Operation dynamics of building with radiant cooling system based on Beijing weather

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ABSTRACT

Radiant cooling systems are currently used in many parts of the world. However, the relatively long thermal response time of such a system causes numerous concerns regarding their operation. This study emphasizes the operation dynamic of radiant systems through on-site measurement and simulation. The results of on-site measurement imply that the capacity of heat extraction at a cooling surface can be improved by altering the operational strategy of the radiant system based on Beijing weather. The feasibility in a typical office building with a same radiant system can be studied by simulation. The results show that 9–15% of cooling energy is required during the occupied period that can be conserved in the thermal mass in advance, and the peak sensible cooling loads of terminal devices decrease at 32–39% compared with that in the conventional scheduling. Although the altered operation strategies lead to increased cooling demands, the electricity consumption and costs decrease because of the improved coefficient of performance and low electricity tariffs at night. The convectional strategy is still recommend for the radiant system with less thermal mass because the indoor environment can be controlled precisely.

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1. Introduction

Radiant cooling systems are regarded as having many advantages in indoor environmental control and energy efficiency [1]. Conroy and Mumma [2] found that the air flow rate of an air-conditioning system combined with a radiant cooling system is approximately 20% of the volume of a conventional all-air system. Feustel and Stetiu [3] indicated that the smaller flow rate leads to a reduction in ductwork dimensions, fan size, and energy consumption. In addition, a number of opportunities enable the direct application of low-grade natural energy sources and optimization of the total performance of a complete system. However, as revealed by Niu et al. [4] in their study, the radiant effect of a chilled ceiling can decrease the heat storage capacity of the building envelope to radiant heat transfer and result in an increase in the start-up cooling load in the temperate Dutch climate. Feng et al. [5] indicated the cooling load differences between radiant and air systems through simulation of 13 situations using Energy-Plus software. They also conducted an experiment to verify the simulation results and compared the cooling loads predicted using the heat balance (HB) and the radiant time series (RTS) methods, respectively, and

then suggested that the HB method should be applied for the calculation of cooling load of a room with a radiant system because the RTS method underestimates the cooling load [6]. Furthermore, a radiant cooling system could have a longer response time compared with a convective air-conditioning system, and a number of ways are available to operate a radiant system in practice [7]. The hydronic system at present can be controlled with variable flow rate but constant supply temperature or with constant flow rate but variable supply temperature [8]. Li et al. [9] used the CFD technique to simulate the cooling storage and release processes for the configuration of polyethylene pipes of 20 mm in diameter and 200 mm in space; they believed that if the room sensible load is equal to or lower than 20 W/m^2, the storage can maintain thermal comfort for 7 h. Haniff et al. [10] stated that proper operation scheduling of an HVAC system not only provides the opportunity to reduce the energy consumption with less initial investment, but also save energy cost by taking advantage of lower electricity tariff at night. In a conventional strategy, an air-conditioning system is available for 24 h a day, and the room temperature set point was adjusted to achieve energy savings [11–14]. Salsbury et al. [15] discussed the technique of 5-period division scheduling, in which a day is divided into 5 sections according to the occupied period and indoor thermal environment: the lower temperature region, the lower or upper temperature region, and the upper temperature region during the occupied period, and the outside-comfort region during the unoc-

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Nomenclature

ESCS	Capillary tube embedded surface cooling system
TABS	Thermally activated building system
XPS	Extrusion polystyrene insulation
ρ_a	Air density kg/m^3
c_{pa}	Air specific thermal capacity kJ/kg K
ρ_w	Water density kg/m^3
c_{pw}	Water specific thermal capacity kJ/kg K
t_o	Outdoor air dry-bulb temperature $^\circ$C
E_o	Outdoor air enthalpy kJ/kg
t_r	Room temperature $^\circ$C
E_r	Room air enthalpy kJ/kg
T_{aj}	Air temperature of adjacent room $^\circ$C
T_f	Floor surface temperature $^\circ$C
T_w	Temperature of water $^\circ$C
T_c	Ceiling surface temperature $^\circ$C
T_a	Room air temperature $^\circ$C
t_{as}	Supply air temperature in primary air system $^\circ$C
t_{was}	Supply water temperature in cooling coil $^\circ$C
t_{war}	Return water temperature in cooling coil $^\circ$C
t_{wi}	Inlet water temperature in hydronic system $^\circ$C
t_{wo}	Outlet water temperature in hydronic system $^\circ$C
C_c	Heat storage of ceiling W
C_f	Heat storage of floor W
C_w	Heat storage of water W
R'_{aj}	Floor adjacent air thermal resistance Km/W
R'_{sf}	Resistance above the internal source Km/W
R'_{sc}	Resistance under the internal source Km/W
R'_a	Ceiling adjacent air resistance Km/W
R'_{aj}	Floor adjacent air resistance Km/W
$\dot{V}_a$	Air volume flow rate in convective air system m^3/s
$\dot{V}_{wa}$	Water volume flow rate in cooling coil m^3/s
$\dot{V}_{wr}$	Water volume flow rate in hydronic system m^3/s
q_{conv}	Convective heat transfer from surfaces in a room W
q''_{conv}	Convective heat flux to zone air from a surface W
q_{IV}	Sensible load caused by infiltration and ventilation W
q''_{SW}	Net short wave radiant flux to surface from lights W
q''_{LWS}	Long wave radiant flux from equipment in zone W
q''_{LWX}	Long wave radiant flux exchange between surfaces W
q''_{ki}	Conductive flux through the inside face of surface W
q''_{sol}	Transmitted solar radiant flux absorbed at surface W
q_{CE}	Convective parts of internal loads W
q_{cs}	Heat extracted by active surfaces W
q_c	Conduction heat transfer of inside face of ceiling W
q_f	Conduction heat transfer of inside face of floor W
q''_{k-ina}	Conduction heat gain at inactive surfaces W
q_{ZH}	Heat extraction from a thermal zone W
q_w	Cooling load of hydronic system W
q_{airsys}	Sensible cooling load of air-conditioning system W
q_{ZT}	Room sensible cooling load handled by combined system W
q_{coil}	Cooling load of cooling coil W
q_a	Total cooling load of air-conditioning system W

