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Performance analysis of pulsed flow control method for radiant slab system

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ABSTRACT

We present a novel pulsed flow control method (PFM) using a two-position valve to regulate the capacity of radiant slab systems. Under PFM, the on-time duration of the valve is short (compared to all prior work, e.g. 4-minute), and fixed, while the off-time varies. We present a novel, open-source, finite difference model that assesses three-dimensional transient slab heat transfer, accounting for the transient heat storage of the pipe fluid. Sensitivity analysis results indicate the dominant factors influencing energy performance of the PFM are: on-time duration; pipe diameter; and spacing. We experimentally validated both the new control strategy and model in full-scale laboratory experiments. Compared with previous intermittent control strategies (with on-time durations over 30 min), at 50% part load the PFM reduces 27% required water flow rate and increases supply to return water temperature differential. Compared with the variable temperature control method, at 50% part load the PFM reduces 24% required water flow rate. The energy performance of PFM is comparable to that of a conventional variable flow rate control. However, it has more accurate capacity control, achieves a more uniform surface temperature distribution, and reduces initial investment by substituting two-position for modulating valves, thus showing promise for engineering applications.

1. Introduction

Radiant slab heating and cooling systems including embedded surface systems (ESS) and thermally activated building systems (TABS), rely on pipes to distribute heated/cooled water throughout a building. These systems have gained appreciable interest and success for a variety of applications in new buildings and renovations [1,2]. Radiant slab systems are widely used due to their utility, energy efficiency, and aesthetics [3]. With the help of the low temperature difference between the floor surface and indoor air, a radiant slab achieves high temperature cooling and low temperature heating in buildings. This greatly increases the feasibility of using a broad range of more efficient cooling sources, such as cooling towers and ground water [4,5]. Compared with a conventional all-air system, radiant cooling systems can achieve energy savings by increasing the efficiency of cooled water generation and reducing transport energy consumption [6–11]. Besides, radiant systems provide equal or better comfort than all-air systems [12,13].

Field test results show that 20%-30% of thermal energy is wasted because of poor heating system regulation in China [14]. Therefore, numerous control methods have been suggested or applied to radiant slab systems. Under optimum operating conditions, the room with the highest load density, operating at maximum flow, should determine the supply water temperature leaving the cooling/heating plant for the building. Yet, many other rooms in the building have lower loads and do not require the extreme supply temperatures. Thus, each individual zone in the building requires a control method to handle these part load conditions. These methods can be broadly classified into supply water temperature control and water flow rate control.

1.1. Supply water temperature control with constant flow rate

In this case, a three-way mixing valve controls the supply temperature into each zone by injecting water into a recirculation loop with a constant speed pump. As shown in Fig. 1(a), the variable temperature control method (VTM) allows each room to have independent control over supply water temperature, and to maintain effective control of room conditions. It has a high control precision on the capacity over a wide range of part loads and also yields a relatively uniform surface temperature distribution across the slab. However, the exergy destruction of a mixing process between the supply and return water fluids degrades the energy efficiency of the heating/cooling plant. The VTM also comes with a high transport (pumping) energy cost due to the constant speed pump.

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Nomenclature

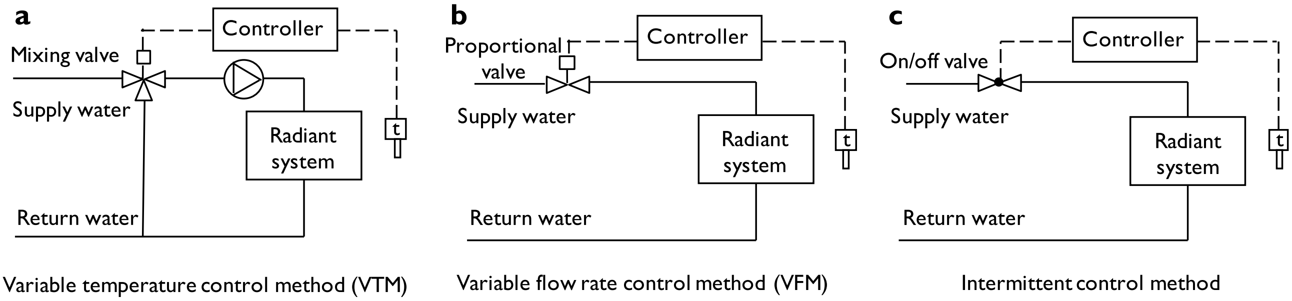
a	Thermal diffusivity (m^2/s)
c_p	Specific heat (J/(kg·K))
d_i	Inner diameter of pipe (m)
d_o	Outer diameter of pipe (m)
EE	Elementary effect of a design parameter (-)
F	Water flow rate (m^3/s)
H	Thickness of radiant floor (m)
h_w	Convective heat transfer coefficient in pipes ($W/(m^2 \cdot K)$)
h_f	Heat transfer coefficient of convection and longwave radiation ($W/(m^2 \cdot K)$)
L_1	Pipe spacing (m)
P	Period in PFM (s)
q_s	Floor surface heat flux (W/m^2)
R_d	Thermal resistance of the pipe wall ($(m^2 \cdot K)/W$)
T	Temperature (°C)
$T_{w,i}$	Chilled water temperature in the ith water pipe (°C)
$T_{w,s}$	Supply water temperature (°C)
T_z	Indoor operative temperature (°C)
Δ_i	A predefined step in Morris method (-)
ΔT_w	Supply and return water temperature difference (°C)
$\Delta T_{s,diff}$	Surface temperature non-uniformity (°C)
v_w	Water velocity in pipes (m/s)

