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COMPARISON OF DOE-2.1E WITH ENERGYPLUS AND TRNSYS FOR GROUND COUPLED RESIDENTIAL BUILDINGS IN HOT AND HUMID CLIMATES

STAGE 2

“Literature Survey on Comparative Studies on Slab-on-grade and Basement Models of DOE-2, EnergyPlus and TRNSYS Programs”

A Report

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Organization of the report

This report includes two sections. The first section summarizes the characteristics and results of the comparative studies on slab-on-grade heat transfer models of DOE-2, EnergyPlus and TRNSYS programs. The second section then summarizes the characteristics and results of the comparative studies on the basement heat transfer models of the same programs.

Introduction

Foundation heat transfer is a significant load component for low-rise residential buildings. For a contemporary code or above code house, ground-coupled heat losses may account for 30%–50% of the total heat loss [1]. Comparative studies on ground coupled heat transfer models of current simulation tools showed a high degree of variation for basements and slab-on-grade floors. For an uninsulated slab-on-grade building, the range of disagreement among simulation tools is estimated to be 25%-60% or higher for simplified models versus detailed models [2]. For basements, the disagreement among the simulation tools with respect to the average values was estimated to be 11%-23% for the annual total heating load [3].

The international residential code compliance (IC3) calculator developed by the Energy Systems Laboratory uses DOE-2 program as the main calculator. *DOE-2* has been used for more than three decades in design studies, analysis of retrofit opportunities and developing and testing standards [4]. In 1996, the U.S.D.O.E.[1] initiated support for the development of *EnergyPlus*, which was a new program based on the best features of *DOE-2* and BLAST [5]. The idea of shift from *DOE-2* to *EnergyPlus* raised questions in the simulation community on the differences between these two simulation programs [4, 6, 7]. Currently, *TRNSYS* is gaining increasing recognition in the field of building energy simulation. The foundation heat transfer models of *EnergyPlus* and *TRNSYS* are more advanced models when compared to those used with DOE-2.

This report summarizes the findings of the studies that compared *DOE-2* with *EnergyPlus* for ground isolated and slab-on-grade buildings. This report also includes the findings of the comparative studies that included the slab-on-grade and basement heat transfer models of DOE-2, EnergyPlus and TRNSYS programs.

1. Studies that compared DOE-2 with EnergyPlus

EnergyPlus has been compared with *DOE-2* by: 1) Henninger and Witte [8] and 2) Huang et al. [9].

Henninger and Witte compared *EnergyPlus* with *DOE-2* based on thermal loads [8], HVAC systems [8] and fuel-fired furnaces [8] using the test cases of ANSI/ASHRAE Standard 140-2007 [10]. The Standard 140 test cases do not include a ground coupled case, because the ground coupled test case showed -36% to +23% difference in heating load and -50% to +51% difference in cooling load among the tested simulation tools in an earlier study by Judkoff and Neymark [3]. For the ground isolated test cases of Standard 140, *EnergyPlus* showed close results to *DOE-2* results.

Henninger and Witte [8] compared *EnergyPlus* thermal loads with those of using 13 test cases of Standard 140. These test cases varied in mass, windows, overhangs and fins. *EnergyPlus* showed a 5%-15% lower annual heating load and a 7%-31% lower annual cooling load when compared to *DOE-2* [8].

Henninger and Witte compared *EnergyPlus* HVAC system models with those of *DOE-2* based on their performance and components [8]. The performances of *EnergyPlus* HVAC systems have been compared with those of *DOE-2*, CA-SIS V1, CLIM2000, TRNSYS, CODYRUN/LGIMAT and HOT3000 using Standard 140 test cases CE100 through CE200 and CE300 through CE545 [8]. These test cases describe a near-adiabatic rectangular single zone building with a unitary vapor compression cooling system [10]. Using these test cases, the *EnergyPlus* HVAC system performances were tested for varying sensible internal gains, latent internal gains, zone thermostat setpoints, outdoor dry bulb temperatures, infiltration rate, outside air fraction and economizer control settings [8]. In these tests, *EnergyPlus* space cooling electricity consumption varied between -1% and +6% when compared to the *DOE-2* results for the same conditions [8]. The total HVAC electricity consumption was at most 5% higher in *EnergyPlus* than in *DOE-2* [8]. For the system component tests, *EnergyPlus* and *DOE-2* showed “exact agreement (0.00% difference)” [8] for the hot water boiler model in heating efficiency versus part load ratio and fuel consumption.

