model, which is detailed in Appendix B.

For the actual design process, the design conditions needed to be used to perform the peak load calculations. By using the peak design temperature and daily range provided by the weather condition files, the ASHRAE hourly outside dry bulb temperature can be determined by (ASHRAE, 2005),

$$t = t_{peak} - f_h DR \tag{4.11}$$

where,

t_{peak} : peak design dry bulb temperature, °C;

f_h : daily temperature range fraction, dimensionless, see Table 4.6;

DR : daily range of dry bulb temperature, °C;

Table 4.6: Daily Temperature Range Fraction (Adapted from ASHRAE, 2005)

Time, h	f	Time, h	f	Time, h	f
1	0.87	9	0.71	17	0.10
2	0.92	10	0.56	18	0.21
3	0.96	11	0.39	19	0.34
4	0.99	12	0.23	20	0.47
5	1.00	13	0.11	21	0.58
6	0.98	14	0.03	22	0.68
7	0.93	15	0.00	23	0.76
8	0.84	16	0.03	24	0.82

An equation that represents the ASHRAE fraction data was presented (Spitler, 2009). This equation was also adopted in RTSM spreadsheet tool, which is given by,

$$t = t_{peak} - DR\sum_{i=0}^{11}[a_i \cos(\frac{2\pi i\theta}{24}) + b_i \sin(\frac{2\pi i\theta}{24})] \tag{4.12}$$

where,

a_i , b_i : equation-fit coefficients, dimensionless, see Table 4.7;

θ : the apparent solar time in decimal form, dimensionless;

Table 4.7: Equation-Fit Coefficients (Adapted from Spitler, 2009)

i	a_i	b_i
0	0.5629	0.0000
1	0.2932	0.3848
2	-0.0348	-0.0835
3	-0.0006	-0.0006
4	-0.0017	0.0000
5	0.0013	-0.0004
6	0.0000	-0.0008
7	0.0004	-0.0010
8	-0.0017	0.0000
9	0.0006	-0.0006
10	-0.0002	0.0002
11	0.0001	0.0003

In order to be consistent with the HBM simulation and make the comparison valid, the measured outside dry bulb and inside room temperatures needed to be used in the RTSM spreadsheet tool for further calculations.

4.2.4.2 Modifications to the RTSM Spreadsheet Tool

In order to efficiently utilize the ASHRAE spreadsheet tool to replicate the heavy-weight and light-weight building cases, certain modifications were needed, which included:

1) A modification to the beam and diffuse solar incidence on the surfaces,
2) A modification to the sol-air temperatures,
3) A modification to the Conduction Time Series Factors (CTSFs),
4) A modification to the heat loss estimation.

4.2.4.2.1 Modification 1: Beam and Diffuse Solar Incidence on the Surfaces

The RTSM spreadsheet tool uses the 1967 ASHRAE clear-sky model with the solar data and coefficients listed in Table B.2. However, the HBM that comes with the ASHRAE LOADS Toolkit uses the first set of solar data and coefficients in Table B.1. Therefore, modifications were made to replace the values in the VBA codes with the values shown in Table B.1 to make the comparisons more consistent. Furthermore, Equation (4.1) was implemented in a Visual Basic (VBA) function so that the measured horizontal solar radiation data could be applied.

Figure 4.12 - Figure 4.16 show the comparison of the measured total solar radiation incidence on the surfaces and the calculated total solar radiation incidence on the surfaces using 1967 ASHRAE clear-sky model. In these figures, the significant solar radiation incidence differences occurred from 7 a.m. to 12 p.m.

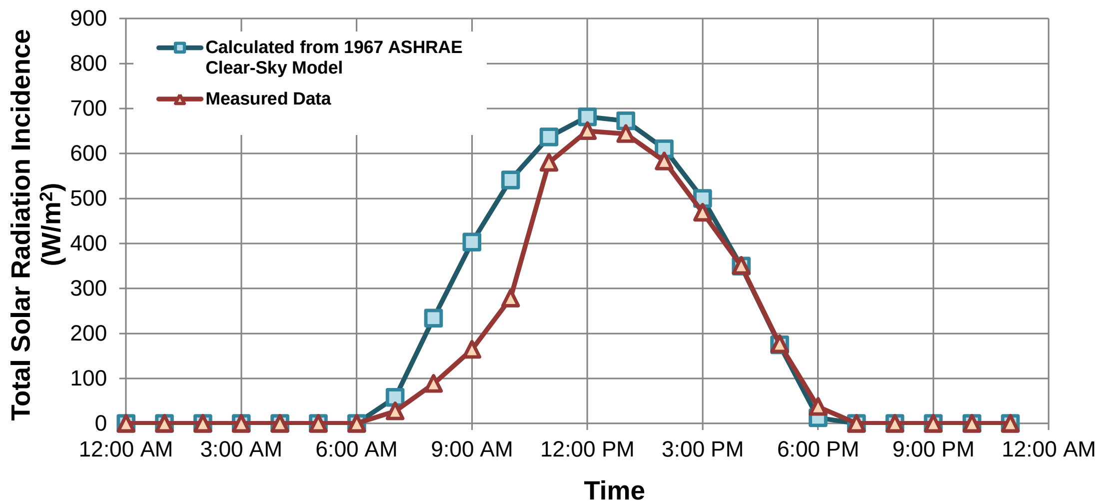

Figure 4.12: Measured Total Solar Radiation Incidence on South Wall/Window versus Calculated Total Solar Radiation Incidence on South Wall/Window by 1967 ASHRAE Clear-Sky Model.

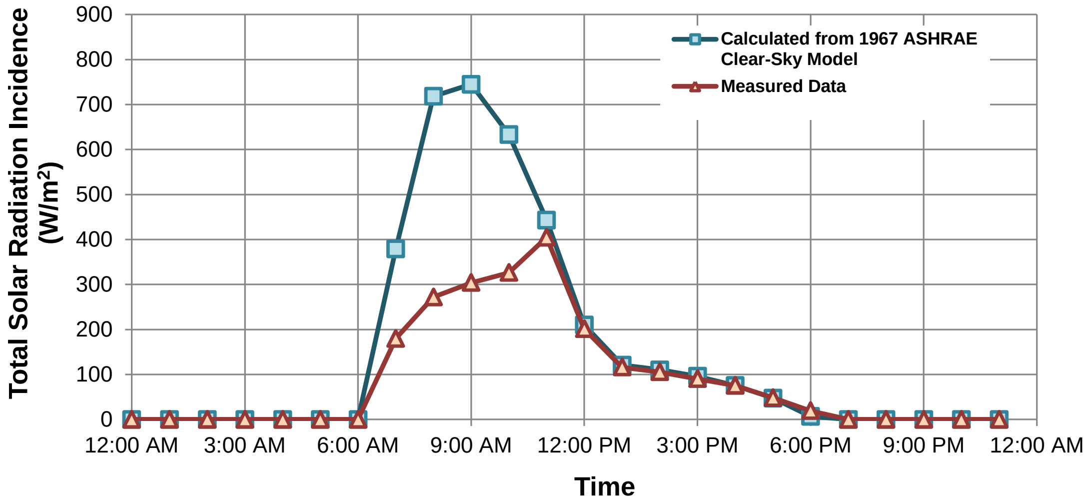

Figure 4.13: Measured Total Solar Radiation Incidence on East Wall versus Calculated Total Solar Radiation Incidence on East Wall by 1967 ASHRAE Clear-Sky Model.

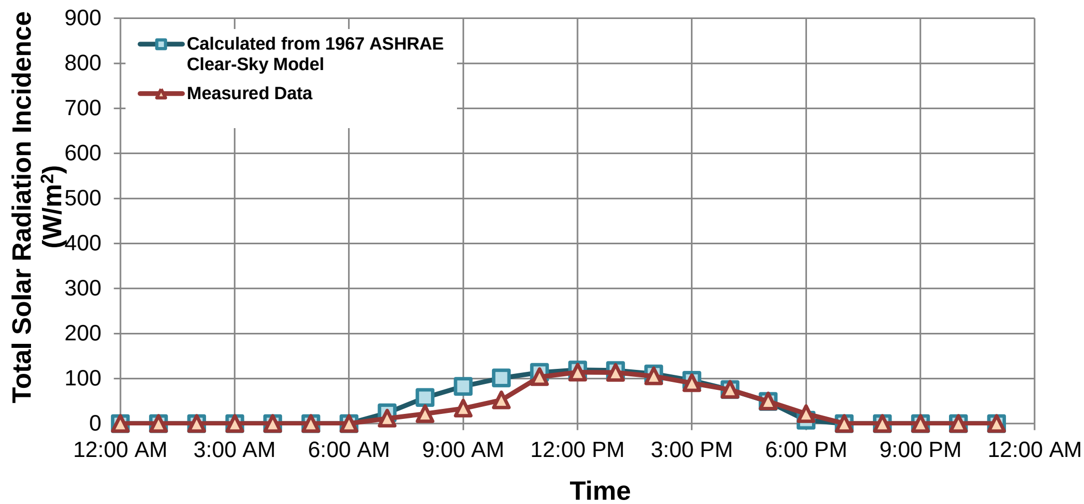

Figure 4.14: Measured Total Solar Radiation Incidence on North Wall versus Calculated Total Solar Radiation Incidence on North Wall by 1967 ASHRAE Clear-Sky Model.

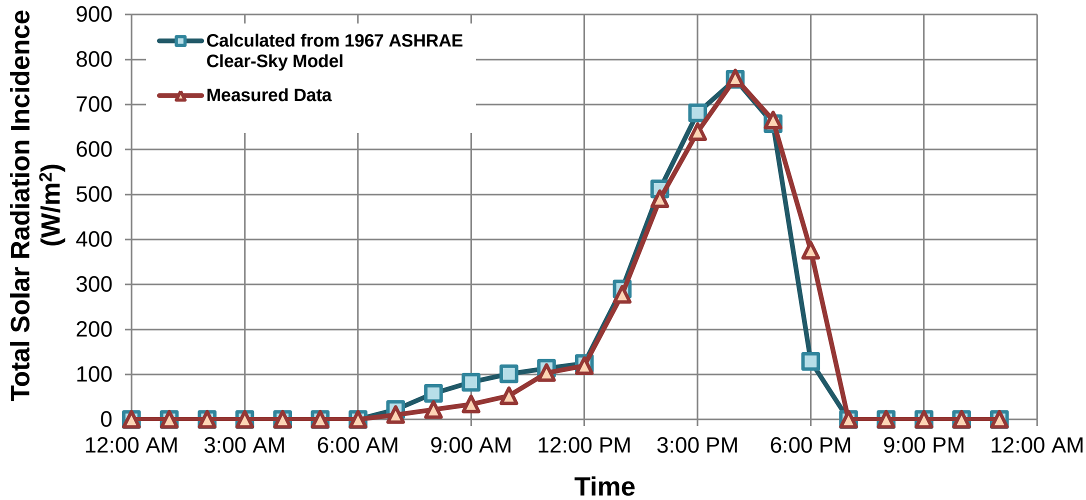

Figure 4.15: Measured Total Solar Radiation Incidence on West Wall/Window versus Calculated Total Solar Radiation Incidence on West Wall/Window by 1967 ASHRAE Clear-Sky Model.

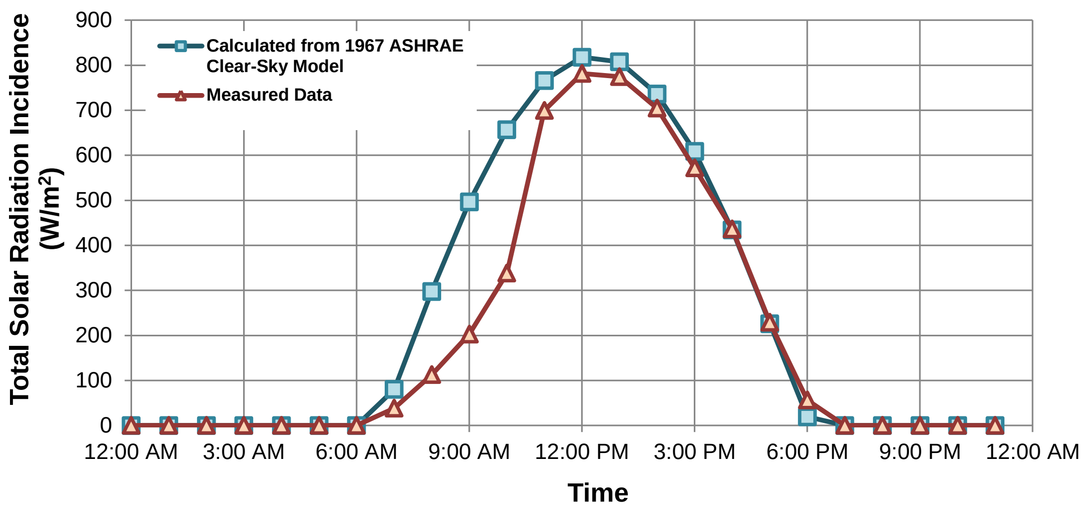

Figure 4.16: Measured Total Solar Radiation Incidence on Roof versus Calculated Total Solar Radiation Incidence on Roof by 1967 ASHRAE Clear-Sky Model.

4.2.4.2.2 Modification 2: Sol-Air Temperatures

For the exterior surfaces with boundary condition to the outside, sol-air temperature relies on the total solar radiation incidence on the specific surface as well as the outside dry bulb temperature. Since the measured data was used, the sol-air temperatures were recalculated for each surface.

4.2.4.2.3 Modification 3: Conduction Time Series Factors (CTSFs)

The RTSM load calculation procedures are listed in Appendix E. In the conduction heat gain calculations for exterior surfaces, two factors are introduced: Periodic Response Factors (PRFs) and Conduction Time Series Factors (CTSFs). The difference between the two is that the CTSFs are dimensionless factors and can be determined by the PRFs divided by the U factor. In the ASHRAE RP-1117 report, the PRFs were input by the users, while the RTSM spreadsheet tool calculates the CTSFs from the user inputs for the construction material layers. If the material layers are the same, only one set of the response factors can be obtained. However, some discrepancies were observed between the calculated CTSFs by RTSM spreadsheet tool and the ones used in the RP-1117 report.

First, though the wall materials were the same, the PRFs input values were different. Figure 4.17 and Figure 4.19 showed the PRFs differences for heavy-weight and light-weight building cases. Figure 4.18 and Figure 4.20 showed the calculated CTSFs comparisons between the ASHRAE RP-1117 report inputs and the ones calculated by the RTSM spreadsheet tool. In the comparison, it can be observed that the hourly CTSFs pattern and values were different. Therefore, in the current study, the inputs from RP-1117 report were adopted to perform the comparisons.

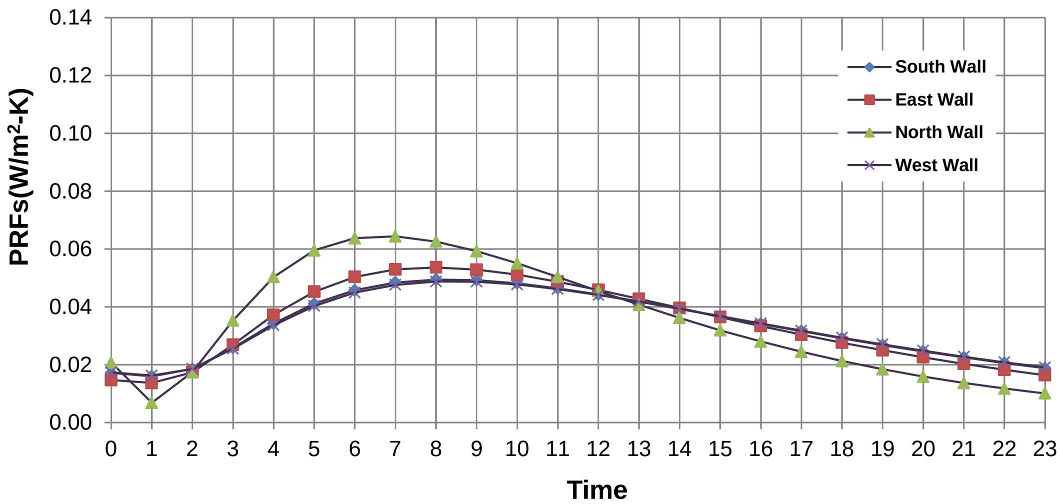

Figure 4.17: Wall PRFs Inputs by ASHRAE RP-1117 Report for Heavy-Weight Building.

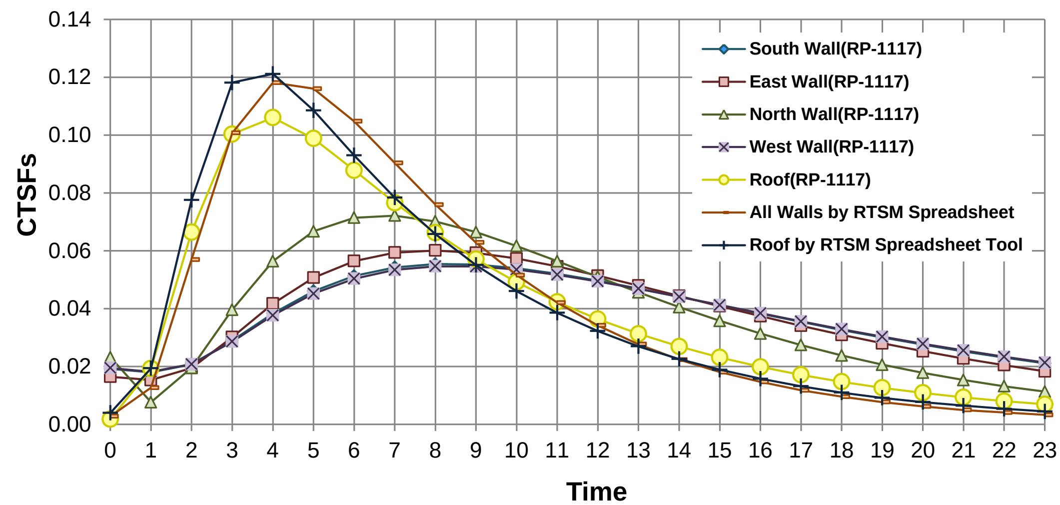

Figure 4.18: Calculated CTSFs Comparisons between the ASHRAE RP-1117 Report Inputs and by RTSM Spreadsheet Tool for Heavy-Weight Building.

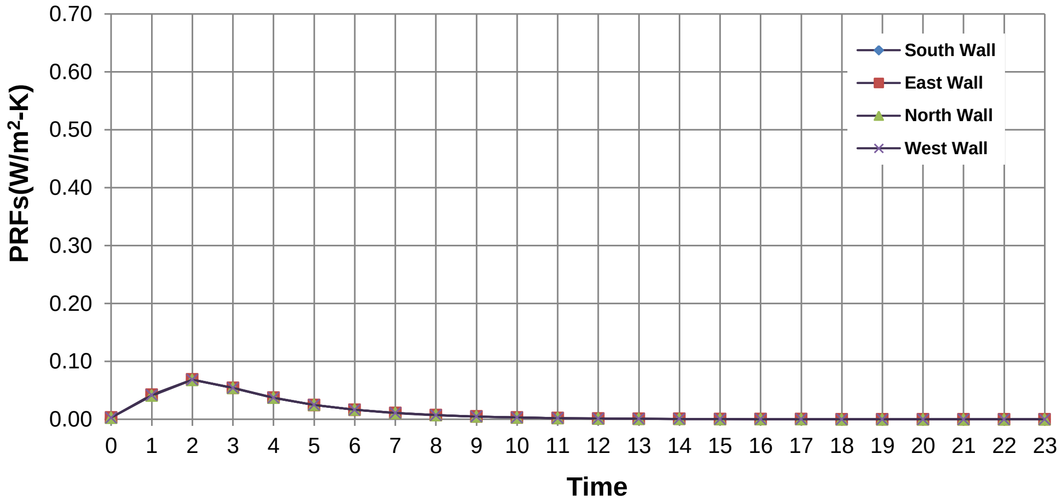

Figure 4.19: Wall PRFs Inputs by ASHRAE RP-1117 Report for Light-Weight Building

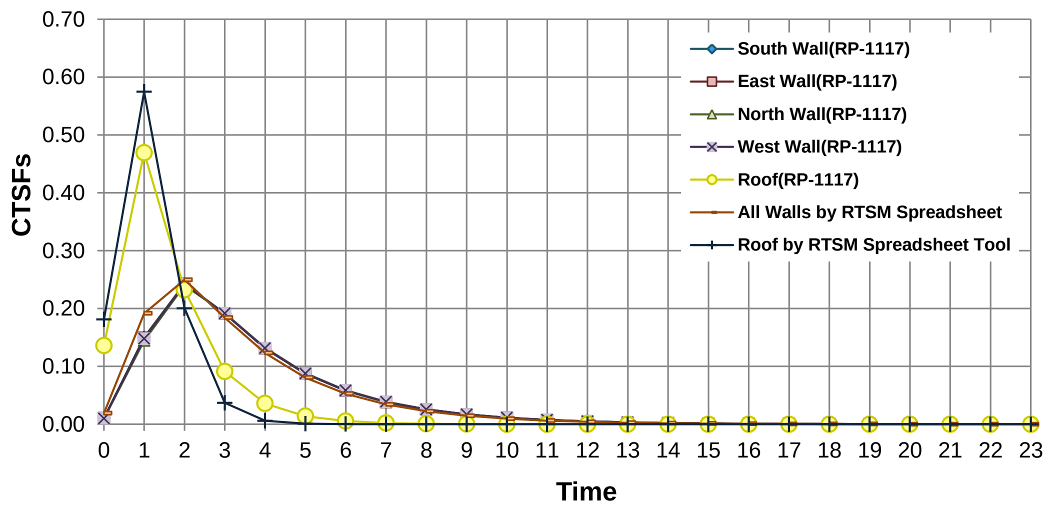

Figure 4.20: Calculated CTSFs Comparisons between the ASHRAE RP-1117 Report Inputs and by RTSM Spreadsheet Tool for Light-Weight Building.

4.2.4.2.4 Modification 4: Heat Loss Estimation

The RTSM tends to over-predict a cooling load when performing the space cooling load calculations. This is due to the assumption of an adiabatic boundary condition when applying the heat balance to the zone model and in generating the Radiant Time Factors (RTFs) (Fisher and Spitler, 2002; Nigusse, 2007; Rees et al., 2000; Rees et al., 1998). In the RTSM, once all types of heat gains enter the space, no heat loss is allowed in the calculation procedure (Fisher and Spitler, 2002).

In contrast, the ASHRAE RP-1117 report proposed a new methodology to account for the radiant heat loss out of the zone (Fisher and Spitler, 2002), and Nigusse derived four new approaches to implement the heat loss calculations by introducing the interior sol-air temperature concept (Nigusse, 2007; Nigusse and Spitler, 2010). However, it was determined that the RTSM spreadsheet tool has yet to implement those heat loss calculation procedures. Therefore, users need to perform the heat loss calculations and subtract it from the total radiant heat gains before applying the RTFs. Using the methodology shown in ASHRAE RP-1117 report. the heat loss calculations were performed in order to simulate the heavy-weight and light-weight building cases.

$$Q_{SW,loss,\theta} = (s_{floor} \cdot \rho_{t,floor} Q_{beam,\theta} + Q_{diffuse,\theta}) \cdot \sum_{k=0}^{\#windows} s_k \tau_{t,k} \tag{4.13}$$

where,

s_{floor} : solar fraction of the floor, dimensionless;

$\rho_{t,floor}$: floor solar reflectance, dimensionless;

$Q_{beam,\theta}$: beam solar radiation that enters the space, W;

$Q_{diffuse,\theta}$: diffuse solar radiation that enters the space, W;

s_k : solar fraction of the window, dimensionless;

$\tau_{t,k}$: window transmittance, dimensionless.

4.2.4.3 Comparison between the RTSM and Measured Data

Figure 4.21 shows the comparisons of peak cooling loads using the RTSM procedure versus the measured data. In the comparison, similar observations to the HBM simulation were found for the thermal mass influences. Compared to the measured data, the RTSM over-predicted the cooling load for both the heavy-weight and light-weight building cases, which were 68.32 % and 57.83% differences, respectively. The estimated peak did occur at 5:00 p.m., which was the same time as the HBM and the measured data for both cases. The cooling load difference between the RTSM and the measured data showed large variations starting from 12:00 p.m. to 5:00 p.m. The light-weight building case tended to have an even larger difference compared to the heavy-weight building case.

There were two reasons mentioned in ASHRAE RP-1117 report for the RTSM over-predicting the space cooling load compared to the HBM. One is the original assumptions used in the RTSM, which converts all types of heat gains to cooling load, using Radiant Time Factors (RTFs). These are generated by applying the HBM to an adiabatic zone. This means the heat can enter into the space but cannot exit. Unfortunately, with a large amount of glazing on south and west walls, a large amount of solar heat gain enters the room and heats up the indoor temperature immediately, which then causes a rise in inside surface temperatures of the exterior surfaces. Sometimes this inside surface temperature can be larger than the outside temperature. Therefore, a heat loss out of the space can be occurring. Unfortunately, the calculated RP-1117 RTFs cannot reflect this situation. Second, there is a difference in conduction calculations. Specifically, the HBM utilizes a surface temperature gradient to perform the calculation, while the RTSM uses the air temperature difference. Even with the corrections of heat loss calculations that were recommended from ASHRAE RP-1117 report, the over-predicting issue still existed. Finally, the RTSM results that were reproduced in this study still did not match the published values in the ASHRAE RP-1117 report. The reasons for this remain unknown.

Finally, considering the fact that the modifications were added for the outside calculations of RTFs, this may not solve the root of the issue. Therefore, in the future it is suggested that the RTFs be recalculated by applying proper boundary conditions.

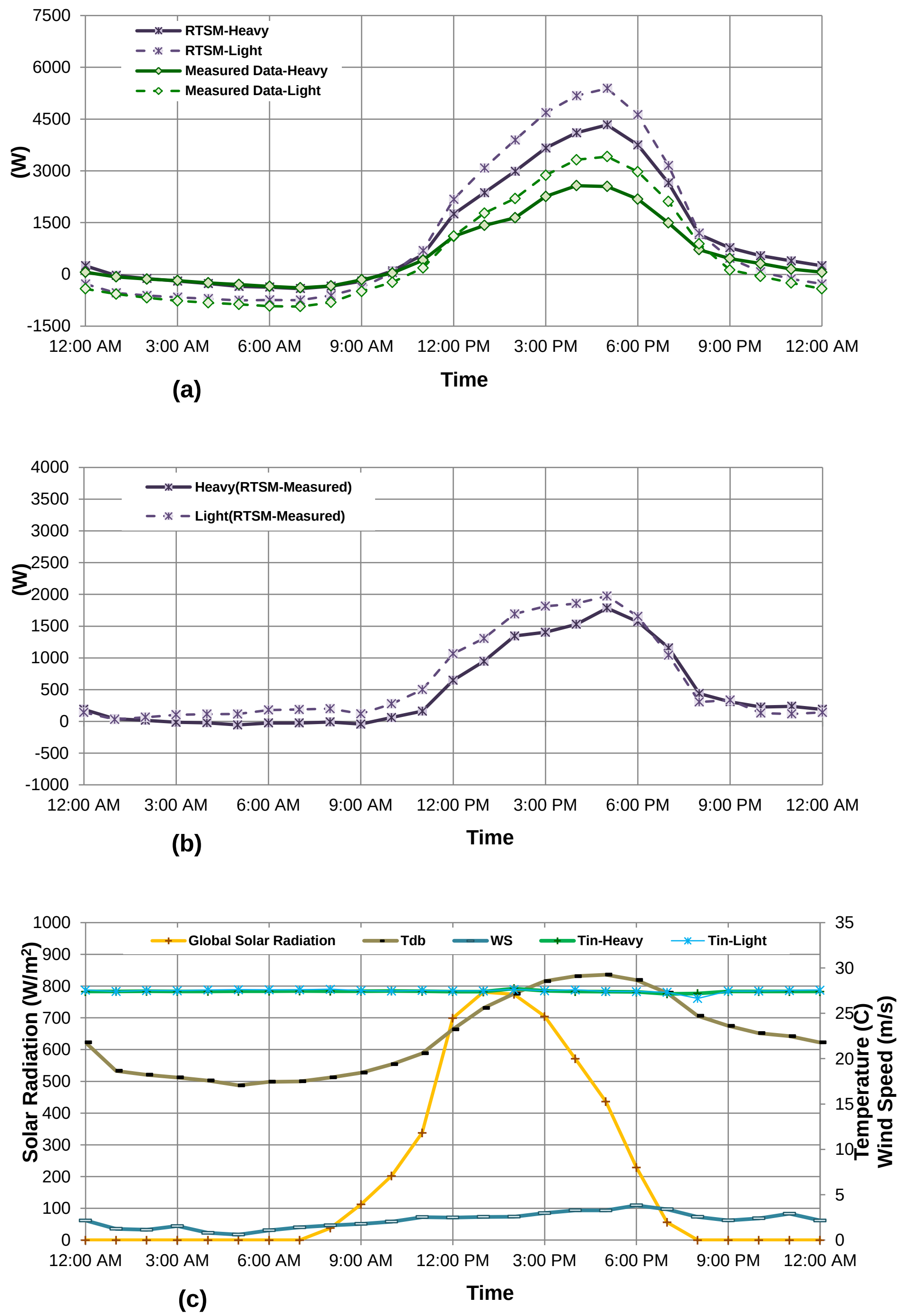

Figure 4.21: RTSM versus Measured Data: (a) Cooling Load Comparisons between RTSM and Measured Data for Heavy-Weight and Light-Weight Buildings; (b) Cooling Load Differences between RTSM and Measured Data for Heavy-Weight and Light-Weight Buildings; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

4.2.5 Transfer Function Method

In the same fashion as the RTSM, the TFM is also a two-step calculation method, involving Conduction Transfer Functions (CTFs) and Room Transfer Functions (RTFs, also called Weighting Factors) to determine the peak cooling load. Appendix F details the TFM cooling load calculation procedure. Compared to the RTSM, the calculations of wall/roof conduction heat gains and cooling load in the TFM are varied. The fenestration heat gain is calculated using Shading Coefficients (SC) and the published DSA Glass coefficients according to the latest published TFM procedure (ASHRAE, 1997). Starting from 2001 ASHRAE Handbook of Fundamentals, the TFM was eliminated from the handbook and replaced with the HBM and the RTSM cooling load calculation methods. As the RTSM was further developed, the fenestration model was updated to use angular Solar Heat Gain Coefficients (SHGC) instead of the older, less accurate SC method. The two fenestration model comparisons are shown in Appendix C. All other heat gain calculations remained the same including the window conduction heat gains, internal heat gains, and infiltration heat gains.

The following are the limitations of the TFM, which were observed from the current study:

- <u>Construction layers' thermal properties and code numbers are pre-defined</u>. The TFM relies on tables of pre-defined material layers. Therefore, the users who apply the TFM must choose the proper code number according to the TFM tables, which uses the published values in 1997 ASHRAE Handbook of Fundamentals (ASHRAE, 1997).

- The layer groups for walls and roofs are fixed. In the TFM, there are 41 wall and 42 roof groups available for calculation. The TFM has its own procedure to guide users to select the closest wall and roof group number. This is because the Conduction Transfer Function Coefficients are only calculated for those layer combinations and tabulated in the tables. This can cause the discrepancies in building construction materials if they do not exactly match the values in the table. However, an adjustment procedure is provided to reduce this discrepancy, which uses $\frac{U_{actual}}{U_{tabulated}}$ factor to multiply the tabulated CTF coefficients b_n and $\sum c_n$ for modifications. In this way, the overall U values can be as close as possible to the actual building U values. As a simplified method, the users are only required to pick the numbers from the tables and perform the peak cooling load calculations. The detailed procedure is shown in Appendix F.

- Perform peak cooling load calculations for several days to achieve steady results. When converting heat gains into the peak cooling load, historical terms of the peak cooling load are in the calculations. When calculating the cooling load for the first hour on the very first day, the historical terms are assumed to be zero. As the calculation proceeds, the peak cooling load calculations count the history terms. Therefore, several days of calculations should be repeated under the same outside and inside conditions until peak cooling load calculations converge on an answer. Usually, the heavy-weight thermal mass requires more days to achieve convergence compared to the light-weight thermal mass.

Finally, in order to perform the proper comparisons, the fenestration model that contains the angular SHGC was adopted in the TFM procedure since this represents the most recent fenestration model published in the ASHRAE Handbook of Fundamentals (ASHRAE, 2013a).

4.2.5.1 Conduction Transfer Function Coefficients

Following the procedure stated in Appendix F, the proper group numbers for the walls and roofs were selected for both the heavy-weight and light-weight building cases. Table 4.8 lists the associated parameters that were required for the group selection.

Table 4.9 shows both the original tabulated Conduction Transfer Function coefficients and the adjusted ones, given by the group number. Figure 4.22 and Figure 4.23 indicate that b_n is associated with the peak cooling load profile and d_n is the fading pulse that is related to the historical terms.

During the peak load design process, it was observed that heavy-weight building case needed nine days to achieve convergence and the light-weight building case needed only four days, by applying the same boundary conditions for every day.

Table 4.8: Group Selections of Heavy-Weight and Light-Weight Buildings

	Heavy-Weight Building		**Light-Weight Building**	
	Wall	**Roof**	**Wall**	**Roof**
Principal Material	C18	C14	B7	B7
Secondary Material	A2	-	A1	-
Mass Location	Mass in	Mass in	Mass integral	Mass integral
Group No.	17	9	4	2

Table 4.9: Wall and Roof Conduction Transfer Function Coefficients of Heavy-Weight and Light-Weight Buildings

	Heavy-Weight Building		Light-Weight Building	
	Wall	Roof	Wall	Roof
Tabulated Values				
b_0	0.00000	0.00000	0.00006	0.00316
b_1	0.00003	0.00139	0.00613	0.06827
b_2	0.00076	0.01234	0.02181	0.07278
b_3	0.00248	0.01424	0.01063	0.00814
b_4	0.00170	0.00315	0.00076	0.00007
b_5	0.00029	0.00013	0.00000	0.00000
b_6	0.00010	0.00000	0.00000	0.00000
d_0	1.00000	1.00000	1.00000	1.00000
d_1	-2.00875	-1.40605	-1.37579	-0.60064
d_2	1.37120	0.58814	0.61544	0.08602
d_3	-0.37897	-0.09034	-0.09389	-0.00135
d_4	0.03962	0.00444	0.00221	0.00000
d_5	-0.00165	-0.00006	0.00000	0.00000
d_6	0.00002	0.00000	0.00000	0.00000
Adjusted Values				
b_0	0.00000	0.00000	0.00006	0.00429
b_1	0.00011	0.00147	0.00651	0.09272
b_2	0.00278	0.01308	0.02316	0.09885
b_3	0.00906	0.01509	0.01129	0.01106
b_4	0.00621	0.00334	0.00081	0.00010
b_5	0.00106	0.00014	0.00000	0.00000
b_6	0.00037	0.00000	0.00000	0.00000
d_0	1.00000	1.00000	1.00000	1.00000
d_1	-2.00875	-1.40605	-1.37579	-0.60064
d_2	1.37120	0.58814	0.61544	0.08602
d_3	-0.37897	-0.09034	-0.09389	-0.00135
d_4	0.03962	0.00444	0.00221	0.00000
d_5	-0.00165	-0.00006	0.00000	0.00000
d_6	0.00002	0.00000	0.00000	0.00000
$\sum c_n = \sum b_n$	0.01958	0.03311	0.04182	0.20701

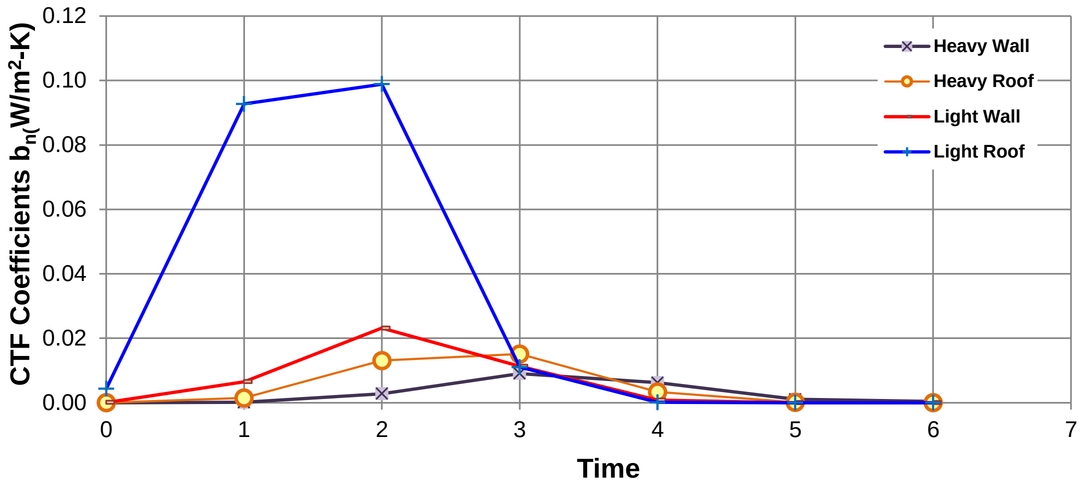

Figure 4.22: Conduction Transfer Function Coefficients b_n

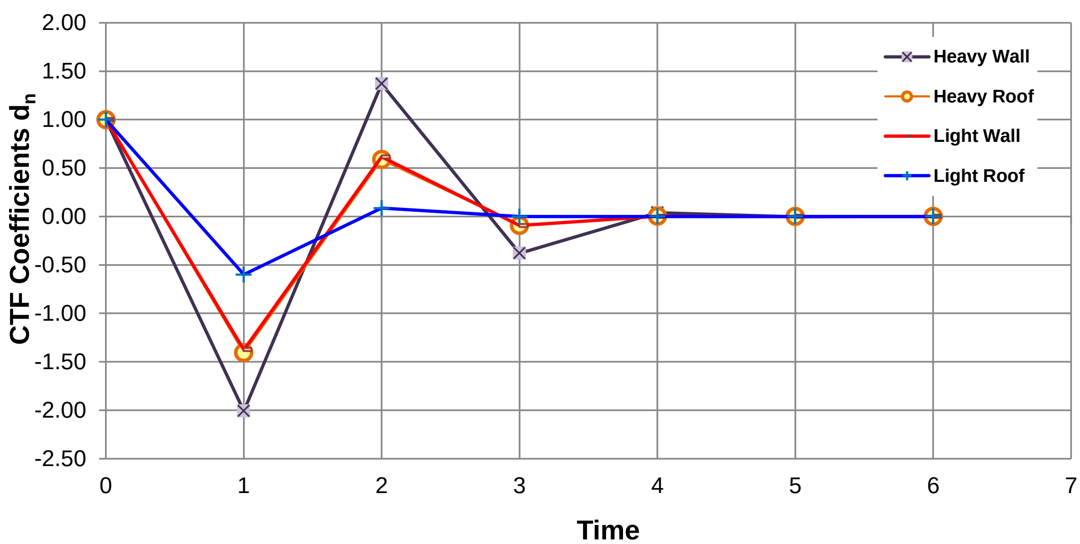

Figure 4.23: Conduction Transfer Function Coefficients d_n

4.2.5.2 Weighting Factors (WFs)

The TFMTAB.EXE was published by McQuiston and Spitler to extract the pre-calculated WFs from an accompanying database (McQuiston and Spitler, 1992). The user interface and the detailed procedure are shown in Appendix F. To obtain the proper WFs using the program, several zone parameters are required as inputs. Those parameters are also limited to certain cases. Therefore, to perform a peak cooling load calculation, a user needs to pick the appropriate parameters.

Since the test cells use a single zone-top floor, only nine parameters needed to be input: the zone geometry; zone height; interior shade; with or without furniture; exterior wall; glass percent; mid-floor type; floor covering; and ceiling type. The parameter selections are listed in Table 4.10. The corresponding WFs that were obtained are shown in Table 4.11 and Figure 4.24.

Table 4.10: Zone Parameters

Parameter	**Meaning**	**Heavy-Weight Building**	**Light-Weight Building**
zg	Zone geometry	4.5 m × 4.5 m	4.5 m × 4.5 m
zh	Zone height	3.0 m	3.0 m
is	Interior shade	0%	0%
fn	Furniture	without	without
ec	Exterior wall	4	1
gl	glass percent	50%	50%
mf	Mid-floor type	65 mm concrete	65 mm concrete
fc	Floor covering	vinyl tile	vinyl tile
ct	Ceiling type	without ceiling	without ceiling

Table 4.11: Weighting Factors

	Heavy-Weight Building		Light-Weight Building	
	Solar	**Conduction**	**Solar**	**Conduction**
v0	0.39834	0.75762	0.42028	0.78651
v1	-0.4486	-0.82615	-0.15978	-0.6424
v2	0.07877	0.19592	0.00088	0.11573
w1	-1.5517	-1.18756	-0.94354	-0.93478
w2	0.58021	0.31495	0.20492	0.19462

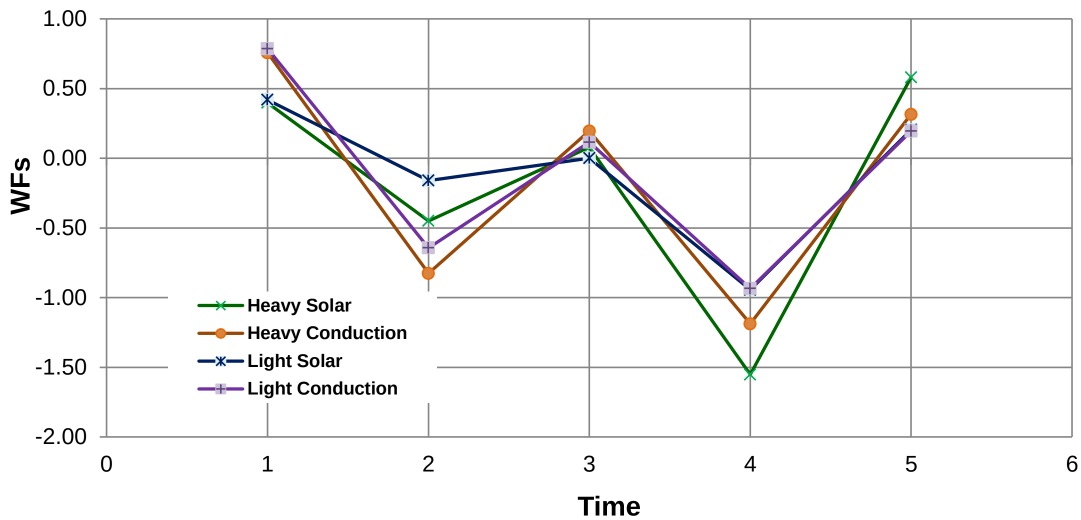

Figure 4.24: Weighting Factors for both Heavy-Weight and Light-Weight Buildings

4.2.5.3 Comparison between the TFM and Measured Data

Figure 4.25 shows the comparisons of the cooling load calculated by the TFM versus measured data. Compared to the measured data, the TFM over-predicted the peak cooling load for both the heavy-weight and light-weight building cases, similar to the RTSM, which were 77.64 % and 57.17% differences, respectively. The estimated peak also occurred at 5:00 p.m., the same time as the HBM, the RTSM and measured data for both cases. The peak cooling load difference plots for both cases had minor differences during the night time. The peak cooling load differences between the TFM and measured data were very similar for the heavy-weight and light-weight building cases.

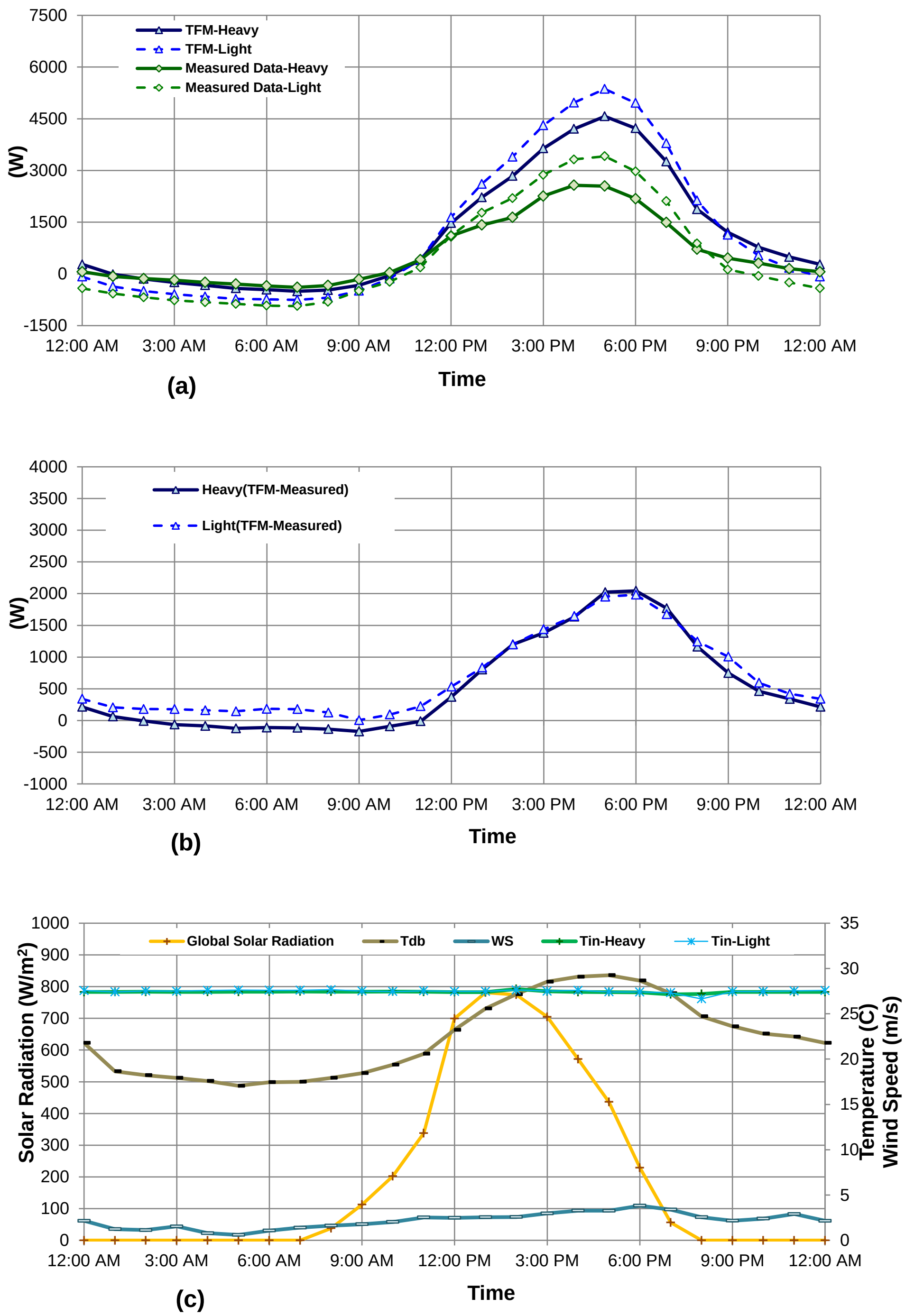

Figure 4.25: TFM versus Measured Data: (a) Cooling Load Comparisons between TFM and Measured Data for Heavy-Weight and Light-Weight Buildings; (b) Cooling Load Differences between TFM and Measured Data for Heavy-Weight and Light-Weight Buildings; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

4.2.6 Total Equivalent Temperature Difference/Time Averaging Method (TETD/TA)

Among all the simplified methods, the TETD/TA Method was first introduced in the ASHRAE Handbook of Fundamentals in 1967 (ASHRAE, 1967), coming from the ETD tables by James P. Stewart in 1948. Appendix G details the TETD/TA methodology. In the TETD/TA Method, the conduction heat gains through walls and roofs depend on TETD multiplied by the *UA*. Hourly and averaged sol-air temperatures are used in the TETD calculation. In addition, the thermal mass effects are calculated in TETD factors by applying the proper decrement factors and time lags that can be found in the published ASHRAE tables by defining specific walls/roofs group numbers, which includes a total of 41 wall and 42 roof types to choose from. The solar heat gains through fenestration are calculated by using Shading Coefficient (SC) according to the most recent updates for TETD/TA Method (ASHRAE, 1997). Starting in 2001, ASHRAE stopped publishing TETD/TA Method, retaining only the HBM and the RTSM in the Handbook. As the RTSM developed, the fenestration solar heat gain calculation model was updated using the angular SHGC. Additional information about the comparison of the two models is contained in Appendix C. The differences between TETD/TA and RTSM are the factors used for calculating the exterior surface conduction heat gains and the method to convert all heat gains into the peak cooling load. Therefore, the fenestration heat gain calculation can be updated for the peak cooling load calculation method comparison process. The peak cooling load is finalized by applying the Time Averaging (TA) process. Unfortunately, this requires a subjective decision to determine the time period for averaging and can be varied by different designers. Typically, the time period is recommended to be 3 hours (ASHRAE, 1997).

4.2.6.1 TETD

According to Table 4.8, the wall group numbers for the heavy-weight and light-weight buildings are No. 17 and No. 4, respectively. The roof numbers for the heavy-weight and light-weight buildings are No.9 and No.2, respectively. Shown in Table 4.12, the wall and roof of heavy-weight building case have time lags of 9.3 hours and 6.32 hours along with the decrement factor of 0.30 and 0.6, respectively. Similarly, the wall and roof of the light-weight building case have time lags of 4.76 hours and 2.43 hours along with the decrement factor of 0.81 and 0.94, respectively.

Table 4.12: Time Lag and Decrement Factor

	Heavy-Weight Building		**Light-Weight Building**	
	Wall	Roof	Wall	Roof
Time Lag, (hr)	9.30	6.32	4.76	2.43
Decrement Factor	0.30	0.60	0.81	0.94

Figure 4.26 and Figure 4.27 shows the calculated TETD of walls and roofs for both heavy-weight and light-weight buildings. TETD are driven by indoor, sol-air temperatures, time lag and decrement factors.

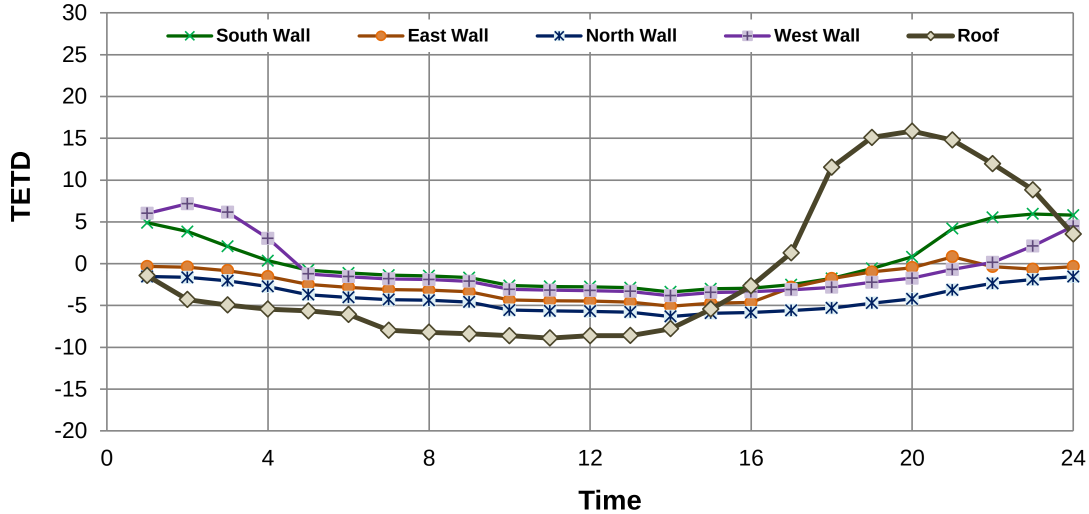

Figure 4.26: TETD Factors for Heavy-Weight Building

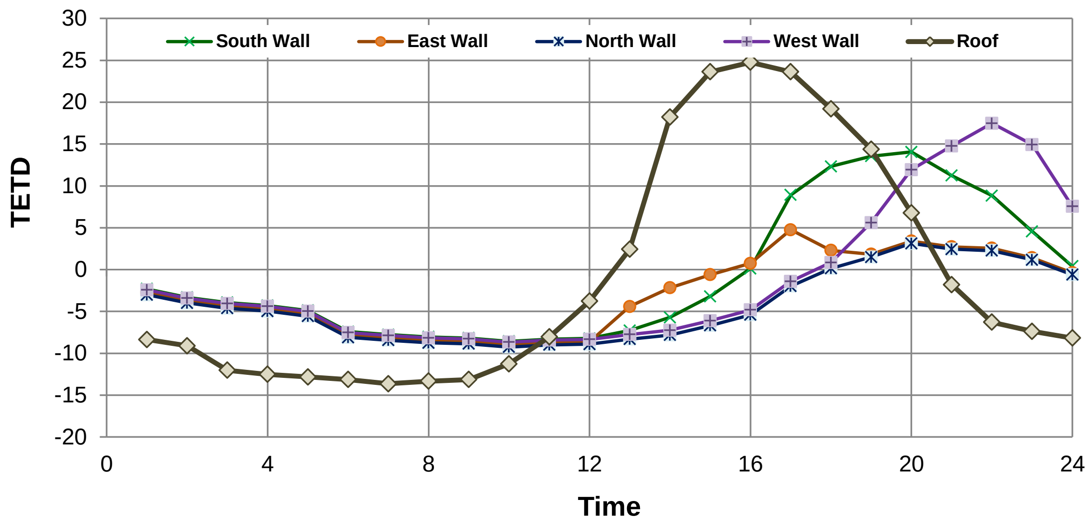

Figure 4.27: TETD Factors for Light-Weight Building

4.2.6.2 Time Averaging Process

Since the solar heat gains through the window are dominant among all types of heat gains, the thermal mass effects play less important role for these special cases. Therefore, 3 hours was selected for the time averaging process for both the heavy-weight and light-weight buildings.

4.2.6.3 Comparison between TETD/TA and Measured Data

Figure 4.28 shows the comparisons of peak cooling load by the TETD/TA calculation and measured data. Compared to the measured data, the TETD/TA Method over-predicted the peak cooling load for both the heavy-weight and light-weight building cases, which were 114.73% and 69.34% differences, respectively. Both these estimated peaks occurred at 5:00 p.m., the same time as previous methods and measured data for both cases. The peak cooling load difference plots for both cases appear large and positive for the majority of the time. The peak cooling load differences between the TETD/TA and measured data were quite close for the heavy-weight and light-weight building cases, which indicated this method was not as sensitive for thermal mass if large amount of glazing was applied.

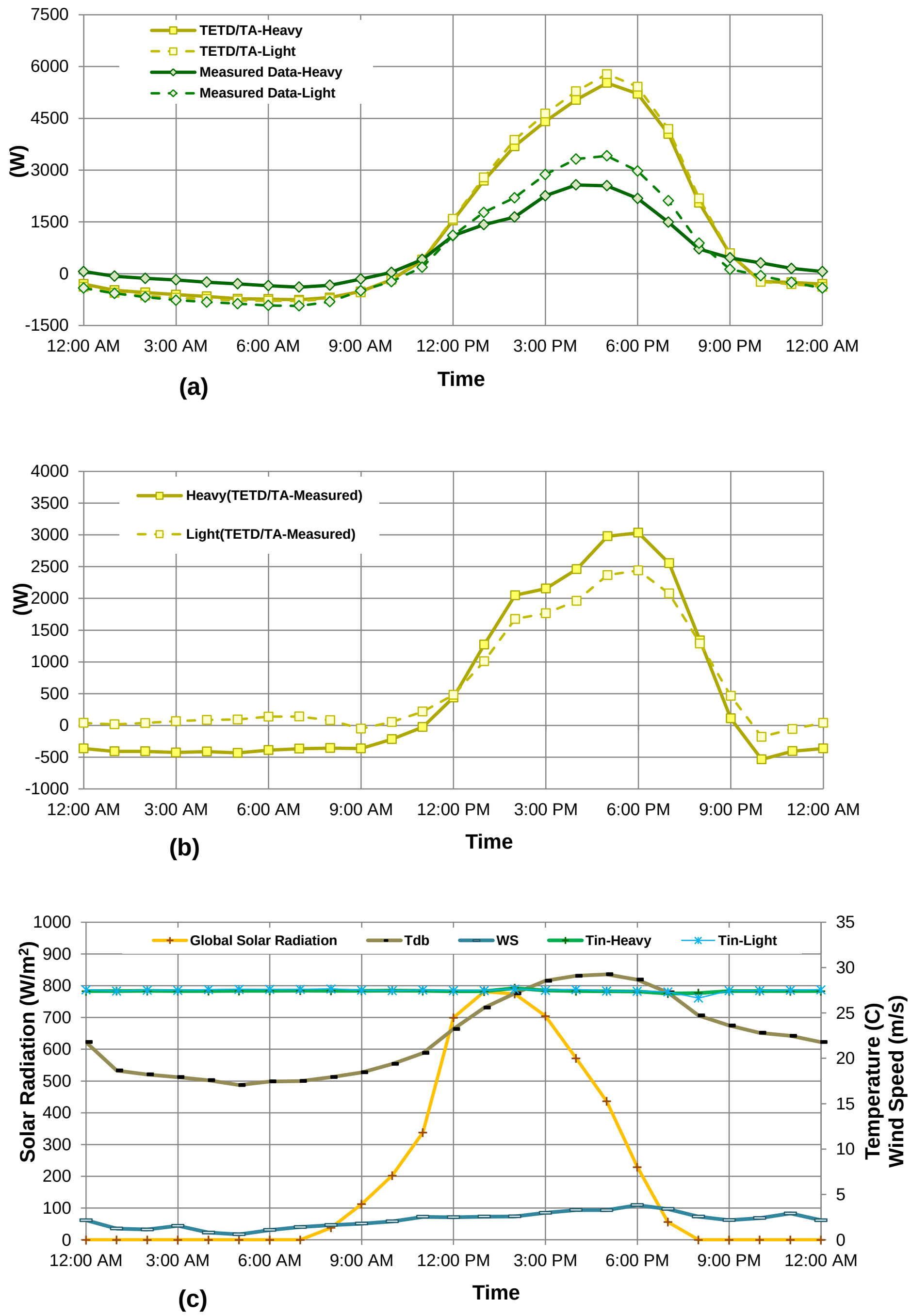

Figure 4.28: TETD/TA Versus Measured Data: (a) Cooling Load Comparisons between TETD/TA and Measured Data for Heavy-Weight and Light-Weight Buildings; (b) Cooling Load Differences between TETD/TA and Measured Data for Heavy-Weight and Light-Weight Buildings; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

4.2.7 Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor Method (CLTD/SCL/CLF)

The CLTD/CLF Method was first introduced by Rudoy and Duran in 1974 (Rudoy and Duran, 1974) to perform the cooling load calculation. The method covered the building envelope conduction heat gain calculations and calculated solar heat gain by using maximum Solar Heat Gain Factor (SHGF), Cooling Load Factor (CLF) and Shading Coefficient (SC). Spitler et al. updated this method to be the CLTD/SCL/CLF Method by adding the "Solar Cooling Load" (SCL) concept to account for solar heat gains through the fenestration in 1993 (Spitler et al., 1993). The intention of this method was to guide engineers to perform one-step manual calculations of the peak space cooling load by utilizing the tabulated numbers. The detailed calculation procedures can be found in Appendix H.

