AN ENERGY ANALYSIS OF A LARGE, MULTIPURPOSE EDUCATIONAL BUILDING IN A HOT CLIMATE

A Thesis

by

VAHIDEH KAMRANZADEH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2011

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	Michael Pate
Committee Members,	Bryan P. Rasmussen
	Christine E. Economides
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ABSTRACT

An Energy Analysis of a Large, Multipurpose Educational Building in a Hot Climate.

(December 2011)

Vahideh Kamranzadeh, B.S., Aachen University

Chair of Advisory Committee: Dr. Michael Pate

In this project a steady-state building load for Constant Volume Terminal Reheat (CVTR), Dual Duct Constant Volume (DDCV) and Dual Duct Variable Air Volume (DDVAV) systems for the Zachry Engineering Building has been modeled.

First, the thermal resistance values of the building structure have been calculated. After applying some assumptions, building characteristics were determined and building loads were calculated using the diversified loads calculation method.

The air handling units for the Zachry building are DDVAV systems. The calibration procedure has been used to compare the calibration signatures with characteristic signatures in order to determine which input variables need to be changed to achieve proper calibration. Calibration signatures are the difference between measured energy consumption and simulated energy consumption as a function of temperature. Characteristic signatures are the energy consumption as a function of temperature obtained by changing the value of input variables of the system. The base simulated model of the DDVAV system has been changed according to the characteristic signatures of the building and adjusted to get the closest result to the measured data. The simulation method for calibration could be used for energy audits, improving energy efficiency, and fault detection.

In the base model of DDVAV, without any changes in the input, the chilled water consumption had an Root Mean Square Error (RMSE) of 56.705577 MMBtu/day and an Mean Bias Error (MBE) of 45.763256 MMBtu/day while hot water consumption had an RMSE of 1.9072574 MMBtu/day and an MBE of 45.763256 MMBtu/day. In the calibration process, system parameters such as zone temperature, cooling coil temperature, minimum supply air and minimum outdoor air have been changed. The decisions for varying the parameters were based on the characteristic signatures provided in the project. After applying changes to the system parameters, RMSE and MBE for both hot and cold water consumption were significantly reduced. After changes were applied, chilled water consumption had an RMSE of 12.749868 MMBtu/day and an MBE of 3.423188 MMBtu/day, and hot water consumption had an RMSE of 1.6790 MMBtu/day and an MBE 0.12513 of MMBtu/day.

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NOMENCLATURE

CVTR	Constant Volume Terminal Reheat
DDCV	Dual Duct Constant Volume
DDVAV	Dual Duct Variable Air Volume
RMSE	Root Mean Square Error
MBE	Mean Bias Error
R-Value	Thermal Resistance Value
U-Value	1/R
QSOL	Solar Heat Gain
$MSHGF_i$	Maximum Solar Heat Gain Factor for orientation i
AG_i	Glass Area for exposure i
SC_i	Shading Coefficient of glass for exposure i
$CLFTOT_i$	24 hour sum of CLF for orientation i
PPS	Percentage of Possible Sunshine
t	Runtime of air conditioning system (hrs)
A_p	Building Conditioned Floor Area (ft^2)
SHGF	Solar Heat Gain Factor
Toa	Outside Air Temperature
QTS	Transmission Solar Gain
q_{lat}	Latent Load
$q_{e,s}$ / $q_{i,s}$	Interior / Exterior sensible load
$q_{e,l}$ / $q_{i,l}$	Interior / Exterior latent load
OAT	Outside Air Temperature
T_{CL}	Coil Temperature
T_s	Supply Fan Temperature
T_{iS} / T_{eS}	Interior/Exterior Zone Supply Temperature
T_{iR} / T_{eR}	Interior/Exterior Return Air Temperature

q_{iRH} /q_{eRH}	Interior Heating Load/ Exterior Heating Load
V_{TD}	Total Design Volume
V_i / V_e	Interior/Exterior Volume Flow Rate
T_{MA}	Mixed Air Temperature
T_{PHe}	Preheating Leaving Temperature
Tdb	Dry Bulb Temperature
Tph	Preheat Temperature
Tpc	Precool Temperature
TCE	Cooling Entering Temperature
qCS	Cooling Sensible Load
q_{RH}	Heating Load
WR’	Return Air Humidity Ratio, dry
WMA’	Mixed Air Humidity Ratio
WCLd	Dry Cooling Coil Humidity Ratio
WOA	Outside Air Temperature Humidity Ratio
WR”	Return Air Humidity Ratio, dry
$\dot{V}_i$ / $\dot{V}_e$	Interior/Exterior Volume Flow Rate
TL	Transmission Load

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Introduction

In this project, I analyzed the energy consumption of the Zachry building as an example of a large, multipurpose educational building in a hot climate and completed the followings tasks related to the project:

1. Developing a diversified load expression for the Zachry Engineering Center.
2. Preparing a spreadsheet program capable of calculating steady-state building loads for the CVTR, DDCV and DDVAV systems.
3. Checking the quality of the data using the “Energy Balance” procedure and eliminating any bad data.
4. Calibrating the program to the approximate remaining 6 months of daily data on hot water, chilled water and electricity consumption from the Zachry Engineering Center, as supplied.
5. Comparing the hot water and chilled water consumption of the building for CVTR, DDCV and DDVAV systems.

This thesis follows the style of *International Journal of Engine Research*.

Actual daily average data of the building was provided. This dataset included outside air temperature (°F), relative humidity (%) of the outside air temperature, chilled water consumption in MMBtu/day, hot water consumption in MMBtu/day and electric power consumed by electric light and other electrical equipment in kWhr/day.

Literature review

Energy analysis plays an essential role when designing an optimal HVAC system for new buildings and modifying the current system for existing buildings [1]. Before the 1960s, most of the energy simulations were conducted using manual methods [2] such as degree day, equivalent full load cooling, and bin heating/cooling methods [3] [4]. In the early 1970s, computer simulations replaced manual methods for load calculations and building simulations.

Computer simulation methods had two generations. The first generation was developed primarily as a result of academic research between 1965 and 1975. The second generation, however, was developed with government sponsorship between 1975 and 1983. The second generation of computer simulation methods consisted of simplified and comprehensive methods [5]. The simplified methods for energy analysis are based on the modified bin method. In modified bin method, building loads are calculated as time-dependent loads (solar and scheduled loads) and temperature-dependent loads (conduction and infiltration). Time-dependent and temperature-dependent loads were calculated separately for occupied and unoccupied periods of the building. Two examples of simplified methods are ASEAM [6] and Air Model [7].

In comprehensive methods, building load is simulated according to an hourly time-step. Two examples of comprehensive simulation methods were BLAST [8] and DOE 2 [9] [10], which were sponsored by the United States Department of Defense (DOD) and United States Department of Energy (DOE) respectively. In both simplified and comprehensive methods steady-state calculation is used for ventilation modeling of a building [11].

Objective

The objective of this thesis is to compare the energy consumption of three different air handling unit configurations for the Zachry engineering building and calibrate the current Dual Duct Variable Air Volume (DDVAV) system using the energy signature method. The air handling unit configurations used for comparison were Constant Volume Terminal Reheat (CVTR), Dual Duct Constant Volume (DDCV) and Dual Duct Variable Air Volume (DDVAV) systems. The steps to the load calculations and energy signature method have been explained step by step, so that they could be used for similar cases. The simulation method for calibration could be used for energy audits, improving energy efficiency, and fault detection [12].

The Zachry building

The Zachry building has an area of 323000 Sq. Ft., which consists of 3 stories, a sub-ground floor, and a basement garage. Fig. 1 shows a southern view of the Zachry building from outside.

Fig. 1 Southern view of Zachry Engineering Center

The first step is to calculate thermal resistance values of the walls and roof. Fig. 2 and Fig. 3 show the material construction of walls as described below. As can be noticed in Fig. 2, the exterior walls of the building are composed of 3-inch concrete with a one-sided finish façade followed by 3⅝-inch insulation wedged between standard “2x4” metal studs.

The interior finished face has a ⅝-inch gypsum wall board. For simplifying the thermal resistance calculation, the building is subdivided into two sections 1 and 2. Section 1 is shown in Fig. 2.

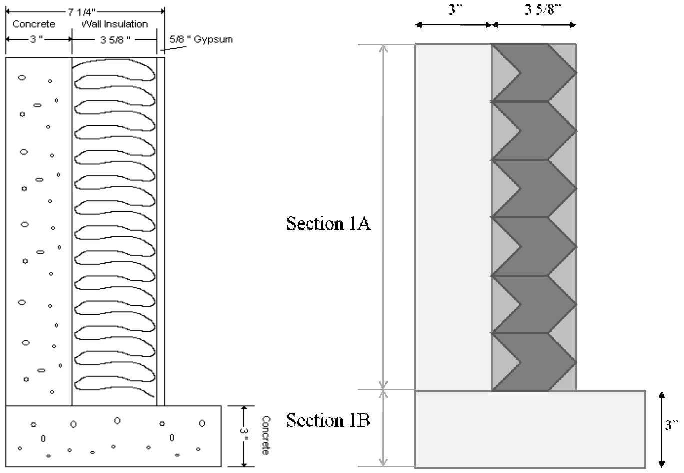

Fig. 2 Side view of material construction of walls, section 1A and 1B

Fig. 3 is the top view of the material construction of the walls. This part is named section 2 in the thermal resistance calculations. Section 2 includes parts 2A, 2B, 2C, 2D and 2E. Sections 2D and 2E are the symmetry of 2A and 2B. So the thermal resistance is calculated just for parts A, B and C.

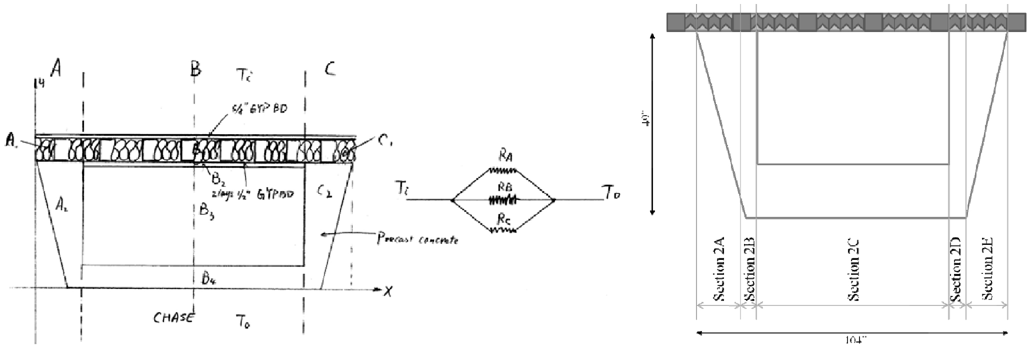

Fig. 3 Top view of material construction of wall (side by side)

Thermal resistance value calculations

To make the thermal resistance calculation easier, the wall is subdivided into Section 1, including 1A and 1B, and Section 2, including 2A, 2B, 2C, 2D and 2E. Fig. 4 shows the front view of the wall, consisting of sections 1 and 2.

The following tables are the details of the calculations. The thermal resistance of the materials were found from ASHRAE [13], Energy Engineering [14] and Dietrich [15].

The U-value is the reciprocal of the R-value. Total UA value is obtained by multiplying the U-value by the corresponding surface area. The total UA value, which has been used in diversified load calculations, is the sum of all the UA values for the walls.

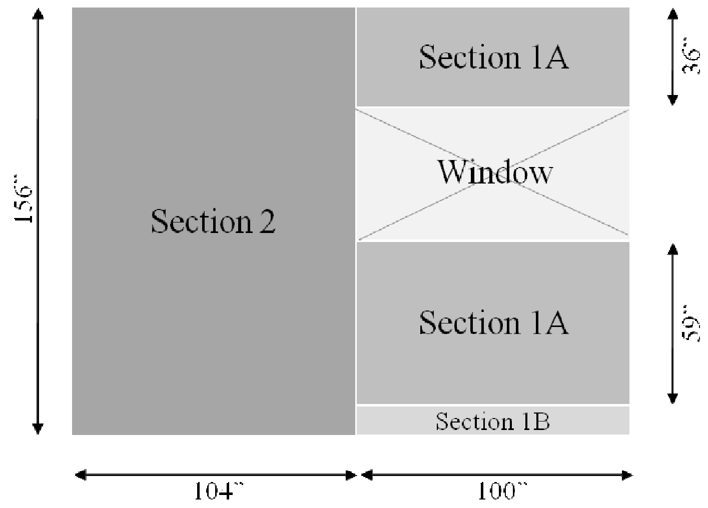

Fig. 4 Front view of material construction of walls, including section 1, section 2, and window

Table 1 is the summary of R-values for section 1A. According to Fig. 2, this section consists of 3-inch concrete, insulation mix and ⅝-inch gypsum board. The corresponding thermal resistance value of each material is shown in Table 1. The thermal resistance of inside and outside air in contact with the wall was also accounted for in determining the total UA value.

Table 1 R-values for walls, section 1A

Section 1A			
R-value of Material	1/h con + rad, o	hr ft^2 F/Btu	0.17
	3" Concrete Heavy Weight		0.33
	Insulation Mix		9.00
	5/8" Gypsum Board		0.56
	1/h con + rad, i		0.68
Total R-value			10.74
TOTAL U		Btu/hr ft^2 F	0.09
Area		ft^2	66.64
UA		Btu/hr F	6.20

Table 2 is the summary of R-values for section 1B. According to Fig. 2, this section consists of 7.25-inch heavyweight concrete. The corresponding thermal resistance value of each material is shown in Table 2. The thermal resistance of inside and outside air in contact with the wall was also accounted for in determining the total UA value.

Table 2 R-values for walls, section 1B

Section 1B			
R-value of Material	1/h con + rad, o	hr ft^2 F/Btu	0.17
	7.25" Heavyweight Concrete		0.80
	1/h con + rad, i		0.68
Total R-value			1.65
TOTAL U		Btu/hr ft^2 F	0.61
Area		ft^2	2.08
UA		Btu/hr F	1.26

Table 3 is the summary of R-values for section 2A. According to Fig. 3, this section consists of 24.5-inch concrete, insulation mix and ⅝-inch gypsum board. The corresponding thermal resistance value of each material is shown in Table 3. The thermal resistance of inside and outside air in contact with the wall was also accounted for in determining the total UA value.

Table 3 R-values for walls, section 2A

Section 2A			
R-value of Material	1/h con + rad, o	hr ft^2 F/Btu	0.17
	24.5" Concrete Heavy Weight		2.69
	Insulation Mix		9.00
	5/8" Gypsum Board		0.56
	1/h con + rad, i		0.68
Total R-value			13.10
TOTAL U		Btu/hr ft^2 F	0.08
Area		ft^2	3.75
UA		Btu/hr F	0.29

Table 4 is the summary of R-values for section 2B. According to Fig. 3, this section consists of 49-inch concrete, insulation mix and ⅝-inch gypsum board. The corresponding thermal resistance value of each material is shown in Table 4. The thermal resistance of inside and outside air in contact with the wall was also accounted for in determining the total UA value.

Table 4 R-values for walls, section 2B

Section 2B			
R-value of Material	1/h con + rad, o	hr ft^2 F/Btu	0.17
	49" Concrete Heavy Weight		5.38
	Insulation Mix		9.00
	5/8" Gypsum Board		0.56
	1/h con + rad, i		0.68
Total R-value			15.79
TOTAL U		Btu/hr ft^2 F	0.06
Area		ft^2	3.75
UA		Btu/hr F	0.24

Table 5 is the summary of R-values for section 2C. According to Fig. 3, this section consists of 3-inch concrete, air, 5/8-inch gypsum board, insulation mix and again ⅝-inch gypsum board. The corresponding thermal resistance value of each material is shown in Table 5. The thermal resistance of inside and outside air in contact with the wall was also accounted for in determining the total UA value.

Table 5 R-values for walls, section 2C

Section 2C			
R-value of Material	1/h con + rad, o	hr ft^2 F/Btu	0.17
	3" Concrete Heavy Weight		0.33
	Air		0.92
	5/8" Gypsum Board		0.56
	Insulation Mix		9.00
	5/8" Gypsum Board		0.56
	1/h con + rad, i		0.68
Total R-value			12.22
TOTAL U		Btu/hr ft^2 F	0.08
Area		ft^2	115
UA		Btu/hr F	9.41

Table 6 shows the total results for the wall's U value. The Total area is the summation of areas of sections 1 and 2. The UA values for sections 1A, 1B, 2A, 2B, 2C, 2D and 2E have been added. The total U value is gained by dividing the total UA value by the total area.

Table 6 Total R-value

Total Area	**(ft^2)**	**194.97**
Total U-Value	**(Btu/hr ft^2 F)**	**0.10**

Table 7 is the summary of R-values for the roofs. The roofs consist of built-up roofing, roof insulation, 4-inch concrete, an air layer, and acoustic tile. The corresponding thermal resistance value of each material is shown in Table 7. The roofs have an R-value of 16.29 h ft^2 F/Btu.

Table 7 R-values for roofs

Section 2A			
R-value of Material	1/h con + rad, o	hr ft^2 F/Btu	0.17
	Built-Up Roofing		0.33
	Roof Insulation		8.33
	4" Concrete		4.44
	Air Layer		0.85
	Acoustic Tile		1.25
	1/h con + rad, i		0.92
Total R-value			16.29
TOTAL U		Btu/hr ft^2 F	0.06

CHAPTER II

DIVERSIFIED LOAD CALCULATIONS

Building characteristics, design conditions and assumptions, space conditions, and the schedule of the Zachry building should be determined before starting the load calculations. The details of the design conditions and assumptions of the building are shown in Table 8[16].

To determine the load characteristics of the Zachry engineering building, the building area was subdivided into interior and exterior zones. The interior and exterior zones are shown in Fig. 5. The exterior zone is the interior perimeter region measuring 14.5ft from any wall. The interior zone is the remaining interior region measuring greater than 14.5ft from any wall. Exterior zones have variable loads because of the changes in outdoor temperature and sun position during the year. Interior zones have relatively constant loads dependent on lighting, office equipment, and occupants. Using this building subdivision, 20% of the total area lies in exterior zones and the remaining 80% of the total area lies in interior zones.

Fig. 5 **I**nterior zone and exterior zone of the Zachry engineering building

The number of occupants for each zone has been calculated using the following equation:

$$\text{Number of occupants} = [\text{Area of interior zone}(\text{ft}^{\wedge}2) / \text{ maximum occupants}(\text{ft}^{\wedge}2/\text{person})] \times \text{ percent of occupants during occupied period}$$

Sensible load for each zone has been calculated by using the following equation:

$$\text{Sensible Load}(\text{Btu/hr}) = \text{Sensible load per person}(\text{Btu/hr person}) \times \text{Interior zone occupants during occupied period (person).}$$

Table 8 Design conditions and assumptions

Inside Temperature (Dry Bulb Temperature, T_{db})	75	°F
Winter Conditions (Preheat Temperature, T_{ph})	17	°F
Summer Conditions (Precool Temperature, T_{pc})	102	°F
Maximum Occupants (total)	200	ft^2/person
Percent of Occupants during Occupied Period	100%	
Percent of Occupants during Unoccupied Period	15%	
Occupants Interior Zone (Occupied)	1292	person
Occupants Interior Zone (Unoccupied)	194	
Occupants Exterior zone (Occupied)	323	person
Occupants Exterior zone (Unoccupied)	48	
Sensible Loads per Person	255	Btu/hr person
Sensible Interior Load (Occupied)	329419	Btu/hr
Sensible Exterior Load (Occupied)	82355	Btu/hr
Sensible Interior Load (Unoccupied)	49413	
Sensible Exterior Load (Unoccupied)	12353	
Latent Loads per Person	255	Btu/hr person
Latent Interior Load (Occupied)	329419	Btu/hr
Latent Exterior Load (Occupied)	82355	Btu/hr
Latent Interior Load (Unoccupied)	49413	
Latent Exterior Load (Unoccupied)	12353	
Run Time of Air Conditioner	24	hr
Outside Air Flow Rate	31489	cfm

Table 9 is the description of the building’s characteristics: the total areas of the interior and exterior zones, area of the walls, windows, and roof, and the height of the building.

