IMPLEMENTATION OF TWO-DIMENSIONAL FOUNDATION MODEL FOR RADIANT FLOORS INTO ENERGYPLUS

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ABSTRACT

In this paper, a two-dimensional transient numerical model for ground coupled heat transfer for radiant floors is developed and integrated into EnergyPlus. The model is first validated against experimental data. As an application of the integration of the model within EnergyPlus, thermal performance of a typical radiant system in a typical residential house is evaluated using both the new two-dimensional model and the existing radiant panel model currently used in EnergyPlus. Moreover, guidelines are presented to illustrate how the model can be used to calibrate the existing model within EnergyPlus.

INTRODUCTION

Radiant floor panel heating systems are widely used in several European and Asian countries. They consist of embedded hot water coils in floor slabs of residential and commercial buildings to provide space heating. Recently, radiant systems have received renewed interest in the US due to their inherent advantages compared to conventional all-air heating systems including low-noise, potential energy savings, uniform temperature distribution within spaces, and superior thermal comfort (ASHRAE, 2000).

Sevral researchers have investigated the performance of radiant floor heating systems through modeling and experimentally analyses (Van Gerpen and Shapiro 1985; Gerpen, 1985; Zhang an Pate, 1989; Yousef 1991, Strand and Pedersen, 1997, Adjali et al., 2000; Hanibuchi et al., 2000; Hauser et al., 2000, Strand and Pedersen, 2002). Only Strand and Pedersen integrated their model within a detailed building simulation program and were able to evaluate the thermal performance of radiant heating systems under various operating conditions. Strand and Pedersen utilized conduction transfer functions and heat source transfer functions to calculate building heating load and heat flux of radiant heating system. The integrated simulation program can be used to evaluate both temperature-modulation and flux-modulation control, but only flux-modulation control is tested and evaluated

(Strand and Pedersen, 1997). However, the radiant floor model of Strand and Pedersen does not fully account for the ground heat transfer. Specifically, The ground in Strand and Pedersen's model as integrated in EnergyPlus (Crawley et al. 2002) is defined as a layer of dirt with a constant and uniform lower surface temperature. Currently, there are no specific guidelines provided to the EnergyPlus user to define the required parameters to adequately model the thermal interaction between the ground and the radiant heating systems.

In this paper, a two-dimensional transient model of ground-coupled heat transfer beneath a typical radiant floor heating system is developed. The model is first validated against experimental data. Then the model is integrated within EnergyPlus and used to estimate the best parameters required to adequately model radiant floor heating system with the current version of EnergyPlus.

NUMERICAL MODEL

Figure shows a model of a typical radiant floor system located above a ground medium. The various parameters illustrated in Figure are defined below:

- a: Half width of the slab-on-grad floor, [m or ft]
- b: Water table depth, [m or ft]
- c: Distance from exterior wall to soil with undisturbed temperature, [m or ft]
- f: Foundation wall depth, [m or ft]
- h_w: Exterior wall height, [m or ft]
- T_o: Outdoor temperature, [°C or °F]
- T_r: Indoor temperature, [°C or °F]
- T_w: Water table temperature, [°C or °F]

The slab-on-grade floor is heated either with electric wires or with hot-water pipes. To analyze the performance of the radiant floor under various operating conditions, the temperature field within the slab and the ground is first determined. The unsteady-state temperature field within building elements (except the heated floor slab) and ground medium is subject to the time-dependent heat conduction equation without heat generation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T(r,t)}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T(r,t)}{\partial y}\right)=\rho c_p\frac{\partial T(r,t)}{\partial t} \qquad (1)$$

The temperature distribution within the heated floor slab subject to the heat conduction equation with heat generation is modified adding the term of Q and presented as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T(r,t)}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T(r,t)}{\partial y}\right)+Q=\rho_w c_{p,w}\frac{\partial T(r,t)}{\partial t} \tag{2}$$

