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Whole-Building Energy Simulation with a Three-Dimensional Ground-Coupled Heat Transfer Model

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Whole-Building Energy Simulation with a Three-Dimensional Ground-Coupled Heat Transfer Model

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ABSTRACT

A three-dimensional, finite-element, heat-transfer computer program was developed to study ground-coupled heat transfer from buildings. It was used in conjunction with the SUNREL whole-building energy simulation program to analyze ground-coupled heat transfer from buildings, and the results were compared with the simple ground-coupled heat transfer models used in whole-building energy simulation programs. The detailed model provides another method of testing and refining the simple models and analyzing complex problems. This work is part of an effort to improve the analysis of the ground-coupled heat transfer in building energy simulation programs. The output from this detailed model and several others will form a set of reference results for use with the BESTEST diagnostic procedure. We anticipate that the results from the work will be incorporated into ANSI/ASHRAE 140-2001, *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*.

INTRODUCTION

Ground-coupled heat transfer from buildings can be a significant fraction of the overall heat transfer; however, the computer models for calculating this mode of heat transfer are less developed than heat transfer models for other parts of buildings. This is because the heat transfer between a building and the surrounding soil is three-dimensional and is complicated by many unknowns, such as the soil's physical properties and complex physical processes, many of which involve effects of moisture. Thus, building energy simulation programs handle ground-coupled heat transfer with simple correlations and one-dimensional calculations based on the results of analytic solutions and numerical simulations. The analytic and numerical solutions used to develop the correlation models are typically limited to a few simple geometries and soil types and are not directly coupled with whole-building energy simulation programs.

This paper presents the results of adding a three-dimensional finite-element-method (FEM) heat-conduction model to a whole-building simulation program. It was developed along with a heat- and moisture-transfer program specifically for heat transfer from buildings (Deru 2001; Deru and Kirkpatrick 2002). The whole-building simulation program used in the work is SUNREL (NREL 2002), which is an updated version of SERI-RES. The combined program was used as part of an effort to upgrade the ground-coupled cases in the International Energy Agency (IEA) Building Energy Simulation Test (BESTEST) procedure (Judkoff and Neymark 1995a) and Home Energy Rating System (HERS) BESTEST procedure (Judkoff and Neymark 1995b).

The current work builds on a long history of research into building ground-coupled heat transfer. One of the earliest analytic solutions was developed by Lachenbruch (1957), who solved the transient heat conduction problem using Green's functions. The earliest numerical solutions were by Kusuda and Achenbach (1963), Wang (1979), and Mitalas (1982, 1987). These solutions were used as the basis of some of the correlation-based methods used in current whole-building energy simulation programs. Recent numerical models have been created by Shen and Ramsey (1988), Krarti et al. (1988), Bahnfleth and Pederson (1990), and Bahnfleth et al. (1998).

MODEL DESCRIPTION

Ground-Coupled Heat Transfer Model

The heat transfer paths in soil include conduction through the soil grains, liquid, and gases; latent heat transfer through evaporation-condensation cycles; sensible heat transfer by vapor and liquid diffusion and convection; and radiation in the gas-filled pores (de Vries 1975). Conduction is the dominant mode of heat transfer under most circumstances; however, the thermal conductivity of soil is usually given as an effective value accounting for conduction and vapor diffusion. The moisture content can have a large effect on the thermal conductivity, which can change by a factor of 10 from dry soil to saturated soil. For most building locations, the soil moisture content does not vary much except for the top few inches of soil, which can change daily or seasonally with atmospheric conditions. The error associated with using a fixed value of thermal conductivity is usually small for calculations over a long period if an appropriate value is chosen. For building locations where the moisture content has large variations with the season or with depth, the thermal conductivity can be varied to account for the changing conditions.

The ground-coupled heat-transfer model used in this work, called GHT, was developed along with a heat- and moisture-transfer model called GHAMT (Deru 2001). GHAMT solves the coupled heat and moisture transfer problem and GHT solves the heat-conduction equation (Eq. [1]) for two- or three-dimensional problems. The current versions of both programs use linear finite elements and a Galerkin weighted residual solution method.

$$\rho C_P \frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T\right) + q''' \tag{1}$$

The detailed thermal energy balance at the atmospheric boundary includes convection, evapotranspiration, short-wave radiation, and long-wave radiation exchange with the environment (Figure 1). The constant temperature condition is defined in Eq. (2), and the flux boundary condition is defined by Eq. (3); all heat flows are taken positive into the control surface. Because of this definition, the evapotranspiration term is positive for moisture addition.

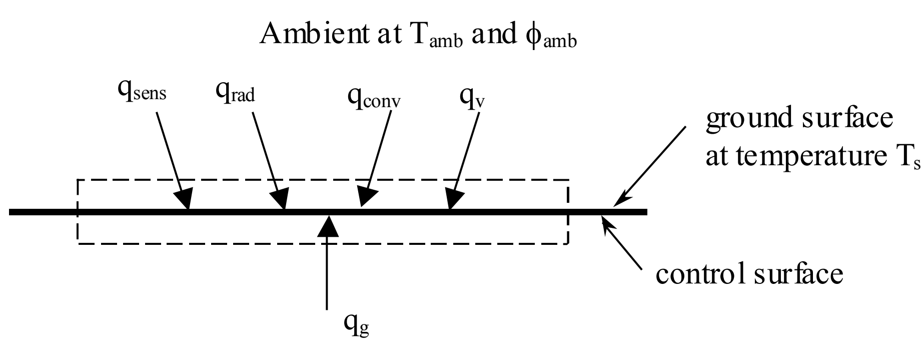

Figure 1. Thermal energy balance at the ground surface

$$T = T_s \tag{2}$$

$$q_g + q_{rad} + q_{conv} + q_v + q_{sens} = 0 \tag{3}$$

The sensible heat q_{sens} accounts for all sources of heat not included in the other terms. The first term in Eq. (3) represents the conduction of heat in the ground caused by thermal gradients normal to the surface as shown in Eq. (4).