However, there are several limitations with this method. First, the method is based on the TFM to generate CLTD, SCL and CLF factors. Therefore, all the limitations of TFM[25] are included in this method. Second, since all the tables are built in, there is less flexibility for users to change parameters, such as, the measured solar data, since the ASHRAE clear-sky model is the default. Therefore, for this study, the measured global horizontal solar data was not able to be implemented. Third, the fenestration model cannot be upgraded. The original fenestration model still uses SC to perform the solar heat gains. Therefore, a fenestration model that uses the angular SHGC was not possible when using CLTD/SCL/CLF Method.

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[25] The TFM limitations were presented in Section 4.2.5.

4.2.7.1 Cooling Load from Conduction Heat Gains

Similar to the TFM, the proper determination of walls/roof group numbers is required for all calculations. Different from the TFM, the tabulated walls/roofs are further regrouped. In the method, a total of 16 wall and 10 roof numbers are available for users to select. Table 4.13 shows the walls/roofs group number selections for heavy-weight and light-weight buildings.

Table 4.13: Group Selections of Heavy-Weight and Light-Weight Buildings

	Heavy-Weight Building		**Light-Weight Building**	
	Wall	**Roof**	**Wall**	**Roof**
Principal Material	C18	C12	B7	B7
Secondary Material	A2	-	A1	-
Mass Location	Mass in	Mass in	Mass integral	Mass integral
R-Value	6.37	16.56	20.04	13.39
Group No.	16	4	4	2

The CLTD is used for calculating conduction heat gains and the tables need to be updated for various design month and latitude. The case study site was located at 36.1° N latitude and the design day was September 22nd, 2001. Unfortunately, the tables were not available from ASHRAE Handbook of Fundamentals (ASHRAE, 1997). Therefore, the "CLTDTAB.EXE[26]" was used for generating the desired tables for September that are shown in Figure 4.29 - Figure 4.31. In these tables, the top row represents the solar time of the peak day. Note this was not local time and should be paid attention to during the calculations. By selecting proper walls/roofs numbers and orientation for the walls, the tabulated CLTD was obtained. However, an adjustment was needed to be made

[26] The CLTDTAB.EXE only generates the tables in IP unit. The IP tables was converted to SI units and used in the calculations.

according to Equation (H.2) in Appendix H. This was due to the certain conditions[27] under that CLTD are generated.

The conduction heat gains through the fenestration were then calculated based on the CLTD numbers in Table H.5.

After obtaining the hourly, adjusted CLTD numbers, the cooling load from the conduction heat gains can be determined according to Equation (H.1).

Roof No. / Solar time, hr

Roof No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	-1	-3	-4	-5	-6	-7	-7	0	14	31	47	62	72	77	77	71	59	43	27	16	10	6	3	1
2	0	-1	-3	-4	-6	-7	-7	-4	4	18	34	50	63	71	75	74	67	55	40	26	17	10	6	3
3	8	5	3	0	-2	-3	-4	-2	4	13	24	36	47	55	61	62	60	54	45	36	28	22	17	12
4	12	8	4	1	-1	-3	-4	-5	-4	0	7	18	30	42	53	61	66	66	61	53	43	33	24	18
5	16	12	8	5	3	1	-1	-2	0	4	12	21	31	41	49	55	57	57	52	46	38	32	26	20
8	22	18	15	13	10	8	6	5	5	8	13	19	26	33	39	43	46	46	44	40	37	33	29	25
9	24	19	15	12	9	6	4	2	0	1	5	10	18	26	35	43	49	52	53	50	45	40	34	29
10	28	24	20	17	14	11	8	6	4	4	6	9	15	21	28	35	41	45	47	46	44	40	36	32
13	26	23	21	19	17	15	13	11	10	11	13	16	20	25	29	33	37	39	39	38	36	33	31	28
14	26	24	23	21	19	17	15	14	13	13	14	17	20	23	27	31	33	35	36	35	34	32	30	28

Figure 4.29: Cooling Load Temperature Differences (CLTD) for Calculating Cooling Load from Flat Roofs - 36° N Latitude, September 21st.

Wall Facing / Wall No. 4 / Solar time, hr

Wall Facing	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
N	9	6	4	3	1	0	-1	-2	-1	0	2	5	9	12	16	19	22	23	23	22	20	17	14	11
NE	9	7	5	3	1	0	-1	-1	2	8	13	17	19	21	22	24	25	25	24	23	20	17	14	12
E	9	7	5	3	2	0	-1	0	5	15	27	37	43	44	41	38	35	32	29	26	22	19	15	12
SE	10	8	5	4	2	1	-1	0	4	14	26	39	49	56	57	54	49	43	37	31	26	21	17	13
S	13	10	7	4	3	1	0	-1	0	4	11	21	32	43	52	59	62	61	56	48	39	31	24	18
SW	17	12	8	5	3	1	0	-1	-1	0	3	6	12	21	32	45	56	65	67	63	53	42	32	23
W	16	12	8	5	3	1	0	-1	-1	0	2	5	9	13	20	29	40	51	57	56	49	39	30	23
NW	12	9	6	4	2	1	-1	-1	-1	0	2	5	9	13	16	20	24	29	34	34	31	26	21	16

Figure 4.30: Cooling Load Temperature Differences (CLTD) for Calculating Cooling Load from Sunlit Walls, Wall No.4 - 36° N Latitude, September 21st.

[27] The conditions are shown in Appendix H.

Wall Facing	Wall No. 16											Solar time, hr												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
N	14	13	12	11	10	9	8	7	5	5	4	4	4	5	6	8	10	11	13	14	15	15	15	15
NE	17	15	14	13	11	10	9	7	6	6	7	8	9	11	12	13	15	16	17	18	18	19	18	17
E	22	20	19	17	15	13	11	10	9	9	11	13	17	20	23	25	27	27	28	28	27	27	25	24
SE	27	25	22	20	18	16	14	12	10	10	11	14	18	23	27	31	33	35	35	35	34	33	31	29
S	33	30	27	24	22	19	17	14	13	11	11	11	13	17	21	25	30	34	37	39	39	39	37	35
SW	35	33	30	27	24	21	19	16	14	12	11	10	10	10	13	16	20	26	31	35	38	39	39	37
W	30	28	26	23	21	18	16	14	12	10	9	9	8	9	10	11	14	19	23	28	31	32	33	32
NW	20	18	17	15	14	12	11	9	8	7	6	6	6	6	7	9	10	13	15	18	20	21	21	21

Figure 4.31: Cooling Load Temperature Differences (CLTD) for Calculating Cooling Load from Sunlit Walls, Wall No.16 - 36° N Latitude, September 21st.

4.2.7.2 Cooling Load from Solar Heat Gains

The cooling load calculation from the solar heat gain through the window relies on the Solar Cooling Load (SCL). The SCL also varies by the design month and latitude. To choose the proper SCL tables, the zone type needed to first be determined. According to Table H.6, Zone Type A was the closest selection for both the heavy-weight and light-weight buildings. By running "CLTDTAB.EXE" program, the SCL tables for 36 ° N latitude and September 21st were generated, shown in Figure 4.32. Using the proper glass facing orientation (i.e., N represents North), the proper hourly SCL was obtained. Next, using Equations (H.4) and (H.5), the cooling load from solar heat gains through the fenestration was calculated.

Glass Facing	Zone type A											Solar time, hr												
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
N	0	0	0	0	0	0	8	17	24	29	33	35	35	34	30	25	17	6	3	2	1	0	0	0
NE	0	0	0	0	0	0	61	79	61	43	40	38	37	34	31	25	17	6	3	2	1	0	0	0
E	0	0	0	0	0	0	102	163	177	155	106	64	49	41	34	27	18	7	3	2	1	0	0	0
SE	0	0	0	0	0	0	84	151	188	198	183	148	98	59	43	31	20	8	4	2	1	0	0	0
S	0	0	0	0	0	0	15	48	89	127	155	170	171	157	129	90	48	20	10	5	2	1	1	0
SW	0	0	0	0	0	0	8	17	24	29	55	103	149	184	202	195	149	53	26	13	6	3	2	1
W	0	0	0	0	0	0	8	17	24	29	33	35	65	118	164	187	161	55	27	13	6	3	2	1
NW	0	0	0	0	0	0	8	17	24	29	33	35	35	34	49	78	85	27	13	6	3	2	1	0
hor	0	0	0	0	0	0	22	70	123	169	204	222	224	207	174	125	68	28	14	7	3	2	1	0

Figure 4.32: Solar Cooling Load (SCL) for the Sunlit Glass, Zone Type A - 36° N Latitude, September 21st.

<u>4.2.7.3 Comparison between the CLTD/SCL/CLF and Measured Data</u>

Figure 4.33 shows the comparisons of the peak cooling load calculated with the CLTD/SCL/CLF Method and the measured data. Unfortunately, the measured global solar radiation could not be applied to the method due to the limitations of the method itself. Therefore, the ASHRAE clear-sky model was used in the tabulated CLTD and SCL tables.

Compared to the measured data, the CLTD/SCL/CLF Method over-predicted the cooling load for both the heavy-weight and light-weight building cases, which were 132.31% and 80.05% differences, respectively. The estimated peak cooling occurred at 5:00 p.m., the same time as previous methods and measured data for both cases. The cooling load difference plots for both cases appeared large for majority of the time. As shown in Figure 4.33, the peak cooling load differences between the CLTD/SCL/CLF predictions and measured data were quite close for heavy-weight and light-weight building cases, which indicated this method was not sensitive to thermal mass if large amounts of glazing were applied.

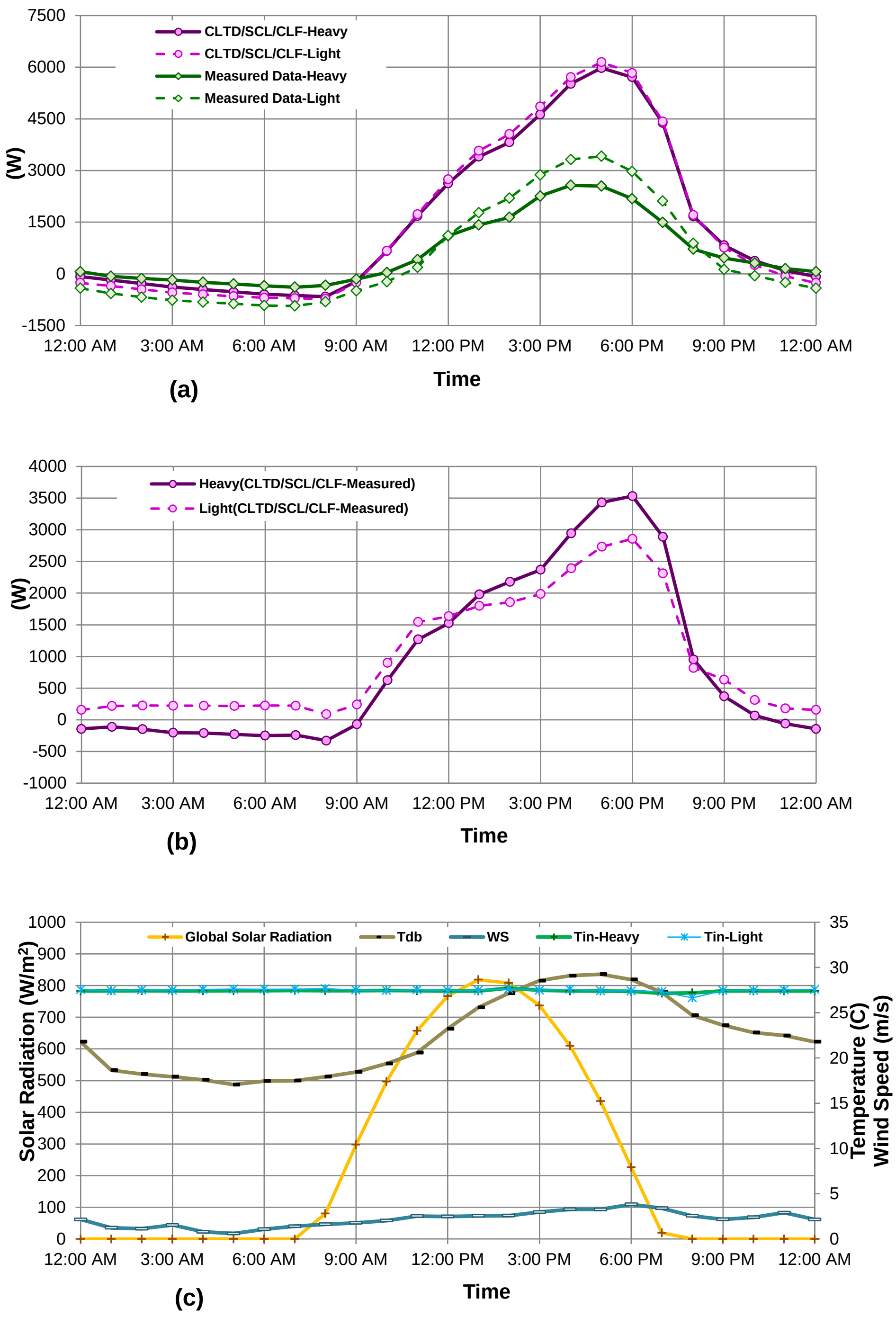

Figure 4.33: CLTD/SCL/CLF Versus Measured Data: (a) Cooling Load Comparisons between CLTD/SCL/CLF and Measured Data for Heavy-Weight and Light-Weight Buildings; (b) Cooling Load Differences between CLTD/SCL/CLF and Measured Data for Heavy-Weight and Light-Weight Buildings; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

4.2.8 Summary of Base-Case Analysis and Comparisons

Figure 4.34 and Figure 4.35 show the sensible cooling load comparisons between the measured data and the five peak load design methods. The HBM simulations in these graphs had already been validated by ASHRAE RP-1117. The peak cooling loads predicted by HBM for heavy-weight and light-weight building cases were 2,619.8 W and 3,588.9 W, respectively, which were within 1.83% and 5.15% compared to the measured peak load data.

The peak cooling load estimated from RTSM[28] over-predicted the cooling load compared to HBM, even after applying all proper modifications on the RTSM Spreadsheet Tool that were suggested in Section 4.2.4. These peak cooling loads for the heavy-weight and light-weight building cases were 4,330.1 W and 5,386.9 W, respectively, with differences of 68.32% and 57.83% compared to the peak load from the measured data. These results showed the thermal mass had a moderate influence on the cooling load predictions. Compared to the peak cooling load by the HBM, the RTSM showed differences of 65.28% and 50.10% for the heavy-weight and light-weight buildings, respectively.

The peak cooling loads predicted by the TFM for the heavy-weight and light-weight building cases were 4,569.9 W and 5,364.2 W, respectively, which were 77.64% and 57.17% differences compared to the measured peak load. Compared to the HBM, the differences in the peak cooling loads were 74.44% and 49.47% for the heavy-weight and light-weight buildings, respectively. The comparison between RTSM and TFM showed

[28] Unfortunately, the exact replication of RTSM simulation using the RTSM Spreadsheet Tool failed to match the published results in RP-1117. Although this issue was discussed with the authors of the RP-1117 report, the reason remains unknown.

peak cooling load differences of 5.54% and -0.42% for the heavy-weight and light-weight buildings, respectively. This indicated that the peak cooling load calculated by the RTSM and the TFM give similar peak cooling load values. The large differences in the sensible cooling loads occurred from 12:00 p.m. to 7:00 p.m. for both TFM and HBM comparison. However, for the afternoon, the RTSM predicted a higher cooling load than the cooling load predicted by the TFM. During the evening, the TFM tended to predict a larger space cooling load.

The peak cooling loads calculated by the TETD/TA Method for the heavy-weight and light-weight building cases were 5,524.1 W and 5,779.7 W, respectively, which represented differences of 114.73% and 69.34% compared to the peak load from the measured data. Compared to the HBM, the differences in the peak cooling load were 110.86% and 61.04% for the heavy-weight and light-weight buildings, respectively. The comparison between the RTSM and the TETD/TA showed peak cooling load differences of 27.57% and 7.29% for the heavy-weight and light-weight buildings, respectively. Furthermore, compared with the TFM, the peak cooling load differences were 20.88% and 7.75% for the heavy-weight and light-weight buildings, respectively.

The peak cooling loads calculated by the CLTD/SCL/CLF Method for the heavy-weight and light-weight building cases were 5,976.3 W and 6,145.2 W, respectively, which represented 132.31% and 80.5% differences compared to the measured peak loads. Compared to the HBM, the differences in the peak cooling load were 128.12% and 71.23% for the heavy-weight and light-weight buildings, respectively. The comparison between the RTSM and the TETD/TA showed peak cooling load differences of 38.02% and 14.08% for the heavy-weight and light-weight buildings, respectively. Furthermore, when compared with the TFM, the peak cooling load differences were 25.46% and 14.56% for the heavy-weight and light-weight buildings, respectively. Finally, the comparisons between the TETD/TA and the CLTD/SCL/CLF showed 8.19% and 10.75% cooling load differences for the heavy-weight and light-weight buildings, respectively.

The time of the peak for both the heavy-weight and light-weight cases by all five methods occurred at 5:00 p.m. This is because the cooling load from solar was the major portion of the cooling load. In the contrast to this, the cooling load from heat conduction through the opaque walls was small. Nevertheless, even though the test case had a large amount of the single-pane glass (overall WWR=29%), the HBM appeared to be the most accurate method, while, the CLTD/SCL/CLF tended to be the least accurate method among all methods, for predicting the peak cooling load.

Table 4.14: Result Summary for Base Case Comparisons[29]

	Heavy-Weight Building		**Light-Weight Building**	
	Peak Cooling (W)	Diff%	Peak Cooling (W)	Diff%
Measured	2572.6	-	3,413.1	-
HBM	2,619.8	1.83%	3,588.9	5.15%
RTSM	4,330.1	68.32%	5,386.9	57.83%
TFM	4,569.9	77.64%	5,364.2	57.17%
TETD/TA	5,524.1	114.73%	5,779.7	69.34%
CLTD/SCL/CLF	5,976.3	132.31%	6,145.2	80.5%

[29] Peak cooling load measured data and HBM data were from ASHRAE RP-1117 Report.

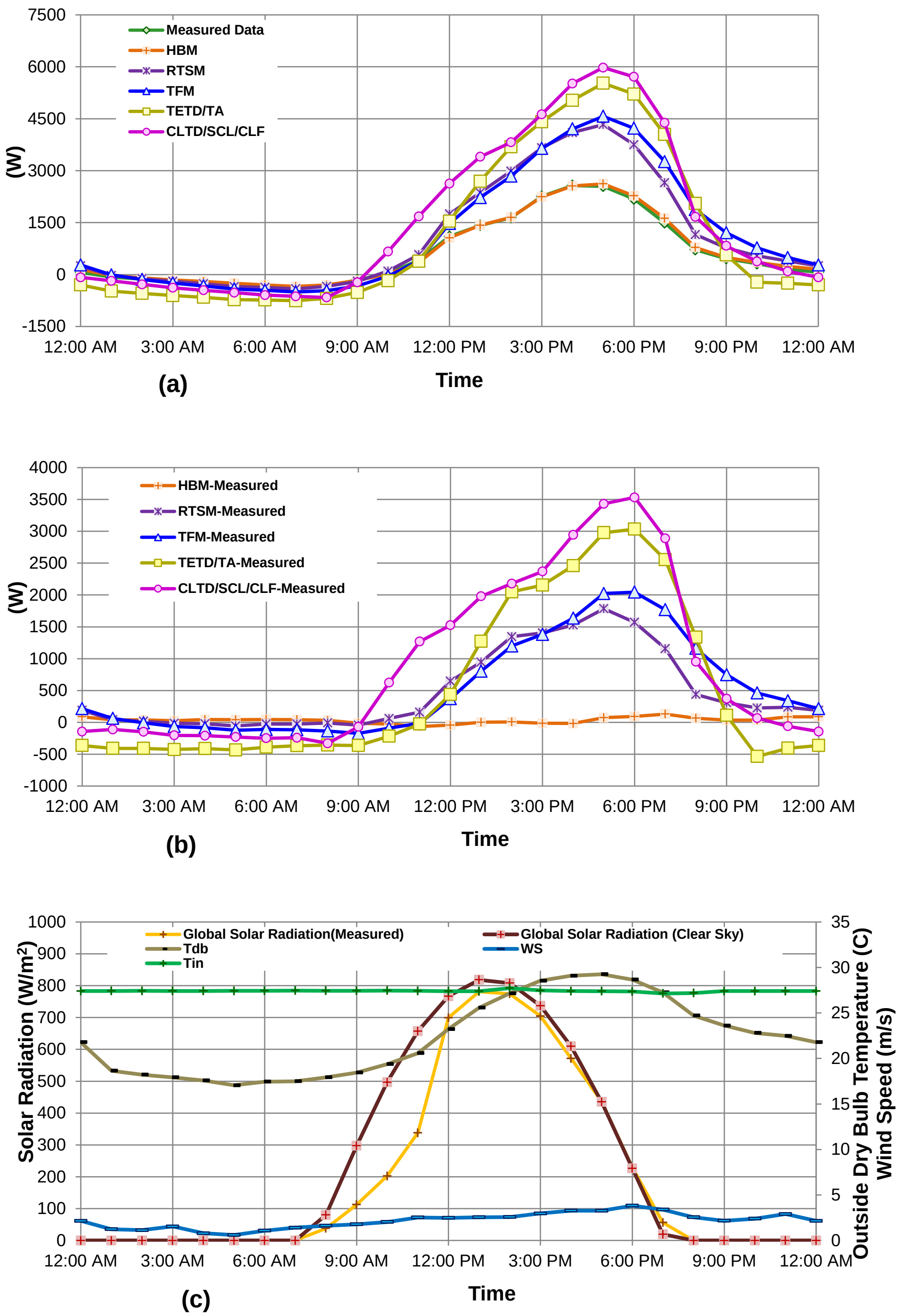

Figure 4.34: Results of the Five Peak Load Methods versus Measured Data: (a) Cooling Load Comparisons between Five Peak Load Methods and Measured Data for Heavy-Weight Building; (b) Cooling Load Differences between Five Peak Load Methods and Measured Data for Heavy-Weight Building; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

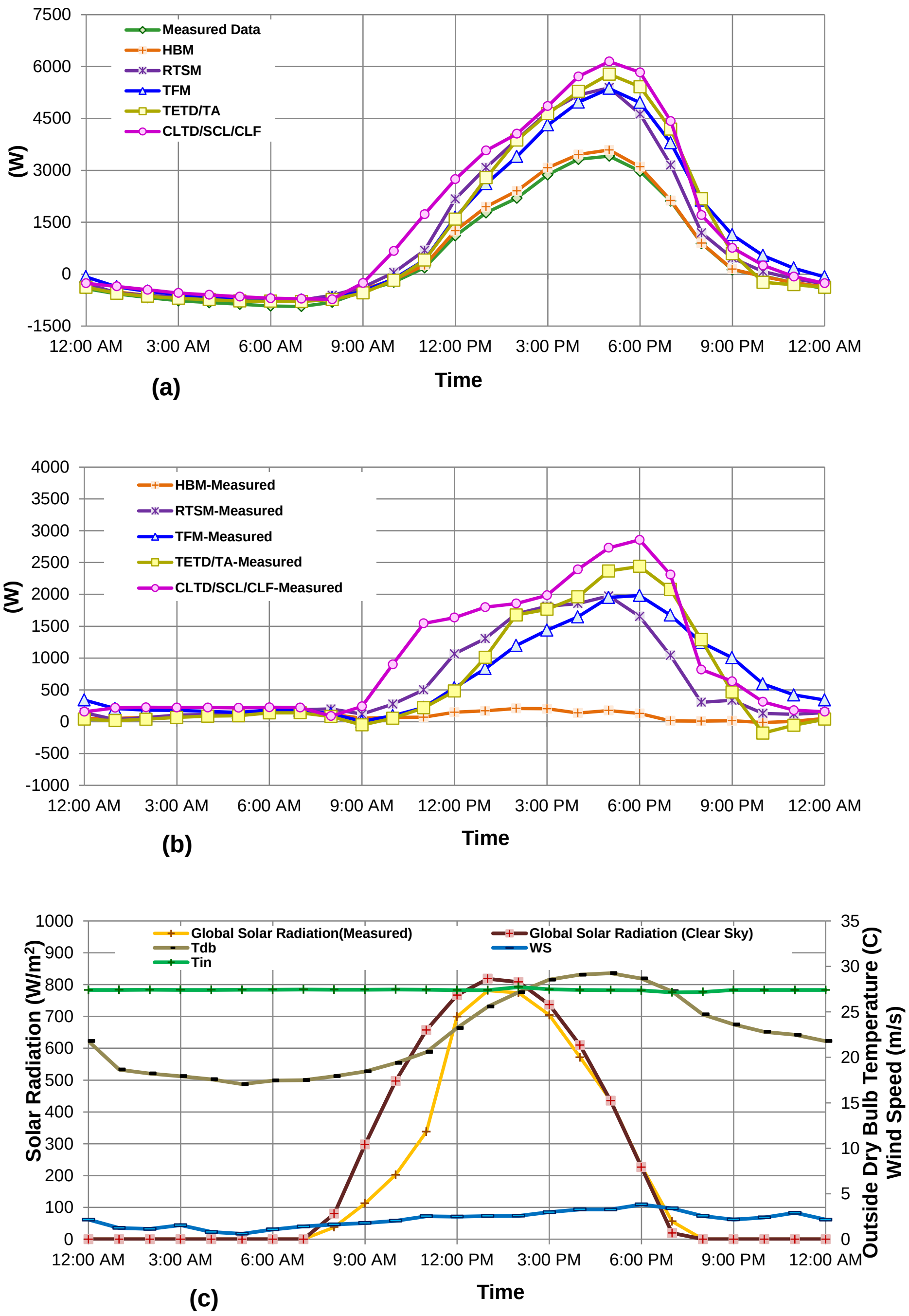

Figure 4.35: Results of the Five Peak Load Methods versus Measured Data: (a) Cooling Load Comparisons between Five Peak Load Methods and Measured Data for Light-Weight Building; (b) Cooling Load Differences between Five Peak Load Methods and Measured Data for Light-Weight Building; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

4.3 Part III: Additional Case-Study Comparison of the Peak Cooling Load Design Methods

This section aims to provide additional case-study analysis to further compare the five methods used to predict the peak sensible cooling load. To accomplish this, the two parameters were varied, including the window area and glazing types. The south and west window areas were always kept the same whenever the window area increased or decreased, according to the percentage of respective wall 11.15 m^2. Fifteen cases were analyzed, as shown in Table 4.15, which included different types and areas of glazing. All parameters were applied to both the heavy-weight and light-weight building cases.

Since measured data for all the variations were not available, the simulation results by the HBM were regarded as the baseline to be compared with the peak cooling load calculations from the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method.

4.3.1 Observations for Peak Cooling Load Comparisons by All Methods

Figure 4.36 and Figure 4.37 show the comparisons of the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method for both heavy-weight and light-weight building cases, respectively. The X-axis shows the test case numbers and Y-axis shows the differences with respect to the HBM.

Table 4.15: Test Case Descriptions

Test Case No.	Glazing Type	U-Value (W/m²-K)	Normal SHGC	Each Window % to Respective Wall	Overall WWR	Overall WFR	South Window Area (m²)	West Window Area (m²)
Base Case	Single Pane Clear	4.65	0.86	58%	29%	96%	6.45	6.45
TC1	Single Pane Clear	4.65	0.86	10%	5%	17%	1.12	1.12
TC2				30%	15%	50%	3.35	3.35
TC3				50%	25%	83%	5.58	5.58
TC4	Double Pane Clear	2.73	0.76	10%	5%	17%	1.12	1.12
TC5				30%	15%	50%	3.35	3.35
TC6				50%	25%	83%	5.58	5.58
TC7	Double Pane Low-e	1.99	0.70	10%	5%	17%	1.12	1.12
TC8				30%	15%	50%	3.35	3.35
TC9				50%	25%	83%	5.58	5.58
TC10	Triple Pane Clear	1.76	0.68	10%	5%	17%	1.12	1.12
TC11				30%	15%	50%	3.35	3.35
TC12				50%	25%	83%	5.58	5.58
TC13	Triple Pane Low-e	1.87	0.62	10%	5%	17%	1.12	1.12
TC14				30%	15%	50%	3.35	3.35
TC15				50%	25%	83%	5.58	5.58

The following were observed for the heavy-weight building test cases:

- For all the heavy-weight building test cases, it appeared that the predicted peak cooling loads from the four simplified methods for the 15% WWR were the closest to the results from the cooling load calculated by the HBM;
- For heavy-weight building, the test cases with a 5% WWR underestimated the peak cooling loads by all four methods compared to the HBM, while the test cases with a 25% WWR over-predicted the cooling loads;
- Across all types of window glazing, the peak cooling load of the test case 12, with a 25% WWR and triple pane clear windows, by the RTSM was 0.83% different compared to the HBM, which was considered the best match between the RTSM and HBM for all heavy-weight building case simulation;

- The cooling load of the test case 5, with a 15% WWR and double pane clear windows by the TFM, was 1.13% different compared to the cooling load predicted by the HBM, which was considered the second closest cooling prediction for all heavy-weight building case simulation;
- The cooling load of the test case 14, with a 15% WWR and triple pane low-e windows, by the TETD/TA Method was -1.12% different compared to the cooling load predicted by the HBM, which was considered the third closest cooling prediction for all heavy-weight building case simulation;
- The RTSM worked fine compared to other methods for heavy-weight building simulation, except the test cases with 5% WWR;
- In addition, for the majority of the heavy-weight building test cases, the CLTD/SCL/CLF Method performed the worst except the test cases with 5% WWR. This indicated that the CLTD/SCL/SCL Method provided a better peak cooling load estimation for small amount of window glazing.

The following were observed for the light-weight building test cases:

- For all light-weight building test cases, the RTSM appeared to be the fine method that brought the cooling load calculation closest to the HBM results, except the test cases with 5% WWR;
- For the light-weight building, the test cases with a 5% WWR underestimated the peak cooling loads by all four methods compared to the HBM, while the test cases with a 25% WWR over-predicted the peak cooling loads;

- For all light-weight building test cases, the RTSM and the TFM had similar estimated cooling loads. This is because the original periodic response factors used by the RTSM could be derived from the conduction transfer functions;

- Across all types of window glazing, the peak cooling load of the test case 5, with 15% WWR and double pane clear windows, by the TFM and the RTSM was -1.09% and -1.85% different, respectively, compared to the HBM, which were considered the first and the second closest peak cooling load estimations for all light-weight building case simulation;

- The peak cooling load of the test case 8, with a 15% WWR and double pane low-e windows, by the TETD/TA Method was 1.4% different compared to the peak cooling load predicted by the HBM, which was considered the third closest cooling prediction for all light-weight building case simulation;

Base on the above observations from the heavy-weight and light-weight building simulations, the followings can be concluded:

- The HBM provided the most accurate peak cooling load estimation. However, the total peak cooling load was predicted as a single value with no component heat gains or peak cooling load breakdown. If only the total cooling load is desired, and both the time and cost requested by the simulation are not a problem, the HBM is the method that should be used for the building design purpose. Otherwise, the simplified methods should be considered;

- For the majority of test cases, the RTSM worked fairly well, which allows its recommendation for use if the HBM cannot be performed;
- The second recommended simplified method is the TFM, since it can provide similar results to the RTSM simulation;
- The TETD/TA Method provides the next best results;
- The least accurate method is the CLTD/SCL/CLF Method.

Details regarding the sensible cooling load comparisons are presented in Appendix I.

4.3.2 Observations about the Test Case Comparisons for Each Method

Figure 4.38 - Figure 4.42 show the case study analysis comparisons by the HBM, the RTSM, the TFM, the TETD/TA Method and the CLTD/SCL/CLF Method for both heavy-weight and light-weight building cases. Due to the thermal mass effects, the peak cooling load for the light-weight building for all test cases tended to produce higher peak cooling load than the heavy-weight building cases.

The RTSM, the TFM, the TETD/TA Method and the CLTD/SCL/CLF Method all are quite sensitive to the glazing areas and glazing types. In contrast, the HBM is quite steady and predicts the peak cooling load well within a certain range. For all methods, either the more efficient window glazing or the smaller window areas the lower peak cooling load are demonstrated.

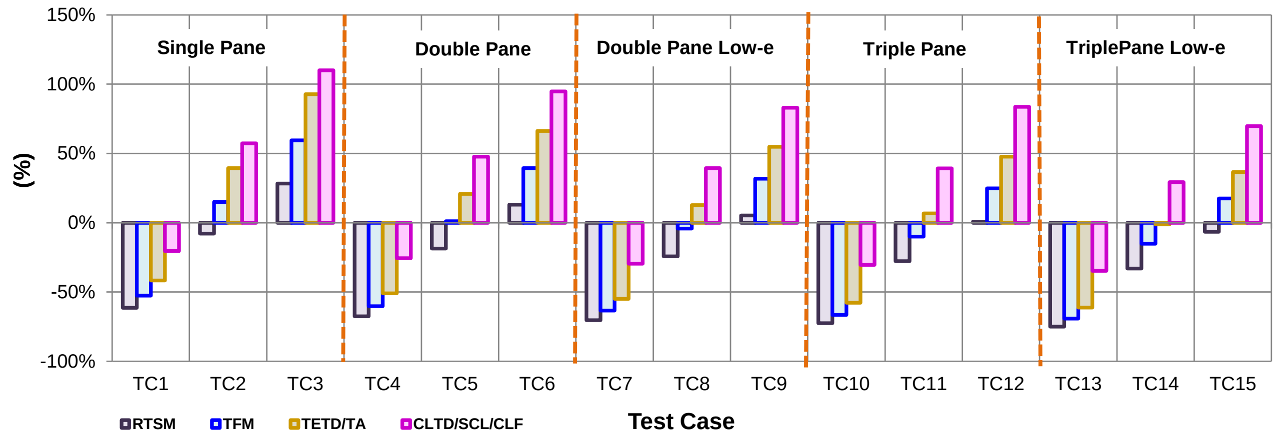

Figure 4.36: Comparison of the Heavy-Weight Building Test Cases

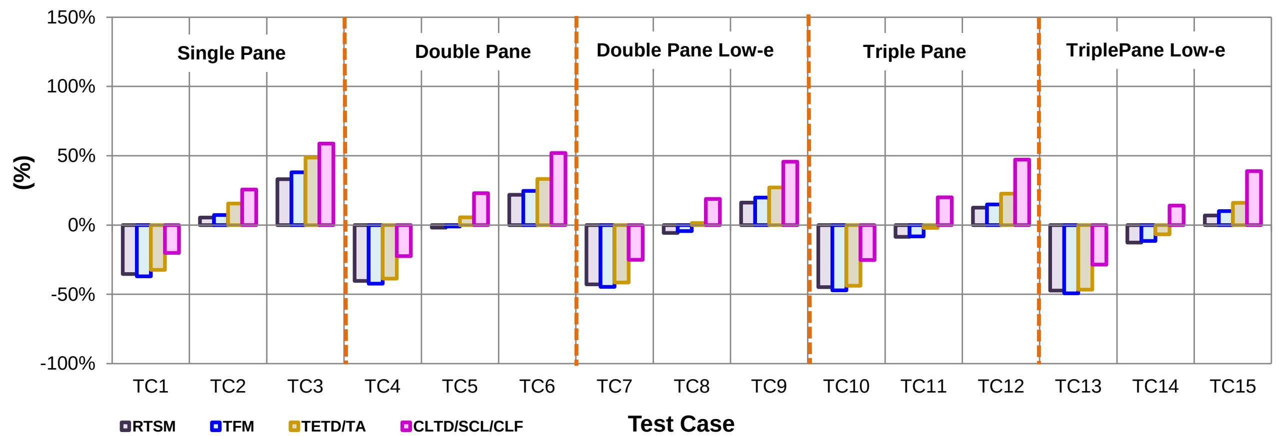

Figure 4.37: Comparison of the Light-Weight Building Test Cases

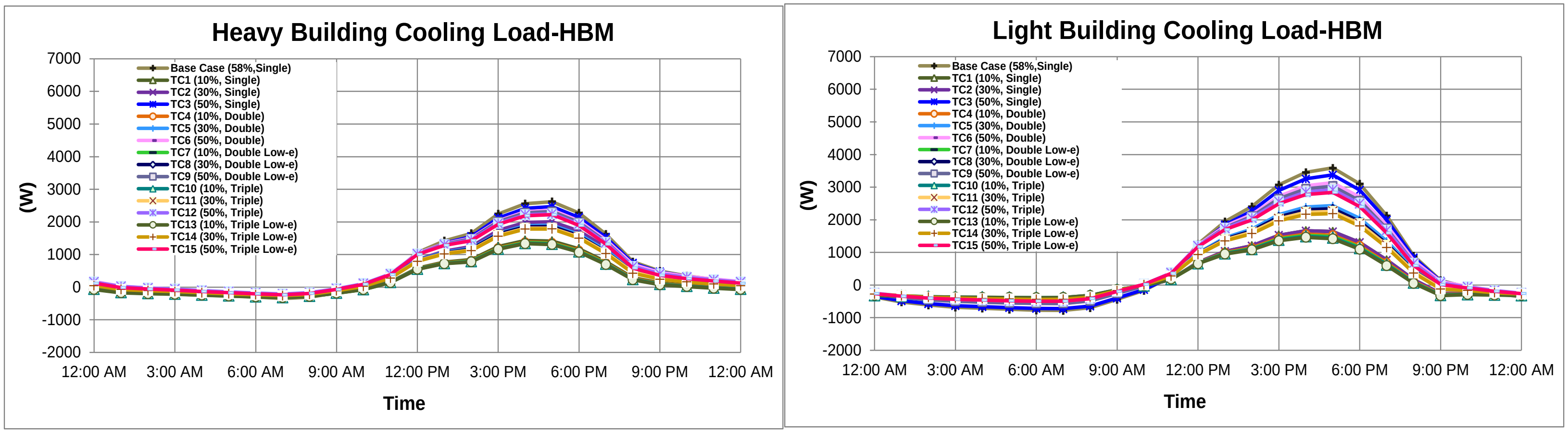

Figure 4.38: Test Case Comparisons by HBM for Both Heavy-Weight and Light-Weight Building Cases

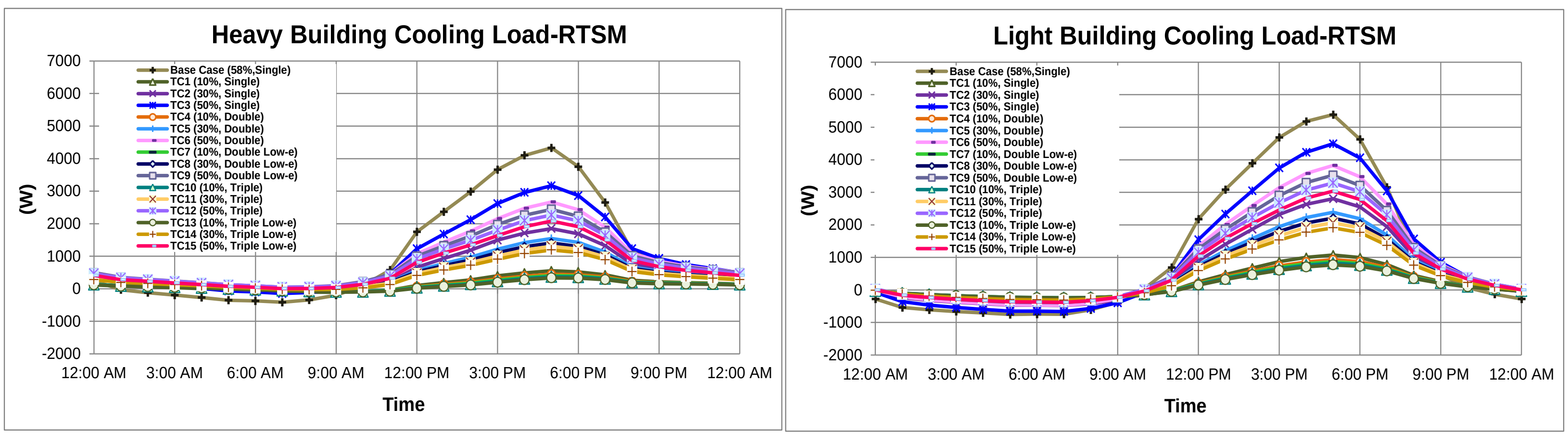

Figure 4.39:Test Case Comparisons by RTSM for Both Heavy-Weight and Light-Weight Building Cases

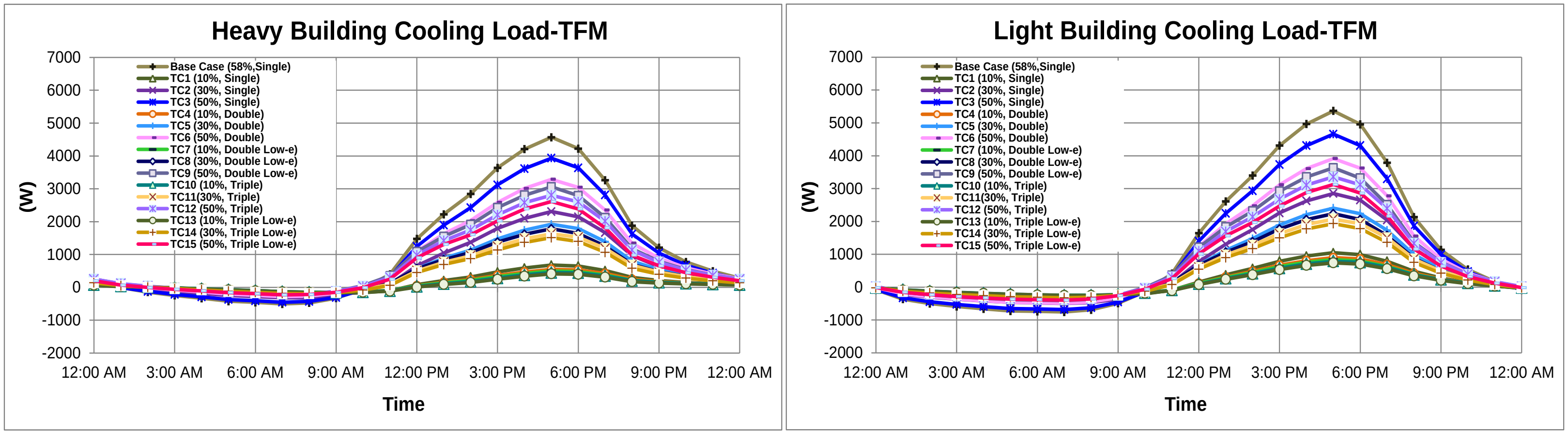

Figure 4.40: Test Case Comparisons by TFM for Both Heavy-Weight and Light-Weight Building Cases

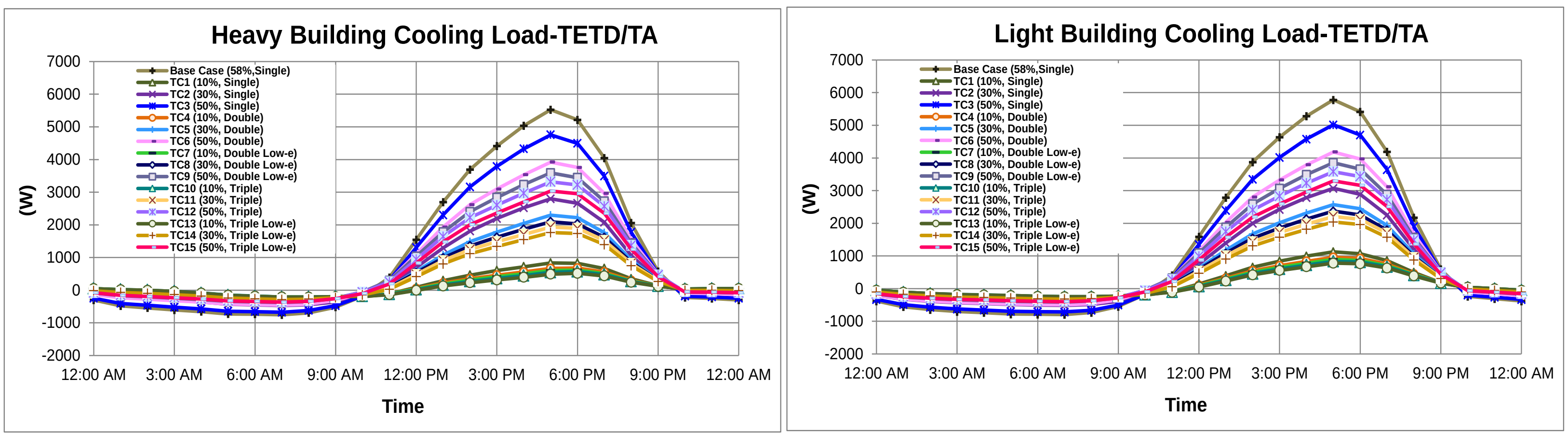

Figure 4.41: Test Case Comparisons by TETD/TA Method for Both Heavy-Weight and Light-Weight Building Cases

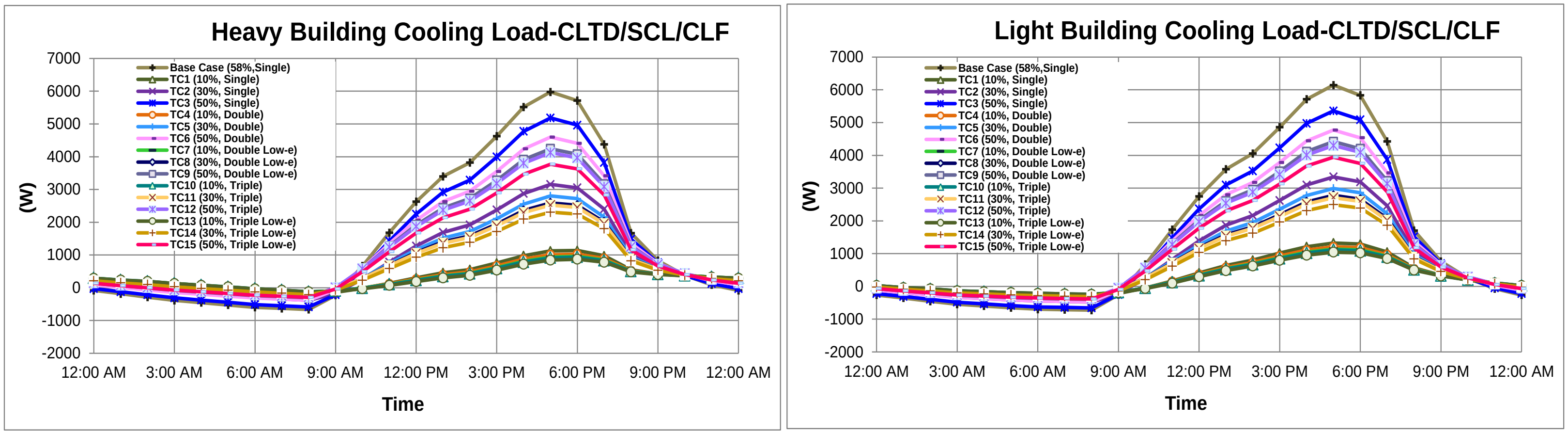

Figure 4.42: Test Case Comparisons by CLTD/SCL/CLF Method for Both Heavy-Weight and Light-Weight Building Cases

4.4 Summary

Chapter IV contained three sections of results of the study, including: survey and interview; base case and additional test case analysis; and comparisons of the peak load design methods. Five of the existing methods that are recognized by the engineers who perform the load calculations including the HBM, the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method were reviewed.

The analysis of the survey and interview provided a great insight into the general building design process in the industry and the methods that are being used by the field engineers to perform the peak cooling load calculations. There were eleven participants in the survey. Nine of them continued with the interview process. The survey showed that most of the participants used the CLTD/SCL/CLF Method since it is easy to use and the accuracy is sufficient for their purpose. The RTSM, which is the only simplified method existing in the 2013 ASHRAE Handbook of Fundamentals, was known by only three of the participants. One of three said the RTSM could be used when it comes to design LEED buildings. One said the RTSM was rarely used, and the last participant was highly interested in using the RTSM. The TETD/TA Method was used by three of the participants and the HBM was mentioned by two participants but not used. However, only one participant knew about TFM, but is not currently using it. Since the number of participants was small, the conclusions drawn from this study may have a bias, but, to some extent, should reflect the industry uses peak cooling load methods in the peak cooling load design.

A comparative analysis was performed based on the published data in the ASHRAE RP-1117 report. In order to perform the study, the FORTRAN source codes for the HBM was obtained from contacting authors of RP-1117 report (Fisher, 2015) and recompiled by using the Elipse FORTRAN compiler. The HBM analysis was rerun and compared to the published results in the RP-1117 report. The same sensible cooling load output was obtained through this analysis. The efforts of duplicating the RTSM simulations were performed using the 2009 ASHRAE RTSM Spreadsheet tool rather than the LOADS Toolkit that was used in the RP-1117. Unfortunately, the sensible cooling load estimated by the ASHRAE RTSM Spreadsheet tool showed a higher value than the values that were published in RP-1117. Since no additional files were provided, the reason for the differences remains unknown, despite the similar profiles. Compared to the RP-1117 report that only covered the analysis of the HBM and the RTSM, the current study performed additional analysis of the sensible cooling load of the heavy-weight and light-weight building cases using the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method to complete the comparisons. For both the heavy-weight and light-weight building cases, the HBM was proved to be the most accurate method that provided the closest peak cooling load estimation to the measured data. Although the RTSM showed an over-prediction, it is still the best simplified method when compared to the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method.

The TFM behaved similar to the RTSM and provided a slightly higher cooling load peak, compared to the RTSM. The TETD/TA Method was the next most accurate. However, this method included subjective information to perform the time averaging process. Therefore, the results depend on the knowledge and background of the users of this method.

Last but not least, the CLTD/SCL/CLF Method, not surprisingly, performed the worst among all the methods. This is because a lot of assumptions were incorporated when generating the CLTD, the SCL, and the CLF tables. Also, for the other four methods, the measured solar data was used, which could not be performed for the CLTD/SCL/CLF Method since it relied only on the published tables and no procedure was provided to make the modifications to the published tables. In addition, the SC was still used in fenestration model calculation of the CLTD/SCL/CLF Method for solar heat gain calculations and was not upgraded to the fenestration model that uses SHGC.

In the current analysis, additional test cases that varied the window area and glazing types were analyzed to further understand the differences between the five methods. In this analysis, the HBM was used as a baseline due to the lack of measured data. For windows with a small amount of glazing area, all simplified methods tended to underestimate the sensible cooling load compared to the HBM. As more glazing was added, a larger solar heat gain came into the space, which made all calculations over-predict the sensible cooling load. Compared to the HBM, all the simplified methods were sensitive to the parameters that could influence the solar heat gains. Their profile seemed more spread out across all the test cases. This new set of analysis showed similar conclusions as the base-case analysis, namely, the RTSM behaved the best. The TFM was the next most accurate and showed close agreement with the RTSM. The TETD/TA

Method was the next in accuracy and the CLTD/SCL/CLF Method was the least accurate.

When one combines the survey and interview results and all the comparison analysis, the CLTD/SCL/CLF Method was most popular but gave the worst accuracy either compared to the measured data or the HBM.

The survey and interview showed that the majority of the participants chose the easy-to-use method rather than the more complicated methods even though the more complex methods were more accurate. Based on this response, it was concluded that if greater accuracy could be developed and demonstrated for the CLTD/SCL/CLF Method then both the requirements of accuracy and simplicity could be achieved. The results of the survey and interview conducted by this study agree with the seminar presentation by Professor Walter Grondzik at the 2016 ASHRAE winter conference. In this presentation, Professor Grondzik also recommended that ASHRAE provide a simple method like the CLTD/SCL/CLF Method for architects to use (Grondzik, 2016).

CHAPTER V

PROPOSED ANALYSIS TO UPDATE THE SCL TABLES FOR THE CLTD/SCL/CLF METHOD USING THE ASHRAE RTSM SPREADSHEET TOOL

5.1 Overview

This Chapter provides a proposed analysis of updating the SCL tables for the CLTD/SCL/CLF Method from the ASHRAE RTSM Spreadsheet Tool. This analysis was motivated by both survey and interview and a detailed comparison of results against the published RP-1117 data. The survey and interview revealed that the CLTD/SCL/CLF Method was still being used by a majority of the participants during the building peak cooling load design process due to the simplicity of its application and acceptable accuracy of the method compared to other methods. The CLTD/SCL/CLF Method most widely is used in the TRACE 700 software. Unfortunately, the comparison of all the current methods against measured data showed the CLTD/SCL/CLF Method performed the worst among all the methods. This is because the CLTD/SCL/CLF Method relies on the published tables that include many assumptions from when they were generated. As mentioned before, there is always a trade-off between the convenience of the easy-to-use and the calculation accuracy. The CLTD/SCL/CLF Method was originally designed as a manual method that intended to provide a simpler procedure than the TFM. In the CLTD/SCL/CLF Method, the tables were calculated on the basis of TFM calculation results. As previously discussed, the results of the comparison process showed the RTSM was found to be the most accurate method among all the simplified methods that provided results closet to the HBM and measured data. Therefore, there is a need to upgrade the CLTD/SCL/CLF tables according to the RTSM calculations to make it more accurate.

In the current study, the proposed analysis procedure to update the SCL tables is demonstrated to show how the potential modifications of the CLTD/SCL/CLF Method can be improved. The original SCL table used in the analysis was shown in Figure 4.32 in Chapter IV.

5.2 Analysis Procedure

As previously noted, the fenestration heat gain model in the CLTD/SCL/CLF Method uses Shading Coefficient (SC) and Double Strength Glass (DSA) coefficients to estimate the solar heat gains through the window (shown in Appendix C, Equations (C.1)-(C.9)). After obtaining the new SCL numbers from the table, Equation (H.4) in the Appendix H was used for solar cooling load calculations. In the 2013 ASHRAE Handbook of Fundamentals, the fenestration heat gains are calculated using the SHGC (shown in Equations (C.10) and (C.11)). Figure 5.1 shows the relationship and connections between the two models.

For each glazing type, the angular-dependent SHGC can be obtained by multiplying the SHGC at a normal incident angle by the published beam and diffuse SHGC angle correction factors. The example of the correction factors are shown in Table 5.1. There are total of 73 types of glazing with the associated SHGC correction factors in the ASHRAE RTSM Spreadsheet Tool.

Table 5.1: SHGC Correction Factors (Adapted from Spitler, 2009)

ID	Layer	Normal SHGC	SHGC Angle Correction Factors and Diffuse Correction Factors						
			0	40	50	60	70	80	Diffuse
1A	Clear	0.86	1	0.977	0.953	0.907	0.779	0.488	0.907
5A	Clear/Clear	0.76	1	0.974	0.934	0.842	0.658	0.342	0.868
29A	Clear/Clear/Clear	0.68	1	0.956	0.912	0.794	0.574	0.265	0.838

To begin with, according to the 2013 ASHRAE Handbook of Fundamentals, the fenestration solar heat gains can be determined by using the following,

$$q_b = AE_{t,b}SHGC(\theta)IAC(\theta,\Omega) \tag{5.1}$$

$$q_d = A(E_{t,d} + E_{t,r})\langle SHGC\rangle_D \, IAC_D \tag{5.2}$$

where,

A : window surface area, m^2;

$E_{r,b}$: beam solar radiation falling on the fenestration, W/m^2;

$E_{t,d}$: diffuse solar radiation from the sky falling on the fenestration, W/m^2;

$E_{t,r}$: diffuse solar radiation from the ground reflection falling on the fenestration, W/m^2;

$SHGC(\theta)$: incidence angle based beam solar heat gain coefficient;

$\langle SHGC\rangle_D$: diffuse solar heat gain coefficient;

$IAC(\theta,\Omega)$: indoor solar attenuation coefficient for beam solar heat gain coefficient;

IAC_D : indoor solar attenuation coefficient for diffuse solar heat gain coefficient;

θ : solar incidence angle;

Ω : shade type.