Table 9 Building characteristics

			NW	**SW**	**SE**	**NE**	**Roof**
Roof Area Total	80,740	ft²					
Roof Area Interior Zone	64,592	ft²					
Roof Area Exterior Zone	16,148	ft²					
Area of Walls without Windows	46,170	ft²	16434	9860	16434	9860	80,740
Windows	5,130	ft²	4109	2465	4109	2465	0
Length NW	367	ft					
Width SW	220	ft					
Height	56	ft					
Levels	4	Floors					
Interior Zone One Level	64,592	ft²					
Exterior Zone One Level	16,148	ft²					
Interior Zone Total Area	258368	ft²					
Exterior Zone Total Area	64592	ft²					
Building Conditioned Floor Area	322960	ft²					
Skylight Area	3584	ft²					

For developing the diversified load calculations, it is assumed that the building is subdivided into an interior zone (258,368 ft²) and an exterior zone (64,592 ft²). The components of the diversified loads are:

- Solar through glass
- Conduction through glass
- Conduction through the walls and roof
- Solar through the walls and roof
- Lights
- People
- Equipment
- Infiltration (which is assumed as zero in these calculations.)

All of the load components are developed as a linear function of outside temperature. The total load profile will be the sum of the individual components.

Solar load through glass

For calculating the solar load through glass, the following equation is used, which is taken from the ASHRAE [13].

$$Q_{SOL} = \frac{\sum_{i=1}^{\#Exposures} (MSHGF_i \cdot AG_i \cdot SC_i \cdot CLFTOT_i \cdot PPS)}{t \cdot A_F} \qquad \textbf{(1)}$$

QSOL: averaged solar contribution

$MSHGF_i$: maximum solar heat gain factor for orientation i at the specified latitude

AG_i : glass area for exposure i

SC_i : shading coefficient of glass for exposure i

$CLFTOT_i$: 24-hour sum of CLF for orientation i, table 3-2 of ASHRAE [13]

PPS: percentage of possible sunshine from table 3-1 of ASHRAE [13]

t: runtime of air-conditioning system (hours)

A_p: building conditioned floor area (ft^2)

Using the (1, diversified solar loads for summer and winter were calculated as the summation of solar loads for Northwest (NW), Southwest (SW), Southeast (SE), and Southwest (SW) directions, as well as the roof. Each solar load is represented in Table 10.

Once the solar load for winter and summer are computed, the diversified solar load profile of the building can be obtained by interpolation between summer and winter values.

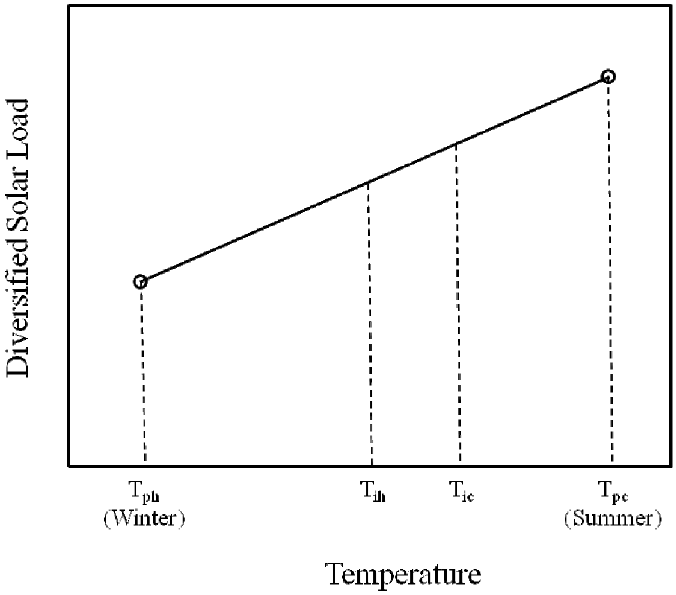

Fig. 6 Diversified solar load for different temperatures

Fig. 6 describes how the interpolation has been applied. The solar load equation can be written as:

$$Average\ Solar\ Heat\ Gain = \frac{[(Solar\ Heat\ Gain\ in\ July) - (Solar\ Heat\ Gain\ in\ January)]}{(Summer\ Conditions\ T_{pc} - Winter\ Condition\ T_{ph})} \times (T_{OA} - T_{ph}) + SHGF_{January} \qquad \textbf{(2)}$$

All the values used for the solar load calculations, as well as the slope of the line, M, used in interpolation are shown in Table 10.

Table 10 Exterior solar gain through glass

Occupied / Unoccupied Period Exterior Zone									
			NW	**SW**	**SE**	**NE**	**Roof**	**Total**	**Reference**
Solar Heat Gain Factor SHGF (January)		Btu/(ft² day)	166	1236	1236	166	1018		Table 2.7 [13]
Solar Heat Gain Factor SHGF (July)		Btu/(ft² day)	869	908	908	869	2178		Table 2.7 [13]
Windows	5130	ft²	4109	2465	4109	2465	0		
Shading Coefficient	0.5		0.5	0.5	0.5	0.5	0.5		
Percent of Possible Sunshine, PPS (January)	0.46		0.46	0.46	0.46	0.46	0.46		Table 3.1 [13]
Percent of Possible Sunshine, PPS (July)	0.76		0.76	0.76	0.76	0.76	0.76		Table 3.1 [13]
Building Conditioned Floor Area	322960	ft²							
Run Time of Air Conditioner	24	h							
Solar heat gain throught glass	**JAN**	**Btu/(h ft²)**	**0.02**	**0.09**	**0.15**	**0.01**	**0**	**0.27**	
	JUL	**Btu/(h ft²)**	**0.17**	**0.11**	**0.18**	**0.10**	**0**	**0.57**	
M								0.003	

As a result, the exterior solar gain through glass function will be:

$$QSOL = 0.003 \times (Toa - 17) + 0.27 \qquad \textbf{(3)}$$

The interior solar gain calculation is similar to the exterior one and is shown in Table 11.

Table 11 Interior solar gain through skylights

Occupied / Unoccupied Period **Interior Zone**									
			NW	**SW**	**SE**	**NE**	**Roof**	**Total**	**Reference**
Solar Heat Gain Factor SHGF (January)		Btu/(ft² day)				166			Table 2.7 [13]
Solar Heat Gain Factor SHGF (July)		Btu/(ft² day)				869			Table 2.7 [13]
Skylight Area	3584	ft²				3584			
Shading Coefficient	0.5					0.50			
Percent of Possible Sunshine, PPS (Jan)	0.46					0.46			Table 3.1 [13]
Percent of Possible Sunshine, PPS (Jul)	0.76					0.76			Table 3.1 [13]
Building Conditioned Floor Area	322960	ft²							
Run Time of Air Conditioner	24	h							
Solar heat gain throught glass	**JAN**	**Btu/(h ft²)**				**0.018**		**0.018**	
	JUL	**Btu/(h ft²)**				**0.15**		**0.15**	
M								0.00159	

As a result, the interior solar gain through glass function will be:

$$QSOL = 0.00159 \times (Toa - 17) + 0.018 \qquad \textbf{(4)}$$

Transmission load through opaque walls and roof

For calculating the solar load through glass, the following equation from ASHRAE [13] was used.

$$Q_{TS} = \frac{\sum_{i=1}^{NSURF} (A_i \cdot U_i \cdot CLTDS_i \cdot K_i \cdot PPS)}{t \cdot A_F} \qquad \textbf{(5)}$$

QTS: solar transmission contribution for January

CLTDS: 24-hour averaged solar component of CLTD table 3-3 of the ASHRAE [13]

K: color correction factor

Using the (5, diversified transmission loads for summer and winter were calculated as the summation of transmission loads for Northwest (NW), Southwest (SW), Southeast (SE), and Southwest (SW) directions, as well as the roof. Each transmission load is represented in Table 12.

Once the transmission load for winter and summer are computed, the transmission load profile of the building can be obtained by interpolation between summer and winter values.

Fig. 6 describes how the interpolation has been applied. The transmission load equation can be written as:

$$Average\ Solar\ Heat\ Gain = \frac{[(Transmission\ Load\ in\ July) - (Transmission\ load\ in\ January)]}{\left(Summer\ Conditions\ T_{pc} - Winter\ Condition\ T_{ph}\right)} \times \left(T_{OA} - T_{ph}\right) + TL_{January} \quad \textbf{(6)}$$

All the values used for the transmission load calculations, as well as the slope of the line, M, used in interpolation are shown in Table 12.

Table 12 Exterior transmission loads - solar component through opaque walls & roof

Occupied / Unoccupied Period **Exterior Zone**									
			NW	**SW**	**SE**	**NE**	**Roof**	**Total**	**Reference**
Area of Walls without windows/roof	46170	ft²	16434	9860	16434	9860	16,148		
U-value (Walls/Roof)		Btu/(ft² h F)	0.21	0.21	0.21	0.21	0.06		
CLTDS(L=32Jan)			2	16	16	2	7		Table 3.3 [13]
CLTDS(L=32Jul)			12	13	13	11	23		Table 3.3 [13]
Ki			0.83	0.83	0.83	0.83	0.75		
Percent of Possible Sunshine, PPS (Jan)	0.46		0.46	0.46	0.46	0.46	0.46		Table 3.1 [13]
Percent of Possible Sunshine, PPS (Jul)	0.76		0.76	0.76	0.76	0.76	0.76		Table 3.1 [13]
Building Conditioned Floor Area	322960	ft²							
Transmission loads - Solar component thru opaque walls & Roof	**JAN**		**0.008**	**0.04**	**0.07**	**0.005**	**0.007**	**0.125**	
	JUL		**0.08**	**0.05**	**0.09**	**0.044**	**0.040**	**0.306**	
M								0.002	

As a result, the exterior transmission function will be:

$$QSOL = 0.002 \times (Toa - 17) + 0.13 \tag{7}$$

The interior solar transmission load calculation is similar to the exterior one and is shown in Table 13.

Table 13 Interior transmission loads - solar component through opaque walls & roof

Occupied / Unoccupied Period **Interior Zone**									
			NW	**SW**	**SE**	**NE**	**Roof**	**Total**	**Reference**
Roof Area Interior Zone	64,592	ft²					64592		
U-value (Walls/Roof)		Btu/(ft² hr F)					0.06		
CLTDS(L=32Jan)							7		Table 3.3 [13]
CLTDS(L=32Jul)							23		Table 3.3 [13]
Ki							0.75		
Percent of Possible Sunshine, PPS (Jan)							0.46		Table 3.1 [13]
Percent of Possible Sunshine, PPS (Jul)							0.76		Table 3.1 [13]
Building Conditioned Floor Area	322960	ft²							
Transmission loads - Solar component thru opaque roof	**JAN**						**0.03**	**0.03**	
	JUL						**0.16**	**0.16**	
M								0.0015	

As a result, the interior transmission function will be:

$$QSOL = 0.0015 \times (Toa - 17) - 0.03 \qquad \textbf{(8)}$$

Transmission loads - conduction through opaque walls, windows, floor, and roof

For calculating conduction through the opaque walls, windows, floor and roof, the following equation from the ASHRAE [13] was used.

$$Q_T = \frac{\sum_{i=1}^{NSURF} A_i \cdot U_i \cdot (T_{OA} - T_i)}{t \cdot A_F} \qquad \textbf{(9)}$$

All the values used for the conduction load calculations, as well as $\frac{\sum_{i=1}^{NSURF} A_i \cdot U_i}{t \cdot A_F}$, are shown in Table 14.

Table 14 Exterior transmission loads - conduction through opaque walls, windows, floor & roof

Occupied / Unoccupied Period Exterior Zone								
			NW	**SW**	**SE**	**NE**	**Roof**	**Total**
Building Conditioned Floor Area	322960	ft²						
Area of Walls without Windows	46170	ft²	16434	9860	16434	9860	16148	
Roof Area Exterior Zone	16148	ft²						
Windows	5130	ft²	4109	2465	4109	2465	0	
U-value (Walls/Roof)	0.21	Btu/(ft² hr F)	0.21	0.21	0.21	0.21	0.06	
U-Value of Windows	1.1	Btu/(ft² hr F)	1.1	1.1	1.1	1.1	1.1	
Inside Temperature Tdb	75	F						
UA Walls / Roof		Btu/(ft² hr F)	3458	2075	3458	2075	991	12056
UA Windows		Btu/(ft² hr F)	4519	2712	4519	2712	0	14462
Ground: UAground	200	Btu/(ft² hr F)						
(UA/Af)			**0.083**					

As a result, the exterior transmission function will be:

$$Q_T = \frac{\sum_{i=1}^{NSURF} A_i \cdot U_i}{t \cdot A_F} \times T_{OA} - \frac{\sum_{i=1}^{NSURF} A_i \cdot U_i}{t \cdot A_F} \times T_i \qquad \textbf{(10)}$$

$$QT = 0.083 \times (Toa) - 6.20 \qquad \textbf{(11)}$$

The interior transmission conduction load calculation is similar to the exterior one and is shown in Table 15.

Table 15 Interior transmission loads - conduction through opaque walls, windows, floor & roof

Occupied / Unoccupied Period Interior Zone								
			NW	**SW**	**SE**	**NE**	**Roof**	**Total**
Building Conditioned Floor Area	322960	ft²						
Roof Area Interior Zone	64,592	ft²						
Skylight Area	3584	ft²						
U-value (Walls/Roof)	0.06	Btu/(ft² hr F)						
U-Value of Windows	1.1	Btu/(ft² hr F)						
Inside Temperature Tdb	75	ft²						
UA windows	3942.4							
UA roof	3966							
Ground: UAground	800							
(UA/Af)	**0.027**							

As a result, the interior transmission function will be:

$$QSOL = 0.027 \times (Toa) - 2.02 \tag{12}$$

The exterior and interior heat gains through lighting, equipment, and people for both the occupied period and the unoccupied period are shown in the Table 16 and Table 17.

Table 16 Exterior heat gain

Occupied Period Exterior Zone		
Total Lighting and Equipment Gain Exterior Zone	581,272	Btu/hr
Sensible Exterior Load (Occupied)	82355	Btu/hr
Latent Exterior Load (Occupied)	82355	Btu/hr
Building Conditioned Floor Area	322960	ft²
Sensible Exterior Loads	2.05	Btu/hr ft²
Latent Exterior Loads	0.26	Btu/hr ft²
Unoccupied Period Exterior Zone		
Total Lighting and Equipment Gain Exterior Zone	261,151	Btu/hr
Sensible Exterior Loads (Unoccupied)	12353	Btu/hr
Latent Exterior Loads (Unoccupied)	12353	Btu/hr
Building Conditioned Floor Area	322960	ft²
Sensible Exterior Loads	0.85	Btu/hr ft²
Latent Exterior Loads	0.04	Btu/hr ft²

Table 17 Interior heat gain

Occupied Period Interior Zone		
Total Lighting and Equipment Gain Interior Zone	2,325,087	Btu/hr
Sensible Interior Load (Occupied)	329,419	Btu/hr
Latent Interior Load (Occupied)	329,419	Btu/hr
Building Conditioned Floor Area	322,960	ft²
Sensible Inerior Loads	8.22	Btu/hr ft²
Latent Interior Loads	1.02	Btu/hr ft²
Unoccupied Period Interior Zone		
Total Lighting and Equipment Gain Interior Zone	1,044,604	Btu/h
Sensible Interior Load (Unoccupied)	49,413	Btu/hr
Latent Interior Loads (Unoccupied)	49,413	Btu/hr
Building Conditioned Floor Area	322,960	ft²
Sensible Interior Loads	3.39	Btu/hr ft²
Latent Interior Loads	0.15	Btu/hr ft²

By adding the obtained linear functions of loads, sensible and latent loads for the interior and exterior zones are gained, which are represented in Table 18.

Table 18 Exterior and interior loads

Exterior Zone- Sensible Loads, Btu/hr ft²	$q_{e,s}=$	0.065	x	Toa	+	-2.86
Interior Zone- Sensible Loads, Btu/hr ft²	$q_{i,s}=$	0.0301	x	Toa	+	3.78
Exterior Zone- Latent Loads, Btu/hr ft²	$q_{e,l}=$					0.15
Interior Zone - Latent Loads, Btu/hr ft²	$q_{i,l}=$					0.59

Latent and sensible loads for the interior and exterior zones according to the outside air temperature are shown in Fig. 7. As can be seen in Fig. 7, the highest energy amount required for the building is for providing the interior sensible load, which is almost 7 times more than the required latent loads.

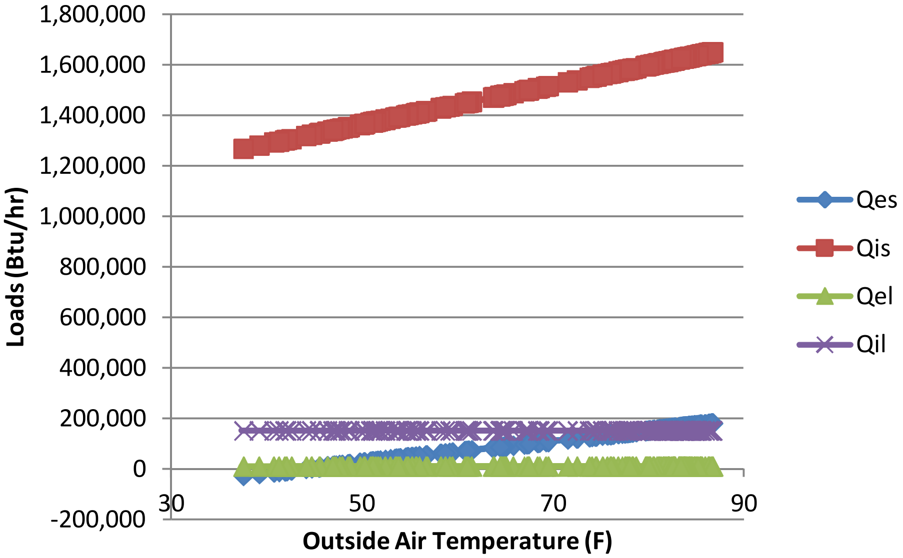

Fig. 7 Latent and sensible loads

CHAPTER III

CONSTANT-VOLUME TERMINAL REHEAT (CVTR) SYSTEM

Constant-volume terminal reheat systems are the simplest air handling units which can keep the room temperature at a comfortable level, but they have the largest energy waste because the supply and return fans run at their full load even when not required. These systems supply conditioned air to the interior space of the building. This conditioned air is provided by mixing the outside fresh air and return air (from the interior space) based on the comfortable temperature demand. Mixed air temperature should be kept at 55°F; therefore when the outside air temperature is between 55°F and 60°F, no heat is added or removed. As the outside air temperature (OAT) goes above 60°F or below 55°F, the system requires cooling or heating. Fig. 8 shows the CVTR system used in the project.

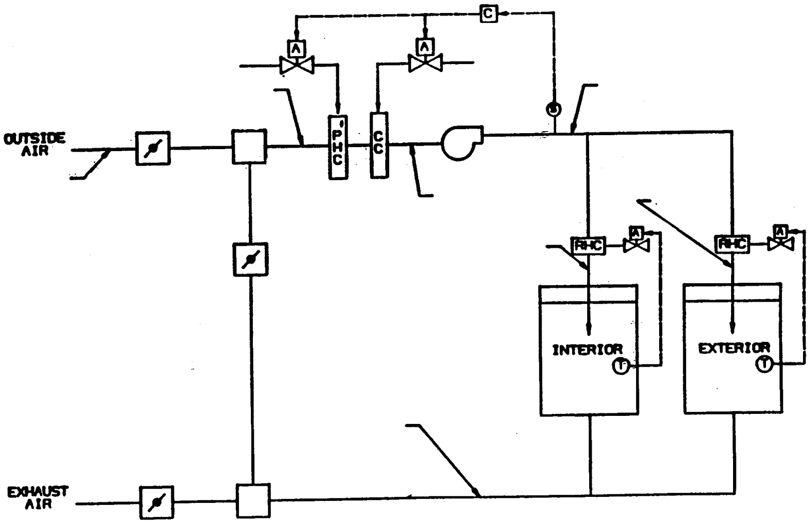

Fig. 8 Constant Volume Terminal Reheat system schematics

The sensible and latent loads of the interior and exterior of the building were calculated in Chapter II. By having this initial data and building characteristics from Chapter I, a simulation for the CVTR system can be started. Inputs for the base case simulation are shown in Table 19.

