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

STAGE 3
"Slab-on-grade Sealed Boxes in the Four U.S. Climates"

A Report

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Nomenclature

IGain	daily internal gain per dwelling unit (Btu/day)
CFA	conditioned floor area (ft^2)
N_{br}	number of bedrooms
SLA	specific leakage area (unitless)
L	effective leakage area (ft^2)
R_{eff}	effective resistance of the slab (hr-ft^2-^oF/Btu)
A	area of the slab (ft^2)
F2	perimeter conduction factor (Btu/hr-^oF-ft)
P_{exp}	exposed perimeter (ft)
U_{eff}	effective U-value of the slab (Btu/hr-ft^2-^oF)
R_{us}	actual slab resistance (hr-ft^2-^oF/Btu)
R_{slab}	resistance of 4in concrete (hr-ft^2-^oF/Btu)
R_{carpet}	resistance of the carpet (hr-ft^2-^oF/Btu)
R_{film}	resistance of the inside air film (hr-ft^2-^oF/Btu)
R_{soil}	resistance of the soil (hr-ft^2-^oF/Btu)
R_{fic}	resistance of the fictitious insulation layer (hr-ft^2-^oF/Btu)
GI	ground isolated
EP	modeled with *EnergyPlus*
D2	modeled with *DOE-2*
TR	modeled with *TRNSYS*
GCW	ground coupled with Winkelmann's slab-on-grade model
GCS	ground coupled with *Slab* model
-eit-	ground coupled by external iteration of *EnergyPlus* and *Slab*
-iit-	ground coupled by a single internal iteration of *EnergyPlus* and *Slab*
-wtEv	evapotranspiration flag of *Slab* is on
-wotEv	evapotranspiration flag of *Slab* is off
GCT	ground coupled with *TRNSYS* slab-on-grade model
GCTh	hourly *TRNSYS* slab/soil interface temperatures entered into *EnergyPlus*
GCTm	monthly *TRNSYS* slab/soil interface temperatures entered into *EnergyPlus*
$Q_{slab/zair}$	heat transfer between the slab and the zone air
$Q_{soil/slab}$	heat transfer between the soil and the slab
Q_{fm}(s)	monthly average floor heat flux(es)
T_{am}(s)	monthly average outside air temperature(s)
T_g(s)	monthly average deep ground temperature(s) calculated by *DOE-2* using Kasuda approach
$T_{slab/soil}$(s)	monthly average interface temperature(s) between the soil and the slab
T_{zair}	zone air temperatures
$U_{effective}$	effective conductivity of the underground surface
Q_{mod}	floor heat flux at 78°F steady state zone air temperature
Q_{LOADS}	floor heat flux at 70°F steady state zone air temperature
T_{mod}	78°F constant zone air temperature
T_{LOADS}	the 70°F default constant zone air temperature that *DOE-2* LOADS uses

1. Organization of the Report

This report consists of two sections. The first section is the introduction to the significance of the topic. The second section is a comparative analysis between DOE-2, EnergyPlus and TRNSYS programs for slab-on-grade heat transfer in empty sealed boxes in four U.S. climates.

2. Introduction

Ground coupled heat transfer (GCHT) through concrete floor slabs can be a significant component of the total load for heating or cooling in 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]. Ground coupling is still considered a hard-to-model phenomenon in building energy simulation since it involves three-dimensional thermal conduction, moisture transport, longtime constants and heat storage properties of the ground [2]. Over the years, many researchers worked on the development of slab-on-grade models. Some used simplified methods for slab-on-grade load calculations [3-5]; whereas others developed more detailed models [6]. 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].

This study compared *EnergyPlus* and *DOE-2.1e (DOE-2)* GCHT for slab-on-grade low-rise residential buildings. *DOE-2* has been used for more than three decades in design studies, analysis of retrofit opportunities and developing and testing standards [7]. 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 [8]. The shift from *DOE-2* to *EnergyPlus* raised questions in the simulation community on the differences between these two simulation programs [9-11]. Ground coupled heat transfer is an area that *EnergyPlus* differs significantly from *DOE-2*. *EnergyPlus* calculates z-transfer function coefficients to compute the unsteady ground coupled surface temperatures [12]; whereas *DOE-2* sets the temperatures of the ground coupled surfaces as steady [13]. The slab-on-grade GCHT models of *DOE-2* and *EnergyPlus* have been compared separately with other programs in order to maintain consistency among the results of current simulation tools for identical cases [2, 14-17]. *EnergyPlus* and *DOE-2* have been compared with each other based on thermal loads, HVAC systems and fuel-fired furnaces using the test cases defined in ANSI[2]/ASHRAE Standard 140-2007[3], which were "effectively decoupled thermally from the ground" [17, 18]. This study extends the previous studies by comparing *EnergyPlus* and *DOE-2* slab-on-grade heat transfer based on the results obtained from IECC[4] [19] compliant residential buildings in four climates of the U.S. In these comparisons, the *TRNSYS* slab-on-grade model is used as the truth standard for slab-on-grade heat transfer modeling. The reliabilities of the *DOE-2* and *EnergyPlus* slab-on-grade models are then discussed and recommendations are made for the building energy modelers.

This study is divided in two sections. In Section I, empty, adiabatic, ground coupled sealed boxes were modeled using *DOE-2, EnergyPlus* and *TRNSYS* programs in order to isolate the slab-on-grade heat transfer from other building load components and compare it between these three programs. In these comparisons, the *TRNSYS* slab-on-grade model was assumed to be the truth standard for slab-on-grade heat transfer modeling. The results of the *DOE-2* and *EnergyPlus* slab-on-grade models were then evaluated based on the closeness of their results to those of the *TRNSYS* slab-on-grade model.

In Section II, load components were added to the sealed boxes modeled in Section I to convert them into fully loaded IECC[4] [19] compliant houses. The effect of slab-on-grade heat transfer on thermal loads of these houses was then quantified and compared between the *DOE-2, EnergyPlus* and *TRNSYS* programs. The findings of this section provided the code users an insight to estimate and understand the thermal load differences they will obtain if *EnergyPlus* replaces *DOE-2* in energy code compliance calculations of low-rise slab-on-grade residential buildings.

This report includes the results of the first section (Section I) of this study.

3. Modeling of the sealed boxes

An empty, ground coupled sealed box with dimensions of 20m x 20m x 3m was modeled with *DOE-2*, *EnergyPlus* and *TRNSYS* programs in hot-humid, hot-dry, temperate and cold climates of the U.S. with the building envelope features required by the International Energy Conservation Code (IECC) 2009. These sealed boxes were located in Austin, TX; Phoenix, AZ; Chicago, IL; and Columbia Falls, MT to represent the hot-humid, the hot-dry, the temperate and the cold climate respectively. Table 1 lists the envelope features and Table 2 describes the construction materials of these boxes. The zone air temperature was set to 23°C in these boxes throughout the year and their resulting ground coupling loads were compared between the results of *DOE-2*, *EnergyPlus* and *TRNSYS* programs.

The sealed boxes modeled in this section had neither infiltration nor ventilation. They had no windows, lights, equipment or occupants. The walls and the ceilings were assigned as adiabatic surfaces and conductive heat transfer was allowed only through the floor. The thermal storages of the sealed boxes were also negligible when compared to the slab-on-grade heat transfer. Thus, the thermal loads of these boxes were driven exclusively by the slab-on-grade heat transfer. In order to quantify the differences between the slab-on-grade models in this study, we, therefore, compared the total sensible thermal loads of these sealed boxes (Q_{sens}) with each other. The corresponding monthly average floor heat fluxes in each model were also plotted.

Table 1. Features of the Building Envelope.