$$q_g = -k\frac{\partial T}{\partial n} \tag{4}$$

The radiation term q_{rad} can be divided into absorbed direct and diffuse short-wave radiation from the sun and the long-wave radiation exchange between the ground and the atmosphere. The long-wave radiation exchange assumes the ground acts as a gray surface and the infrared emissivity, ε_s, and the absorbtivity are equal. Martin and Berdahl (1984) linearized the radiation exchange equation between the surface and the sky as shown in Eq. (5). Where σ is the Stefan-Boltzman constant, T_s is the surface temperature, and T_{sky} is the temperature of a blackbody emitting the same amount of radiation as the sky. The sky temperature is calculated by Eq. (6), where ε_{sky} accounts for the effects of cloud cover.

$$q_{lw} = 4\varepsilon_s \sigma T_{amb}^3 (T_s - T_{sky}) \tag{5}$$

$$T_{sky} = \varepsilon_{sky}^{1/4} T_{amb} \tag{6}$$

The convection and evapotranspiration terms depend on wind speed, surface conditions, and gradients of temperature and vapor density. The forced convection heat transfer is calculated from Eq. (7), where D_h is the thermal-diffusivity coefficient in air and is estimated from eddy diffusivity models.

$$\begin{aligned} q_{conv} &= h(T_{amb} - T_s) \\ &= \rho_a C_{P,a} D_h (T_{amb} - T_s) \end{aligned} \tag{7}$$

Four eddy diffusivity models were tested. Those presented by Jensen (1973) were chosen for this work. The thermal-diffusivity coefficient varies with the stability of the air mass, which can be estimated with the Richardson number. The Richardson number relates the buoyancy and frictional forces and can be estimated by Eq. (8). For neutrally stable conditions, the momentum-transfer coefficient can be calculated as Eq. (9). Here, κ is the von Karman constant, u_w (m/s) is the local wind speed, z_w (m) is the height of the wind speed measurement, and z_o (m) is the roughness height of the ground surface. The thermal-diffusivity coefficient is determined by using the stability-correction relationships in Eq. (10). The forced-convection heat-transfer coefficient is combined with a natural-convection coefficient at low wind speeds, which is estimated by correlations for natural convection from a flat plate.

$$Ri \approx \frac{g(T_{amb} - T_s)}{u_w^2} \frac{(z_o z)^{1/2}}{\ln(z/z_o)} \tag{8}$$

$$D_m = \frac{\kappa^2 u_w}{[\ln(z_w/z_o)]^2} \tag{9}$$

$$\begin{aligned} D_h &= D_m(1-16Ri)^{0.75} \quad &&\text{, for } Ri \le 0 \\ D_h &= D_m(1+10Ri)^{-1} \quad &&\text{, for } Ri > 0 \end{aligned} \tag{10}$$

The approach taken for the evapotranspiration is slightly different because the moisture at the surface is not modeled. Jensen (1973) presents a detailed derivation of an evapotranspiration model with three components, shown in Eq. (11): one for the portion of the incoming thermal energy from solar radiation and conduction from the ground that is converted directly to latent heat, one for the energy removed from the air and supplied for evaporation at the surface, and one for the latent energy released by condensation at the surface when the vapor pressure is less than the saturation vapor pressure. If the vapor pressure at the surface is equal to the saturated value, the final term in Eq. (11) is zero. In this case, water is not the limiting factor and evapotranspiration occurs at the maximum rate, called *potential evapotranspiration*. The last term is dropped because no information about the wet bulb temperature at the surface is known. Because evapotranspiration often does not occur at the potential value, the results can be bracketed with an evapotranspiration ratio, K_{evap}, defined as the ratio of the actual evapotranspiration and the potential evapotranspiration. The ratio $\Delta/(\Delta + \gamma)$ is the fraction of the energy added to the surface used for evaporation. The term Δ is the derivative of the saturated water vapor pressure with temperature and γ is called the psychrometric constant and is defined in Eq. (12). By combining equations for each of the flux terms in Eq. (3), the final equation for the flux boundary condition can be represented by Eq. (13).

$$h_{fg}E = \frac{\Delta}{\Delta + \gamma}(q_r + q_g) + \rho_a C_{Pa} D_v (T_{amb} - T_{wb}) - \rho_a C_{Pa} D_v (T_s - T_{wb,s}) \tag{11}$$

$$\gamma = \frac{\rho_a C_{Pa} R_w T}{h_{fg}} \tag{12}$$

$$\begin{aligned} -q_g = &(1 - \rho_{grd})I_{horz} + h_r(T_{sky} - T_s) + h\left(1 + K_{evap}\frac{\Delta}{\gamma}\right)(T_{amb} - T_s) - \\ &K_{evap} h_v \frac{\Delta + \gamma}{\gamma}(T_{amb} - T_{wb}) \end{aligned} \tag{13}$$

The current model accounts for the effects of surface cover, such as grass, but not for shading or snow cover. Long periods of snow cover provide an insulating layer and can lead to higher ground temperatures.

The transient problem can be solved explicitly or implicitly. The implicit approach allows longer time steps; however, the need to invert the coefficient matrix greatly increases the storage requirements and the number of calculations for three-dimensional geometries. Because only simple matrix multiplications are required with an explicit solution, a very efficient matrix storage technique can be used to store only those elements that are non-zero plus an indexing array. The storage requirements are further reduced because the coefficient matrix is symmetric. The storage method is called row-indexed sparse storage (Press et al. 1992) and is approximately two orders of magnitude less than a skyline storage approach.