According to ASHRAE RTSM Spreadsheet Tool (Spitler, 2009),

$$IAC(\theta, \Omega) = IAC_D = IAC \tag{5.3}$$

Next, the angular-dependent beam solar $SHGC(\theta)$ and diffuse solar $\langle SHGC \rangle_D$ can be obtained multiplying SHGC at a normal incident angle by the corresponding correction factors, which modified the Equations (5.1) and (5.2) to be written as,

$$q_b = A \cdot E_{t,b} \cdot IAC \cdot SHGC_{Normal} \cdot CorrectionFactor(\theta) \tag{5.4}$$

$$q_d = A(E_{t,d} + E_{t,r}) \cdot IAC \cdot SHGC_{Normal} \cdot CorrectionFactor_{diffuse} \tag{5.5}$$

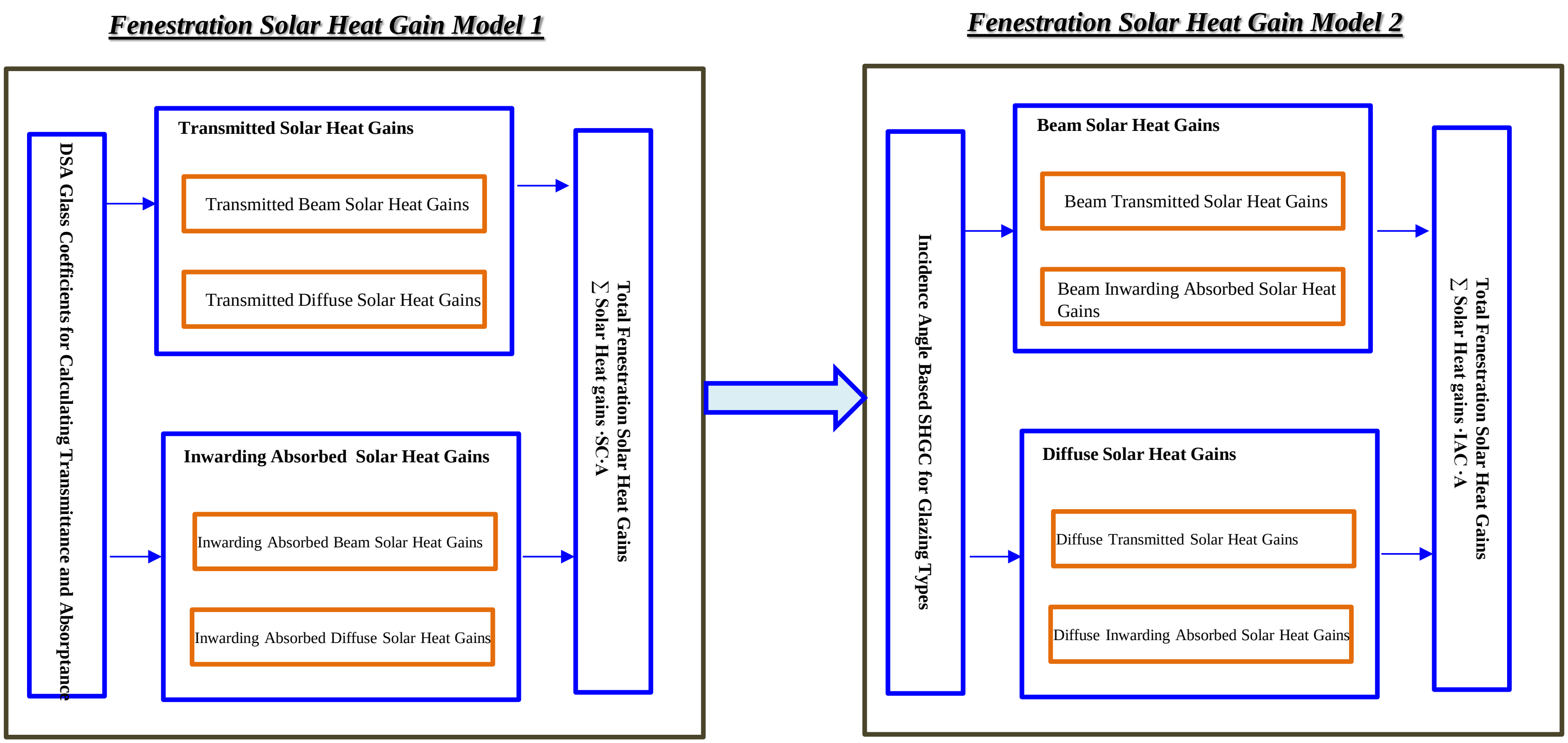

Figure 5.1: Relationship and Connections between Two Fenestration Heat Gain Calculation Models

By applying RTSM principles shown in Appendix E, the sensible cooling load from fenestration solar heat gains can be given as,

$$\begin{aligned} Q_{Solar} &= \sum_{i=0}^{23}(r_{solar,i}\cdot q_{b,\theta-i\delta}) + \sum_{j=0}^{23}(r_{non-solar,j}\cdot q_{d,\theta-j\delta}) \\ &= \sum_{i=0}^{23}\{r_{solar,i}\cdot[A\cdot E_{t,b}\cdot IAC\cdot SHGC_{Normal}\cdot CorrectionFactor(\theta)]_{\theta-i\delta}\} \\ &\quad + \sum_{j=0}^{23}\{r_{non-solar,j}\cdot[A(E_{t,d}+E_{t,r})\cdot IAC\cdot SHGC_{Normal}\cdot CorrectionFactor_{diffuse}]_{\theta-j\delta}\} \\ &= A\cdot IAC\cdot SHGC_{Normal}\cdot \left\langle \begin{array}{l} \sum_{i=0}^{23}\{r_{solar,i}\cdot[E_{t,b}\cdot CorrectionFactor(\theta)]_{\theta-i\delta}\} \\ +\sum_{j=0}^{23}\{r_{non-solar,j}\cdot[(E_{t,d}+E_{t,r})\cdot CorrectionFactor_{diffuse}]_{\theta-j\delta}\} \end{array} \right\rangle \end{aligned} \tag{5.6}$$

Which yields the SCL modified to be,

$$SCL_{Modified} = \left\langle \begin{array}{l} \sum_{i=0}^{23}\{r_{solar,i}\cdot[E_{t,b}\cdot CorrectionFactor(\theta)]_{\theta-i\delta}\} \\ +\sum_{j=0}^{23}\{r_{non-solar,j}\cdot[(E_{t,d}+E_{t,r})\cdot CorrectionFactor_{diffuse}]_{\theta-j\delta}\} \end{array} \right\rangle \tag{5.7}$$

Therefore, the modified solar cooling load calculation becomes,

$$Q_{Solar} = SCL_{Modified}\cdot SHGC_{Normal}\cdot A\cdot IAC \tag{5.8}$$

where,

$SCL_{Modified}$: modified solar cooling load, W/m^2.

Once the solar cooling load is calculated by RTSM, the modified SCL can be determined by,

$$SCL_{Modified} = Q_{Solar} / A \cdot IAC \cdot SHGC_{Normal} \tag{5.9}$$

Since the radiant time factors in the RTSM are different for heavy-weight and light-weight building cases, the SCL table was generated for each case. It should also be noted that although the original SCL tables used an hourly solar time, in this study, the local time was used for convenience for the current study.

In this study, three attempts were made to update the SCL tables from ASHRAE RTSM Spreadsheet Tool, which included the base case (single pane clear glazing), TC 6 (double pane clear glazing), and TC12 (triple pane clear glazing). This yielded a total of six corresponding SCL tables that were calculated for heavy-weight and light-weight building cases, shown in Table 5.2 to Table 5.7, which are expressed by dividing the hourly solar sensible cooling load by the SHGC at a normal incident angle and window area. In this analysis, the hourly solar sensible cooling load was obtained from the ASHRAE RTSM Spreadsheet Tool. Next, using the format from the original SCL tables, the fenestration SCL for nine orientations were calculated, which are: North, Northeast, East, Southeast, South, Southwest, West, Northwest, and Horizontal. In the current analysis, the updated SCL tables for the south and west orientations were used in the test cases.

Table 5.2: Modified SCL Tables for the Heavy-Weight Building Base Case

Glass Face	Local Time, hr 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
N	18	17	16	15	14	13	12	24	41	55	68	77	83	87	86	82	74	62	40	30	26	23	21
NE	23	22	20	19	18	16	15	159	246	201	147	118	112	108	103	96	86	72	48	38	33	30	28
E	37	34	31	29	27	25	24	252	471	530	486	366	245	183	158	138	120	100	73	59	52	47	43
SE	46	42	39	36	34	31	29	204	424	541	584	562	482	353	250	187	155	126	93	76	67	60	54
S	53	48	44	41	38	35	33	59	127	236	344	432	488	508	489	428	334	224	140	106	88	75	66
SW	64	57	51	47	43	40	37	46	62	75	89	158	266	406	521	596	609	532	268	161	124	101	84
W	55	48	44	40	36	33	31	40	57	71	82	90	99	177	308	458	555	548	270	147	111	89	74
NW	31	28	25	23	21	20	18	28	46	60	72	81	87	90	93	145	221	280	146	75	58	47	40
Hor	17	16	15	14	13	12	11	28	47	57	64	69	72	74	75	75	73	65	41	29	25	23	21

Table 5.3: Modified SCL Tables for the Light-Weight Building Base Case

Glass Face	Local Time, hr 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
N	1	1	0	0	0	0	0	19	46	71	90	105	114	117	114	105	90	69	33	15	8	4	2
NE	1	1	0	0	0	0	0	165	286	258	196	154	139	130	121	109	92	69	33	15	8	4	2
E	1	1	0	0	0	0	0	259	538	642	607	465	306	208	161	130	104	75	36	17	9	5	3
SE	1	1	1	0	0	0	0	200	474	641	711	691	592	427	283	187	133	91	44	21	11	6	4
S	3	2	1	1	0	0	0	36	124	262	401	516	590	615	588	507	383	236	112	56	29	16	9
SW	7	4	2	1	1	1	0	17	46	70	95	178	308	476	621	714	729	632	310	144	75	40	22
W	7	4	2	1	1	1	0	17	46	70	90	105	118	206	359	538	660	657	334	150	78	42	22
NW	3	2	1	1	0	0	0	17	46	70	90	105	114	117	118	173	258	326	175	75	39	21	11
Hor	1	1	0	0	0	0	0	25	56	75	86	92	96	97	97	95	89	76	38	16	8	4	2

Table 5.4: Modified SCL Tables for the Heavy-Weight Building TC6

Glass Face	Local Time, hr 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
N	25	23	22	21	20	19	18	26	36	46	55	61	67	69	70	68	64	56	42	35	32	30	28
NE	34	33	31	29	28	27	25	124	180	149	118	102	98	95	92	87	81	71	56	48	44	41	39
E	60	57	54	51	49	47	44	204	364	417	387	300	222	180	160	144	130	115	95	84	77	72	67
SE	76	72	68	65	62	59	56	177	336	428	468	458	399	306	239	196	170	148	123	109	99	92	86
S	82	77	73	69	65	62	59	73	111	183	263	332	380	401	393	351	286	213	158	132	116	105	96
SW	98	91	84	79	74	70	66	70	80	87	96	137	205	311	407	474	495	450	270	189	157	136	120
W	82	75	70	65	61	58	55	59	69	77	84	89	95	143	230	351	434	442	256	166	136	115	101
NW	42	39	37	35	33	31	29	35	46	55	63	70	74	77	79	111	159	209	128	80	66	57	51
Hor	24	22	21	20	19	18	17	28	40	47	52	56	59	61	62	63	62	57	42	34	31	28	27

Table 5.5: Modified SCL Tables for the Light-Weight Building TC6

Glass Face	Local Time, hr 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
N	3	2	1	1	1	0	0	14	36	57	75	90	100	106	106	100	89	72	43	26	16	10	7
NE	3	2	1	1	1	0	0	125	221	210	176	150	137	129	120	109	95	75	45	27	17	11	7
E	4	3	2	1	1	1	0	201	437	553	546	439	320	238	188	152	122	93	56	34	22	14	9
SE	6	4	3	2	1	1	1	155	382	544	630	635	561	429	312	226	168	122	75	46	29	19	12
S	11	7	5	3	2	2	1	25	86	192	313	424	506	545	537	478	379	259	156	96	61	39	25
SW	23	15	10	7	5	3	2	14	36	57	79	139	236	383	526	632	671	615	370	218	136	86	55
W	22	15	10	6	4	3	2	14	36	57	76	90	104	166	283	448	575	603	371	213	133	84	53
NW	10	7	4	3	2	1	1	13	35	57	75	90	100	106	109	146	207	273	177	98	61	38	24
Hor	3	2	1	1	1	0	0	19	43	61	73	81	86	89	91	90	86	76	46	27	17	11	7

Table 5.6: Modified SCL Tables for the Heavy-Weight Building TC12

	Local Time, hr																						
Glass Face	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
N	24	23	21	20	19	18	18	25	35	45	53	59	64	67	68	66	61	54	40	34	31	29	27
NE	33	31	30	28	27	26	24	120	170	137	110	96	93	91	88	83	77	68	53	46	42	39	37
E	58	55	52	50	47	45	43	201	359	409	375	283	211	173	154	139	125	111	92	81	74	69	65
SE	73	69	66	62	59	57	54	173	329	419	458	446	382	289	227	188	164	142	119	105	96	89	83
S	78	73	69	65	61	58	55	68	102	168	246	315	363	384	374	331	267	199	149	125	110	99	90
SW	95	88	82	76	72	68	64	68	77	84	92	129	189	295	394	461	483	439	262	184	153	131	116
W	79	73	68	63	59	56	53	57	67	75	81	87	92	134	215	339	423	433	250	162	132	112	98
NW	40	37	35	33	31	29	28	34	44	53	61	67	72	74	76	103	146	198	122	75	63	54	48
Hor	23	22	21	20	19	18	17	27	38	46	50	54	57	59	60	61	60	55	40	33	30	27	26

Table 5.7: Modified SCL Tables for the Light-Weight Building TC12

	Local Time, hr																						
Glass Face	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
N	3	2	1	1	1	0	0	13	34	55	73	87	97	102	102	97	86	70	42	25	15	10	6
NE	3	2	1	1	1	0	0	121	210	194	164	141	130	123	115	105	91	73	43	26	16	10	7
E	4	3	2	1	1	1	0	199	431	543	530	417	304	227	180	146	117	89	54	33	21	14	9
SE	5	4	2	2	1	1	1	152	375	533	617	619	540	406	296	215	160	116	71	44	28	18	12
S	10	7	5	3	2	1	1	23	77	175	293	402	483	522	513	452	354	241	145	89	56	36	23
SW	23	15	10	7	4	3	2	13	35	55	76	130	217	362	507	614	655	601	361	212	133	84	54
W	22	14	9	6	4	3	2	13	35	55	73	87	100	156	264	431	560	591	364	209	130	82	52
NW	10	6	4	3	2	1	1	13	34	55	73	87	97	102	105	136	190	257	168	93	58	36	23
Hor	3	2	1	1	1	0	0	18	42	59	71	78	83	86	87	87	83	73	45	26	16	10	7

Figure 5.2 and Figure 5.3 show the comparisons of base-case sensible cooling load predicted by the HBM, the RTSM, the CLTD/SCL/CLF Method and the modified CLTD/SCL/CLF Method for both the heavy-weight (Figure 5.2) and light-weight (Figure 5.3) building cases. The results showed the peak sensible cooling load for the heavy-weight building using the original CLTD/SCL/CLF Method decreased from 5,976.3 W to 5,022.4 W by applying the updated SCL tables, which had a difference of -15.96%. The peak cooling load using CLTD/SCL/CLF Method was decreased by 28%, compared to HBM baseline. The peak sensible cooling load for the light-weight building using the original CLTD/SCL/CLF Method decreased from 6,145.2 W to 6,049.4 W by applying updated SCL tables, which had a difference of -1.56%. The peak cooling load using CLTD/SCL/CLF Method was decreased by 3.5%, compared to HBM baseline. Since the SCL tables were derived from the RTSM, the modified CLTD/SCL/CLF Method brought the peak cooling load closer to the RTSM and HBM results, when compared to the original CLTD/SCL/CLF Method. However, the profile still did not exactly match by the RTSM profile. This is because the sensible cooling load profile was driven by both CLTD and SCL tables. In the results shown, only the SCL tables were updated and the CLTD tables remained unchanged.

For both the heavy-weight and light-weight building cases, the peak sensible cooling load peaks from the different methods all occurred at 5:00 P.M., which indicated a good alignment of peak time. During the morning and night time, the peak cooling load by the modified CLTD/SCL/CLF Method was above the peak cooling load by the RTSM, which appeared asymmetric pattern.

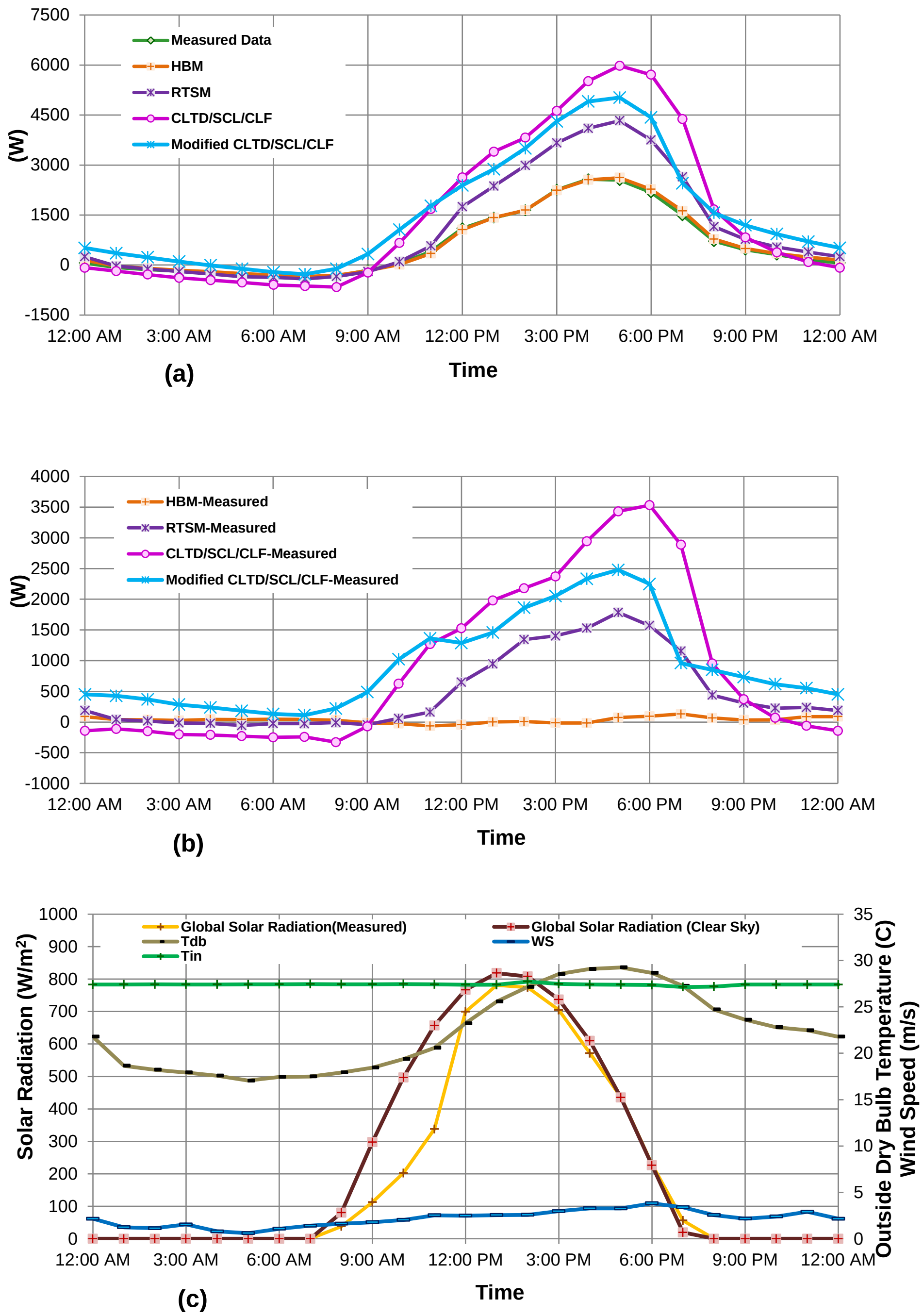

Figure 5.2: Base-Case, Single-Pane Clear Case: (a) Cooling Load Comparisons between Modified CLTD/SCL/CLF Method, Original Methods and Measured Data for Heavy-Weight Building; (b) Cooling Load Differences between Methods and Measured Data for Heavy-Weight Building; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

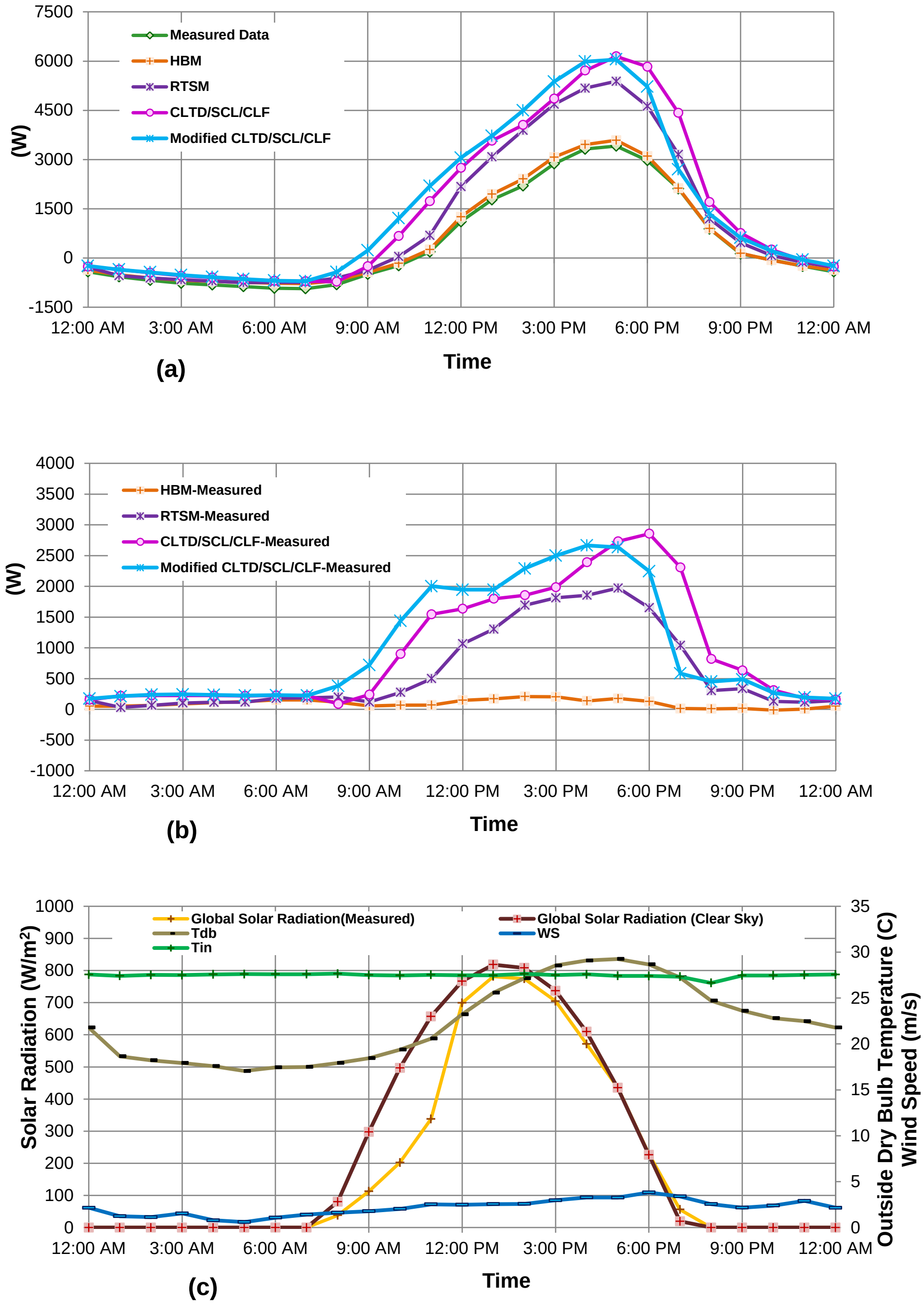

Figure 5.3: Base-Case, Single-Pane Clear Case: (a) Cooling Load Comparisons between Modified CLTD/SCL/CLF Method, Original Methods and Measured Data for Light-Weight Building; (b) Cooling Load Differences between Methods and Measured Data for Light-Weight Building; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

Figure 5.4 and Figure 5.5 show the comparisons of TC6 test case sensible cooling load predicted by the HBM, the RTSM, the CLTD/SCL/CLF Method and the modified CLTD/SCL/CLF Method for both the heavy-weight (Figure 5.4) and light-weight (Figure 5.5) building cases. The results showed the peak sensible cooling load for the heavy-weight building using the original CLTD/SCL/CLF Method decreased from 4,597.2 W to 3,145.5 W using the updated SCL tables, which had a difference of -31.58%. The peak cooling load using CLTD/SCL/CLF Method was decreased by 64%, compared to HBM baseline. The peak sensible cooling load for light-weight building using the original CLTD/SCL/CLF Method decreased from 4,771.1 W to 4,310.1 W using the updated SCL tables, which had a difference of -9.66%. The peak cooling load using CLTD/SCL/CLF Method was decreased by 28%, compared to HBM baseline. The peak sensible cooling load profile using the modified CLTD/SCL/CLF Method in the TC6 test case (i.e., double-pane clear glazing) matched more closely with the RTSM profile, compared to the base case (i.e., single-pane clear glazing). The peak sensible cooling load using the modified CLTD/SCL/CLF Method for the heavy-weight building case in the TC6 test case was decreased more than the peak of the light-building case, which had similar observation as the base case. The asymmetric pattern was also improved for the double-pane clear versus the single-pane clear.

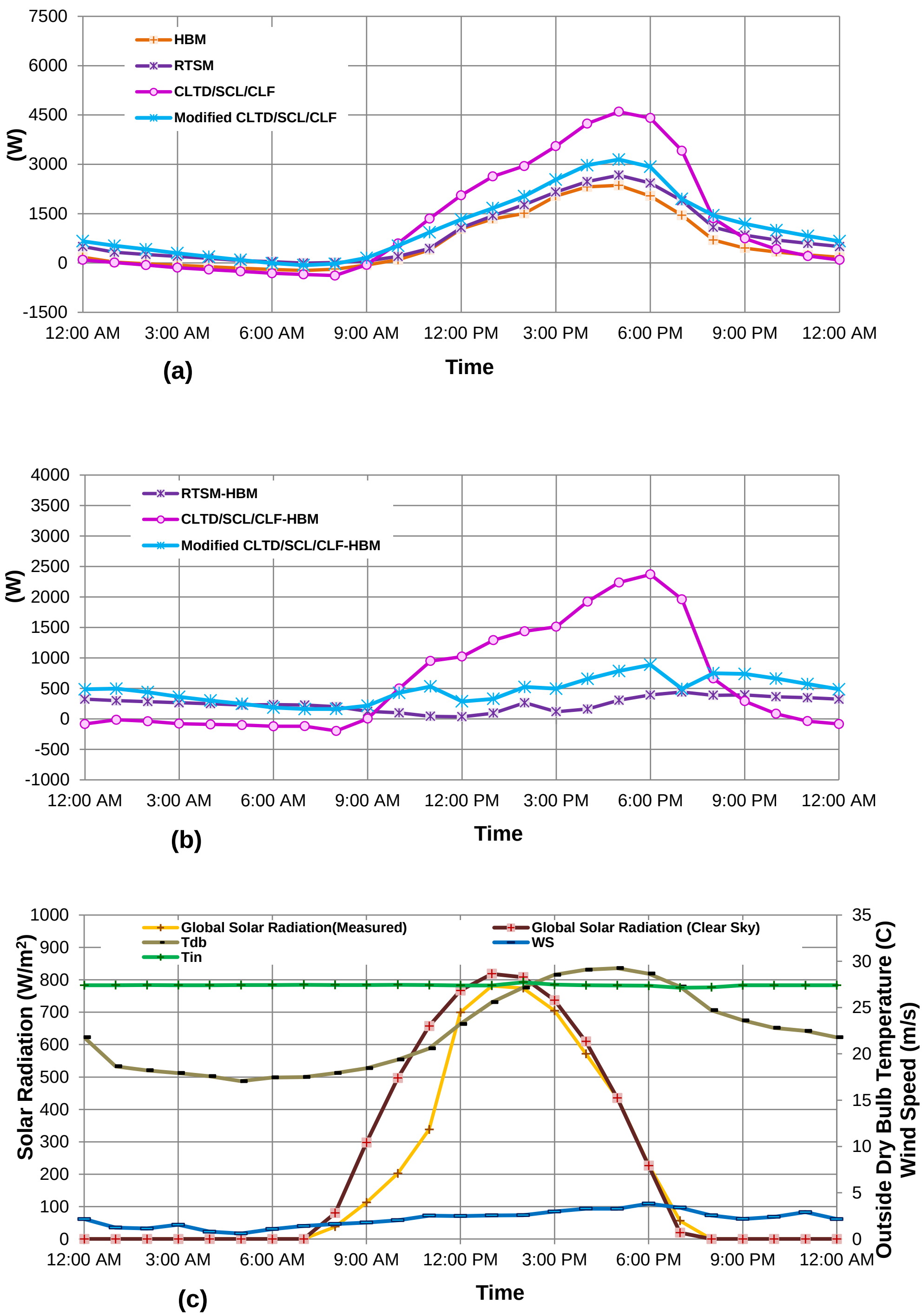

Figure 5.4: TC 6, Double-Pane Clear Case: (a) Cooling Load Comparisons between Modified CLTD/SCL/CLF Method and Original Methods for Heavy-Weight Building; (b) Cooling Load Differences between Methods and HBM for Heavy-Weight Building; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

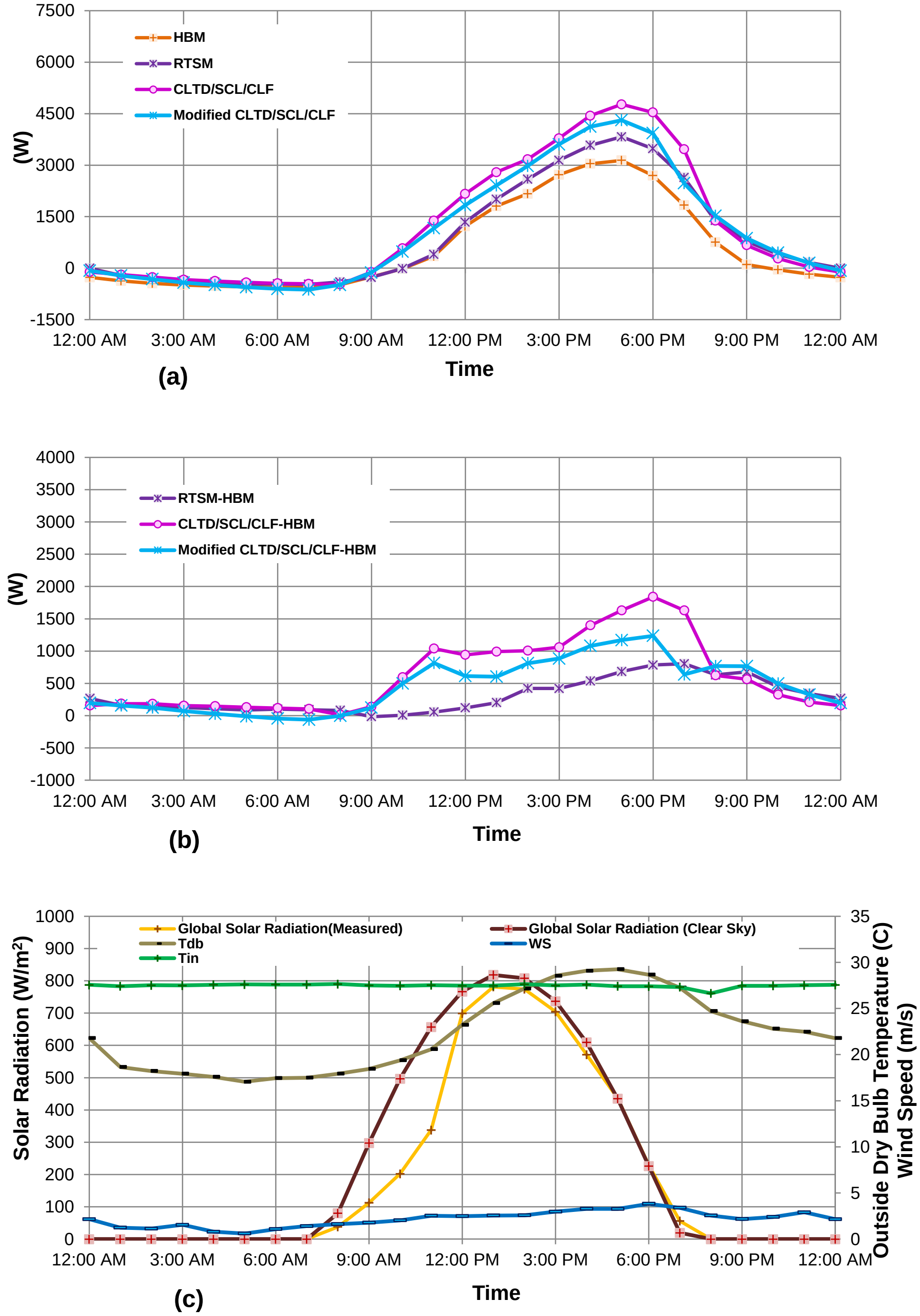

Figure 5.5: TC 6, Double-Pane Clear Case: (a) Cooling Load Comparisons between Modified CLTD/SCL/CLF Method and Original Methods for Light-Weight Building; (b) Cooling Load Differences between Methods and HBM for Light-Weight Building; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

Figure 5.6 and Figure 5.7 show the comparisons of TC12 test case sensible cooling load predicted by the HBM, the RTSM, the CLTD/SCL/CLF Method and the modified CLTD/SCL/CLF Method for both the heavy-weight and light-weight building cases. The peak sensible cooling for the heavy-weight building using the original CLTD/SCL/CLF Method decreased from 4,127.2 W to 2,707.1 W using the updated SCL tables, which had a difference of -34.41%. The peak cooling load using CLTD/SCL/CLF Method was decreased by 75%, compared to HBM baseline. The peak sensible cooling load for the light-weight building using the original CLTD/SCL/CLF Method decreased from 4,301.4 W to 3,729.8 W using the updated SCL tables, which had a difference of -13.29%. The peak cooling load using CLTD/SCL/CLF Method was decreased by 41%, compared to HBM baseline. The peak sensible cooling load profile using the modified CLTD/SCL/CLF Method in the TC12 test case (i.e., triple-pane clear glazing) more closely matched the RTSM profile, compared to the base case (i.e., single-pane clear glazing) and TC6 test case (i.e., double-pane clear glazing). The asymmetric pattern was also improved for the triple-pane clear when compared to the double-pane clear glazing.

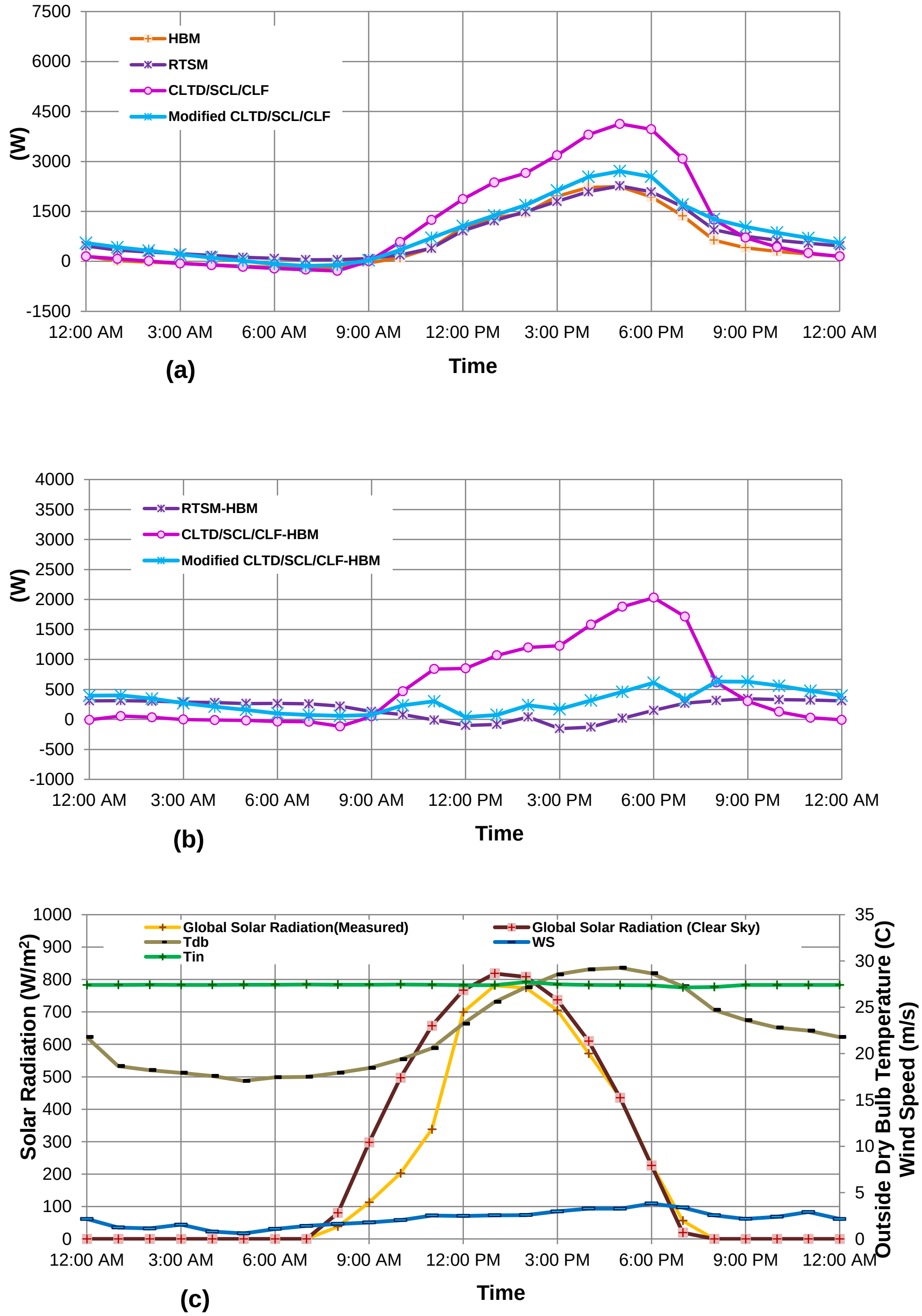

Figure 5.6: TC 12, Triple-Pane Clear Case: (a) Cooling Load Comparisons between Modified CLTD/SCL/CLF Method and Original Methods for Heavy-Weight Building; (b) Cooling Load Differences between Methods and HBM for Heavy-Weight Building; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

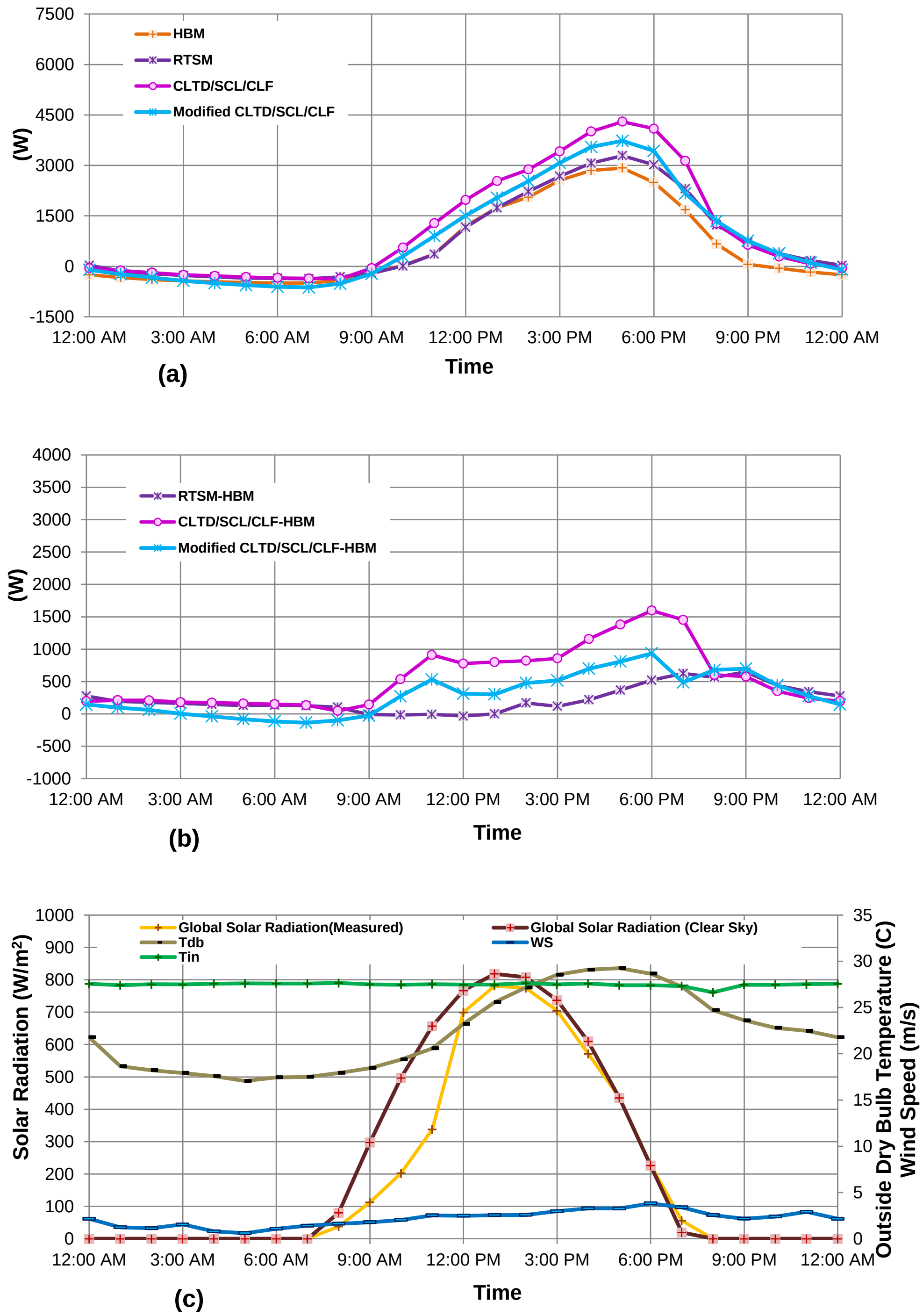

Figure 5.7: TC 12, Triple-Pane Clear Case: (a) Cooling Load Comparisons between Modified CLTD/SCL/CLF Method and Original Methods for Light-Weight Building; (b) Cooling Load Differences between Methods and HBM for Light-Weight Building; and (c) Weather Conditions for September 22nd 2001, Stillwater, OK.

5.3 Summary

This section presented a proposed procedure to update the SCL tables that were used in the CLTD/SCL/CLF Method using the most recent fenestration heat gain calculation model. Specifically, this model replaced the SC with an incidence angle-based SHGC. The shading device influence can be further adjusted by indoor solar attenuation coefficient (IAC). This new procedure was motivated by both the survey and interview results as well as the discoveries made during the method comparisons shown in Chapter IV.

Three test cases were chosen for this study to generally show results of the sensible peak cooling loads estimated by the modified CLTD/SCL/CLF Method. All the results showed decreased peak sensible cooling load using the updated SCL tables in the modified CLTD/SCL/CLF Method, which brought the calculated peak closer to the HBM results. One reason for this is that the new SCL tables were derived from the ASHRAE RTSM Spreadsheet Tool. Therefore, the majority of the sensible cooling load profiles followed the similar pattern of the RTSM profiles.

CHAPTER VI

RESULT SUMMARY, CONCLUSIONS AND FUTURE WORK

6.1 Result Summary and Conclusions

This dissertation has analyzed peak sensible cooling load calculation methods for commercial building design in the U.S., including all cooling loads methods that have been published in the 1967-2013 ASHRAE Handbook of Fundamentals.

The major contributions of this work are as follows:

1) A survey and phone interview of selected HVAC design professionals who specialized in HVAC system design and load calculations.

2) A comprehensive analysis and comparison of five sensible peak cooling load calculation methods, which are: the Heat Balance Method (HBM); the Radiant Time Series Method (RTSM); the Transfer Function Method (TFM); the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method; and the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method. The comparison analysis was presented in two parts. The first part focused on an analysis and the comparison of five methods against measured data from the RP-1117 report. The second part of the analysis was additional case-study analysis that compared the four methods against the HBM varying the window parameters (i.e., the window area and glazing properties).

3) Finally, a proposed analysis that updates the SCL tables used in the CLTD/SCL/CLF Method was performed and a method provided to integrate the most recent fenestration heat gain model by using SHGC.

6.1.1 Results from the Survey and Phone Interview Study

Both a one-page survey and a fifteen-minute phone interview were conducted with the selected participants. The following findings were obtained:

- All peak load calculation methods are still available for engineers to use.
- The majority of the engineers interviewed used the CLTD/SCL/CLF Method. Most people who used this method used the TRACE 700 software.
- The second most popular method used by the participants was the TETD/TA Method, the RTSM, followed by the HBM. None of the participants are using the TFM, even though some were familiar to the TFM principles.
- Several participants said the HBM was the most accurate method, although it had drawbacks of being complex and lacked a breakdown of cooling load component output.
- With the exception of LEED design requirements, the RTSM was rarely in use since other simplified methods were easier-to-use and had acceptable accuracy.
- All the current methods were deemed to be good enough for designing today's commercial buildings. In some instances, the inputs for the software need to be better managed.

6.1.2 Results from the Analysis and Comparison of the Peak Cooling Load Design Methods

In the first part of the analysis, the data from the ASHRAE RP-1117 report were used as a comparison for the peak cooling design load methods. In this analysis, the building configurations and construction materials remained unchanged. The sensible cooling load analysis from the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method were analyzed along with the calculation that represented the HBM and the RTSM. This analysis showed the following:

- <u>Differences in the published ASHRAE clear-sky models</u>. Two clear-sky models were published by ASHRAE from 1967 to 2013, which were the 1967 ASHRAE clear-sky model and the 2009 ASHRAE clear-sky model. In the 1967 ASHRAE clear-sky model, two sets of A, B, C coefficients were published in the ASHRAE Handbook. One set was in the 1967-2001 ASHRAE Handbook of Fundamentals and the other set was in the 2005 ASHRAE Handbook of Fundamentals. The 2009 ASHRAE clear-sky model calculates a larger beam solar radiation component compared to the 1967 ASHRAE clear-sky model. In addition, the diffuse solar radiation from the 2009 ASHRAE clear-sky model falls between the values predicted by the 1967 ASHRAE clear-sky model using the two sets of A, B, C coefficients. The total solar radiation calculated by the 2009 ASHRAE clear-sky model is the largest among all methods. Finally, no case studies were found that fully compared the ASHRAE clear-sky models. Even in the 2009 and 2013 ASHRAE Handbook of Fundamentals different coefficients were presented to calculate air mass components, without explanation. Therefore, before calculating a peak cooling load, the choice of clear-sky model should be carefully reviewed to avoid any unexpected results.

- Differences in FORTRAN source code. The FORTRAN source codes published in the ASHRAE LOADS Toolkit CD does not allow the reader to replicate the results published in RP-1117 report. This was resolved by contacting the authors of this project.

- Limitations in the HB LOADS Toolkit Output. The sensible peak cooling load produced by the HB LOADS Toolkit did not provide a detailed breakdown of each component that was contributing to the total cooling load. Unfortunately, in order to obtain a detailed output, the source code needed to be modified and recompiled.

- Replication of the RP-1117 results could not be performed with the ASHRAE RTSM Spreadsheet Tool. Instead of using the RTSM LOADS Toolkit to estimate the sensible peak cooling load, the 2009 ASHRAE RTSM Spreadsheet Tool was selected to perform the analysis. Unfortunately, the RP-1117 results could not be exactly replicated. The reason remains unknown because the simulation files that were used by RP-1117 could not be obtained. Nevertheless, the over-prediction issues reported by RP-1117 were also found in this study for cases with a large single-pane clear glazing. Compared to the measured data, the RTSM over-predicted the cooling load for both the heavy-weight and light-weight building cases, which were 68.32 % and 57.83% differences, respectively.

- The TFM over-predicted the peak cooling load. To apply the TFM principles to the base case, the proper wall and roof group was selected and the fenestration heat gain model used SHGC instead of SC. Compared to the measured data, the TFM over-predicted the cooling load for both the heavy-weight and light-weight building cases, which were 77.64 % and 57.17% differences, respectively.

- The TETD/TA Method required subjective input and over-predicted the cooling load. The TETD/TA Method tends to be subjective since the designer needs to pick a period for the time-averaging process, which can vary from one person to the next. In the analysis, the fenestration heat gain model used SHGC analysis. Compared to the measured data, the TETD/TA over-predicted the cooling load for both the heavy-weight and light-weight building cases, which were 114.73% and 69.34% different, respectively.

- It was difficult to modify the CLTD/SCL/CLF Method for use with measured solar data. The CLTD/SCL/CLF Method was designed as a manual method. By directly applying the equations, the sensible cooling load can be achieved in one step. Unfortunately, many assumptions are required to generate the CLTD, SCL, and CLF tables. For example, the 1967 ASHRAE clear-sky model was used to generate the original published tables. In addition, the SC was used in the fenestration heat gain calculations. Therefore, there was little room to apply measured solar data and SHGC fenestration heat gain model. Nevertheless, the CLTD/SCL/CLF Method over-predicted the peak cooling load for both the heavy-weight and light-weight building cases, which were 132.31% and 80.05%, respectively.

- The most accurate cooling load calculation was the HBM, followed by the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method. The sensible cooling load comparisons of the HBM, the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method were analyzed. In general, all simplified methods tended to over-predict the peak cooling load. The RTSM and TFM showed the close peak cooling load estimation. The comparison between RTSM and TFM showed differences to be 5.54% and -0.42% for the heavy-weight and light-weight buildings, respectively. Compared to the measured data, the HBM provided the most accurate peak prediction, followed by the RTSM, the TFM and the TETD/TA Method. The less accurate method was proved to be CLTD/SCL/CLF Method.

In the second part of the analysis, additional peak cooling loads were analyzed to further understand the impact of window area and glazing types on the sensible cooling load by applying the HBM, the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method. To perform this comparison, the HBM was treated as the baseline and other methods compared with it. Fifteen cases were prepared for this second comparison analysis. The following conclusions were obtained during this second analysis:

- All the cases with a 5% WWR tended to under-estimate the peak cooling loads compared to the HBM. For the heavy-weight building, the RTSM under-estimated the cooling load the most, while, for light-weight building, the TFM underestimated the cooling load the most, other than the RTSM.

- For the remainder of the test cases, the simplified methods tended to over-estimate the sensible peak cooling load. The results from the RTSM and the TFM were fairly close. The worst prediction was still the CLTD/SCL/CLF Method.

- The RTSM for test case 12 provided the best estimation of sensible cooling load for all heavy-weight building case simulations. Across all types of window glazing, the cooling load of the test case 12 with a 25% WWR and triple pane clear windows by the RTSM was 0.83% percentage difference compared to the HBM, which was considered the best match between the RTSM and HBM for all heavy-weight building case simulation.

- The RTSM for test case 5 provided the best estimation of sensible peak cooling load for all light-weight building case simulations, followed by the TFM. Across all types of window glazing, the cooling load of the test case 5 with 15% WWR and double pane clear windows by the TFM and the RTSM was -1.09% and -1.85% percentage difference, respectively, compared to the HBM, which were considered the best and the second best peak cooling load estimations for all light-weight building case simulation.

- The most accurate simplified peak cooling load calculation method was the RTSM, followed by the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method. For most test cases, the RTSM worked fairly well. The second most accurate method was the TFM. The least accurate method was the CLTD/SCL/CLF method. The TETD/TA Method results were in between the TFM and the CLTD/SCL/CLF Method. This was consistent with the base case results.

- The simplified methods were more sensitive to the glazing area and glazing type. The RTSM, the TFM, the TETD/TA Method and the CLTD/SCL/CLF Method were very sensitive to the glazing area and glazing type. In contrast, the HBM was very steady and predicted the cooling load reasonably over a range of test cases. For all methods, the use of better SHGC lowered the peak cooling load.

6.1.3 Results from the Proposed Analysis to Update the SCL Tables for CLTD/SCL/CLF Method Using ASHRAE RTSM Spreadsheet Tool

An attempt to update SCL tables in the CLTD/SCL/CLF Method was made by using the ASHRAE RTSM Spreadsheet Tool. The purpose of this was to update the fenestration heat gain model by using an angular-based SHGC, rather than the SC. Based on this analysis, the following conclusions were obtained:

- It is possible to re-define the SCL by deriving it from a more accurate fenestration heat gain model. The previous SCL tables were based on the SC, the Double Strength (DSA) Glass coefficients and the TFM calculations. Since the comparisons showed the RTSM performed better than the TFM, the new sets of tables were based on the RTSM principles to update fenestration heat gain model.

- Three selected examples showed a decreased cooling load peak using the updated, modified SCL tables. In all cases, the peak cooling load was closer to the RTSM and HBM results.

- As glazing was varied from single-pane clear to double and triple-pane clear, the peak cooling load profile using modified SCL tables showed a more accurate profile compared to the RTSM and decreased peak load.

6.2 Future Work

The following work needs to be performed in the future:

- ASHRAE should confirm the survey results in this study with additional interviews of field professionals throughout the U.S. who use peak load calculations.
- The 2009 ASHRAE clear-sky model needs to be further analyzed to assure its accuracy.
- All peak cooling load methods should be updated with the most recent 2009 ASHRAE clear-sky model.
- ASHRAE should reconsider updating the CLTD/SCL/CLF Method for both architects and engineers to use and publishing the newly updated method in an ASHRAE special publication.
- The CLTD and CLF tables should be updated using the 2006 spreadsheet tool proposed by TC 4.1 volunteers and the results published in an ASHRAE special publication.
- The SCL tables should be updated following the proposed methodology.
- The ETD tabulated tables can be updated based on the TETD/TA Method with an updated fenestration heat gain model.
- The HBM should be further analyzed to provide a detailed cooling load component output to facilitate the comparison;
- Additional experiments should be set up to further study the comparison of all methods.

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APPENDIX A

SURVEY AND INTERVIEW RESULTS

This section covers the study approval from Institutional Review Board (IRB), survey and interview result summary.

A.1 IRB Approval

DIVISION OF RESEARCH

Research Compliance and Biosafety

TEXAS A&M UNIVERSITY

DATE: January 12, 2015

MEMORANDUM

TO: Jeff Haberl
TAMU - College Of Architecture - Architecture

FROM: Dr. James Fluckey
Chair
Institutional Review Board

SUBJECT: Expedited Approval

Study Number: IRB2014-0295D

Title: ANALYSIS OF BUILDING PEAK HEATING AND COOLING LOAD CALCULATION METHODS FOR DESIGNING TODAY'S COMMERCIAL BUILDINGS IN THE UNITED STATES

Approval Date: 01/12/2015

Continuing Review Due: 12/01/2015

Expiration Date: 01/01/2016

Documents Reviewed and Approved:

Submission Components			
Study Document			
Title	Version Number	Version Date	Outcome
citiCompletionReport4247321-Nov 2014_Dr Baltazar	Version 1.0	01/06/2015	Approved
citiCompletionReport4249601_Dr Jeff Haberl	Version 1.0	01/06/2015	Approved
letter of support	Version 1.0	null	Approved
Interview questions	Version 1.0	null	Approved
Recruitment email	Version 1.0	06/23/2014	Approved
Study Introduction	Version 1.0	06/23/2014	Approved
Survey form_Peak Load_Final	Version 1.0	06/23/2014	Approved
Dissertation proposal_Chunliu Mao _Final rev	Version 1.0	06/23/2014	Approved
Survey form draft_Chunliu Mao	Version 1.0	03/10/2014	Approved
Study Consent Form			
Title	Version Number	Version Date	Outcome
Study consent infomation	Version 1.2	06/23/2014	Approved
Study consent infomation	Version 1.1	06/23/2014	

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Figure A.1: Approval Letter 1 from IRB

Study consent infomation	Version 1.0	06/23/2014	

Document of Consent: Waiver approved under 45 CFR 46.117 (c) 1 or 2/ 21 CFR 56.109 (c)1
Waiver of Consent:

Provisions:

Comments: Researchers were responsive to the requests of the Reviewer.

