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A nodal model to predict vertical temperature distribution in a room with floor heating and displacement ventilation

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ABSTRACT

In this paper, the development of a nodal model that predicts vertical temperature distribution in a typical office room with floor heating and displacement ventilation (FHDV) is described. The vertical air flow distribution is first determined according to the principle of displacement ventilation, taking into account the effects of the cold external envelope and those of the warm floor surface. The vertical temperature distribution can then be predicted by the proposed model, which identifies four temperature nodes at different heights above the floor. The vertical temperature distribution can be calculated by solving energy balance equations for each node, using boundary parameters as inputs. The predictions agree quite well with experimentally measured data for floor surface temperatures between 25 and 28 °C, supply air temperatures between 14 and 18 °C and air change rates from 3.1 to 4.5. The proposed vertical temperature distribution can be used in the design and analysis of hybrid systems with floor heating and displacement ventilation.

1. Introduction

In the last two decades, the application of floor heating systems has significantly increased all over the world [1]. Compared to traditional heating systems, such as radiator and convector heating systems, a floor heating system can reach the same level of thermal comfort (the same operative temperature) at a lower indoor air temperature [2,3]. Due to the lower room air temperature and lower supply water temperature in floor heating buildings, both lower building energy consumption and better air quality can be obtained at the same time [4,5]. Floor heating systems, now regarded as energy efficient and comfortable heating systems, have been extensively used in residential and non-residential buildings.

In order to decrease energy consumption in the operation of heating systems, many different energy efficient building technologies have been applied in modern buildings, many involving increased thermal insulation and air tightness. Unfortunately, these energy efficient building technologies may cause insufficient fresh air to be supplied by infiltration and may thus lead to poor indoor air quality. To avoid this problem, a mechanical ventilation system for fresh air supply must be integrated with the floor heating systems. Due to the higher ventilation effectiveness of displacement ventilation, in comparison with traditional mixing ventilation [6], one of the most interesting solutions is the combination of floor heating with displacement ventilation [7].

Compared to a floor heating system (FH), a hybrid system with floor heating and displacement ventilation (FHDV) has a higher vertical temperature gradient due to the principle of displacement ventilation, which may increase the risk of local thermal discomfort [8,9]. In addition, since displacement ventilation directly supplies cold air to the occupied zone, attention must be paid to the draught caused by the cold supply air [10]. Although many researchers have examined the problems caused by vertical air temperature distribution and the local thermal discomfort caused by displacement ventilation [11–15], the combination of displacement ventilation with floor heating creates a new situation.

The cold air supplied by displacement ventilation will be heated by the floor heating system before it enters the occupied zone. Additionally, due to the effect of downdraft caused by a cold external window and wall, the dimensionless vertical air temperature distribution in the occupied zone does not follow the "50%-rule", is with a function of the installed floor heating capacity [16,17]. Further studies of the vertical temperature distribution and local thermal discomfort in a room with floor heating and displacement ventilation are therefore required.

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Although some full-scale experimental studies have been carried out to investigate the vertical temperature distribution and local thermal discomfort in a room with floor heating and displacement ventilation [8,9,16,17], due to the large expenditure of cost and time to make such measurements, the experiments have concerned a limited number of conditions. To solve this problem, Causone et al. [18] developed a validated CFD model to predict room vertical temperature distribution, but CFD simulations are unlikely to be used with current building simulation programs as this would involve too much simulation time. In this paper, anodal model that predicts vertical temperature distribution in atypical office room with floor heating and displacement ventilation has therefore been developed.

2. A nodal model for floor heating and displacement ventilation

The principle of floor heating and displacement ventilation can be seen in Fig. 1. Cold air at low velocity is supplied by displacement ventilation outlets and spreads out above the floor, where it is mixed with downdraft air caused by the cold external window and wall. Meanwhile, the resulting still cold air is heated by the floor heating system. Due to the updraft currents caused by the heat sources present in the room, such as computers and occupants (as shown in Fig. 1), air from the floor region is transported to the upper part of the room and as updraft. Subsequently, a proportion of the updraft is transported to the region near the external window and wall to replace the air volume that was reduced by downdraft, while the rest of the updraft rises further and is removed from the room by the exhaust ventilation system.