Table 19 Inputs for the base case simulation for CVTR, CVDD, and DDVAV

Building Conditioned Floor Area	322960	ft^2
Minimum Supply air	0.3	cfm/ft^2
Minimum outdoor air	20%	
qfan, rated	0	Btu/hr
Design Volume	322960	cfm
Cooling coil temp, TCL	55	°F
Economizer (1=yes, 0=no)	0	Building Doesn't Have
Hot Deck Add	0	°F
Add Load Sensible	0	$Btu/hr\ ft^2$
Add Load Latent	0	$Btu/hr\ ft^2$

The following steps are used for simulating the energy consumption of the building for the CVTR system.

1. Compute cooling coil-leaving air temperature (fan after coil)

$$T_{CL} = T_s - \Delta T_{Sf}$$

2. Compute zone supply temperatures

$$T_{iS} = T_i - \frac{q_{iS}}{1.08V_i}$$

$$T_{eS} = T_e - \frac{q_{eS}}{1.08V_i}$$

3. Compute zone reheat energy

If $T_{is}>T_s$ then: $q_{iRH} = 1.08V_i(T_{is} - T_s)$ Else: $q_{iRH}=0$

If $T_{es}>T_s$ then: $q_{eRH} = 1.08V_e(T_{es} - T_s)$ Else: $q_{eRH}=0$

4. Compute zone return temperatures

$$T_{iR} = T_i + \frac{q_{iR}}{1.08V_i}$$

$$T_{eR} = T_e + \frac{q_{eR}}{1.08V_i}$$

5. Compute average return temperature

$$T_R = \frac{T_{iR}V_i + T_{eR}V_e}{V_{TD}}$$

$$V_{TD} = V_i + V_e$$

6. Compute mixed air dry bulb temperature

$$T_{MA} = T_R + X_{OA}(T_{OA} - T_R)$$

$$T_{PHe} = T_{MA}$$

7. Compute preheat coil-leaving air dry bulb temperature and preheat coil energy

If $T_{PHe} < T_{CL}$ $\qquad q_{PH} = 1.08V_{TD}(T_{CL} - T_{PHe})$

$T_{PH} = T_{CL}$

Else: $\quad q_{PH} = 0 \quad and\ T_{PH} = T_{PHe}$

8. Compute cooling coil sensible load

$$T_{CE} = T_{PH}$$

$$q_{CS} = 1.08V_{TD}(T_{CE} - T_{CL})$$

9. Compute total reheat load

$$q_{RH} = q_{RHi} + q_{RHe}$$

10. Determine if coil is wet or dry

If coil is wet,

$$W_R' = W_{CLw} + \Delta W_{latload} \simeq W_{CL} + \frac{q_{le} + q_{li}}{4840V_{TD}} = W_{CLw} + \frac{q_{lat}}{4840V_{TD}}$$

$$W_{MA}' = W_R' + X_{OA}(W_{OA} - W_R')$$

If coil is dry,

$$W_{CLd} = X_{OA}W_{OA} + (1 - X_{OA})\mathrm{W_R}''$$

$$W_R = \mathrm{W_{CLd}} + \left(\frac{\mathrm{q_{lat}}}{4840\mathrm{V_{TD}}}\right) = \mathrm{X_{OA}W_{OA}} + (1\text{-}\mathrm{X_{OA}})\mathrm{W_R} + \frac{\mathrm{q_{lat}}}{4840\mathrm{V_{TD}}}$$

$$\Rightarrow \quad \mathrm{W_R}''(1 - 1 + X_{OA}) = \mathrm{X_{OA}W_{OA}} + \frac{\mathrm{q_{lat}}}{4840\mathrm{V_{TD}}}$$

$$\mathrm{W_R}'' = \mathrm{W_{OA}} + \frac{\mathrm{q_{lat}}}{4840\mathrm{X_{OA}}\ \mathrm{V_{TD}}}$$

$$W_{MA} = \mathrm{W_R}'' + X_{OA}(W_{OA} - \mathrm{W_R}'')$$

$$W_R = MIN\ (W_R', \mathrm{W_R}''\ )$$

$$W_{MA} = MIN\ (W_{MA}', \mathrm{W_{MA}}''\ )$$

$$W_{CL} = W_{CLd} \quad \text{if} \quad W_R = \mathrm{W_R}''$$

$$= W_{CLw} \quad \text{if} \quad W_R = W_R'$$

a) Compute return air humidity ratio

$$W_{iR} = W_{CL} + \frac{q_{iL}}{4840V_i}$$

$$W_{eR} = W_{CL} + \frac{q_{eL}}{4840V_e}$$

$$W_R = (W_{iR}V_i + W_{eR}V_e)/V_{TD}$$

b) Compute mixed air humidity ratio

$$W_{MA} = W_R + X_{OA}(W_{OA} - W_R)$$

11. Compute cooling coil latent load

If $W_{CL} > W_{CLw}$ where W_{CLw} is the coil leaving humidity ratio for wet coil conditions, then:

$$q_{CL} = 4840V_{TD}(W_{MA} - W_{CL})$$

Else: $q_{CL} = 0$

12. Compute total cooling coil load

$$q_{CT} = q_{CS} + q_{CL}$$

After running the simulation, cooling loads and heating loads were drawn according to the outside air temperature as shown in Fig. 9.

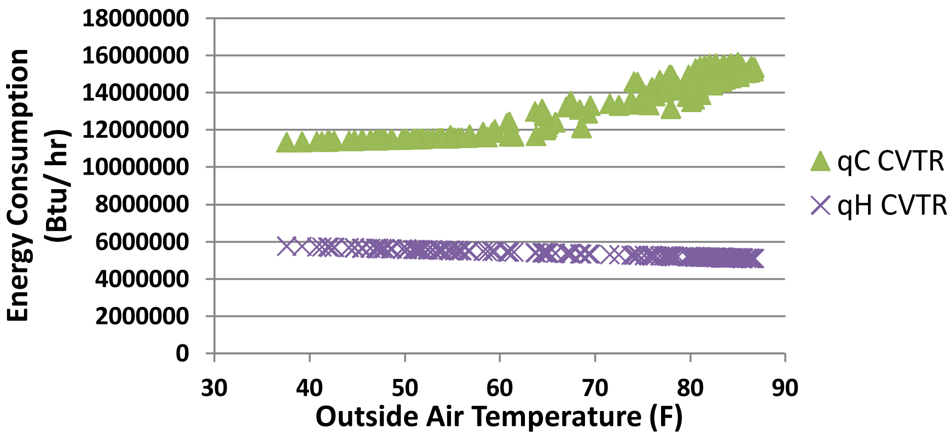

Fig. 9 Energy consumption for CVTR system

Fig. 10 represents the relative humidity ratio and outside air humidity ratio according to the outside air temperature.

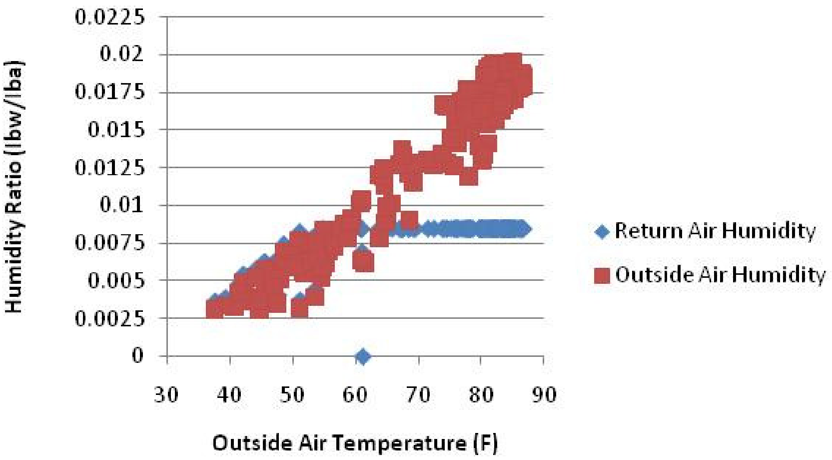

Fig. 10 Return air and outside air humidity ratio for CVTR system

Dual-Duct Constant Volume (DDCV)

Dual duct constant volume units perform almost the same as CVTR but the mixed air exiting the supply fan in DDCV is separated and sent to two different paths: continuously operating heating coils and continuously operating cooling coils. The air streams exiting the cooling and heating coils are mixed again to reach the desired temperature before entering the interior and exterior zones. Fig. 11 shows the DDCV system used in the project.

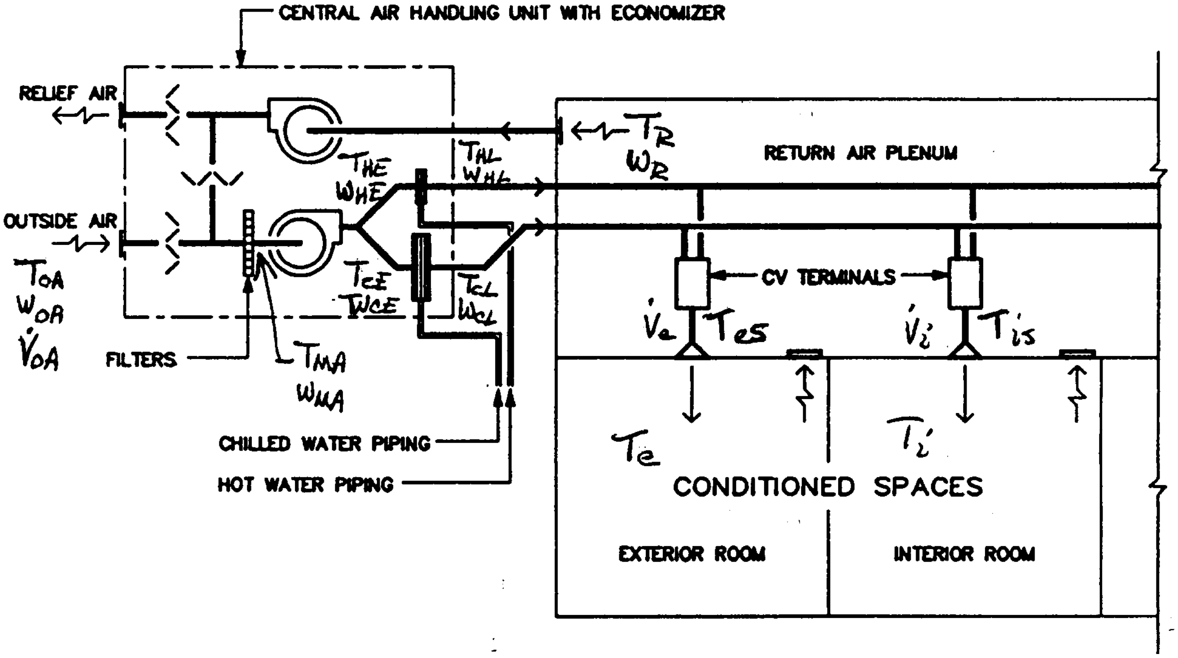

Fig. 11 Dual-duct constant volume system schematics

For calculating the CVDD system, again the calculated data from Chapters I and II is used as the input of the simulation and the steps presented below are followed in the Excel simulation. The input data are the same as the inputs in Table 19.

Summary of the CVDD system solution

To solve for the coil loads in a dual-duct constant volume system:

1. Find supply air temperatures.

$$T_{iS} = T_i - \frac{q_{iS}}{1.08\dot{V}_i} \qquad T_{eS} = T_e - \frac{q_{eS}}{1.08\dot{V}_e}$$

2. Compute return air temperatures.

$$T_{iR} = \mathrm{T_i} + \frac{\mathrm{q_{iR}}}{1.08\dot{V}_i} \qquad T_{eR} = \mathrm{T_e} + \frac{\mathrm{q_{eR}}}{1.08\dot{V}_e}$$

3. Compute average return air temperature.

$$T_R = \frac{\mathrm{T_{iR}}\dot{V}_i + \mathrm{R_{eR}}\dot{V}_e}{\dot{V}_i + \dot{\mathrm{V}}_\mathrm{e}}$$

4. Compute mixed air temperature.

$$T_{MA} = T_R + X_{OA}\,(T_{OA} - T_R) \qquad X_{OA} = \frac{\dot{V}_{OA}}{\dot{V}_{TD}}$$

5. Compute preheat coil load and leaving conditions

If $T_{MA} < T_{CL} - \Delta T_{sf}$, Then $q_{PH} = 1.08\ \dot{V}_{TD}\ (T_{CL} - T_{PH})$ and $T_{PH} = T_{CL} - \Delta T_{sf}$

Otherwise $q_{PH} = 0$ and $T_{PH} = T_{MA}$

6. Compute coil entering temperature.

$T_{CE} = T_{HE} = T_{PH} + \Delta T_{sf}$

7. Determine heating coil leaving air temperature.

This is done using the reset schedule for the system being analyzed.

8. Compute air flow through the coils for <u>each zone</u> (mixed air calculation).

$$\dot{V}_{iH} = \dot{V}_i \frac{T_{iS} - T_{CL}}{T_{HL} - T_{CL}} \quad \text{and} \quad \dot{V}_{iC} = \dot{V}_i - \dot{V}_{iH}$$

$$\dot{V}_{eH} = \dot{V}_e \frac{T_{eS} - T_{CL}}{T_{HL} - T_{CL}} \quad \text{and} \quad \dot{V}_{eC} = \dot{V}_e - \dot{V}_{eH}$$

9. Compute total flow through each coil.

$$\dot{V}_H = \dot{V}_{iH} + \dot{V}_{eH} \quad \text{and} \quad \dot{V}_C = \dot{V}_{iC} + \dot{V}_{eC}$$

10. Compute cooling coil sensible load.

$$q_{cs} = 1.08\ \dot{V}_C\ (T_{CE} - T_{CL})$$

11. Compute system humidity ratios.

(a) Return air humidity ratio

$$\text{Let} \quad x_C = \frac{\dot{V}_C}{\dot{V}_{TD}} \qquad x_H = \frac{\dot{V}_H}{\dot{V}_{TD}} \qquad x_{OA} = \frac{\dot{V}_{OA}}{\dot{V}_{TD}} \quad x_R = \frac{\dot{V}_R}{\dot{V}_{TD}}$$

$$w_R = \frac{x_C w_{CL} + x_H x_{OA} w_{OA} + \dfrac{q_{iL} + q_{eL}}{4840\ \dot{V}_{TD}}}{1 - x_H x_R} \quad \text{When } w_{MA} > w_{CLwet}$$

$$w_R = \frac{x_{OA} w_{OA} + \dfrac{q_{iL} + q_{eL}}{4840 \dot{V}_{TD}}}{1 - x_R} \quad \text{When } w_{MA} < w_{CLwet}$$

(b). Compute mixed air humidity ratio

$$w_{MA} = w_R + x_{OA}\ (w_{OA} - w_R)$$

12. Compute cooling coil latent load.

If $w_{CE} > w_{CLwet}$ $\qquad q_{CLat} = 4840\ \dot{V}_C\ (w_{CE} - w_{CLwet})$

Otherwise $q_{CLat} = 0$

13. Compute cooling coil total load.

$$q_{CT} = q_{CS} + q_{CLat}$$

14. Compute heating coil load.

$$q_H = 1.08\ \dot{V}_H (T_{HE} - T_{HL})$$

The cooling and heating loads according to the outside air temperature of CVDD are shown in Fig. 12.

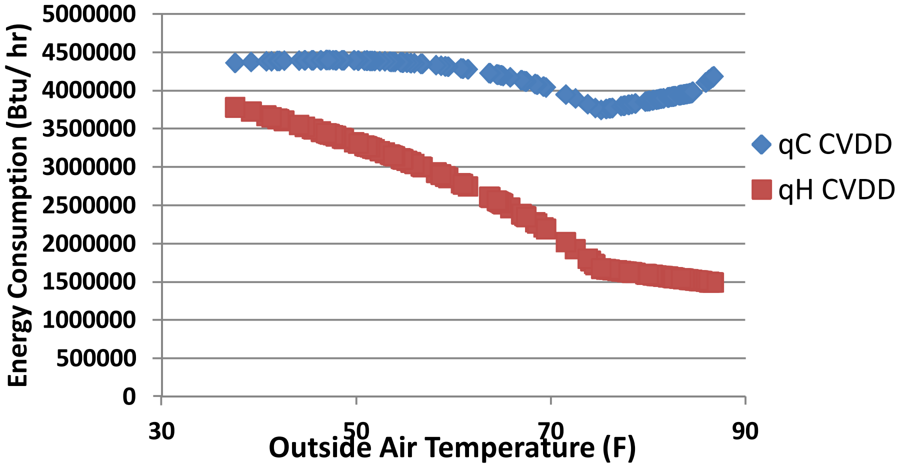

Fig. 12 Cooling and heating loads for CVDD

Relative humidity ratio and outside air humidity ratio according to the outside air temperature of CVDD are also represented in Fig. 13.

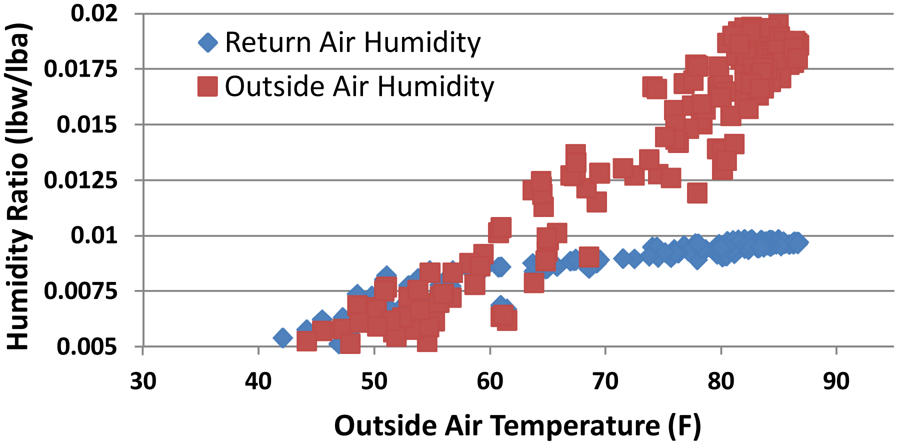

Fig. 13 Return and outside air humidity ratios for CVDD

CHAPTER IV

SYSTEMS MODEL DESCRIPTION

The AHU (air handling unit) for the Zachry building is a dual duct variable air volume (DDVAV) system. DDVAVs have the potential to be efficient and comfortable, but they often have significant opportunities for improvement.

In dual-duct systems, the air handling unit has two coils, a continuously-operating cooling coil and a continuously-operating heating coil. The cooling coil feeds chilled air into a cold-air duct. The heating coil feeds hot air into a hot-air duct. The two ducts run in parallel throughout the building. At each space, air is tapped from the two ducts by a terminal unit. The terminal unit has a hot air damper and a cold air damper. When the space thermostat calls for heating, the hot air damper opens. When the thermostat calls for cooling, the cold air damper opens. Efficiency suffers if a terminal unit mixes chilled air with heated air under any conditions. The system may be designed to do this deliberately under low conditioning loads to maintain a minimum airflow into the spaces. Fig. 14 shows the DDVAV system used in the project.