This research project has been approved. As principal investigator, you assume the following responsibilities:

1. **Continuing Review:** The protocol must be renewed by the expiration date in order to continue with the research project. A Continuing Review application along with required documents must be submitted by the continuing review deadline. Failure to do so may result in processing delays, study termination, and/or loss of funding.
2. **Completion Report:** Upon completion of the research project (including data analysis and final written papers), a Completion Report must be submitted to the IRB.
3. **Unanticipated Problems and Adverse Events:** Unanticipated problems and adverse events must be reported to the IRB immediately.
4. **Reports of Potential Non-compliance:** Potential non-compliance, including deviations from protocol and violations, must be reported to the IRB office immediately.
5. **Amendments:** Changes to the protocol must be requested by submitting an Amendment to the IRB for review. The Amendment must be approved by the IRB before being implemented.
6. **Consent Forms:** When using a consent form or information sheet, you must use the IRB stamped approved version. Please log into iRIS to download your stamped approved version of the consenting instruments. If you are unable to locate the stamped version in iRIS, please contact the office.
7. **Audit:** Your protocol may be subject to audit by the Human Subjects Post Approval Monitor. During the life of the study please review and document study progress using the PI self-assessment found on the RCB website as a method of preparation for the potential audit. Investigators are responsible for maintaining complete and accurate study records and making them available for inspection. Investigators are encouraged to request a pre-initiation site visit with the Post Approval Monitor. These visits are designed to help ensure that all necessary documents are approved and in order prior to initiating the study and to help investigators maintain compliance.
8. **Recruitment:** All approved recruitment materials will be stamped electronically by the HSPP staff and available for download from iRIS. These IRB-stamped approved documents from iRIS must be used for recruitment. For materials that are distributed to potential participants electronically and for which you can only feasibly use the approved text rather than the stamped document, the study's IRB Protocol number, approval date, and expiration dates must be included in the following format: TAMU IRB#20XX-XXXX Approved: XX/XX/XXXX Expiration Date: XX/XX/XXXX.
9. **FERPA and PPRA:** Investigators conducting research with students must have appropriate approvals from the FERPA administrator at the institution where the research will be conducted in accordance with the Family Education Rights and Privacy Act (FERPA). The Protection of Pupil Rights Amendment (PPRA) protects the rights of parents in students ensuring that written parental consent is required for participation in surveys, analysis, or evaluation that ask questions falling into categories of protected information.
10. **Food:** Any use of food in the conduct of human subjects research must follow Texas A&M University Standard Administrative Procedure 24.01.01.M4.02.
11. **Payments:** Any use of payments to human subjects must follow Texas A&M University Standard Administrative Procedure 21.01.99.M0.03.

This electronic document provides notification of the review results by the Institutional Review Board.

Figure A.1 Continued

DIVISION OF RESEARCH

Research Compliance and Biosafety

TEXAS A&M UNIVERSITY

DATE: February 19, 2015

MEMORANDUM

TO: Jeff Haberl
TAMU - College Of Architecture - Architecture

FROM: Dr. James Fluckey
Chair
Institutional Review Board

SUBJECT: Expedited Approval

Study Number:	IRB2014-0295D
Title:	ANALYSIS OF BUILDING PEAK HEATING AND COOLING LOAD CALCULATION METHODS FOR DESIGNING TODAY'S COMMERCIAL BUILDINGS IN THE UNITED STATES
Approval Date:	01/12/2015
Continuing Review Due:	12/01/2015
Expiration Date:	01/01/2016

Documents Reviewed and Approved:

Submission Components			
Study Document			
Title	Version Number	Version Date	Outcome
Survey form_Peak Load_Final	Version 1.0	02/13/2015	Approved
Recruitment email	Version 1.0	02/13/2015	Approved
Interview questions_Final	Version 1.0	02/13/2015	Approved
Study Consent Form			
Title	Version Number	Version Date	Outcome
Consent Information Sheet	Version 1.0	02/19/2015	Approved

Document of Consent: Waiver approved under 45 CFR 46.117 (c) 1 or 2/ 21 CFR 56.109 (c)1

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Figure A.2: Approval Letter 2 from IRB

This research project has been approved. As principal investigator, you assume the following responsibilities:

1. **Continuing Review:** The protocol must be renewed by the expiration date in order to continue with the research project. A Continuing Review application along with required documents must be submitted by the continuing review deadline. Failure to do so may result in processing delays, study termination, and/or loss of funding.
2. **Completion Report:** Upon completion of the research project (including data analysis and final written papers), a Completion Report must be submitted to the IRB.
3. **Unanticipated Problems and Adverse Events:** Unanticipated problems and adverse events must be reported to the IRB immediately.
4. **Reports of Potential Non-compliance:** Potential non-compliance, including deviations from protocol and violations, must be reported to the IRB office immediately.
5. **Amendments:** Changes to the protocol must be requested by submitting an Amendment to the IRB for review. The Amendment must be approved by the IRB before being implemented.
6. **Consent Forms:** When using a consent form or information sheet, you must use the IRB stamped approved version. Please log into iRIS to download your stamped approved version of the consenting instruments. If you are unable to locate the stamped version in iRIS, please contact the office.
7. **Audit:** Your protocol may be subject to audit by the Human Subjects Post Approval Monitor. During the life of the study please review and document study progress using the PI self-assessment found on the RCB website as a method of preparation for the potential audit. Investigators are responsible for maintaining complete and accurate study records and making them available for inspection. Investigators are encouraged to request a pre-initiation site visit with the Post Approval Monitor. These visits are designed to help ensure that all necessary documents are approved and in order prior to initiating the study and to help investigators maintain compliance.
8. **Recruitment**: All approved recruitment materials will be stamped electronically by the HSPP staff and available for download from iRIS. These IRB-stamped approved documents from iRIS must be used for recruitment. For materials that are distributed to potential participants electronically and for which you can only feasibly use the approved text rather than the stamped document, the study's IRB Protocol number, approval date, and expiration dates must be included in the following format: TAMU IRB#20XX-XXXX Approved: XX/XX/XXXX Expiration Date: XX/XX/XXXX.

1. **FERPA and PPRA:** Investigators conducting research with students must have appropriate approvals from the FERPA administrator at the institution where the research will be conducted in accordance with the Family Education Rights and Privacy Act (FERPA). The Protection of Pupil Rights Amendment (PPRA) protects the rights of parents in students ensuring that written parental consent is required for participation in surveys, analysis, or evaluation that ask questions falling into categories of protected information.
2. **Food:** Any use of food in the conduct of human subjects research must follow Texas A&M University Standard Administrative Procedure 24.01.01.M4.02.
3. **Payments:** Any use of payments to human subjects must follow Texas A&M University Standard Administrative Procedure 21.01.99.M0.03.

This electronic document provides notification of the review results by the Institutional Review Board.

Figure A.2 Continued

DIVISION OF RESEARCH

TEXAS A&M UNIVERSITY

DATE: November 20, 2015

MEMORANDUM

TO: Jeff Haberl
TAMU - College Of Architecture - Architecture

FROM: Dr. James Fluckey
Chair, TAMU IRB

SUBJECT: Expedited Approval

Study Number:	IRB2014-0295D
Title:	ANALYSIS OF BUILDING PEAK HEATING AND COOLING LOAD CALCULATION METHODS FOR DESIGNING TODAY'S COMMERCIAL BUILDINGS IN THE UNITED STATES
Date of Determination:	
Approval Date:	01/12/2015
Continuing Review Due:	10/15/2016
Expiration Date:	11/15/2016
Documents Reviewed and Approved:	Only IRB-stamped approved versions of study materials (e.g., consent forms, recruitment materials, and questionnaires) can be distributed to human participants. Please log into iRIS to download the stamped, approved version of all study materials. If you are unable to locate the stamped version in iRIS, please contact the iRIS Support Team at 979.845.4969 or the IRB liaison assigned to your area.

Submission Components			
Study Document			
Title	Version Number	Version Date	Outcome
Survey form_Peak Load_Final	Version 1.2	02/13/2015	Approved
Survey form_Peak Load_Final	Version 1.1	02/13/2015	Void
Recruitment email	Version 1.1	02/13/2015	Approved
Recruitment email	Version 1.0	02/13/2015	Void
Interview questions_Final	Version 1.1	02/13/2015	Approved
Interview questions_Final	Version 1.0	02/13/2015	Void

750 Agronomy Road, Suite 2701
1186 TAMU
College Station, TX 77843-1186
Tel. 979.458.1467 Fax. 979.862.3176
http://rcb.tamu.edu

Figure A.3: Approval Letter 3 from IRB

letter of support	Version 1.1	null	Approved
letter of support	Version 1.0	null	Void
Dissertation proposal_Chunliu Mao _Final rev	Version 1.1	06/23/2014	Approved
Dissertation proposal_Chunliu Mao _Final rev	Version 1.0	06/23/2014	Void
Study Consent Form			
Title	Version Number	Version Date	Outcome
Consent Information Sheet	Version 1.1	02/19/2015	Approved
Consent Information Sheet	Version 1.0	02/19/2015	Void

Document of Consent: Waiver approved under 45 CFR 46.117 (c) 1 or 2/ 21 CFR 56.109 (c)1

Comments:

- Research is to be conducted according to the study application approved by the IRB prior to implementation.
- Any future correspondence should include the IRB study number and the study title.

Investigators assume the following responsibilities:

1. **Continuing Review:** The study must be renewed by the expiration date in order to continue with the research. A Continuing Review application along with required documents must be submitted by the continuing review deadline. Failure to do so may result in processing delays, study expiration, and/or loss of funding.
2. **Completion Report:** Upon completion of the research study (including data collection and analysis), a Completion Report must be submitted to the IRB.
3. **Unanticipated Problems and Adverse Events:** Unanticipated problems and adverse events must be reported to the IRB immediately.
4. **Reports of Potential Non-compliance:** Potential non-compliance, including deviations from protocol and violations, must be reported to the IRB office immediately.
5. **Amendments:** Changes to the protocol and/or study documents must be requested by submitting an Amendment to the IRB for review. The Amendment must be approved by the IRB before being implemented.
6. **Consent Forms:** When using a consent form or information sheet, the IRB stamped approved version must be used. Please log into iRIS to download the stamped approved version of the consenting instruments. If you are unable to locate the stamped version in iRIS, please contact the iRIS Support Team at 979.845.4969 or the IRB liaison assigned to your area. Human participants are to receive a copy of the consent document, if appropriate.
7. **Post Approval Monitoring:** Expedited and full board studies may be subject to post approval monitoring. During the life of the study, please review and document study progress using the PI self-assessment found on the RCB website as a method of preparation for the potential review. Investigators are

Figure A.3 Continued

responsible for maintaining complete and accurate study records and making them available for post approval monitoring. Investigators are encouraged to request a pre-initiation site visit with the Post Approval Monitor. These visits are designed to help ensure that all necessary documents are approved and in order prior to initiating the study and to help investigators maintain compliance.

8. **Recruitment:** All approved recruitment materials will be stamped electronically by the HRPP staff and available for download from iRIS. These IRB-stamped approved documents from iRIS must be used for recruitment. For materials that are distributed to potential participants electronically and for which you can only feasibly use the approved text rather than the stamped document, the study's IRB Study Number, approval date, and expiration dates must be included in the following format: TAMU IRB#20XX-XXXX Approved: XX/XX/XXXX Expiration Date: XX/XX/XXXX.
9. **FERPA and PPRA:** Investigators conducting research with students must have appropriate approvals from the FERPA administrator at the institution where the research will be conducted in accordance with the Family Education Rights and Privacy Act (FERPA). The Protection of Pupil Rights Amendment (PPRA) protects the rights of parents in students ensuring that written parental consent is required for participation in surveys, analysis, or evaluation that ask questions falling into categories of protected information.
10. **Food:** Any use of food in the conduct of human research must follow Texas A&M University Standard Administrative Procedure 24.01.01.M4.02.
11. **Payments:** Any use of payments to human research participants must follow Texas A&M University Standard Administrative Procedure 21.01.99.M0.03.
12. **Records Retention:** Federal Regulations require records be retained for at least 3 years. Records of a study that collects protected health information are required to be retained for at least 6 years. Some sponsors require extended records retention. Texas A&M University rule 15.99.03.M1.03 Responsible Stewardship of Research Data requires that research records be retained on Texas A&M property.

This electronic document provides notification of the review results by the Institutional Review Board.

Figure A.3 Continued

A.2 Survey Results

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: __________5/1/15_________________________

1. What is your background?

   ☒ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify____

2. How many years have you designed actual buildings/HVAC systems?______11____________________

3. Do you have any professional licenses?

   ☒ PE; ☐ Other, please specify____

4. Type and numbers of building designed?

   ___Residential, single family ___Residential, multi-family _1_K-12 schools __5_Office building

   ___Retail _8__Hospital ___Warehouse ___Hotel ___Restaurant _3_Museum

   __12_Institution ___Other, please specify____________________________________

5. Where is the building location(s): City:_______Varies__________; State:_____Varies____________

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☒ Radiant time series method ☐ Other, please specify_________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☐ CLTD/SCL/CLF

   ☒ Radiant time series method ☐ Other, please specify_________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☐ Elite Software

   ☐ Spreadsheet ☐ Other, please specify_____________________________

Figure A.4: Survey Result for SFP 1

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: _____March 29, 2015______________________________

1. What is your background?

   ☐ Engineering ☐ Architecture ☒ Architectural Engineering

   ☐ Other, please specify____

2. How may years have you designed actual buildings/HVAC systems?_____19 years__________________

3. Do you have any professional licenses?

   ☒ PE; ☐ Other, please specify____

4. Type and numbers of building designed?

   ___Residential, single family _X__Residential, multi-family _X__K-12 schools _X_Office building

   __X_Retail _X__Hospital _X__Warehouse _X__Hotel _X_Restaurant X_Museum

   _X__Institution _X__Other, please specify____Refrigeration / Laboratory / Church/ _________

5. Where is the building location(s): City:______Various_________; State:___Many – Mostly Texas_____

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☒ Elite Software

   ☐ Spreadsheet ☐ Other, please specify____

Figure A.5: Survey Result for SFP 2

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: ________3-20-15_______________________

1. What is your background?

   ☒ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify____

2. How may years have you designed actual buildings/HVAC

   systems?__________22___________________

3. Do you have any professional licenses?

   ☒ PE; ☐ Other, please specify________LEED ______________________________________

4. Type and numbers of building designed?

   _2__Residential, single family _5_Residential, multi-family ___K-12 schools _50_Office building

   ___Retail ___Hospital ___Warehouse 3__Hotel ___Restaurant ___Museum

   ___Institution ___Other, please specify____

5. Where is the building location(s): City:_____All over the world__; State:______________________

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☒ TETD/TA ☒ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☒ TETD/TA ☐ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☐ Elite Software

   ☐ Spreadsheet ☐ Other, please specify__________________________________

Figure A.6: Survey Result for SFP 3

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: March 19, 2015

1. What is your background?

   ☒ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify____

2. How many years have you designed actual buildings/HVAC systems? Since 1981

3. Do you have any professional licenses?

   ☒ PE; ☐ Other, please specify____

4. Type and numbers of building designed?

   _X_Residential, single family ___Residential, multi-family _X_K-12 schools _X_Office building

   _X_Retail ___Hospital ___Warehouse ___Hotel _X_Restaurant ___Museum

   _X_Institution __Other, please specify_____________________________________

5. Where is the building location(s): City: Various; State: California

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☒ Radiant time series method ☐ Other, please specify________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☒ Heat balance ☐ TETD/TA ☐ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☐ Elite Software

   ☐ Spreadsheet ☒ Other, please specify___IES_____________________________

Figure A.7: Survey Result for SFP 4

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: _3/17/15________________________________

1. What is your background?

   ☒ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify____

2. How may years have you designed actual buildings/HVAC systems?_____________________

3. Do you have any professional licenses?

   ☒ PE; ☐ Other, please specify____

4. Type and numbers of building designed?

   ___Residential, single family ___Residential, multi-family _2__K-12 schools _5__Office building

   ___Retail ___Hospital ___Warehouse ___Hotel ___Restaurant ___Museum

   _20+__Institution ___Other, please specify___________________________________

5. Where is the building location(s): City:_Through out the state ____________________;

   State:_TX____________________

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☒ TETD/TA ☐ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☒ TETD/TA ☐ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☐ Elite Software

   ☐ Spreadsheet ☒ Other, please specify: IES VE______________________________

Figure A.8: Survey Result for SFP 5

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: ____04/19/15_______________________________

1. What is your background?

   ☒ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify____

2. How many years have you designed actual buildings/HVAC systems?__23 years_____________

3. Do you have any professional licenses?

   ☒ PE; ☐ Other, please specify____

4. Type and numbers of building designed?

   ___Residential, single family ___Residential, multi-family _10_K-12 schools _40 Office building

   _60_Retail ___Hospital _40_Warehouse ___Hotel _60_Restaurant ___Museum

   ___Institution ___Other, please specify____

5. Where is the building location(s): City: Multiple cities_______; State: Texas, Louisiana, Colorado, Arizona_

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☒ Elite Software

   ☒ Spreadsheet ☐ Other, please specify___________________________________

Figure A.9: Survey Result for SFP 6

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: 3/25/15

1. What is your background?

   ☒ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify____

2. How many years have you designed actual buildings/HVAC systems? 20 years

3. Do you have any professional licenses?

   ☒ PE; ☒ Other, please specify Certified Commissioning Authority

4. Type and numbers of building designed?

   0 Residential, single family 0 Residential, multi-family +20 K-12 schools +20 Office building

   +100 Retail 0 Hospital +20 Warehouse +20 Hotel +20 Restaurant 0 Museum

   0 Institution +100 Other, please specify multiple: office build-outs, clinics, industrial

   Where is the building location(s): City Varies State Varies

5. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

6. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

7. What software are you using for peak load design? (Check all that apply)

   ☒ DOE-2 ☒ eQuest ☐ EnergyPlus ☒ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☒ Elite Software

   ☐ Spreadsheet ☐ Other, please specify_________________________

Figure A.10: Survey Result for SFP 7

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: __4-17-2015________________________

1. What is your background?

   ☒ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify________________________________

2. How many years have you designed actual buildings/HVAC systems?_______7.5_______________

3. Do you have any professional licenses?

   ☒ PE; ☐ Other, please specify________________________________

4. Type and numbers of building designed?

   ___Residential, single family _1_Residential, multi-family _1_K-12 schools _12_Office building

   ___Retail ___Hospital _1_Warehouse ___Hotel ___Restaurant ___Museum

   ___Institution ___Other, please specify___(3)Laboratories___(3) Corporate Amenities Buildings

5. Where is the building location(s): City: Houston (1 office building in Monterrey, MX); State: TX

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☒ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☒ Radiant time series method ☐ Other, please specify_________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify_________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☒ Elite Software

   ☒ Spreadsheet ☐ Other, please specify________________________________

Figure A.11: Survey Result for SFP 8

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: 03-30-15

1. What is your background?

   ☒ Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify______

2. How many years have you designed actual buildings/HVAC systems? 4

3. Do you have any professional licenses?

   ☐ PE; ☐ Other, please specify None

4. Type and numbers of building designed?

   2 Residential, single family 1 Residential, multi-family __K-12 schools 100 + (tenant remodels, etc) Office building

   3 Retail 10/9 Hospital 3 Warehouse __Hotel 5 Restaurant 2 Museum

   __Institution __Other, please specify Medical office (1), Labratory (2), Banks (5), Churches (2

5. Where is the building location(s): City: Houston; State: TX

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☒ CLTD/SCL/CLF

   ☒ Radiant time series method ☐ Other, please specify____ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☐ CLTD/SCL/CLF

   ☒ Radiant time series method ☐ Other, please specify____ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP ☒ TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☒ Elite Software

   ☐ Spreadsheet ☐ Other, please specify______

Figure A.12: Survey Result for SFP 9

ID: ☐☐☐
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: 16 MARCH 2015

1. What is your background?

   ☐ Engineering ☐ Architecture ☑ Architectural Engineering

   ☐ Other, please specify________

2. How may years have you designed actual buildings/HVAC systems? 30 years.

3. Do you have any professional licenses?

   ☑ PE; ☐ Other, please specify________

4. Type and numbers of building designed?

   ✓ Residential, single family ✓ Residential, multi-family __ K-12 schools ✓ Office building

   __ Retail __ Hospital __ Warehouse __ Hotel __ Restaurant __ Museum

   __ Institution ✓ Other, please specify FIRE STATION / POLICE STATION

5. Where is the building location(s): City: C.S, BELTON, HOUSTON, CANYON LAKE, BRENHAM; State: TEXAS, MASS, IND, ILL.

6. What peak load design methods have you used? (Check all that apply)?

   ☐ Transfer function method ☑ Heat balance ☑ TETD/TA ☐ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify________ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☑ Heat balance ☑ TETD/TA ☐ CLTD/SCL/CLF

   ☐ Radiant time series method ☐ Other, please specify________ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☑ eQuest ☐ EnergyPlus ☐ HAP ☐ TRACE

   ☐ TRNSYS ☑ ENER-WIN ☐ Energy-10 ☐ ESP-r ☐ Elite Software

   ☐ Spreadsheet ☐ Other, please specify________

Figure A.13: Survey Result for SFP 10

ID: [redacted]
(Please do not fill out this area)

Building Peak Heating and Cooling Load Design Method Survey for HVAC Designers

Any information provided by the participants are completely confidential, and no individual will be identified.

Date of Survey: 3/23/2015

1. What is your background?

   [x] Engineering ☐ Architecture ☐ Architectural Engineering

   ☐ Other, please specify______

2. How may years have you designed actual buildings/HVAC systems? 42 years

3. Do you have any professional licenses?

   [x] PE; ☐ Other, please specify______

4. Type and numbers of building designed?

   ✓ Residential, single family ✓ Residential, multi-family ✓ K-12 schools ✓ Office building

   ✓ Retail ✓ Hospital ✓ Warehouse ✓ Hotel ✓ Restaurant ✓ Museum

   ✓ Institution __Other, please specify over 2000 projects, don't have count of each type

5. Where is the building location(s): City: All over USA + China, Thailand, Germany, England, Panama, Brazil State:

6. What peak load design methods have you used? (Check all that apply)?

   [x] Transfer function method [x] Heat balance [x] TETD/TA [x] CLTD/SCL/CLF

   [x] Radiant time series method ☐ Other, please specify____ ☐ None

7. What peak load design methods are you currently using? (Check all that apply)

   ☐ Transfer function method ☐ Heat balance ☐ TETD/TA ☐ CLTD/SCL/CLF

   [x] Radiant time series method ☐ Other, please specify____ ☐ None

8. What software are you using for peak load design? (Check all that apply)

   ☐ DOE-2 ☐ eQuest ☐ EnergyPlus ☐ HAP [x] TRACE

   ☐ TRNSYS ☐ ENER-WIN ☐ Energy-10 ☐ ESP-r ☐ Elite Software

   [x] Spreadsheet ☐ Other, please specify______

Figure A.14: Survey Result for SFP 11

A.3 Interview Results

Phone Interview Summary

Date: 3/31/2015

1. **What kinds of building do you primarily design?**

   Probe: What information do you gather to start the design process?

   <u>Answer:</u>

   Commercial buildings are primarily designed.

2. **What aspects of HVAC design are you most familiar with?**

   Probe: What is the step-by-step process to design HVAC system based on your experience?

   <u>Answer:</u>

   The common step-by-step process to design HVAC system is the following:

   (1) Run building zone load calculations and select system types.

   (2) Work with architects to select equipment and learn the space requirements.

   (3) Layout the distribution, such as chilled water distribution, including both air-side and water-side distributions.

   (4) Finish contract documents, e.g., notes and specifications.

3. **What do you use to size HVAC system?**

   Probe: How do you calculate peak heating and cooling loads for a commercial building?

   <u>Answer:</u>

   (1) Use CLTD/SCL/CLF method.

   (2) Use TRACE and Elite software.

Figure A.15: Interview Result for SFP 2

4. **What are the pros and cons for the current peak heating and cooling methods?**
   Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?

   Answer:

   TRACE software with the implementation of CLTD/SCL/CLF method is easy to use. The accuracy of load calculation is good enough for design a typical commercial building.

5. **How did you learn HVAC system sizing design methods?**
   Probe: -Was it in college or on the job?
   -How long did it take for you to master the methods?

   Answer:

   (1) Educated CLTD/SCL/CLF method in the school. At that time, it was a manual calculation.

   (2) Learned TRACE at work. Believe TRACE was not available when at school.

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**
   Probe: -Why do you think about this?
   -Are you aware of any other methods?

   Answer:

   For typical buildings, the current methods/tools are good enough to perform the load calculations, e.g., TRACE. TRACE is capable of doing energy modeling. Elite software is popular but it has own limitations. Elite is not capable of doing energy modeling.

Figure A.15 Continued

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**
   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?
   Answer:
   The current methods/tools cover the typical features.

8. **What do you think is the future trend of peak heating and cooling methods?**
   Probe: How important do you think they play a role in design commercial buildings today?
   Answer:
   People tend to use software to perform the load calculations, e.g, TRACE, HAP. Sometimes, the spreadsheet/manual calculation will be performed as a quick check.

9. **Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?**
   Answer:
   People should understand that the load software is a tool and that HVAC loads are not an exact science. The maximum loads should be designed for; however, attention should be given to controls and equipment efficiency to help save energy and money and make the systems as flexible as possible to shifting load profiles and requirements.

Figure A.15 Continued

Phone Interview Summary

Date: 3/26/2015

1. **What kinds of building do you primarily design?**
   Probe: What information do you gather to start the design process?
   Answer:
   Primarily design offices and laboratories.

2. **What aspects of HVAC design are you most familiar with?**
   Probe: What is the step-by-step process to design HVAC system based on your experience?
   Answer:
   The common step-by-step process to design a building is the following:
   (1) Get drawings from architects, such as elevation, windows, glass types, etc.
   (2) Input the information into the TRACE program and run annual load calculations.
   (3) Size chillers and air handlers, according to the block load.
   (4) Size the terminal units, such as fans, according to the peak of the building exposures.

3. **What do you use to size HVAC system?**
   Probe: How do you calculate peak heating and cooling loads for a commercial building?
   Answer:
   Use TRACE software (TETD/TA and CLTD/SCL/CLF methods).

Figure A.16: Interview Result for SFP 3

4. **What are the pros and cons for the current peak heating and cooling methods?**
   Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?

   Answer:

   TETD/TA and CLTD/SCL/CLF methods are easy to use and user friendly. Plus, the calculation accuracy is good enough.

5. **How did you learn HVAC system sizing design methods?**
   Probe: -Was it in college or on the job?
   -How long did it take for you to master the methods?

   Answer:

   Learned TRACE at work.

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**
   Probe: -Why do you think about this?
   -Are you aware of any other methods?

   Answer:

   Yes. They work well.

Figure A.16 Continued

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**
   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?
   Answer:
   Double skin feature.

8. **What do you think is the future trend of peak heating and cooling methods?**
   Probe: How important do you think they play a role in design commercial buildings today?
   Answer:
   Some architecture design software e.g, Revit, will be implemented with the load calculation methods.

9. **Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?**
   Answer:
   It needs to corporate with architects to achieve energy savings and minimize the building peak loads. For example, daylighting can bring the light into the space as well as the heat gains.

Figure A.16 Continued

Phone Interview Summary

Date: 3/24/2015

1. **What kinds of building do you primarily design?**

   Probe: What information do you gather to start the design process?

   Answer:

   Primarily design commercial buildings.

   To start the design process, two types of information need to be obtained:

   (1) Building location, which determines climate zone.

   (2) Building envelope information. If it is an existing building, certain measurements need to be performed. If it is a new designed building, all related drawings are needed.

2. **What aspects of HVAC design are you most familiar with?**

   Probe: What is the step-by-step process to design HVAC system based on your experience?

   Answer:

   The whole design process involves many assumptions. The step-by-step design process is the following:

   (1) First, the owner brings the typical descriptions to the architects. For examples, the owner wants two office rooms which are capable of having 100 people, etc.

   (2) Then, the architects can prepare for several approaches and show the owners advantages and disadvantages of each approach as well as the cost estimation. The architects will have basic concepts first and bring it to the engineers.

   (3) Finally, the engineers will decide layout and the size of the HVAC equipment, which can be very general at first. For instance, this room needs a central unit, etc. The approximation will be made. As architects bring more detailed design (e.g., window-to-wall ratio), the engineer can perform the detailed load calculations by using simulation software, e.g., TRACE.

Figure A.17: Interview Result for SFP 4

3. **What do you use to size HVAC system?**
   Probe: How do you calculate peak heating and cooling loads for a commercial building?
   <u>Answer:</u>
   Use TRACE software and IES. Perform 12-month calculations.

4. **What are the pros and cons for the current peak heating and cooling methods?**
   Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?
   <u>Answer:</u>
   (1) Mostly accurate one is heat balance.
   (2) CLTS/SCL/CLF is user friendly and has a detailed breakdown which heat balance does not have.
   (3) RTSM is derived from heat balance and have a detailed breakdown. However, when using RTSM, the load calculations by using heat balance is also performed. RTSM simulation results are regarded as a reference.

5. **How did you learn HVAC system sizing design methods?**
   Probe: -Was it in college or on the job?
   -How long did it take for you to master the methods?
   <u>Answer:</u>
   (1) Learned CLTD/SCL/CLF at school. At that time, it was a manual calculation method.
   (2) Learned heat balance and RTSM at work.

Figure A.17 Continued

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**
   Probe: -Why do you think about this?
   -Are you aware of any other methods?

   Answer:

   Yes. The current methods/tools are good enough for designing today's commercial buildings in the U.S. However, some features, such as shading and a lot of glazing, need more accurate models. Load calculation has two types. One is for envelope (room load calculation)

   and the other is for the equipment (system load analysis).

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**
   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?

   Answer:

   There are some difficulties in giving a value to a plug load. Asymmetrical space surface temperatures are not well understand for non-well mixed spaces such as radiant floors and displacement ventilation.

8. **What do you think is the future trend of peak heating and cooling methods?**
   Probe: How important do you think they play a role in design commercial buildings today?

   Answer:

   People will use simulation software.

9. **Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?**

   Answer:

   There is a challenge in peak load diversities and non-well mixed spaces.

Figure A.17 Continued

Phone Interview Summary

Date: 4/30/2015

1. **What kinds of building do you primarily design?**

   Probe: What information do you gather to start the design process?

   Answer:

   Commercial buildings are primarily designed.

2. **What aspects of HVAC design are you most familiar with?**

   Probe: What is the step-by-step process to design HVAC system based on your experience?

   Answer:

   The common step-by-step process to design a typical building is the following:

   (1) Architects provide the conceptual design

   (2) Engineers perform preliminary load calculations and determine the type of the systems, and preliminary design of electrical, plumbing, and fire protection.

   (3) Architects provide more detailed designs with structural engineers.

   (4) Engineers perform the final load calculations, equipment selection, physical dimensions, duct work. Work with electrical and local utility to determine how to fit the components into the building. Work with civil engineers to make the decisions about the location and water sewers.

   (5) Finish all detail design. Prepare for the construction documents as well as the specifications.

Figure A.18: Interview Result for SFP 6

3. **What do you use to size HVAC system?**

   Probe: How do you calculate peak heating and cooling loads for a commercial building?

   Answer:

   (1) Use CLTD/SCL/CLF method.

   (2) Use TRACE and Elite software (primary tool).

4. **What are the pros and cons for the current peak heating and cooling methods?**

   Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?

   Answer:

   This method was adopted because it was taught in the college.

5. **How did you learn HVAC system sizing design methods?**

   Probe: -Was it in college or on the job?

   -How long did it take for you to master the methods?

   Answer:

   Educated CLTD/SCL/CLF method and Elite software in the school.

   At that time, it was a manual calculation.

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**

   Probe: -Why do you think about this?

   -Are you aware of any other methods?

   Answer:

   For typical buildings, the current methods/tools are good enough to perform the load

Figure A.18 Continued

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**
   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?
   Answer:
   The current methods/tools cover the typical features. Some features such as solar and wind power may not be covered.

8. **What do you think is the future trend of peak heating and cooling methods?**
   Probe: How important do you think they play a role in design commercial buildings today?
   Answer:
   More implemented tool in the Autodesk may be the future trend to be selected. Combine the architectural design and local calculation together, such as Revit.

9. **Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?**
   Answer:
   There may be some communication issues during the design process. The engineers work on modeling and equipment selection. However, the architects select the building envelope components.

Figure A.18 Continued

Phone Interview Summary

Date: 4/17/2015

1. **What kinds of building do you primarily design?**
   Probe: What information do you gather to start the design process?
   <u>Answer:</u>
   For new buildings, primarily design commercial and light-weight buildings.
   For existing building, primarily design K-12 schools, commercial and light-weight buildings.
2. **What aspects of HVAC design are you most familiar with?**
   Probe: What is the step-by-step process to design HVAC system based on your experience?
   <u>Answer:</u>
   (1) Before doing the design, budge the project and bring the cost estimation and possibilities to the owners.
   (2) Schematic design phase. Architects provide the building envelope information, including wall, window, etc.
   (3) Run load calculation to design HVAC by using TRACE and HAP.

3. **What do you use to size HVAC system?**
   Probe: How do you calculate peak heating and cooling loads for a commercial building?
   <u>Answer:</u>
   Use TRACE, HAP, Elite to perform load calculations. Use eQuest and DOE 2 to perform the energy use calculations. For cooling load, pick the hottest day in a year. For heating load, need to know the temperature difference between the coil.

Figure A.19: Interview Result for SFP 7

4. **What are the pros and cons for the current peak heating and cooling methods?**

   Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?

   <u>Answer:</u>

   (1) Mostly favorite one is Elite software. It is easy to use and flexible.

   (2) HAP is a quick software for retail modeling.

   (3) TRACE can model all types of the systems. However, the eQuest and DOE2 can only model certain types of the systems.

5. **How did you learn HVAC system sizing design methods?**

   Probe: -Was it in college or on the job?

   -How long did it take for you to master the methods?

   <u>Answer:</u>

   (1) Learned manual calculations in the school.

   (2) Learned software at work.

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**

   Probe: -Why do you think about this?

   -Are you aware of any other methods?

   <u>Answer:</u>

   Yes.

Figure A.19 Continued

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**
   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?
   Answer:
   They should cover all the features for typical buildings.

8. **What do you think is the future trend of peak heating and cooling methods?**
   Probe: How important do you think they play a role in design commercial buildings today?
   Answer:
   People will use simulation software because of the time and cost.

9. **Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?**
   Answer:
   (1) Architects usually do not participate in the energy modeling process. But many details need to be obtained for engineers to perform the simulation.
   (2) Humidity issue during the design process. More dehumidification methods are needed.

Figure A.19 Continued

Phone Interview Summary

Date: 4/20/2015

1. **What kinds of building do you primarily design?**

   Probe: What information do you gather to start the design process?

   Answer:

   Primarily design office buildings.

2. **What aspects of HVAC design are you most familiar with?**

   Probe: What is the step-by-step process to design HVAC system based on your experience?

   Answer:

   The step-by-step procedures are:

   (1) Schematic Design Phase (Conceptual Design Phase). The HVAC and plumbing engineers provide the generic information about the systems in the building. For example, provide simple drawings, equipment layout and location of the central plant. Those are the basis for the pricing.

   (2) Design Development Phase. Layout mechanical room, size the equipment. For load calculation, use guess and rules of thumbs, for example, sqft/ton.

   (3) Construction Document Phase. The detailed load calculation occurs in this phase. With detailed information input, use TRACE to perform the load calculations.

3. **What do you use to size HVAC system?**

   Probe: How do you calculate peak heating and cooling loads for a commercial building?

   Answer:

   Use TRACE. In the early design phase, may use spreadsheet.

Figure A.20: Interview Result for SFP 8

4. **What are the pros and cons for the current peak heating and cooling methods?**
   Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?

   <u>Answer:</u>

   HBM: use heat balance equation for hand calculation or in the excel.

   CLTD/SCL/CLF: this method has been used for years. It is well-known.

   RTSM: most accurate method. But at most of time it is not necessary to use it.

5. **How did you learn HVAC system sizing design methods?**
   Probe: -Was it in college or on the job?
   -How long did it take for you to master the methods?

   <u>Answer:</u>

   (1) Learned software during the work

   (2) Learned methods in the college, from Dr. Spitler and Dr. Fisher.

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**
   Probe: -Why do you think about this?
   -Are you aware of any other methods?

   <u>Answer:</u>

   Yes. The accuracy is good enough.

Figure A.20 Continued

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**

   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?

   <u>Answer:</u>

   Some difficulties of simulation exist.

   (1) Shading. TRACE is not well treating the shading. For example, for every window, you can choose either overhang and fins or an adjacent building. You cannot choose both of them. But in the eQuest/DOE2/EnergyPlus, the software can provide 3D building model, which can better model the shading devices.

   (2) Heat recovery. For an opening cooling power system, it is difficult to model heat recovery from chiller water return/rejected heat from water heater.

8. **What do you think is the future trend of peak heating and cooling methods?**

   Probe: How important do you think they play a role in design commercial buildings today?

   <u>Answer:</u>

   People will use simulation software.

9. **Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?**

   <u>Answer:</u>

   All are well covered.

Figure A.20 Continued

Phone Interview Summary

Date: 5/5/2015

1. **What kinds of building do you primarily design?**

   Probe: What information do you gather to start the design process?

   Answer:

   Primarily design office buildings.

2. **What aspects of HVAC design are you most familiar with?**

   Probe: What is the step-by-step process to design HVAC system based on your experience?

   Answer:

   The step-by-step procedures are:

   (1) Check the architectural information and obtain the floor plans from the architects.

   (2) Run load calculation by using load programs.

   (3) Select the equipment according to the load estimation.

   (4) Layout the design

   (5) Prepare the key notes, documents, and specifications.

3. **What do you use to size HVAC system?**

   Probe: How do you calculate peak heating and cooling loads for a commercial building?

   Answer:

   Use TRACE (primary use) and Elite software.

Figure A.21: Interview Result for SFP 9

4. **What are the pros and cons for the current peak heating and cooling methods?**
   Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?

   Answer:

   CLTD/SCL/CLF: easy to use. Show the basic understanding of the load calculation. It is adopted in design small buildings.

   RTSM: it is used when designing LEED buildings.

5. **How did you learn HVAC system sizing design methods?**
   Probe: -Was it in college or on the job?
   -How long did it take for you to master the methods?

   Answer:

   (1) Learned software during the work

   (2) Learned manual load calculation in college

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**
   Probe: -Why do you think about this?
   -Are you aware of any other methods?

   Answer:

   Yes. They are good enough. Sometimes, it may need to manipulate the design input a little.

Figure A.21 Continued

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**

   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?

   Answer:

   There is a little downside when high performance mechanical systems are not built in the TRACE software.

8. **What do you think is the future trend of peak heating and cooling methods?**

   Probe: How important do you think they play a role in design commercial buildings today?

   Answer:

   Some people in other companies use spreadsheet for small buildings. People in this company use TRACE software.

9. **Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?**

   Answer:

   The coordination among the engineers, architects and owners sometimes has issues.

Figure A.21 Continued

Phone Interview Summary

Date: 3/16/2015

1. **What kinds of building do you primarily design?**

   Probe: What information do you gather to start the design process?

   Answer:

   Primarily design fire stations and police stations.

   To start the design process,

   (1) Get the building plans from architects.

   (2) Interview with architects for specific requirements, energy codes, mechanical codes, plumbing codes, and fire codes.

2. **What aspects of HVAC design are you most familiar with?**

   Probe: What is the step-by-step process to design HVAC system based on your experience?

   Answer:

   Be familiar with the full aspects of building design process, which is due to the independent design experience. This includes assumptions, profiles, envelope, system and etc.

3. **What do you use to size HVAC system?**

   Probe: How do you calculate peak heating and cooling loads for a commercial building?

   Answer:

   Use Heat Balance and TETD/TA methods.

Figure A.22: Interview Result for SFP 10

4. **What are the pros and cons for the current peak heating and cooling methods?**
Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?
<u>Answer:</u>
The pros: all methods that have been used are transient methods with time delay consideration.
The cons: EnerWin does not have sophisticated modeling for HVAC auxiliary equipment, not dealing with the cooling tower and terminal mixing box.

5. **How did you learn HVAC system sizing design methods?**
Probe: -Was it in college or on the job?
-How long did it take for you to master the methods?
<u>Answer:</u>
(1) Learned the design methods from the HVAC courses at Penn State University.
(2) It took 12 years to master the design methods.

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**
Probe: -Why do you think about this?
-Are you aware of any other methods?
<u>Answer:</u>
Yes. In the old days, there were no computers. Only available Carrier tables, ETD tables and manual calculations were used. Today, load and energy simulation can fulfill the tasks for designing today's commercial buildings.

Figure A.22 Continued

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**

   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?

   Answer:

   Some building features are not covered in the EnerWin software:

   (1) Double skin

   (2) PV integration

   (3) Chilled beam

   (4) Radiant floor slabs

   (5) Comfort control

   (6) Occupancy sensors, but can be simulated by using the average profiles for performing the simulation.

8. **What do you think is the future trend of peak heating and cooling methods?**

   Probe: How important do you think they play a role in design commercial buildings today?

   Answer:

   People will use simulation software. Do not see improvements that should be done in the future for the method itself.

Figure A.22 Continued

9. Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?

Answer:

(1) For simulation perspective, the BACNET control has not been discussed. The control can make the calculation different, e.g., smart building.

(2) If the definition of climate zone changes, this will affect the load estimation.

(3) The design conditions (ASHRAE Standard 169) can have an impact on the load calculation and energy codes.

(4) If new energy conservation measures are introduced, such as renewable energy or ice storage or smart features of the building envelope (e.g., PV panels), the calculation methods will should be updated.

Figure A.22 Continued

Phone Interview Summary

Date: 3/26/2015

1. **What kinds of building do you primarily design?**

   Probe: What information do you gather to start the design process?

   Answer:

   Have designed over 2000 projects but do not have the count of building types.

2. **What aspects of HVAC design are you most familiar with?**

   Probe: What is the step-by-step process to design HVAC system based on your experience?

   Answer:

   To design a building, the step-by-step process is:

   (1) Architects provide the floor plans, exterior elevation, definition of building skin, wall, glass, insulation, etc.

   (2) Hand over the information to the engineers to perform the heating and cooling load calculations. The engineers will reference the code requirements, other references (e.g., ASHRAE Handbook of Fundamentals), and prepare for the engineering drawings.

   - For heating load, pick one value for the calculation , which is the worst case in the year.
   - For cooling load, perform 12-month design day calculations.

3. **What do you use to size HVAC system?**

   Probe: How do you calculate peak heating and cooling loads for a commercial building?

   Answer:

   Use RTSM and TRACE.

Figure A.23: Interview Result for SFP 11

4. What are the pros and cons for the current peak heating and cooling methods?

Probe: Have you ever used the Transfer Function Method (TFM), the Heat Balance Method (HBM), the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method, the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) Method and the Radiant Time Series Method (RTSM)?

<u>Answer:</u>

(1) The least favorite method is CLTD/SCL/CLF method since it is too simplified with too many assumptions in the CLTD/SCL/CLF tables.

(2) The second least favorite method is Transfer Function method. The procedure itself is complicated. Again, too many assumptions are in the transfer function tables.

(3) HBM is scientifically most accurate method. But, it is easy to screw up. Wrong calculation can be obtained due to the wrong inputs.

(4) The most favorite method is RTSM. It is derived from HBM. For large glazing and single pane, it is over predicting the load. However, for practical building, the RTSM results are very close to the HBM. Even though RTSM maybe be complicated to some architects, they usually hire engineers to perform the load calculations. Buildings with characteristics where RTSM over predicts are not legal under modern energy codes.

5. How did you learn HVAC system sizing design methods?

Probe: -Was it in college or on the job?

-How long did it take for you to master the methods?

<u>Answer:</u>

Learned methods on the job and through the engagement of ASHRAE TC 4.1. Have worked, studied, and developed the methods for 30 years.

Figure A.23 Continued

6. **Do you think the current tool/methods are good enough for designing today's commercial buildings in the U.S.?**

   Probe: -Why do you think about this?

   -Are you aware of any other methods?

   Answer:

   Yes. They are good enough for designing today's practical buildings.

7. **What new features of today's commercial buildings do you think are not covered in the peak heating and cooling methods that you use?**

   Probe: have you designed any new buildings that were not covered by the TFM, the HBM, the TETD/TA Method, the CLTD/SCL/CLF Method and the RTSM?

   Answer:

   All methods cannot adequately address some high-performance features. The proper approximation needs to be made.

8. **What do you think is the future trend of peak heating and cooling methods?**

   Probe: How important do you think they play a role in design commercial buildings today?

   Answer:

   People will use software to perform the load calculations. In the future, the Revit (BIM) may implement the load calculation methods for engineers to use. Now, the TRACE can exchange the information with Revit. Architects more focus on the energy modeling, not the load calculations. The energy use depends on the systems.

9. **Are there any other issues you have observed that are important for peak heating and cooling load calculation that we have not discussed?**

   Answer:

   More trends in the industry are to reduce the lighting load (e.g., LED), equivalent load for Efficient computers, EnergyStar on building design. Issues are not so much with methodology, big issues are having good data available as inputs to the calculations.

Figure A.23 Continued

APPENDIX B

CALCULATIONS OF SOLAR RADIATION AND SOL-AIR TEMPERATURE

B.1 Solar Time and Solar Angles

Two solar angles are involved in order to calculate solar intensities, which are solar altitude and solar incidence angle by (ASHRAE, 2013a). To start with, solar time can be determined,

$$AST = LST + ET/60 + (LON - LSM)/15 \tag{B.1}$$

where,

AST : apparent solar time, hour;

LST : local standard time, hour;

ET : equation of time, min;

LON : longitude of site, degree;

LSM : longitude of local standard time meridian, degree.

The solar altitude β can be calculated by,

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta \tag{B.2}$$

where,

L : latitude, degrees;

δ : declination, degrees;

H : hour angle, degrees.

The solar incidence angle θ can be given by,

$$\cos\theta = \cos\beta\cos\gamma\sin\Sigma + \cos\beta\cos\Sigma \qquad \text{(B.3)}$$

where,

γ : surface solar azimuth, degrees;

Σ : surface tilt, degrees.

B.2 The ASHRAE Clear-Sky Models

The ASHRAE clear-sky radiation models are used to calculate beam, diffuse and total solar radiation, which are the basis to calculate solar irradiation on the building exterior surfaces. Two models have been proposed by the ASHRAE. The first ASHRAE clear-sky model was first proposed in 1967 (ASHRAE, 1967) and utilizes three coefficients (A, B, C) to perform the solar radiation calculations. This model was replaced by a new ASHRAE clear-sky model in 2009 based on calculation components such as beam optical depth, diffuse optical depth, beam air mass exponent, and diffuse air mass exponent (ASHRAE, 2009d).

B.2.1 The 1967 ASHRAE Clear-Sky Model

The 1967 ASHRAE clear-sky model was adopted to calculate solar radiation before 2009. When calculating peak cooling loads, the assumption of a clear sky is selected in order to account for the worst summer condition. This allows the most solar heat gain into the building. The model involves A, B, C coefficients and atmosphere clearness to perform the calculations. Two different sets of A, B, C coefficients have been published from 1967 to 2005 ASHRAE Handbook of Fundamentals, shown in Table B.2 and Table B.2.

Two components of solar radiation need to be calculated, which are the beam and diffuse radiation. The direct normal solar intensity is given by (ASHRAE, 1967-2005),

$$E_{DN} = CN \frac{A}{\exp(B / \sin \beta)} \quad \text{(B.4)}$$

where,

A, B: ASHRAE clear-sky model coefficients;

CN: sky clearness, shown in Figure B.4.

Table B.1: Solar Data and Coefficients (Adapted from ASHRAE, 1967-2001)

	Equation of Time (min)	**Declination (degree)**	**A (W/m^2)**	**B**	**C**
Jan	-11.2	-20.0	1230	0.142	0.058
Feb	-13.9	-10.8	1215	0.144	0.060
Mar	-7.5	0.0	1186	0.156	0.071
Apr	1.1	11.6	1136	0.180	0.097
May	3.3	20.0	1104	0.196	0.121
Jun	-1.4	23.45	1088	0.205	0.134
Jul	-6.2	20.6	1085	0.207	0.136
Aug	-2.4	12.3	1107	0.201	0.122
Sep	7.5	0.0	1151	0.177	0.092
Oct	15.4	-10.5	1192	0.160	0.073
Nov	13.8	-19.8	1221	0.149	0.063
Dec	1.6	-23.45	1233	0.142	0.057

Table B.2: Solar Data and Coefficients (Adapted from ASHRAE, 2005)

	Equation of Time (min)	**Declination (degree)**	**A (W/m^2)**	**B**	**C**
Jan	-11.2	-20.0	1202	0.141	0.103
Feb	-13.9	-10.8	1187	0.142	0.104
Mar	-7.5	0.0	1164	0.149	0.109
Apr	1.1	11.6	1130	0.164	0.120
May	3.3	20.0	1106	0.177	0.130
Jun	-1.4	23.45	1092	0.185	0.137
Jul	-6.2	20.6	1093	0.186	0.138
Aug	-2.4	12.3	1107	0.182	0.134
Sep	7.5	0.0	1136	0.165	0.121
Oct	15.4	-10.5	1166	0.152	0.111
Nov	13.8	-19.8	1190	0.142	0.106
Dec	1.6	-23.45	1204	0.141	0.103

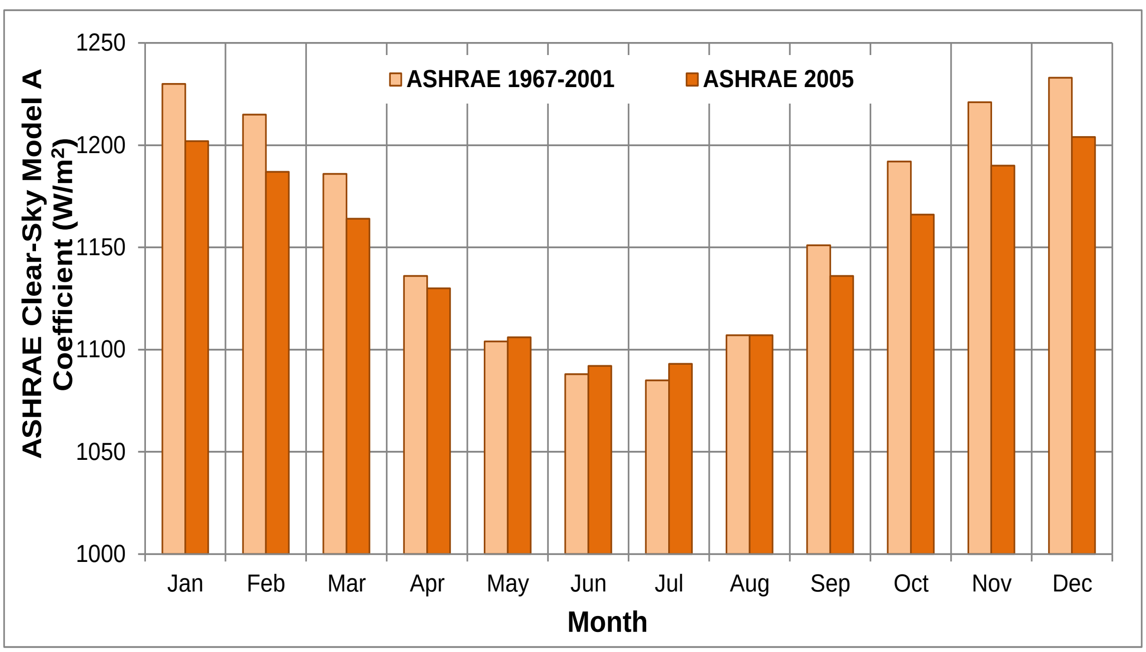


Figure B.1: ASHRAE Clear-Sky Model A Coefficient Comparisons

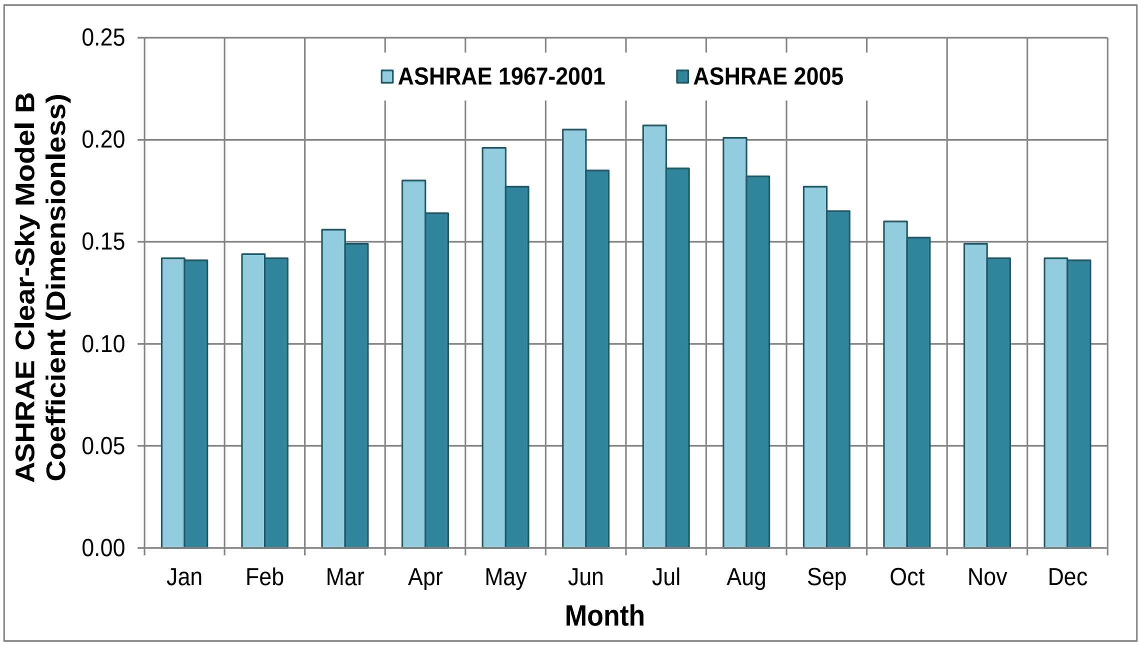


Figure B.2: ASHRAE Clear-Sky Model B Coefficient Comparisons

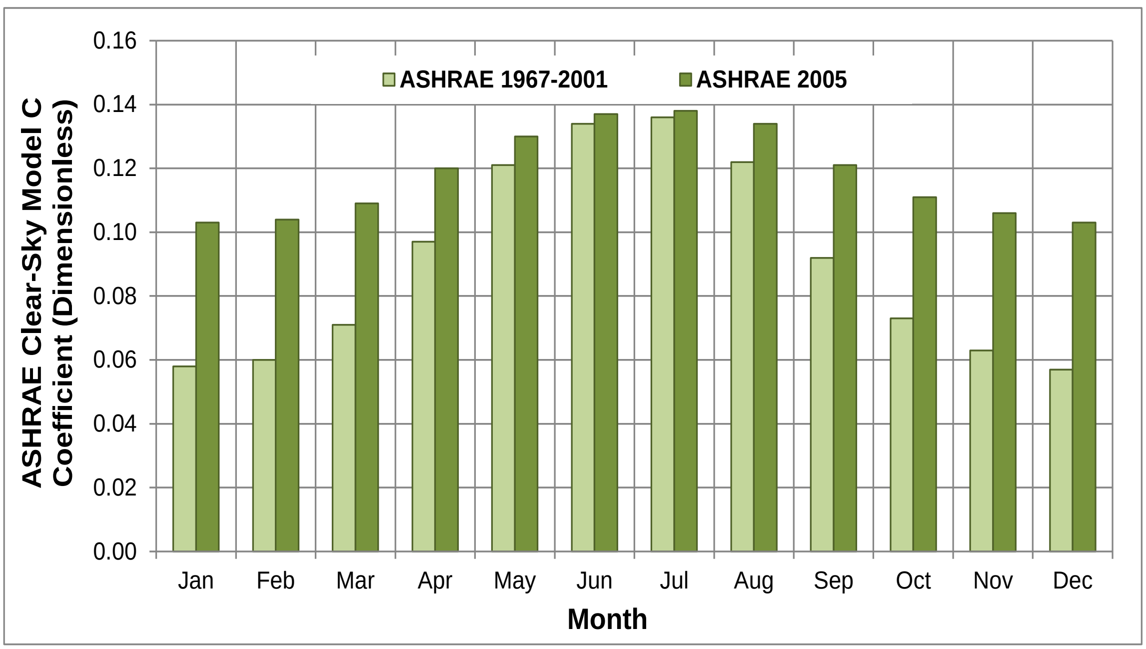


Figure B.3: ASHRAE Clear-Sky Model C Coefficient Comparisons

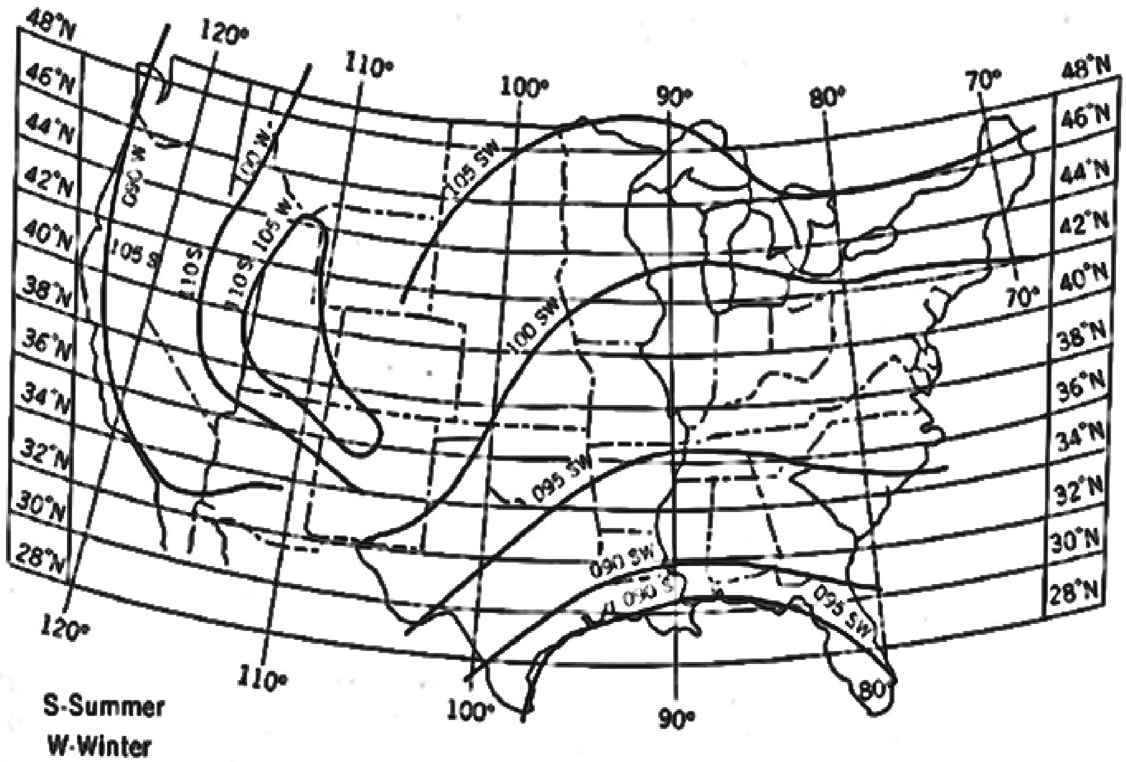


Figure B.4: Atmospheric Clearness Number CN (McQuiston and Spitler, 1992; with permission*)

According to solar incidence angle and direct normal intensity, the beam radiation on the exterior surfaces can be determined (ASHRAE, 2005),

$$E_D = E_{DN} \cos\theta, \qquad \text{when } \cos\theta > 0 \tag{B.5}$$

$$E_D = 0, \qquad \text{when } \cos\theta \le 0 \tag{B.6}$$

The diffuse solar radiation E_d consists of the diffuse radiation from the sky, E_{ds} and reflected from the ground, E_{dg}, which gives,

$$E_d = E_{ds} + E_{dg} \tag{B.7}$$

* Reprinted from *Cooling and Heating Load Calculation Manual*, McQuiston, F.C. and Spitler, J.D., 1992, Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Copyright 1992 ASHRAE.