	Austin/Phoenix	Chicago	Montana		
Exterior Walls	U= 0.082 Btu/hr.ft^2.°F; Construction Layers: 0.076m face brick (BK), 0.013m plywood (PW), 0.1m soft wood (WD) frame with 25% framing ratio filled with 0.112m mineral wool (IN), 0.013m gypsum board (GP)	U= 0.06 Btu/hr.ft^2.°F; Construction Layers: Same as the Austin/Phoenix house except that the thickness of the mineral wool (IN) layer is 0.177m	U=0.06 Btu/hr.ft^2.°F; Construction Layers: Same as the Chicago house	**USED WITH THE SEALED BOXES**	**USED WITH THE FULLY INHABITED RESIDENTIAL BUILDINGS**
Ceiling	U= 0.035 Btu/hr.ft^2.°F; Construction Layers: 0.254m soft wood (WD) frame with 25% framing ratio filled with 0.3m mineral wool (IN), 0.013m gypsum board (GP)	U= 0.03 Btu/hr.ft^2.°F; Construction Layers: Same as the Austin/Phoenix house except that the thickness of the mineral wool (IN) layer is 0.362m.	U= 0.027 Btu/hr.ft^2.°F; Construction Layers: Same as the Austin/Phoenix house except that the thickness of the mineral wool (IN) layer is 0.433m.		
Floor	Uninsulated slab with 0.6m foundation depth; Construction Layers: 0.1m heavyweight concrete (CC), massless carpet (CP)	Insulated Slab with 2ft of foundation depth; Construction Layers: Same as Austin/Phoenix house with vertical external insulation (R=10 hr.ft^2.°F/Btu).	Insulated Slab with 4ft of foundation depth; Construction Layers: Same as Austin/Phoenix house with vertical external insulation (R=10 hr.ft^2.°F/Btu).		
Roof	Uninsulated roof; Construction Layers: massless shingle (AR), 0.254m soft wood (WD) frame with 25% framing ratio, 0.013m plywood (WD)	Same as the Austin/Phoenix house.	Same as the Austin/Phoenix house.		
Fenestration	U= 0.75 Btu/hr.ft^2.°F for the Austin house; U= 0.65 Btu/hr.ft^2.°F for the Phoenix house. For both houses, SHGC: 0.4, total of four windows; one on each wall; each with dimensions of 1.5m x10m; double-pane.	U= 0.35 Btu/hr.ft^2.°F; SHGC: 0.7. Total of four windows; one on each wall; each with dimensions of 1.5m x10m; double-pane.	Same as the Chicago house.		
Door	R = 1.33 hr.ft^2.°F/Btu for the Austin house, R= 1.54 hr.ft^2.°F/Btu for the Phoenix house. Faces north; with dimensions of 1.8m x 2.1m; modeled as a massless opaque layer.	R= 2.857 hr.ft^2.°F/Btu. Faces north; with dimensions of 1.8m x 2.1m; modeled as a massless opaque layer.	Same as the Chicago house.		

*The building envelope features described in this table are adopted from International Energy Conservation Code (IECC) 2009

Table 2. Properties of the materials used in the building envelope.

	Conductivity		Density		Specific heat		Resistance	
	W/m-K	Btu/hr-ft-°F	kg/m^3	Lb/ft^3	J/kg-K	Btu/Lbm-°F	m^2-K/W	hr-ft^2-°F/Btu
*BK	1.31	0.757	2083	130	920	0.22	-	-
*PW	0.115	0.066	545	34	1213	0.29	-	-
*WD	0.115	0.066	513	32	1381	0.33	-	-
*IN	0.043	0.025	96	6	837	0.20	-	-
*GP	0.16	0.093	801	50	837	0.20	-	-
*CC	1.310	0.757	2243	140	837	0.20	-	-
*AR	-	-	1121	70	1464	0.35	0.078	0.440
*CP	-	-	-	-	-	-	0.300	1.704
*SL	1.73	1	1842	115	418	0.1	-	-

*Materials are adopted from the DOE-2.1e Materials Library.

Three primary models were compared in this section.

1) *DOE-2* with Winkelmann's slab-on-grade model *(D2-GCW)*
2) *EnergyPlus* with the *Slab* model *(EP-GCS)*

3) *TRNSYS* with the *TRNSYS* slab-on-grade model *(TR-GCT)*

There were two major reasons why the GCHT (Q_{floor}) differed between the above mentioned three models. First, the *DOE-2*, *EnergyPlus* and *TRNSYS* programs calculated the heat transfer between the slab and the zone air ($Q_{slab/zair}$) differently. Second, Winkelmann's model, the *Slab* model and the *TRNSYS* slab-on-grade model calculated the heat transfer between the soil and the slab ($Q_{soil/slab}$) differently. In order to isolate the effects of $Q_{soil/slab}$ and $Q_{slab/zair}$ calculation differences and to examine them separately, two intermediate models were introduced to the study. These models were *EnergyPlus* with Winkelmann's slab-on-grade model *(EP-GCW)* and *EnergyPlus* with the *TRNSYS* slab-on-grade model *(EP-GCT)*. Using these two intermediate models, the comparison process was then divided into two steps. These steps were:

Step 1: The same slab-on-grade model was used with different aboveground energy modeling programs and then the resulting Q_{sens} were compared. Thus, the effect of $Q_{slab/zair}$ calculation differences between programs were isolated and quantified with two comparisons:

1) The *EP-GCW* model vs the *D2-GCW* model:
   -quantified the $Q_{slab/zair}$ calculation differences between *EnergyPlus* and *DOE-2*.
2) The *EP-GCT* model vs the *TR-GCT* model:

-quantified the $Q_{slab/zair}$ calculation differences between *EnergyPlus* and *TRNSYS*.

Step 2: The same above ground energy modeling program (*EnergyPlus*) was used with different slab-on-grade models (Winkelmann's, *Slab* and *TRNSYS* slab-on-grade models) and the resulting Q_{sens} were compared. Thus, the $Q_{soil/slab}$ calculation differences between programs were isolated and quantified. This step included two comparisons:

1) The *EP-GCW* model vs the *EP-GCT* model:
   -quantified the $Q_{soil/slab}$ calculation differences between Winkelmann's model and the *TRNSYS* slab-on-grade model.
2) The *EP-GCS* model vs the *EP-GCT* model:
   -quantified the $Q_{soil/slab}$ calculation differences between the *Slab* model and the *TRNSYS* slab-on-grade model.

3.1. Winkelmann's slab-on-grade model

In this study, Winkelmann's slab-on-grade model was used in *DOE-2* (D2-GCW) and in *EnergyPlus* (EP-GCW). In order to apply this model in both programs, the perimeter conduction factors (F2) are selected from the list of Huang et al. [20] for the sealed boxes based on their floor insulation configuration and foundation depth. These values were determined to be 1.33 W/m-K (0.77 Btu/hr.ºF.ft) for the Austin, TX and Phoenix, AZ boxes, 0.64 W/m-K (0.37 Btu/hr.ºF.ft) for the Columbia Falls, MT box and 0.85 W/m-K (0.49 Btu/hr.ºF.ft) for the Chicago, IL box. Using these F2 values, the effective resistance (R_{eff}) values for the floors of these boxes were then calculated using the Equation 1.

$$R_{eff} = A/(F2 \times P_{exp}) \;\ldots\ldots\ldots\ldots\text{(Equation 1)}$$

Then, the effective U-values of the floors (U_{eff}) were calculated using the Equation 2.

$$U_{eff} = 1/R_{eff} \;\ldots\ldots\ldots\ldots\ldots\ldots\text{(Equation 2)}$$

Assuming that the air film resistance is 0.136m^2-K/W (0.77 hr-ft^2-ºF/Btu), the actual slab resistance (R_{us}) was then calculated as 0.213m^2-K/W (1.21 hr-ft^2-ºF/Btu) from the Equation 3.

$$R_{us} = R_{slab} + R_{carpet} + R_{film} \;\ldots\ldots\ldots\ldots\text{(Equation 3)}$$

The resistance of the 12 inch soil layer (R_{soil}) was assumed as 0.176m^2-K/W (1 hr-ft^2-^{o}F/Btu). The resistances of the fictitious layers (R_{fic}) under the soil layers were then calculated using the Equation 4.

$$R_{fic} = R_{eff} - R_{us} - R_{soil} \ \ldots\ldots\ldots \text{(Equation 4)}$$

The calculated R_{fic} values were directly entered into *DOE-2* and *EnergyPlus* as inputs. The U_{eff} values were, however, entered only into *DOE-2*. The underground floor constructions were then modeled with three layers both in *DOE-2* and *EnergyPlus*. These layers were 1) the massless fictitious insulation layer with the R_{fic} resistance, 2) the 1 ft (0.3 m) soil layer and 3) the 4 in (0.1 m) concrete slab.

3.2. The *Slab* model of *EnergyPlus*

In this study, the *Slab* preprocessor of *EnergyPlus* was used with *EnergyPlus* version 5.0.0.031 *(EP-GCS)*. In this version, *EnergyPlus* program is integrated with the *Slab* program. *EnergyPlus* does a single internal automatic iteration with the *Slab* program *(EP-GCSiit)* for slab-on-grade buildings. *EnergyPlus* documentation, however, does not provide information on whether there are any internal adjustments in this combined model for quick convergence.