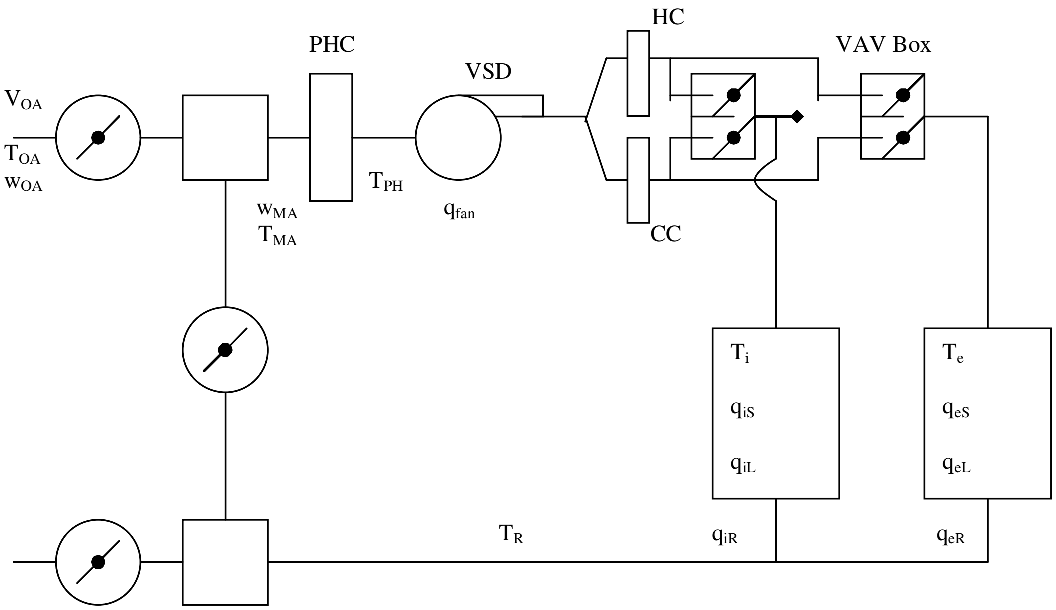

Fig. 14 DDVAV system

The input data used for basic simulation of the DDVAV is the same as the data used in the CVTR and CVDD simulations and are taken from Chapters I and II. The following steps are processed in the simulation in Excel and the results are shown in Figures 15-19.

1. Compute zone supply volumes

$V_i \;=\; V_{iC}$ if $q_i > 0$ & $V_{iC} > V_{i\,min}$

V_{iH} if $qi < 0$ & $V_{iH} > V_{i\,min}$

If $q_{is} > 0$

$V_{iC} = q_{is}/[1.08(T_i - T_s)] = q_{is}/[1.08(T_i - T_{CL})]$

If $q_{is} < 0$

$V_{iH} = |q_{is}|/[1.08(T_i - T_{HL})]$

If $V_i < V_{i,min}$ is as calculated above, then set $V_i = V_{i,min}$ and determine V_{iH} and V_{iC} as for a DDCV system with flow $V_{i,min}$.

Likewise,

If $q_{es} > 0$

$V_{eC} = q_{es}/[1.08(T_i - T_{CL})]$

If $q_{es} < 0$

$V_{eH} = |q_{es}|/[1.08(T_i - T_{HL})]$

If $V_e < V_{e,min}$ is as calculated above, then set $V_e = V_{e,min}$ and determine V_{eH} and V_{eC} as for a DDCV system with flow $V_{e,min}$.

2. Compute return air temperature

$T_{iR} = T_i + q_{iR}/1.08V_i$

$T_{eR} = T_e + q_{eR}/1.08V_e$

3. Compute average return air temperature

$T_R = [V_eT_{eR} + V_iT_{iR}] / [V_e + V_i]$

4. Compute mixed air temperature

$T_{MA} = T_R + X_{OA}(T_{OA} - T_R);\quad X_{OA} = V_{OA} / V_T$

5. Compute preheat coil load and leaving conditions

if $T_{MA} > T_{CL} - \Delta T_{sf}$ then $q_{PH} = 0$ and $T_{PH} = T_{MA}$

if $T_{MA} < T_{CL} - \Delta T_{sf}$ then $q_{PH} = 1.08V_T(T_{PH} - T_{MA})$ and $T_{PH} = T_{CL} - \Delta T_{sf}$

where,

$\Delta T_{sf} = q_{fan}/1.08V_T$

$q_{fan} = [0.00153 + 0.0052(PLR) + 1.1086(PLR)^2 - 0.1164(PLR)^3]q_{rated}$

$PLR = V_T/V_{TD}$

6. Compute coil entering temperature

$T_{CE} = T_{HE} = T_{PH} + \Delta T_{sf}$

7. Compute total flow through each coil for each zone

If $V_i > V_{i,min}$ & $q_{is} > 0$, $V_{iC} = V_i$ & $V_{iH} = 0$

If $V_i > V_{i,min}$ & $q_{is} < 0$, $V_{iH} = V_i$ & $V_{iC} = 0$

If $V_i < V_{i,min}$ determine V_{iH} and V_{iC} as for a DDCV system with flow $V_{i,min}$.

Similarly,

If $V_e > V_{e,min}$ & $q_{es} > 0$, $V_{eC} = V_e$ & $V_{eH} = 0$

If $V_e > V_{e,min}$ & $q_{es} < 0$, $V_{eH} = V_e$ & $V_{eC} = 0$

If $V_e < V_{e,min}$ determine V_{eH} and V_{eC} as for a DDCV system with flow $V_{e,min}$.

8. Compute total flow through each coil

$$\dot{V}_H = \dot{V}_{iH} + \dot{V}_{eH} \quad \text{and} \quad \dot{V}_C = \dot{V}_{iC} + \dot{V}_{eC}$$

9. Compute cooling coil sensible load

$$q_{cS} = 1.08V_c(T_{CE} - T_{CL})$$

10. Compute return air humidity ratio

$$\text{Let} \quad X_C = \frac{\dot{V}_C}{\dot{V}_T} \qquad X_H = \frac{\dot{V}_H}{\dot{V}_T} \qquad X_{OA} = \frac{\dot{V}_{OA}}{\dot{V}_T} \qquad X_R = \frac{\dot{V}_R}{\dot{V}_T}$$

$$w_R = \{X_c w_{CL} + X_H X_{OA} w_{OA} + [q_{iL}+q_{eL}/4840V_T]\}/[1 - X_H X_R] \quad \text{when } w_{MA} > w_{CLwet}$$

$$w_R = \frac{x_{OA} w_{OA} + \dfrac{q_{iL} + q_{eL}}{4840\dot{V}_T}}{1 - x_R} \quad \text{when } w_{MA} < w_{CLwet}$$

11. Compute mixed air humidity ratio

$$w_{MA} = w_R + X_{OA}(w_{OA} - w_R)$$

12. Compute cooling coil latent load

If $w_{CE} > w_{CLwet}$

then $q_{CLat} = 4840V_C(w_{CE} - w_{CLwet})$

Otherwise $q_{CLat} = 0$

13. Compute cooling coil total load

$$q_{CT} = q_{cS} + q_{CLat}$$

14. Compute q_H

$$q_H = 1.08V_H(T_{HE} - T_{HL})$$

Measured data analysis

For analyzing measured data, the energy balance method is used. This is a thermodynamic model. The heat flow and the enthalpy flow across the boundary of the control volume and the work performed on the control volume may be broken into seven major components: internal heat gain from lighting and equipment ($fWbele$), heating provided to the building by the HVAC system ($Wbheat$), heat removed from the building by the cooling system ($Wbcool$), solar radiation through the envelope (Q_{sol}), ventilation air and infiltration via doors, windows, and air-handling units (Q_{air}); heat transmission through the building structure (Q_{con}); and heat gain from occupants (Q_{occ})[13].

Assuming constant internal temperature of the building, constant building space, no energy stored in the system, and no energy generated in the system, heat balance may be expressed as [18]:

$$fWbele + Wbheat - Wbcool + Q_{sol} + Q_{air} + Q_{con} + Q_{occ} = 0 \qquad \textbf{(13)}$$

$Wbele$, $Wbcool$ and $Wbheat$ are separately metered and monitored in the buildings considered in this paper while the last four terms in (13 are not metered. A term, herein called energy balance load (E_{BL}), is introduced to represent all the measured values of the energy balance equation. Then

$$E_{BL} = -(Q_{sol} + Q_{air} + Q_{con} + Q_{occ}) \\ = fWbele + Wbheat - Wbcool \qquad \textbf{(14)}$$

Note that the term $fWbele$ contains a fraction, f of the non-cooling electric consumption in the building that is converted to internal gain. This fraction f must be estimated. In our case f is set to 1. All other portions of E_{BL} are given in measured data. All these calculations are shown in the raw data page of the base case spreadsheet. The following plot on Fig. 15, compares the measured hot and chilled water with simulated hot and chilled water.

As observed in the graph, most of the errors of simulation are for chilled water and measured hot water and simulated hot water values are better-matched.

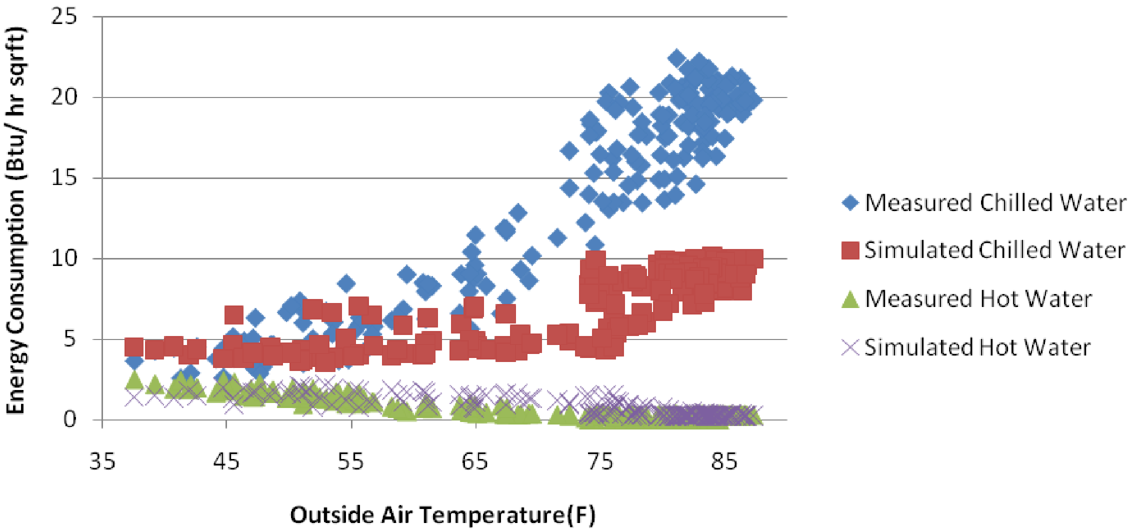

Fig. 15 Measured and simulated energy consumption

The next two plots on Fig. 16 and Fig. 17 represent the total energy consumption of the system according to the outside air temperature and time. As seen in Fig. 16, the energy balance load becomes more negative at higher temperatures, which means more cooling loads are required.

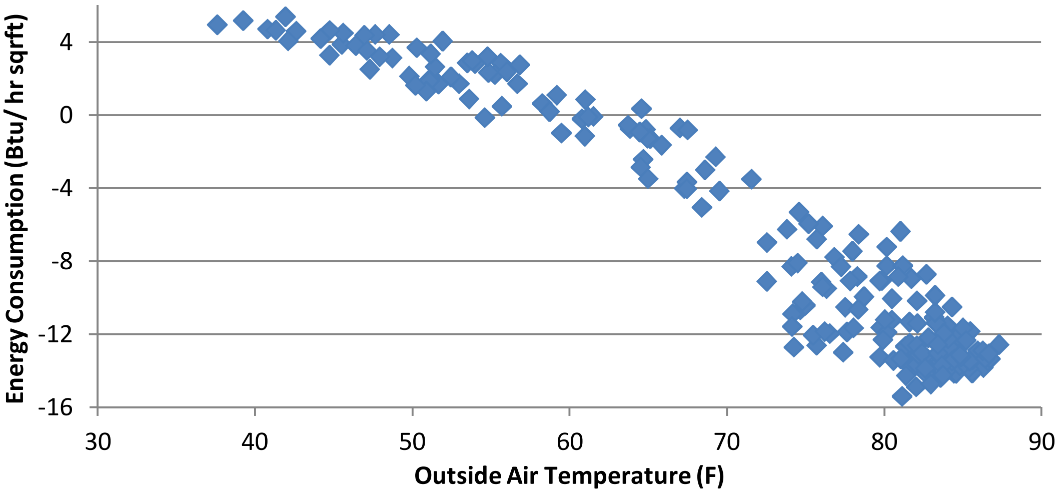

Fig. 16 Energy balance for measured data as a function of outside air temperature

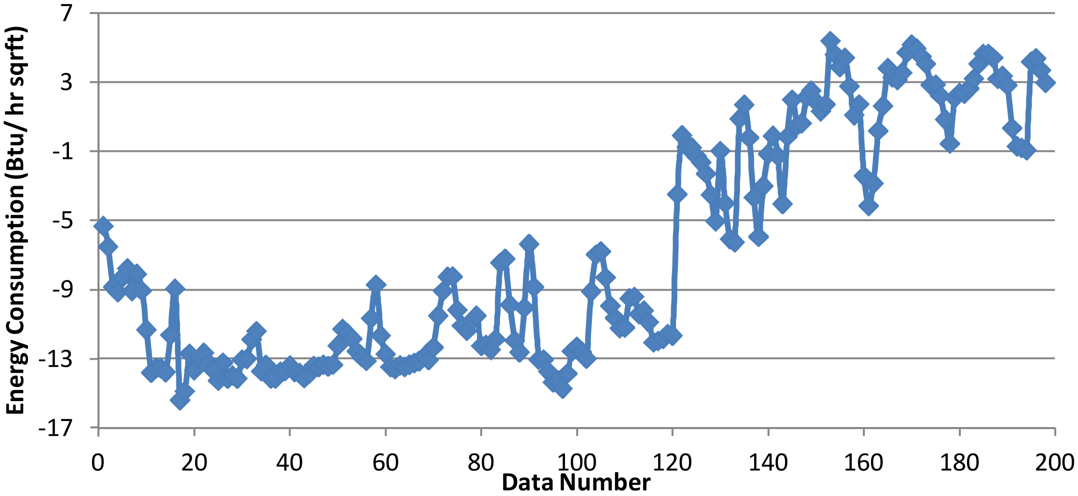

Fig. 17 Energy balance for measured data

Fig. 18 and Fig. 19 are the plots of detailed energy consumption which include measured chilled water, hot water and LTEQ energy consumption according to the outside air temperature and time. As interpreted in Fig. 18 and Fig. 19, most of the energy prepared for the building is to for the cooling needs of the building.

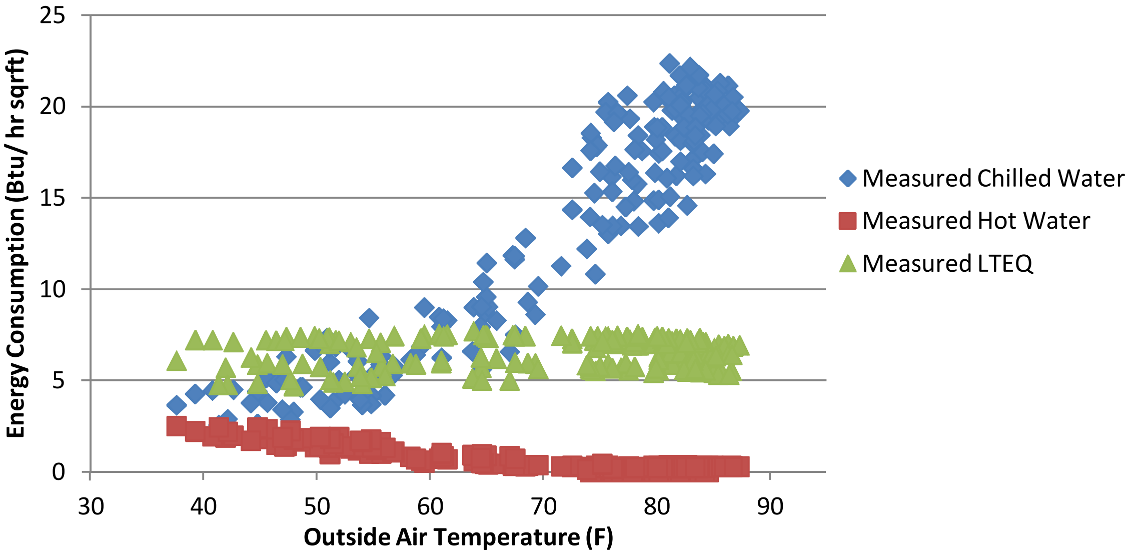

Fig. 18 Energy consumption of chilled water

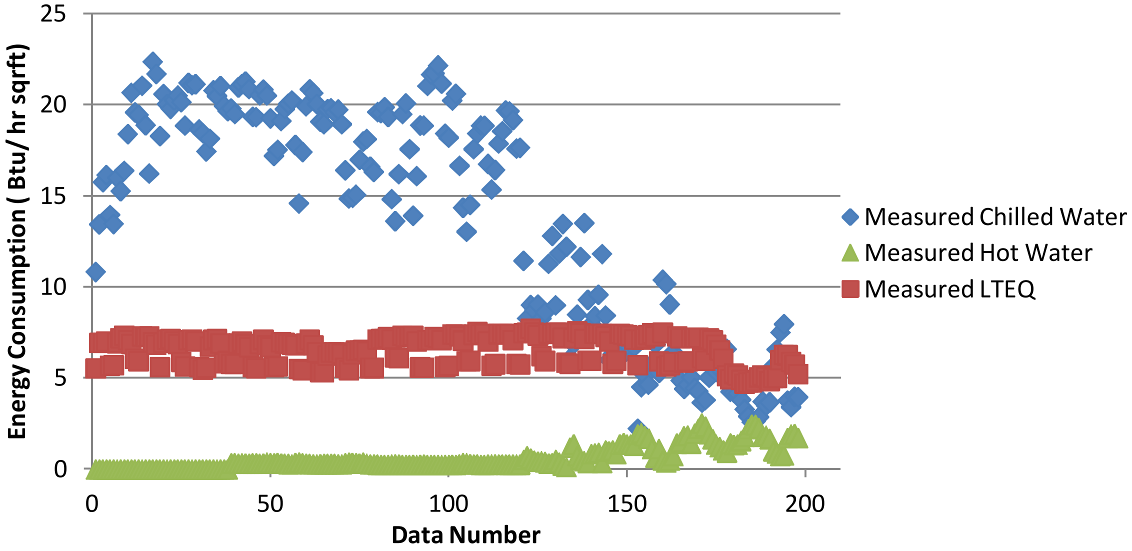

Fig. 19 Energy consumption of chilled water, hot water and LTEQ

Calibration process description

For the calibration part of the project, the calibration signatures for both cooling and heating water consumption are calculated. Calibration signatures can be calculated from the following equation:

$$Calibration\,Signature = \frac{-Residual}{Maximum\,Measured\,Energy} \times 100 \tag{15}$$

$$Residual = Simulated\,Energy\,Consumption - Measured\,Energy\,Consumption \tag{16}$$

Maximum measured energy is the maximum heating or cooling energy from the measured data. The negative sign of residual in (15 is for making the comparison between calibration signatures and characteristic signatures easier. One can easily find the characteristic signature which has a similar shape to the calibration signature instead of looking for the mirror shape. Cooling and heating calibration signatures are drawn according to the outdoor air temperature. Then, the calibration signature is compared to the characteristic signature obtained for the building [17]. Characteristic signatures are similar to calibration signatures. In a characteristic signature, two simulations are compared instead of comparing simulated and measured values. The measured value is going to be considered as one simulation. Then by varying parameters one by one, signatures can be plotted and compared. The published characteristic signature of the Zachry building is used to figure out which one of the parameters in the simulation should be changed to achieve the proper calibration.

Characteristic Signature is defined in the following equation:

$$Characteristic\ Signature = \frac{Change\ in\ Energy\ Consumption}{Maximum\ Energy\ Consumption} \times 100 \quad \textbf{Eqn. 17}$$

The model inputs of the characteristic signatures used during the calibration process were limited to the following parameters: cooling coil temperature, minimum air flow ratio, envelope U-value, floor area, internal heat gain, outside air ratio, zone temperature, and economizer range [11]. Decisions on which parameter to change have been made according to the characteristic signatures which are shown in Figure A1 of appendix. The amount of change has been obtained by minimizing Root Mean Square Error (RMSE) and Mean Bias Error (MBE) for each input parameter.

RMSE and MBE are defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \text{Residual}^2}{n-2}} \quad \textbf{(18)}$$

$$MBE = \sqrt{\frac{\sum_{i=1}^{n} \text{Residual}}{n}} \quad \textbf{(19)}$$

Base case

The following plots are for the base case model simulation, in which the initial input data from Table 20 was applied. The results from the simulation spreadsheet are compared with data from the measured data. The following graphs are for measured and simulated daily chilled water consumption and hot water consumption versus daily average dry bulb temperature and time. The residual graph defined as $E_{measured}$-$E_{simulated}$ is plotted as well.