Verification and Validation

Ensuring that algorithms and computer programs produce the expected results is often quite difficult, especially for complicated programs. Each routine in these programs was first verified for correct coding and operation through unit testing. The program as a whole was then verified with simple two- and three-dimensional patch tests consisting of a few elements with fixed linear thermal gradients. Next, the programs were validated against an analytic solution of the temperature field in a two-dimensional region with fixed temperature boundaries.

A more comprehensive test of the GHAMT was completed by validation with measured data (Deru and Kirkpatrick 2002). Weather data and ground temperatures at depths to 1 m deep were measured in an open field over a period of seven months. A one-dimensional simulation was conducted and compared with five months of the measured data. The maximum error in the temperature prediction at a depth of 0.65 m was 1.7°C, and the root-mean-square error was 0.5°C. The surface temperature was more difficult to predict with the maximum error of 12.5°C, and the mean square error was 2.4°C.

Building Energy Simulation Model

The building simulation program used for this work was SUNREL, which was developed as an upgrade to SERI-RES version 1.0 (Deru et al. 2002). SERI-RES has been widely used and tested, and two versions of it were used as base programs for the IEA and HERS BESTEST procedures (Judkoff and Neymark 1995a, 1995b). SERI-RES is an hourly simulation program created primarily for small envelope dominated buildings. The upgrades in SUNREL have been tested and successfully put through the BESTEST procedure. To complete this work, a special version of SUNREL version 1.07.1 GC was created to operate with the FEM heat-conduction program.

In this combined program, GHT models the three-dimensional heat transfer in the ground and in the concrete floors and walls in contact with the ground and SUNREL models the above-grade part of the building. Each hour SUNREL calls GHT with the new weather parameters, interior solar gains, and zone air temperature inputs. GHT uses this information to calculate the new surface temperatures, which are passed back to SUNREL. SUNREL then performs the energy balance on the zone air node with sub-hourly time steps to satisfy the stability requirements of the one-dimensional forward-finite-difference scheme.

BUILDINGS MODELED

This work is part of an effort to provide a more detailed analysis of the ground-coupled building cases in the IEA and HERS BESTEST procedures. The buildings modeled include insulated and uninsulated slabs-on-grade and basements. Descriptions and diagrams for each case follow. The three-dimensional calculation domains analyzed by GHT included the concrete floors and walls and exterior insulation in contact with the ground. Symmetry was assumed in both horizontal directions for all cases, so only one-quarter of the ground-coupled part of the building was modeled.

IEA BESTEST Case

For IEA BESTEST case 990, the building is an 8 m x 6 m x 2.7 m (26.2 ft x 19.7 ft x 8.9 ft) rectangular box with its long axis running east to west. Half the building is below grade and half above grade. The windows completely cover the above-grade portion of the south wall. A summary of the construction details is presented in Table 1, and additional details are found in the IEA BESTEST manual (Judkoff and Neymark 1995a). The soil was assumed to be homogeneous with constant properties (shown in Table 2) and described as “dry packed” in the IEA BESTEST manual.

Table 1. IEA BESTEST case 990 construction details

Component	Construction (inside to outside)	Area ft^2 (m^2)	U-value (surf - surf) Btu/h·ft^2·°F (W/m^2·K)	R-value (surf - surf) h·ft^2·°F/Btu (m^2·K/W)
Above-grade walls	4 in (10 cm) conc. block, foam insul., and wood siding	406.9 (37.8)	0.098 (0.556)	10.199 (1.797)
Below-grade walls	4 in (10 cm) conc. block	406.9 (37.8)	0.899 (5.100)	1.113 (0.196)
Floor	3.15 in (8 cm) concrete	516.7(48)	2.489 (14.125)	0.402 (0.071)
Roof	plaster board, fiberglass ins., and roofdeck	516.7(48)	0.059 (0.334)	16.979 (2.992)
Windows (south wall)	clear double pane	116.25 (10.8)	0.528 (3.0) (air-to-air)	1.893 (0.333) (air-to-air)

Table 2. IEA BESTEST soil thermal properties

Thermal conductivity Btu/h·ft·°F (W/m·K)	0.75 (1.3)
Density lb/ft^3 (kg/m^3)	93.75 (1500)
Specific heat Btu/lb·°F (J/kg·K)	0.19 (800)

A two-dimensional cross-section of the 10 m x 10 m x 10 m (32.8 ft x 32.8 ft x 32.8 ft) computation domain is shown in Figure 2. Based on previous work by one of the authors, this domain was thought to be large enough to validate the boundary condition assumptions. The coordinate origin was placed in the center of the building at ground level. The two boundaries at x = 0 and y = 0 are planes of symmetry and can be treated as adiabatic. The two boundaries at x = 10 m and y = 10 m are assumed to be far enough away from the building and other sources of heat to be treated as adiabatic. The deep ground boundary is assumed to remain at a constant temperature (a valid assumption of average conditions for most cases). The deep-ground temperature was taken to be the annual average air temperature, which is 50°F (10°C). The soil boundary exposed to the atmosphere was modeled assuming a ground cover 4 in (10 cm) high to simulate grass and an evapotranspiration ratio of 0.5, which is half the potential value. The boundary conditions on the inside surfaces of the below-grade walls and floor consisted of the distributed direct solar gain through the windows and convection with the zone air temperature. The walls above grade were modeled in SUNREL, which performs only one-dimensional heat conduction calculations. Because the model for the top section of the wall does not accept vertical heat transfer, the top surface of the below-grade section of the wall was assumed to be adiabatic. This assumption is reasonable for a wood frame wall on top of a concrete basement wall, but it is not as good for a concrete wall on top of a concrete wall. The insulation on the outside of the above-grade wall helps reduce the amount of vertical heat flow in the wall and thus the error associated with this assumption.