In this study, in order to have full control over the iteration process, *EnergyPlus* was iterated with the *Slab* program externally by writing a code in Python *(EP-GCSeit)*. In these external iterations, first, the main *EnergyPlus* input file was run to obtain monthly average zone air temperatures. The zone air temperatures were then entered into the *Slab* input file and the *Slab* program was run. The monthly average ground temperatures calculated by *Slab* were then reentered into the main *EnergyPlus* input file and *EnergyPlus* was rerun with the new ground temperatures. *EnergyPlus* was iterated with *Slab* until the difference between the monthly average zone air temperatures calculated by the last two *EnergyPlus* runs were 0.0001^{o}C or lower.

The course material for *EnergyPlus* [21] describes three different methods for iterating *EnergyPlus* with the *Slab* program *(EP-GCSeit)*. These methods differ only in the initial *EnergyPlus* run. The first method recommended assigning 18^{o}C for the monthly average ground temperatures in the initial run. The second method recommended assigning a high insulation layer underneath the slab in the initial run. The third method recommended simulating the slab as an interior surface in the initial run. In this study, test runs were made using all of these three methods. The second method, where a high insulation layer is added underneath the slab in the first *EnergyPlus* run, was found to need fewer iterations to achieve a convergence of 0.0001^{o}C. Therefore, it was selected and used in the study. A high resistance (500 m^2-K/W) insulation layer was placed underneath the slab in the initial *EnergyPlus* run. The insulation layer was then removed in the later runs and the iteration was continued until the convergence (within 0.0001^{o}C) was achieved.

For each climate, both the internally iterated and the externally iterated *EP-GCS* models were used in this study. Each of these models was run with and without evaporative transpiration (evapotranspiration). Thus, the following four runs were done for each location.

- -iitwtEv: *EnergyPlus* iterated with the *Slab* program internally considering evapotranspiration
- -eitwtEv: *EnergyPlus* iterated with the *Slab* program externally considering evapotranspiration
- -iitwotEv: *EnergyPlus* iterated with the *Slab* program internally disregarding evapotranspiration
- -eitwotEv: *EnergyPlus* iterated with the *Slab* program externally disregarding evapotranspiration

In all of these runs, the floor model required two construction layers: 1) a 0.1m (4 in) concrete slab with a thermal resistance value of 0.076 m^2-K/W (0.433 hr-ft^2-ºF), and 2) a massless carpet with a resistance of 0.3 m^2-K/W (1.702 hr-ft^2-ºF). The physical properties of the slab and soil (SL) used in the *Slab* model are listed in Table 2.

In order to reflect the typical user behavior, the default values of the *Slab* program were used for multiple parameters. The surface albedo was assumed to be 0.379 with snow and 0.158 without snow. The surface emissivity with/without snow was 0.9. The surface roughness was assumed to be 0.03 with snow and 0.75 without snow. The indoor convection coefficient was 9.26 upward and 6.13 downward. The slab convergence was 0.1. The distance from the edge of the slab to the domain edge and the depth of the region below the slab were assigned to be 15 m. The annual average outside air temperature of each city was then entered as the deep ground temperature (TDEEPin) of that city. These values were 20.1°C, 22.5°C, 9.8°C and 12.1°C for Austin, Phoenix, Chicago and Montana respectively. The ground surface heat transfer coefficient was automatically calculated by the program.

3.3. The *TRNSYS* slab-on-grade model

The ground coupled test cases were modeled in *TRNSYS* version 17-00-0019 *(TR-GCT)* by using the *Type 49* slab-on-grade model with the *Type 56* multi-zone building model. In order to compare the results of the *TRNSYS* slab-on-grade model with the other slab-on-grade models, the hourly *(EP-GCTh)* and the monthly average *(EP-GCTm)* slab/soil interface temperatures of the *TR-GCT* model were also entered into *EnergyPlus*.

The *TRNSYS* slab-on-grade model is a finite difference model; therefore, the initial temperatures of the various soil nodes make a significant difference on the calculated heat transfer. For this reason, it is necessary to run the model for multiple years until the ground temperature profiles of the last two years are within an acceptable convergence tolerance. The IEA Task work [2] showed that, in *TRNSYS* runs, less than 0.2% change occurs after 5 years. Based on this finding, all *TRNSYS* simulations were run for 5 years and the results of the 5th run were presented.

The node sizes of *TRNSYS* slab-on-grade model have been determined for the horizontal and vertical directions through a set of initial test runs. The smallest node size along the perimeter of the slab was finally set to 0.1m. The distance between the nodes was multiplied by a factor of 2 as the nodes expanded away from the slab perimeter. The near-field far-field boundary was defined as "conductive" in all x, y and z axes. In *TRNSYS,* deep ground temperature is assumed to be very close to the yearly average outside air temperature. Therefore, the yearly average outside air temperatures were calculated for all four climates and entered into the *Type 49* models as the deep ground (average surface soil) temperatures. In *TRNSYS*, the amplitude of the annual surface temperature profile of the soil is assumed to be equal to the half of the maximum monthly average outside air temperature minus one half of the minimum monthly average outside air temperature. These values were calculated to be 9.3 deltaºC, 11.0 deltaºC, 14.1 deltaºC and 14.1 deltaºC for Austin, Phoenix, Chicago and Columbia Falls respectively and entered into the *Type 49* models. The soil temperature was also assumed to be unaffected by the building at a distance of 15m beneath from the bottom of the footer in the vertical direction and 15m from the edge of the building in horizontal direction.

4. Results and discussion

The results of the study are discussed in two sections: 1) The Sealed Boxes and 2) The Fully Loaded Houses. The first section presents the results obtained for the adiabatic, ground coupled, sealed boxes and compares the three slab-on-grade models by isolating the ground coupling effect. The second section presents the results obtained for the fully loaded code-compliant houses and quantifies the significance of the discrepancies in slab-on-grade heat transfer modeling relative to the fully loaded building energy requirement. This report includes the results for the sealed boxes. The abbreviations used in this section are explained in the nomenclature section of this paper and the generation of the results from the program outputs is described below.

The *DOE-2* thermal loads presented in this study were obtained from the System Monthly Loads Summary (SS-A) reports of *DOE-2* after "SUM" was assigned to the test houses as the "system-type". Similarly, the thermal loads of the *EnergyPlus* houses were obtained from the "Zone/Sys Sensible Heating Energy" and "Zone/Sys Sensible Cooling Energy" reports of *EnergyPlus* after the "Ideal Loads Air System" was assigned to the test houses. The *DOE-2* monthly average floor heat fluxes were obtained by modifying the "underground floor conduction gain" values reported by *DOE-2*. This modification was necessary due to the load calculation and reporting differences between *DOE-2* and *EnergyPlus*. In *DOE-2*, thermal loads are calculated in the LOADS subroutine based on a constant zone air temperature throughout the year [22]. The thermal loads calculated in the LOADS subroutine are then transferred into the SYSTEMS subroutine of *DOE-2* where the variations in the zone air temperatures are taken into account [22]. The output for floor conduction heat gain is available only from the LOADS subroutine of *DOE-2*. The values obtained from the LOADS subroutine of *DOE-2*, therefore, had to be multiplied by correction factors to obtain floor heat gain/loss values for the varying zone air temperatures. The resulting *DOE-2* values then became comparable with *EnergyPlus* values. The *EnergyPlus* results were generated by subtracting the "Opaque Surface Inside Face Conduction Loss" values from the "Opaque Surface Inside Face Conduction Gain" values for the ground coupled floor.

4.1. Results for the sealed boxes

For slab-on-grade floors, *DOE-2, EnergyPlus* and *TRNSYS* programs solve a heat balance on the inside surface of the floor [22, 23, 24]. In this heat balance, the heat transferred from the soil to the inside surface of the floor ($Q_{slab/soil}$) is assumed to be equal to the heat transferred from the zone to the inside surface of the floor ($Q_{slab/zair}$). In all three programs, the heat is transferred between the soil and the slab ($Q_{slab/soil}$) by conduction. The heat transfer between slab and the zone air ($Q_{slab/soil}$) then occurred by convection and radiation [22, 23, 24]. The methods and assumptions used to calculate the conduction, convection and radiation components of the slab-on-grade heat transfer; however, differed between programs. In this section, the ground coupling loads of the slab-on-grade empty sealed boxes were compared between *DOE-2, EnergyPlus* and *TRNSYS* in order to isolate and quantify the slab-on-grade heat transfer calculation differences between these programs. First the $Q_{slab/zair}$ (Step 1) and then the $Q_{soil/slab}$ (Step 2) of the sealed boxes were compared between these programs.