Henninger and Witte [8] compared *EnergyPlus* fuel-fired furnaces with those of *DOE-2,* ESP-r and HOT3000 using Standard 140 test cases HE100 through HE230. The energy delivered to the space by the *EnergyPlus* and *DOE-2* furnaces was almost identical. The *EnergyPlus* yearly fuel consumption varied between -1% and +2% when compared to the *DOE-2* results obtained for the same furnaces. The total fan power consumption of the furnaces was 0%-3% lower in *EnergyPlus* than in *DOE-2*.

Huang et al. [9] compared *EnergyPlus* with *DOE-2* using the ACM[12] certification suite to test different building shells, equipment, and operations in California climates. This study included ground coupled test cases which were modeled using simple GCHT models [9]. Table 1 summarizes the conclusions of the study and shows how *EnergyPlus* heating and cooling energy consumption differed from those of *DOE-2* for various wall assemblies (WA), window-to-wall ratios (WWR), lighting levels (LL) and ventilation rates (VR).

Table 1. Summary of *EnergyPlus* results compared to *DOE-2* results [9, 11].

	heating	**cooling**
variable	***EnergyPlus* is:**	***EnergyPlus* is:**
WA	Lower (within 20%)	Higher (within 10%)
WWR	Lower (30% - 60%)	identical
LL	Lower (60% - 70%)	Higher (15% - 20%)
VR	Lower (15% - 20%)	Higher (15%)

2. Comparative studies on slab-on-grade models of DOE-2 and EnergyPlus

Comparative testing has long been used for validation and debugging of energy simulation tools [2, 3, 12]. The slab-on-grade models of *EnergyPlus*, *DOE-2* and *TRNSYS* have been tested in comparison to multiple other models. This section summarizes the contents and the major conclusions of these studies.

2.1. Comparative studies on slab-on-grade models of DOE-2

DOE-2 uses simplified, steady state slab-on-grade GCHT models. The slab-on-grade GCHT models of *DOE-2* have been compared with those of other tools by: 1) Judkoff and Neymark [3] and 2) McDowell et al. [13].

Judkoff and Neymark [3] compared the GCHT models of *DOE-2* with those of BLAST-3.0 and SERIRES/SUNCODE using the HERS[4] BESTEST[5] test suite. The HERS BESTEST test suite includes uninsulated and insulated slab-on-grade test cases [3]. Two GCHT calculation methods are used with *DOE-2* to model these test cases: 1) Wang's [14] slab-on-grade perimeter heat loss method and 2) a more detailed method that accounts for the effects of mass and solar radiation incident on soil, which eventually leads to lower loads when compared to Wang's method [3]. In this more detailed method, soil is modeled as large amount of mass in contact with the ambient air and the soil thicknesses are regarded as curved path lengths for one-dimensional heat conduction between the slab/soil and the soil/air boundaries [3]. For the slab-on-grade test cases of HERS BESTEST, these two GCHT methods lead to 18%-19% lower heating loads in *DOE-2* than they did in BLAST and SERIRES [3]. The same slab-on-grade test cases of HERS BESTEST are currently used by RESNET[6] to test energy simulation tools in comparison with *DOE-2*, BLAST and SERIRES for certification as a residential code compliance calculator [15].

McDowell et al. [13] compared *DOE-2*'s slab-on-grade model, Winkelmann's model, with three other slab-on-grade GCHT calculation methods. These methods were 1) Wang's [14] slab-on-grade perimeter heat loss method, which was restricted to four construction types, 2) a modified form of Krarti and Chuangchid's [16] slab-on-grade floor design tool, which was based on a design value and an amplitude value and 3) the *TRNSYS* slab-on-grade model. McDowell et al. [13] concluded that Wang's [14] method performed the worst in comparison to the detailed *TRNSYS* model. The method of Krarti and Chuangchid [16] showed similar results to the *TRNSYS* model in heating (within 8%) but exhibited significantly different results for cooling (up to 60%). Winkelmann's method showed good agreement in heating (within 13%) and high disagreement in cooling (up to 42%) with the detailed *TRNSYS* model.