Where,

- r : vector space of x or y, [m or ft]
- c_p : specific heat, [J/kg·°C or Btu/lb·°F]
- k : thermal conductivity, [W/m·°C or Btu/hr·ft·°F]
- ρ: density, [kg/m^3 or lb/ft^3]
- t : time, [sec or hr]
- Q: generated heating rate per unit volume [W/m^3 or Btu/hr.ft^3]
- *Subscript w :* water

Using a control volume approach and pure implicit finite difference technique (Pantankar, 1980), the heat conduction equation represented by Eqs. (1) and (2) can be solved. The implicit method was chosen since it is suitable for long-term analysis of a large two-dimensional domain. Indeed, the implicit method has the important advantage of being unconditionally stable. That is, the solution remains stable for all space and time increments. The space-time domain (*x, y, t*) is subdivided into a rectangular grid system with variable space and time increments. Variable space increments are used with very fine grid in the region near the heat source, slab, and soil surface.

Figure 2 describes typical control volumes for heated floor model: a control volume with a heat source and another with no heat source (such as ground medium), which includes continuous hot water pipe and two control volumes for general and heat source nodal points. In this 2, L_{pipe} presents the parallel length of each pipe which goes through one heat source node. Additionally, PH, PH-1, and PH+1 indicate heat source nodes.

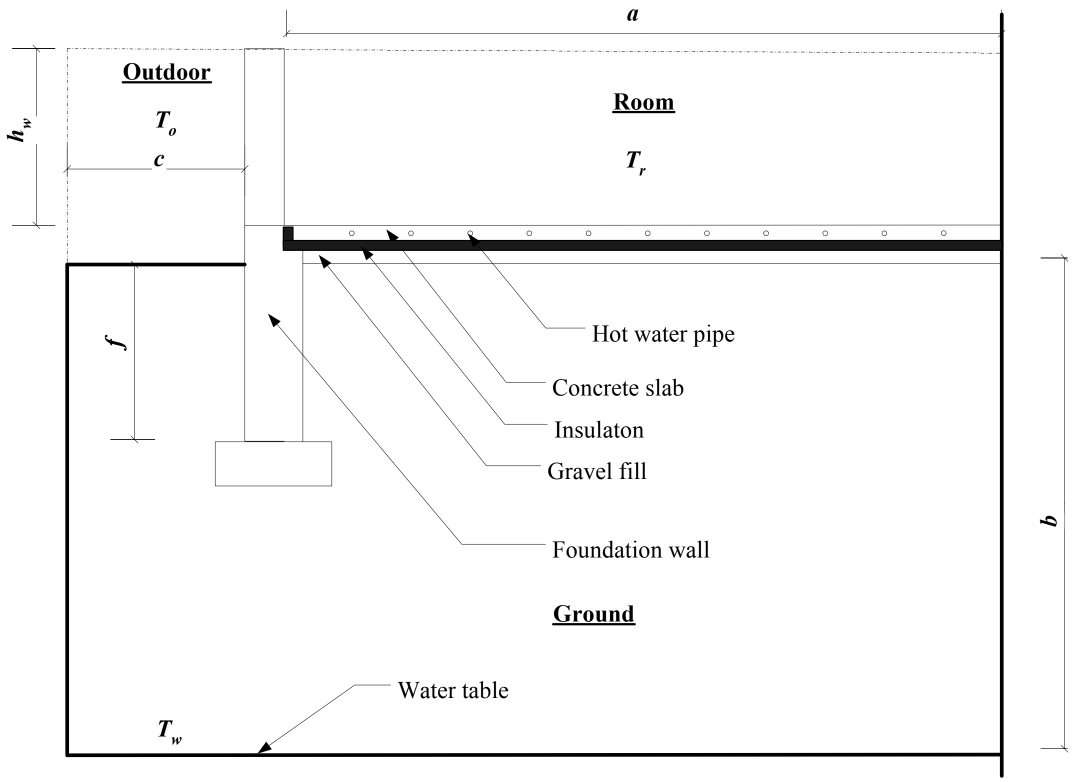

Figure 1 Two-dimensional model for ground-coupled heat transfer for a typical hot water radiant floor heating system