4.1.1. Step 1: Heat transfer between the slab and the zone ($Q_{slab/zair}$)

At this step, the $Q_{slab/zair}$ calculation differences between the *EnergyPlus, DOE-2* and *TRNSYS* programs are quantified. In order to explain these $Q_{slab/zair}$ differences, the inside convection and radiation models of these programs are compared (See Table 3).

Table 3. Differences between the calculations of DOE-2, EnergyPlus and TRNSYS programs for interior surface convection and radiation.

	Convection	Radiation
DOE-2	Provides a single option; uses user defined constant convective heat resistance (R_C). Convective heat resistance is entered within the Inside-Film-Resistance (I-F-R) input of DOE-2 along with the radiative heat resistance (R_R) [37]. Equation 7 show the relationship between the radiative heat resistance (R_R), convective heat resistance (R_C) and the I-F-R input of DOE-2: $1/\text{I-F-R} = 1/R_C + 1/R_R$……… (Equation 7)	Provides a single option; uses user defined constant radiative resistance (R_R). The radiative resistance (R_R) is entered within the I-F-R input of DOE-2 along with the convective resistance (R_C) as described on the left in DOE-2/Convection section [37].
EnergyPlus	Provides four options: 1) *user-defined*, 2) *simple algorithm*, 3) *detailed algorithm* and 4) *ceiling diffuser* and 5) *trombe wall algorithm* [38]. The *user defined* option allows the user to input constant convection coefficients for interior and exterior surfaces. The *simple algorithm* is based on using constant coefficients for different heat transfer configurations to determine reduced and enhanced convection. The coefficients are taken directly from Walton [44] and they are not user-defined. The *detailed algorithm* is based on Walton's [44] algorithm that correlates the convective heat transfer coefficient to the surface orientation and the temperature difference between the interior surface and the zone air. The *ceiling diffuser algorithm* is based on empirical correlations of Fisher and Pedersen [45] between the supply air changes per hour (ACH) and the convective heat transfer coefficient (h_{con}). These correlations were reformulated in *EnergyPlus* to use the room outlet temperature as the reference temperature. The *trombe wall algorithm* is used to model convection in a "trombe wall zone", i.e. the air space between the storage wall surface and the exterior glazing. ➢ In this study, the default interior convection algorithm of EnergyPlus i.e. the *detailed algorithm* was used.	Provides a single option and includes three heat components [38]: 1) *For long wave radiation heat exchange among zone surfaces:* uses a grey interchange model based on the "ScriptF" concept developed by Hottel and Sarofim [41]. This procedure relies on a matrix of exchange coefficients between pairs of surfaces that include all exchange paths between the surfaces. In other words all reflections, absorptions and re-emissions from other surfaces in the enclosure are included in the exchange coefficient, which is called ScriptF. The major assumptions are that all surfaces are grey and the radiation from these surfaces is diffuse. 2) *For long wave radiation from internal sources:* a radiative/convective split is entered for the heat introduced into the zone from equipment. The radiative part is distributed over the surfaces in a prescribed manner. 3) *For short wave radiation:* the short wave radiation from lights and the transmitted solar radiation is distributed over the surfaces in the zone in a prescribed manner.
TRNSYS	Provides two options: 1) *user defined* and 2) *internal calculation* [41]. *User defined* option allows the user to input constant convective heat transfer coefficients for interior and exterior surfaces. The default convective heat transfer coefficient is 11 kJ/h.m²K for the interior surfaces and 64 kJ/h.m²K for the exterior surfaces. *Internal calculation* of convective heat transfer calculation option calculates the convective heat transfer coefficient based on the temperature difference between the surface and the air near the surface. ➢ In this study, since the *internal calculation* option was available only for interior surfaces, *user-defined* option was selected for the exterior walls. The default convective heat transfer coefficient for interior surfaces (11 kJ/h.m²K) was assigned for the inside surface of the floor.	Provides three options: 1) the standard model, 2) the simple model and 3) the detailed model. *Standard model* is based on Seem's [40] star network which uses an artificial temperature node i.e. the star node. The star node is connected to the zone air node by convection and to the other wall and window elements by a combined radiative and convective heat component. *Simple model* is a one node model that uses combined radiative and convective heat transfer coefficients. *The detailed model* does not use an artificial star node. It calculates longwave radiative heat transfer separate from convection using view factors. ➢ In this study, the standard (starnet) model was used.

In *DOE-2*, the heat transfer between the interior surfaces and the zone air is modeled by assigning a single massless fictitious air layer to the inside surface of each building envelope construction [22]. This fictitious air layer is then assigned an invariant thermal resistance that accounts for the combined effect of the inside radiation and convection on the surface [22]. The combined radiation and convection heat transfer on each inside surface is then calculated as part of the building envelope conduction heat transfer calculations with a single 1-D conduction heat transfer equation. For the inside film resistances (I-F-R) of the floors in the *DOE-2* sealed boxes, the average of the cooling (0.92) and heating (0.61) mode air film resistances recommended by ASHRAE Handbook of Fundamentals were used.

In *TRNSYS*, the standard Starnet model was used in this study. In this model, each zone is represented with two nodes: 1) the Starnet node and 2) the zone air node [24]. The heat transfer between the inside surfaces and the zone air then occurs in two steps: 1) between the inside surfaces and the Starnet node and 2) between the Starnet node and the zone air node. The heat transfer between the inside surfaces and the Starnet node includes 1) the solar radiation and the long wave radiation generated from the internal objects such as people or furniture, 2) a combined convective and radiative heat flux, and 3) a user defined floor energy flow to the surface. The "combined convective and radiative heat flux" component corresponds to the equivalent sum of 1) the radiative heat transfer between the inside surfaces, and 2) the convective heat transfer between the inside surfaces and the zone air. The heat transfer between the Starnet node and the zone air node occurs only by convection. This convection heat transfer represents the sum of the heat transfer to the zone air 1) by infiltration from outside, 2) by ventilation from outside, 3) by convection from the internal gains (people, lights, equipment, etc.), and 4) by connective airflow from the neighboring air nodes.

In the *TRNSYS* sealed boxes, there were no infiltration, no ventilation, no neighboring zone air node, no heat generating internal objects and no additional energy flow defined towards the floor. Thus, the heat transfer between the slab and the zone air ($Q_{slab/zair}$) included only the combined radiative and convective heat flux component between the slab and the Starnet node in these boxes. The convective part of this combined heat flux was defined by entering the default *TRNSYS* convection heat transfer coefficient for interior surfaces (11 kJ/hr.m^{2}K) for the floor. Using this input, *TRNSYS* calculated a combined radiative and convective heat resistance as described by Seem [25].

In the *EnergyPlus* inside heat balance equation, the heat transfer between the inside surfaces and the zone air includes four heat transfer components. These are: 1) the shortwave radiation from solar and internal sources, 2) the long wave radiation exchange with other surfaces in the zone, 3) the long wave radiation from internal sources and 4) the convective heat exchange with the zone air [23]. In the *EnergyPlus* sealed boxes modeled in this study, there were no windows (no solar gains) and no internal sources. Thus, the $Q_{slab/zair}$ included only two components: 1) the long wave radiation heat exchange between the floor and the other surfaces, and 2) the convective heat exchange between the floor and the zone air. For the radiation component of the $Q_{slab/zair}$, *EnergyPlus* used a matrix of exchange coefficients between pairs of surfaces, which was developed by Hottel and Sarofim [26]. For the convection component, the default "detailed" inside convection model of *EnergyPlus* was selected. This model recalculated the convective heat transfer coefficients *(h)* at each time step based on the orientation of the surface and the temperature difference between the surface and the zone air, which resulted in varying convection coefficient (*h)* values during the simulation [23].

In this study, Winkelmann's ground temperatures and underground construction were entered into *DOE-2 (D2-GCW)* and *EnergyPlus (EP-GCW)*, and the resulting ground coupling loads in these two models were compared. The results showed that the *EP-GCW* model calculated slightly (0.1-0.3 W/m^2) lower floor heat fluxes than the *D2-GCW* model throughout the year (Figures 1 through 4). This variation resulted in slightly (0.2-0.4 GJ) lower annual ground coupling loads in the *EP-GCW* models than in the *D2-GCW* models (see the **I–a** arrows in Figure 5).