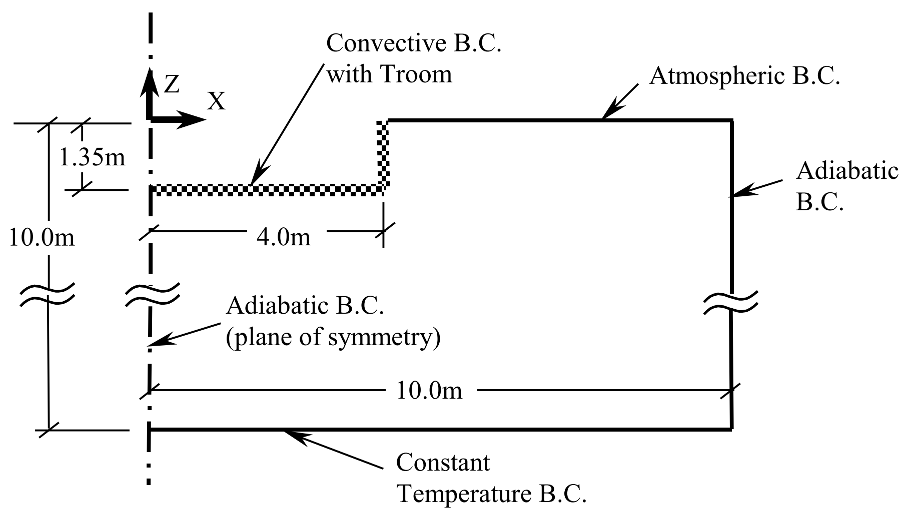

Figure 2. Two-dimensional view of the computation domain and boundary conditions for the IEA BESTEST case 990

The mesh generated for the geometry shown in Figure 2 contained 22,584 nodes and 20,150 hexahedron elements. The runtimes for an annual simulation were approximately five hours on a Pentium-III 930-MHz desktop computer. To establish an equilibrium temperature distribution in the ground, the model was run for three years with a constant zone-air temperature before the final simulation. Similar buildings with a revised mesh have reduced the runtimes to two hours on the same computer and 1.3 hours on a 1.4-GHz computer.

HERS BESTEST Cases

The building used for the HERS BESTEST cases was 57 ft x 27 ft x 8 ft (17.4 m x 8.2 m x 2.4 m) with an attic formed by a sloped roof and the long axis running east –to west. The windows were equally distributed around the building. In the four cases completed with this building, the above-grade section remained the same and the ground-coupled section changed as summarized in Table 3. The soil thermal properties are listed in Table 4, and the building construction details and thermal properties are shown in Table 5.

Table 3. HERS BESTEST case summary

Number	Description
L302BC	Uninsulated slab-on-grade
L304BC	Perimeter insulated slab-on-grade
L322B2	Uninsulated conditioned basement
L324B2	Wall insulated conditioned basement

Table 4. HERS BESTEST soil thermal properties

Thermal conductivity Btu/h·ft·°F (W/m·K)	0.8 (1.38)
Density lb/ft^3 (kg/m^3)	94.0 (1504)
Specific heat Btu/lb·°F (J/kg·K)	0.19 (800)

Table 5. HERS BESTEST building construction details

Component	Construction (inside to outside)	Area ft^2 (m^2)	U-value (surf-surf) Btu/h·ft^2·°F (W/m^2·K)	R-value (surf-surf) h·ft^2·°F/Btu (m^2·K/W)
Above-grade walls	plasterboard, 2 x 4 with fiberglass batt, fiberboard, and hardboard siding	1034 (96.1)	0.092 (0.521)	10.901 (1.920)
Ceiling	plasterboard, 2 x 6 joists with fiberglass batt	1539 (143)	0.059 (0.335)	16.922 (2.985)
Roof	plywood, asphalt shingle	1622 (150.7)	0.939 (5.331)	1.065 (0.188)
Gable ends	plywood, hardboard siding	121.5 (11.3)	0.772 (4.385)	1.295 (0.228)
Windows	Clear single pane, aluminum frame	270 (25.1)	1.039 (5.90) (air-to-air)	0.962 (0.170) (air-to-air)

Component	Construction (inside to outside)	Area ft^2 (m^2)	U-value (surf-surf) Btu/h·ft^2·°F (W/m^2·K)	R-value (surf-surf) h·ft^2·°F/Btu (m^2·K/W)
Slab-on-grade floor	carpet and fibrous pad, 4 in (10.16 cm) concrete	1539 (143)	0.417 (2.366)	2.40 (0.423)
Foundation wall (unins.)	6 in (15.24 cm) concrete	420 (39)	0.747 (4.24)	1.34 (0.236)
Foundation wall (ins.)	6 in (15.24 cm) concrete, R-5.4 rigid insulation	420 (39)	0.148 (0.842)	6.74 (1.187)
Basement floor	4 in (10.16 cm) concrete	1539 (143)	3.125 (17.74)	0.32 (0.056)
Rim Joist (uninsulated)	2 x 8 joist, fiberboard, and hardboard siding	126 (11.7)	0.2 (1.136)	5.0 (0.881)
Basement walls (unins)	6 in (15.24 cm) concrete	1218 (113.2)	0.747 (4.24)	1.34 (0.236)
Rim Joist (insulated)	R-11 fiberglass batt, 2 x 8 joist, fiberboard, and hardboard siding	126 (11.7)	0.076 (0.432)	13.14 (2.314)
Basement walls (insulated)	plaster board, wood 2 x 4 with fiberglass batt, 6 in (15.24 cm) conc.	1218 (113.2)	0.094 (0.531)	10.69 (1.883)

For the HERS cases, the three-dimensional computation domains were 35 ft x 50 ft x 30 ft (10.7 m x 15.2 m x 9.1 m), with 12,320 elements for the slab-on-grade cases and 13,104 elements for the basement cases. Two-dimensional cross sections of the domains are shown in Figures 3 and 4. Case L304BC included insulation on the outside of the footing wall and case L324B2 included insulation on the inside of the basement wall. Because GHT models the heat transfer in the concrete floor, the thermal resistance of the carpet in the slab-on-grade cases was included in the film coefficient. The insulation in the basement case is also internal and was modeled in a similar manner as the carpet.