cupied period. Optimized demand-limiting set-point trajectories are also discussed in several studies, which presented numerical models to predict cooling and heating demands and to optimize the temperature set-points [16–19].
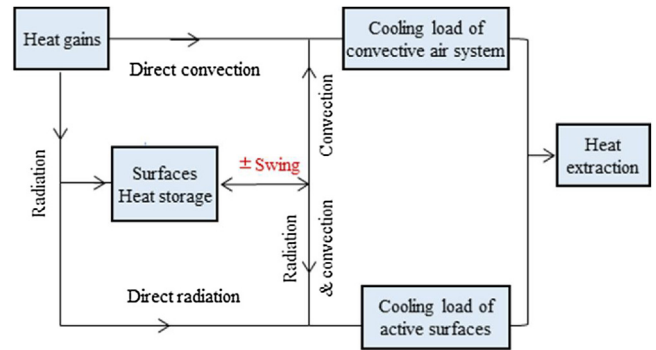

Fig. 1. Heat transfer process in the zone with convective air and radiant systems [4].
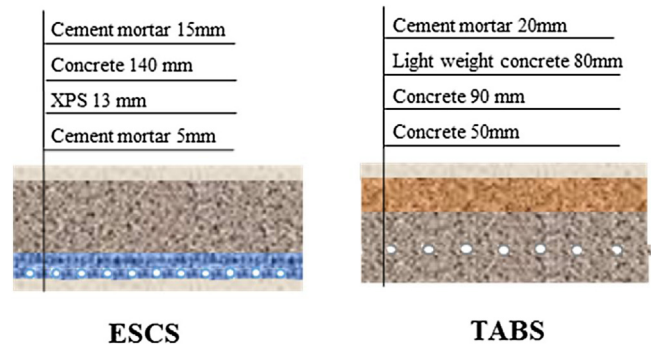
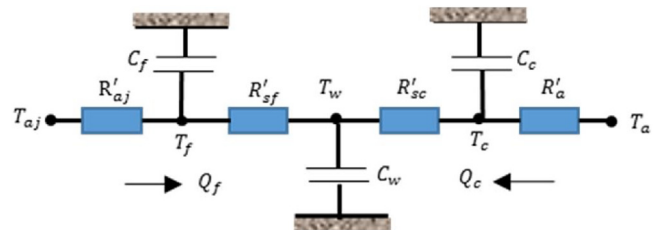

Fig. 2. Configurations of radiant systems.

Fig. 3. Heat transfer in active surface.

This study emphasizes the characteristics of radiant systems in dynamic operation by on-site measurement and simulation, and the corresponding optimal strategies are also proposed. Considering that the variable inlet water temperature would reduce the effect of thermal mass in the configuration of radiant system, only the control approach of variable flow rate but constant inlet temperature is concerned in the study.

1.1. Heat balance analysis

As illustrated in Fig. 1, the convection heat gain directly becomes cooling load of a convective air system, and a portion of the radiation heat gain can be directly absorbed by cooling surface (active surface), and the other radiation heat gain can be absorbed by the structure or furniture, and then extracted by convective air system and active surface. While the heat gain removed by a convective air system is the cooling load of the system, the heat gain extracted by the active surface is not necessarily equal to the load of the hydronic system. Fig. 2 illustrates two radiant system configurations, which have been widely applied, and Fig. 3 shows the heat transfer process in the structures.