For vertical surfaces,

$$E_{ds} = CYE_{DN} \tag{B.8}$$

$$E_{dg} = 0.5E_{DN}(C + \sin\beta)\rho_g \tag{B.9}$$

For other surfaces,

$$E_{ds} = CE_{DN}(1 + \cos\Sigma)/2 \tag{B.10}$$

$$E_{dg} = E_{DN}(C + \sin\beta)\rho_g(1 - \cos\Sigma)/2 \tag{B.11}$$

where,

C: ASHRAE clear-sky model coefficients;

ρ_g : ground reflectance.

Prior to calculating diffuse component of solar radiation, a ratio Y has to be determined first, which represents a fraction of diffuse solar radiation incidence on the exterior vertical surface over the ones on the horizontal surface. The calculations yield,

$$Y = 0.55 + 0.437\cos\theta + 0.313\cos^2\theta\text{, when } \cos\theta > -0.2 \tag{B.12}$$

$$Y = 0.45\text{, when } \cos\theta \le -0.2 \tag{B.13}$$

The total solar radiation intensities on the exterior surfaces are calculated by,

$$E_t = E_D + E_d \tag{B.14}$$

B.2.2 The 2009 ASHRAE Clear-Sky Model

The updated 2009 ASHRAE clear-sky model was developed by Thevenard in ASHRAE Research Project RP 1453 (ASHRAE, 2009d) and introduced in the 2009 ASHRAE Handbook of Fundamentals (ASHRAE, 2009c). The calculations of solar radiation under clear-sky condition involves parameters of extraterrestrial normal irradiance E_0, air mass m, beam optical depth τ_b, diffuse optical depth τ_d, beam air mass exponent ab, and diffuse air mass exponent ad. The 2013 ASHRAE Handbook of Fundamentals (ASHRAE, 2013a) updated the equation coefficients of determining bean and diffuse air mass exponents.

Extraterrestrial normal irradiance E_0 can be obtained either from ASHRAE tabulated table or calculated by the equation.

Table B.3: Extraterrestrial Normal Irradiance E_0 for 21st Day of Each Month (Adapted from ASHRAE, 2013a)

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Day of Year	21	52	80	111	141	172	202	233	264	294	325	355
E_0, W/m^2	1410	1397	1378	1354	1334	1323	1324	1336	1357	1380	1400	1400

$$E_0 = E_{sc}\{1 + 0.033\cos[360^\circ \frac{n-3}{365}]\} \quad \text{(B.15)}$$

where,

E_{sc} :solar constant;

n : the day of year.

Air mass m can be calculated by,

$$m = 1/[\sin\beta + 0.50572(6.07995 + \beta)^{-1.6364}] \quad \text{(B.16)}$$

where, β is solar altitude, in degrees.

Air mass exponents are given by[30],

$$ab = 1.454 - 0.406\tau_b - 0.268\tau_d + 0.021\tau_b\tau_d \quad \text{(B.17)}$$

$$ad = 0.507 + 0.205\tau_b - 0.080\tau_d - 0.190\tau_b\tau_d \quad \text{(B.18)}$$

where,

τ_b : beam optical depth;

τ_d : diffuse optical depth.

Therefore, the beam normal irradiance E_b and diffuse horizontal irradiation E_d are,

$$E_b = E_0 \exp[-\tau_b m^{ab}] \quad \text{(B.19)}$$

$$E_d = E_0 \exp[-\tau_d m^{ad}] \quad \text{(B.20)}$$

Given by incidence angle, the beam irradiance on the exterior surfaces $E_{t,b}$ are calculated by,

$$E_{t,b} = E_b \cos\theta, \text{ when } \cos\theta > 0 \quad \text{(B.21)}$$

$$E_{t,b} = 0, \qquad \text{when } \cos\theta \le 0 \quad \text{(B.22)}$$

To calculate diffuse irradiance on the exterior surface from the sky $E_{t,d}$, the ratio Y is also used in the 2009 ASHRAE clear-sky model. This can be calculated by,

$$E_{t,d} = E_d Y, \text{ for vertical surfaces} \quad \text{(B.23)}$$

For non-vertical surfaces with slope Σ,

$$E_{t,d} = E_d (Y \sin\Sigma + \cos\Sigma), \text{ when } \Sigma \le 90° \quad \text{(B.24)}$$

[30] The coefficients are different from the ones in the 2009 ASHRAE Handbook of Fundamentals.

$$E_{t,d} = E_d Y \sin\Sigma, \qquad \text{when } \Sigma > 90° \tag{B.25}$$

Finally, the diffuse irradiance on the exterior surfaces from the ground reflectance $E_{t,r}$ is determined by,

$$E_{t,r} = (E_b \sin\beta + E_d)\rho_g \frac{1-\cos\Sigma}{2} \tag{B.26}$$

The total solar radiation intensities on the exterior surfaces are given by,

$$E_t = E_{t,b} + E_{t,d} + E_{t,r} \tag{B.27}$$

B.2.3 The ASHRAE Clear-Sky Model Comparisons

This section presents the comparisons of 1967 and 2009 ASHRAE clear-sky models. Stillwater, OK and College Station, TX are the selected cities for comparisons. The date of the weather conditions is September 22nd in 2001.

Figure B.5 shows the ASHRAE clear-sky model comparisons for Stillwater, OK. This city is selected because it is where the experiments were performed by Oklahoma State University for validating the HBM and RTSM. In the figure, direct normal, beam, diffuse, and total horizontal solar irradiance predicted by three models are presented. For the 1967 ASHRAE model, the two sets of A, B, C coefficients provide roughly equal direct normal solar irradiance. This is because the A and B changes have a small impact. The same observations were found for the beam solar irradiance, because it is calculated by direct normal solar irradiance multiplied by the cosine of the incidence angle ($\cos\theta$). However, the c coefficients for September increases 32%, compared to the first published number, and the diffuse solar irradiance appears to be different, as shown in

Figure B.5. The second sets of coefficients tend to over-predict the diffuse solar compared to the first set, which makes the total solar irradiance larger than the one predicted using the first sets of A, B, C coefficients. The 2009 ASHRAE model estimates a larger beam solar irradiance component compared to the 1967 ASHRAE model. The diffuse solar irradiance from the 2009 ASHRAE model is between the values predicted by the 1967 ASHRAE model using two sets of A, B, C coefficients. The total solar irradiance by 2009 ASHRAE model is the largest among all methods.

Figure B.6 reveals the ASHRAE clear-sky model comparisons for College Station, TX. The same observations from the 1967 ASHRAE models with the two sets of coefficients are the same. However, the beam solar irradiance from the 2009 ASHRAE model is underestimated, compared to the 1967 ASHRAE model. Similar to Stillwater, OK, the diffuse solar irradiance from the 2009 ASHRAE model is between the values predicted by the 1967 ASHRAE model using the two sets of A, B, C coefficients. The total solar irradiance from the 2009 ASHRAE model gives roughly the same estimates as the 1967 ASHRAE model using the first set of coefficients. However, it is smaller than the numbers predicted by the 1967 ASHRAE model using the second sets of coefficients.

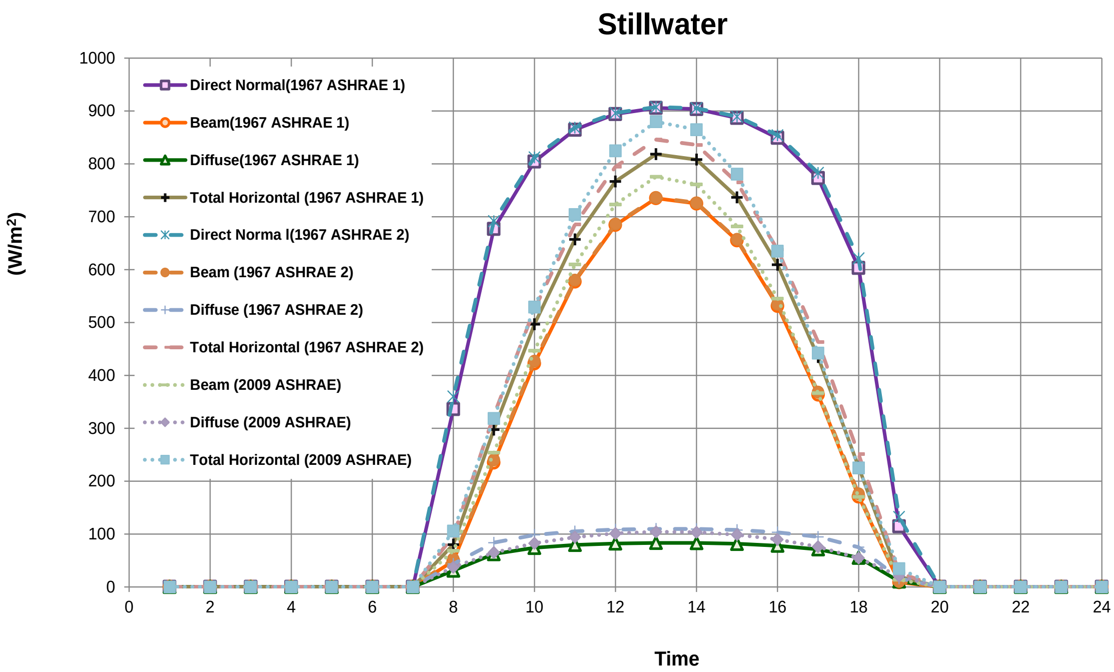


Figure B.5: ASHRAE Clear-Sky Model Comparisons for Stillwater, OK City

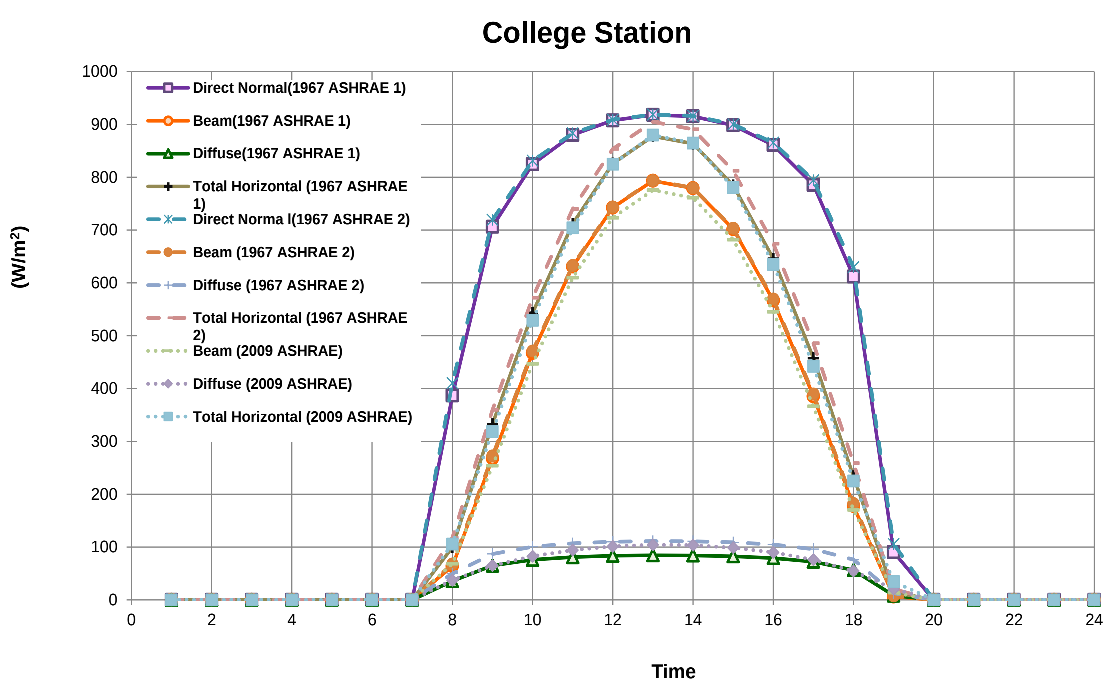


Figure B.6: ASHRAE Clear-Sky Model Comparisons for College Station, TX City

B.3 Sol-Air Temperature

Sol-air temperature t_e is defined as "*the temperature of the outdoor air that, in the absence of all radiation changes, gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchanges with the outdoor air*" (ASHRAE, 2013a). This concept was originally introduced by Mackey and Wright in 1944. They also proposed an equation to calculate building inside surface temperature by daily average sol-air temperature, a decrement factor and a lag angle. Later, sol-air temperature was introduced into ASHRAE as the foundation of the ASHRAE simplified peak cooling load methods to calculate building sensible cooling load.

Usually, the conduction heat gain q transferred into the building exterior surfaces can be determined by (ASHRAE, 2013a),

$$q / A = \alpha E_t + h_o (t_o - t_s) - \varepsilon \Delta R \tag{B.28}$$

where,

A: exterior surface area, m^2;

α: exterior surface solar absorptance;

E_t: total solar radiation intensities on the exterior surface, W/m^2;

h_o: combined heat transfer coefficient that includes long-wave radiation and convection at the exterior surface, W/m^2-K;

t_o: outdoor dry bulb temperature, °C;

t_s: exterior surface temperature, °C;

ε : hemispherical surface emittance;

ΔR : difference between the long-wave radiation incident on the surface from the sky and surroundings and the radiation emitted by a blackbody at outdoor air temperature, W/m^2; 63 W/m^2 for horizontal surfaces and 0 W/m^2 for vertical surfaces.

Assume the same heat gain can be provided using sol-air temperature concept,

$$q / A = h_o(t_e - t_s) \tag{B.29}$$

Inserting Equation (B.28) into Equation (B.29), the sol-air temperature t_e can be obtained,

$$t_e = t_o + \alpha E_t / h_o - \varepsilon \Delta R / h_o \tag{B.30}$$

In practice, $\varepsilon \Delta R / h_o$ is assumed to be 4 K and 0 K for horizontal and vertical surfaces, respectively.

APPENDIX C

FENESTRATION SOLAR HEAT GAIN MODELS

There are two fenestration models for calculating solar heat gains available in ASHRAE. One model relies on the Transmitted Solar Heat Gain Factor (TSHGF), Absorbed Solar Heat Gain Factor (ASHGF), and Shading Coefficient (SC) to perform solar heat gains through the fenestration (McQuiston and Spitler, 1992). The other model uses the incidence angle-based Solar Heat Gain Coefficient (SHGC) and Indoor Attenuation Coefficient (IAC) to calculate solar heat gains (ASHRAE, 2013a; Nigusse, 2007).

C.1 Overview of Fenestration Solar Heat Gains

The incoming solar consists of beam and diffuse solar radiation. For a single pane, clear window exposed to the solar radiation, of the 100% incoming solar radiation, approximately 80% is transmitted thru the window glazing, while 8% is reflected to the outside space. The remaining 12% is absorbed by the window glazing. Of this amount, only 4% of it goes into the space, called the "inward flow", and 8% goes to the outside, called the "outward flow". Therefore, to count for the solar heat gains through the fenestration, both transmitted solar and the inward flow of the absorbed solar need to be determined, see Figure C.1.

C.2 Fenestration Model 1

According to the published coefficients in Table C.1, the transmittance τ_D and absorptance α_D of beam solar radiation are given by (McQuiston and Spitler, 1992),

$$\tau_D = \sum_{j=0}^{5} t_j \cos\theta^j \tag{C.1}$$

$$\alpha_D = \sum_{j=0}^{5} \alpha_j \cos\theta^j \tag{C.2}$$

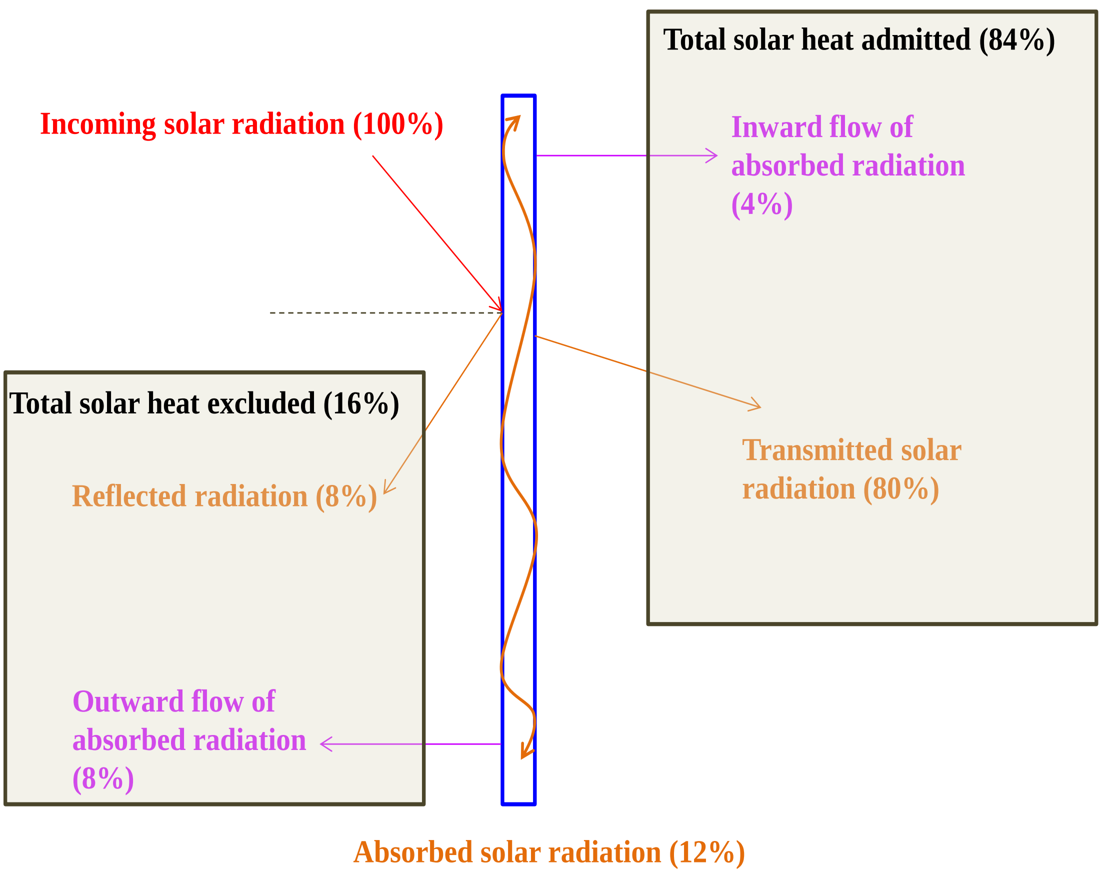


Figure C.1: Solar Radiation Falling onto the Single Pane Clear Glass (Adapted from McQuiston et al., 2000)

Table C.1: Coefficients for DSA Glass for calculation of Transmittance and Absorptance (Adapted from McQuiston and Spitler, 1992)

i	$\boldsymbol{\alpha_j}$	$\boldsymbol{t_j}$
0	0.01154	-0.00885
1	0.77674	2.71235
2	-3.94657	-0.52062
3	8.57881	-7.07329
4	-8.38135	9.75995
5	3.01188	-3.89922

The transmittance τ_d and absorptance α_d of diffuse solar radiation are given by,

$$\tau_d = \sum_{j=0}^{5} t_j / (j+2) \tag{C.3}$$

$$\alpha_d = \sum_{j=0}^{5} \alpha_j / (j+2) \tag{C.4}$$

Using the 1967 ASHRAE clear-sky model, TSHGF and ASHGF can be defined as,

$$TSHGF = E_D \sum_{j=0}^{5} t_j \cos\theta^j + 2E_d \sum_{j=0}^{5} t_j / (j+2) \tag{C.5}$$

$$ASHGF = E_D \sum_{j=0}^{5} \alpha_j \cos\theta^j + 2E_d \sum_{j=0}^{5} \alpha_j / (j+2) \tag{C.6}$$

where,

E_D : beam solar radiation falling on the fenestration, W/m^2;

E_d : diffuse solar radiation falling on the fenestration, W/m^2.

The inward flow fraction of absorbed solar heat gain N_i is given by,

$$N_i = h_i / (h_i + h_o) \tag{C.7}$$

where,

h_i : heat transfer coefficient at inner surface, W/m^2-K;

h_o : heat transfer coefficient at outer surface, W/m^2-K.

Using Eqns (C.5), (C.6) and (C.7), the transmitted solar heat gain (TSHG) and absorbed solar heat gain (ASHG) yield,

$$TSHG = TSHGF(SC)A \quad (C.8)$$

$$ASHG = ASHGF(SC)N_i A \quad (C.9)$$

where,

SC : shading coefficient;

A : window surface area, m^2.

C.3 Fenestration Model 2

Instead of separately calculating transmitted and absorbed solar radiation through the fenestration, another way is to calculate beam and diffuse solar radiation by using incidence angle-based SHGC and IAC. The transmitted and the inward flow of absorbed solar is considered in the SHGC. Using the 2009 ASHRAE clear-sky model, the beam and diffuse solar heat gains thru the fenestration are given by (ASHRAE, 2013a),

$$q_b = AE_{t,b}SHGC(\theta)IAC(\theta,\Omega) \quad (C.10)$$

$$q_d = A(E_{t,d} + E_{t,r})\langle SHGC\rangle_D IAC_D \quad (C.11)$$

where,

A: window surface area, m^2;

$E_{r,b}$: beam solar radiation falling on the fenestration, W/m^2;

$E_{t,d}$: diffuse solar radiation from the sky falling on the fenestration, W/m^2;

$E_{t,r}$: diffuse solar radiation from the ground reflection falling on the fenestration, W/m^2;

$SHGC(\theta)$: incidence angle based beam solar heat gain coefficient;

$\langle SHGC \rangle_D$: diffuse solar heat gain coefficient;

$IAC(\theta, \Omega)$: indoor solar attenuation coefficient for beam solar heat gain coefficient;

IAC_D: indoor solar attenuation coefficient for diffuse solar heat gain coefficient.

C.4 Fenestration Model Comparison

Figure C.2 shows the total fenestration solar heat gain comparison using two fenestration models for the base case in the current study.

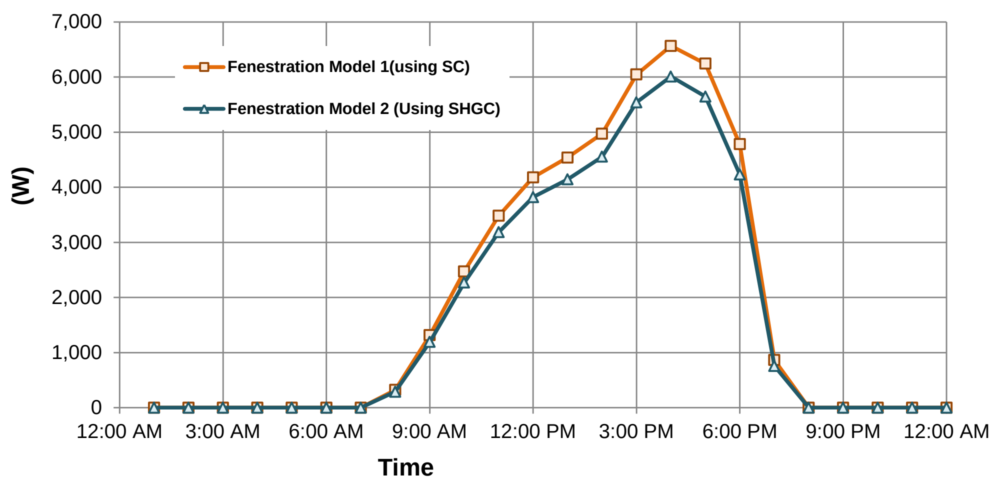


Figure C.2: Total Fenestration Solar Heat Gain Comparison Using Fenestration Model 1 and 2 for Base Case on September 22nd 2001, Stillwater, OK.

APPENDIX D

HEAT BALANCE METHOD (HBM)

This section presents the heat balance method, which is used to calculate building peak loads. According to 2013 ASHRAE Handbook of Fundamentals, the following assumptions and processes must be considered for the HBM:

- The zone air temperature is well mixed and uniform;
- The zone surfaces have uniform surface temperatures;
- The zone has uniform long-wave and short-wave irradiation;
- The zone has diffuse radiative surfaces;
- The heat conduction process is one-dimensional.

The HBM includes four sub-calculations,

- Outside surface heat balance;
- Wall conduction process;
- Inside surface heat balance;
- Zone air heat balance.

D.1 Outside Surface Heat Balance

The heat balance at the outside surface is given by (ASHRAE, 2013a),

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0, \qquad \text{(D.1)}$$

where,

$q''_{\alpha sol}$: absorbed direct and diffuse solar radiation heat flux, W/m^2;

q''_{LWR} : net long wave radiation heat exchange with the air and surroundings, W/m^2;

q''_{conv} : convection heat exchange with outside air, W/m^2;

q''_{ko} : conduction heat exchange through the wall, W/m^2.

D.2 Wall Conduction Process

The HBM uses conduction transfer functions (CTFs) to calculate the one-dimensional wall heat conduction process. In the HBM, the inside and outside heat flux are given by (ASHRAE, 2013a),

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,i,t-j\delta}, \qquad \text{(D.2)}$$

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{i=1}^{nq} \Phi_j q''_{ko,i,t-j\delta}, \qquad \text{(D.3)}$$

where,

X_j : outside CTF, $j = 0,1,\ldots,nz$;

Y_j : cross CTF, $j = 0,1,\ldots,nz$;

Z_j : inside CTF, $j = 0,1,\ldots,nz$;

Φ_j : flux CTF, $j = 0,1,\ldots,nq$;

T_i : inside surface temperature, °C;

T_o : outside surface temperature, °C;

q''_{ki} : conduction heat flux on inside face, W/m^2;

q''_{ko} : conduction heat flux on outside face, W/m^2.

D.3 Inside Surface Heat Balance

The inside surface heat balance is modeled as a heat exchange among conduction process, the convection to the room air, and the shortwave and long wave radiation inside the zone. For each surface, it can be given by (ASHRAE, 2013a),

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0, \qquad \text{(D.4)}$$

where,

q''_{LWX} : net long wave radiant exchange flux between zone surfaces, W/m^2;

q''_{SW} : net shortwave radiation flux to surface from lights, W/m^2;

q''_{LWS} : longwave radiation flux from equipment in zone, W/m^2;

q''_{ki} : conduction flux through the wall, W/m^2;

q''_{sol} : transmitted solar radiation flux absorbed at the surface, W/m^2;

q''_{conv} : convection heat flux to the zone air, W/m^2.

D.4 Air Heat Balance

By performing an air heat balance, the building cooling load can be obtained. The air heat balance can be given by (ASHRAE, 2013a),

$$q_{conv} + q_{CE} + q_{IV} + q_{sys} = 0, \qquad \text{(D.5)}$$

where,

q_{conv} : convection heat transfer from the surfaces, W;

q_{CE} : convective part of internal loads, W;

q_{IV} : sensible load due to infiltration and direct zone ventilation air, W;

q_{sys} : heat transfer to/from the HVAC system, W.

D.5 Zone Heat Balance

A general zone heat balance procedure includes 12 surfaces, which are four walls, four windows, one roof, one skylight, one floor, and thermal mass. This is shown in Figure D.1.

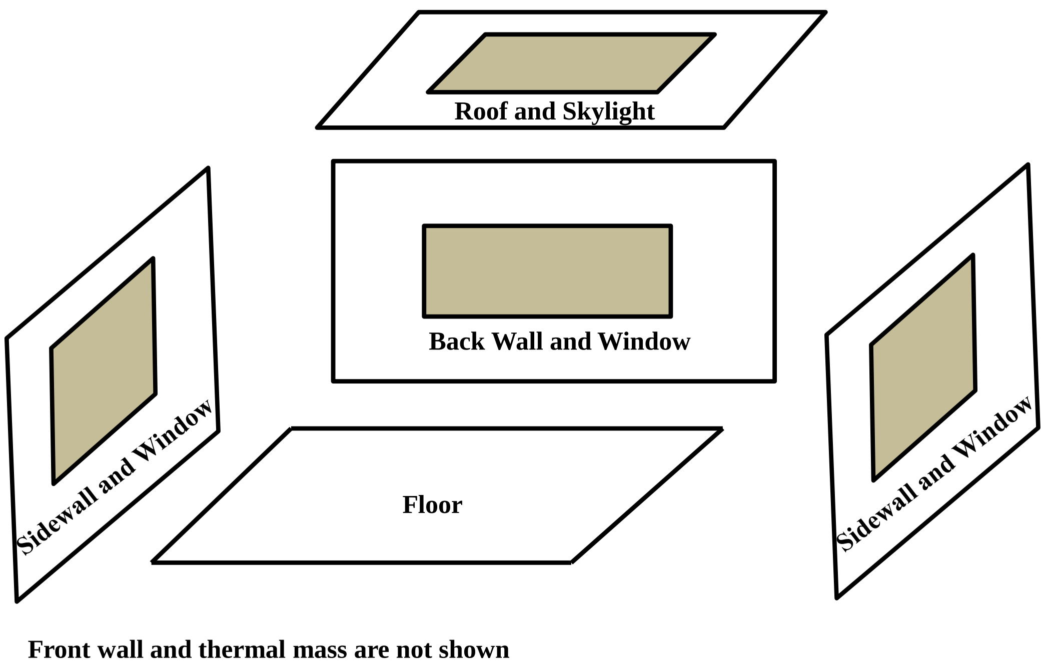


Figure D.1: Schematic View of General Heat Balance Zone (Adapted from ASHRAE, 2013a)

Combining Equations (D.1) and (D.3) yields the outside face temperature (ASHRAE, 2013a),

$$T_{so_{i,j}} = \frac{\sum_{k=1}^{nz} T_{si_{i,j-k}} Y_{i,k} - \sum_{k=1}^{nz} T_{so_{i,j-k}} X_{i,k} - \sum_{k=1}^{nq} \Phi_{i,k} q''_{ko_{i,j-k}} + q''_{\alpha sol_{i,j}} + q''_{LWR_{i,j}} + T_{si_{i,j}} Y_{i,o} + T_{o_j} h_{co_{i,j-k}}}{X_{i,0} + h_{co_{i,j}}} \quad \text{(D.6)}$$

where,

$Y_{i,k}$: cross CTF, $k = 0,1,\ldots,nz$;

$X_{i,k}$: inside CTF, $k = 0,1,\ldots,nz$;

$\Phi_{i,k}$: flux CTF, $k = 0,1,\ldots,nq$;

T_{si} : inside face temperature, °C;

T_{so} : outside face temperature, °C;

q''_{ko} : conductive heat flux into the wall, W/m^2;

$q''_{\alpha sol}$: absorbed direct and diffuse solar radiant heat flux, W/m^2;

q''_{LWR} : net longwave radiant flux exchange with the air and surroundings, W/m^2;

q''_{conv} : convective flux exchange with outside air, W/m^2.

Combining Equations (D.2) and (D.4) yields the outside face temperature (ASHRAE, 2013a),

$$T_{si_{i,j}} = \frac{T_{so_{i,j}} Y_{i,o} + \sum_{k=1}^{nz} T_{so_{i,j-k}} Y_{i,k} - \sum_{k=1}^{nz} T_{si_{i,j-k}} Z_{i,k} + \sum_{k=1}^{nq} \Phi_{i,k} q_{ki_{i,j-k}} + T_{a_j} h_{ci_j} + q''_{LWS} + q''_{LWX_{i,j}} + q''_{SW} + q''_{sol}}{Z_{i,0} + h_{ci_{i,j}}}$$

(D.7)

where,

$Y_{i,k}$: cross CTF, $k = 0,1,\ldots,nz$;

$Z_{i,k}$: inside CTF, $k = 0,1,\ldots,nz$;

$\Phi_{i,k}$: flux CTF, $k = 0,1,\ldots,nq$;

T_{si} : inside face temperature, °C;

T_{so} : outside face temperature, °C;

T_a : zone air temperature, °C;

h_{ci} : convective heat transfer coefficient on the inside W/m^2-K.

APPENDIX E

RADIANT TIME SERIES METHOD (RTSM)

This section contains the details of radiant time series method procedure, which is one of the simplified methods, compared to heat balance method. This method was first introduced in 1997 by Spitler *et al* (Spitler, *et al*., 1997). Ten years later, it was improved by Nigusse and Spitler (Nigusse, 2007; Nigusse and Spitler, 2010). The original RTSM uses Periodic Response Factors (PRFs) to calculate the dynamic condition heat gains through the opaque surfaces, while the improved RTSM introduces Conduction Time Series Factors (CTSFs), a set of dimensionless factors, to perform the calculations. The window solar heat gains are determined by solar heat gain coefficient (SHGC) in the improved RTSM instead of shading coefficient (SC) used in original method. Here, the original RTSM is called RTSM V1 and the later updated RTSM is called RTSM V2. The overview flow charts of both methods are shown in Figure E.1 and Figure E.2, respectively.

As one of the simplified methods for calculating building cooling loads, the RTSM is implemented in both the ASHRAE LOADS Toolkit in the RTSM V1 and the ASHRAE RTSM spreadsheet in the RTSM V2. Four types of heat gains are first determined, including: conduction heat gains, solar heat gains through fenestration, internal heat gains, and infiltration heat gain. All heat gains are split into radiative and convective portions according to recommended split ratios. By applying radiant time series factors, all radiative heat gains are converted into the cooling loads. All convective heat gains directly become building cooling loads.

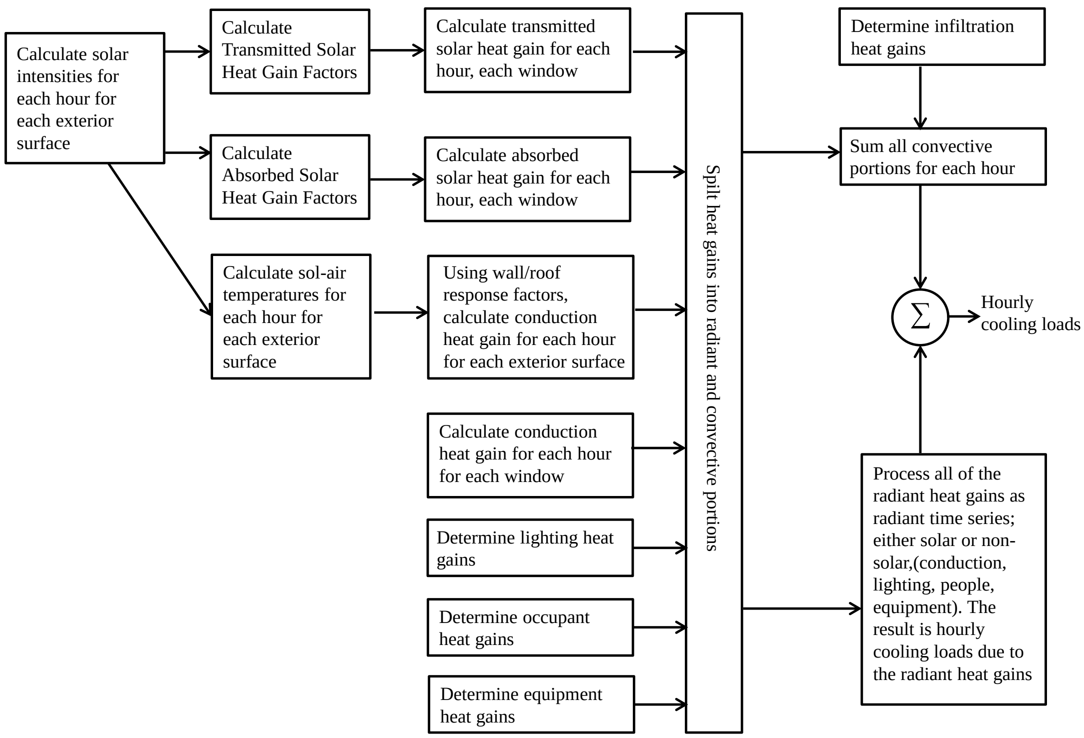


Figure E.1: RTSM V1 Overview (Adapted from Spitler, *et.al*, 1997)

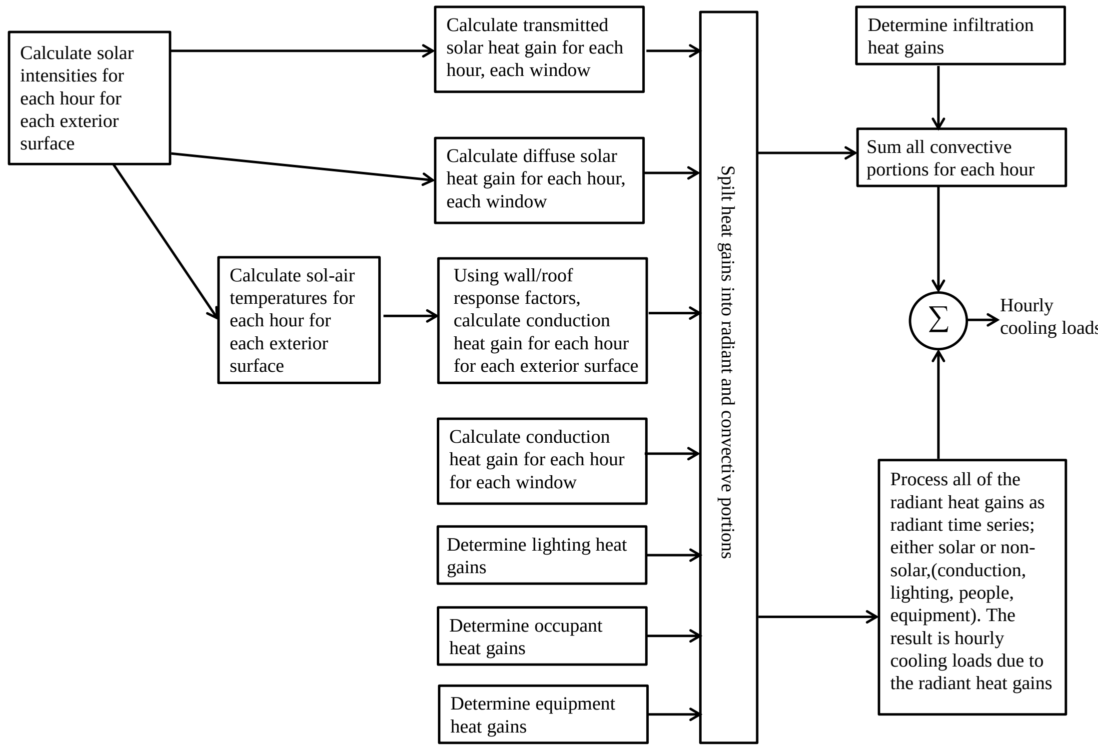


Figure E.2: RTSM V2 Overview (Adapted from ASHRAE, 2013a)

E.1 Exterior Conduction Heat Gains

The conduction heat gains include walls, roofs, and fenestration conduction heat gains. For walls and roofs, the calculations depend on the sol-air temperature (See Appendix B).

E.1.1 RTSM V1

For the walls and roofs, the conduction heat gain q_θ can be determined using the PRFs (Spitler *et.al*, 1997),

$$q_\theta = A\sum_{j=0}^{23} Y_{Pj}(t_{e,\theta-j\delta} - t_{rc}) \quad \text{(E.1)}$$

where,

A : exterior surface area, m^2;

Y_{Pj} : periodic response factor (PRFs), W/m^2-K;

$t_{e,\theta-j\delta}$: sol-air temperature, *j* hour ago, °C;

t_{rc} : constant room air temperature, °C.

For fenestration conduction heat gains (ASHRAE, 2013a),

$$q_f = UA(T_{out} - T_{in}) \tag{E.2}$$

where,

U : overall U factor, W/m^2-K;

A : window area, m^2;

T_{out} : outdoor temperature, °C;

T_{in} : indoor temperature, °C.

E.1.2 RTSM V2

The RTSM V2 replaces the PRFs for the wall and roof conduction heat gain q_θ can be determined using dimensionless CTSFs (Spitler, 2009; ASHRAE, 2013a),

$$q_\theta = \sum_{j=0}^{23} c_j UA(t_{e,\theta-j\delta} - t_{rc}) \tag{E.3}$$

where,

A : exterior surface area, m^2;

c_j : conduction time series factor (CTSF);

U : overall heat transfer coefficient for the surface, W/m^2-K;

$t_{e,\theta-j\delta}$: sol-air temperature, j hour ago, °C;

t_{rc} : constant room air temperature, °C.

In the RTSM V2, the fenestration conduction heat gain is also calculated using Eqn (E.2).

E.2 Fenestration Solar Heat Gains

The fenestration solar heat gain calculations are detailed in Appendix C. The RTSM V1 adopts the fenestration model 1, while the RTSM V2 uses the fenestration model 2. As previously mentioned, the fenestration model 1 uses the shading coefficient concept, while the model 2 uses the SHGC and IAC involved in the calculation procedures.

E.3 Partition, Ceiling, Floor Conduction Heat Gains

According to the 2013 ASHRAE Handbook of Fundamentals Chapter 18, the conduction heat gains for interior partitions, ceiling and floor can be calculated as a steady state conduction heat transfer,

$$q = UA(t_b - t_i) \tag{E.4}$$

where,

U : overall heat transfer coefficient between adjacent and conditioned space, W/m^2-K;

A : surface area, m^2;

t_b : average air temperature in adjacent space, °C;

t_i : air temperature in conditioned space, °C.

E.4 Internal Heat Gains

Internal heat gains include occupancy, lighting, and equipment heat gains. According to the 2013 ASHRAE Handbook of Fundamentals Chapter 18, they can be calculated as follows:

For occupants,

$$q_s = q_{s,per} N \tag{E.5}$$

$$q_l = q_{l,per} N \tag{E.6}$$

where,

q_s : total occupant sensible heat gain, W;

q_l : total occupant latent heat gain, W;

$q_{s,per}$: sensible heat gain per person W/person;

$q_{l,per}$: latent heat gain per person, W/person;

N : number of occupants.

For lights,

$$q_{el} = W F_{ul} F_{sa} \tag{E.7}$$

where,

q_{el} : lighting heat gain, W;

W : total light wattage, W;

F_{ul} : lighting use factor, fraction;

F_{sa} : lighting special allowance factor, fraction;

For electric motors,

$$q_{em} = (P / E_M) F_{UM} F_{LM} \qquad \text{(E.8)}$$

where,

q_{em} : heat equivalent of equipment operation, W;

P : motor power rating, W;

E_M : motor efficiency, fraction;

F_{UM} : motor use factor, fraction;

F_{LM} : motor load factor, fraction;

For hooded cooking appliances,

$$q_s = q_{input} F_U F_R \qquad \text{(E.9)}$$

where,

q_s : sensible heat gain, W;

q_{input} : nameplate or rated energy input, W;

F_U : usage factor, fraction;

F_R : radiation factor, fraction.

E.5 Ventilation and Infiltration Air Heat Gain

$$q_s = 1.23\, Q_s\, \Delta t \quad \text{(E.10)}$$

$$q_l = 3130\, Q_s\, \Delta W \quad \text{(E.11)}$$

where,

Q_s : infiltration airflow at standard air conditions, m^3/s;

Δt : temperature difference between outdoor and indoor air, °C;

ΔW : humidity ratio difference between outdoor and indoor air, kg/kg;

1.23: air sensible heat factor at standard air conditions, W/m^3-s-°C;

3130: air latent heat factor at standard air conditions, W/m^3-s.

E.6 Convert All Heat Gains into Cooling Loads

The RTSM utilizes two sets of the radiant time factors (RTFs) to convert all heat gains into the cooling loads, which are solar RTFs and non-solar RTFs. Before applying any time series factors, all heat gains need to be categorized as radiative and convective heat gains. RTSM V1 and RTSM V2 have different recommended ratios for splitting radiative and convective heat gains, see in Table E.1 and Table E.2.

The convective portion of heat gains directly become the cooling loads. However, the radiative portion of heat gains must be absorbed by the interior surfaces or the furniture, and then be convected into the space air temperature with a time delay. Two sets of RTFs are applied to convert the radiative heat gains into the cooling load. The solar beam heat gain is assumed to be distributed on the floor only, while other types of heat gains are distributed uniformly to the interior surfaces, including radiative portion of conduction heat gains and internal heat gains as well as diffuse solar heat gains.

Table E.1: Recommended Radiative-Convective Splits for Heat Gains for RTSM V1 (Adapted from Spitler *et al*., 1997)

Heat Gain Type	Recommended Radiative Fraction	Recommended Convective Fraction
Occupants	0.70	0.30
Lighting		
Suspended fluorescent-unvented	0.67	0.33
Recessed fluorescent-vented to return air	0.59	0.41
Recessed fluorescent-vented to supply and return air	0.19	0.81
Incandescent	0.71	0.29
Equipment	0.2-0.8	0.8-0.2
Conduction heat gain through walls	0.63	0.37
Conduction heat gain through roofs	0.84	0.16
Transmitted solar radiation	1.00	0.00
Absorbed solar radiation	0.63	0.37

Table E.2: Recommended Radiative-Convective Splits for Heat Gains for RTSM V2 (Adapted from ASHRAE, 2013a)

Heat Gain Type	Recommended Radiative Fraction	Recommended Convective Fraction
Occupants, typical office conditions	0.60	0.40
Equipment	0.10-0.80	0.90-0.20
Office equipment with fan	0.10	0.90
Office equipment without fan	0.30	0.70
Lighting		
Recessed fluorescent luminaire without lens	0.48-0.68	0.64-0.74
Recessed fluorescent luminaire with lens	0.61-0.73	0.40-0.50
Downlight compact fluorescent luminaire	0.95-1.00	0.12-0.24
Downlight incandescent luminaire	0.95-1.00	0.70-0.80
Non-in-ceiling fluorescent luminaire	0.50-0.57	1.00
Conduction heat gain		
Through walls and floors	0.46	0.54
Through roofs	0.60	0.40
Through windows		
SHGC>0.5	0.33	0.67
SHGC<0.5	0.46	0.54
Solar heat gain through fenestration		
Without interior shading	1.00	0.00
With interior shading		
SHGC>0.5	0.33	0.67
SHGC<0.5	0.46	0.54
Infiltration	0.00	1.00

Therefore, the solar RTFs are applied to the solar beam heat gains. The non-solar RTFs are applied onto the diffuse solar heat gains and the radiative portion of other types of heat gains to calculate the cooling loads $Q_{r,\theta}$, which gives,

$$Q_{r,\theta} = r_0 q_{r,\theta} + r_1 q_{r,\theta-1} + r_2 q_{r,\theta-2} + r_3 q_{r,\theta-3} + \cdots + r_{23} q_{r,\theta-23} \quad \text{(E.12)}$$

where,

$q_{r,\theta}$: radiant heat gains for current hour, W;

$q_{r,\theta-n}$: radiant heat gain n hours ago, W;

r_0, r_1, etc.: radiant time factors (RTFs).

APPENDIX F

TRANSFER FUNCTION METHOD (TFM)

This section reviews the Transfer Function Method (TFM) for building peak load calculations. It was first developed as a computer algorithm in 1972 (ASHRAE, 1972). The TFM is a two-step, simplified method that incorporates the concepts of Conduction Transfer Functions (CTFs) and Room Transfer Functions (RTFs, also called Weighting Factors). Figure F.1 presents an overview of the methodology.

The TFM requires the solar intensities estimations for each exterior surface to determine the sol-air temperatures. The conduction heat gains of walls and roofs are calculated through sol-air temperatures and CTFS. The transmitted and absorbed solar heat gains are calculated using the TSGHF and ASHGF, respectively. The fenestration conduction heat gains can be obtained through steady state conduction heat transfer process. If any internal heat gains exist, they need to be calculated individually. The cooling loads from solar heat gains, conduction heat gains, and internal heat gains are obtained applying the solar weighting factors, conduction weighting factors, lighting weighting factors, and occupant/equipment weighting factors, respectively. The infiltration heat gains directly contribute to the cooling load. Summing up all types of cooling load can achieve the total cooling load for the space.

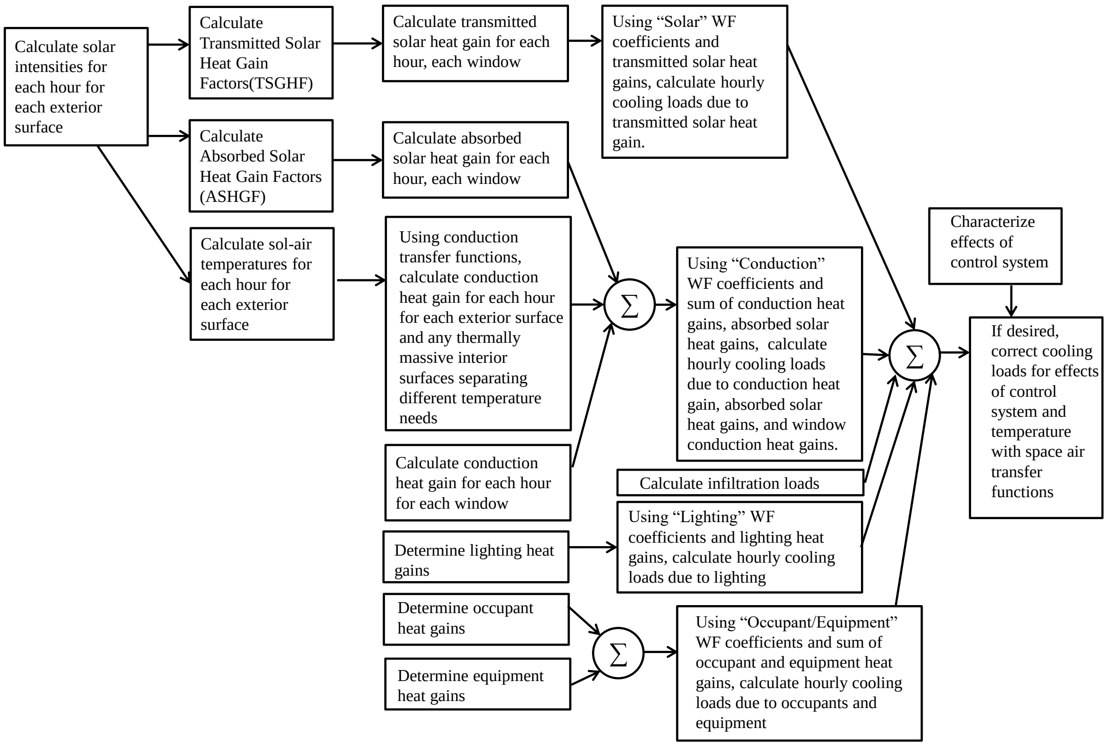


Figure F.1: TFM Overview (Adapted from McQuiston and Spitler, 1992)

F.1 Exterior Conduction Heat Gains

Relying on the CTFs, the conduction heat gains through walls and roofs can be determined. Tabulated CTFs values are published by ASHRAE (ASHRAE, 1997). The specific wall and roof layer combinations were first recommended by Harries and McQuiston in 1988 (Harries and McQuiston, 1988). Forty-one types of walls and forty-two types of roofs are available. Therefore, to use the TFM, it is needed to pick the closest wall and roof combination types in the database.

In the TFM, the conduction heat gain through the walls and roofs is formulated by (ASHRAE, 1997),

$$q_{e,\theta} = A[\sum_{n=0} b_n t_{e,\theta-n\delta} - \sum_{n=1} d_n (q_{e,\theta-n\delta} / A) - t_{rc} \sum_{n=0} c_n] \quad \text{(F.1)}$$

where,

$q_{e,\theta-n\delta}$: heat gain through walls or roofs, Btu/h, at time $\theta - n\delta$;

A : wall or roof surface area, m^2;

θ : current hour, h;

δ : time interval, h;

n : summation index, dimensionless;

$t_{e,\theta-n\delta}$: sol-air temperature at time $\theta - n\delta$, °C;

t_{rc} : indoor room temperature, °C;

b_n , c_n : Conduction Transfer Function Coefficients, W/m^2-K;

d_n : Conduction Transfer Function Coefficients, dimensionless.

The TFM general procedure to determine the Conduction Transfer Function (CTF) coefficients is detailed next.

Step 1: wall and roof material layers

The code names of wall and roof layers need to be selected from outside to inside according to Table F.1, which shows the predetermined layer properties used in TFM. Unfortunately, not all materials fall into the categories that are defined by Table F.1. In such cases, the closest material needs to be selected. The full table of available materials can be found in 1997 ASHRAE Handbook of Fundamentals.

Step 2: wall and roof group numbers

The determination of the wall group number is based on four parameters: principal wall material; secondary wall material; R-value range; and mass location. The pre-defined principal and secondary wall materials can be found in Table F.2 and Table F.3, respectively. These two tables present the principal and secondary finishes with the respective layer code numbers in the TFM. For instance, if the wall materials contain 4 in. heavy concrete and gypsum, the principal and the secondary wall material number would be No. 8 and No. 1 accordingly. The wall R value range number can be chosen from Table F.5 according to the overall wall R value. "Mass location" means the principal wall material location relative to the insulation layer. Finally, mass location needs to be determined from Table F.7.Three options are available: mass in; mass integral; mass out. "Mass in" case represents the principal wall material is inside the wall insulation. "Mass integral" case means the principal wall materials evenly distributed among the wall insulation. "Mass out" case reveals the principal wall material lays outside the wall insulation.

The wall group number can be determined by Table F.8. The column and row numbers represents the principal material and R-value range numbers, respectively. In the section of secondary material, the wall group number can be obtained. For example, for a wall with principal material number 17 combined with secondary wall material A1 or/and E1, R-value range number 1 and a mass-in situation, the wall group number would be No. 2.

Table F.1: Wall and Roof Layers Code Names and Thermal Properties[31] (Adapted from ASHRAE, 1997)

Code Name	Description	*L* (mm)	*k* (W/m-K)	*ρ* (kg/m^3)	c_p (kJ/kg-K)	*R* (m^2-K/W)	Mass (kg/m^2)
A0	Outside surface resistance	0	0.000	0	0.00	0.059	0.00
A1	25 mm Stucco	25	0.692	1858	0.84	0.037	47.34
A2	100 mm Face brick	100	1.333	2002	0.92	0.076	203.50
A3	Steel siding	2	44.998	7689	0.42	0.000	11.71
A4	12 mm Slag	13	0.190	1121	1.67	0.067	10.74
A5	Outside surface resistance	0	0.000	0	0.00	0.059	0.00
A6	Finish	13	0.415	1249	1.09	0.031	16.10
A7	100 mm Face brick	100	1.333	2002	0.92	0.076	203.50
B1	Air space resistance	0	0.000	0	0.00	0.160	0.00
B2	25 mm Insulation	25	0.043	32	0.84	0.587	0.98
B3	50 mm Insulation	51	0.043	32	0.84	1.173	1.46
⋮			⋮			⋮	
C19	300 mm Low density concrete block (filled)	300	0.138	304	0.84	2.200	92.72
C20	300 mm High density concrete block (filled)	300	0.675	897	0.84	0.451	273.28
E0	Inside surface resistance	0	0.000	0	0.00	0.121	0.00
E1	20 mm Plaster or gypsum	20	0.727	1602	0.84	0.026	30.74
E2	12 mm Slag or stone	12	1.436	881	1.67	0.009	11.22
E3	10 mm Felt and membrane	10	0.190	1121	1.67	0.050	10.74
E4	Ceiling air space	0	0.000	0	0.00	0.176	0.00
E5	Acoustic title	19	0.061	481	0.84	0.314	9.27

Similarly, three parameters need to be known to determine a roof group number: roof principal material; mass location parameter; R-value range number. Twenty principal roof materials are available to be chosen in Table F.4. Three mass locations are listed in Table F.7. The R-value range number can be picked in Table F.6.