The boundary conditions were identical to those used in the IEA BESTEST case. The annual runtimes for these cases were approximately 3 hours on a Pentium-III 930-MHz desktop computer. The initial conditions for the HERS cases were computed by starting with a uniform temperature distribution in the ground and running the uninsulated case for one year, then running the whole-building model for two years for a total of three "warm-up" years. For the uninsulated slab-on-grade, the difference in the building heating load between years one and two was less than 5% and less than 0.5% between years two and three. For the uninsulated basement case, the difference in the building heating load between years one and two was approximately 25%; there was no difference between years three and four. For the basement cases, the model should be run for at least two years to develop the initial conditions.

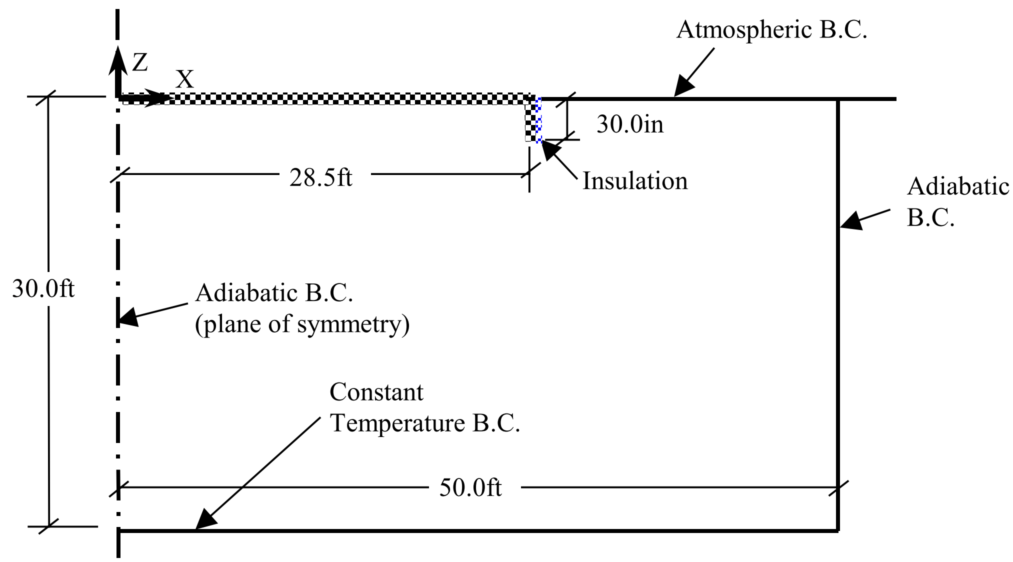

Figure 3. Two-dimensional view of the computation domain and boundary conditions for the HERS BESTEST cases L302BC and L304BC

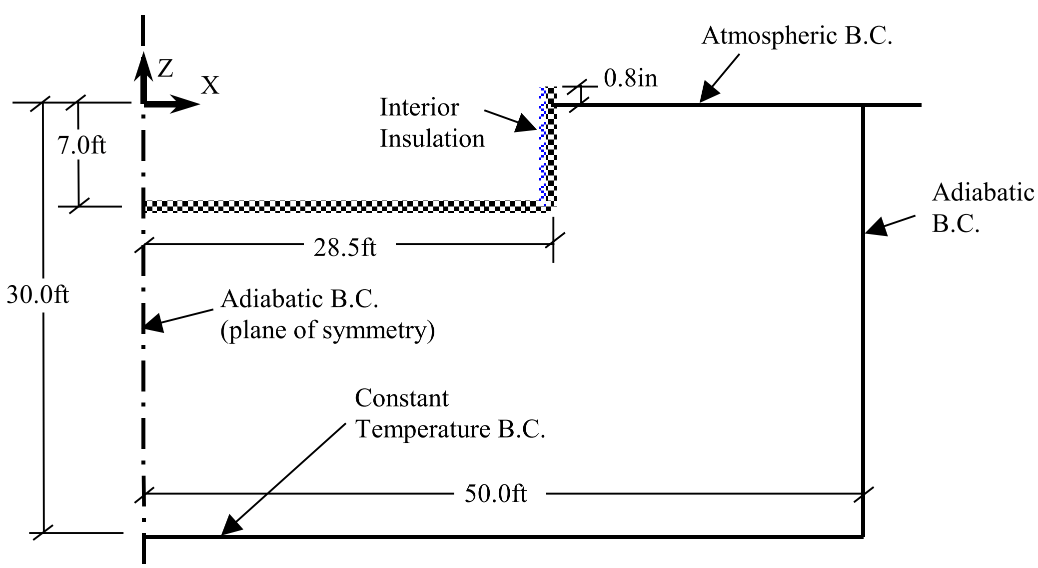

Figure 4. Two-dimensional view of the computation domain and boundary conditions for the HERS BESTEST cases L322B2 and L324B2

RESULTS

Annual simulations of the five cases were completed using Denver, Colorado, typical meteorological year (TMY) weather data for the IEA case and Colorado Springs, Colorado, TMY weather data for the HERS cases. The annual space conditioning loads from SUNREL 1.07.1 GC and SUNREL 1.07 are compared with the original BESTEST data published in the respective manuals in Figures 5 to 7. The results from SUNREL 1.07.1 GC are labeled SUNREL-GC. The results from SUNREL 1.07 are labeled as SUNREL and were obtained using one-dimensional heat transfer calculations following the methods presented in the *ASHRAE Handbook of Fundamentals* (2001) for basements and slab floors. The basement ground-coupled heat transfer was estimated using the effective path lengths from the wall and floor to the ground surface. Effective path lengths for the slab-on-grade floors were estimated from the F_2 heat loss coefficient for a metal stud wall.