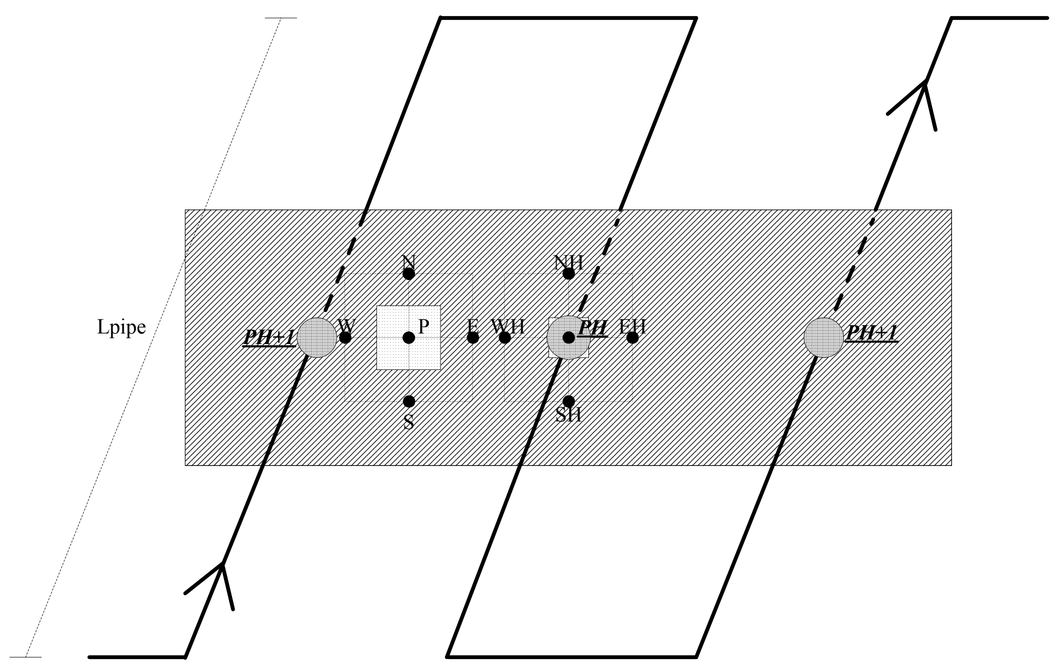

Figure 2 Simplified heated floor embedded hot-water pipe for the two-dimensional heat conduction problem

A more detailed description of the solution technique of Eqs. (1) and (2) and associated boundary conditions is provided by Ihm and Krarti (2004a).

IMPLEMENTATION WITHIN ENERGYPLUS

Crawley et al. (2001 and 2002) describes the general features and capabilities of EnergyPlus including a comparative analysis with other major building simulation programs. In EnergyPlus, all the modules are integrated and controlled by the Integrated Solution Manager. Figure 3 illustrates the interconnection of three heat balance procedures for a typical opaque building envelope component (such as an exterior wall) using the general heat balance method. The heat balance procedures consist of outside heat balance process, wall conduction process, and inside heat balance process.

