The Performance of Under-floor Electric Heating System with Latent Thermal Storage

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Abstract
This paper illustrates a structure of electric floor heating system with latent heat thermal storage plate. This system can charge heat by using cheap nighttime electricity and discharge the heat stored at daytime. A theoretical model is developed, which can analyze the thermal performance of buildings applying such system in winter. The thermal performance of the heating system and the effects of various factors on it are analyzed by modeling and simulation. For a given room located in different climate regions, the optimal effect of using such system is predicted, which testifies the feasibility of this heating mode in different climate regions.

Keywords: thermal energy storage; phase change material (PCM); electric floor heating

Introduction
In almost all cities of north China, coal is the main energy source for residential space heating, which causes serious pollution. Beijing will host the Olympic Games in 2008, and is inclined to take other clean energy such as electricity instead of coal for space heating. However, electrical consumption varies greatly during day and night, which conflicts relatively steady output of power plant. In order to narrow the gap between the peak and valley loads of electricity demands, night and day tariff policy is being used in many cities of China. The electricity tariff at night is 1/3 - 1/5 of that at daytime. Then the shift of electrical consumption from peak periods to valley periods will provide significant economic benefit. Moreover, it is of importance for power plants in leveling the electrical load.

Athienitis described an electric floor heating system with integrated thermal storage, with 1-cm-thick sand, and 4-cm-thick concrete blocks as the main thermal storage mass. But the great indoor temperature swing might bring thermal discomfort [1].

An electrically heated thermal storage floor was used in a passive-solar-heated system as a heating system at night in Ref. [2]. Chuangchid and Krarti considered a more realistic and flexible model for heated or cooled concrete slab floors to determine the heat transfer between the concrete slab and the ground [3]. Olesen presented a theoretical discussion and calculated the heat exchange coefficient between a cooled floor and a test space [4]. Holmes and Wilson gave a numerical model of a ventilated floor slab storing energy of night ventilation to shift the cooling load [5].

These papers are focusing on the thermal storage by concrete. From an application point of view, the temperature swing on the floor surface may cause large fluctuation of indoor temperature. Phase change materials can provide significant latent heat storage over the narrow range of temperature typically encountered in buildings, thus they can improve the thermal comfort degree.

The purpose of the present paper is to introduce an under-floor electric heating system with PCM thermal energy storage plate, and to investigate the effect of some factors that can influence the thermal performance of the heating mode by modeling and simulation.

Mathematical Model
The dimensions of the room are 6m (length) x 4m (width) x 3m (height). It has a 2m x 2m double-glazed window facing south (see Fig.1). The external wall facing south is 370mm in thickness while the inner walls are 240mm. They are made of brick. The occupied period is from 8:30 to 17:00 and the inner disturbance is 15W/m² during this period. Air change per hour (ACH) is supposed 1.0 h⁻¹ while the phase transition temperature is 30°C. The heating period is from 23:00 to 7:00, which is the off-peak period. Thermal physical properties used in this simulation are shown in Table 1.
In order to simplify the analysis, the following assumptions are made: (1) Heat transfer through the wall, the floor and the ceiling is one-dimensional; (2) Thermophysical properties of the building materials are constant except the specific heat of PCM during melting or freezing process; (3) The boundary below the heaters is thermally insulated; (4) Natural convection of PCM during melting process and the super-cooling effect during freezing process can be ignored; (5) Outdoor wind velocity is 5m/s.

The floor is made up of four layers (see Fig.2). Subjected to the foregoing assumptions, the transient enthalpy equation is:

$$\rho_j \frac{\partial H}{\partial \tau} = k_j \frac{\partial^2 t}{\partial x^2} \tag{1}$$

where $H = \int_{t_0}^{\tau} c_{p,j} \, dt \int_{t_0}^{\tau} c_{p,m} \, dt \int_{t_0}^{\tau} c_{p,i} \, dt$ for the PCM, while $H = \int_{t_0}^{\tau} c_{p,j} \, dt$ for the brick layer and the insulation layer. The temperature of phase transition is from $t_1$ to $t_2$, $\rho_j$, $k_j$ and $C_{p,j}$ are as follows:

$$\begin{cases} \rho_j = \rho_i, k_j = k_i, C_{p,j} = C_{p,i} \quad \text{for insulation layer} \\ \rho_j = \rho_s, k_j = k_s, C_{p,j} = C_{p,s} \quad \text{for cover of floor} \\ \rho_j = \rho_c, k_j = k_c \quad \text{for PCM layer} \end{cases}$$

The boundary conditions on the surfaces of the floor are:

$$q_r + h(t_m - t) \big|_{x=L_1} = k \frac{\partial t}{\partial x} \big|_{x=L_1} \tag{2}$$

$$q_{power} = -k \frac{\partial t}{\partial x} \big|_{x=0} \tag{3}$$

The initial condition is:

$$t(x, \tau) \big|_{\tau=0} = t_{ini} \tag{4}$$

where $q_r$ is the thermal radiation heat flux to the upper surface of floor, and $q_{power}$ is the heating power that is determined according to the heat load of the room. The heater is on when the upper surface of the PCM is less than the phase transition temperature during the off-peak period; otherwise it's off.