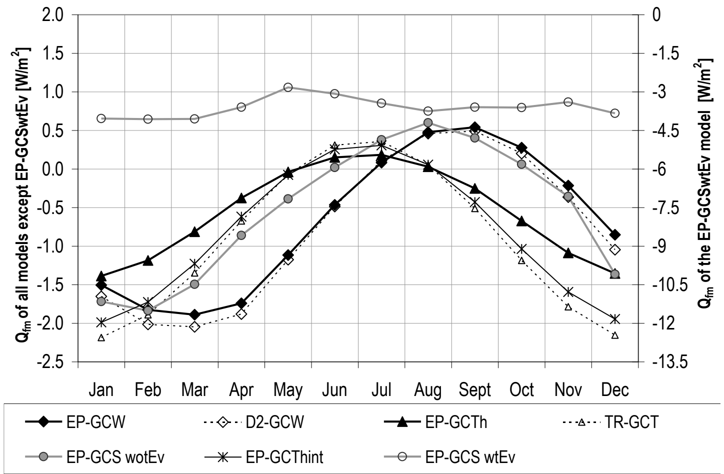

Figure 1. Monthly average floor heat fluxes of the Austin sealed box.

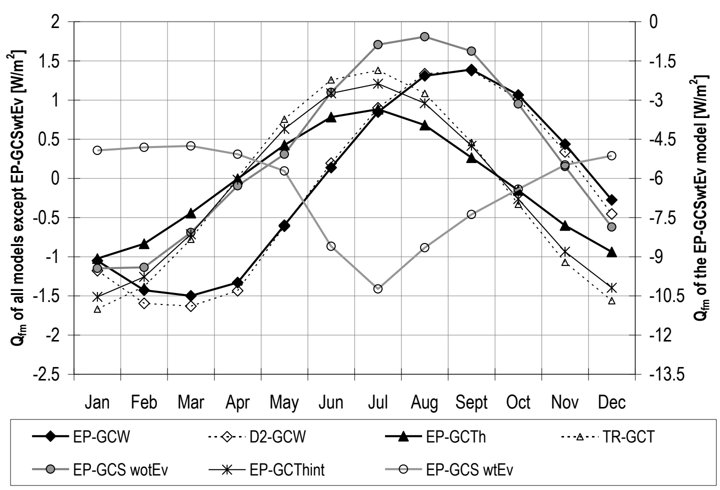

Figure 2. Monthly average floor heat fluxes of the Phoenix sealed box.

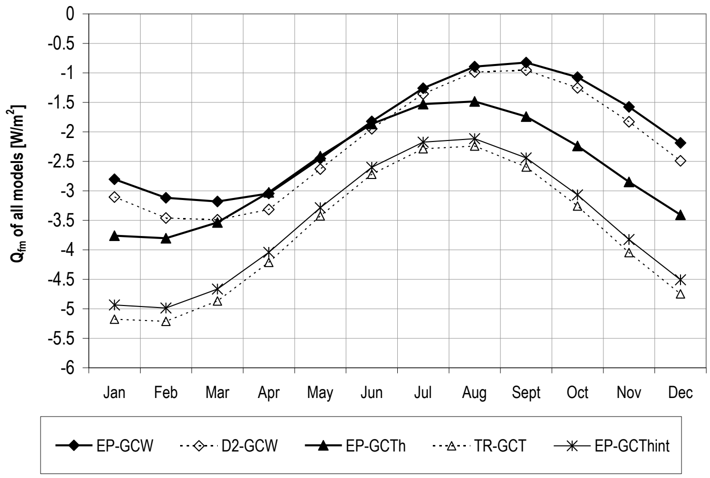

Figure 3. Monthly average floor heat fluxes of the Chicago sealed box.

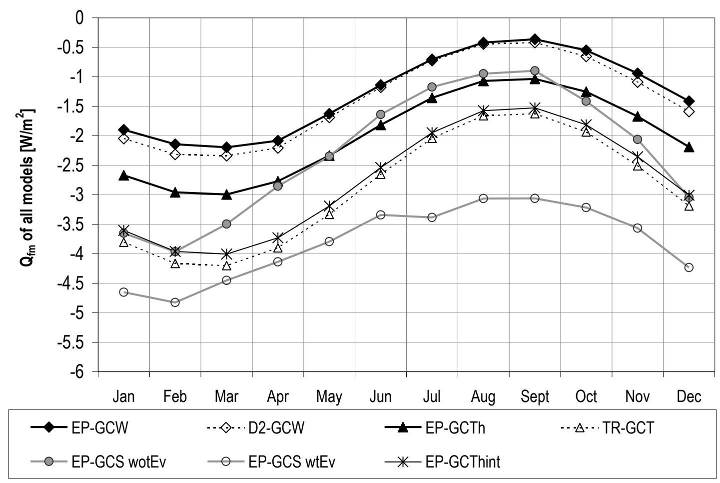

Figure 4. Monthly average floor heat fluxes of the Columbia Falls sealed box.

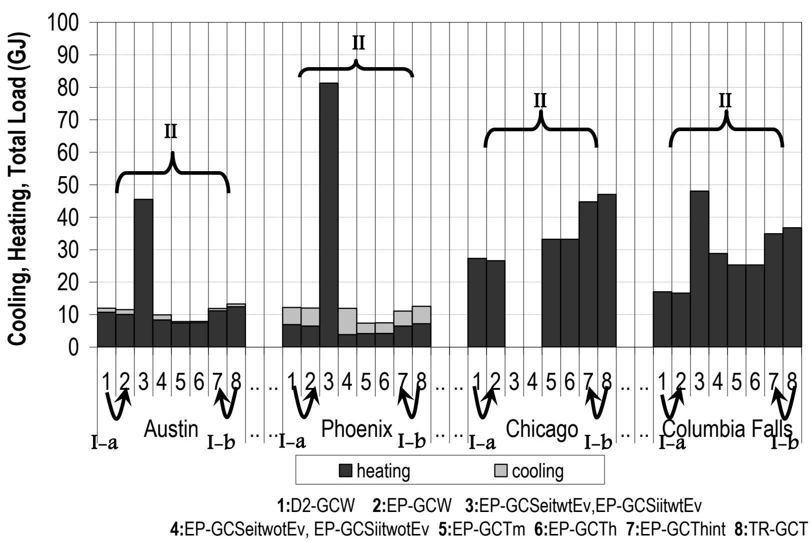

Figure 5. Cooling, heating and total thermal loads of the sealed boxes.

Among the radiation and convection models used in this study, those of *EnergyPlus* were the most detailed models. The *D2-GCW* models showing close floor heat fluxes to those of the *EP-GCW* models, therefore, indicated that the simple combined radiation and convection model of *DOE-2* makes good estimations for $Q_{slab/zair}$ when the inside air film resistance (I-F-R) of 0.136 m^2-K/W (0.77 hr-ft^2-°F/Btu) is used for the floor. Besides the differences between the inside radiation and convection models of *DOE-2* and *EnergyPlus* programs, there were two other factors that caused the 0-0.2 W/m^2 heat flux variation between the *D2-GCW* and *EP-GCW* models. First, the zone air temperatures (T_{zair}) fluctuated in *DOE-2* throughout the year; whereas they were constant at 23°C in *EnergyPlus* all year (Figure 6). Second, *DOE-2* assumed that the inside surface temperatures of the floor (T_{is}) are equal to zone air temperatures [22]; whereas *EnergyPlus* calculated the T_{is} at each time step as part of its inside heat balance calculations [23]. These differences in interior boundary conditions between the *D2-GCW* and *EP-GCW* models caused these two models to have different slab-soil interface temperatures ($T_{slab/soil}$). Figure 7 shows the $T_{slab/soil}$ of the *D2-GCW* and *EP-GCW* models for the sealed boxes.

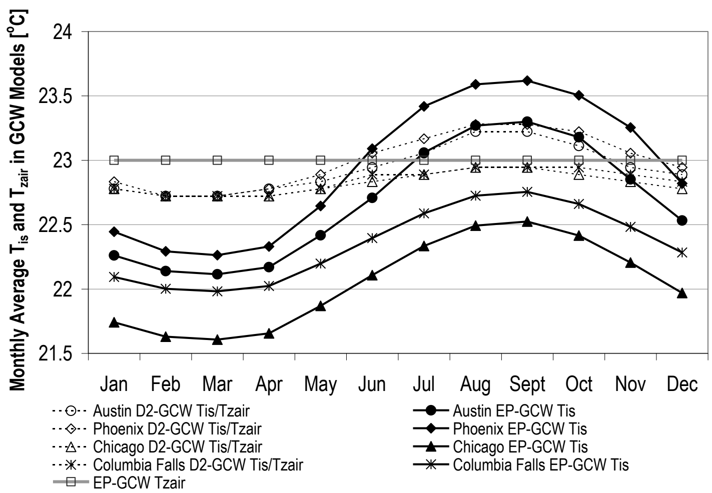

Figure 6. Monthly average inside surface temperatures (T_{is}) and zone air temperatures (T_{zair}) of the Winkelmann floors of the sealed boxes.