The roof group number can be determined from Table F.9. The column is selected based on the R value range number and the row number is chosen according to the roof principal material.

[31] This table shows partial material properties. Please check the full tables from 1997 ASHRAR Handbook of Fundamentals on page 28.19.

Table F.2: Principal Wall Materials (Adapted from ASHRAE, 1997)

Material Number	Layer Code	Description
1	A1,A3,A6, or E1	25 mm stucco, steel siding, finish, or gypsum
2	A2 or A7	100 mm face brick
3	B7	25 mm wood
4	B10	50 mm wood
5	B9	100 mm wood
6	C1	100 mm clay tile
7	C2	100 mm low density concrete block
8	C3	100 mm high density concrete block
9	C4	100 mm Common brick
10	C5	100 mm high density concrete block
11	C6	200 mm. clay tile
12	C7	200 mm low density concrete block
13	C8	200 mm high density concrete block
14	C9	200 mm Common block
15	C10	200 mm high density concrete
16	C11	300 mm high density concrete
17	C12	50 mm high density concrete
18	C13	150 mm high density concrete
19	C14	100 mm low density concrete
20	C15	150 mm low density concrete
21	C16	200 mm low density concrete
22	C17	200 mm low density concrete block (Filled)
23	C18	200 mm high density concrete block (Filled)
24	C19	300 mm low density concrete block (Filled)
25	C20	300 mm high density concrete block (Filled)

Table F.3: Secondary Wall Materials (Adapted from ASHRAE, 1997)

Material Number	Layer Code	Description
1	A1	25 mm stucco
1	E1	20 mm plaster or gypsum
2	A3	Steel siding
3	A6	Finish
3	A2	100 mm face brick
3	A7	100 mm face brick

Table F.4: Principal Roof Materials (Adapted from ASHRAE, 1997)

Material Number	**Layer Code**	**Description**
1	B7	25 mm Wood
2	B8	65 mm. Wood
3	B9	100 mm Wood
4	C5	100 mm high density concrete block
5	C12	50 mm high density concrete
6	C13	150 mm high density concrete
7	C14	100 mm low density concrete
8	C15	150 mm low density concrete
9	C16	200 mm low density concrete
10	A3	Steel deck
11	B7 and E3	Attic ceiling combination
12	C12-C12	50 mm high density concrete (outer layer) to 50 mm high density concrete (inner layer)-Roof Terrance System
13	C12-C5	50 mm high density concrete (outer layer) to 100 mm high density concrete block (inner layer)-Roof Terrance System
14	C12-C13	50 mm high density concrete (outer layer) to 150 mm high density concrete (inner layer) Roof Terrance System
15	C5-C12	100 mm high density concrete block (outer layer) to 50 mm high density concrete (inner layer)-Roof Terrance System
16	C5-C5	100 mm high density concrete block (outer layer) to 100 mm high density concrete block (inner layer)-Roof Terrance System
17	C5-C13	100 mm high density concrete block (outer layer) to 150 mm high density concrete (inne layer)-Roof Terrance System
18	C13-C12	150 mm high density concrete (outer layer) to 50 mm high density concrete (inner layer) Roof Terrance System
19	C13-C5	150 mm high density concrete (outer layer) to 100 mm high density concrete block (inne layer)-Roof Terrance System
20	C13-C13	150 mm high density concrete (outer layer) to 150 mm high density concrete (inner laye Roof Terrance System

Table F.5: Wall R-Value Range Definitions (Adapted from ASHRAE, 1997)

R-Value Range Number	**R Value (m^2-K/W)**
1	0.00 - 0.35
2	0.35 – 0.44
3	0.44 – 0.53
4	0.53 – 0.62
5	0.62 – 0.70
6	0.70 – 0.84
7	0.84 – 0.97
8	0.97 – 1.14
9	1.14 – 1.36
10	1.36 – 1.58
11	1.58 – 1.89
12	1.89 – 2.24
13	2.24 – 2.64
14	2.64 – 3.08
15	3.08 – 3.52
16	3.52 – 4.05
17	4.05 – 4.76

Table F.6: Roof R-Value Range Definitions (Adapted from ASHRAE, 1997)

R-Value Range Number	**R Value (m^2-K/W)**
1	0.00 – 0.88
2	0.88 – 1.76
3	1.76 – 2.64
4	2.64 – 3.52
5	3.52 – 4.40
6	4.40 – 5.28

Table F.7: Mass Location Parameter (Adapted from ASHRAE, 1997)

Mass Location Parameter	**Mass Location**
1	Mass in
2	Mass Integral
3	Mass out

Table F.8: Wall Group Numbers for Mass-In Case[32] (Adapted from ASHRAE, 1997)

R	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Combined with Wall Material A1, E1, or both																									
1																	2								
2		5								5					11		2	6							
3		5				3		2	5	6			5		12	18	2	6							
4		5				4	2	2	5	6			6	12	12	19	2	7							
5		5				4	2	3	6	6	10	4	6	17	12	19	2	7					5		
6		6				5	2	4	6	6	11	5	10	17	13	19	2	11					10		16
7		6				5	2	4	6	6	11	5	10	18	13	20	2	11	2				10		16
8		6				5	2	5	10	7	12	5	11	18	13	26	2	12	2				10		17
9		6				5	4	5	11	7	16	10	11	18	13	20	3	12	4	5			11		18
10		6				5	4	5	11	7	17	10	11	18	13	20	3	12	4	9	10		11		18
11		6				5	4	5	11	7	17	10	11	19	13	27	3	12	4	10	15	4	11		18
12		6				5	4	5	11	11	17	10	11	19	19	27	3	12	4	10	16	4	11		24
13		10				10	4	5	11	11	17	10	11	19	18	27	4	12	5	11	17	9	12	15	25
14		10				10	5	5	11	11	18	11	12	25	19	27	4	12	5	11	17	10	16	16	25
15		11				10	5	9	11	11	18	15	16	26	19	28	4	12	5	11	17	10	16	22	25
16		11				10	9	9	16	11	18	15	16	26	19	34	4	17	9	16	23	10	16	23	25
17											24	16							9	16	24	15	17	24	25

[32] This table only shows one combination case for mass-in. The full table covers more group combinations as well as mass integral and mass out cases (1997 ASHRAE Handbook of Fundamentals on page 28.23).

Table F.9: Roof Group Numbers for Integral Mass Case[33] (Adapted from ASHRAE, 1997)

Roofs without Suspended Ceilings						
Material No.\ R	**1**	**2**	**3**	**4**	**5**	**6**
1	1	2	2	4	4	
2	4	5	9	10	18	
3	19	21	27	27	28	
4	3					
5	2					
6	5					
7	2	2				
8		4				
9		9				
10	1	1	1	2	2	
11	1	2	2	2	4	
Roof Terrace Systems						
12	4	5	9	9	9	
13	6	11	12	18	18	
14	11	20	20	21	27	
15	5	10	10	17	17	
16	10	20	20	26	26	
17	20	27	28	28	35	
18	10	18	20	20	26	
19	18	27	27	28	35	
20	21	29	30	36	36	

Step 3: wall and roof CTF coefficients

With the selections of wall and roof group numbers in step 2, the tabulated CTF coefficients b_n, d_n, and $\sum c_n$ can be obtained from Table F.10 to Table F.13. The given tables only list certain examples. The full table information of forty-one wall and forty-two roof combinations can be found in 1997 ASHRAE Handbook of Fundamentals.

As given material layers not match exactly with the actual building materials during the design process, the CTF coefficients b_n and $\sum c_n$ need to be adjusted to reduce the calculation errors by using the factor of $\frac{U_{actual}}{U_{tabulated}}$ (ASHRAE, 1997). The tabulated U

[33] This table only shows roof without suspended ceiling with integral mass case. The full table covers roof with suspended ceilings as well as mass integral and mass out cases (1997 ASHRAE Handbook of Fundamentals on page 28.20).

factor can be obtained from Table F.11 and Table F.13. The adjusted b_n can be simply calculated by multiplying the tabulated b_n by $\frac{U_{actual}}{U_{tabulated}}$ factor. The adjusted $\sum c_n$ simply equals to $\sum b_n$. There is no need to modify CTF coefficients d_n. Finally, the conduction heat gains through the walls and roofs can be determined by using the CTF coefficients in Equation F.1.

Table F.10: Wall Conduction Transfer Functions Coefficients b_n and d_n [34](Adapted from ASHRAE, 1997)

Group No.	Layers (Inside to Outside)		n=0	n=1	n=2	n=3	n=4	n=5	n=6
1	Layers E0 A3 B1 B13 A3 A0	b_n	0.04361	0.19862	0.04083	0.00032	0.00000	0.00000	0.00000
	Steel siding with 100 mm insulation	d_n	1.00000	-0.24072	0.00168	0.00000	0.00000	0.00000	0.00000
2	Layers E0 E1 B14 A1 A0 A0	b_n	0.00089	0.03097	0.05456	0.01224	0.00029	0.00000	0.00000
	Frame wall with 13 mm insulation	d_n	1.00000	-0.93389	0.27396	-0.02561	0.00014	0.00000	0.00000
3	Layers E0 C3 B5 A6 A0 A0	b_n	0.02332	0.18344	0.08372	0.00264	0.00000	0.00000	0.00000
	100 mm h.w. concrete block with 25 mm insulation	d_n	1.00000	-0.76963	0.04014	-0.00042	0.00000	0.00000	0.00000
	• • •				• • •			• • •	
39	Layers E0 A2 C16 B14 A6 A0	b_n	0.00000	0.00000	0.00000	0.00003	0.00014	0.00017	0.00007
	Face brick and 300 mm l.w. concrete with 175 mm insulation	d_n	1.00000	-2.99390	3.45880	-1.95830	0.57704	-0.08844	0.00687
40	Layers E0 A2 C20 B15 A6 A0	b_n	0.000000	0.000000	0.000000	0.00003	0.00013	0.00016	0.00006
	Face brick, 300 mm h.w. block(fld.), 150 mm insulation	d_n	1.00000	-2.97580	3.42240	-1.93320	0.56765	-0.08568	0.00652
41	Layers E0 E1 C11 B14 A2 A0	b_n	0.00000	0.00000	0.00000	0.00004	0.00012	0.00011	0.00003
	300 mm h.w. concrete with 125 mm insulation and face brick	d_n	1.00000	-3.08300	3.66620	-2.11990	0.62142	-0.08917	0.00561

[34] For full table information, refer to 1997 ASHRAE Handbook of Fundamentals on page 28.26.

Table F.11: Wall Conduction Transfer Functions Coefficients $\sum c_n$, Time Lag, U Factor, and Decrement Factors [35](Adapted from ASHRAE, 1997)

Group No.	Layers (Inside to Outside)	$\sum c_n$	*TL, h*	*U*	*DF*
1	Layers E0 A3 B1 B13 A3 A0	0.283372	1.30	0.372389	0.98
2	Layers E0 E1 B14 A1 A0 A0	0.098947	3.21	0.314501	0.91
3	Layers E0 C3 B5 A6 A0 A0	0.29312	3.33	1.085249	0.78
	• • •		• • •		• • •
39	Layers E0 A2 C16 B14 A6 A0	0.000416	14.64	0.227365	0.10
40	Layers E0 A2 C20 B15 A6 A0	0.00039	14.38	0.234753	0.08
41	Layers E0 E1 C11 B14 A2 A0	0.000296	14.87	0.294532	0.06

Table F.12: Roof Conduction Transfer Functions Coefficients b_n and d_n [36](Adapted from ASHRAE, 1997)

Group No.	Layers (Inside to Outside)		n=0	n=1	n=2	n=3	n=4	n=5	n=6
1	Layers E0 A3 B25 E3 E2 A0	b_n	0.02766	0.19724	0.07752	0.00203	0.00000	0.00000	0.00000
	Steel deck with 85 mm insulation	d_n	1.00000	-0.35451	0.02267	-0.00005	0.00000	0.00000	0.00000
2	Layers E0 A3 B14 E3 E2 A0	b_n	0.00316	0.06827	0.07278	0.00814	0.00007	0.00000	0.00000
	Steel deck with 125 mm insulation	d_n	1.00000	-0.60064	0.08602	-0.00135	0.00000	0.00000	0.00000
3	Layers E0 E5 E4 C12 E3 E2 A0	b_n	0.03483	0.22616	0.07810	0.00141	0.00000	0.00000	0.00000
	50 mm h.w. concrete deck with suspended ceiling	d_n	1.00000	-0.75615	0.01439	-0.00006	0.00000	0.00000	0.00000
	• • •				• • •			• • •	
40	Layers E0 E5 E4 C5 B26 E3 E2 C13 A0	b_n	0.00000	0.00000	0.00010	0.00040	0.00032	0.00006	0.00000
	100 mm h.w. 90 mm ins, 150 mm h.w. RTS w/susp.ceil.	d_n	1.00000	-2.26980	1.68340	-0.45628	0.04712	-0.00180	0.00002
41	Layers E0 E5 E4 C13 B6 E3 E2 C13 A0	b_n	0.00000	0.00000	0.00011	0.00042	0.00033	0.00006	0.00000
	150 mm h.w. 50 mm ins, 150 mm h.w. RTS w/susp.ceil.	d_n	1.00000	-2.35843	1.86626	-0.56900	0.06466	-0.00157	0.00001
42	Layers E0 E5 E4 C13 B14 E3 E2 C13 A0	b_n	0.00000	0.00000	0.00001	0.00006	0.00012	0.00007	0.00001
	150 mm h.w. 125 mm ins, 150 mm h.w. RTS w/susp.ceil.	d_n	1.00000	-2.68630	2.63090	-1.16850	0.24692	-0.02269	0.00062

[35] For full table information, refer to 1997 ASHRAE Handbook of Fundamentals on page 28.27.
[36] For full table information, refer to 1997 ASHRAE Handbook of Fundamentals on page 28.21.

Table F.13: Roof Conduction Transfer Functions Coefficients $\sum c_n$, Time Lag, U Factor, and Decrement Factors [37](Adapted from ASHRAE, 1997)

Group No.	Layers (Inside to Outside)	$\sum c_n$	*TL, h*	*U*	*DF*
1	Layers E0 A3 B25 E3 E2 A0	0.304451	1.63	0.455689	0.97
2	Layers E0 A3 B14 E3 E2 A0	0.152411	2.43	0.314886	0.94
3	Layers E0 E5 E4 C12 E3 E2 A0	0.340508	3.39	1.318848	0.75
	• • •		• • •		• • •
40	Layers E0 E5 E4 C5 B26 E3 E2 C13 A0	0.000895	12.68	0.332306	0.06
41	Layers E0 E5 E4 C13 B6 E3 E2 C13 A0	0.000927	12.85	0.480459	0.05
42	Layers E0 E5 E4 C13 B14 E3 E2 C13 A0	0.000264	14.17	0.260255	0.03

F.2 Fenestration Solar Heat Gains

The TFM uses fenestration model 1 that was detailed in Appendix C. The TSGHF, ASHGF, and the SC are all involved in the fenestration heat gain calculations.

F.3 Other Heat Gains

Other heat gains include interior partition conduction heat gains, ceiling conduction heat gains, floor conduction heat gains (if any), internal heat gains, infiltration heat gains. The calculation procedures for interior partitions are the same as the ones of RTSM, shown in Equations E.4-E.11.

F.4 Convert All Heat Gains into the Cooling Loads

To determine the space cooling load, Room Transfer Functions (RTF) concept (also called Weighting Factors, WF) is used. The cooling load is formulated by (ASHRAE,1997),

[37] For full table information, refer to 1997 ASHRAE Handbook of Fundamentals on page 28.22.

$$Q_{\theta} = v_0 q_{\theta} + v_1 q_{\theta-\delta} + v_2 q_{\theta-2\delta} - w_1 Q_{\theta-\delta} - w_2 Q_{\theta-2\delta} \quad \text{(F.2)}$$

Where,

$v_0, v_1, v_2, w_1,\ w_2$: Room Transfer Function Coefficients (Weighting Factors);

q_{θ}: heat gain, W, at time θ;

$q_{\theta-\delta}$: heat gain, W, at time $\theta - \delta$;

$q_{\theta-2\delta}$: heat gain, W, at time $\theta - 2\delta$;

$Q_{\theta-\delta}$: cooling load, W, at time $\theta - \delta$;

$Q_{\theta-2\delta}$: cooling load, W, at time $\theta - 2\delta$;

Weighting Factor determination requires the zone information that is also pre-defined and limited to certain cases. When one uses the TFM, the closest selections must be chosen from the tables. According to the design case information, all the parameters listed from Table F.14 to Table F.17 need to be determined. The procedure of converting all heat gains to cooling load was simplified in the *1997 ASHRAE Handbook of Fundamentals*. The published tables only provided the values of Room Transfer Function Coefficients v_0, v_1, and w_1. The values of v_2 and w_2 were not included in the *1997 ASHRAE Handbook of Fundamentals*. Once this step is performed, the Weighting Factors can be obtained by software that was published in the second edition of *Cooling and Heating Load Calculation Manual* (McQuiston and Spitler, 1992) and was designed to extract the Weighting Factors from the pre-calculated values. Therefore, it can either follow the ASHRAE procedure to perform the simplified calculation or use the software to perform the calculation with all weighting factors involved.

Table F.14: Zone parameter Level Definitions (Adapted from ASHRAE, 1997)

No.	Parameter	Meaning	Levels
1	ZG	Zone geometry	30 m × 6 m, 4.5 m × 4.5 m, 30 m × 30 m
2	ZH	Zone height	2.4 m, 3.0 m, 6 m
3	NW	No. exterior walls	1,2,3,4,0
4	IS	Interior shade	100%, 50%, 0%
5	FN	Furniture	With, without
6	EC	Exterior wall construction	1,2,3,4 (**Error! Reference source not found.**)
7	PT	Partition type	16 mm gypsum board-air space 16 mm gypsum board 20 mm concrete block
8	ZL	Zone location	Single story, top floor, bottom floor, mid-floor
9	MF	Mid-floor type	200 mm concrete, 65 mm concrete, 25 mm wood
10	ST	Slab type	Mid-floor type, 100 mm slab on 300 mm soil
11	CT	Ceiling type	19 mm acoustic tile and air space, w/o ceiling
12	RT	Roof type	1,2,3,4
13	FC	Floor covering	Carpet with rubber pad, vinyl tile
14	GL	Glass percent	10,50,90

Table F.15: Exterior Wall Construction Types (Adapted from ASHRAE, 1997)

Type	Descriptions
1	Outside surface resistance, 25 mm stucco, 25 mm insulation, 19 mm plaster or gypsum, inside surface resistance (A0, A1, B1, E1, E0)
2	Outside surface resistance, 25 mm stucco, 200 mm HW concrete, 19 mm plaster or gypsum, inside surface resistance (A0, A1, C10, E1, E0)
3	Outside surface resistance, steel sliding, 75 mm insulation, steel siding, inside surface (A0, A3, B12, A3, E0)
4	Outside surface resistance, 100 mm face brick, 75 mm insulation, 300 mm HW concrete, 19 mm plaster or gypsum, inside surface resistance (A0, A2, B3, C11, E1, E0)

Table F.16: Floor and Ceiling Types by Zone Location Parameter (Adapted from ASHRAE, 1997)

Zone Location	Floor	Ceiling
Single story	Slab-on-grade	Roof
Top floor	Mid-floor	Roof
Bottom floor	Slab-on-grade	Mid-floor
Mid-floor	Mid-floor	Mid-floor

Table F.17: Roof Construction Types (Adapted from ASHRAE, 1997)

Type	Descriptions
1	Outside surface resistance, 13 mm slag or stone, 10 mm felt membrane, 25 mm insulation, steel siding, inside resistance (A0, E2, E3, B4, A3, E0)
2	Outside surface resistance, 13 mm slag or stone, 10 mm felt membrane, 150 mm LW concrete, inside resistance (A0, E2, E3, C15, E0)
3	Outside surface resistance, 13 mm slag or stone, 10 mm felt membrane, 50 mm insulation, steel siding, ceiling air space, acoustic tile, inside resistance (A0, E2, E3, B6, A3,E4, E5, E0)
4	Outside surface resistance, 13 mm slag or stone, 10 mm felt membrane, 200 mm LW concrete, ceiling air space, acoustic tile, inside resistance (A0, E2, E3, C16,E4, E5, E0)

Figure F.2 shows the user interface of the software TFMTAB. By entering the selected parameters, the program will return the Weighting Factors that can be used to convert solar, conduction, and internal heat gains. Inserting all Weighting factors to Equation (F.2) allows for the cooling loads to be determined. It is important to note that several days of calculations with the exact same outside and inside conditions are needed in order to achieve steady results since the cooling load equation involves the history terms.

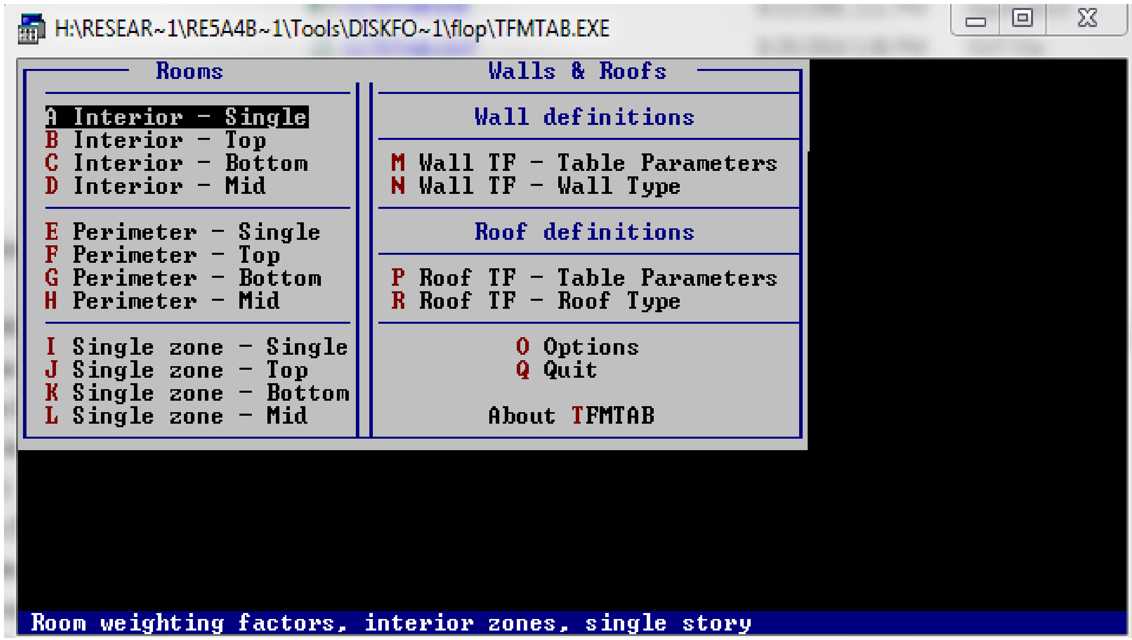


Figure F.2: Software user Interface

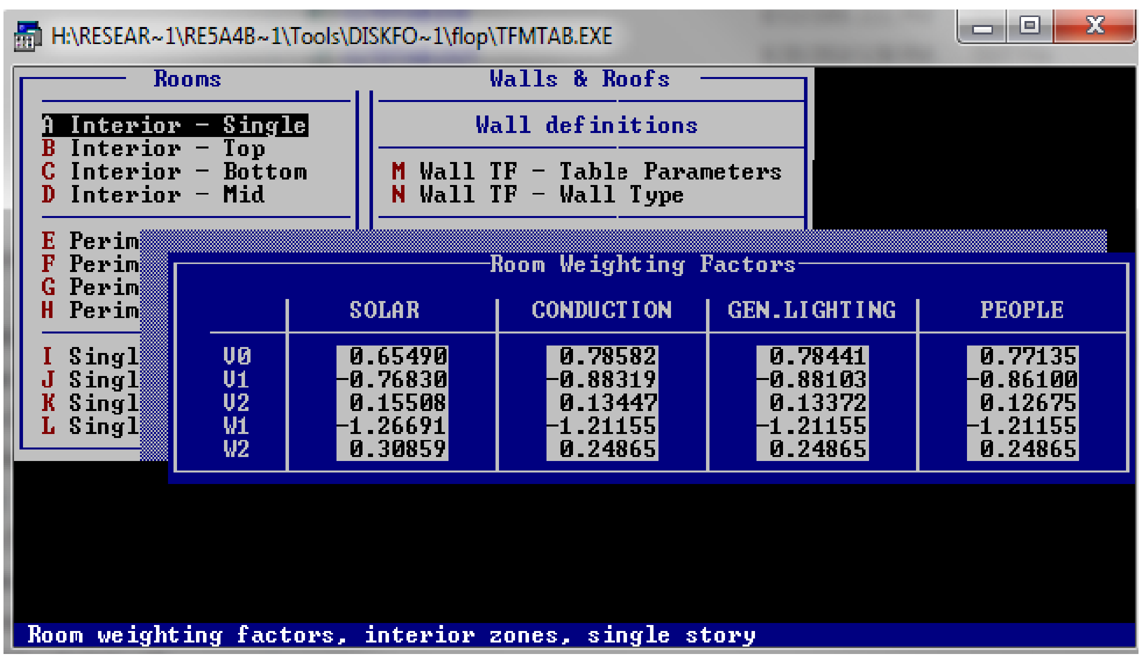


Figure F.3: Weighting Factor Results

APPENDIX G

TOTAL EQUIVALENT TEMPERATURE DIFFERENCE/TIME AVERAGING METHOD (TETD/TA)

This section details the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) Method for peak cooling load calculations. Figure G.1 shows an overview of this method (McQuiston and Spitler, 1992). Similar to the RTSM and the TFM, this method uses the sol-air temperature concept. When calculating the conduction heat gains through the walls and roofs, the Total Equivalent Temperature Difference (TETD) is used. The fenestration model 1 is used for calculating the fenestration heat gains. Once all heat gains are obtained, the radiative and convective portions are determined, using the same procedure as RTSM. All the convective heat gains directly become the cooling load. However, the radiative portions need a Time Averaging (TA) process to achieve the final cooling load.

G.1 Exterior Conduction Heat Gains

The sol-air temperature can be calculated by Equation (B.30) using the solar intensities detailed in Appendix B. The TETD is formulated by (ASHRAE, 1997),

$$TETD = t_{ea} - t_i + DF(t_{e,TL} - t_{ea}) \qquad \text{(G.1)}$$

where,

t_{ea} : daily average sol-air temperature, °C;

t_i : indoor air temperature, °C;

DF : decrement factor, dimensionless;

$t_{e,TL}$: sol-air temperature at time lag (TL) hours ago, °C.

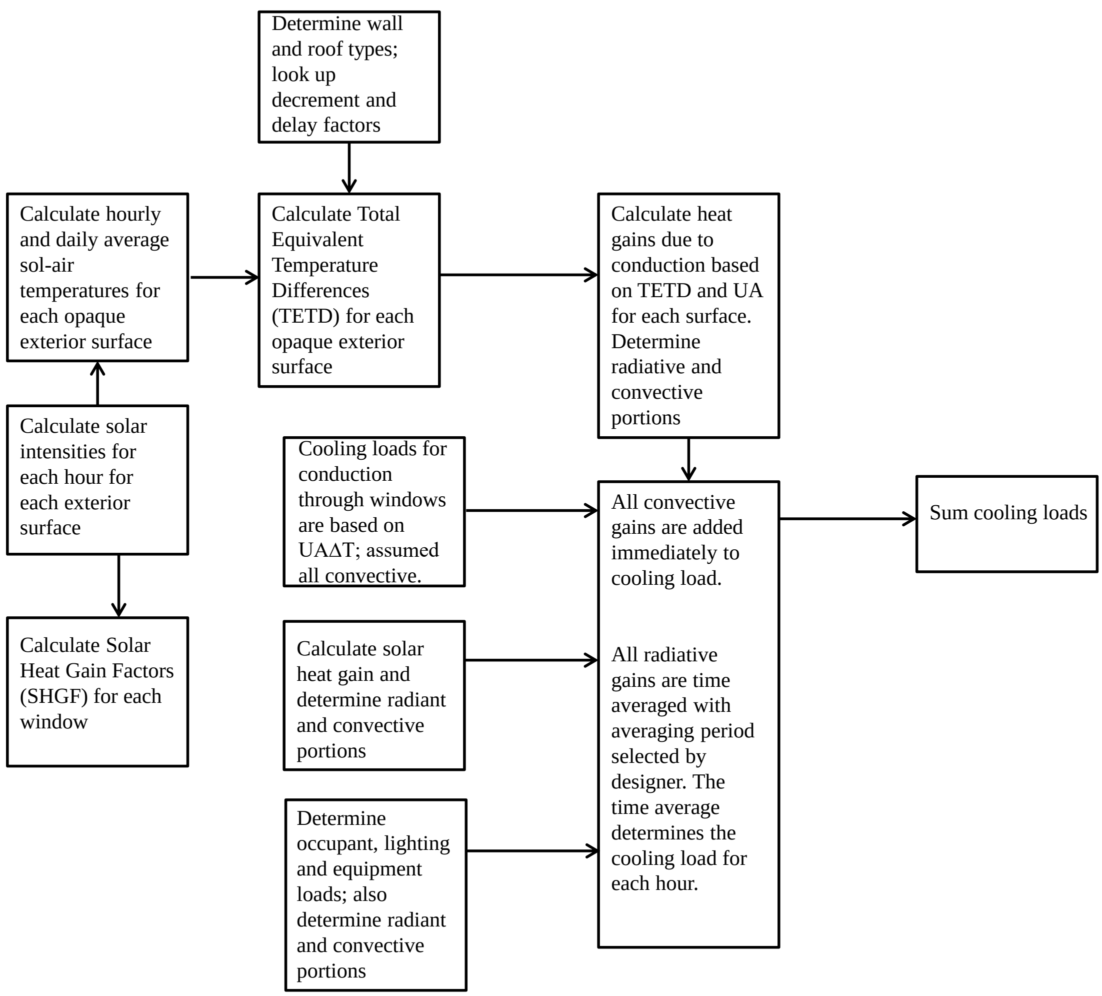


Figure G.1: Overview of TETD Method (Adapted from McQuiston and Spitler, 1992)

And,

$$t_{ea} = \sum_{i=1}^{24} t_{e,i} / 24 \tag{G.2}$$

where,

$t_{e,i}$: sol-air temperature for hour i, °C.

Following the same steps shown in Appendix F determines the wall and roof numbers. Once the group numbers are determined, the decrement factor (DF) and time lag (TL) can be obtained by using Table F.11 and Table F.13 for the walls and roofs, respectively.

Then, the conduction heat gains through walls and roofs can be calculated by (ASHRAE, 1997),

$$q = UA(TETD) \tag{G.3}$$

where,

U : overall heat transfer coefficient, W/m^2-K;

A : surface area, m^2.

G.2 Fenestration Solar Heat Gains

Fenestration model 1 is used in this method. However, in this method there is no necessary to differentiate between the transmitted and absorbed solar heat gains, since only total solar heat gain matters (see Appendix C).

G.3 Other Heat Gains

In this method, other heat gains include interior partition conduction heat gains, ceiling conduction heat gains, floor conduction heat gains (if any), internal heat gains, and infiltration heat gains. The calculation procedures for these other heat gains are the same as the ones of RTSM, shown in Equations (E.4)-(E.11) in Appendix E.

G.4 Cooling Load by Time Averaging Process

Similar to the RTSM, after obtaining all types of heat gains, the convective and radiative portions of heat gains need to be calculated using the most appropriate convective and radiative proportions of total heat gains. Table G.1 shows the percentages that were last updated by ASHRAE for TETD/TA Method. Later, when the RTSM was introduced, the updated percentages for the convective and radiative portions were recommended, shown in Table E.1 and Table E.2.

In the TETD/TA Method, all convective heat gains become cooling load directly, while all radiative heat gains need the Time Averaging (TA) process. The purpose of this is to account for the effects of the radiative heat gains from previous hours. However the TA process time period needs to be selected by the designers. Unfortunately, this tends to be a subjective decision that has a significant impact on the cooling load results. In general, normal selection of time period for commercial construction is three hours. This can vary from six to eight hours for a heavy construction (ASHRAE, 1993).

Table G.1: Convective and Radiative Percentages of Total Sensible Heat Gain for Hour Averaging Purposes (Adapted from ASHRAE, 1997)

Heat Gain Source	Radiant Heat, %	Convective Heat, %
Window solar, no inside shade	100	-
Window solar, with inside shade	58	42
Fluorescent lights	50	50
Incandescent lights	80	20
People	67	33
Transmission, external roofs and walls	60	40
Infiltration and ventilation	-	100
Machinery and appliances	20 to 80	80 to 20

APPENDIX H

COOLING LOAD TEMPERATURE DIFFERENCE/SOLAR COOLING LOAD/COOLING LOAD FACTOR METHOD (CLTD/SCL/CLF)

This section discusses the procedure for peak cooling load calculation by the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor Method (CLTD/SCL/CLF). As a one-step method, it relies on the CLTD, SCL, and CLF tables that are generated based on Transfer Function Method (TFM). Different from TFM, the principal material layers of walls and roofs are further regrouped. Varying on the months and locations, the CLTD, SCL, and CLF tables need to be provided for each latitude and month in order to perform calculations. The tabulated values are under the following conditions (ASHRAE, 1997):

- Dark surface;
- Indoor temperature constant at 25.5 °C;
- Outdoor maximum temperature of 35 °C, mean temperature 29.5 °C;
- Daily range of 11.6 °C;
- Clear sky on 21st day of the month;
- Outside surface film resistance of 0.059 (m^2-K/W);
- No ceiling plenum air return system;
- Inside surface resistance of 0.121 (m^2-K/W)

H.1 Cooling Load from Conduction Heat Gains

The conduction heat gains come from walls, roofs and fenestration. The cooling load is given by (ASHRAE, 1997),

$$q = UA(CLTD) \tag{H.1}$$

where,

U : overall heat transfer coefficient, W/m^2-K;

A : surface area, m^2;

$CLTD$: cooling load temperature difference for walls, roofs and windows, °C.

The tabulated $CLTD$ needs to be adjusted if the actual outdoor and indoor conditions do not match with the default conditions, which is calculated by (ASHRAE, 1997),

$$CLTD = CLTD_T + (25.5 - t_r) + (t_m - 29.4) \tag{H.2}$$

where,

$CLTD_T$: tabulated $CLTD$, °C;

t_r : indoor temperature, °C;

t_m : mean outdoor temperature, °C.

With given outdoor temperatures, mean temperature can be calculated by,

$$t_m = T_{o,\max} - DR/2 \tag{H.3}$$

where,

$T_{o,\max}$: maximum outdoor temperature, °C;

DR : daily range, °C;

Similar to TFM, the wall and roof group numbers need to be determined first in order to obtain tabulated CLTD values. The difference is that the wall and roof numbers are regrouped once again. Compared to forty-one wall and forty-two roof numbers, CLTD/SCL/CLF Method only has sixteen wall and ten roof numbers.

Table H.1 and Table H.2 are used to select proper wall and roof numbers. There are fifteen and four principal materials for walls and roofs, respectively. The column can be selected according to the principal material and the row number is up to R-value ranges in the proper secondary material section for walls and proper suspended ceiling category for roofs. The wall and roof numbers can be obtained by crosschecking the specific row and column numbers.

Given by the wall and roof numbers of the design case, the tabulated CLTD values can be obtained from Table H.3 and Table H.4. The wall CLTD values are generated for a specific latitude and design month. Table H.3 shows an example table of tabulated CLTD values for July and 40° N latitude. Only wall numbers 1 and 16 are presented in this table. The full table with 16 wall numbers can be found in 1997 ASHRAE Handbook of Fundamentals. The wall orientation finally determines the sets of tabulated CLTD values that need to be used. Ten roof numbers are available for roof tabulated CLTD value selections, shown in Table H.4. It is very important to note that the 24 hours represent the solar time instead of the local time. The cooling load can be time shifted if the wrong time is used. Finally, the tabulated CLTD values for glass are shown in Table H.5. Only one table is available for fenestration conduction cooling load calculation by neglecting the latitude and month effects.

After adjusting the tabulated CLTD values by using Equation (H.2), the cooling load from conduction heat gains can be calculated by using Equation (H.1). Not all the tabulated CLTD values are available. A tool named "CLTDTAB"[38] developed for the Cooling and Heating Load Calculation Manual (McQuiston and Spitler, 1992) can be used to generate the desired tables. Figure H.1 shows the user interface. By entering the desired latitude and moth number, the tabulated CLTD values for walls and roofs are generated, shown in Figure H.2. The program uses the linear interpolation for the latitudes other than 24, 36, and 48 North. Even though the tables only reflect the 21st day of each month, they are valid and suffice for the period of two weeks from the 21st (McQuiston and Spitler, 1992).

Table H.1: Wall Group Numbers for Mass-In Case with Secondary Material of Stucco and/or Plaster[39] (Adapted from ASHRAE, 1997)

R-Factor (m^2-K/W)	Principal Wall Material														
	A1	**A2**	**B7**	**B10**	**B9**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C17**	**C18**
0.0-0.35															
0.35-0.44		5								5					
0.44-0.53		5				3		2	5	6			5		
0.53-0.62		5				4	2	2	5	6			6		
0.62-0.70		5				4	2	3	6	6	10	4	6		5
0.70-0.84		6				5	2	4	6	6	11	5	10		10
0.84-0.97		6				5	2	4	6	6	11	5	10		10
0.97-1.14		6				5	2	5	10	7	12	5	11		10
1.14-1.36		6				5	4	5	11	7	16	10	11		11
1.36-1.59		6				5	4	5	11	7		10	11		11
1.59-1.89		6				5	4	5	11	7		10	11	4	11
1.89-2.24		6				5	4	5	11	11		10	11	4	11
2.24-2.64		10				10	4	5	11	11		10	11	9	12
2.64-3.08		10				10	5	5	11	11		11	12	10	16
3.08-3.52		11				10	5	9	11	11		15	16	10	16
3.52-4.05		11				10	9	9	16	11		15	16	10	16
4.05-4.76												16		15	

[38] CLTDTAB.EXE only generated the tables with IP unit.
[39] This table only shows one kind of secondary material for walls with mass-in case. The full tables can be found in 1997 ASHRAE Handbook of Fundamentals on page 28.46.

Table H.2: Roof Group Numbers for Mass-In Case[40] (Adapted from ASHRAE, 1997)

Suspended Ceiling	R-Factor (m^2-K/W)	B7, Wood 25 mm	C12, HW Concrete 50 mm	A3, Steel Deck	Attic-Ceiling Combination
Without	0 to 0.9		2		
	0.9 to 1.8		2		
	1.8 to 2.6		4		
	2.6 to 3.5		4		
	3.5 to 4.4		5		
	4.4 to 5.3				
With	0 to 0.9		5		
	0.9 to 1.8		8		
	1.8 to 2.6		13		
	2.6 to 3.5		13		
	3.5 to 4.4		14		
	4.4 to 5.3				

Table H.3: July Wall CLTD Values for 40° N Latitude[41] (Adapted from ASHRAE, 1997)

Wall No.1, Solar Time, hr																								
Wall Face	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
N	1	0	-1	-1	-2	-1	4	6	6	7	9	12	14	15	16	16	16	16	15	9	6	4	3	2
NE	1	0	-1	-1	-2	1	13	23	26	24	19	16	15	16	16	16	15	13	11	8	6	4	3	2
E	1	0	-1	-1	-1	1	16	28	34	36	33	27	20	17	17	17	16	14	11	8	6	4	3	2
SE	1	0	-1	-1	-2	0	8	18	26	31	32	31	27	22	18	17	16	14	11	8	6	4	3	2
S	1	0	-1	-1	-2	-1	0	2	6	12	18	24	28	29	28	24	19	15	11	8	6	4	3	2
SW	1	0	-1	-1	-1	-1	0	2	4	7	9	14	22	29	36	39	38	34	25	13	7	4	3	2
W	1	1	-1	-1	-1	-1	1	2	4	7	9	12	15	23	33	41	44	44	34	18	9	5	3	2
NW	1	0	-1	-1	-1	-1	0	2	4	7	9	12	14	16	21	28	34	36	31	16	8	5	3	2
●					●												●							
●					●												●							
●					●												●							
Wall No.16, Solar Time, hr																								
Wall Face	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
N	10	9	9	8	7	6	6	5	4	4	4	4	4	5	6	6	7	8	9	9	10	11	11	11
NE	12	11	10	9	8	7	6	6	6	6	7	8	9	11	12	12	13	13	13	14	14	13	13	13
E	14	13	12	11	9	8	7	6	6	7	8	11	12	14	16	17	17	17	18	18	17	17	16	15
SE	14	13	12	11	9	8	7	6	6	6	7	8	10	12	14	15	16	17	17	17	17	17	16	15
S	13	12	11	10	9	8	7	6	5	4	4	4	5	6	8	9	11	13	14	15	15	15	15	14
SW	18	17	16	14	13	11	10	8	7	7	6	6	6	6	7	8	10	12	15	17	18	19	19	19
W	20	18	17	16	14	12	11	9	8	7	7	6	6	6	7	8	9	11	14	17	19	21	21	21
NW	16	15	14	13	11	10	9	8	7	6	6	5	5	6	6	7	8	9	11	13	15	16	17	17

[40] Full table that covers all mass locations can be found in 1997 ASHRAE Handbook of Fundamentals on page 28.42.
[41] The full table includes CLTD values for 16 wall numbers in 1997 ASHRAE Handbook of Fundamentals on page 28.43.

Table H.4: July Roof CLTD Values for 40° N Latitude[42] (Adapted from ASHRAE, 1997)

Roof No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	-1	-2	-3	-3	-3	0	7	16	25	33	41	46	49	49	46	41	33	24	14	8	5	3	1
2	1	0	-1	-2	-3	-3	-2	2	9	18	27	34	41	46	48	47	44	39	31	22	14	8	5	3
3	7	4	3	1	0	-1	0	3	7	13	19	26	32	37	40	41	41	37	33	27	21	17	13	9
●						●												●						
●						●												●						
●						●												●						
10	21	18	15	13	11	8	7	6	5	6	7	9	13	17	21	24	28	31	32	32	31	29	26	23
13	19	17	16	14	12	11	10	9	9	9	11	13	16	18	21	23	26	27	27	27	26	24	22	21
14	19	18	17	15	14	13	12	11	11	11	12	13	16	18	20	22	23	24	25	25	24	23	22	21

Table H.5: CLTD Values for Glass (Adapted from ASHRAE, 1997)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
CLTD, °C	1	0	-1	-1	-1	-1	-1	0	1	2	4	5	7	7	8	8	7	7	6	4	3	2	2	1

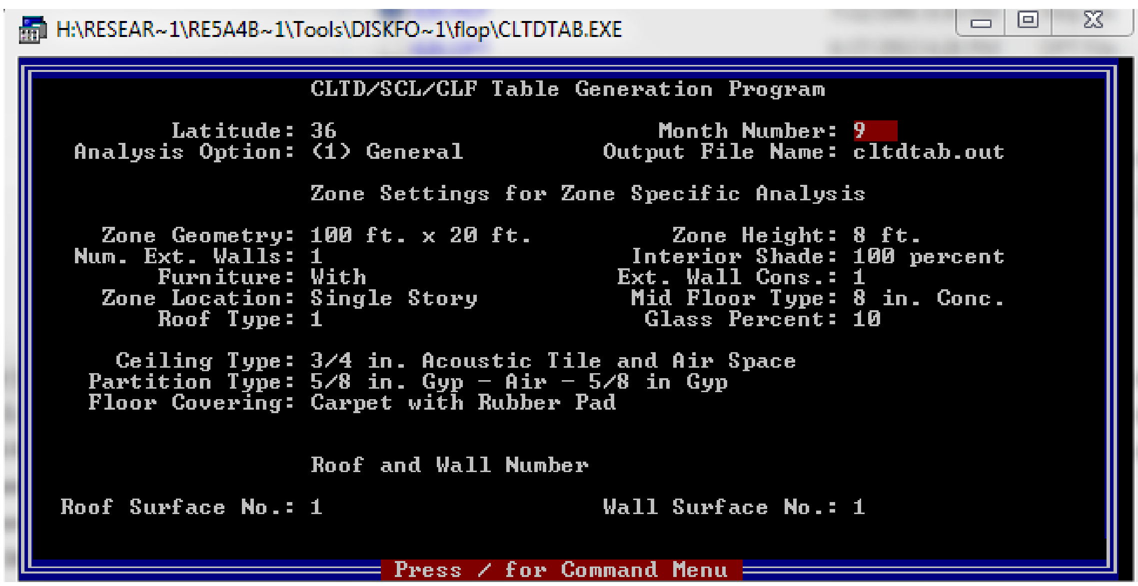
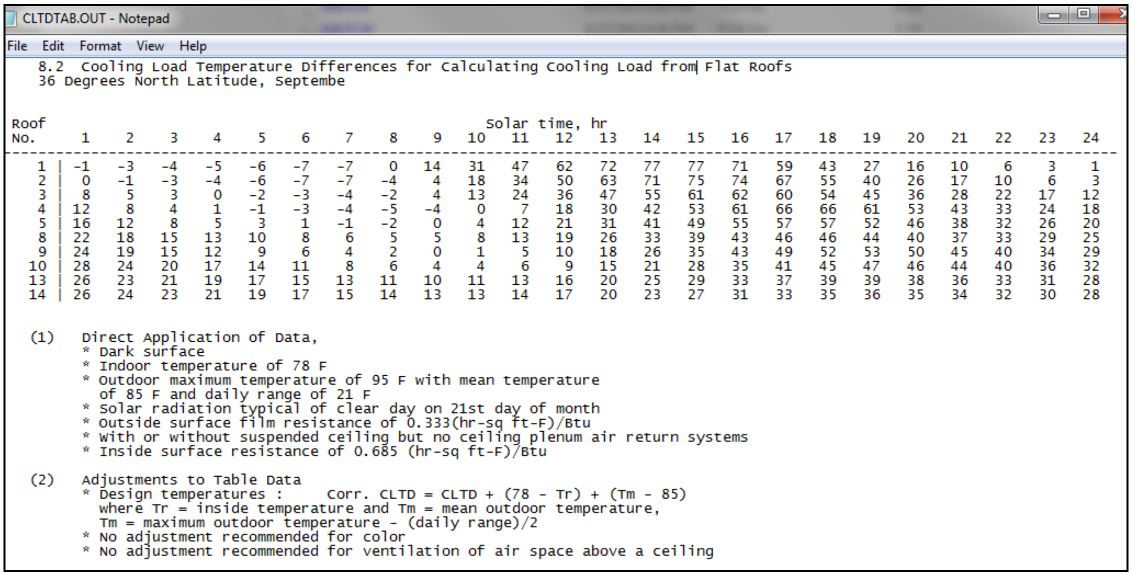


Figure H.1: CLTDTAB Program user Interface

[42] The full table includes CLTD values for 10 roof numbers in 1997 ASHRAE Handbook of Fundamentals on page 28.42.



CLTDTAB.OUT - Notepad

File Edit Format View Help

8.2 Cooling Load Temperature Differences for Calculating Cooling Load from Flat Roofs
36 Degrees North Latitude, Septembe

Roof No.	Solar time, hr 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	-1	-3	-4	-5	-6	-7	-7	0	14	31	47	62	72	77	77	71	59	43	27	16	10	6	3	1
2	0	-1	-3	-4	-6	-7	-7	-4	4	18	34	50	63	71	75	74	67	55	40	26	17	10	6	3
3	8	5	3	0	-2	-3	-4	-2	4	13	24	36	47	55	61	62	60	54	45	36	28	22	17	12
4	12	8	4	1	-1	-3	-4	-5	-4	0	7	18	30	42	53	61	66	66	61	53	43	33	24	18
5	16	12	8	5	3	1	-1	-2	0	4	12	21	31	41	49	55	57	57	52	46	38	32	26	20
8	22	18	15	13	10	8	6	5	5	8	13	19	26	33	39	43	46	46	44	40	37	33	29	25
9	24	19	15	12	9	6	4	2	0	1	5	10	18	26	35	43	49	52	53	50	45	40	34	29
10	28	24	20	17	14	11	8	6	4	4	6	9	15	21	28	35	41	45	47	46	44	40	36	32
13	26	23	21	19	17	15	13	11	10	11	13	16	20	25	29	33	37	39	39	38	36	33	31	28
14	26	24	23	21	19	17	15	14	13	13	14	17	20	23	27	31	33	35	36	35	34	32	30	28

```
(1)   Direct Application of Data,
      * Dark surface
      * Indoor temperature of 78 F
      * Outdoor maximum temperature of 95 F with mean temperature
        of 85 F and daily range of 21 F
      * Solar radiation typical of clear day on 21st day of month
      * Outside surface film resistance of 0.333(hr-sq ft-F)/Btu
      * With or without suspended ceiling but no ceiling plenum air return systems
      * Inside surface resistance of 0.685 (hr-sq ft-F)/Btu

(2)   Adjustments to Table Data
      * Design temperatures :     Corr. CLTD = CLTD + (78 - Tr) + (Tm - 85)
        where Tr = inside temperature and Tm = mean outdoor temperature,
        Tm = maximum outdoor temperature - (daily range)/2
      * No adjustment recommended for color
      * No adjustment recommended for ventilation of air space above a ceiling
```

Figure H.2: CLTDTAB.OUT

H.2 Cooling Load through Fenestration

The Solar Cooling Load (SCL) and Shading Coefficient (SC) are used to calculate space cooling load through the fenestration, which is given by (ASHRAE, 1997),

$$q = A(SC)(SCL) \tag{H.4}$$

where,

A : window surface area, m^2;

SC : shading coefficient, dimensionless;

SCL : solar cooling load, W/m^2;

SC can be calculated by,

$$SC = \frac{SHGC}{0.87} \tag{H.5}$$

where,

$SHGC$: normal solar heat gain coefficient of fenestration, dimensionless;

0.87 : normal solar heat gain coefficient for single-pane, double-strength, clear glass, dimensionless;

Equation (H.4) uses SC instead of SHGC, which means the Fenestration Model 1 is implemented in CLTD/SCL/CLF Method (see Appendix C).

Before using SCL tables, zone types need to first be determined. Four zone types are available: zone type A, zone type B, zone type C, and zone type D. Four zone parameters are involved to define a zone type: 1) number of exterior walls; 2) floor covering; 3) partition type; 4) and inside shade. Similar to the TFM, the zone parameters are limited and cannot cover all the actual design cases. Therefore, the users need to pick the best fit. Table H.6 shows the zone types for glass solar, people & equipment, and lights. Table H.7 shows the tabulated hourly SCL values for sunlit glass in July for 40° N Latitude. The hours still mean the solar hours, not the local hours. For a specific latitude, CLTDTAB could be used to generate the desired tables, shown in Section H.1.

Table H.6: Zone Types for SCL and CLF Tables, Single-Story Building [43](Adapted from ASHRAE, 1997)

Zone Parameters				Zone Types			Error Band	
No. Walls	**Floor Covering**	**Partition Type**	**Inside Shade**	**Glass Solar**	**People and Equipment**	**Lights**	**Plus**	**Minus**
1 or 2	Carpet	Gypsum	Negligible	A	B	B	9	2
1 or 2	Carpet	Concrete block	Negligible	B	C	C	9	0
	•				•		•	
	•				•		•	
	•				•		•	
4	Vinyl	Gypsum	Full	B	C	C	11	6
4	Vinyl	Gypsum	Half to None	C	C	C	19	-1

Table H.7: July SCL for Sunlit Glass for 40° N Latitude [44] (Adapted from ASHRAE, 1997)

	Zone Type A , Solar Time, hr																					
Glass Face	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
N	0	0	0	0	3	79	85	88	101	110	120	126	126	123	113	98	98	113	38	19	9	3
NE	0	0	0	0	6	268	406	422	353	236	173	151	139	126	117	101	82	57	22	9	6	3
E	0	0	0	0	6	293	495	583	576	485	334	211	167	142	123	104	82	57	22	9	6	3
SE	0	0	0	0	3	148	299	413	473	473	413	306	198	154	129	107	85	57	22	9	6	3
S	0	0	0	0	0	28	54	79	129	202	268	306	302	265	198	132	98	63	25	13	6	3
SW	0	0	0	0	0	28	54	76	95	110	123	202	318	419	476	479	419	293	110	54	25	13
W	3	0	0	0	0	28	54	76	95	110	120	126	205	359	498	589	605	491	180	85	41	19
NW	3	0	0	0	0	28	54	76	95	110	120	126	126	158	265	381	450	410	145	69	35	16
Hor	0	0	0	0	0	76	217	378	532	665	759	810	816	772	684	554	394	221	91	44	22	9

H.3 Cooling Load from Partitions, Ceilings, and Floors

The calculations remain the same as Equation (E.4) in Appendix E.

H.4 Internal Cooling Load

For occupants,

$$q_s = q_{s,per}\, N\,(CLF) \tag{H.6}$$

[43] This table only contain a partial content. The full table can be found in 1997 ASHRAE Handbook of Fundamentals on page 28.49.
[44] The full table includes SCL values for four zone types in 1997 ASHRAE Handbook of Fundamentals on page 28.50.

$$q_l = q_{l,per}\, N \tag{H.7}$$

where,

q_s : occup1ant sensible heat gain, W;

q_l : occupant latent heat gain, W;

$q_{s,per}$: sensible heat gain per person W/person;

$q_{l,per}$: latent heat gain per person, W/person;

N : number of occupants;

CLF : cooling load factor, dimensionless.

For lights,

$$q_{el} = W\, F_{ul}\, F_{sa}\, (CLF) \tag{H.8}$$

where,

q_{el} : lighting heat gain, W;

W : total light wattage, W;

F_{ul} : lighting use factor;

F_{sa} : lighting special allowance factor;

CLF : cooling load factor, dimensionless.

For powers,

$$q_{em} = P\, E_F\, (CLF) \tag{H.9}$$

where,

P : motor power rating, W;

E_F : efficiency factors and arrangements to suit circumstances;

CLF : cooling load factor, dimensionless;

For appliances,

$$q_s = q_{input} F_U F_R (CLF) \tag{H.10}$$

where,

q_s : sensible heat gain, W;

q_{input} : nameplate or rated energy input, W;

F_U : usage factor;

F_R : radiation factor;

CLF : cooling load factor, dimensionless.

Table H.8 shows an example CLFs table for people and unhood equipment. Similar CLFs tables can be found in 1993 ASHRAE Handbook of Fundamentals for lights and hooded equipment.

H.5 Cooling Load from Ventilation and Infiltration Air

The calculations remain the same as Equations (E. 10) and (E.11) in Appendix E.

Table H.8: CLFs for People and Unhood Equipment [45] (Adapted from ASHRAE, 1997)

	Zone Type A , No. of Hours after Entry into Space or Equipment Turned on, hr																							
Hrs in Space	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
2	0.75	0.88	0.18	0.08	0.04	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.75	0.88	0.93	0.95	0.22	0.10	0.05	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.75	0.88	0.93	0.95	0.97	0.97	0.33	0.11	0.06	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.75	0.88	0.93	0.95	0.97	0.97	0.98	0.98	0.24	0.11	0.06	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
10	0.75	0.88	0.93	0.95	0.97	0.97	0.98	0.98	0.99	0.99	0.24	0.12	0.07	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00
12	0.75	0.88	0.93	0.96	0.97	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.25	0.12	0.07	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01
14	0.76	0.88	0.93	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	1.00	1.00	0.25	0.12	0.07	0.05	0.03	0.03	0.02	0.02	0.01	0.01
16	0.76	0.89	0.94	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	0.25	0.12	0.07	0.05	0.03	0.03	0.02	0.02
18	0.77	0.89	0.94	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.25	0.12	0.07	0.05	0.03	0.03

[45] The full table includes SCL values for four zone types in 1997 ASHRAE Handbook of Fundamentals in page 28.51.

APPENDIX I

SENSIBLE COOLING LOAD COMPARISON RESULTS FOR ADDITIONAL CASE-STUDY COMPARISONS

This appendix presents the space sensible cooling load comparisons of the HBM, the RTSM, the TFM, the TETD/TA Method, and the CLTD/SCL/CLF Method for both the heavy-weight and light-weight building cases, shown in Figure I.1 to Figure I.30. Each set of comparison includes the cooling load estimations from the five methods as well as the cooling load difference respectively to the HBM and weather conditions. The test cases are shown in Table I.1 and a detailed discussion of the results is provided in Section 4.3.