Figure 5 shows the results from the IEA BESTEST manual (Judkoff and Neymark 1995a) along with the results from SUNREL and SUNREL-GC. There is a wide range of results from the IEA BESTEST manual and the results from the three-dimensional ground model are in the middle of these results. The wide variation in the results cannot be entirely attributed to the difference in the ground models. In all of the BESTEST cases there are differences in the results, which are due to the model and modeler. The differences are difficult to track down; determining which results are correct is even more difficult. This said, the simple ground-coupled heat transfer models performed similar to the detailed model for this basic building. Compared to SUNREL with a one-dimensional heat transfer model, the annual heating load increased by 13%, the annual cooling load decreased by 17%, the peak-heating load increased 5%, and the peak-cooling load showed very little difference.

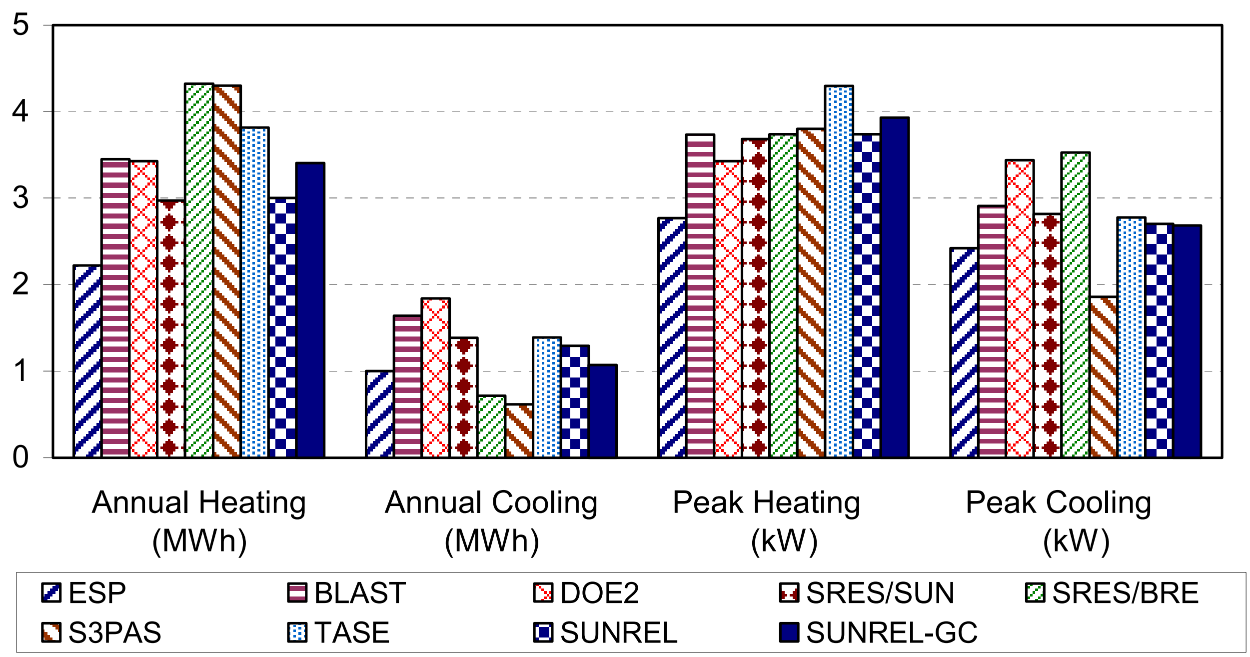

Figure 5. Annual heating and cooling energy and peak hourly heating and cooling loads for the uninsulated basement of the IEA case 990

Figure 6 shows the annual heating loads for the HERS base case L100AC and all the ground-coupled HERS BESTEST cases (Judkoff and Neymark 1995b). The ground-coupled buildings are identical to L100AC, except the floor over a vented crawl space is replaced by the ground-coupled section of the building. For case L100AC, SERI-RES/SUNCODE, SUNREL, and SUNREL-GC produce nearly identical results, which are 15% and 20% higher than BLAST or DOE2. For the uninsulated slab-on-grade case L302BC, the results for SUNREL-GC are lower than SUNREL by 25% and 12% lower for the insulated slab-on-grade case L304BC. The smaller difference in the insulated case may be due to the geometry assumptions made for the SUNREL-GC. The description of case L304BC in the HERS BESTEST manual does not include a specification for the foundation wall height or the material properties, because these are not inputs to the simple ground-coupled models. For the uninsulated basement case of L322B2, SUNREL and SUNREL-GC produce very similar results. Both are significantly higher than the other programs (specifically 22% higher than the SERI-RES/SUNCODE result). It is difficult to determine why the results are higher without seeing the input files and running the other programs side by side. The heating load from SUNREL-GC for the insulated basement case of L324B2 is 10% higher than the SUNREL result.

The monthly heating loads for the uninsulated slab-on-grade building are shown in Figure 7 to investigate the seasonal variations. The relative magnitude of the loads remains similar for all models except BLAST, which shows relatively higher loads from April to October. The SUNREL-GC and DOE2 models produced very comparable results, which are slightly lower than the other models. Figure 8 shows the monthly heating loads for the uninsulated basement case. The SUNREL and the SUNREL-GC models are similar and are higher than the other models for every month except July and August, which have zero heating loads. The SERI-RES/SUNCODE model has relatively lower loads from May to November.