Greek symbols

φ	Ratio of floor surface heat capacity (-)
ξ	Ratio of water flow rate (-)
λ	Thermal conductivity (W/(m·K))
τ	Time (s)
ρ	Density (kg/m^3)
μ	Average of the elementary effect (-)
σ	Standard deviation of the elementary effect (-)

Subscripts

on	On-time duration
off	Off-time duration
cyc	One control cycle
ref	Reference case
w	Water



Variable temperature control method (VTM) Variable flow rate control method (VFM) Intermittent control method

Fig. 1. Schematic of control methods for a radiant system: (a) Variable temperature control method (VTM); (b) Variable flow rate control method (VFM); and (c) intermittent control method.

1.2. Flow rate control with constant supply water temperature

Two types of control methods are used to manipulate water flow rate. The first one is a variable flow rate control method (VFM) equipped with a proportional (i.e. modulating) valve (see Fig. 1(b)). It maintains design conditions via a proportional integral control or an augmented constant gain control [15]. However, according to the experiment conducted by Jin et al. [16], the cooling capacity of the radiant slab ranges from 35.5 to 39.5 W/m^2 with a varying water flow rate from 0.096 to 0.581 m^3/h. The effect of the water flow rate on the capacity of the radiant slabs is not great within this range of flows, even though the flow is laminar; only lower flow rates show significant differences in capacity. However, the proportional valve has a low control precision at low flows, and thus also on capacity, which in turn results in overcooling/overheating at part loads [17]. Furthermore, due to the relatively high initial cost of the modulating valve and the precision actuator in both of the VTM and VFM, developers and heating companies often simplify indoor systems by using manual regulating valves [18]. It has a negative influence on energy efficiency and is detrimental to regulating heat use.

The second method, i.e., intermittent control, which supplies water by intermittently fully opening or fully closing a two-position valve (see Fig. 1(c)), is widely spread attributed to the low initial costs. Previous studies proposed and investigated many intermittent control methods, including conventional on-off control, fuzzy logic-based on-off control [19], two-parameter switching control [20], pulse width modulation [21,22], and model predictive intermittent control [23,24]. However, these intermittent control strategies cited here all have relatively long valve open phases, ranging from 30 min to several hours that are comparable to the response time (at 63.2% of the steady state value) of the radiant slab. As a result, they are found to yield large changes in the floor surface temperature as well as indoor operative temperature [25].

Inspired by the possibility of using the high thermal inertia of radiant slabs to mitigate the effects of relatively high frequency water temperature fluctuation, we propose a novel pulsed flow control method (PFM) based on intermittent control with a fixed and short on-time duration (4 min or less). This is far less than the response time of the slab, implying that the periodic steady state results will not vary significantly due to the pulsed nature of the flow. We than use varying off-time duration to allow for control of flow to very load part loads. The key difference from all intermittent control strategies published before is that the proposed approach is designed with an on-time duration less than or equal to the time taken to replace the stored water in pipes.

To address the dynamic behavior of a radiant slab in the pulsed flow control, the transient heat transfer processes need to be considered in numerical simulation. The finite difference method and finite element method are typically used to calculate the radiant slabs with a two-dimensional heat conduction problem [26,27]. The RC-network model and heat conduction transfer function method are two representative simplified heat transfer models [28–31] and they are used in TRNSYS 18.0 and EnergyPlus 8.2.0, respectively. The 2D heat conduction model and the RC-network model of the radiant slab simplify the water temperature into one node, i.e., the average of the supply and return water temperature, and ignore the heat storage of the water in the pipe. However, in the short on-time duration of the PFM, the cooled water