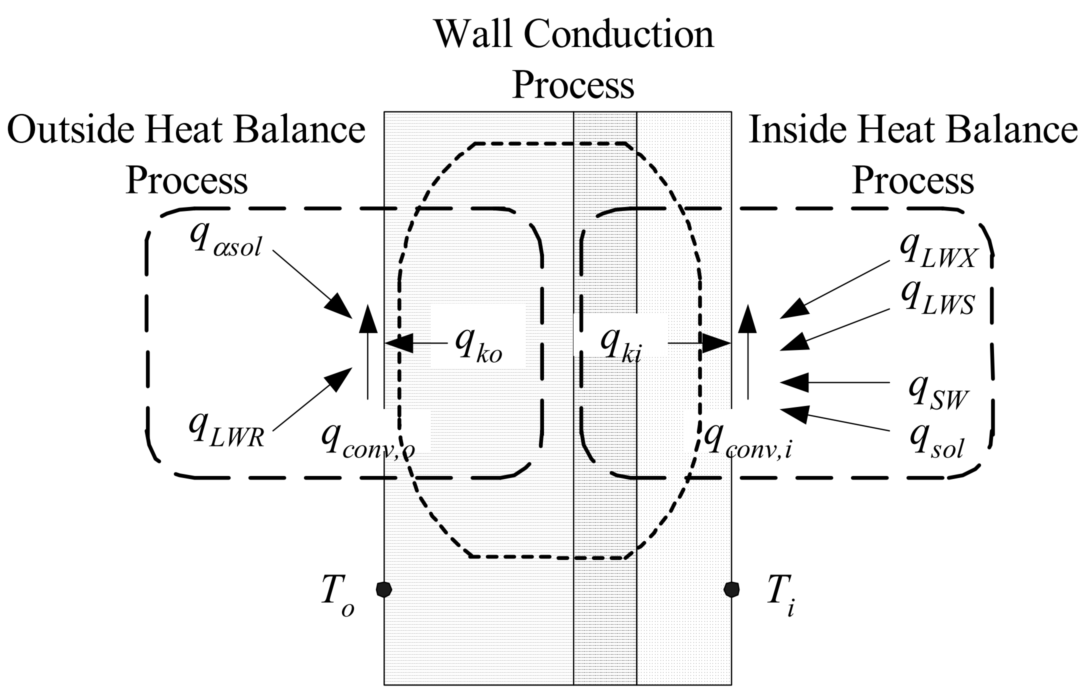

Figure 3 Heat balance procedures for a typical opaque building envelope

The difficulty of linking ground-coupled heat transfer module to EnergyPlus stems from the fact that heat conduction calculations in EnergyPlus are based on one-dimensional analysis. In its current version, EnergyPlus assumes that the radiant floor and the ground medium as one-dimensional layers connected with a “known” (i.e., user defined) outside surface temperature (i.e., T_o in Figure 3). However, the developed ground and radiant floor heat transfer module utilizes two-dimensional analysis. To link the two-dimensional model, an artificial floor is defined as part of the building components in EnergyPlus. The artificial floor directly links the developed ground-coupled heat transfer module with the floor configuration of EnergyPlus using the heat balance method. This approach is validated for a typical building foundation using a two-dimensional ground-coupled model (Ihm and Krarti, 2004b) for a small building model.

A building model consists of one single zone of 4.2 m × 4.2 m × 3.0 m (13.8 x 13.8 x 9.8 ft). The exterior walls and the roof constructions include 2” insulation and concrete blocks. The floor construction consists of 4” heavy weight concrete with 1” dense insulation above 12” dirt. One window with 3/8” clear glass is placed in the south-faced wall. Figure 4 illustrates the building configuration and the materials used for the building envelope. The material properties are listed in Table 1.