Table I.1: Test Case Descriptions

Test Case No.	Glazing Type	U-Value (W/m^2-K)	Normal SHGC	Each Window % to Respective Wall	Overall WWR	Overall WFR	South Window Area (m^2)	West Window Area (m^2)
Base Case	Single Pane Clear	4.65	0.86	58%	29%	96%	6.45	6.45
TC1	Single Pane Clear	4.65	0.86	10%	5%	17%	1.12	1.12
TC2				30%	15%	50%	3.35	3.35
TC3				50%	25%	83%	5.58	5.58
TC4	Double Pane Clear	2.73	0.76	10%	5%	17%	1.12	1.12
TC5				30%	15%	50%	3.35	3.35
TC6				50%	25%	83%	5.58	5.58
TC7	Double Pane Low-e	1.99	0.70	10%	5%	17%	1.12	1.12
TC8				30%	15%	50%	3.35	3.35
TC9				50%	25%	83%	5.58	5.58
TC10	Triple Pane Clear	1.76	0.68	10%	5%	17%	1.12	1.12
TC11				30%	15%	50%	3.35	3.35
TC12				50%	25%	83%	5.58	5.58
TC13	Triple Pane Low-e	1.87	0.62	10%	5%	17%	1.12	1.12
TC14				30%	15%	50%	3.35	3.35
TC15				50%	25%	83%	5.58	5.58