Table 20 RMSE and MBE errors – base case

Heating RMSE (Btu/hr	0.25
Cooling RMSE (Btu/hr	7.32
Heating MBE (Btu/hr	-0.09
Cooling MBE (Btu/hr	5.90

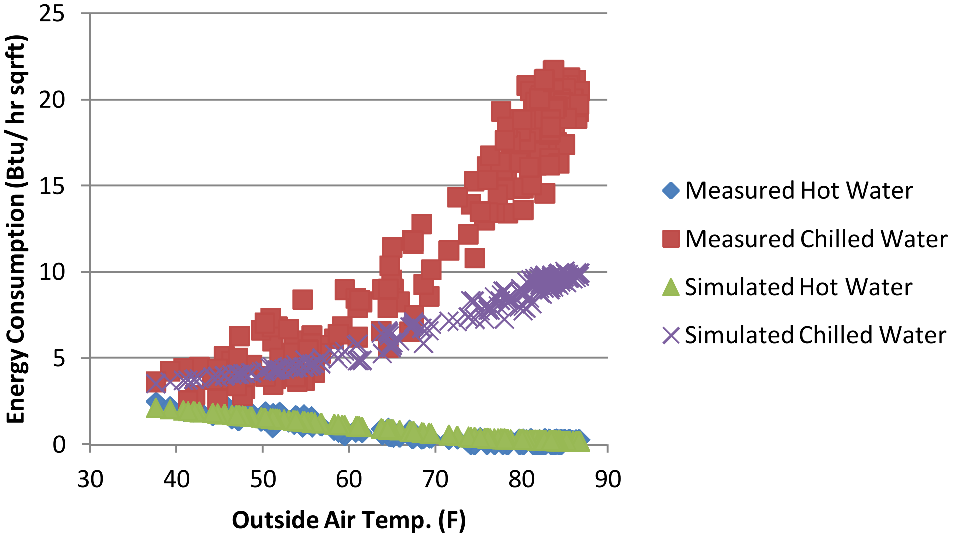

Fig. 20 Simulated and measured consumption for chilled and hot water – base case

By comparing the data from Table 20, it is noticeable that the simulation result matches the measured data better for heating load than for the cooling load. The graphs in Fig. 20 and Fig. 21 offer further proof.

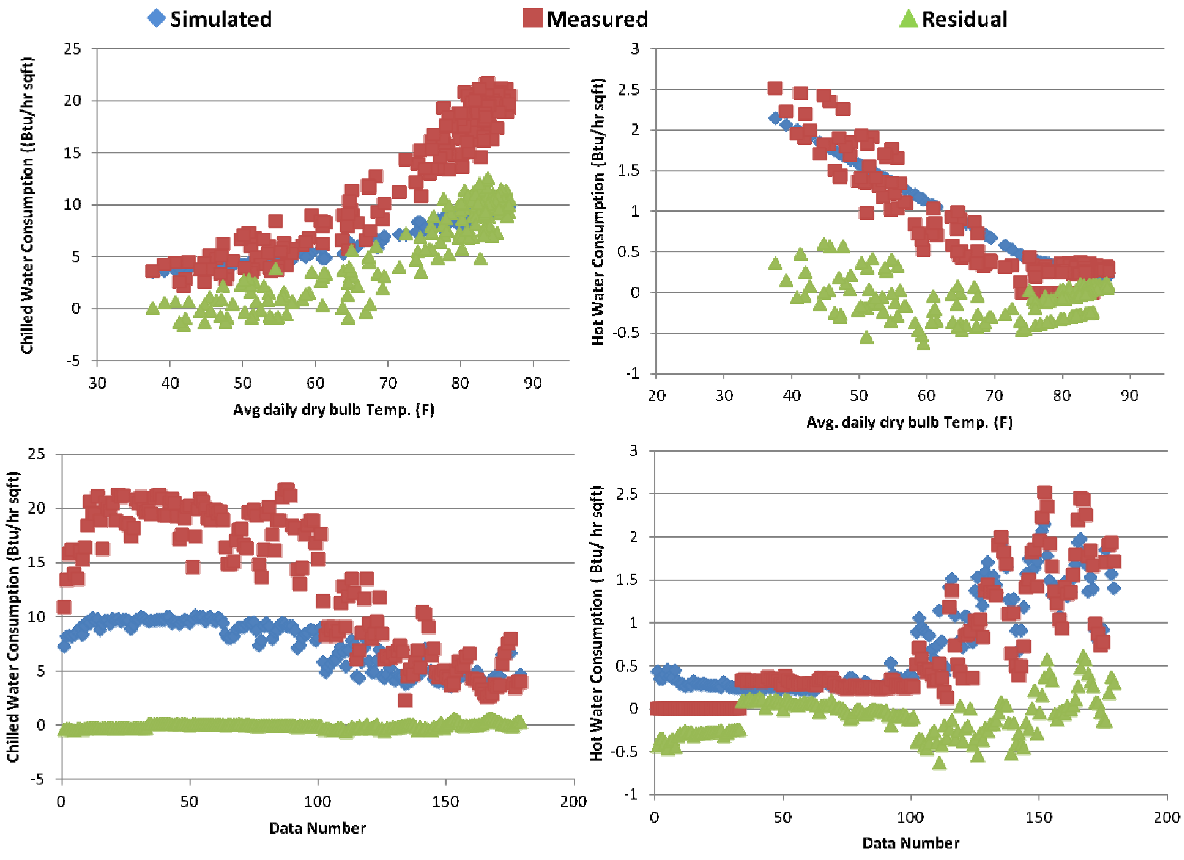

Fig. 21 Simulated, measured, and residual energy consumption for chilled and hot water – base case

Step 1: Increasing min. outdoor air from 20% to 48%

For this step, the characteristic signatures for change to outside air were considered. These signatures were chosen from the characteristic signatures provided for the Zachry building, which can be found in Figure A1. The initial input of minimum outdoor air was changed from 20% to 48%. The results are shown in Fig. 22 after the change is applied.

Table 21 RMSE and MBE errors – step 1 applied

Heating RMSE (Btu/hr ft^2)	0.29
Cooling RMSE (Btu/hr ft^2)	0.29
Heating MBE (Btu/hr ft^2)	-0.15
Cooling MBE (Btu/hr ft^2)	4.26

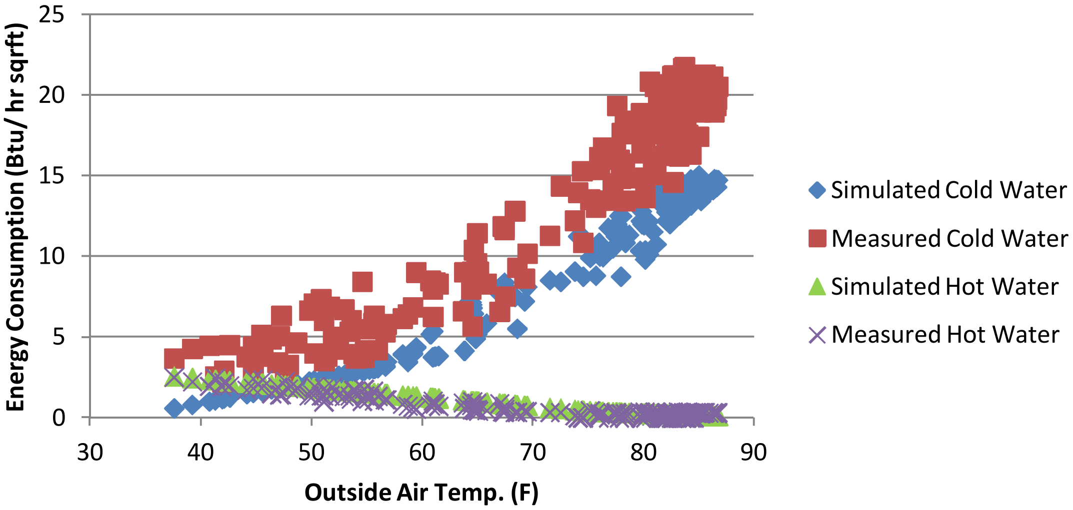

Fig. 22 Simulated and measured consumption for chilled and hot water – step 1 applied

By evaluating the data from Table 21 and the above graph, we can conclude that increasing minimum outdoor air had better effects for cooling than heating. The change applied in the first case, had positive effect on cooling; the cooling MBE and RMSE were decreased by 27% and 96% relatively and had negative effect on heating; the heating MBE and RMSE were increased by 62% and 19% relatively. Fig. 23 shows the measured and simulated Energy consumption for hot water and chilled water after the first change is applied.

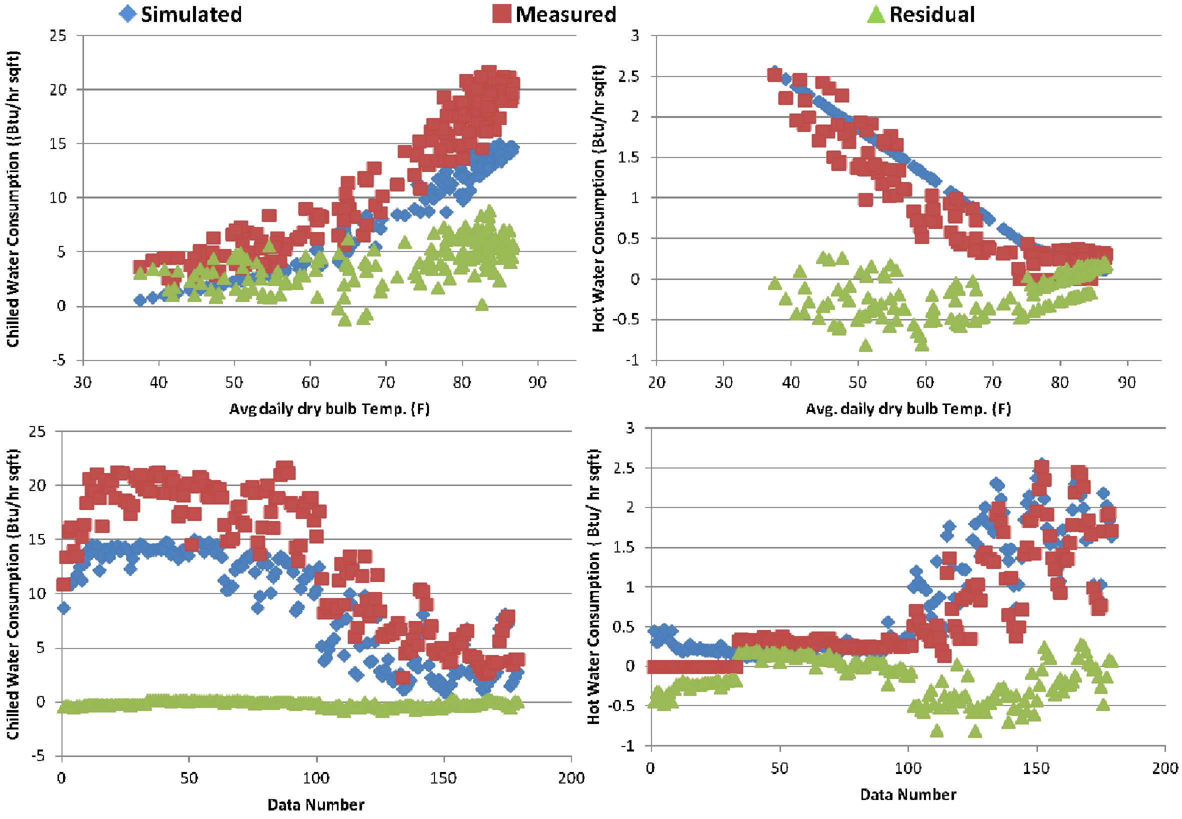

Fig. 23 Simulated, measured, and residual energy consumption for chilled and hot water – step 1 applied

Step 2: Decreasing cooling coil temperature from 55°F to 52°F

For this step, the characteristic signatures for changing the cooling coil leaving temperature were used. These signatures were chosen from the characteristic signatures provided for Zachry building. Cooling coil temperature was changed to 52°F from the 55°F. The results are shown in Fig. 24 after the second change is applied.

Table 22 RMSE and MBE errors – step 2 change applied

Heating RMSE (Btu/hr ft^2)	0.52
Cooling RMSE (Btu/hr ft^2)	7.17
Heating MBE (Btu/hr ft^2)	-0.45
Cooling MBE (Btu/hr ft^2)	5.59

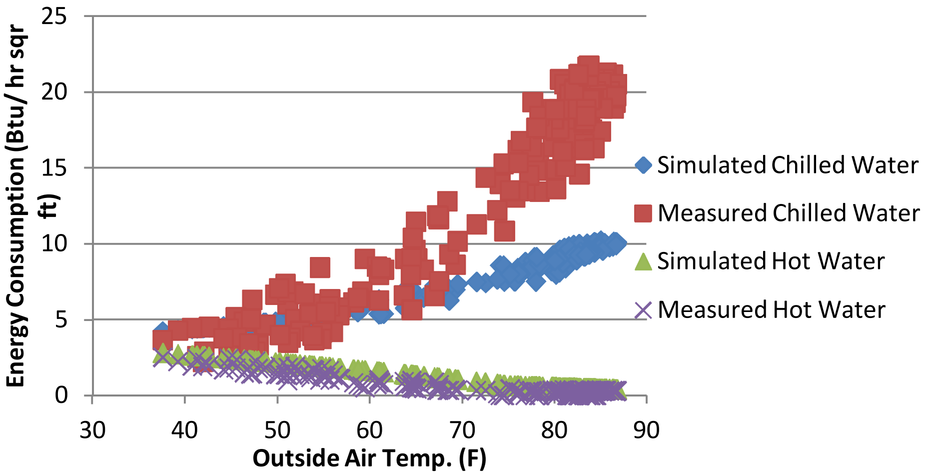

Fig. 24 Simulated and measured consumption for chilled and hot water – step 2 change applied

For this step, the characteristic signatures for changing the cooling coil leaving temperature were used. These signatures were chosen from the characteristic signatures provided for Zachry building. Cooling coil temperature was changed to 52°F from the 55°F.For this step, the characteristic signatures for changing the cooling coil leaving temperature were used. These signatures were chosen from the characteristic signatures provided for Zachry building. Cooling coil temperature was changed to 52°F from the 55°F. The results are shown in Fig. 24 after the second change is applied.

Table 22 and the plots in Fig. 25, we can see that decreasing cooling coil temperature influenced the cooling coil better and had a negative effect on the heating coil. Heating RMSE and MBE are increased by 100% and 400% relatively, while cooling RMSE and MBE are decreased by 2% and 5% relatively.

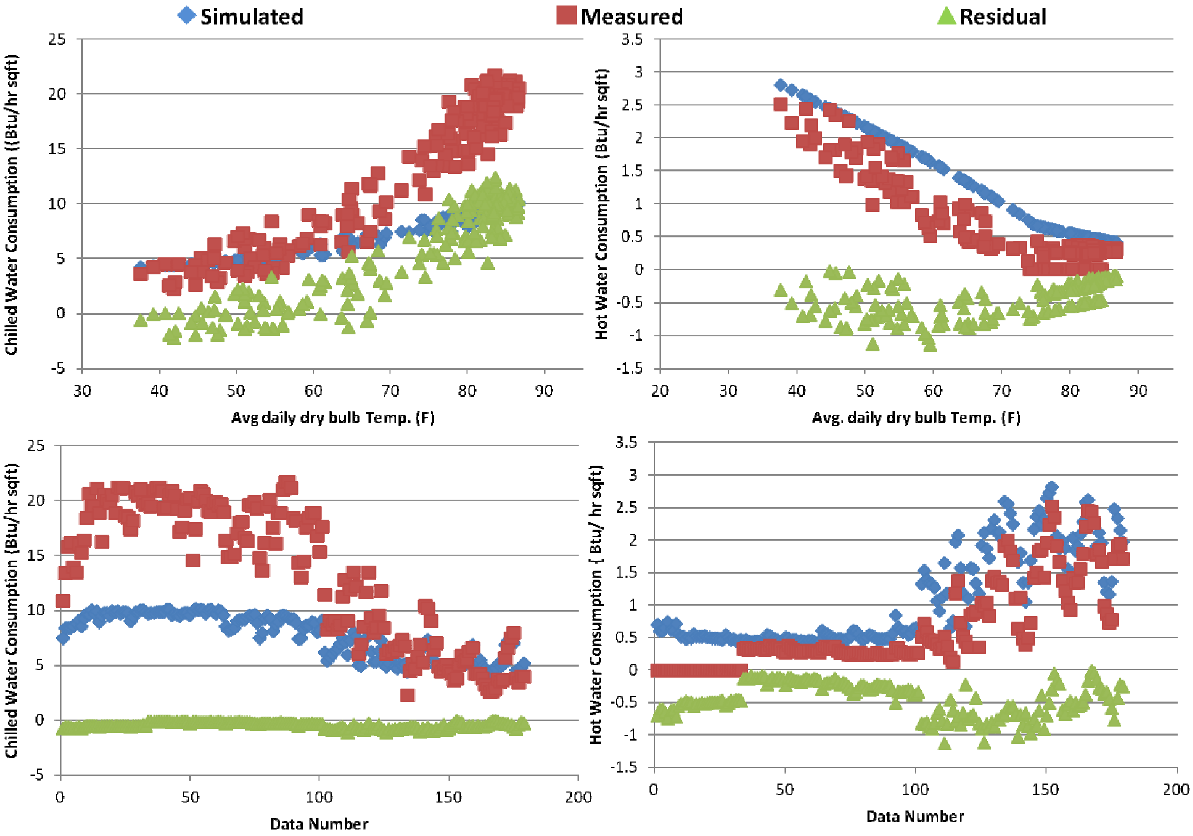

Fig. 25 Simulated, measured, and residual energy consumption for chilled and hot water – step 2 change applied

Step 3: Increasing minimum supply air from 0.30 cfm/ft^2 to 0.39 cfm/ft^2

For this step, the characteristic signatures for changing min. supply air were considered. These signatures were chosen from the characteristic signatures provided for the Zachry building. The min. supply air was varied from 0.30 cfm/sqft to 0.39 cfm/ft2.

Table 23 is a summary of RMSE and MBE after the change was applied. The results are shown in Fig. 26 after the third change is applied.

Table 23 RMSE and MBE errors – step 3 change applied

Heating RMSE (Btu/hr sqft)	1.05
Cooling RMSE (Btu/hr sqft)	6.28
Heating MBE (Btu/hr sqft)	-0.961
Cooling MBE (Btu/hr sqft)	4.74

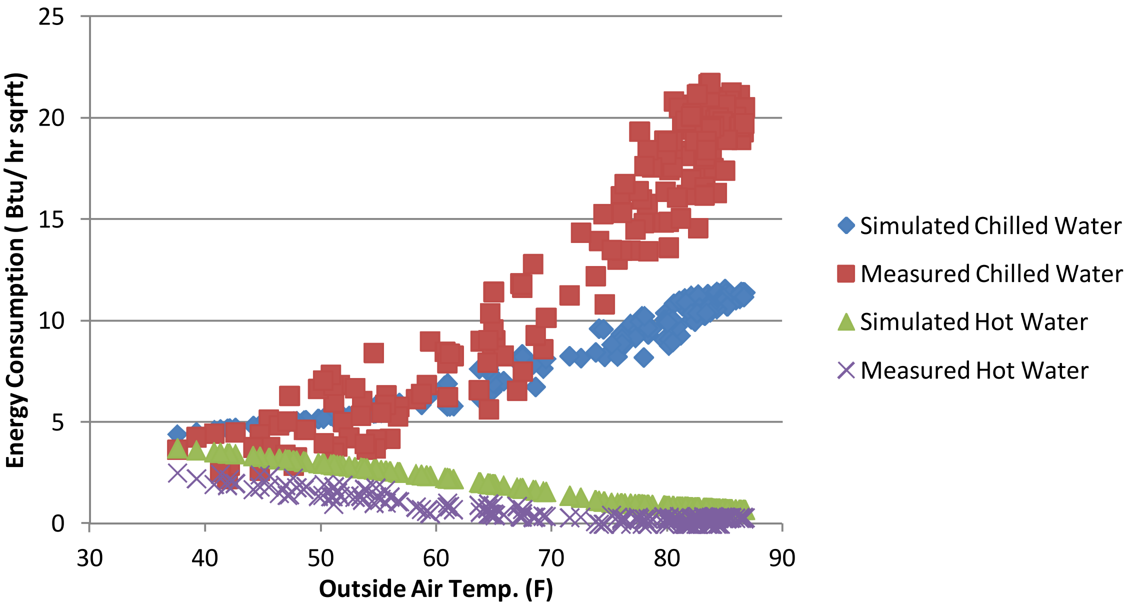

Fig. 26 Simulated and measured consumption for chilled and hot water – step 3 change applied

Similar to two previous changes, increasing min. supply air had positive affects for cooling RMSE(decrease of 14%) and cooling MBE (decrease of 19%), while had significant bad effects on Heating. Heating RMSE was increased three times and heating MBE was increased more than nine times. Fig. 27 shows the measured and simulated Energy consumption for hot water and chilled water after the third change is applied.

