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Indoor temperatures for calculating room heat loss and heating capacity of radiant heating systems combined with mechanical ventilation systems

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ABSTRACT

In this study, a typical office room with a radiant heating system and a mechanical ventilation system was selected as the research subject. Indoor temperature formulas for calculating the room heat loss (including transmission heat loss and ventilation heat loss) and heating capacity of the hybrid system were determined according to the principle of heat transfer. A model to predict indoor temperatures in the room was proposed, and it was determined that the predicted indoor temperatures agreed well with the measured data. Qualitative analyses of the effects of heated surface temperature and air change rates on the indoor temperatures were performed using the proposed model. When heated surface temperatures and air change rates were from 21.0 to 29.0 °C and from 0.5 to 4.0 h^{-1}, the indoor temperatures for calculating the transmission heat loss and ventilation heat loss were between 20.0 and 20.3 °C and between 19.6 and 20.5 °C, respectively, and the indoor temperature for calculating the heating capacity of the hybrid system was between 18.2 and 19.8 °C. Accordingly, the relative calculation errors were between 0.3% and 0.5% and between −10.2% and 11.8% for calculating the transmission heat loss and ventilation heat loss, respectively, and between 16.0% and 17.4% for calculating the heating capacity of the hybrid system. Due to large relative calculation errors, it is necessary to consider the effect of heated surface and cool supply air on indoor temperatures for calculating ventilation heat loss and heating capacity of radiant heating systems combined with mechanical ventilation systems.

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1. Introduction

Radiant heating systems, such as floor and ceiling heating systems, are now regarded as energy efficient and comfortable heating systems; thus, these systems have been extensively used in buildings of different types [1–5]. Additionally, many energy efficient building technologies with increased thermal insulation and air tightness have also been applied in buildings with radiant heating systems, which may contribute to low building heat loss and reduced energy consumption. Conversely, the application of these energy efficient technologies may cause insufficient fresh air supply due to low infiltration and lead to poor indoor air quality and increased human healthy symptom [6,7]. To avoid this problem, a mechanical ventilation system, such as a mixing ventilation system or a displacement ventilation system, should be installed in buildings for increasing fresh air supply [8–10].

A hybrid system with a radiant heating system and a mechanical ventilation system, which is regarded as an advanced HVAC system, has been applied in many buildings worldwide [11–15]. The radiant heating system was used to control the indoor thermal environment in term of indoor temperature, and the mechanical ventilation system was used to control the indoor air quality in term of outdoor air flow rate. Meanwhile, supply air temperature was kept as constant, normally from 14 °C to 18 °C to avoid uneven air temperature distribution [10,12]. Therefore the radiant heating system and mechanical ventilation system could operate independently and would not fight with each other due to the different control objectives.

Indoor temperatures, such as indoor air temperature and operative temperature, are the key parameters to determine the heat loss of a room and the heating capacity of a radiant heating system.

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Nomenclature

A	area (m^2)
ACH	Air change rate (h^{-1})
c_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
D	Diameter (m)
error	Relative error (%)
F	view factor (–)
h	convective heat transfer rate ($W\,m^{-2}$)
H	Height (m)
L	Length (m)
m	mass flow rate ($kg\,s^{-1}$)
Q	heat transfer rate ($W\,m^{-2}$)
t	temperature (°C)
v	velocity ($m\,s^{-1}$)
W	Width (m)

Greek symbols

ε	emissivity (–)
ρ	density ($m^3\,kg^{-1}$)
σ	Stefan–Boltzmann constant (=$5.67 \times 10^{-8}\,J\,s^{-1}\,m^{-2}\,K^{-4}$)

Subscripts

a	space air
e	exhaust
c	ceiling
ew	external window and wall
f	floor
is	internal heat sources
iw	internal wall
r	radiation
s	supply
sys	system
w	wall

When indoor physical parameters are within the thermal comfort range in a room with a radiant heating system without a mechanical ventilation system, the indoor air temperature is approximately equal to the operative temperature and can be used as reference for calculating the room heat loss and the heating capacity of the radiant heating system [16–19]. Compared to a radiant heating system without a mechanical ventilation system, a hybrid system with a radiant heating system and a mechanical ventilation system can create a new situation with regard to indoor air temperature and operative temperature, i.e., the indoor air temperature may not equal the operative temperature, and they may not be merely influenced by the heated surface and also by the cool supply air [20–22]. However, very few studies have considered the effect of heated surface and cool supply air on indoor temperatures for calculating room heat loss and heating capacity of a hybrid system, and irrational indoor temperatures may result in large errors in the sizing of the hybrid system as a result.