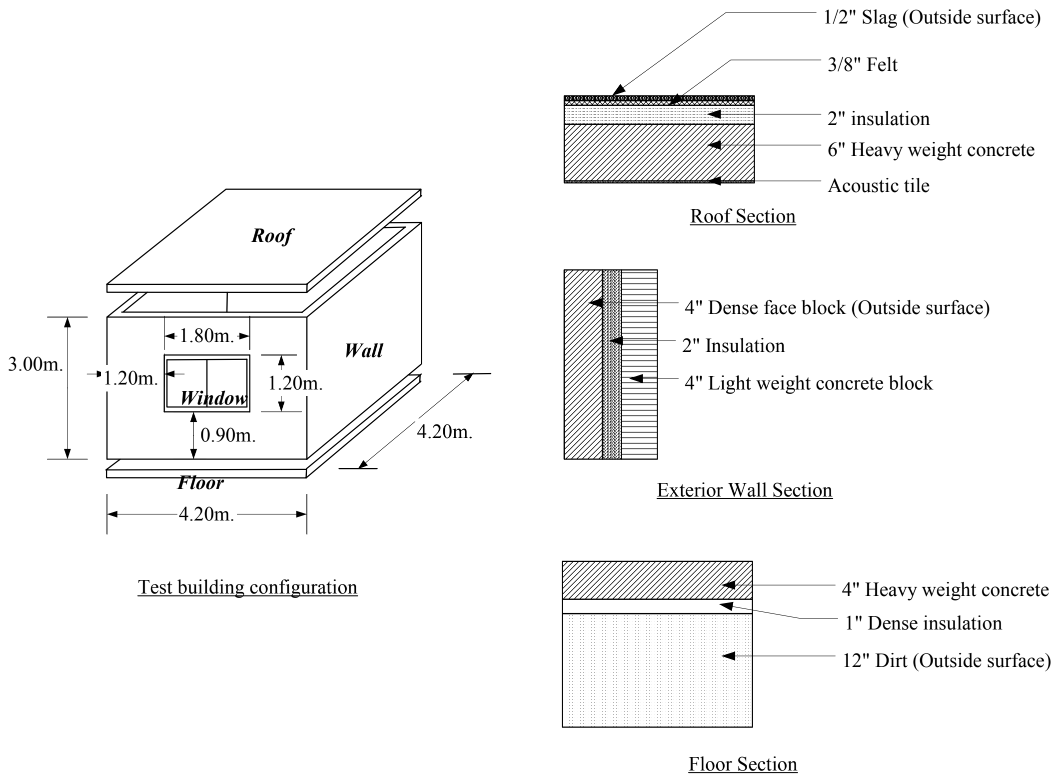

Figure 4 The building configuration considered to validate implementation of two-dimensional building foundation model

Table 1 Material properties for the test building configuration (Material library in EnergyPlus)

Material	Conductivity (W/m.°C)	Density (kg/m^3)	Specific heat (J/kg.°C)
Roof			
1/2” Slag	1.43	881.0	1670
3/8” Felt	0.19	1121.29	1670
2” insulation	0.04	32.03	830
6” Heavy weight concrete	1.72	2242.58	830
Acoustic tile	0.06	480.55	830
Exterior wall			
4” Heavy weight concrete block	0.81	997.12	830
2” Insulation	0.04	32.03	830
4” Light weight concrete block	0.38	608.7	830
Floor			
4” Heavy weight concrete	1.72	2242.58	830
2” Dense insulation	0.04	91.3	830
12” Dirt	0.173	1041.2	830

In particular, the results obtained from the ground-coupled heat transfer model are compared with those obtained from the conduction transfer functions (CTFs) of EnergyPlus. For the simplified building model of Figure 3, two insulation configurations are considered: uniformly insulated floor with 2” dense insulation and uninsulated floor. Outdoor environment uses TMY (Typical Meteorological Year) data for Denver, CO. The simplified building model is assumed to have no HVAC system. Thus, the indoor building temperature is allowed to float. The two EnergyPlus simulation models consist of the following:

- The original EnergyPlus with a simplified floor model including ground medium below slab region.
- The modified EnergyPlus with the ground-coupled heat transfer module based on a two-dimensional solution for the slab/ground section as depicted in Figure 4 but with adiabatic vertical surfaces so that one-dimensional heat flow is ensured (Ihm and Krarti, 2004a).

In Figures 5 and 6, room temperatures and averaged floor surface temperatures obtained from the two EnergyPlus simulation models are compared. Both temperatures are in good agreement for two different EnergyPlus modeling approaches for building foundation heat transfer. The good agreement proves that the developed two-dimensional building foundation model is well implemented into EnergyPlus.