In order to establish a model that predicts air distribution in the room, the following assumptions about building heat transfer and room air flow must be made:

(1) Uniform distribution of surface temperature on windows and walls and of horizontal air temperature.
(2) Linear distribution of vertical air temperature from the close to the floor to close to the ceiling.
(3) Same proportion of radiation to convection of all internal heat sources, 50% convection, 50% radiation (evenly distributed by area on the inside surfaces).
(4) Negligible updraft caused by warm internal walls due to the small temperature difference between internal wall surfaces and indoor air.

Based on the above assumptions, the vertical air flow distribution for floor heating and displacement ventilation is predetermined, as shown in Fig. 2(a), where m_w is the downdraft caused by the temperature difference between indoor air and the inside surface of the window and external wall and m_s is the supply air flow rate. The effect of internal heat sources on the vertical air flow distribution has been taken into account by the downdraft. The greater the heat gain contributed by internal heat sources, the greater the temperature difference between indoor air and inside surface of external window and wall will be.

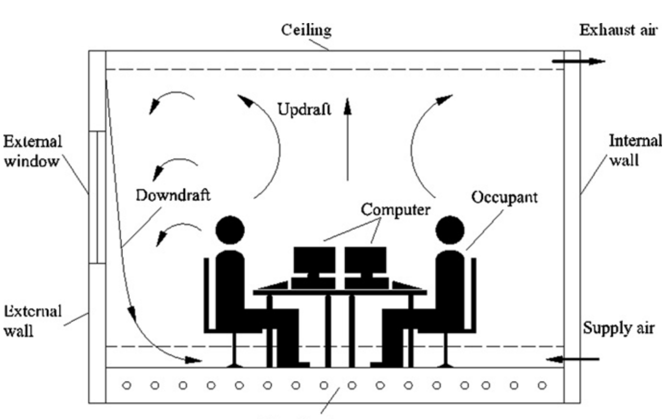

Fig. 1. A typical office room with floor heating and displacement ventilation.

Fig. 2(b) shows the proposed vertical temperature distribution prediction model, which consists of four temperature nodes: the area-weighted mean floor surface temperature t_f, the local air temperature near the floor t_{af} (0.1 m above the floor is taken to be the thickness of the thermal boundary layer), the local air temperature near the ceiling t_{ac} (0.1 m below the ceiling is taken to be the thickness of the thermal boundary layer) and the area-weighted mean ceiling surface temperature t_c.

3. Mathematical description of the nodal model for floor heating and displacement ventilation

The mathematical description of the nodal model for floor heating and displacement ventilation is to be shown in Fig. 3, which consists of eight energy balance equations: 1) energy balance equation on the floor surface, 2) energy balance equation near the floor, 3) energy balance equation on the ceiling surface, 4) energy balance equation near the ceiling, 5) energy balance equation on the inside surfaces of the window and external wall, 6) energy balance equation near the external window and wall, 7) energy balance equation on the inside surface of the internal walls, and 8) energy balance equation of the indoor air.

3.1. Energy balance equation on the floor surface

The energy balance equation for the floor surface can be written as follows:

$$Q_{cf} + Q_{rf} + Q_{rsf} + Q_f = 0 \tag{1}$$

where Q_{cf} is the convective heat transfer rate between floor surface and indoor air (as shown in Eq. (2)),Q_{rf} is the radiant heat transfer rate between the floor surface and the other inside surfaces (as shown in Eq. (3)), Q_{rsf} is the radiation incident on the floor surface from internal heat sources (as shown in Eq. (4)) and Q_f is the upward heat flow from the floor heating system (which is somewhat less than the total floor heating capacity).

$$Q_{cf} = A_f h_{cf}(t_{af} - t_f) \tag{2}$$

where h_{cf} is the convective heat transfer coefficient between floor surface and indoor air which will be discussed in detail in Section 4.

$$Q_{rf} = A_f F_{f-ew} h_{rf}(t_{ew} - t_f) + A_f F_{f-c} h_{rf}(t_c - t_f) + A_f F_{f-iw} h_{rf}(t_{iw} - t_f) \tag{3}$$

where h_{rf} is the radiant heat transfer coefficient between the floor surface and other inside surfaces of the room envelope, which will be discussed in detail in Section 4.

$$Q_{rsf} = \text{rsf} Q_i \tag{4}$$

where rsf is the percentage of radiation from internal heat sources that is incident on the floor surface and depends on the ratio of floor surface area to the total room surface area.

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