2.2. Comparative studies on slab-on-grade models of EnergyPlus and TRNSYS

The slab-on-grade GCHT model of *EnergyPlus*, *Slab*, has been compared to other modeling tools by: 1) Deru et al. [17], 2) Neymark et al. [2] and 3) Henninger and Witte [8].

Deru et al. [17] compared *EnergyPlus* with HOT3000, SUNREL and VA114 for various slab-on-grade construction using the IEA[7] SHC[8] Task 22 test cases. For these test cases, the annual ground coupling heating load results of HOT3000, SUNREL and VA114 showed up to ~52% disagreement with the *EnergyPlus* results [1, 17]. Since the test cases were not designed for diagnostic purposes, the source of this disagreement could not be identified. The study concluded that an in-depth diagnostics needs to be developed to identify the reasons for this high variation [1, 17].

In 2001, Spitler et al. [18] presented a set of analytical solutions for the ground coupled heat transfer problem of slab-on-grade constructions. These solutions included a 3-D steady-state analytical solution for rectangular buildings which was originally developed by CSIRO[10], Australia [19]. Neymark et al. [2] then designed a set of in-depth diagnostic test cases for slab-on-grade GCHT based on the CSIRO analytical solution. These test cases were improved in collaboration with IEA SHC Task 34 and ECBCS[11] Annex 43 (IEA 34/43) [2]. Using these diagnostic test cases, Neymark et al. [2] compared the slab-on-grade GCHT model of *EnergyPlus* with those of BASECALC, BASESIMP, EN ISO 13370, *TRNSYS* [20] and SUNREL-GC. Nakhi and Crowley developed two additional stand-alone models respectively using FLUENT [21, 22] and MATLAB [23, 24] to be tested in the study. With this study, the range of disagreement among the programs for the in-depth diagnostic test cases was reduced from 9%-55% to 1%-24% [2]. The IEA BESTEST building thermal fabric envelope tests were expanded to include these in-depth diagnostic analytical verification test cases for slab-on-grade GCHT. Neymark et al. [2] currently plan to expand ASHRAE Standard 140 by adding new GCHT test cases that will be used to test and compare the current simulation tools.

After the improvements of Neymark et al. [2], *TRNSYS* steady state floor conduction compared well with the Delsante analytical solution case (within 0.5%) and to Fluent (within 2.2%) and Matlab (within -1.7%). Therefore, *TRNSYS* ground coupling method currently appears to be the closest method to a "truth" standard (in the absence of empirical data) for the modeling of ground coupling effect in a whole building energy simulation program. In the same study, *EnergyPlus* steady state floor heat flow and steady-periodic annual floor heat conduction compared with those of *TRNSYS* within 4% to 9%, and within -11% to +16%.

Later, Henninger and Witte [8] compared *EnergyPlus* slab-on-grade GCHT with ASHRAE 1052-RP Toolkit along with other modes of heat transfer for the 16 different envelopes specified in the ASHRAE 1052-RP report. In this study, the *EnergyPlus* zone load for the ground coupling test case varied from the results of ASHRAE 1052-RP Toolkit by 44% [10].

3. Comparative studies on basement heat transfer calculation methods

Basement heat transfer has long been studied by many researchers and many methods have been developed during the years. The results of the newly developed methods have also been compared with those of the earlier ones simultaneously. The studies conducted by Parker [25], McDonald *et al.* [26], Yuill and Wray [27], Krarti [28], Sobotka *et al.* [29] and Amjad *et al.* [30] are examples of these comparative studies.