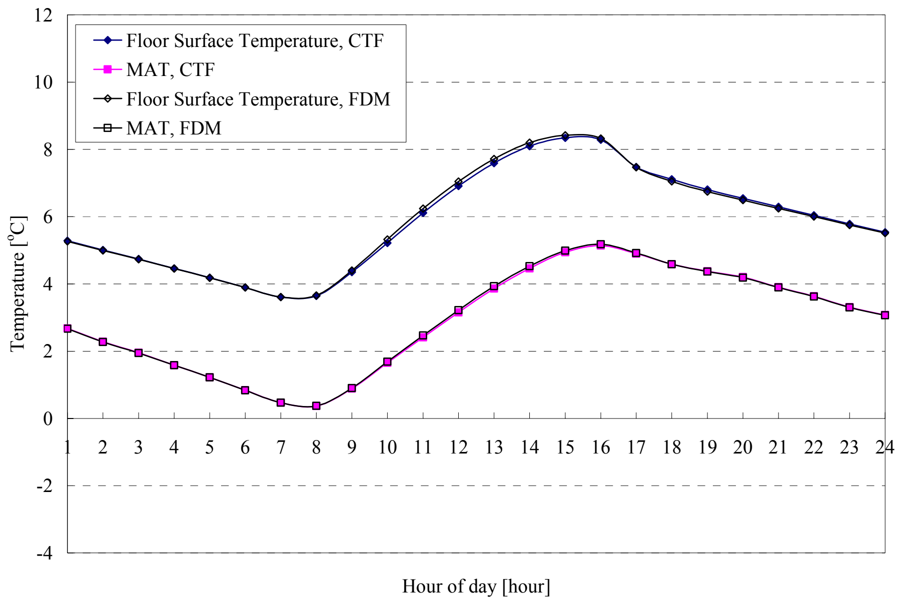

Figure 5 Floor surface and indoor space temperature for an uninsulated slab

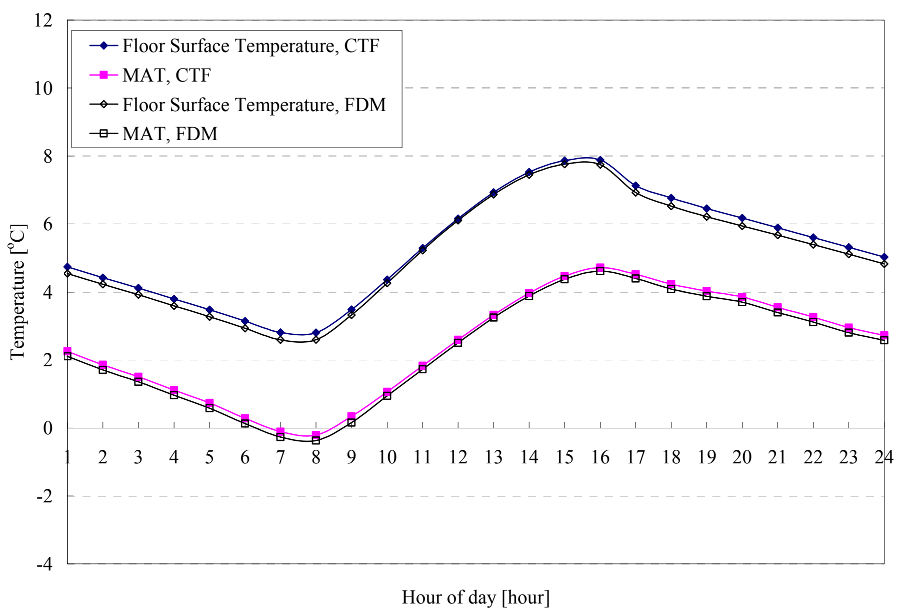

Figure 6 Floor surface and indoor air temperature for a uniformly insulated slab

COMPARISON WITH EXISTING ENERGYPLUS RADIANT FLOOR MODEL

In this section, the developed radiant heated slab model is compared with the existing radiant floor model in EnergyPlus program. Currently, EnergyPlus contains a radiant floor model developed by Strand (1995) and Strand and Pedersen (1997). The model uses heat source/sink conduction transfer functions (CTFs) to model the radiant heating and cooling systems. The heat source/sink transfer functions (QTFs) are developed to account for internal heat sources/sinks, and implemented in EnergyPlus using an effectiveness-NTU heat exchanger algorithm to account for the effects of the embedded water pipes in the radiant floor. The heat source from the hot water pipes is modeled by one single node with single temperature within the slab construction.