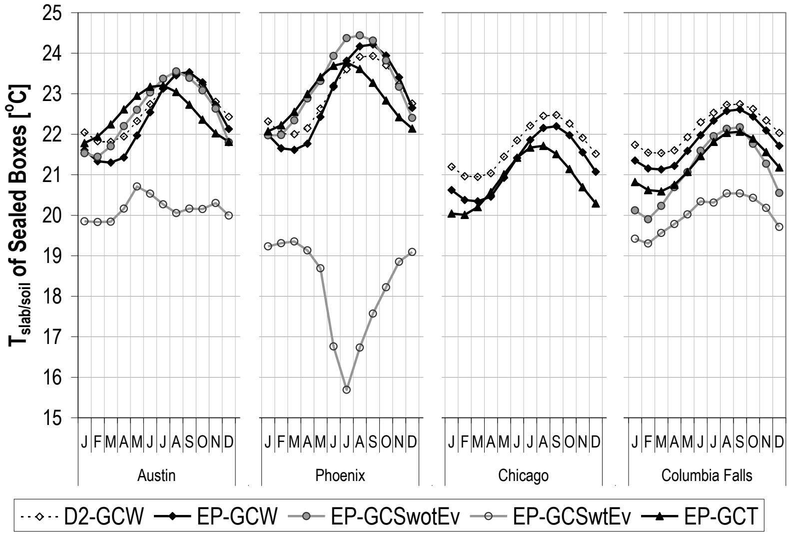

Figure 7. The slab-soil interface temperatures ($T_{slab/soil}$) of the sealed boxes.

The $Q_{slab/zair}$ calculation differences between *EnergyPlus* and *TRNSYS* programs were also quantified in this study. The $T_{slab/soil}$s of the *TR-GCT* models were entered into *EnergyPlus* (*EP-GCT*) and the variation in the ground coupling load was quantified. The results showed that the *EP-GCT* models calculated 5-14 GJ lower ground coupling loads than the *TR-GCT* models with a 0-1.2 W/m^2 monthly average variation (See Figures 1 through 4 and I–*b* arrows in Figure 5). The monthly average differences between the *EP-GCT* and *TR-GCT* fluxes were particularly higher in the cold (0.6-1.2 W/m^2) and temperate (0.8-1.4 W/m^2) climates than in the hot-humid (0-0.8 W/m^2) and hot-dry (0-0.6 W/m^2) climates. Thus, the annual ground coupling load difference between the *EP-GCT* and the *TR-GCT* models ended up being higher in the cold (11 GJ) and temperate (14 GJ) climates than in the hot-humid (5 GJ) and hot-dry (5 GJ) climates.

An intermediary model was introduced between the *EP-GCT* and *TR-GCT* models, the *EP-GCTint*, in order to further analyze the high ground coupling load variation between these two models (See Figure 5). This intermediary model had the same interior convection coefficients with the *TRNSYS* (*TR-GCT*) model, but it did the interior radiation heat transfer calculations using the detailed interior radiation algorithm of the *EnergyPlus* (*EP-GCT*) model. Thus, it allowed us to isolate and compare the radiation and convection heat transfer components of the ground coupling load difference between the *EP-GCT* and the *TR-GCT* models. The *EP-GCTint* models showed closer ground coupling loads to the *TR-GCT* models (within -12%) than to the *EP-GCT* models (within +50%) in all four climates. This result showed that the high variation between the ground coupling loads of the *EP-GCT* and *TR-GCT* models was caused primarily by the differences in the inside convection heat transfer calculations of the *EnergyPlus* and *TRNSYS* programs. This difference was explained by the 63%-88% higher convective heat transfer coefficients used in *TRNSYS* than those calculated by *EnergyPlus.* Figure 8 presents the monthly averages of the inside convection heat transfer coefficients of the *EP-GCT* models in comparison with those of the *TR-GCT* models. These findings revealed that the surface convection properties (particularly the *h* value) of the floor can have a significant effect on the calculated ground coupling load in low load conditions.

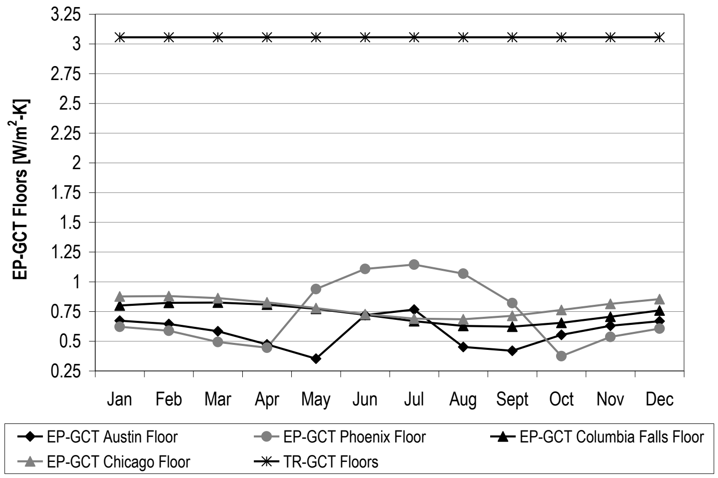

Figure 8. The convection coefficients of the *TRNSYS* floors.

4.1.2. Step 2: Heat transfer between the soil and the slab ($Q_{soil/slab}$)

At this step, the conductive heat transfer between the soil and the slab ($Q_{soil/slab}$) is compared between Winkelmann's model, the *Slab* model and the *TRNSYS* slab-on-grade model for the sealed boxes modeled in *EnergyPlus*. Below are the compared models.

- The *TRNSYS* slab-on-grade model with *EnergyPlus (EP-GCT)*
- The *Slab* model with *EnergyPlus (EP-GCS)*
- Winkelmann's slab-on-grade model with *EnergyPlus (EP-GCW)*

The ground coupling load differences between these three models were quantified and explained for the sealed boxes by referring to their primary assumptions and the calculation methods. The results are shown in Figure 5 with column 2. This analysis was started by examining the parameters that affected the conductive heat transfer between the soil and the slab ($Q_{soil/slab}$). These parameters were: 1) the inside surface temperatures of the floor (T_{is}), 2) the ground temperatures that the slab was exposed to ($T_{slab/soil}$), and 3) the overall heat transfer coefficient of the floor without the air film (U_{floor}). The U_{floor} was assigned as 2.647 W/m^2-K in all of the three slab-on-grade models. The calculated inside (T_{is}) and outside ($T_{slab/soil}$) temperatures of the slab, however, differed significantly between these models.

The inside temperatures (T_{is}) of the *EP-GCT*, *EP-GCS* and *EP-GCW* floors depended on the assumptions and calculation methods of the aboveground heat transfer calculator program (which in this case is *EnergyPlus*) for inside convection and radiation (see Step 1). Since the aboveground heat transfer calculator program was the same in all of the three models compared at Step 2, the differences in the T_{is} of these models were triggered primarily by the ground temperatures ($T_{slab/soil}$) that the slabs were exposed to. The soil-slab interface temperatures ($T_{slab/soil}$) of these floors then depended on the assumptions and the calculation methods of the slab-on-grade models used to simulate the floor, the soil and the heat transfer between them.

Among the studied slab-on-grade models, the *TRNSYS* slab-on-grade model was the most detailed one (see Table 4). This model assumes that the slab and the soil consist of cubic nodes which have six unique heat transfers to analyze. A simple iterative analytical method then solves the interdependent differential equations of a 3-D finite difference soil model at each time step. In this study, the soil-slab interface temperatures ($T_{slab/soil}$) of the test houses modeled in *TRNSYS (TR-GCT)* were entered into *EnergyPlus* hourly *(EP-GCTh)* and monthly *(EP-GCTm).* The ground coupling loads obtained with these two coupling methods were found to be very similar (within 6%) in all studied climates (Figure 5). This finding showed that ground temperatures do not show significant hourly variation and; therefore, monthly coupling of aboveground and belowground heat transfer calculations are reasonable. This finding was in agreement with an important assumption of the *Slab* model, which states that the time scales of the ground heat transfer processes are much longer than those of the building heat transfer processes (Table 4). Thus, the monthly average floor heat fluxes (Q_{fm}s) were used to compare the slab-on-grade models with each other in this step of the study.