In this study, a typical office room with a radiant heating system and a mechanical ventilation system was selected as the research subject. A model that predicts indoor room temperatures will firstly be proposed, and then a qualitative analysis on the effect of heated surface temperature and air change rate on the indoor temperatures using the model are performed. The results in this paper are believed to be beneficial for the design of radiant heating systems combined with mechanical ventilation systems.

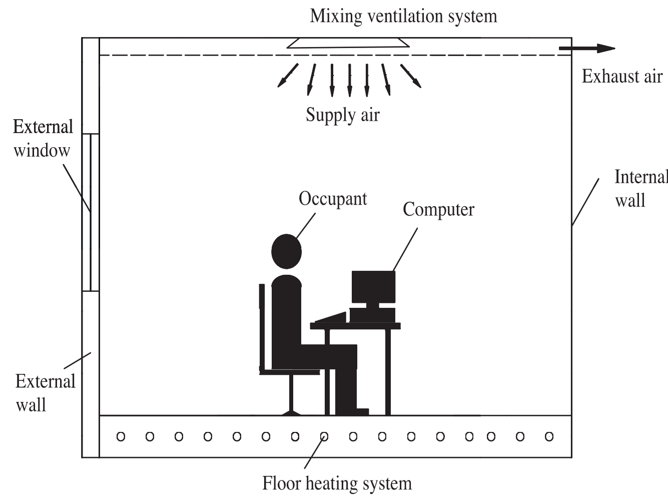

Fig. 1. A typical office room with floor heating system and mixing ventilation system.

2. Establishment of the indoor temperature prediction model

A hybrid system with a radiant heating system and a mechanical ventilation system normally includes at least one of the following cases: (1) a floor heating system combined with a mixing ventilation system, (2) a floor heating system combined with a displacement ventilation system, (3) a ceiling heating system combined with a mixing ventilation system or (4) a ceiling heating system combined with a displacement ventilation system. In this study, a typical office room with a floor heating system and a mixing ventilation system was selected as the research subject, as shown in Fig. 1.

The high velocity cool air is supplied from the mixing ventilation system outlets and enters the occupied zone, where it is mixed with the updraft air caused by the internal heat sources present in the room, such as computers or occupants (as shown in Fig. 1). To establish a model that predicts indoor temperature in the room, some assumptions regarding to building heat transfer must be made, as seen in Ref. [22]. In this study, the only difference from Ref. [22] is the assumption of vertical distribution of indoor air temperature, which is not linear but uniform due to the mixing ventilation in the room.

Based on the above assumptions, the mathematical description of the heat transfer processing the room with floor heating and mixing ventilation can be obtained, which consists of five energy balance equations, as shown in Eq. (1). It should be noted that the heat storing effect at the floor surface mass was ignored due to the steady heat transfer processes in the room.

$$\begin{cases} Q_{cf} + Q_{rf} + Q_{rsf} + Q_f = 0 \\ Q_{cc} + Q_{rc} + Q_{rsc} = 0 \\ Q_{cew} + Q_{rew} + Q_{rsew} + Q_{ew} = 0 \\ Q_{ciw} + Q_{riw} + Q_{rsiw} = 0 \\ Q_{cs} - Q_{cf} - Q_{cc} - Q_{cew} - Q_{ciw} - Q_s = 0 \end{cases} \quad (1)$$

where Q_{cf}, Q_{cc}, Q_{cew} and Q_{ciw} are the convective heat transfer rate between the envelope surface and the indoor air (as shown in Eq. (2)), Q_{rf}, Q_{rc}, Q_{rew} and Q_{riw} are the radiant heat transfer rate between any two envelope surfaces (as shown in Eq. (3)), Q_{rsf}, Q_{rsc}, Q_{rsew} and Q_{rsiw} are the radiation incident on the envelope surface from the internal heat sources (as shown in Eq. (4)), Q_f is the upward heat flow from the floor heating system (which is somewhat less than

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