When EnergyPlus radiant heated slab is in contact with the ground medium, the temperature of the ground-floor interface is required as an input parameter for EnergyPlus. Based on results from EnergyPlus integrated with the developed two-dimensional solution of radiant heating slab proposed in this paper, averaged surface temperatures are estimated for selected depths beneath the slab.

Several analyses are carried out to select proper lower boundary surface temperature for the EnergyPlus radiant floor model which minimizes error in estimating total heating energy use as shown in Table 2. The depth of 0.6 m for the lower boundary was found to provide the lowest error for simplified model when a typical single-family home is considered (Ihm and Krarti, 2004b). Its associated surface temperature is 15.1 °C, and percent error is 0.6 % when it is compared against the predictions from the numerical radiant slab model outlined in this paper and integrated within EnergyPlus.

Figure 7 compares indoor air and heated slab surface temperature during one day for the two radiant slab models (both integrated within EnergyPlus). During the occupied hours, a constant indoor setpoint temperature is set to be 20 °C. For the simplified EnergyPlus radiant floor model, the constant lower boundary surface temperature is defined as 15.1 °C at the depth of 0.6 m below the slab. When the radiant floor heating system is not operated during the daytime, the slab surfaces and indoor air temperatures predicted by the simplified model are slightly higher than those predicted by the numerical model. However, when the radiant heating floor system is operated during occupied period (nighttime), the temperatures predicted by both models are in good agreement.

Figure 8 illustrates the heating energy use of the heated slab during the entire day as predicted by both models. The hourly variation of the heating energy use is similar for both models. The total daily heating energy use is 81.8 kW and 81.1 kW, predicted by the numerical model and the simplified model, respectively. From this analysis, it can be concluded that if the temperature of the slab lower boundary temperature is properly set, the simplified model provides fairly comparable predictions with the detailed numerical model outlined in paper.

Table 2 Total energy use as a function of ground depth predicted by the EnergyPlus radiant heating floor model

Ground depth (ground temperature)	Total Heating energy of numerical model [kW]	Total Heating energy of EnergyPlus model [kW]	Percent error [%]
0.2 m (18.4 °C)	81.8	84.7	3.9
0.6 m (15.1 °C)	81.8	81.1	0.6
1.0 m (14.1 °C)	81.8	87.5	7.0
1.2 m (14.1 °C)	81.8	76.8	6.1
1.6 m (14.0 °C)	81.8	77.7	5.0
2.2 m (13.8 °C)	81.8	82.9	1.4