Parker [25] found that the Mitalas method [31], which implements 2-D and 3-D physical models of the basement, calculates uniformly greater annual heat loss when compared to the previous methods that were entirely based on 1-D and/or 2-D modeling such as the conduction path length method of ASHRAE [32], the F-factor method [25] and the methods of Yard *et al.* [33] and Akridge *et. al.* [34]. McDonald *et al.* [26] compared two variations of the Latta-Boileau method [35], which is the basis of the ASHRAE's conduction path length method [32], with the methods of Mitalas [31], Yard *et al*. [33], Akridge *et al.* [34], Shipp [36] and Swinton *et al.* [37] and obtained significant disagreements among all methods for the uninsulated walls and floors. For the well-insulated basement walls, however, they obtained agreement between the methods of Yard *et al*. [33], Mitalas [31] and Shipp [36], which are all of a similar mathematical background based on two-dimensional numerical programs. Later, Yuill and Wray [27] compared Krarti's [28] semi-analytical two-dimensional interzone temperature profile estimation (ITPE) method with the Mitalas method and with the finite-difference heat conduction program (ESHD) developed in the Underground Space Center [39] for heavily insulated (R=3.5 m^2K/W) basement walls and uninsulated basement floors. They obtained good agreement in the wall and floor heat loss in all cases except for the floor heat loss predicted by the 2-D ESHD program, which was significantly lower. Krarti [38] then used his ITPE method to determine the steady-state temperature distribution for basements with different insulation configurations, compared his results with the Mitalas method and obtained good agreement. Sobotka *et al.* [29] compared measured data with the conduction path length method of ASHRAE, the Mitalas method, the European Standard and the two-dimensional finite element method program. They found that the Mitalas method shows good agreement with the measured data due to its combined 2-D/3-D solution. Their study also showed the shortcomings of one-dimensional modeling of deep basements which results in lower predicted heat loss, especially around the basement corner. Amjad *et al.* [30] then developed a method which numerically solves two-dimensional heat conduction problems in large calculation domains using the two-dimensional transfer functions method and the substructuration technique. They also compared the results of this method with those calculated with the alternative directions implicit (ADI) method and obtained good agreement with considerably reduced computation time.

3.1. Comparative studies on basement models of DOE-2

The basement models of *DOE-2* have been compared with those of other building energy simulation programs by Judkoff and Neymark using two test suites: 1) International Energy Agency (IEA) Building Energy Simulation Test and Diagnostic Method (BESTEST) [41]; 2) Home Energy Rating System (HERS) Building Energy Simulation Test and Diagnostic Method (BESTEST) [3].

Using the IEA BESTEST test suite, Judkoff and Neymark [41] compared *DOE-2* with BLAST-3.0, SERIRES/SUNCODE, SERIRES-1.2, ESP, S3PAS, TRNSYS, TASE, DEROB-LTH and CLIM2000. The basement test case of the IEA BESTEST (Case 990) was a building 1.35m sunk into the ground [2]. To model this case, *DOE-2* was used with ASHRAE's conduction path length method [28] that calculates average U-values for underground walls and floors based on their conduction path lengths through the ground to the ambient air. For the basement case of IEA BESTEST, the *DOE-2* ground coupling heating load varied between -40% and +47% when compared to the results of other programs for the identical conditions. The *DOE-2* ground coupling cooling load was 33%-76% lower than the results of other programs for the same cases. Due to these unresolved disagreements between the tested programs, the basement test case (Case 990) has been the only test case of IEA BESTEST excluded from ASHRAE Standard 140 [41].

Using the HERS BESTEST test suite, Judkoff and Neymark [41] compared *DOE-2* with BLAST-3.0 and SERIRES/SUNCODE. The HERS BESTEST included two basement types: 1) uninsulated basement and 2) basement with internally-insulated wall. These basements were modeled as one large zone including the upper main floor and then as two smaller zones where the main floor and the basement were two separate zones. These basements were modeled using two ASHRAE GCHT calculation methods [32]. The first method was the perimeter heat loss calculation method, which assumes that the primary heat loss occurs from the perimeter of the ground coupled construction. This method uses a heat loss coefficient together with the perimeter length of the underground wall/floor to simplify the GCHT into a steady state thermal conduction [2]. The second ASHRAE GCHT calculation method was the conduction path length method. This method accounted for the effects of mass and solar radiation incident on soil and eventually led to lower thermal loads when compared to the perimeter heat loss method of ASHRAE. The results showed that, for the same basement case, *DOE-2* calculated 4% to 14% lower heating load than BLAST and 10% to 21% lower heating load than SERIRES. The basement test cases of HERS BESTEST are currently being used by Residential Energy Services Network (RESNET) to test simulation tools in comparison with *DOE-2*, BLAST and SERIRES results for certification as a residential code compliance calculator [15]

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