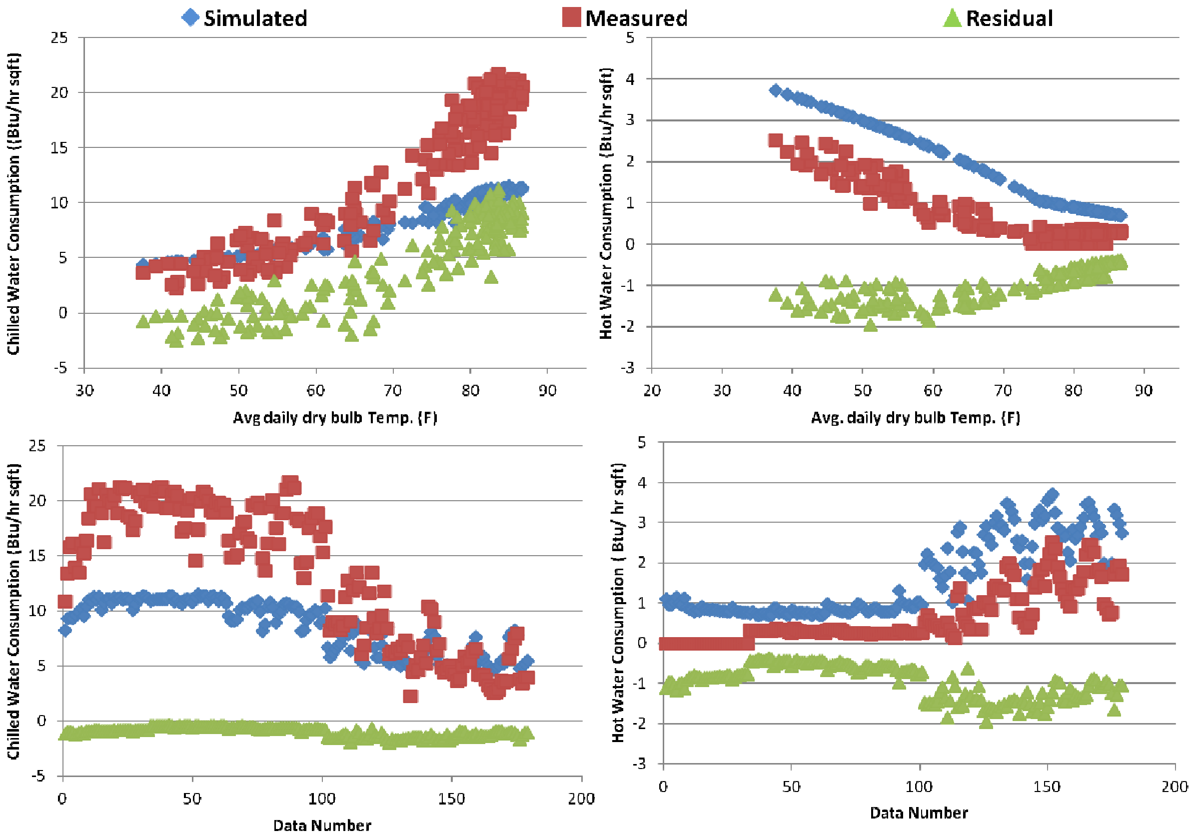

Fig. 27 Simulated, measured, and residual energy consumption for chilled and hot water – step 3 change applied

Step 4: Decreasing zone temperature from 75°F to 74°F

For this step, the characteristic signatures for changing zone temperature were considered. These signatures were chosen from characteristic signatures provided for the Zachry building. In this step the zone temperature was changed from 75°F to 74°F. A summary of obtained RMSE and MBE values after decreasing the zone temperature is represented in Table 24. The results are shown in Fig. 28 after the fourth change is applied.

Table 24 RMSE and MBE errors – step 4 change applied

Heating RMSE (Btu/hr ft^2)	0.25
Cooling RMSE (Btu/hr ft^2)	7.24
Heating MBE (Btu/hr ft^2)	0.03
Cooling MBE (Btu/hr ft^2)	5.88

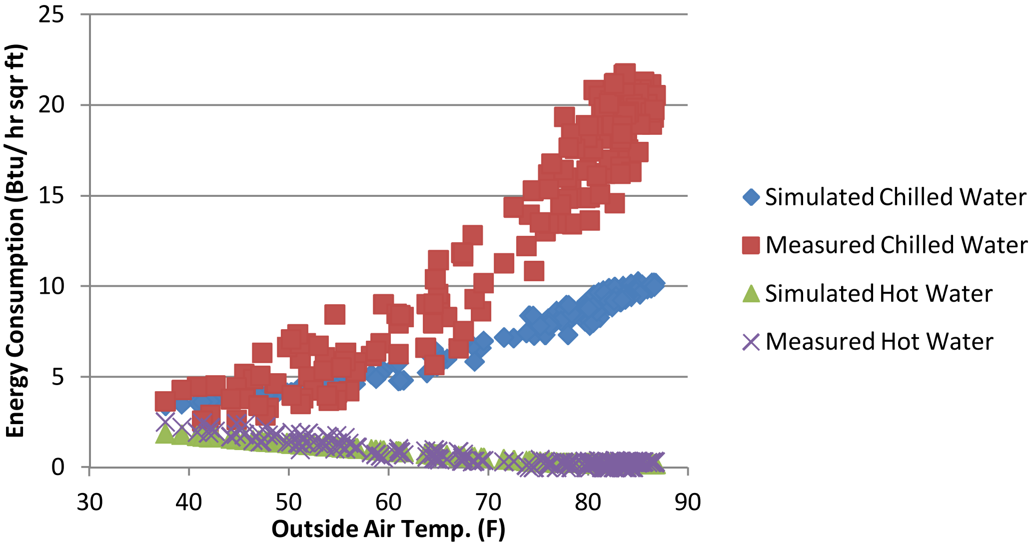

Fig. 28 Simulated and measured consumption for chilled and hot water –step 4 change applied

Unlike the previous changes, decreasing the zone temperature for 1 degree had nice effects on all four variables. By comparing Table 24 with RMSE table in base case, we can see that heating MBE is decreases by 130%, while heating RMSE is remained constant. Cooling variables also had 1% decrease for RMSE and 0.3% decrease for MBE. Fig. 29 shows the measured and simulated Energy consumption for hot water and chilled water after the fourth change is applied.

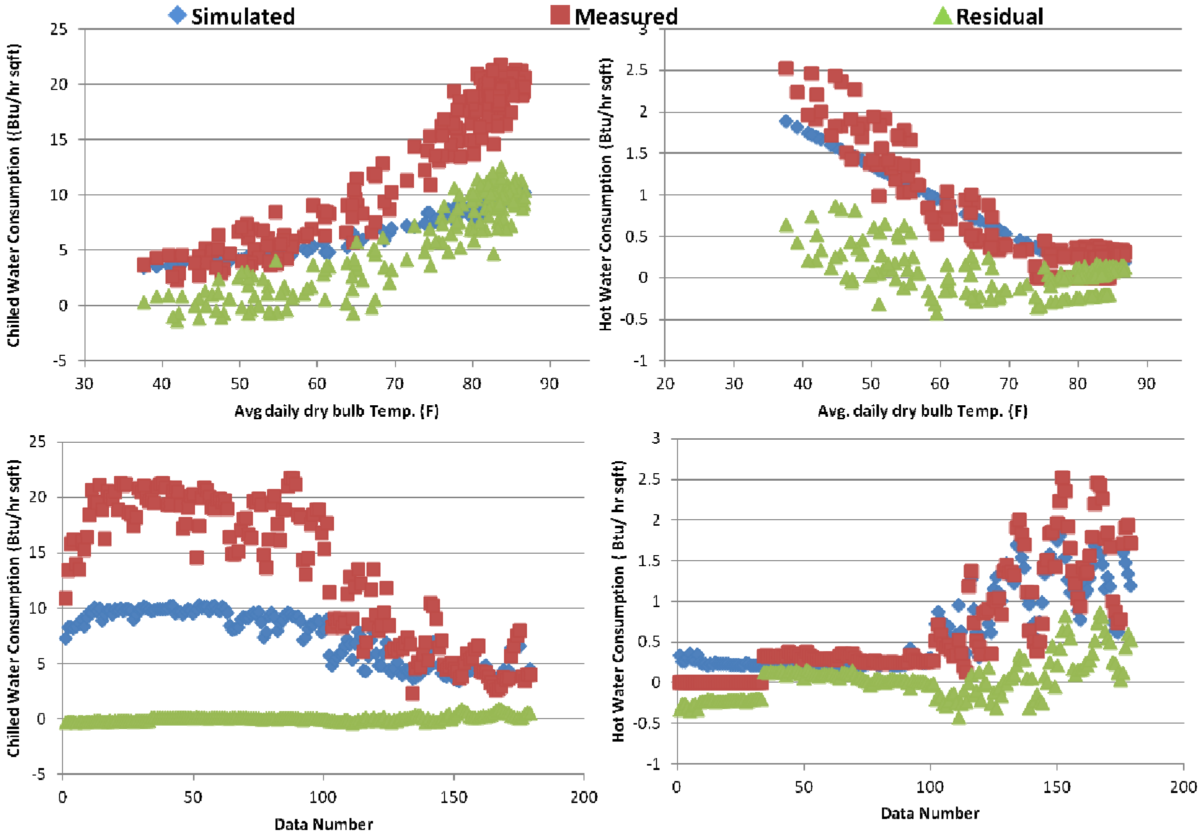

Fig. 29 Simulated, measured, and residual energy consumption for chilled and hot water –step 4 change applied

Step 5: Add sensible load of 3.08 Btu/ hr ft^2

For this step, the characteristic signatures for changing sensible load were considered. These signatures were chosen from the characteristic signatures provided for the Zachry building. The sensible load of 3.08 Btu/hr sq ft was added to the model. A summary of RMSE and MBE values after this change were applied is represented in Table 25. The results are shown in Fig. 30 after the change is applied.

Table 25 RMSE and MBE errors – step 5 change applied

Heating RMSE (Btu/hr ft^2)	0.68
Cooling RMSE (Btu/hr ft^2)	4.32
Heating MBE (Btu/hr ft^2)	0.45
Cooling MBE (Btu/hr ft^2)	2.81

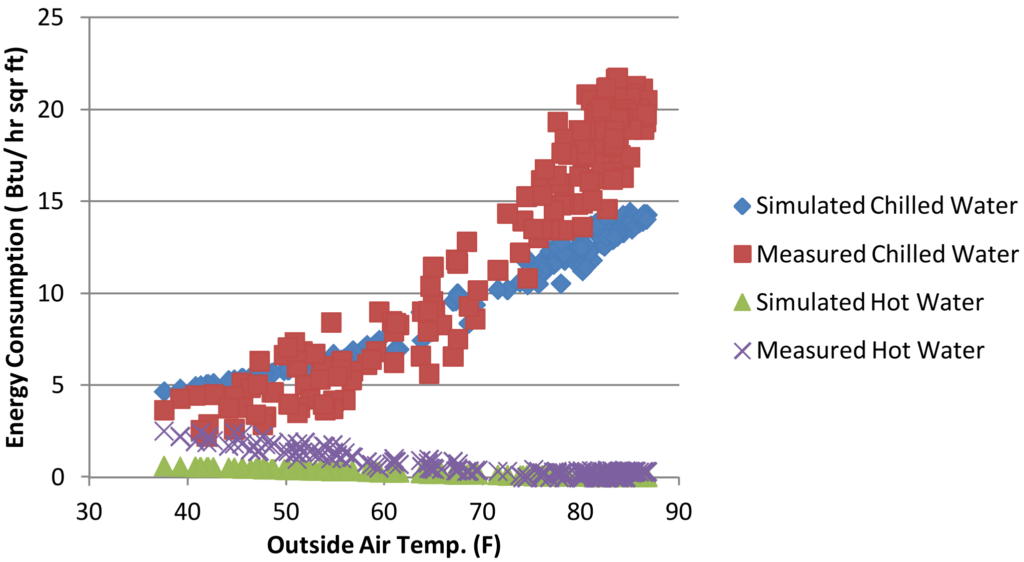

Fig. 30 Simulated and measured consumption for chilled and hot water – step 5 change applied

Referring to the base case RMSE table and comparing it with Table 25 and the plots in Fig. 31, we notice that adding sensible load data improved the simulation for cooling loads, while it caused negative effects on heating loads. Referring to the base case RMSE table and comparing it with Table 25, we notice that cooling RMSE and MBE is decreased by 40% and 52% respectively, while heating RMSE and MBE have an increase of 100% and 500% each.

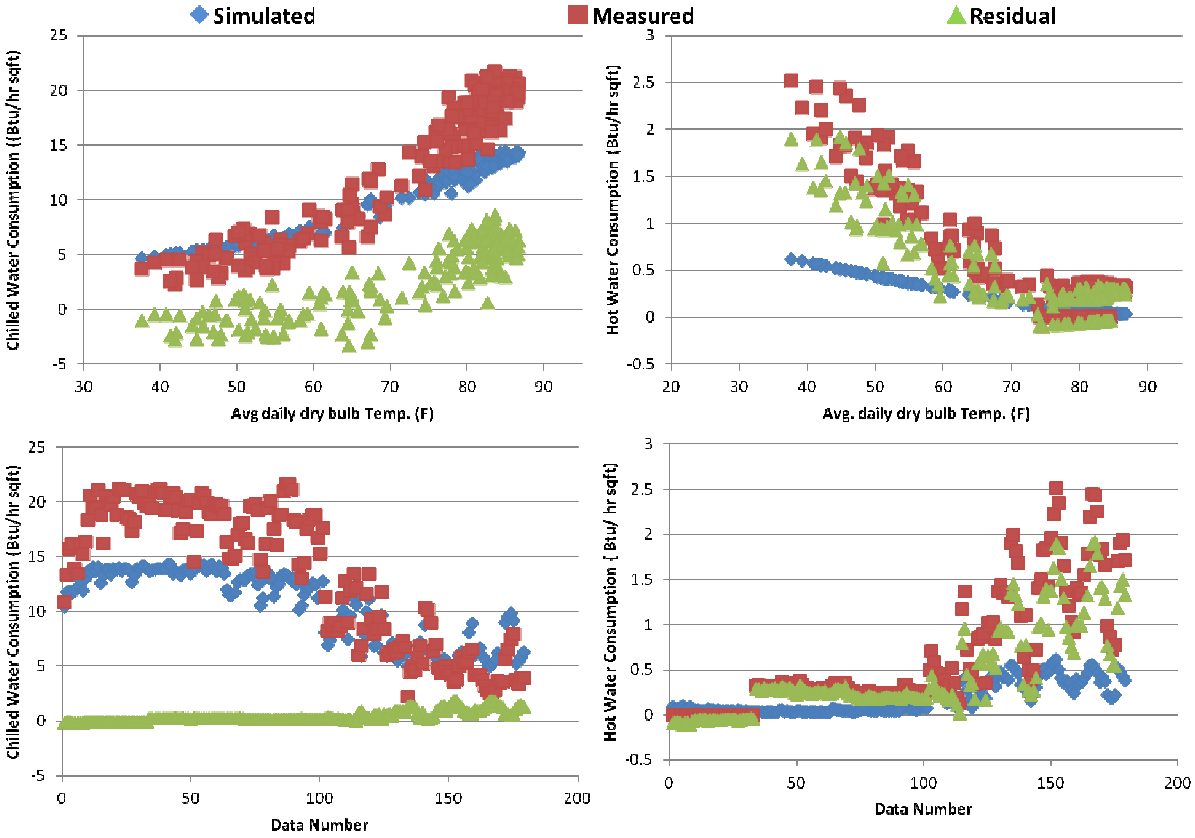

Fig. 31 Simulated, measured, and residual energy consumption for chilled and hot water – step 5 change applied

Step 6: Change latent load of -1.12 Btu/hr ft^2

For this step, the characteristic signatures for changing latent load were considered. . These signatures were chosen from the characteristic signatures provided for the Zachry building. The latent load of amount of -1.12 Btu/hr ft^2 was applied to the model. The RMSE and MBE values obtained after the change was applied are summarized in Table 26. The results are shown in Fig. 32 after the last change is applied.

Table 26 RMSE and MBE errors – step 6 change applied

Heating RMSE (Btu/hr ft^2)	0.25
Cooling RMSE (Btu/hr ft^2)	8.01
Heating MBE (Btu/hr ft^2)	-0.09
Cooling MBE (Btu/hr ft^2)	6.54

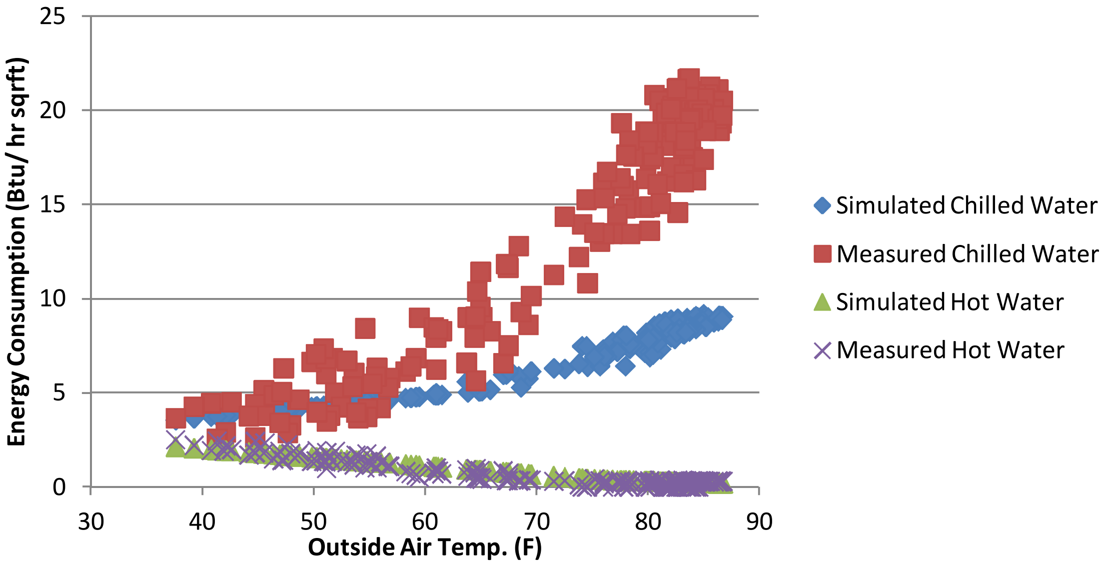

Fig. 32 Simulated and measured consumption for chilled and hot water – step 6 change applied

By comparing Table 26 with the base case RMSE table and looking at the plots in Fig. 33, we observe that changing the latent load hasn't caused any changes to the heating load. But it has increased cooling RMSE by 9% and cooling MBE by 10%.