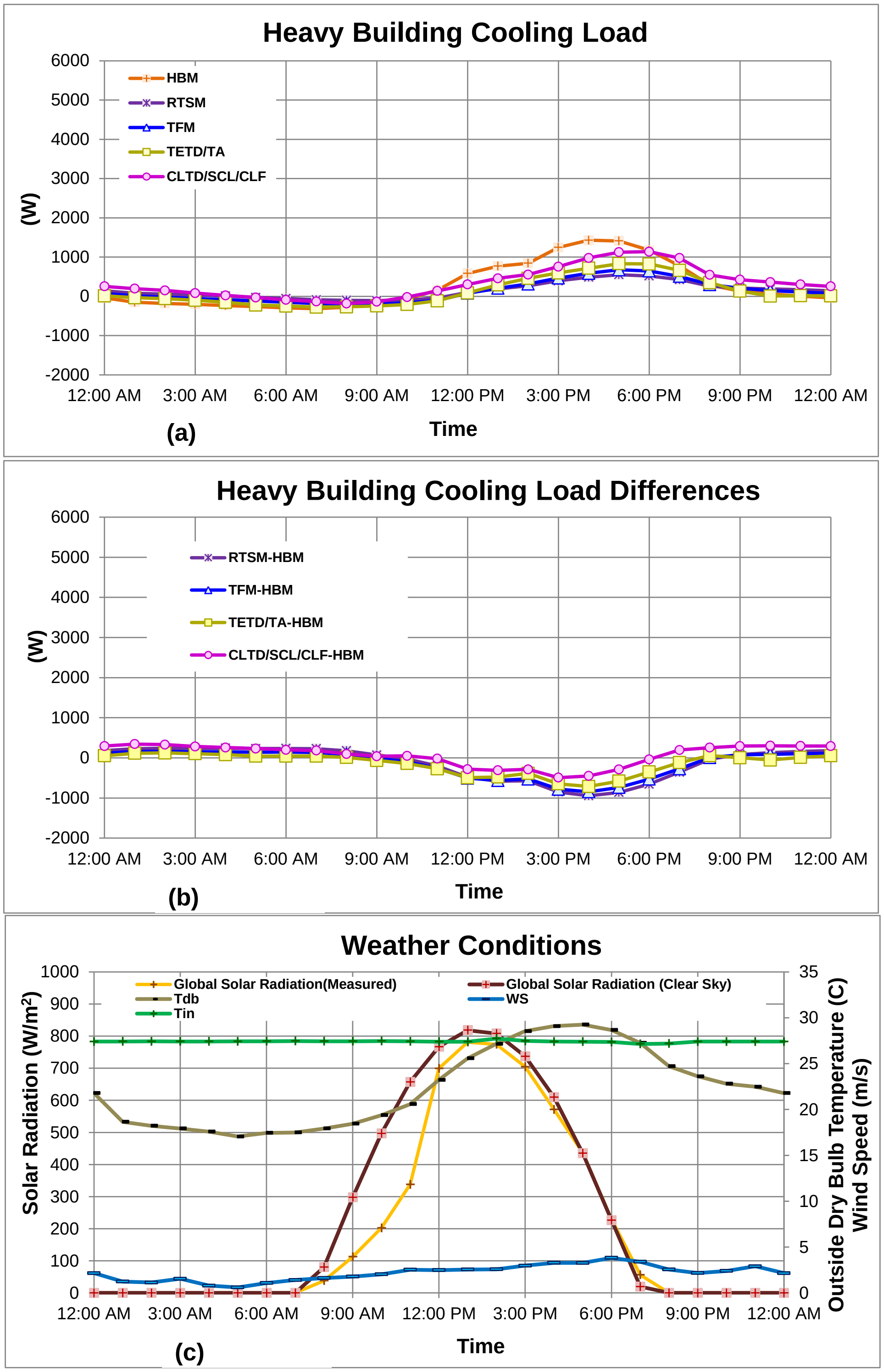


Figure I.1: TC 1 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

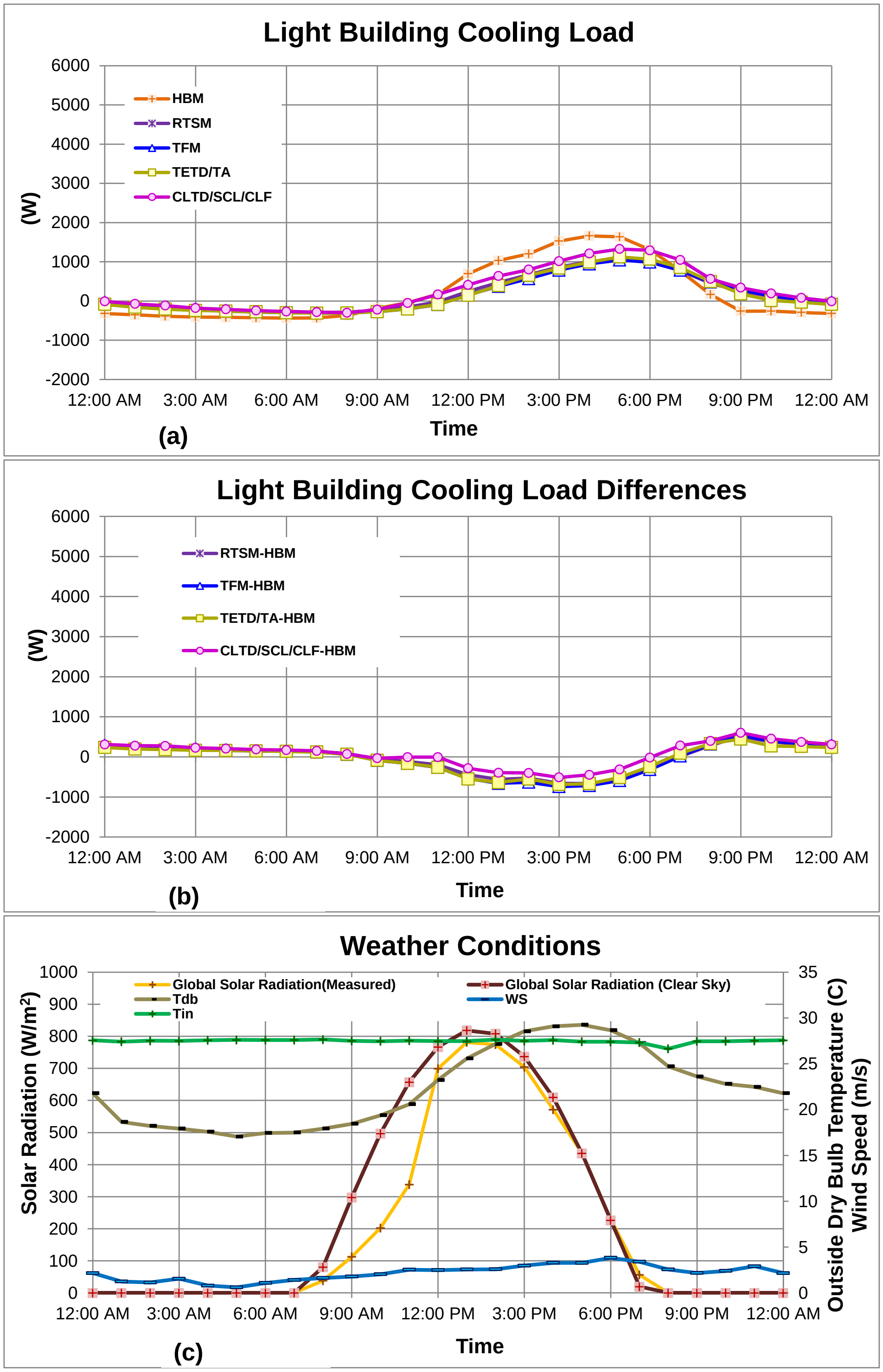


Figure I.2: TC 1 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

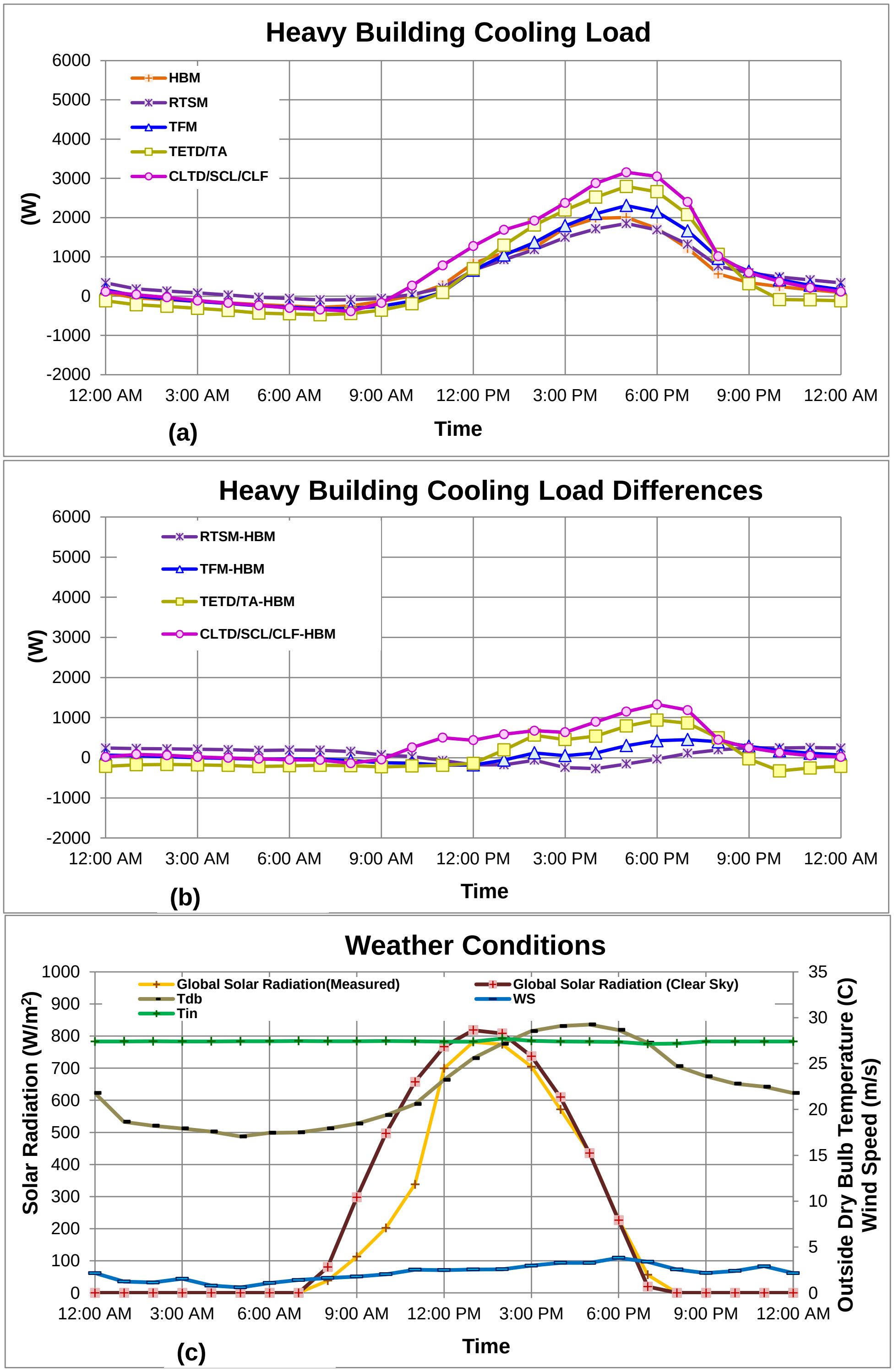


Figure I.3: TC 2 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

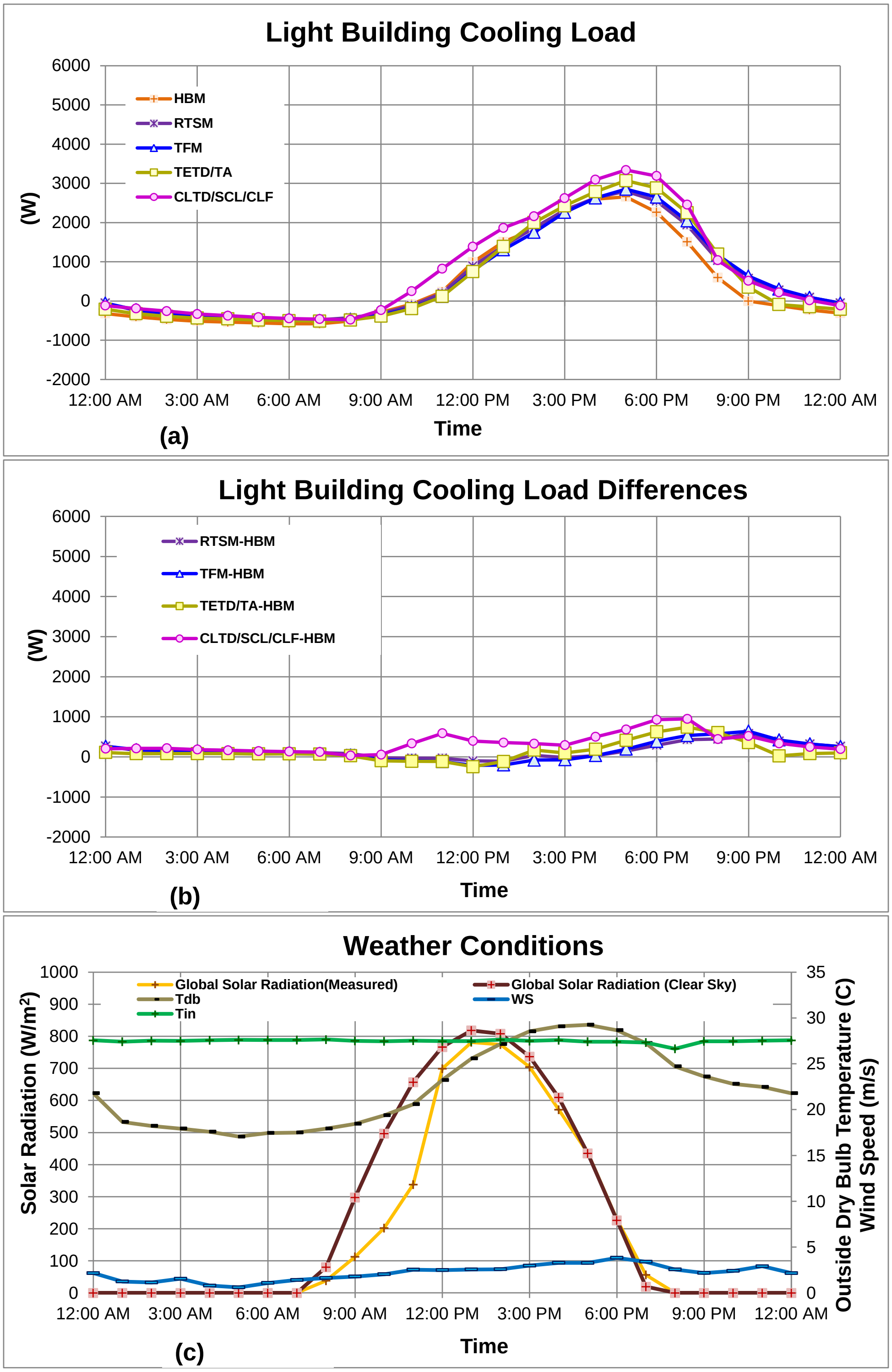


Figure I.4: TC 2 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

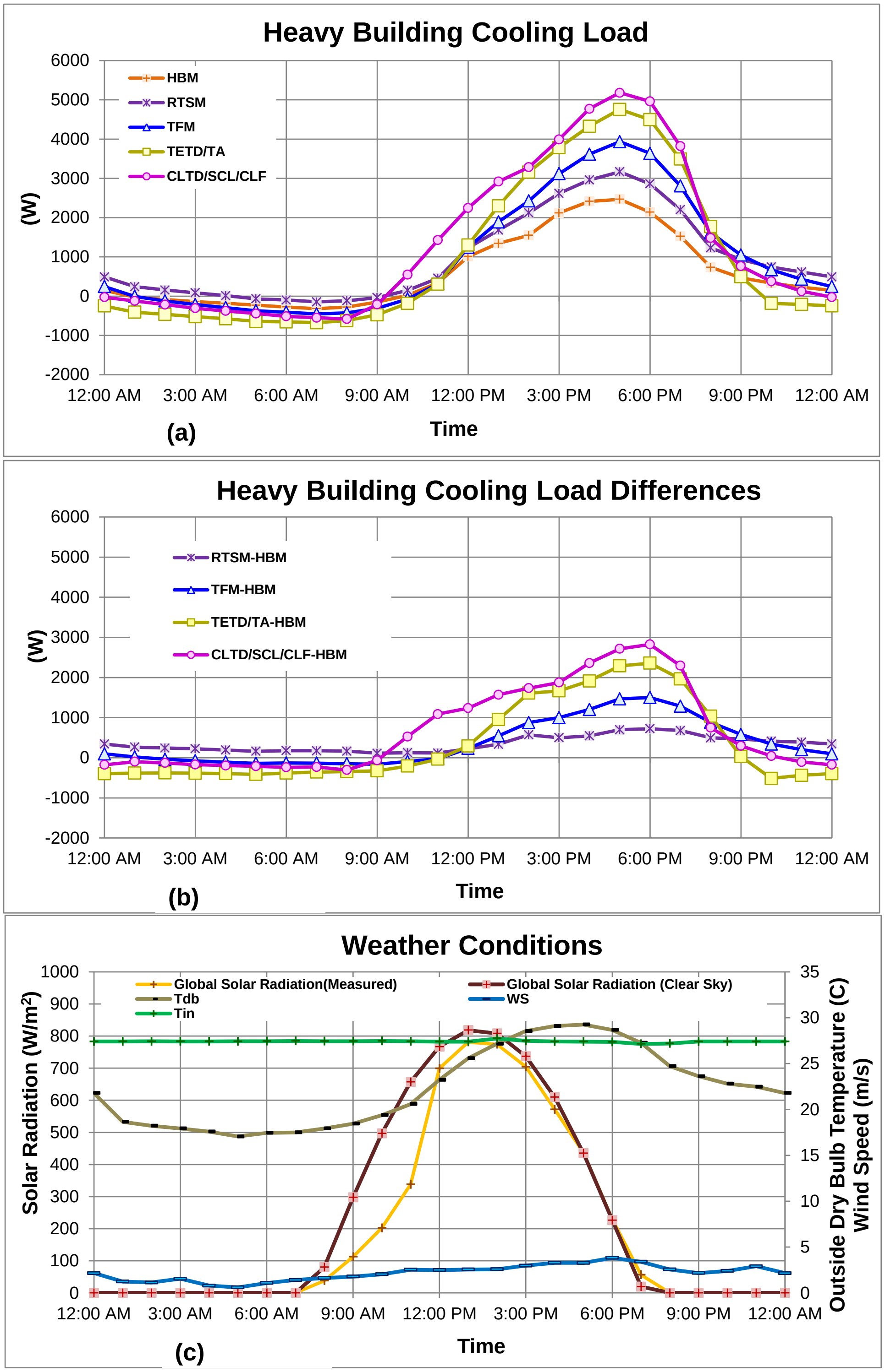


Figure I.5: TC 3 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

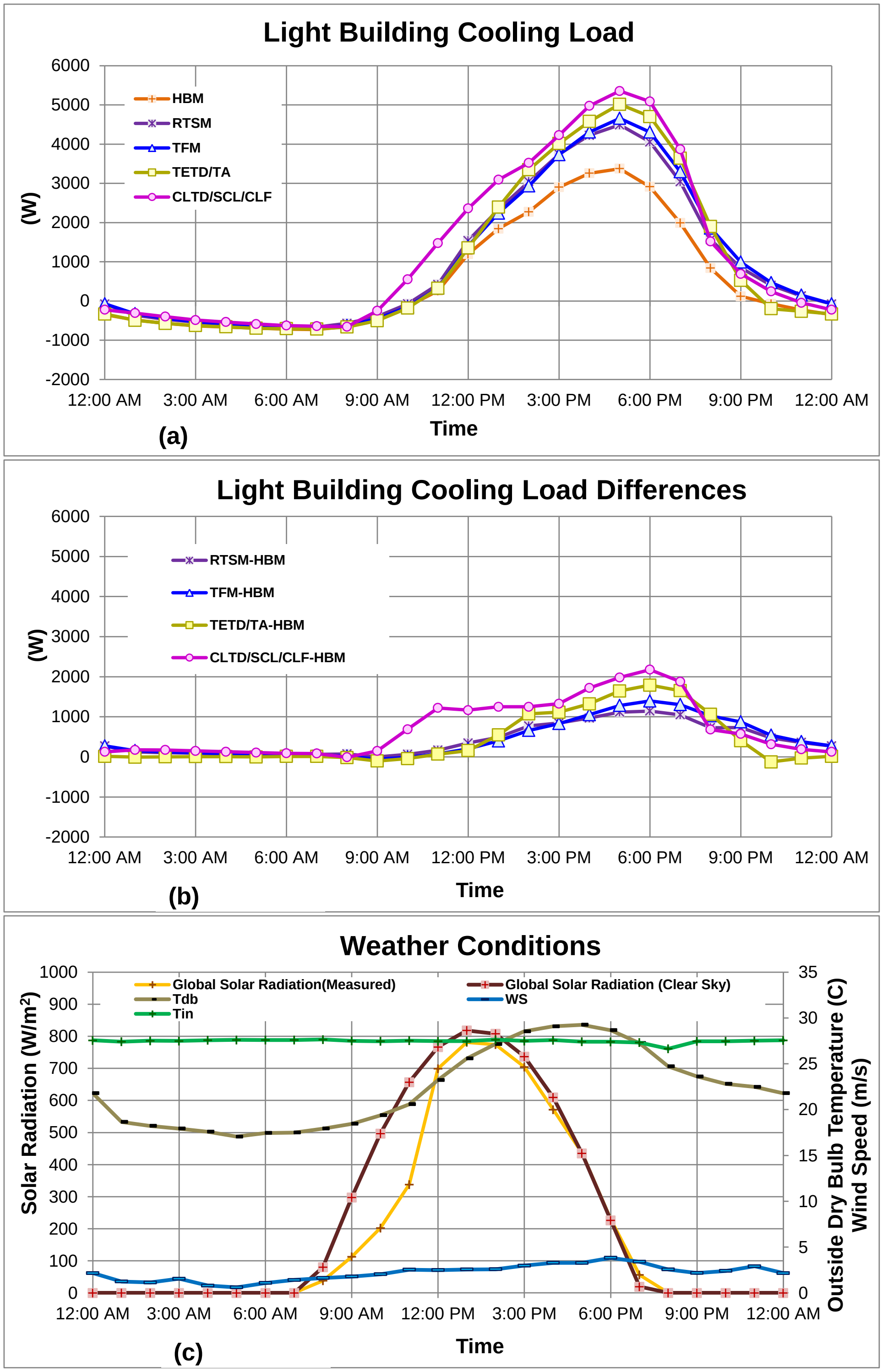


Figure I.6: TC 3 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

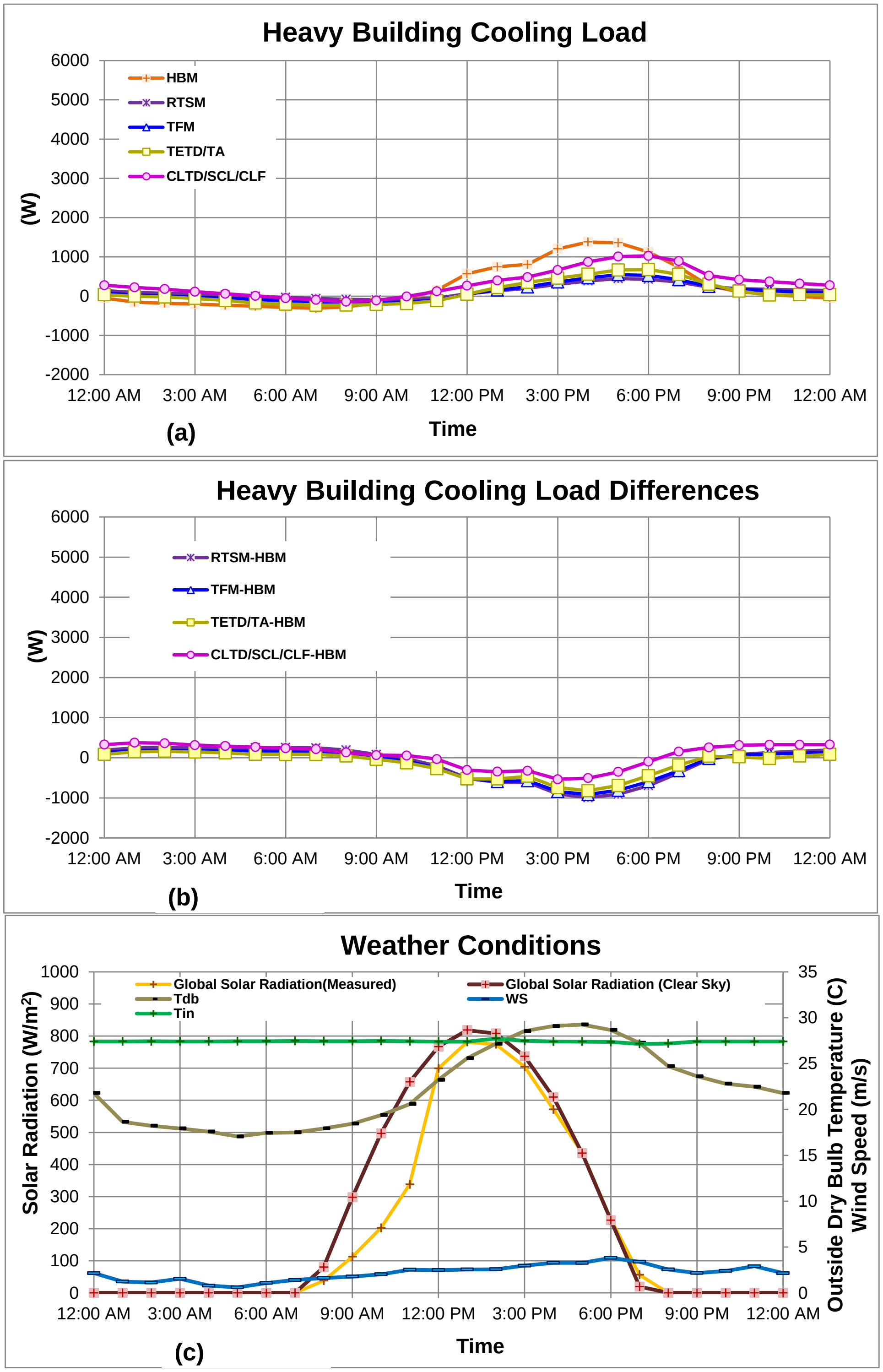


Figure I.7: TC 4 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

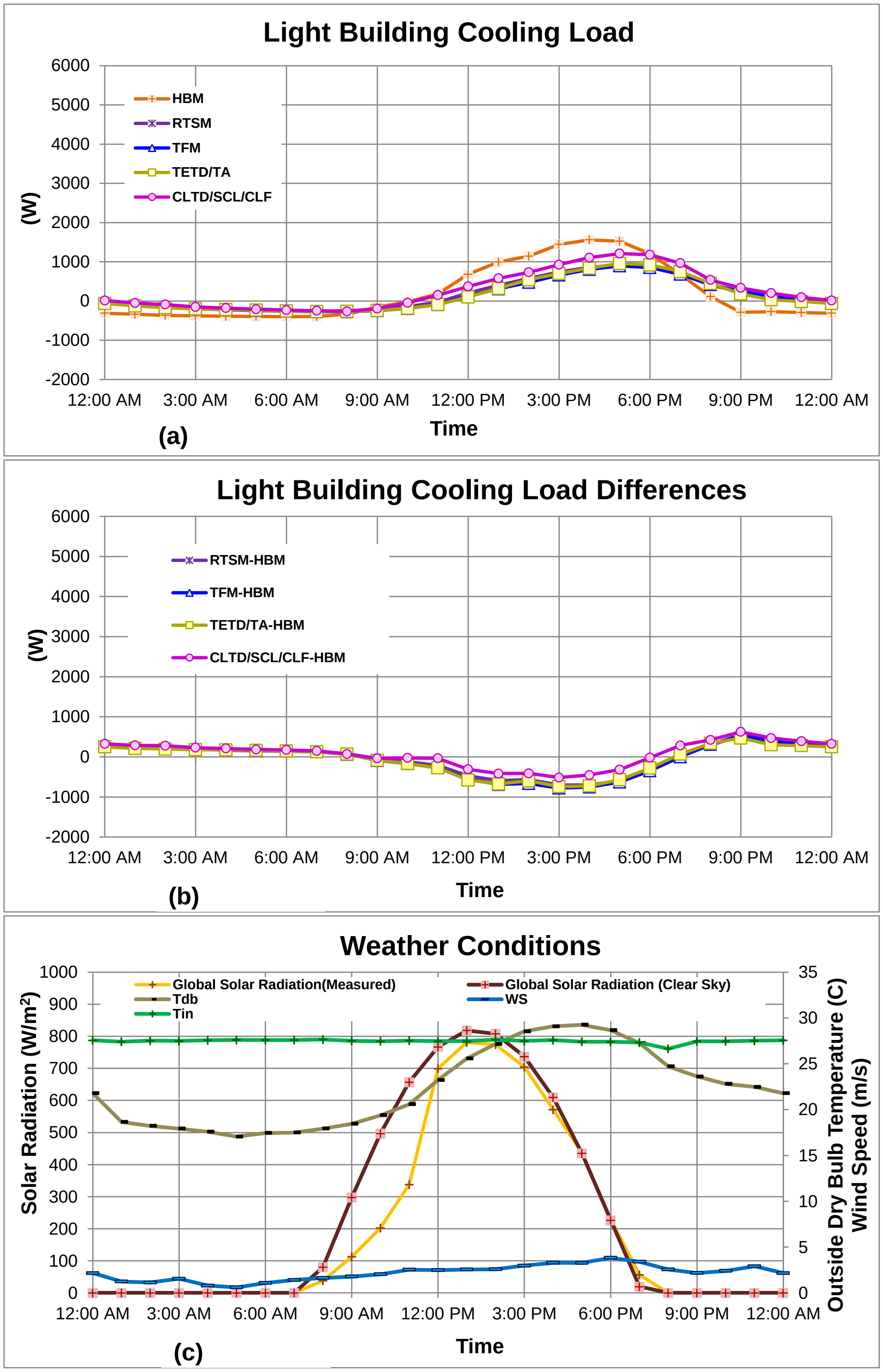


Figure I.8: TC 4 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

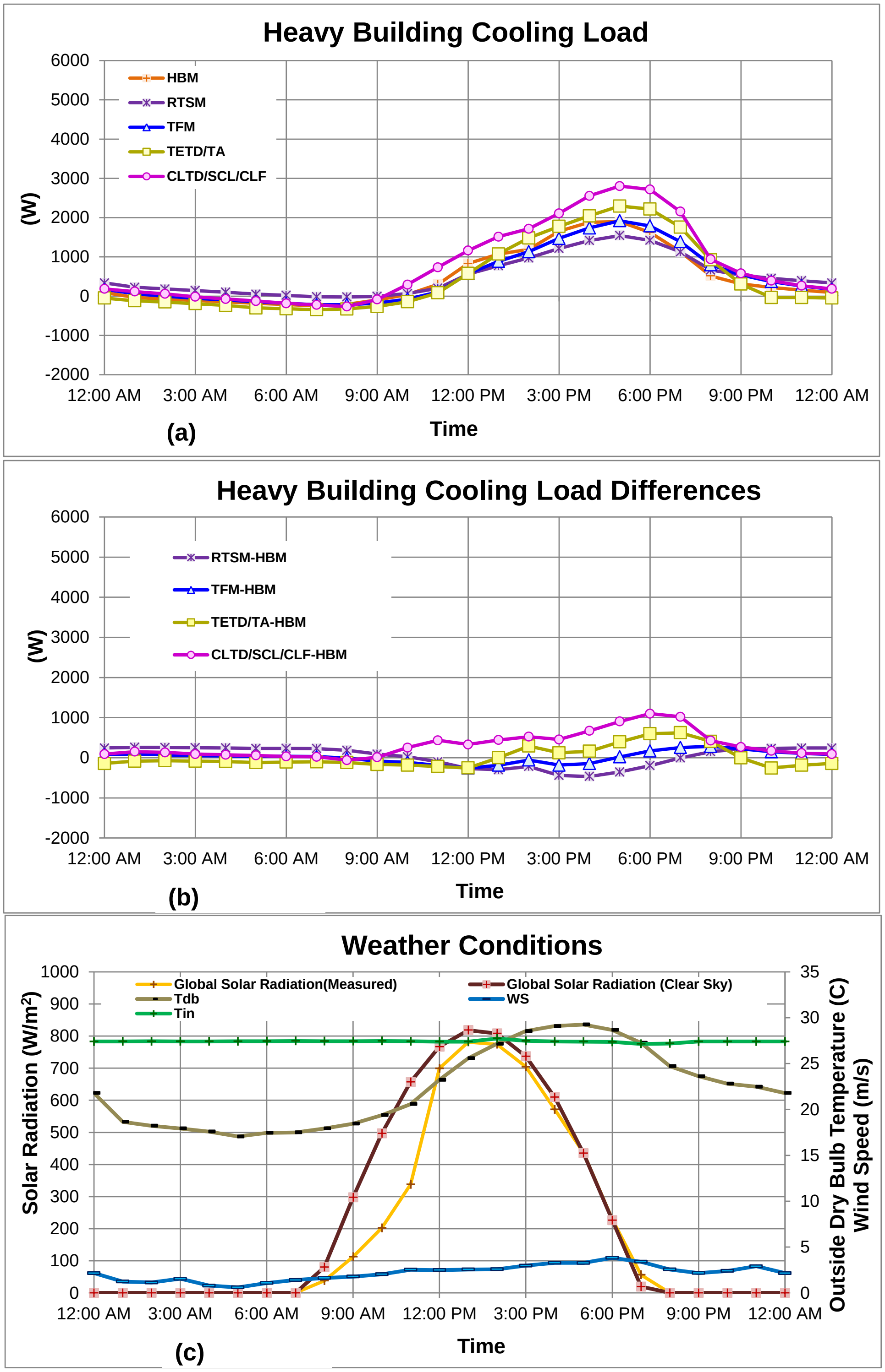


Figure I.9: TC 5 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

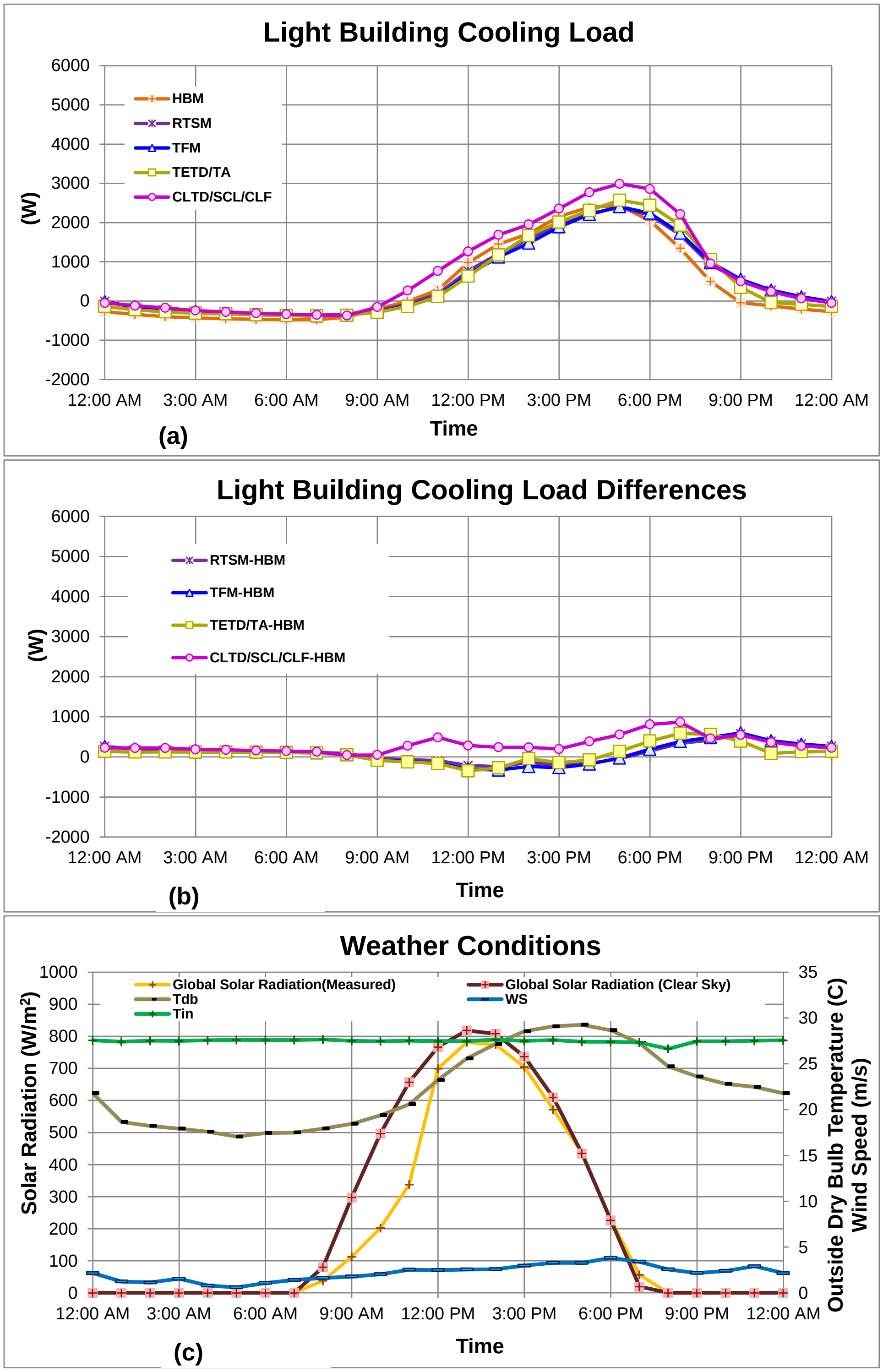


Figure I.10: TC 5 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

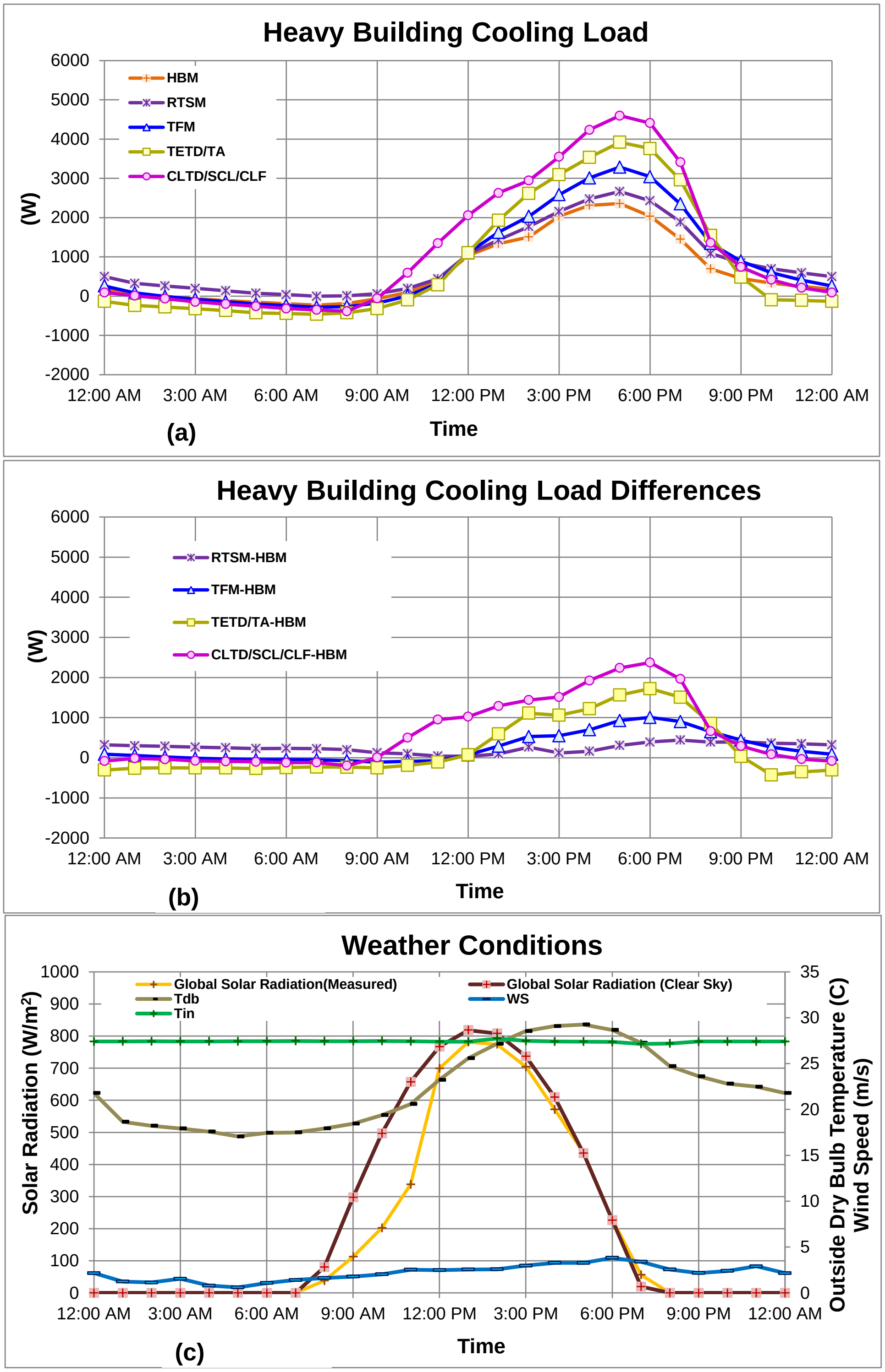


Figure I.11: TC 6 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

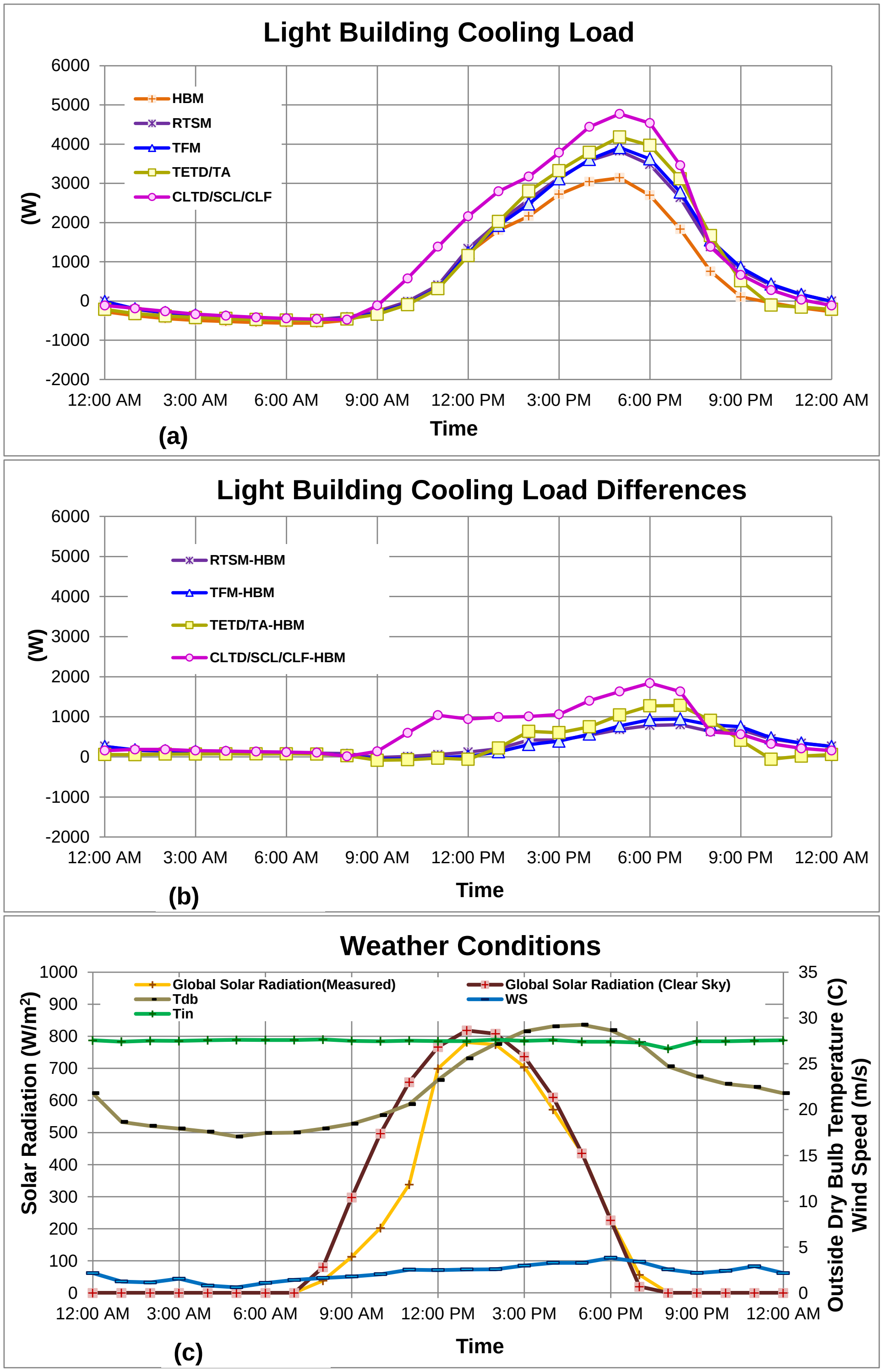


Figure I.12: TC 6 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

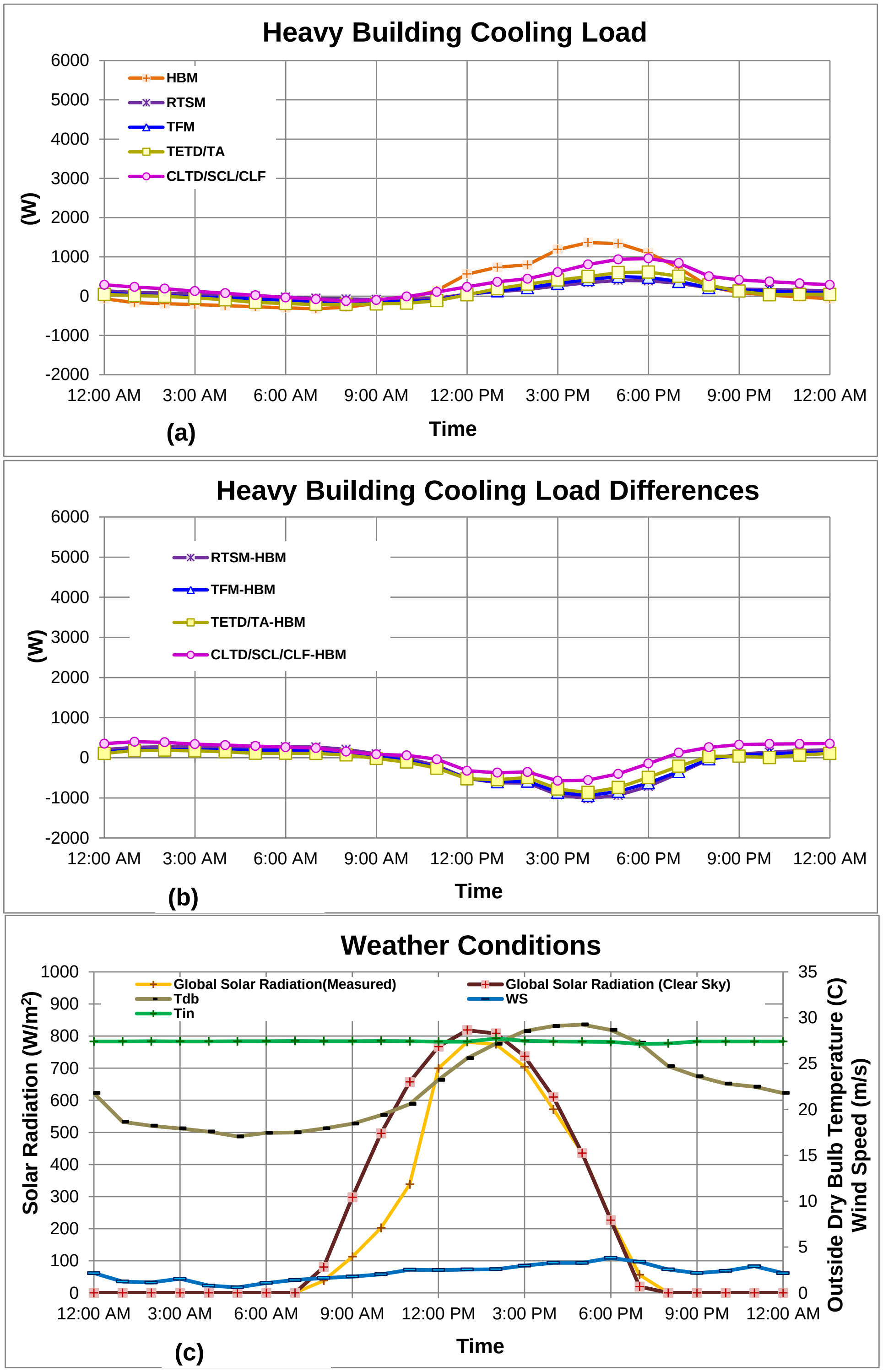


Figure I.13: TC 7 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

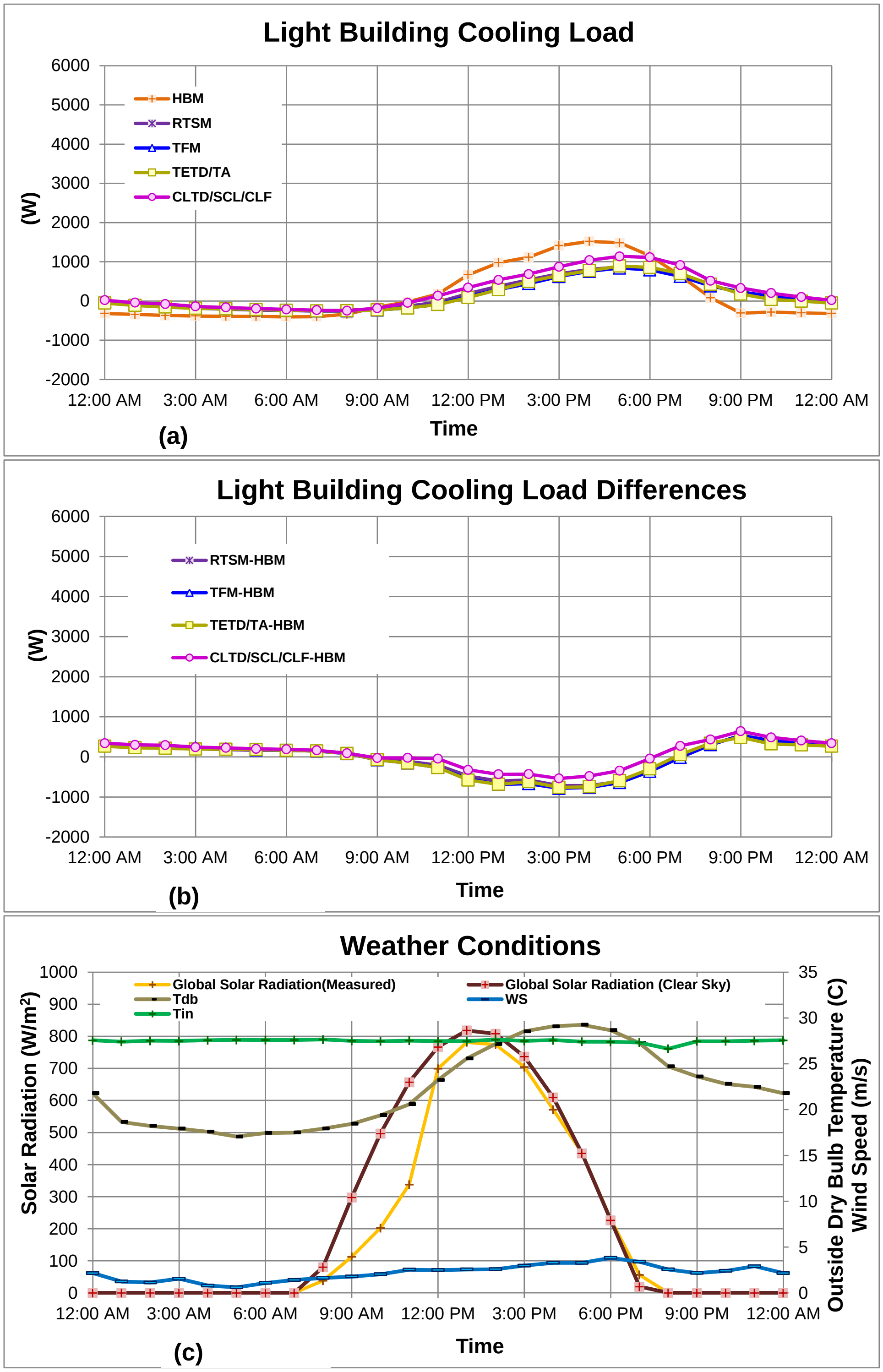


Figure I.14: TC 7 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

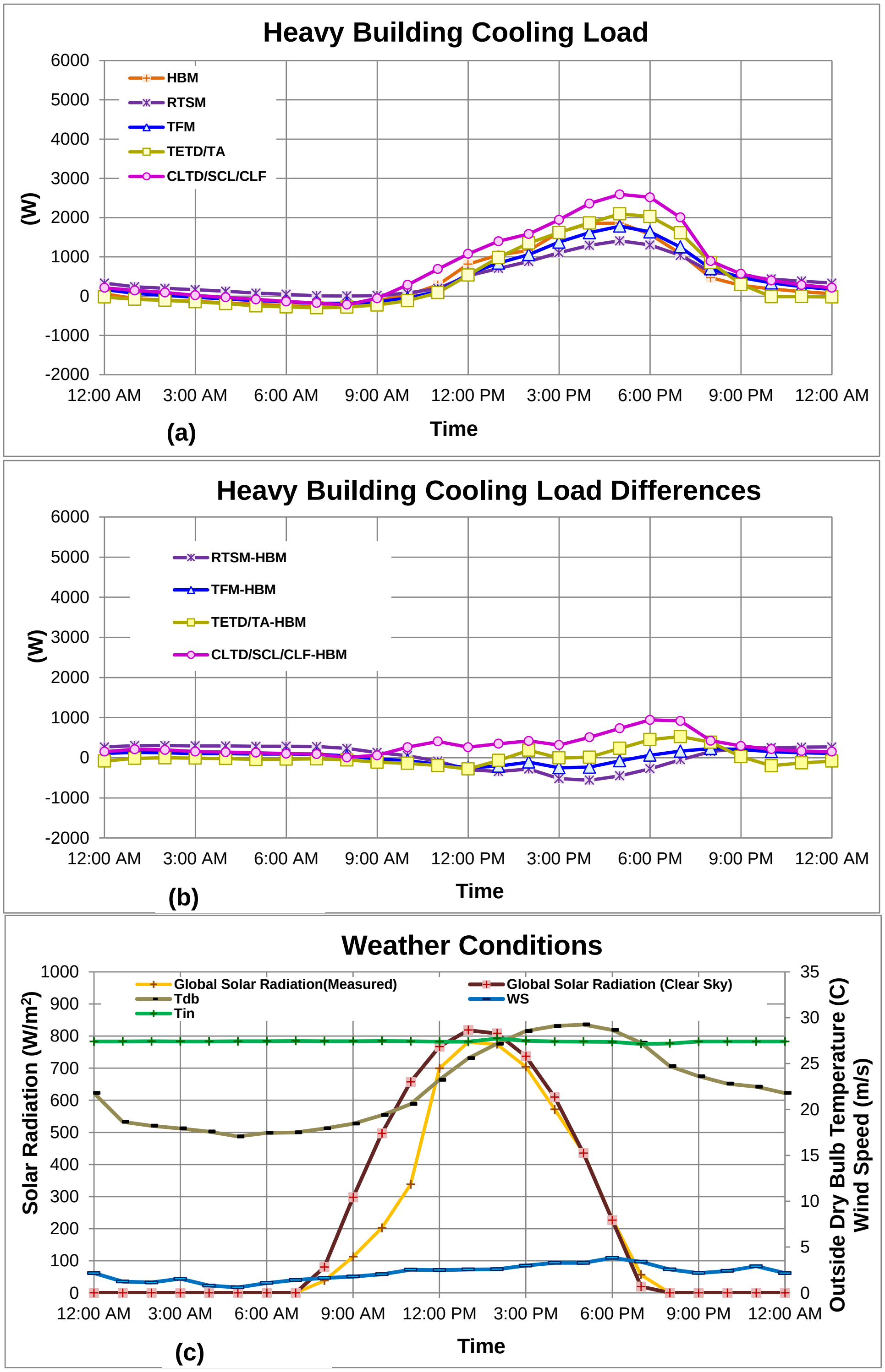


Figure I.15: TC 8 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

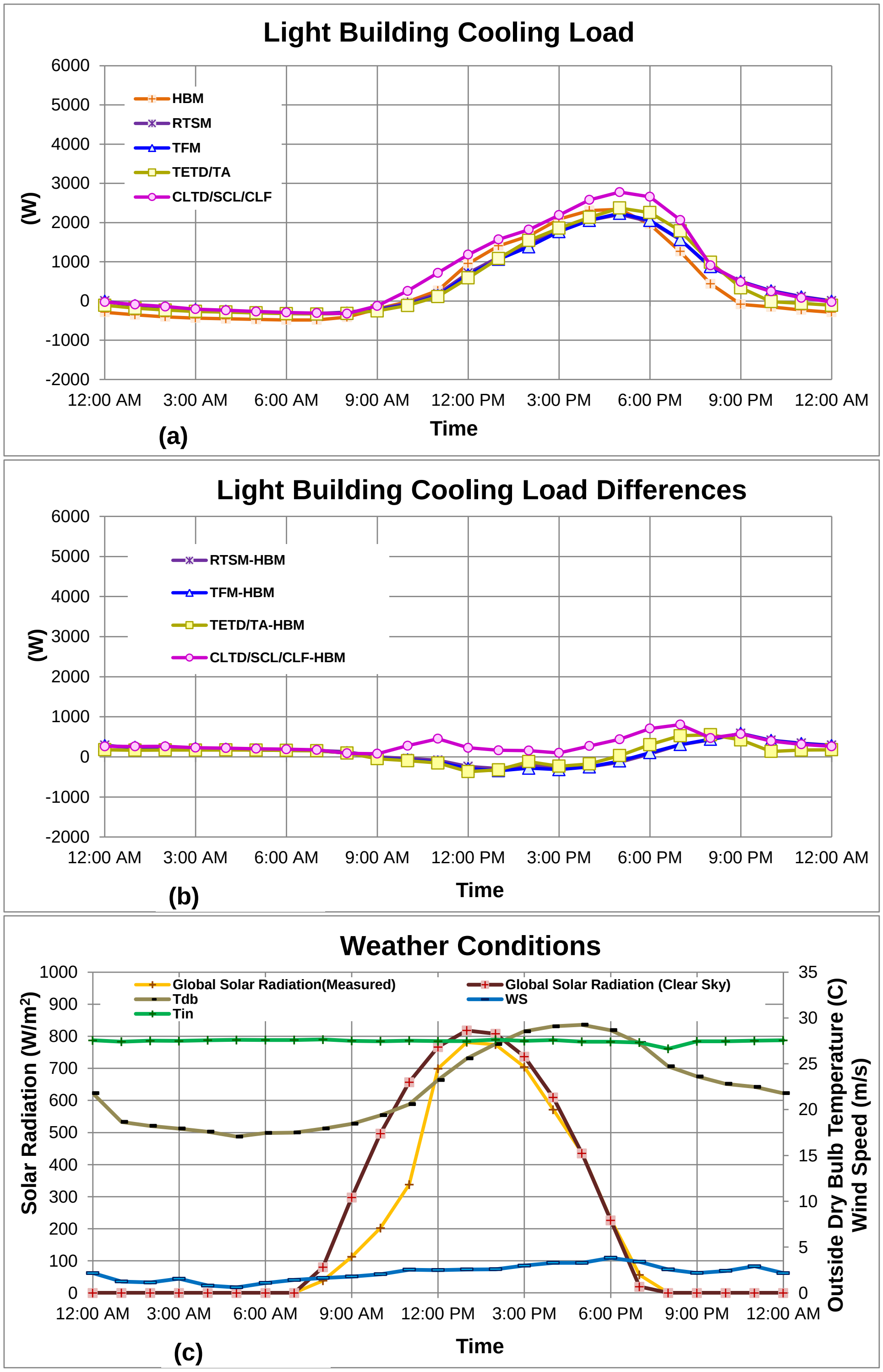


Figure I.16: TC 8 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

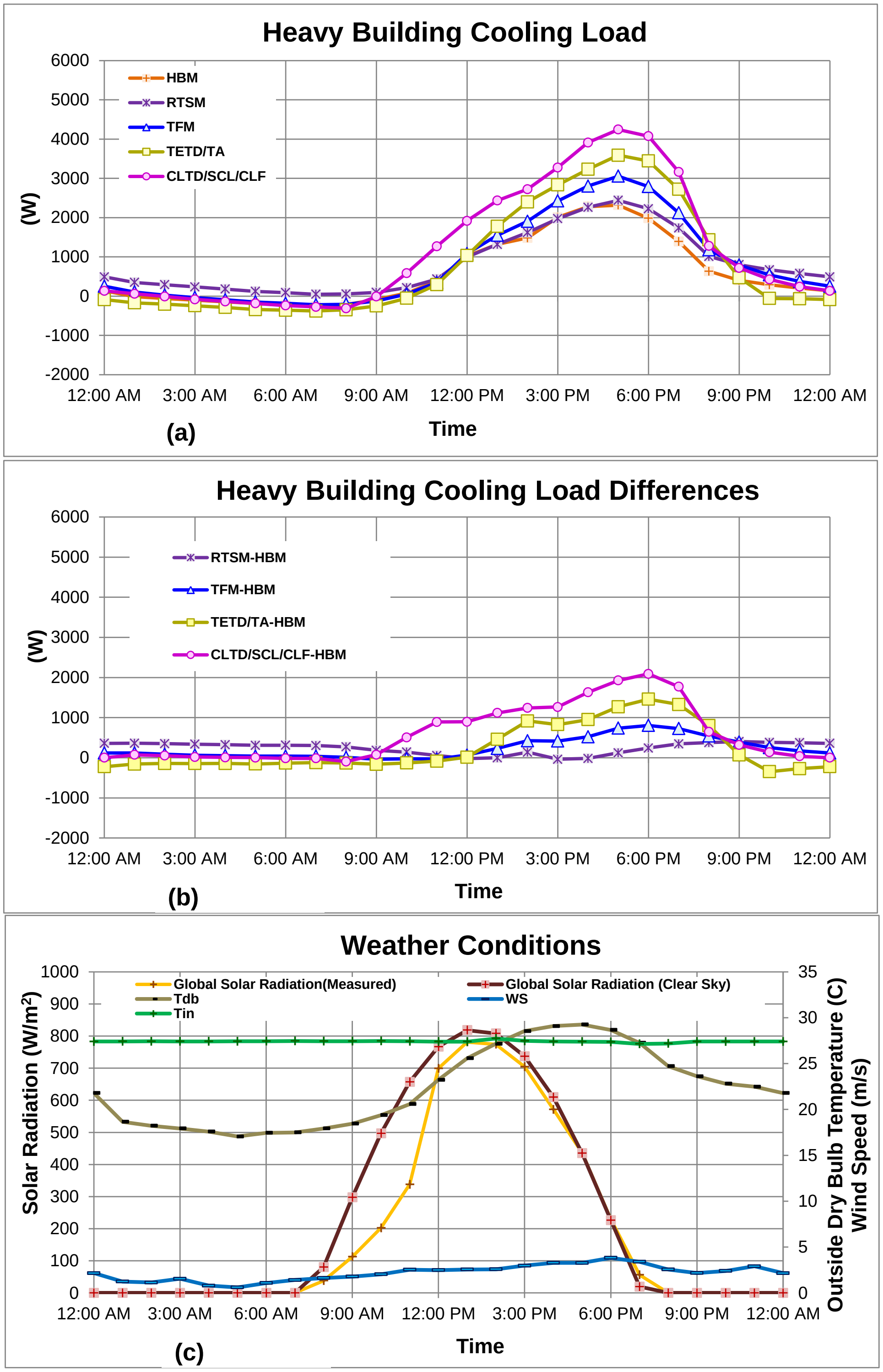


Figure I.17: TC 9 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

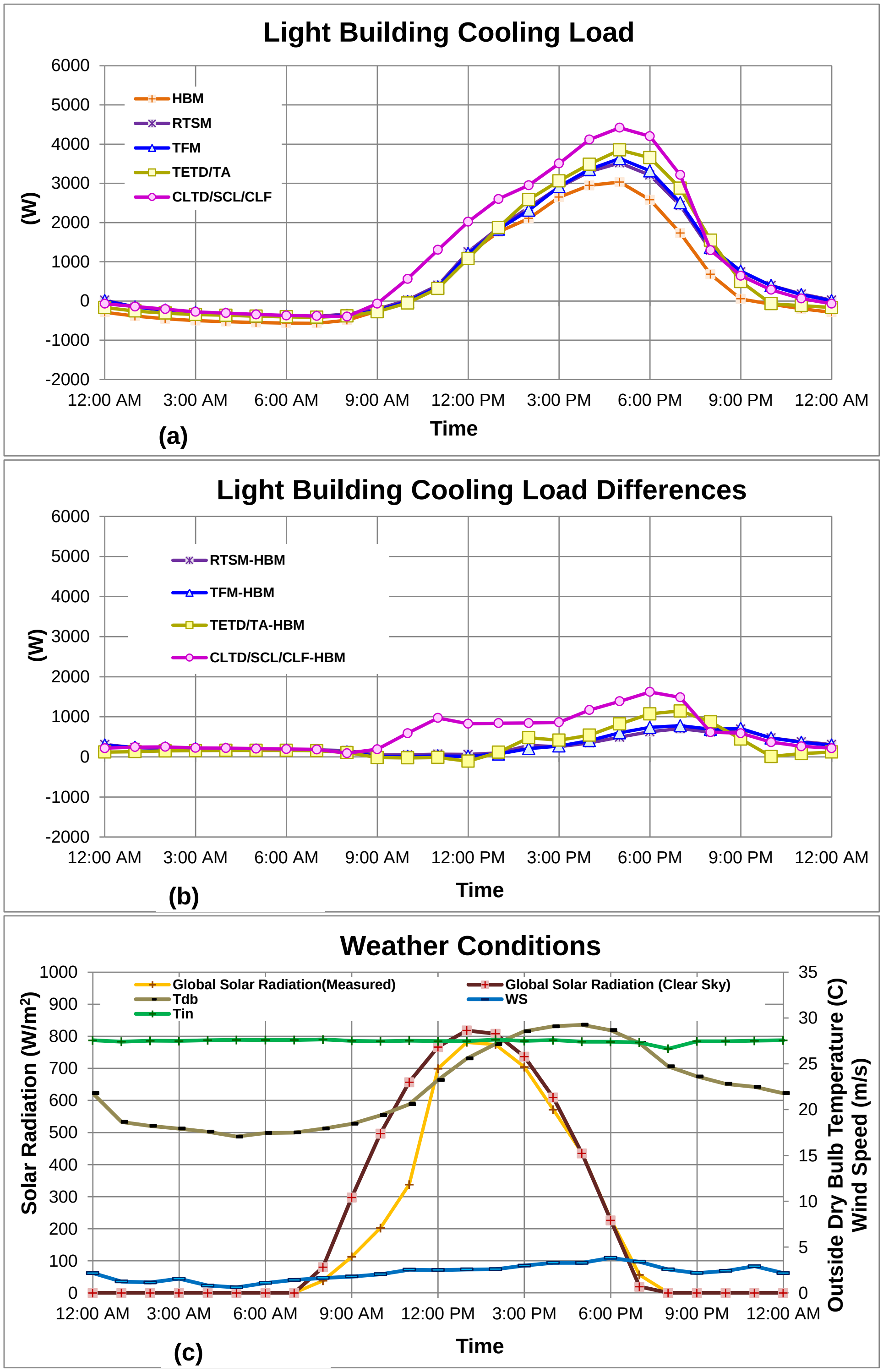


Figure I.18: TC 9 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

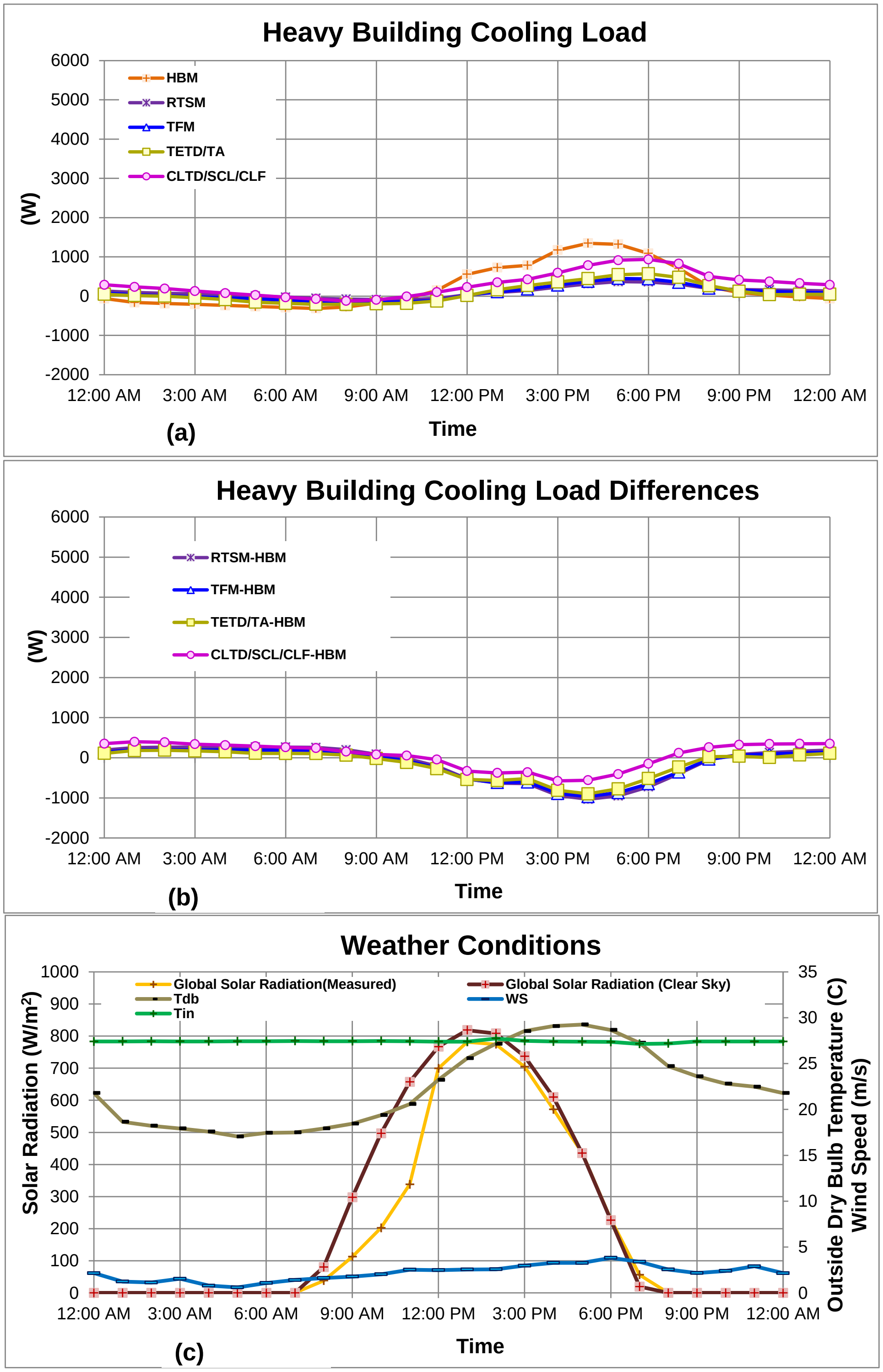


Figure I.19: TC 10 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

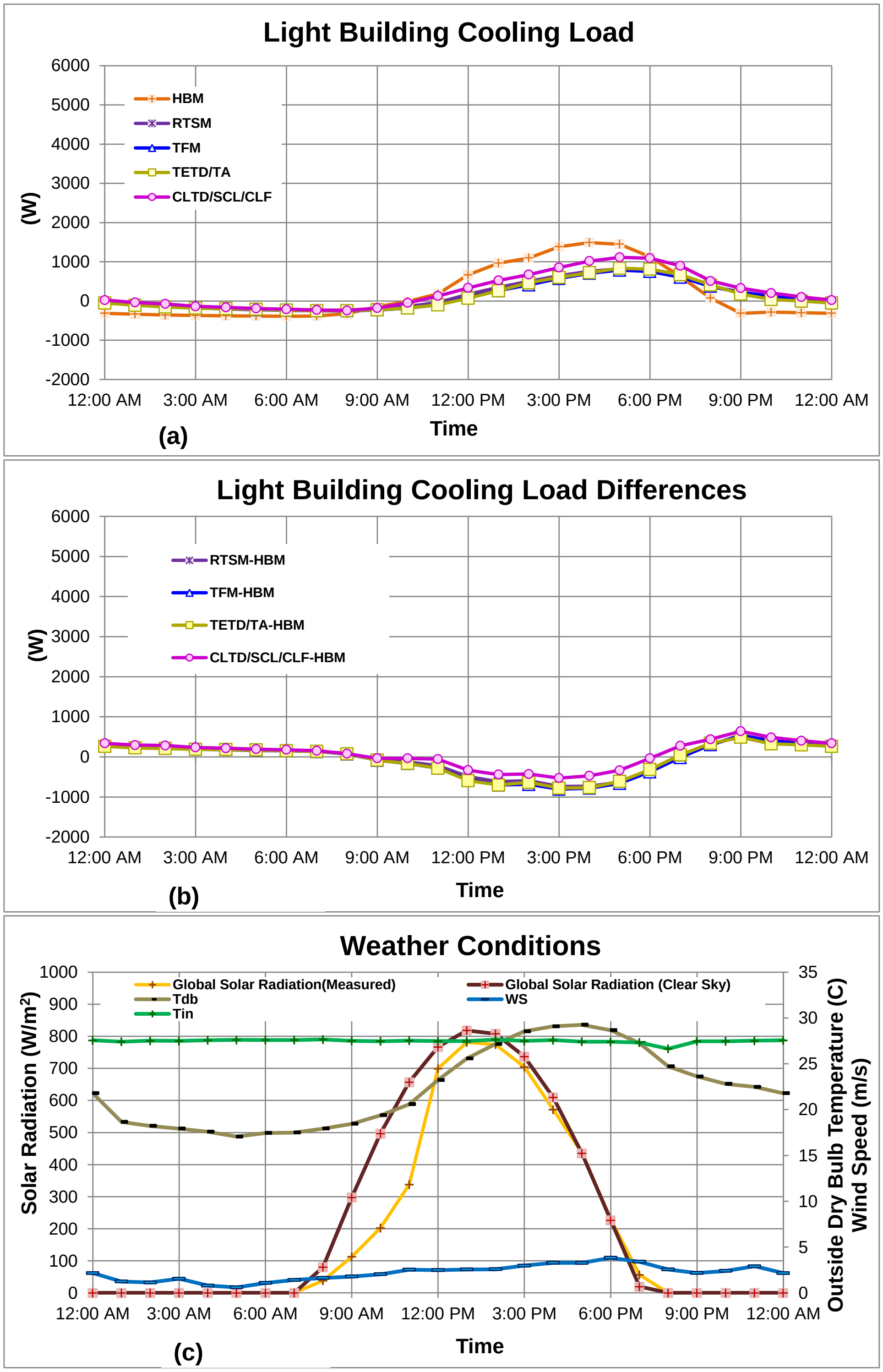


Figure I.20: TC 10 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

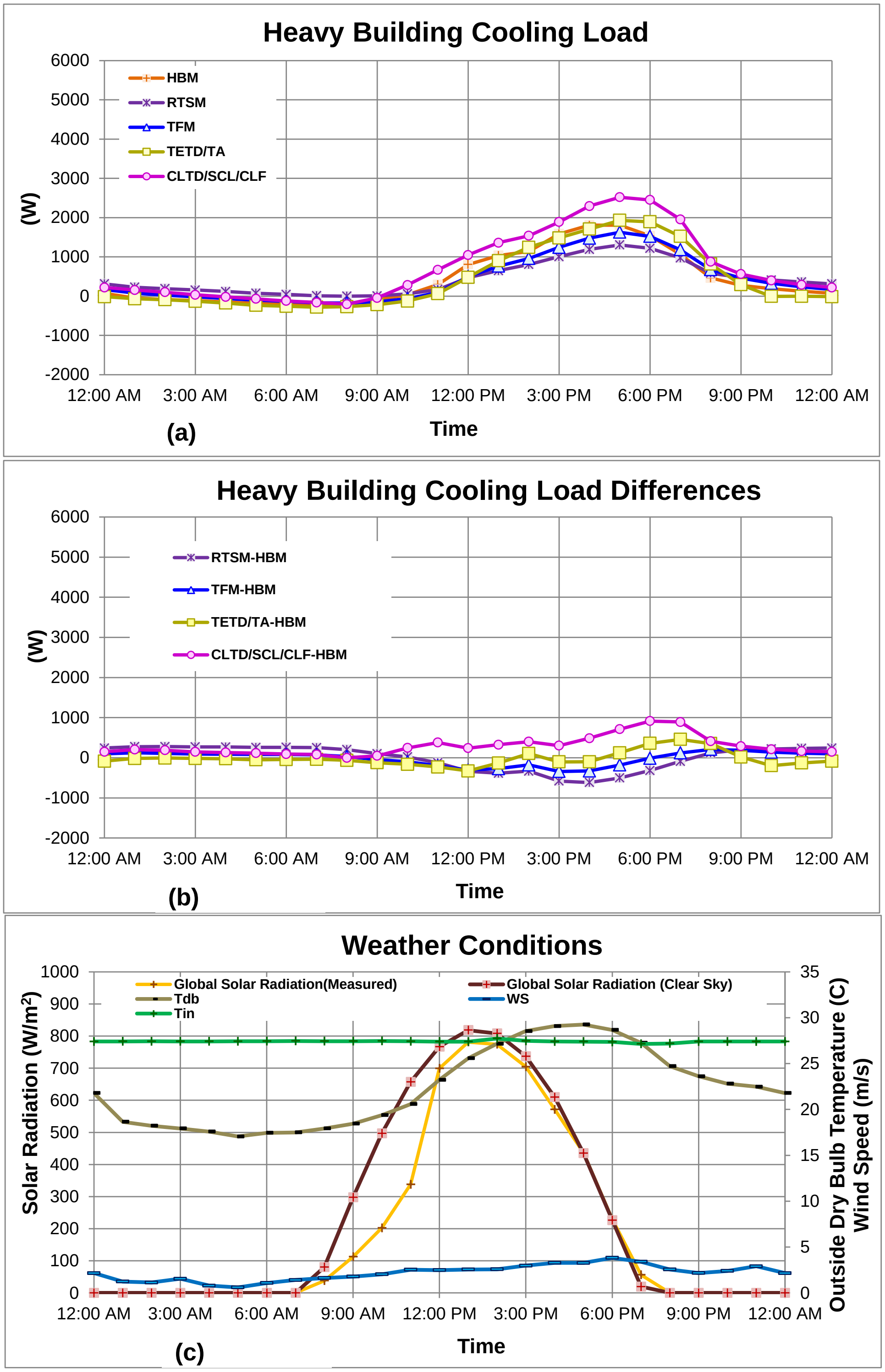


Figure I.21: TC 11 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

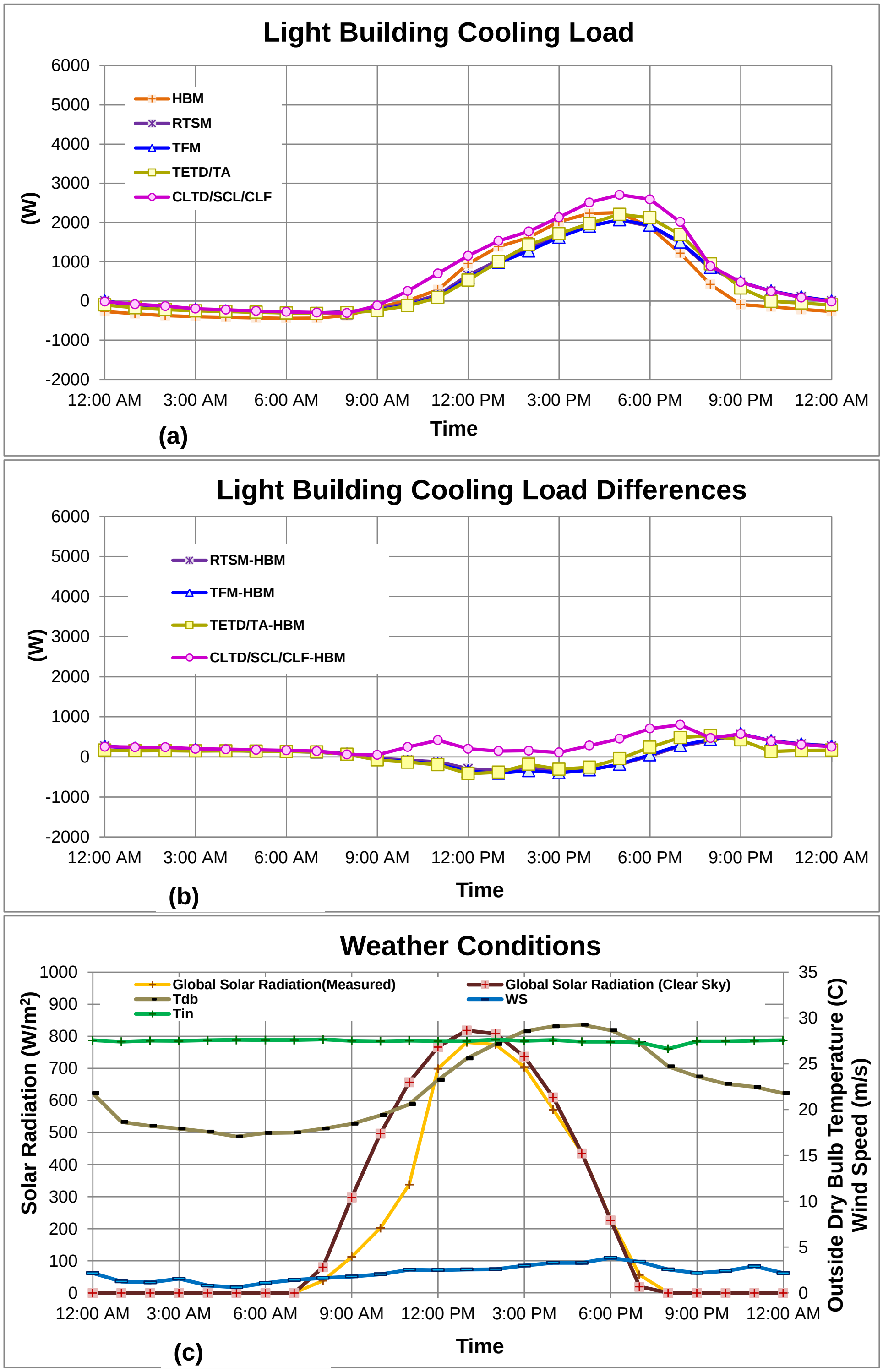


Figure I.22: TC 11 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

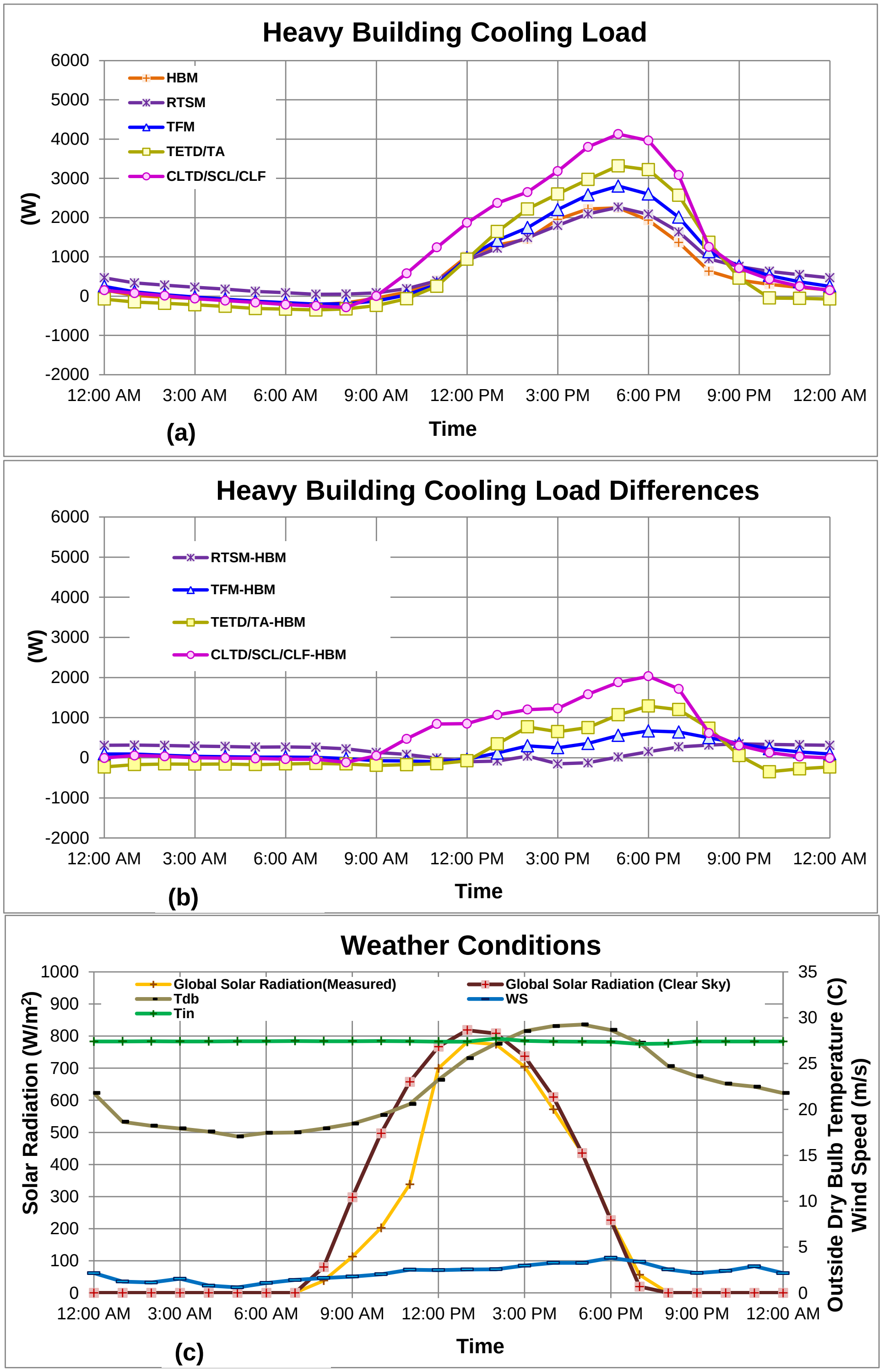


Figure I.23: TC 12 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

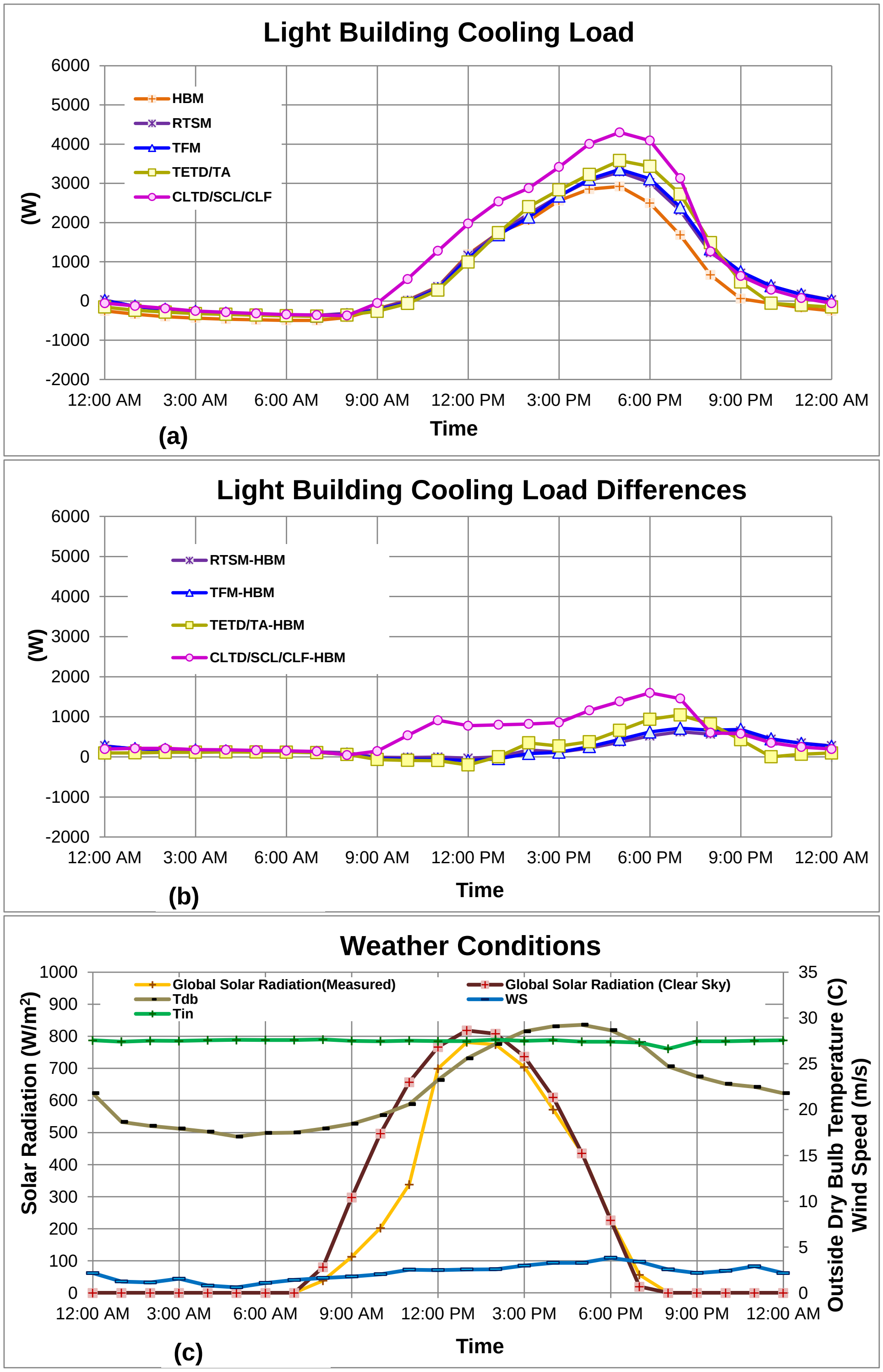


Figure I.24: TC 12 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

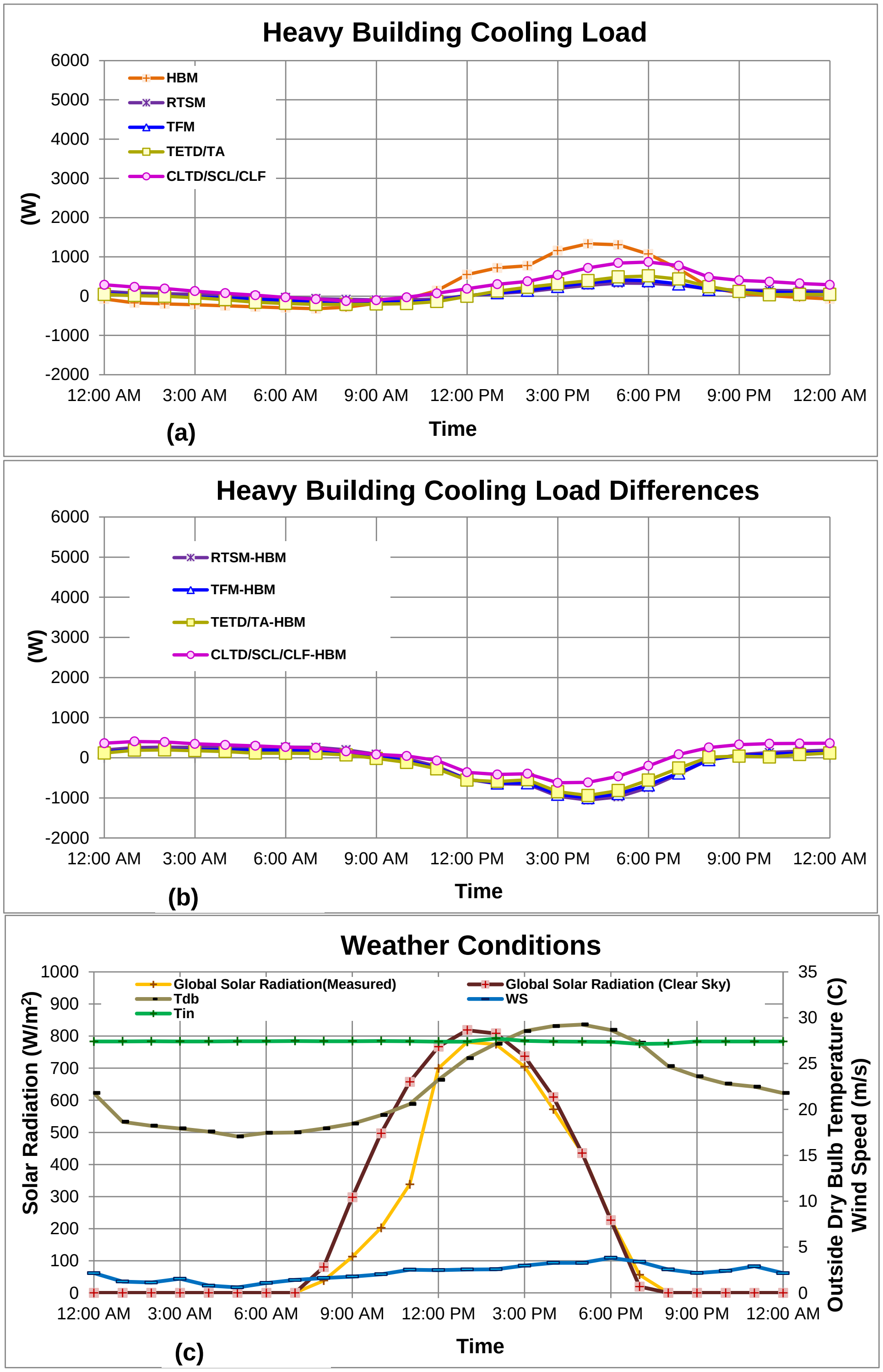


Figure I.25: TC 13 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

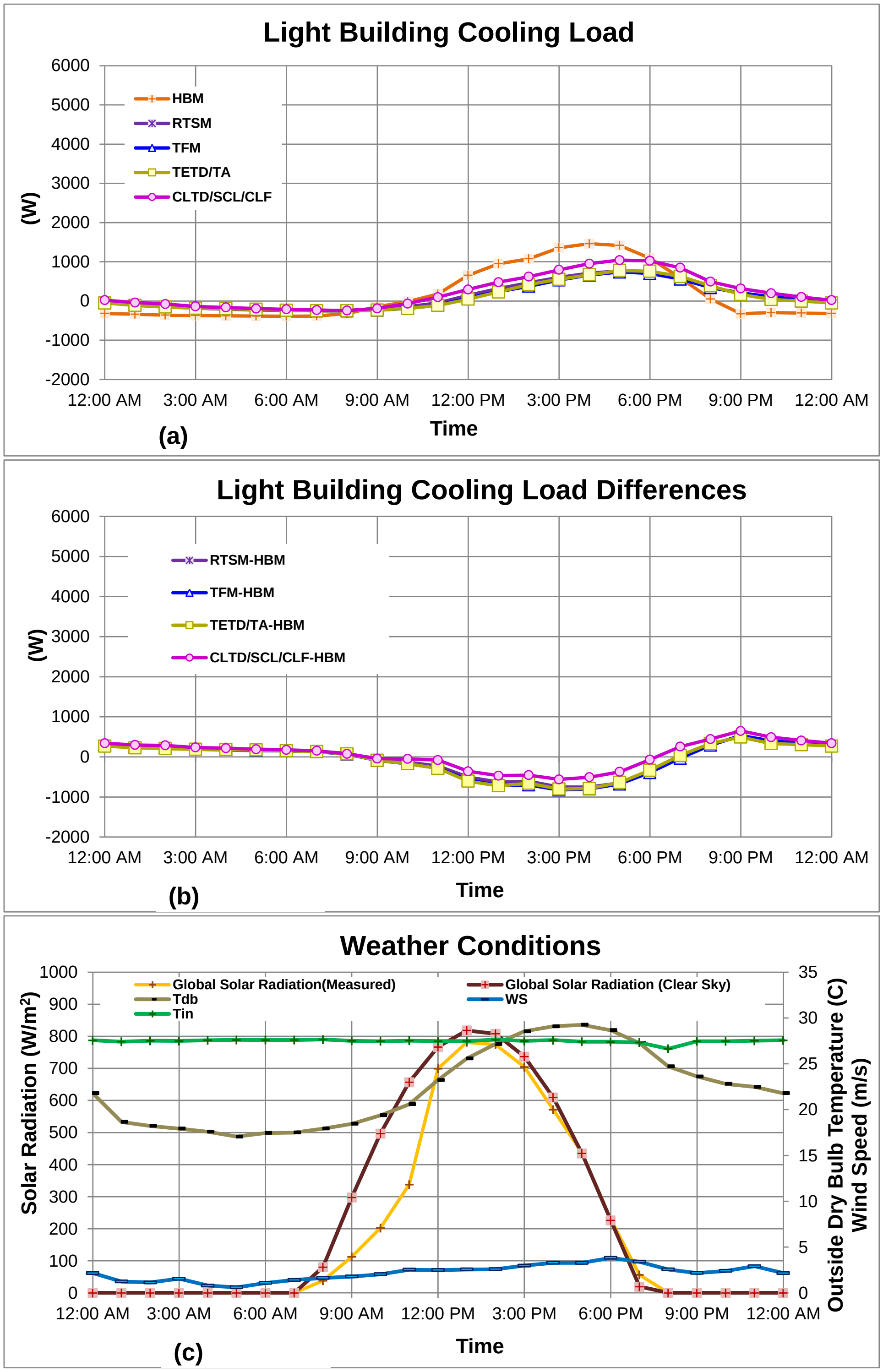


Figure I.26: TC 13 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

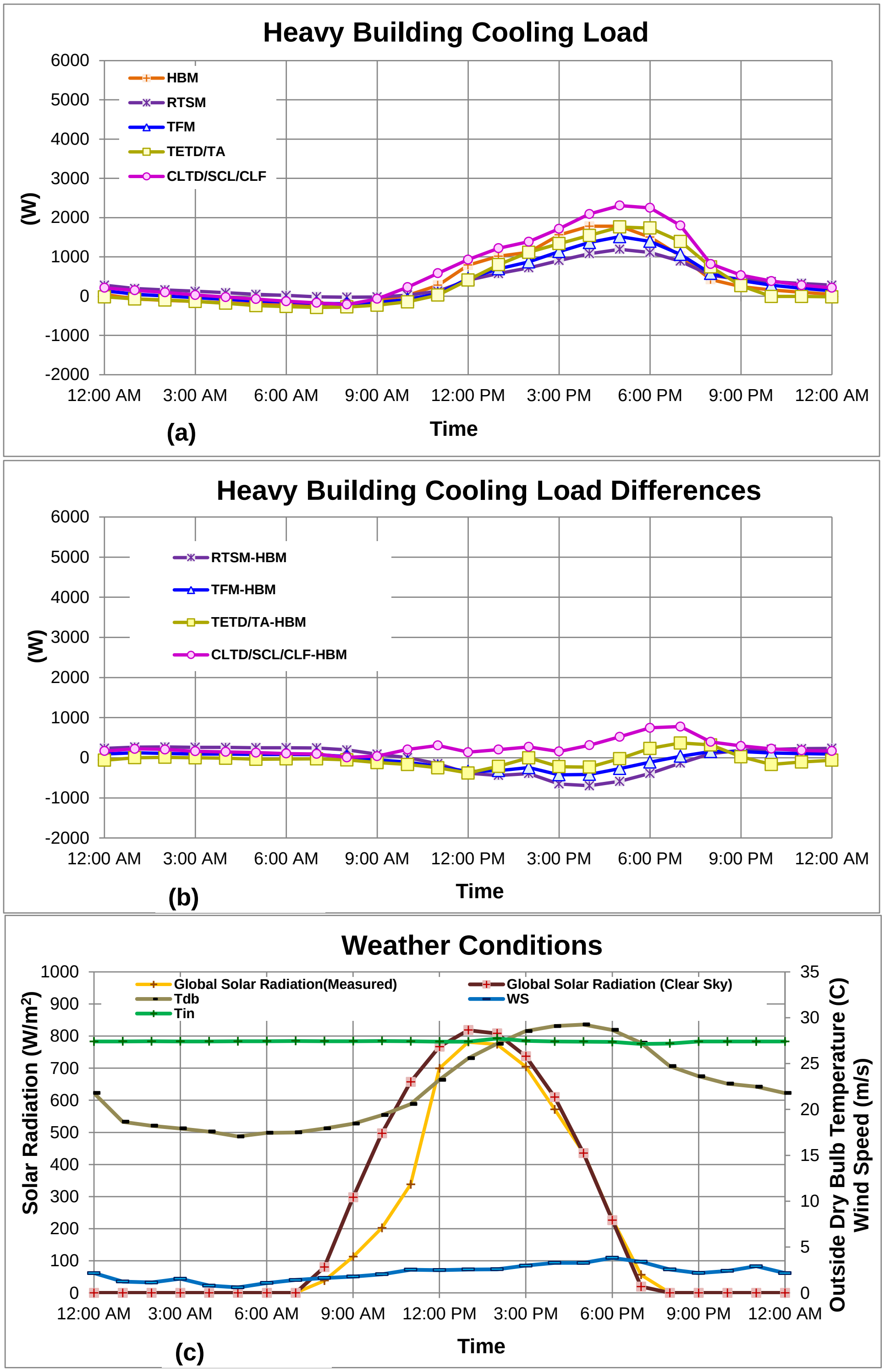


Figure I.27: TC 14 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

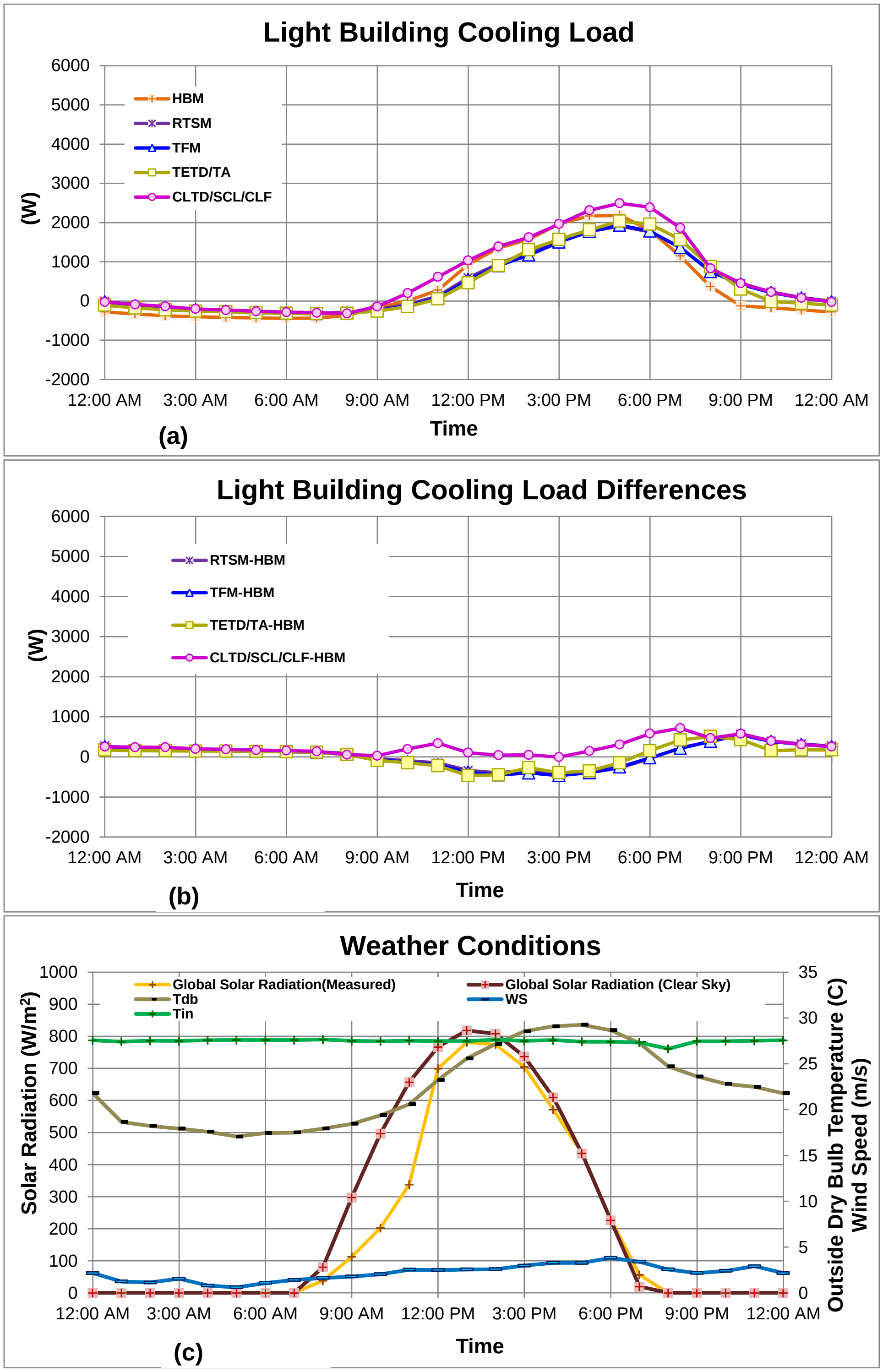


Figure I.28: TC 14 Space Sensible Cooling Load Comparisons for Light-Weight Building Case

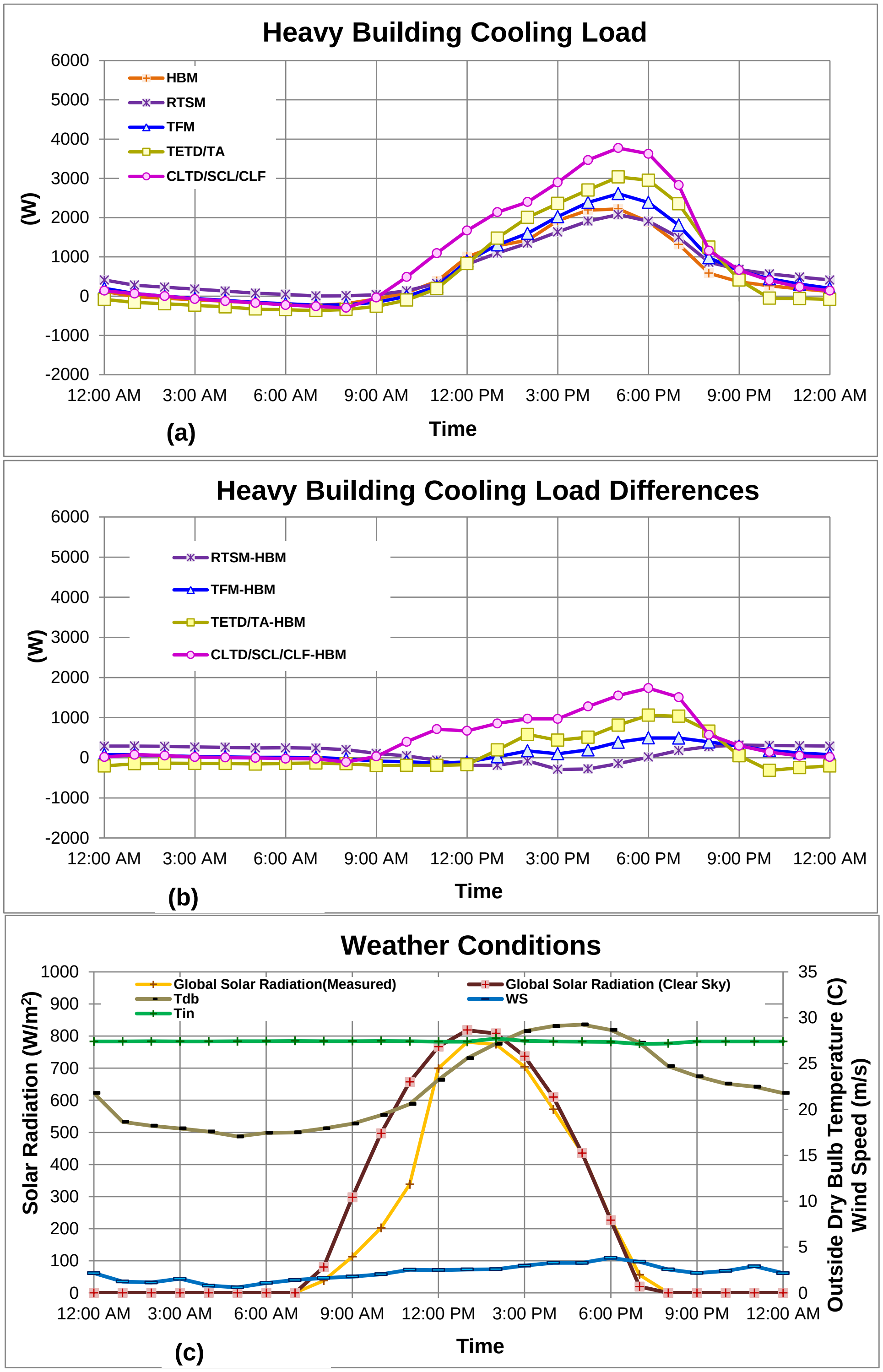


Figure I.29: TC 15 Space Sensible Cooling Load Comparisons for Heavy-Weight Building Case

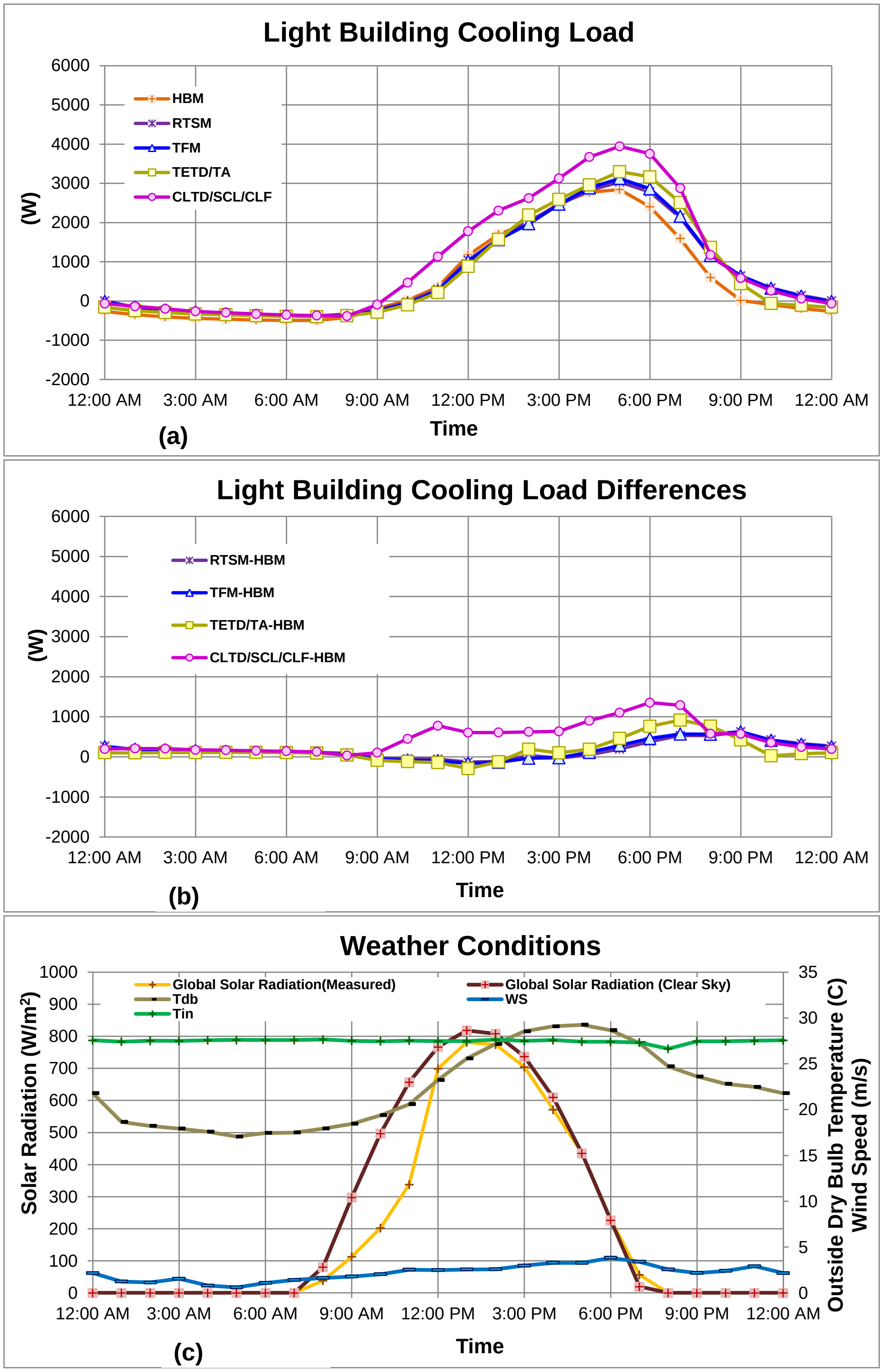


Figure I.30: TC 15 Space Sensible Cooling Load Comparisons for Light-Weight Building Case