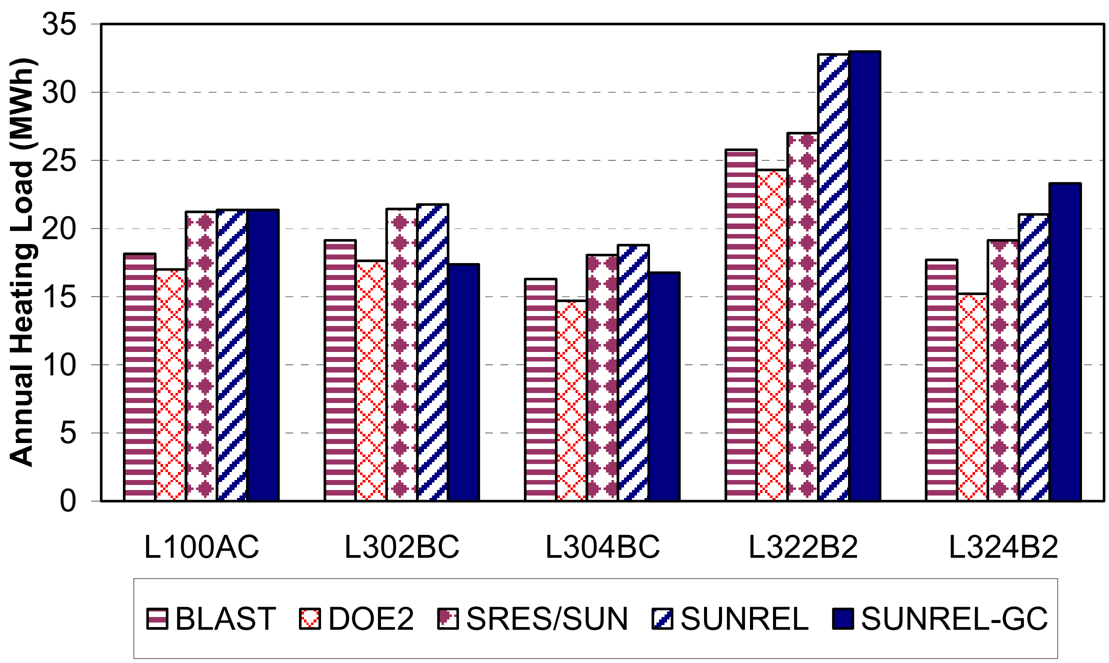

Figure 6. Annual heating loads for the HERS base case and the ground-coupled cases

