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Numerical and experimental analysis of floor heat storage and release during an intermittent in-slab floor heating process

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HIGHLIGHTS

- The relationship between the intermittent time and the preheating time is obtained.
- The heat storage–release characteristics of intermittent heating floor are fully mastered.
- The numerical simulation method is demonstrated to be at least accurate within 7%.

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ABSTRACT

In this paper, the floor heat storage in the preheating period and the heat release in the intermittent period during an intermittent in-slab floor heating process are investigated. Numerical simulations are used to determine the effect of the design and operating parameters, i.e., the pipe spacing, the filling layer thickness and the pipe water temperature, on the floor heat storage and heat release. The relationship between the intermittent time and the preheating time is also obtained. The results show that pipe spacing has the dominant effect on the preheating time. In the intermittent period, 2 h later, the two-dimensional heat transfer process can be modeled as a one-dimensional vertical heat transfer process, and the filling layer thickness has a relatively large effect on the heat release time. The numerical simulation method is shown to be accurate to at least within 7% of the experimental measurements.

1. Introduction

An in-slab floor heating system offers many advantages, such as amenity, energy conservation, aesthetics, etc. [1,2]. However, people's life patterns frequently result in the intermittent operation of the in-slab floor heating system, where the operation mode is determined by the heat gain from the floor and the floor heat storage and release. Most importantly, the floor heat storage and release are affected by several factors, including the floor structure, the filling layer thickness, the material properties, the spacing between the laid pipes, the pipe diameter and the water temperature, making it difficult to determine the operation mode of the intermittent heating.

Previous studies have mainly focused on modeling and simulating floor heating systems [3–6]. Computational steady state methods have been widely applied to the in-slab heating floor transfer process [7,8]. In 1992, Kilkis [9] introduced a steady heat transfer composite-fin model, in which the areas between the pipes were modeled as plate fins. A fin efficiency was used to account for the difference between the indoor air temperature and the mean radiant temperature and to incorporate contributions to the floor surface heat transfer from both the convection heat between the upper floor surface and the indoor air and the radiant heat from other internal surfaces. In 1995, the aforementioned models were simplified and the modeling procedures were programmed in FORTRAN. The calculated results were summarized using a convenient series of charts [10,11]. S.T. Hu [12] developed a two-dimensional steady state mathematical model for floor heat transfer: a dynamic simulation program based on the finite element method was used to calculate the operating parameters, such as the highest floor surface temperature, the indoor operating temperature, the heat-flow density and the pre-heating time, for different pipe water supply temperatures and pipe spacings. X.M. Feng and Y.Q. Xiao [13]

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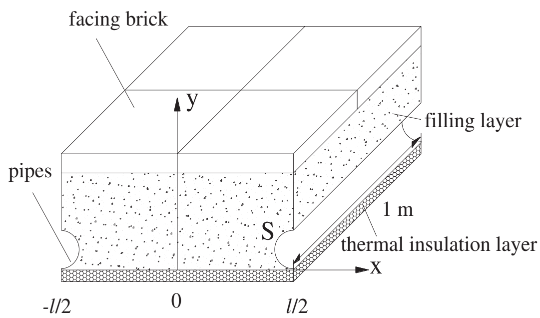

Fig. 1. Schematic of an in-slab heating floor.

developed a two-dimensional unsteady state floor heat transfer model to determine the relationships among the floor surface temperature, the pipe spacing, the filling layer thickness and the pipe water temperature. I. Pyeongchan [14] developed a two-dimensional unsteady state floor heat transfer model, which was validated by comparing results from experiments with those from numerical simulations of the model. Y.F. Liu [15] developed a mathematical model to describe the thermal processes in a floor heating room. The solver of this model was programmed using the Duhamel theorem. Gilles Fraisse [16] analyzed the relationships among the required pre-heating time of the intermittent heating system, the pre-heating time, the thermal comfort level and the energy consumption. Other researchers [5] have primarily studied the heat exchange process and the system performance. The aforementioned studies have served as a foundation for the present study.

The aforementioned models are used in this study to investigate the floor heat storage in the preheating period and the heat release in the intermittent period for an intermittent in-slab floor heating process. Numerical simulations are used to determine the effects of the design and operating parameters, i.e., the pipe spacing, the filling layer thickness and the pipe water temperature, on the floor heat storage and heat release, and to obtain a relationship between the intermittent time and the preheating time. In the following sections, the numerical simulation results are verified by comparison with experimental measurements.

2. Theoretical analysis

2.1. Differential equation for heat conduction

The fundamental assumptions used in the model are given below.

(i) The materials in each layer are homogeneous with constant property parameters.
(ii) The pipe surface is insulated during the heating system stops.
(iii) The heat conduction along the pipe axis is neglected, and the heat conduction inside the floor is modeled as a two-dimensional steady state process [17–19].
(iv) The pipelines are symmetrically distributed.
(v) The bottom of the pipe is insulated.

A differential equation describing two-dimensional unsteady state heat-conduction in an embedded-pipe heated floor has been previously developed [20,21] and is given in Equation (1).

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right) \tag{1}$$

The schematic of an in-slab heating floor is shown in Fig. 1. The initial and boundary conditions are prescribed during the pre-heating period and the intermittent period, respectively.

2.2. Definite conditions

2.2.1. Pre-heating period

We first consider the case in which the intermittent time is sufficiently long that the temperature of the in-slab heating floor is approximately equal to that of the indoor air. We next consider the case with a short intermittent time such that the initial temperature of the in-slab heating floor is the same as the temperature at the end of the intermittent period.

(1) Boundary conditions

① The boundary surfaces along the x-axis are assumed to be adiabatic and can be described by the Equation (2), and it relates to the surfaces not contacting the pipes.

$$\left.\frac{\partial t}{\partial x}\right|_{x=-\frac{l}{2}} = \left.\frac{\partial t}{\partial x}\right|_{x=\frac{l}{2}} = 0 \tag{2}$$

② The boundary surfaces along the y-axis are modeled using the following equations:

$$\left.\frac{\partial t}{\partial y}\right|_{y=0} = 0 \tag{3}$$

and

$$-\lambda\left.\frac{\partial t}{\partial y}\right|_{y=h} = (\alpha_c + \alpha_r) \times (t - t_a) \tag{4}$$

where α_c and α_r are the heat convection coefficient and the radiant heat transfer coefficient for the floor surface, respectively, in W/(m^2 K), the values for which are taken from the literature [22].

③ The boundary of the pipe surface is described by

$$t|_{(x+\frac{l}{2})^2+(y-R)^2=R^2} = t|_{(x-\frac{l}{2})^2+(y-R)^2=R^2} = t_s \tag{5}$$

(2) Initial condition

The initial condition for the first case is given by

$$t_{\tau 0} = t_a \tag{6}$$

The initial condition for the second case is given by

$$t_{\tau 0} = g\left(x_i, y_j, n\right) \tag{7}$$

Where $g(x_i,y_i,n)$ is the temperature field at the end of the intermittent period. MATLAB is used to construct the interpolating function int (x,y,n).

2.2.2. Intermittent period

(1) Boundary condition

The pipe surface is assumed to be adiabatic. The boundary condition on the pipe surface is given by Equation (8).

$$\left.\frac{\partial t}{\partial R}\right|_{(x+\frac{l}{2})^2+(y-R)^2=R^2} = \left.\frac{\partial t}{\partial R}\right|_{(x-\frac{l}{2})^2+(y-R)^2=R^2} = 0 \tag{8}$$