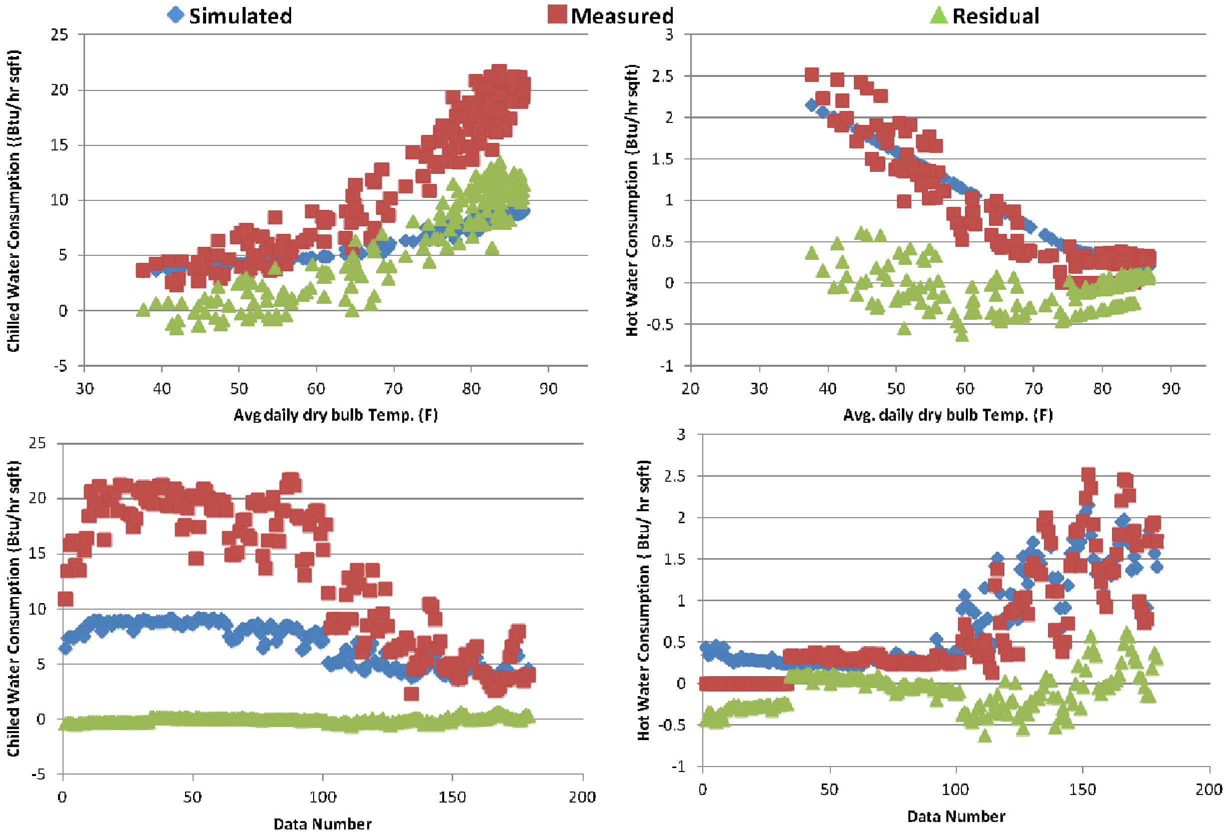

Fig. 33 Simulated, measured, and residual energy consumption for chilled and hot water – step 6 change applied

Final case: Applying all the changes at the same time

The final model is a combination of changing the cooling coil temperature, changing the zone temperature, changing the min. supply air, changing the min. outdoor air, changing the latent load, and changing the sensible load. In the final model we acquired the lowest heating RMSE and the lowest cooling RMSE, which demonstrated the best simulation for the model. RMSE and MBE results are represented in Table 27.

Table 27 RMSE and MBE errors – final case

Heating RMSE (Btu/hr ft^2)	0.22
Cooling RMSE (Btu/hr ft^2)	1.64
Heating MBE (Btu/hr ft^2)	0.02
Cooling MBE (Btu/hr ft^2)	0.44

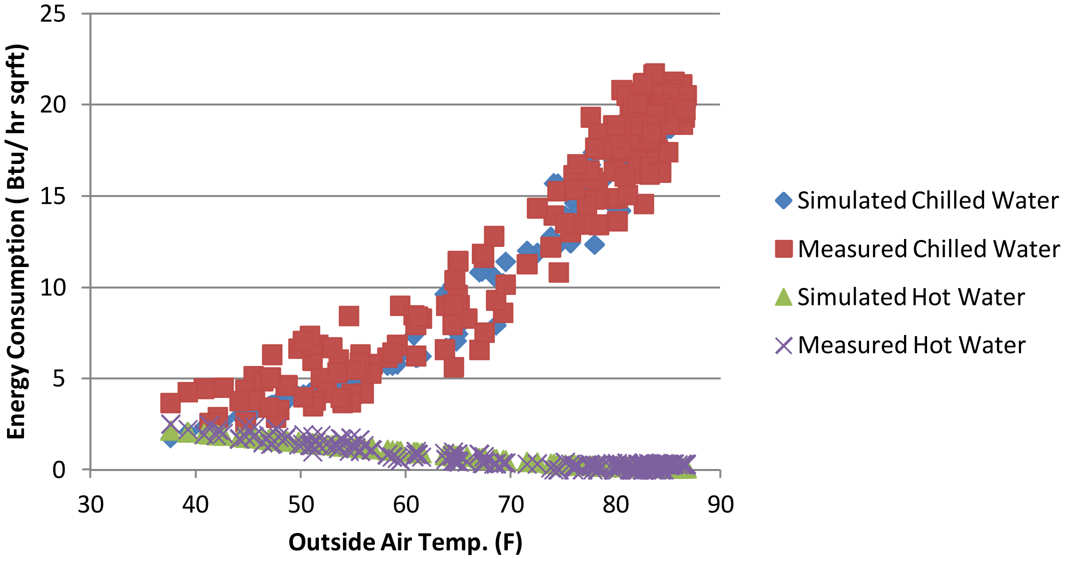

Fig. 34 Simulated and measured consumption for chilled and hot water – final case

Plots in Fig. 34 and Fig. 35 show the best simulated graphs for the system. This is the only case in which all four variables are decreased. By looking at Table 27, we notice that heating RMSE is decreased by 12% and heating MBE is decreased by 117%, while cooling RMSE is decreased by 1% and cooling MBE is decreased by 0.44%.

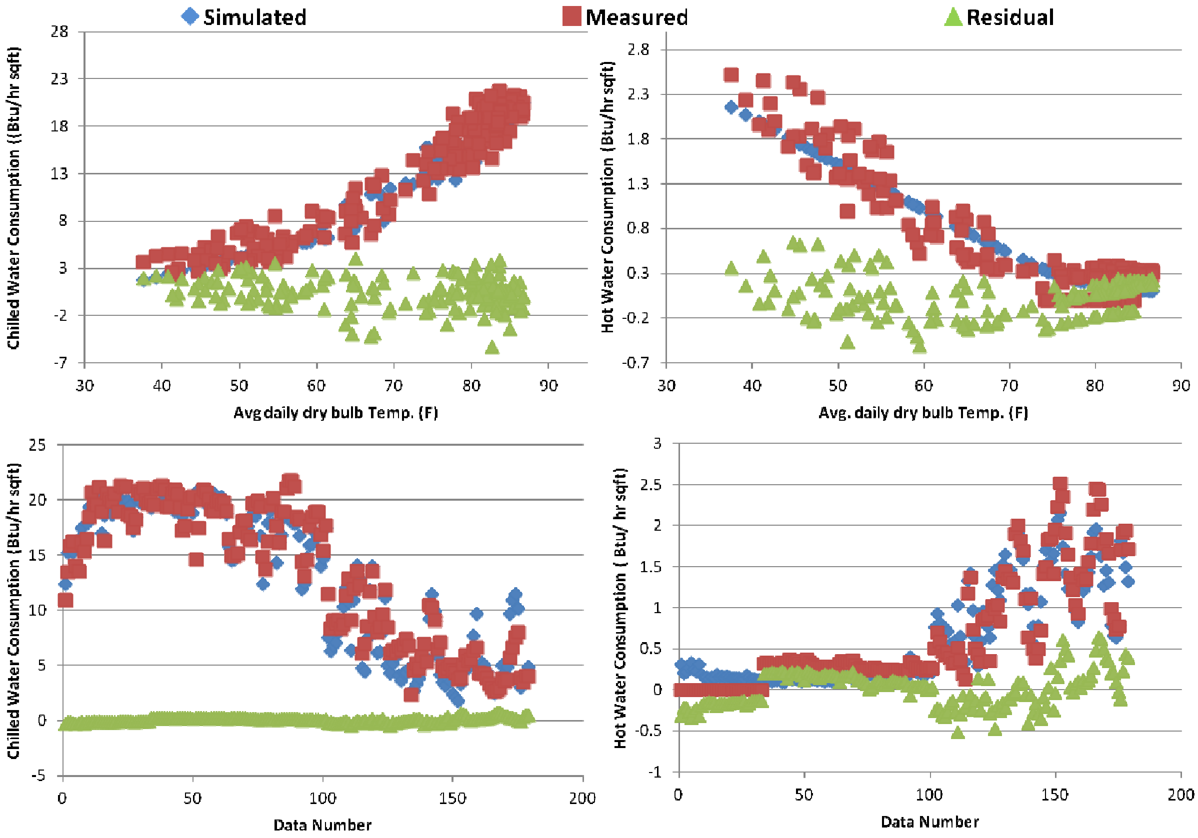

Fig. 35 Simulated, measured, and residual energy consumption for chilled and hot water – final case

CHAPTER V

SUMMARY OF RESULTS

In the course of this project six parameters were varied and acceptable numbers for RMSE and MBE for both chilled and hot water energy consumptions were derived. Fig. 36 demonstrates the energy consumption of CVTR, CVDD, and DDVAV systems.

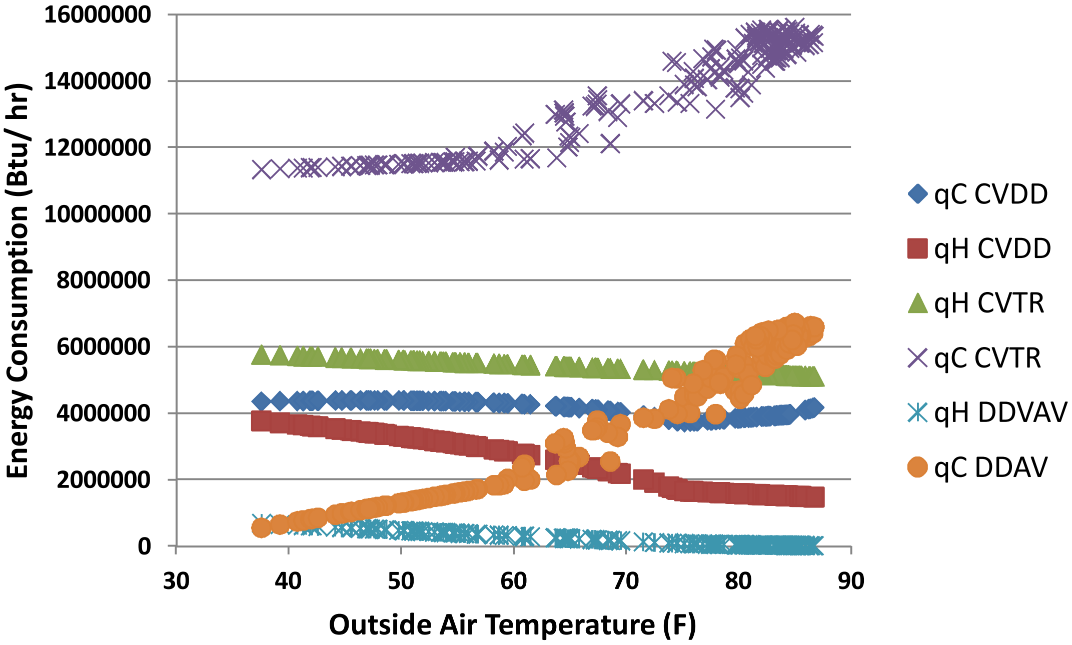

Fig. 36 Energy consumption comparison between CVTR, CVDD and DDVAV

The changes made to improve the DDVAV simulation have all been summarized in Table 28, and the RMSE and MBE for both hot water and chilled water energy consumption are listed in the table.

Table 28 Comparison table based on RMSE and MBE errors

Parameter	From	To	CHW RMSE (Btu/hr ft^2)	CHW MBE (Btu/hr ft^2)	HW RMSE (Btu/hr ft^2)	HW MBE (Btu/hr ft^2)
Base Case			7.32	5.90	0.25	-0.09
Min. Outdoor Air	20%	48%	4.74	4.26	0.29	-0.15
Cooling Coil Temp.	55°F	52°F	7.17	5.59	0.52	-0.45
Min. Supply Air	0.3 (cfm/ft^2)	0.39 (cfm/ ft^2)	6.28	4.74	1.05	-0.96
Zone Temp.	75°F	74°F	7.24	5.88	0.25	0.03
Sensible Load	0	3.08 (Btu/hr ft^2)	4.32	2.81	0.68	0.42
Latent Load	0	-1.12	8.00	6.54	0.25	-0.09
Final Case			1.64	0.44	0.22	0.02

Conclusion

In this project we performed simulation and calibration of energy analysis in the Zachry building as an example of a large, multipurpose educational building in a hot climate. We also performed comparisons between the CVTR, CVDD, and DDVAV systems used in such buildings.

According to our results, CVTR has the highest heating load (almost twice that of the DDVAV system) and the highest cooling load. CVDD is an improved version of CVTR and has higher efficiency, but it is still not as efficient as DDVAV. The current AHU system used in Zachry building – DDVAV – is the most efficient system, which has the lowest cooling and heating loads.

Characteristic signatures have been used to calibrate the energy simulation of the Zachry engineering building. In this method, calibration signatures were compared to the characteristic signatures of the building. According to the similarities of these signatures, changes have been applied to achieve the proper calibration. Two statistical parameters, RMSE and MBE were the best guides for determining the amount of change for each of the input variables. The simulation method for calibration could be used for energy audits, improving energy efficiency, and fault detection.

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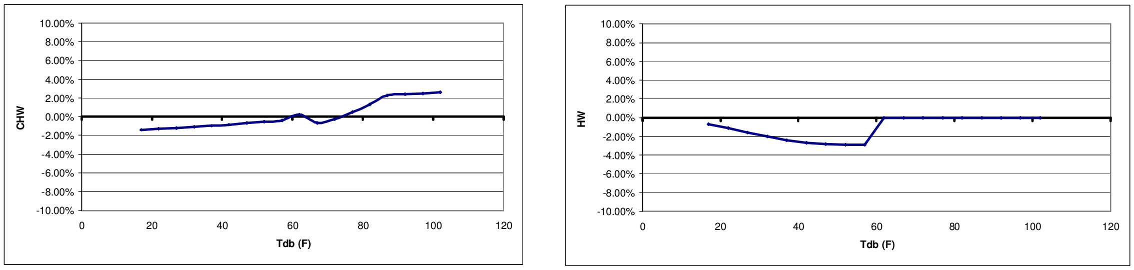
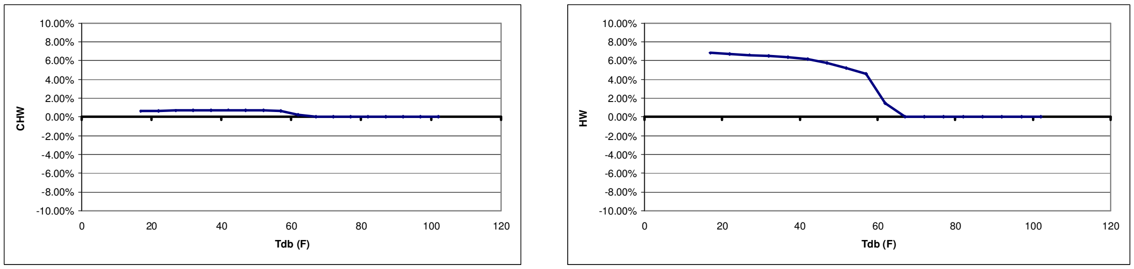
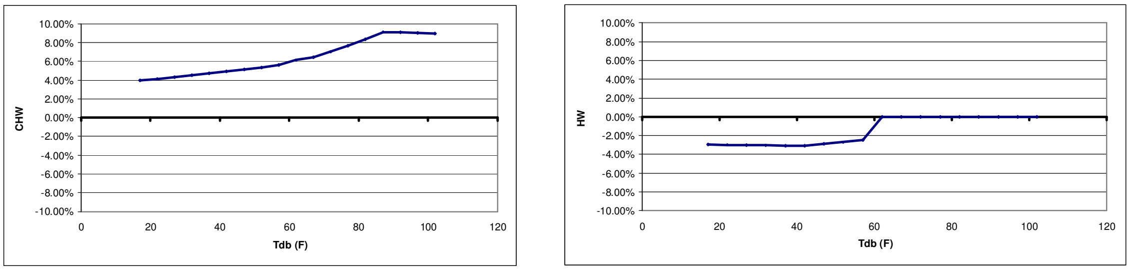
APPENDIX



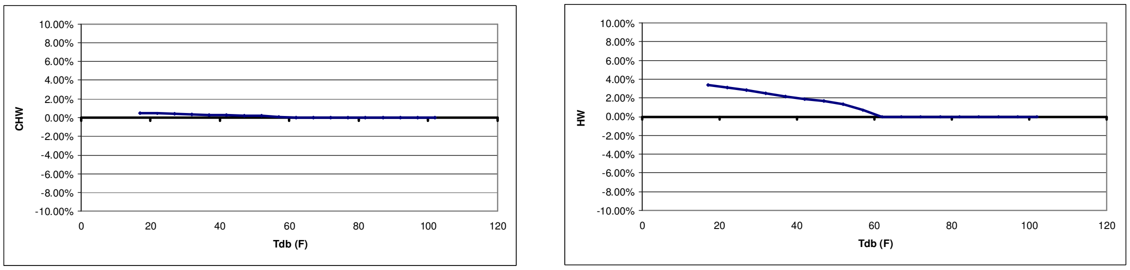
1. Change T_c from 55 F > 57 F



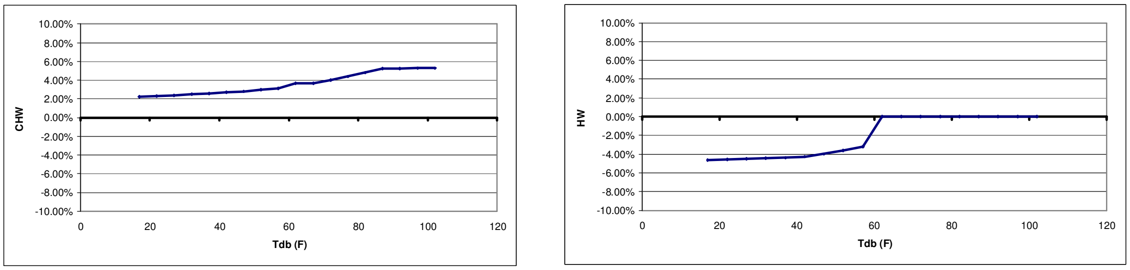
2. Change Minimum Air Flow Ratio from 0.30 > 0.35



3. Change Floor Area from 240000 sqft > 270000 sqft

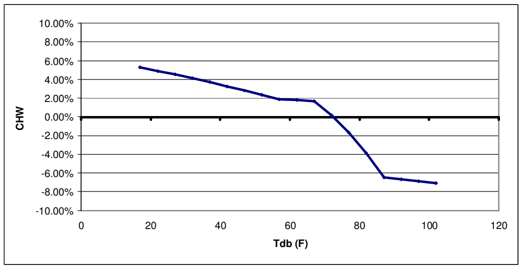


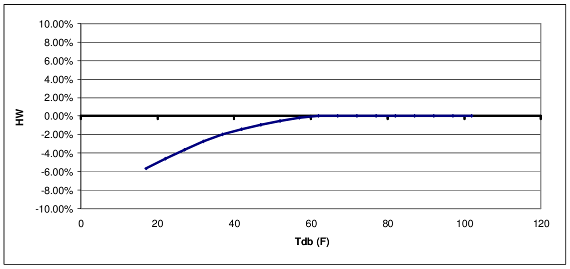
4. Increase T_h by 6 F



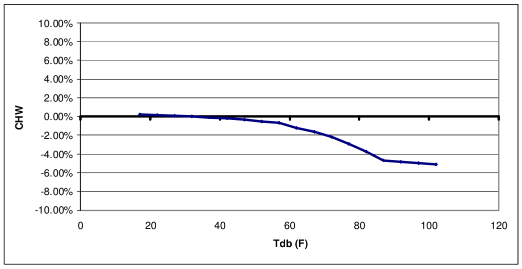
5. Change Internal Heat Gain from 2.5 W/sf > 2.7 W/sf