$h$ can be calculated by the following equation [7]:

$$h = 2.5 \times 4 \sqrt{t_{floor} - t_m}$$

Figure 3 illustrates heat transfer on wall surfaces. The transient heat transfer equation is

$$\rho_b C_{p,b} \frac{\partial t}{\partial \tau} = k_b \frac{\partial^2 t}{\partial y^2} \tag{5}$$
The boundary conditions are:
\[ q_{\text{out}} + h_{\text{out}} (t_{\text{out}} - t) |_{y=0} = -k_\alpha \frac{\partial t}{\partial y} |_{y=0} \] 
\[ q_{\text{in}} + h_{\text{in}} (t_{\text{in}} - t) |_{y=l_2} = k_\beta \frac{\partial t}{\partial y} |_{y=l_2} \]

The initial condition is:
\[ t(y, \tau) |_{\tau=0} = t_{\text{init}} \]

where \( q_{\text{in}} \) and \( q_{\text{out}} \) are indoor and outdoor thermal radiation heat flux (Fig.3). The empirical value of convection coefficients \( h_{\text{out}} \) is calculated for 5m/s wind velocity and \( h_{\text{in}} \) is determined by the natural convection correlation [7]:
\[ h_{\text{in}} = 2 \sqrt{\frac{1}{l_1 - t_{\text{in}}} \quad h_{\text{out}} = 2.5 + 4.2v \]

For the inner walls and ceiling, the central planes are assumed insulated.

Thermal radiation among the walls, floor and ceiling is calculated by network method [8].

For the air in the room:
\[ c_p \rho V_R \frac{dT}{d\tau} = \sum_{k=1}^{N} Q_{W,k} + Q_{S,C} + Q_L \]

where \( V_R \) represents cubage of the room, \( Q_{W,K} \) the convection heat transfer rate between air and inner surfaces of the room, \( Q_{S,C} \) the convection heat transfer rate from the indoor heat source and \( Q_L \) the heat transfer rate by ventilation.

The aforementioned simulative equations can be solved numerically and Gauss-Seidel method is used in solving the equations. The number of grids is checked.
to make results correct and calculating several days before the needed time eliminates the initial errors. The software Medpha is used to generate the climate data of different regions.

**Results and Discussions**

In order to investigate the thermal performance of the heating system and design practical system, the main factors of influencing the thermal performance of the system must be clarified.

Figure 4 shows the effects of the following factors to the aforementioned room: thermal conductivity of the floor cover $k$, phase transition temperature $t_m$, thickness of floor cover $L$ and air change per hour (ACH). As seen from Fig.4, $t_m$ is an important factor that determines the characteristics of heat source, and ACH must be considered which can change the heating load of the house. $k$ and $L$ cannot be ignored because they will impact the thermal resistance.

The effect of the heating mode in winter in different climates can be seen in Fig.5. Table 2 presents the conditions used in the calculation.

| City  | Thickness of Outer Wall (mm) | Heating Load (W/m²) | Thickness of PCM (mm) |
|-------|-------------------------------|---------------------|-----------------------|
| Beijing | 370                           | 40.0                | 9.3                   |
| Shanghai | 240                           | 26.0                | 6.0                   |
| Dalian  | 370                           | 45.0                | 10.4                  |
| Harbin  | 490                           | 76.0                | 17.5                  |

The indoor temperatures of the room located in Beijing, Shanghai and Dalian are between 16-25°C, which is in the thermal comfort range. Indoor floor temperature is lower than 29°C, which can be accepted. But discomfort may appear in the room with great and unsteady heating load (see Fig.5 (d)).

**Conclusions**

A general modeling work in simulation thermal behaviors of building envelope, electric floor heating system with PCM heat storage and indoor air under the condition of outdoor variation is presented. Effects of several factors are investigated.
The results testify the feasibility of under-floor electric heating system with PCM latent thermal storage plate in several different regions.

Acknowledgments
This work was supported by the National Key Basic Research Special Funds Project of China, No. 2001CB409600, and by the Fundamental of Tsinghua University, No.JC2002001.

References
1) Athienitis A.K. and Chen T.Y. (1993) Experimental and theoretical investigation of floor heating with thermal storage. ASHRAE Trans, 99 (1), 1049-1057
2) Bakos G. (2000) Energy management method for auxiliary energy saving in a passive-solar-heated residence using low-cost off-peak electricity. Energy and Buildings, 31, 237-241
3) Chuangchid P. and Krarti M. (2001) Foundation heat loss from heated concrete slab-on-grade floors. Building and Environment, 36 (5), 637-655
4) Bjarne W. O., Eric M., Frederic B., et al. (2000) Heat exchange coefficient between floor surface and space by floor cooling - theory or a question of definition. ASHRAE Transactions, 106, 684-694
5) Holmes J. M. and Wilson A. (1996) Assessment of the performance of ventilated floor thermal storage systems. ASHRAE Transactions, 102, 698-707
6) Shamsundar, N. and Sparrow, E. M. (1975) Analysis of multidimensional conduction phase change via the enthalpy model. Journal of Heat Transfer, 97 (3), 333-340
7) Wang J. (1978) Building Physics, Beijing: China Architecture & Building Press, in Chinese
8) Oppenheim A. K. (1956) Radiation analysis by network method. Trans ASME, 65 (3), 725-735