In the *EP-GCT* models, it was observed that there is a clear relationship between the Q_{fm}s and the monthly average outside air temperatures (T_{am}s) (Figures 1, 2, 3, 4 and 9). This relationship, however, varied depending on the insulation configuration of the floor. For the uninsulated floors in the hot-humid and hot-dry climates, for instance, the peak Q_{fm}s and the peak T_{am}s occurred in the same month in the *EP-GCT* models (Figures 1 through 4). The maximum floor heat gains occurred in the hottest month (July) and the maximum floor heat losses occurred in the coldest month (January) (Figures 1 and 2). This was explained with the two assumptions of the *TRNSYS* slab-on-grade model. First, the average surface soil temperature was assumed to be equal to the annual average air temperature in *TRNSYS*. Second, the amplitude of the soil surface temperature was assumed to be equal to the one half of the maximum monthly average air temperature minus one half of the minimum monthly average air temperature. The vertical floor insulation used for the temperate and cold climates delayed the peaks of the Q_{fm}s in the *EP-GCT* models and the time delay between the peaks of the Q_{fm}s and T_{am}s in this model increased with increasing insulation depth in these climates (Figures 3 and 4). For instance, in the *EP-GCT* models that had 2 ft deep insulation in Chicago, the maximum Q_{fm} to the ground occurred one month later than the minimum T_{am} (Figure 3). In the *EP-GCT* models that had 4 ft deep insulation in Columbia Falls, however, the maximum Q_{fm} to the ground occurred two months later than the minimum T_{am} (Figure 4).

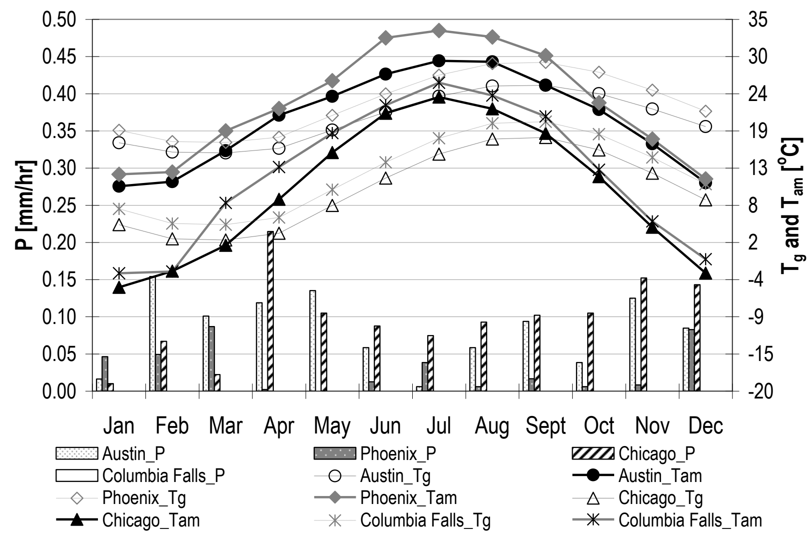

Figure 10. The monthly average precipitation (P), ground temperatures (T_g) and outside air temperatures (T_{am}) in Austin, Phoenix, Chicago and Montana.

The *Slab* model of *EnergyPlus* was the second most detailed slab-on-grade heat transfer model discussed in this study and it used a numerical method to solve a boundary value problem on the 3-D heat conduction equation and produced monthly slab-soil interface temperatures. These temperatures were then entered into *EnergyPlus* as the exterior boundary temperatures of the floor and were used in the aboveground 1-D heat conduction calculations of *EnergyPlus*. This coupled *EnergyPlus-Slab* model was represented with "EP-GCS" in this study.

Our results showed that, for the sealed boxes at 23°C constant zone air temperature, the internal *(EP-GCSiit)* and external *(EP-GCSeit)* iterations of *EnergyPlus* and *Slab* programs showed exactly the same ground coupling loads in all climates (Figure 5). The *Slab* program gave an error for the required insulation configuration for temperate climates (0.6m deep R-10 vertical insulation) by reporting a contradictory error note (Figure 3). The error note indicated that an invalid insulation depth was entered for the slab, whereas the entered insulation depth (0.6m) was one of the values suggested by the program. When all available insulation depths were tried for this climate (0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 2.5, 3), it was found that the *Slab* model could not model the R-10 vertical insulation with depths less than 1m. This error was attributed to an internal limitation of the *Slab* model for providing convergence. It was determined that it is necessary to overcome this limitation before the *EP-GCS* model is used for residential code compliance in temperate climates.

When the evapotranspiration flag was off, the *EP-GCS* models *(EP-GCSwotEv)* exhibited 0.3-1 W/m^2 higher Q_{fm} peaks to the ground and 0.2-1.4 W/m^2 higher Q_{fm} peaks into the space when compared to the *EP-GCT* models (Figures 1, 2 and 4). This was primarily because the *EP-GCSwotEv* models showed lower minimum ground temperatures in winter and higher maximum ground temperatures in summer by 0.1-0.7°C when compared to the *EP-GCT* models (Figure 7). Consequently, the *EP-GCSwotEv* models showed 2.0-4.4 GJ higher annual ground coupling loads than the *EP-GCT* models for identical sealed boxes (Figure 5).

It was observed that, for the uninsulated floors in the hot climates, the peaks of the Q_{fm}s in the *EP-GCSwotEv* model were a month delayed when compared to the peaks of the T_{am}s. Since the peak Q_{fm}s of the *EP-GCT* models occurred at the peak outside air temperatures in these climates, the Q_{fm}s of the *GCSwotEv* models was also a month late when compared to those of the *EP-GCT* models. This was because the *Slab* model of *EnergyPlus* shifted the ground temperatures by a phase lag to account for the effect of the soil thermal mass [6]. For the insulated floor in the cold climate, however, the peak Q_{fm}s of the *EP-GCSwotEv* and the *EP-GCT* models occurred in the same months (Figure 4).

In the finite difference calculations of the *Slab* model, insulation is represented by an additional surface resistance on the exterior of the floor cells [6]. This additional resistance reduces the peak heat gains and losses through the floor resulting in smaller peak to peak amplitudes in the insulated conditions of the same floors. Our results showed that the peak to peak amplitudes of the Q_{fm}s in the *EP-GCSwotEv* models were 1.5 times higher than those in the *EP-GCT* models for both the insulated and uninsulated floors (Figures 1, 2 and 4).

According to Bahnfleth [6], ground surface condition is the most significant boundary condition for the floor heat transfer and evaporative transpiration (evapotranspiration) is a significant parameter for this boundary. The *Slab* program models a potential evapotranspiration case which accounts for a number of naturally occurring situations, most often through the action of vegetation [6]. In this case, grasses and other similar ground cover, when well watered, are assumed to transpire moisture into the atmosphere at near the potential rate even when the ground surface is relatively dry [6]. According to Bahnfleth [6], the evapotranspiration model of *Slab* takes these processes into account and brackets the range of boundary evapotranspiration effects. He claims that this model is, therefore, a useful asymptotic model that does not require specification of moisture conditions at the surface [6]. Figure 9 shows the annual total precipitation of the four cities studied in this paper. It was realized that although the weather file showed zero annual precipitation for Columbia Falls, the *Slab* model identified a difference in ground coupling load with the use of evapotranspiration model (Figure 5). This result supported Bahnfleth's statement by showing that the evaporative transpiration case modeled by the *Slab* model is independent from the precipitation level.

In our runs for the sealed boxes, evapotranspiration decreased the mean ground temperature several degrees below the mean zone air temperatures resulting in higher heat losses from the floor (Figures 1, 2, 4 and 7). For the floors located in Austin, Phoenix and Columbia Falls, a drastic decrease occurred in the $T_{slab/soil}$ values in July and August, which happened to be the hottest months (Figures 7 and 9). This result showed that the peak floor heat losses observed in the *EP-GCSwtEv* models (see Figures 1, 2 and 4) in summer were triggered by the high outside air temperatures. This finding also explained the peak basement heat losses that Andolsun et al. [11] obtained in summer using the *Basement* preprocessor of *EnergyPlus* in an earlier study.

The *EP-GCSwtEv* models showed significantly higher Q_{fm}s when compared to the *EP-GCT* models (Figures 1, 2 and 4). In earlier test runs, it was also observed that *Slab* program often resets the slab thickness to a higher value to achieve the user-defined internal convergence. This problem resulted in inconsistent slab thicknesses between the aboveground and belowground models of *EnergyPlus*. These findings showed that the *Slab* model of *EnergyPlus* needs urgent improvements. Particularly the evapotranspiration model of *Slab* needs to be validated through experimental studies. Thus, it was determined that it is important to avoid using the *Slab* model in residential code compliance calculations until the necessary validations and improvements are made on this model.