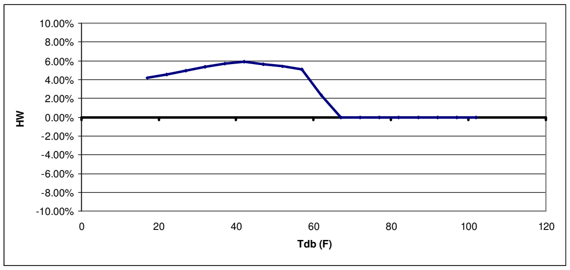
Figure A1 Characteristic signatures of the Zachry Engineering Building



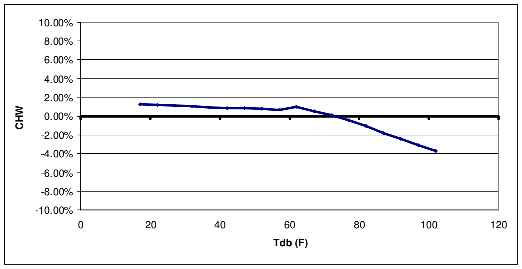


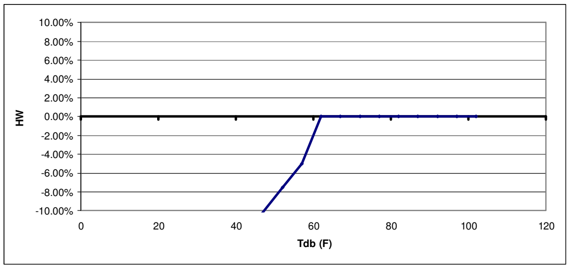
6. Change OA ratio from 0.12 > 0.08



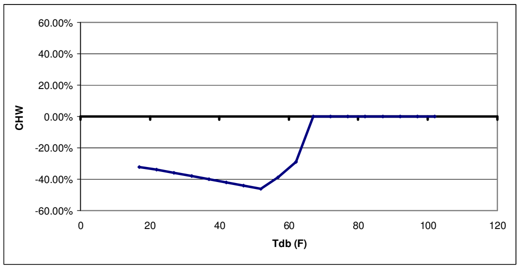


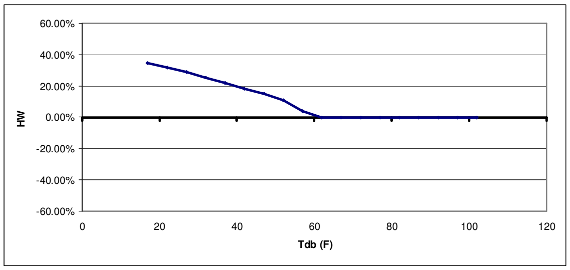
7. Change Zone Temperature from 73 F **>** **75** F





8. UA decreased by 20 %





9. Economizer No > Yes

Table A1 Raw data

Data Number	WBE	CHW	HW	TOA	RH	MCC	LTEQ
#	(kWh/day)	(MMBtu /day)	(MMBtu /day)	(°F)	(%)	(kWh/day)	(kWh/day)
1	15475.952	84.00	0	74.5573	68.2415	2903.872	12572.08
2	19094.104	104.20	0	78.356	70.3897	3333.995	15760.109
3	19335.581	122.20	0	78.2662	71.3808	3565.805	15769.776
4	19467.31	125.20	0	75.9682	79.6039	3504.972	15962.338
5	16060.998	108.20	0	74.0782	90.6768	3132.606	12928.392
6	16000.852	104.40	0	76.8103	83.2559	3034.783	12966.069
7	19095.488	124.00	0	77.802	84.5463	3342.979	15752.509
8	19637.843	118.40	0	74.46	88.913	3283.871	16353.972
9	20041.179	127.00	0	79.8268	78.4509	3357.95	16683.229
10	20070.316	142.60	0	81.5819	79.0975	3959.674	16110.642
11	19735.165	160.20	0	81.799	76.3935	4087.203	15647.962
12	17413.933	151.80	0	83.5018	75.7271	3639.835	13774.098
13	17058.68	150.80	0	82.1434	76.9823	3584.843	13473.837
14	20581.027	163.20	0	82.6524	78.6271	3983.76	16597.267
15	20372.829	146.40	0	79.752	74.5621	3851.866	16520.963
16	21084.82	125.80	0	81.7018	75.062	4501.184	16583.636
17	20428.584	173.40	0	81.1142	77.8933	4542.402	15886.182
18	20014.562	168.20	0	82.005	76.5743	4481.618	15532.944
19	16925.698	141.80	0	74.2243	91.1216	4181.307	12744.391
20	20072.828	159.60	0	81.5035	80.8452	4300.229	15772.599
21	20364.033	155.40	0	81.9151	79.1942	4185.694	16178.339
22	20192.752	153.40	0	81.3163	76.7773	3949.906	16242.846
23	20051.23	157.00	0	79.6846	83.1523	4093.312	15957.918
24	19784.884	159.00	0	82.046	80.1213	4148.491	15636.393
25	17313.472	156.20	0	81.3687	80.1785	3897.655	13415.817
26	16687.236	146.20	0	82.4952	77.402	3846.598	12840.638
27	20334.269	164.40	0	82.7047	78.0672	4221.592	16112.677
28	20463.992	163.40	0	82.6337	75.32	4276.088	16187.904
29	20037.796	163.80	0	82.6127	77.4303	4102.417	15935.379
30	16382.974	144.60	0	83.4009	74.7476	3612.255	12770.719
31	16038.651	143.00	0	83.8238	71.2547	3621.604	12417.047
32	16109.599	135.20	0	80.1637	73.9106	3453.821	12655.778
33	19150.487	140.60	0	82.0722	72.9731	3822.107	15328.38
34	20422.425	161.20	0	83.9061	72.709	4291.83	16130.595
35	20548	158.80	0	83.6817	72.9863	4299.157	16248.843
36	20056.377	163.00	0	84.3963	73.225	4363.918	15692.459
37	17406.02	154.60	0	84.5535	71.993	4149.428	13256.592
38	17528.201	152.40	0	84.2355	71.2789	4024.088	13504.113
39	17612	153.50	2.525	84.767	67.2784	4481	13131
40	17553	151.10	2.616	83.8088	71.569	4418	13135
41	20346	162.50	2.417	85.4293	66.3058	4651	15695
42	20476	163.80	2.542	86.2827	63.8313	4551	15925

Data Number	WBE	CHW	HW	TOA	RH	MCC	LTEQ
#	(kWh/day)	(MMBtu /day)	(MMBtu /day)	(°F)	(%)	(kWh/day)	(kWh/day)
43	19971	164.90	2.467	85.5678	66.3006	4393	15578
44	19539	161.70	2.461	85.3582	66.9143	4314	15225
45	16870	149.90	2.502	85.5641	66.6498	4073	12797
46	16724	149.80	2.567	86.5745	66.3589	4115	12609
47	19969	159.10	2.422	86.7242	65.6963	4322	15647
48	20417	161.50	2.476	80.5641	81.204	4272	16145
49	19678	159.00	2.888	81.028	81.257	4196	15482
50	19421	149.30	2.646	84.5235	66.6678	4191	15230
51	16771	133.30	2.559	83.2886	68.8285	4028	12743
52	16597	135.90	2.744	83.9961	70.3249	3740	12857
53	19981	148.20	2.472	85.4442	66.4703	4137	15844
54	19961	153.30	2.345	87.2745	64.2558	4214	15747
55	19889	155.50	2.254	85.9195	64.3407	4243	15646
56	19927	156.90	2.122	82.1883	74.4015	4342	15585
57	19286	138.00	2.771	74.6322	88.949	3839	15447
58	16569	113.10	2.94	82.6598	77.7663	4041	12528
59	16201	135.00	2.587	84.9877	73.1393	3825	12376
60	19887	154.40	2.431	84.1568	73.6861	4193	15694
61	20437	161.70	2.295	84.2803	74.1673	4295	16142
62	19775	160.10	2.159	85.0663	70.8713	4333	15442
63	18858	155.40	2.157	84.445	68.6477	4278	14580
64	16187	147.90	2.211	85.4068	69.3609	4051	12136
65	16150	146.80	2.247	86.3875	67.1155	4023	12127
66	18301	153.20	2.287	84.8642	69.0725	4111	14190
67	18730.229	153.70	2.293	84.7922	67.1619	4159.28	14570.949
68	18737.099	151.80	2.262	86.2451	66.3116	4168.536	14568.563
69	18833.792	153.00	2.084	86.6343	63.7504	4247.928	14585.864
70	18657.113	146.80	2.118	85.1859	63.6222	4241.683	14415.43
71	16426.168	127.20	2.545	77.4989	76.5231	3742.375	12683.793
72	15761.877	115.20	2.778	79.6845	62.3381	3389.821	12372.056
73	17879.683	115.50	2.738	80.1336	61.0448	3534.233	14345.45
74	18506.799	116.80	2.626	81.1518	60.2227	3729.373	14777.426
75	18741.117	131.70	2.491	82.061	66.5169	3945.679	14795.438
76	18938.774	139.40	2.791	83.1427	65.4868	4031.981	14906.793
77	18639.535	140.50	2.346	83.2737	64.7537	3963.228	14676.307
78	16249.735	128.70	2.041	83.2025	64.9764	3615.589	12634.146
79	15987.414	126.50	2.079	84.2917	64.9274	3349.338	12638.076
80	20333.145	152.00	1.96	84.0258	67.4872	4139.151	16193.994
81	20504.93	151.60	1.872	82.7833	70.8393	4267.896	16237.034
82	20661.643	154.00	1.837	81.5857	78.1706	4380.042	16281.601
83	20758.712	149.90	1.886	77.6037	81.6405	4298.685	16460.027
84	20016.95	114.90	1.994	77.9592	56.6383	3810.364	16206.586
85	17522.804	105.60	2.117	80.1374	57.2469	3551.16	13971.644
86	17606.939	125.60	1.964	83.2064	66.4529	3761.218	13845.721

Data Number	WBE	CHW	HW	TOA	RH	MCC	LTEQ
#	(kWh/day)	(MMBtu /day)	(MMBtu /day)	(°F)	(%)	(kWh/day)	(kWh/day)
87	20882.902	151.10	1.853	83.7752	69.1168	4229.93	16652.972
88	20743.519	155.70	1.784	82.0611	69.9202	4262.26	16481.259
89	20676.081	136.20	1.872	80.4668	58.3473	4084.082	16591.999
90	20536.945	107.90	1.937	81.0094	42.0206	3897.927	16639.018
91	20477.553	124.70	1.887	80.8596	66.2582	4548.126	15929.427
92	17109.541	146.30	1.943	82.3792	64.2322	4388.577	12720.964
93	17078.272	146.20	1.975	83.3935	68.3705	4388.07	12690.202
94	20738.497	163.10	1.881	83.6479	68.8631	4613.849	16124.648
95	20763.603	168.00	1.827	83.5655	68.1002	4644.934	16118.669
96	21261.506	168.40	1.834	83.7041	65.0903	4743.639	16517.867
97	21196.708	171.80	1.836	82.9293	69.895	4790.32	16406.388
98	20803.164	164.10	1.85	82.585	68.3396	4689.483	16113.681
99	17243.78	142.80	1.885	83.3783	65.7394	4443.728	12800.052
100	17272.161	141.10	1.899	79.8942	72.7999	4383.475	12888.686
101	21417.849	156.90	1.953	75.6763	91.1413	4578.889	16838.96
102	21447.984	159.70	1.815	77.368	92.0616	4622.919	16825.065
103	21043.135	129.10	2.091	72.5064	74.7206	4453.265	16589.87
104	20405.851	111.30	2.626	72.5138	72.8517	4352.125	16053.726
105	17690.442	101.10	2.593	75.6801	64.7341	4211.727	13478.715
106	17746.576	112.50	2.192	77.2296	72.1909	4237.175	13509.401
107	21332.708	136.20	2.041	78.6853	72.6922	4553.747	16778.961
108	21704.658	142.80	2.052	78.3223	74.7016	4577.794	17126.864
109	21426.514	146.20	1.914	80.4593	71.9197	4604.299	16822.215
110	21515.166	146.10	1.899	80.0214	71.9125	4644.938	16870.228
111	20494.25	129.90	2.032	76.3164	71.3121	4559.885	15934.365
112	17218.665	119.00	2.074	76.0506	76.0748	4288.653	12930.012
113	17323.14	127.40	2.08	74.9579	88.8769	4212.288	13110.852
114	21256.36	138.60	2.04	74.7594	87.2981	4393.54	16862.82
115	21338.99	143.8	2.037	74.1419	89.6349	4464.885	16874.105
116	21284.611	152.70	1.993	75.4517	93.7925	4447.131	16837.48
117	21426.762	152.30	1.986	76.5183	87.1386	4510.815	16915.947
118	20569.596	148.60	1.957	76.1965	87.2465	4460.858	16108.738
119	17304.431	136.40	2.004	74.1193	92.1544	4162.462	13141.969
120	17258.347	136.80	1.992	78.0304	83.5165	4179.384	13078.963
121	20543.102	88.70	3.948	64.9615	69.4856	3582.038	16961.064
122	20175.42	64.30	5.495	61.4772	52.4507	3095.662	17079.758
123	20552.142	69.90	4.545	63.8125	61.4034	3035.2	17516.942
124	20058.136	67.70	3.604	64.8194	66.6842	3034.156	17023.98
125	19644.747	70.10	3.296	65.0888	72.9713	2943.245	16701.502
126	16975.43	64.30	3.529	65.8223	73.367	2859.596	14115.834
127	16494.983	66.80	3.074	69.2504	73.9807	2986.1	13508.883
128	20623.216	87.40	2.481	71.5334	77.3404	3675.385	16947.831

Data Number	WBE	CHW	HW	TOA	RH	MCC	LTEQ
#	**(kWh/day)**	**(MMBtu /day)**	**(MMBtu /day)**	**(°F)**	**(%)**	**(kWh/day)**	**(kWh/day)**
129	20510.701	99.30	2.578	68.3784	80.4135	3602.617	16908.084
130	19927.411	69.80	4.041	59.4526	83.638	2853.583	17073.828
131	20240.724	91.90	2.788	67.2594	87.4317	3205.901	17034.823
132	19990.577	104.40	1.524	76.0581	72.6629	3598.877	16391.7
133	16539.558	94.70	0.999	73.7938	73.594	3242.952	13296.606
134	15721.826	47.00	9.149	53.5843	44.4767	2597.386	13124.44
135	19316.496	53.20	10.649	51.6457	68.7411	2955.27	16361.226
136	19933.567	65.80	5.673	60.7512	88.1375	2756.293	17177.274
137	20025.108	90.30	3.98	67.4353	93.613	3030.751	16994.357
138	19775.97	104.80	3.418	75.1673	75.4666	3521.489	16254.481
139	16549.855	72.10	2.698	68.5881	59.4416	2990.664	13559.191
140	16229.525	61.60	6.579	60.9421	54.9366	2694.104	13535.421
141	19799.581	65.10	6.707	61.148	55.1377	2901.657	16897.924
142	20089.407	74.30	6.961	64.9166	74.1765	3204.533	16884.874
143	20146.913	91.60	2.749	67.424	88.3387	3243.09	16903.823
144	19510.627	65.40	7.959	54.5798	56.992	2969.462	16541.165
145	18897.455	46.60	7.66	51.1085	76.0391	2963.412	15934.043
146	15908.045	49.10	8.016	55.6613	76.1433	2741.794	13166.251
147	15918.098	47.70	6.482	58.2286	83.553	2381.09	13537.008
148	19726.744	51.60	10.653	49.7781	88.319	2848.777	16877.967
149	19835.366	49.00	11.186	47.2744	83.3738	3027.472	16807.894
150	19848.303	52.90	10.49	51.0619	95.6576	3136.798	16711.505
151	19932.312	57.00	10.536	50.8597	94.1789	3303.305	16629.007
152	19549.94	52.00	10.179	52.9555	83.9358	3370.707	16179.233
153	16446.134	17.30	14.765	41.9076	65.3747	3459.487	12986.647
154	19579.82	35.00	15.494	42.5925	67.4241	3400.552	16179.268
155	19822.555	39.90	14.133	45.4837	87.7992	3442.931	16379.624
156	19782.126	36.00	13.105	48.5188	93.8815	3028.216	16753.91
157	19924.149	44.90	8.573	56.8029	83.7361	2988.663	16935.486
158	19385.442	53.10	4.974	59.1606	79.5164	2775.337	16610.105
159	16265.432	41.10	8.63	56.6606	72.9119	2820.429	13445.003
160	19825.195	80.60	3.858	64.6509	85.3977	2806.985	17018.21
161	15581.053	78.80	2.976	69.4975	81.6239	2773.093	12807.96
162	15634.174	70.20	3.853	64.4937	92.6163	2630.636	13003.538
163	15833.835	49.80	5.612	58.704	73.1635	2428.977	13404.858
164	19735.534	54.80	10.938	50.1748	85.869	3140.521	16595.013
165	19498.954	37.80	11.645	46.3781	60.6996	3151.23	16347.724
166	16325.077	34.20	14.152	44.7089	48.8924	2968.372	13356.705
167	16430.563	36.00	14.361	48.6966	82.7061	2960.212	13470.351
168	19476.1	39.20	11.014	47.0947	60.1446	3152.927	16323.173
169	19491.296	34.60	15.154	40.7624	60.0369	3068.62	16422.676
170	19176.233	33.20	17.28	39.2224	65.642	2750.014	16426.219
171	16010.77	28.40	19.516	37.5756	65.2666	2155.075	13855.695
172	15700.102	29.50	18.243	45.5847	68.4692	2174.865	13525.237

Data Number	**WBE**	**CHW**	**HW**	**TOA**	**RH**	**MCC**	**LTEQ**
#	**(kWh/day)**	**(MMBtu /day)**	**(MMBtu /day)**	**(°F)**	**(%)**	**(kWh/day)**	**(kWh/day)**
173	18666.902	39.00	14.836	51.9057	65.882	2364.106	16302.796
174	18624.961	45.60	12.834	55.5977	73.394	2526.674	16098.287
175	18035.147	41.40	10.62	53.4608	65.6105	2492.59	15542.557
176	17293.877	42.70	9.435	55.216	65.5339	2459.693	14834.184
177	16335.627	48.50	8.033	60.972	89.4868	2524.217	13811.41
178	14105.064	51.20	7.186	63.6928	94.3007	2431.417	11673.647
179	13471.677	33.00	10.952	52.4297	74.5491	2241.094	11230.583
180	14224.735	32.60	10.369	55.9834	76.5687	2301.834	11922.901
181	14035.752	32.30	10.505	54.8156	90.0364	2314.167	11721.585
182	13302.396	29.60	12.075	51.4137	75.7922	2155.23	11147.166
183	12748.863	25.50	13.866	47.9087	72.1032	2045.105	10703.758
184	12886.249	22.50	17.056	42.0873	85.668	2041.05	10845.199
185	12845.053	20.00	19.035	41.2901	76.3482	1989.598	10855.455
186	12983.444	20.40	18.851	44.722	58.2098	1975.186	11008.258
187	13473.302	22.30	17.516	47.6242	49.7752	2024.601	11448.701
188	13834.197	28.90	13.744	54.752	63.9993	2106.251	11727.946
189	13477.199	27.20	14.251	51.1386	39.7321	2034.154	11443.045
190	13089.555	28.50	12.907	53.9716	74.0904	2073.687	11015.868
191	13762.498	43.80	7.68	64.5387	90.082	2356.274	11406.224
192	13855.421	51.00	6.743	66.9862	88.4376	2462.591	11392.83
193	16196.116	58.30	5.675	67.4727	90.9323	2584.86	13611.256
194	16708.585	61.70	6.01	64.4375	94.7578	2456.786	14251.799
195	16392.643	29.30	13.247	44.1438	85.1783	2157.761	14234.882
196	15592.417	26.50	14.782	46.925	67.143	2199.782	13392.635
197	15389.682	30.90	15.021	50.261	75.876	2322.091	13067.591
198	14051.698	30.70	13.286	53.7751	84.9423	2168.309	11883.389

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