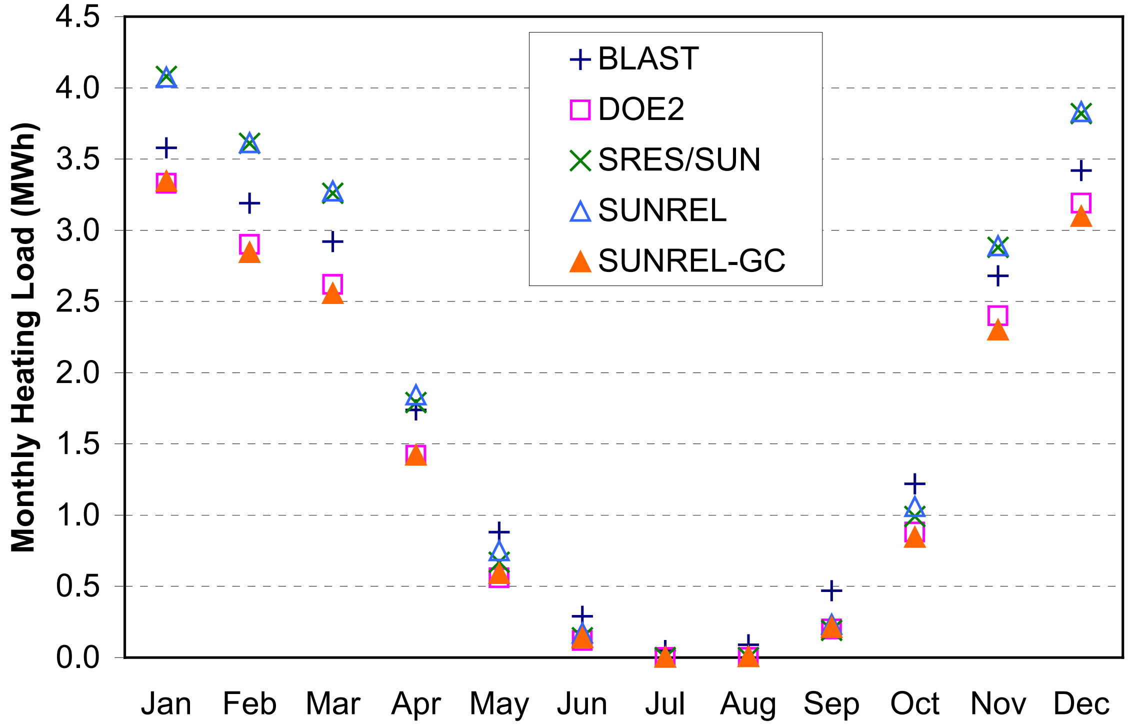

Figure 7. Monthly heating loads for the uninsulated slab-on-grade case L302BC

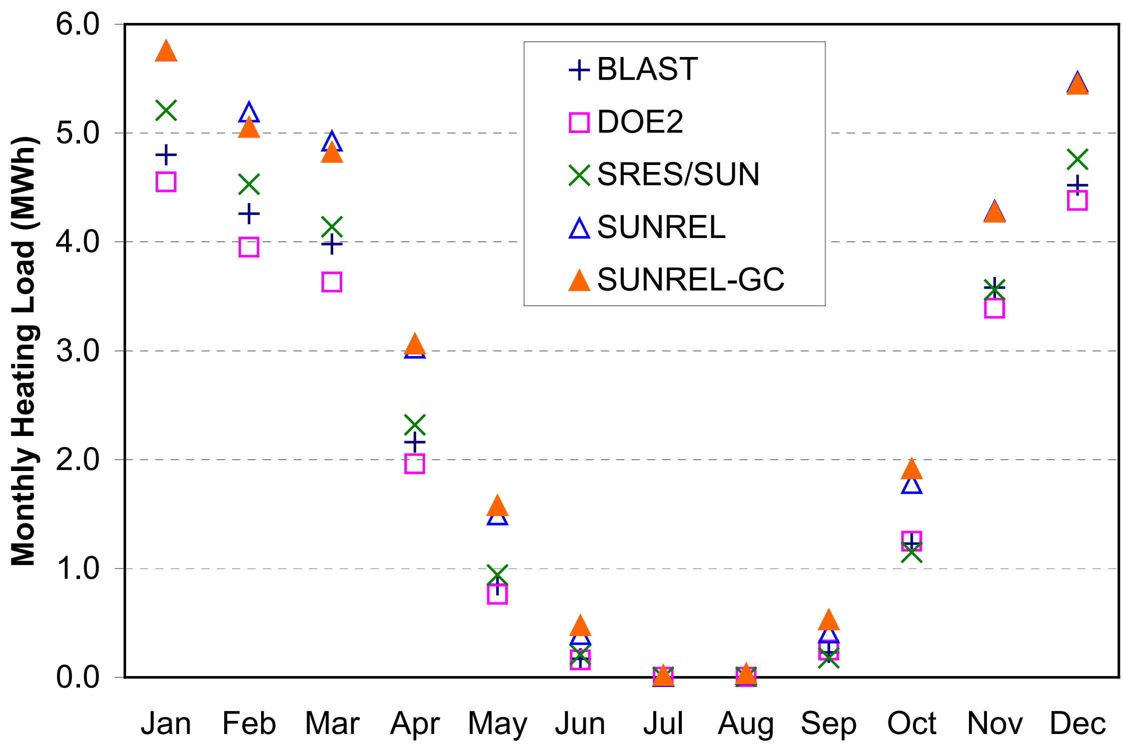

Figure 8. Monthly heating loads for the uninsulated basement case L322B2

CONCLUSIONS

With the exception of the HERS BESTEST full basement case, the results from the detailed three-dimensional model were similar to the results from the simple models. It is reassuring to know that these models can match the results from an independently developed detailed simulation. One reason for the agreement is that the building geometries and soil properties fit in the range of test cases used to develop the correlations used in the simple models. In addition, the buildings and modeling approaches were carefully described in the BESTEST manuals. Deviations from the prescribed modeling approaches and from the straightforward buildings may produce very different results.

The three-dimensional ground-coupled model used in this work is computationally intensive, with annual runtimes ranging from two to five hours on a Pentium 930-MHz processor. These runtimes are for only one-quarter of the building/ground domain and do not account for the two-three year initialization period. These long runtimes make the model impractical as a design tool, but it is useful as a research tool for the analysis of more complex buildings. Cases that are difficult to analyze with the simple models include analyses of different insulation configurations, underground buildings, refrigerated buildings, variations in the boundary conditions around the building, seasonal changes in the water table depth, and variations in the soil properties. The detailed model can also be used as a benchmark for simple models.

The ground-coupled program, GHT, is also capable of performing the calculations with a two-dimensional mesh, which takes three to five minutes to run on the same computer. The two-dimensional model must be used with correction factors for the three-dimensional effects near the corners. This offers a much more useful analysis tool with nearly the same accuracy as the three-dimensional model. The work of determining these correction factors has not been completed. A set of generic correction factors can probably be developed for the most common geometries. For complicated geometries, the three-dimensional model can be used to determine the problem-specific correction factors.

Related work under way is the development of additional series of test cases, and results from other detailed ground models to create a set of reference results for testing and diagnosing the ground heat transfer models in whole-building simulation software. The new test cases are designed to isolate the important ground-coupled heat-transfer characteristics similar to the test cases for other areas of building heat transfer in the BESTEST method. We anticipate that this test method will be incorporated into ANSI/ASHRAE 140-2001, *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*.

Nomenclature

C_P	specific heat capacity
D_h	heat diffusivity in air
D_m	neutral stability momentum transfer coefficient
D_v	vapor diffusivity in air
E	evaporation rate
h	convective heat transfer coefficient
h_{fg}	latent heat of vaporization of water
I	solar radiation
k	thermal conductivity
K_{evap}	evapotranspiration ratio
n	normal
q	heat flux
q'''	volumetric heat generation
Ri	Richardson number
R_w	gas constant for water vapor
t	time

T	temperature
u_w	wind velocity
z	vertical displacement, positive upward
z_o	roughness length
Δ	derivative of saturated water vapor pressure with temperature
φ	relative humidity
γ	psychrometric constant
κ	von Karman's constant
ρ	density and reflectivity
σ	Stefan-Boltzman constant (5.6686 x 10^{-8} W/m^2 K)

Subscripts

a	air
amb	ambient conditions
conv	convection
g	ground
horz	horizontal
rad	radiation
s	surface
sens	sensible heat
sky	effective sky conditions
v	water vapor
wb	wetbulb

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A three-dimensional, finite-element, heat-transfer computer program was developed to study ground-coupled heat transfer from buildings. It was used in conjunction with the SUNREL whole-building energy simulation program to analyze ground-coupled heat transfer from buildings, and the results were compared with the simple ground-coupled heat transfer models used in whole-building energy simulation programs. The detailed model provides another method of testing and refining the simple models and analyzing complex problems. This work is part of an effort to improve the analysis of the ground-coupled heat transfer in building energy simulation programs. The output from this detailed model and several others will form a set of reference results for use with the BESTEST diagnostic procedure. We anticipate that the results from the work will be incorporated into ANSI/ASHRAE 140-2001, *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*.

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