Winkelmann's method was a simplified slab-on-grade heat transfer modeling method based on the earlier findings of Huang et al. [20]. Huang et al. [20] did 2-D finite difference calculations in 1980s to calculate the daily heat fluxes at each interior node point of a representative one-foot vertical section of the foundation and surrounding soil. They then derived the total heat fluxes through the 28 x 55 feet foundation of the prototypical house by multiplying the fluxes at each node point of the vertical section by the length of that nodal condition. The resultant foundation fluxes for the 65 different below grade configurations in the 13 cities were stored in utility files [19]. These fluxes were stored for 123 three-day periods of the year to fit the memory limitations of the Function feature in the LOADS subprogram of DOE-2.1C. Linear interpolations were then done between the sequential three-day average fluxes in *DOE-2* in order to produce smoothly varying fluxes for each hour [19].

Huang *et al.* [20] determined the daily floor heat fluxes for each foundation configuration by assuming 70°F constant zone air temperature all year. The 70°F was the default indoor air temperature that *DOE-2* LOADS uses (T_{LOADS}). Huang *et al.* [20] also found that there is a linear relationship between the variation in underground heat flux ($\Delta Q= Q_{mod}-Q_{LOADS}$) and the variation in the constant zone air temperature ($\Delta T= T_{mod}-T_{LOADS}$). They defined this relationship as a linear function the slope of which equaled to the effective conductivity of the slab ($U_{effective}$). They then calculated the $U_{effective}$ value of each slab configuration using Equation 7.

$$U_{effective}= (Q_{mod}-Q_{LOADS})/[(T_{mod}- T_{LOADS})xA] \quad \text{(Equation 7)}$$

In Winkelmann's method, these $U_{effective}$ values are currently entered into *DOE-2* as an input and used in the SYSTEM subprogram in *DOE-2*. In SYSTEMS, the U-effective values correct the floor heat fluxes calculated in *DOE-2* LOADS to account for the constant zone air temperatures different than 70°F. For slabs, the floor heat transfer calculations of Winkelmann's model are complete after this correction, and no further correction is made to take the varying indoor temperatures into consideration. In the sealed boxes modeled in this study, the zone air temperatures were set to 23°C (73.4°F) all year. Thus, the possible errors Winkelmann's slab-on-grade model for varying zone air temperatures were avoided for these boxes. There was, however, another limitation of Winkelmann's slab-on-grade model, which was still valid for the sealed boxes. The 2-D finite difference calculation of Huang et al. [20] was made on a rectangular prototype building with unequal sides; therefore, the obtained $U_{effective}$ values were expected to be somewhat off for the square slabs of the sealed boxes modeled in this study. When Winkelmann's slab-on-grade model was used in *EnergyPlus (EP-GCW)*, the same underground construction layers used in the *D2-GCW* model was assigned to the floor. Thus, the resistances of the fictitious layer, soil, slab and carpet were identical to those in the *D2-GCW* model. Only the air film resistances of the *EP-GCW* models were different than those of the *D2-GCW* models due to the varying inside convection coefficients in *EnergyPlus*.

For the uninsulated sealed boxes in Austin and Phoenix, the *EP-GCW* models showed 3.6 GJ and 4.5 GJ higher ground coupling loads when compared to the *EP-GCT* models respectively (Figure 5). For the insulated floors in Chicago and Columbia Falls, however, the ground coupling loads of the *EP-GCW* boxes were 6.6 GJ and 8.7 GJ lower than those of the *EP-GCT* models respectively (Figure 5).

It was observed that, for the uninsulated floors in the hot climates, the *EP-GCW* models showed very similar (with a maximum of 0.5°C difference) soil-slab interface temperatures ($T_{slab/soil}$) to those of the *EP-GCT* models with a two month time delay (Figure 7). This then caused the Q_{fm}s of the *EP-GCW* models to be similar (with a maximum of 0.6 W/m^2 difference) but two month delayed when compared to those of the *EP-GCT* models (Figures 1 and 2). These delayed $T_{slab/soil}$s and Q_{fm}s in the *EP-GCW* models were attributed to the deep ground temperatures (T_gs) calculated by *DOE-2* using Kasuda correlation [22]. Figure 9 shows that these deep ground temperatures (T_gs) were two months delayed when compared to the monthly average outside air temperatures (T_{am}s). These findings indicated that if an internal back shifting is done on the floor heat fluxes of Huang et al. [20], significant improvement can be obtained in annual ground coupling loads under constant zone air temperatures. It was also observed that, for the insulated floors, the *EP-GCW* models made close estimates for the peak months (with a maximum of 1 month shift) to those of the *EP-GCT* models (Figures 3 and 4). The peak months of the *EP-GCW* models approached those of the *EP-GCT* models with increasing insulation depth.

The peak to peak amplitudes of the *EP-GCW* and *EP-GCT* heat fluxes were closer for the insulated floors than for the uninsulated floors (Figures 1, 2, 3 and 4). For the uninsulated floors in hot-humid and hot-dry climates, the peak-to-peak amplitudes of the *EP-GCW* fluxes were 1.4 times higher than those of the *EP-GCT* fluxes (Figures 1 and 2). For the insulated floors in temperate and cold climates, however, the *EP-GCW* models showed identical peak to peak amplitudes with the *EP-GCT* models (Figures 3 and 4). This finding showed that, the peak to peak amplitudes of the heat fluxes calculated by Huang et al. [20] for uninsulated floors need to be reduced by ~1.4 times for better ground coupling load estimations under constant zone air temperatures.

5. Summary and conclusions

Early studies have shown that the current energy modeling tools calculate dissimilar results for the slab-on-grade heat transfer. This study quantifies the discrepancies between *DOE-2* and *EnergyPlus* slab-on-grade heat transfer for International Energy Conservation Code (IECC) compliant low-rise 20m x 20m x 3m residential buildings with unconditioned attics in four U.S. climates (hot-humid, hot-dry, cold, and temperate). For the modeling of the slab-on-grade heat transfer, Winkelmann's slab-on-grade model was used with *DOE-2* and the *Slab* model was used with *EnergyPlus*. The reliabilities of these models were then discussed by comparing their results with those of a more detailed *TRNSYS* slab-on-grade model.

The study included two steps. In the first step, the effect of ground coupling was isolated by modeling empty slab-on-grade sealed boxes at 23°C constant zone air temperature in four U.S. climates with the IECC required insulation configurations. The ground temperatures calculated by Winkelmann's (GCW), *Slab* (GCS) and *TRNSYS* (GCT) slab-on-grade models were entered into *EnergyPlus* and the resulting ground coupling loads were compared. At the second step, load components (i.e. wall heat transfer, ceiling heat transfer to/from an unconditioned attic, windows, doors, shades, lights, equipment and infiltration) were added to these boxes to convert them into fully loaded IECC compliant houses. Discrepancies between the results of the obtained models were then quantified and explained both for the ground isolated and the ground coupled conditions. This report includes the results obtained for the sealed boxes modeled in hot-humid, hot-dry, temperate and cold climates.

For the sealed boxes, the floor heat fluxes of the *GCW* and *GCS* models differed from those of the *GCT* slab-on-grade models in the magnitudes, the peak months and the peak-to-peak amplitudes of the floor heat fluxes.

- Magnitudes: The *GCS* models without evaporative transpiration showed much less variation in annual ground coupling loads (2-4 GJ) from those of the *GCT* models than the *GCW* models did (4-9 GJ). The *GCS* models with evaporative transpiration, however, showed significantly (23 GJ-74 GJ) higher annual ground coupling loads than those exhibited by the *GCT* models.
- Peak Months: For the uninsulated floors in the hot climates, the peaks of the floor heat fluxes in the *GCW* and *GCS* models were two months and one month delayed respectively when compared to those of the *GCT* models. For the insulated floors in the cold climate, however, all three models had identical peak months.
- Peak to Peak Amplitudes: The *GCS* floor heat fluxes showed 1.5 times higher peak-to-peak amplitudes than those of the *GCT* floor heat fluxes did for all floor configurations and climates. The peak-to-peak amplitudes of the *GCW* models were 1.4 times higher than those of the *GCT* models for the uninsulated floors in the hot climates and identical to the *GCT* models for the insulated floors in the temperate and cold climates.

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