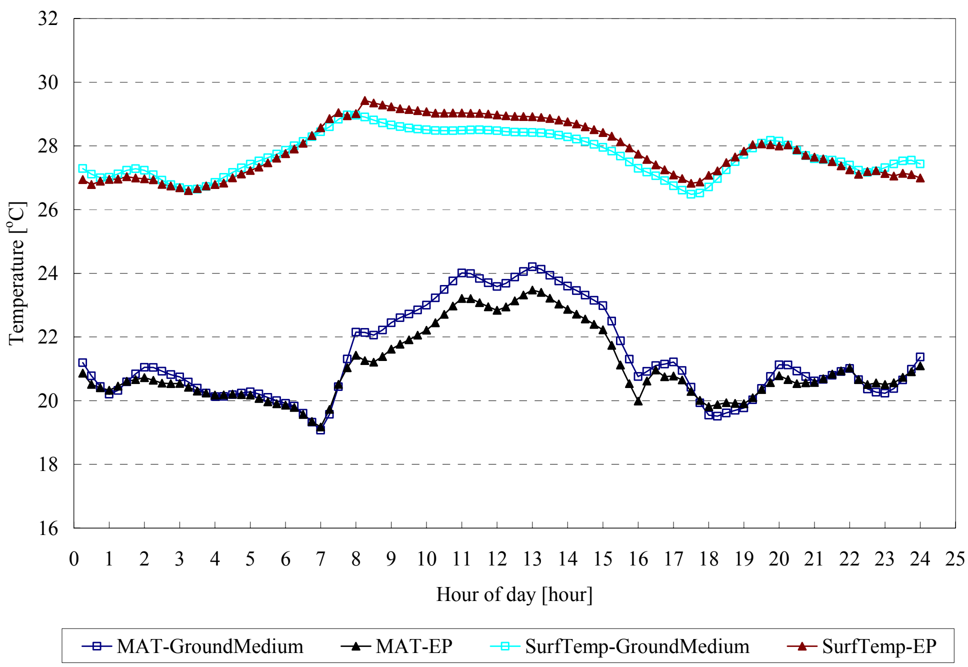

Figure 7 Comparison of mean air and slab surface temperatures.

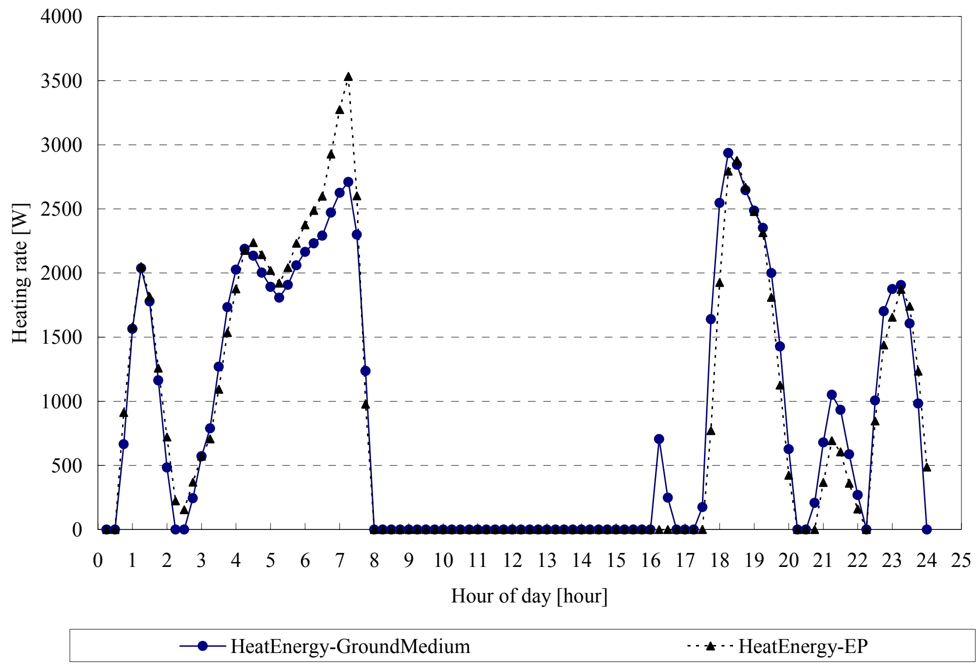

Figure 8 Comparison of heating energy use predicted by the numerical model and existing EnergyPlus model for radiant heating floor systems.

SUMMARY

In this paper, a two-dimensional numerical solution is developed and validated to model radiant slab floor with embedded hot water pipes. The numerical model is first integrated within EnergyPlus and then used to estimate the values of user input parameters required for the radiant floor model currently used in EnergyPlus. It was found that when the depth and the temperature of the slab lower boundary are properly set, the simplified model provides fairly comparable predictions with the detailed numerical model outlined in paper.

The developed model can be utilized to determine the performance of radiant floor systems under various design and operating conditions including the effect of pipe spacing, supplied hot water temperature, hot water mass flow rate, and insulation configurations. The effects of these parameters are described in a companion paper (Ihm and Krarti, 2004b). In addition, the developed model can be utilized with EnergyPlus to determine the best controls for radiant systems to minimize energy costs while maintaining thermal comfort within occupied spaces.

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