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# Dynamic performance of water-based radiant floors during start-up and high-intensity solar radiation

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**Abstract**

In this paper, two typical types of radiant floors are examined: concrete core radiant floors and light radiant floors. Their variant dynamic behaviors during intermittent operation are illustrated, and the impact of transient solar radiation is determined through numerical calculation. The concept of the time constant is used to estimate quantitatively the thermal inertia of the different types of radiant floors, especially the response time in the start-up period of the cooling/heating systems. The response time of the concrete core radiant floor is estimated to be 1–3 h, and that of the light floor is estimated to be 10–20 min; these values are consistent with the actual cool-down/heat-up times. When exposed to solar radiation, the cooling capacity of the radiant floors is much higher compared to applications without solar radiation. To estimate the real-time floor surface temperature and cooling capacity with transient solar radiation for both design and operation, a simple calculation method based on thermal capacity of the radiant floor is introduced, and the results accord well with the numerical calculation results. And the dynamic equivalent heat resistance is defined to reflect the thermal behavior of radiant floor with transient solar radiation. In addition, the heat extraction by chilled water in the radiant floor is distinct from the heat absorbed at the floor surface due to the heat storage of the radiant floor, which is also estimated by simple calculation.


*Keywords:* Radiant floor; Intermittent operation; Solar radiation; Dynamic performance

## 1. Introduction

Water-based radiant floors are widely used in heating systems due to their utility, energy efficiency, and aesthetics (Olesen, 2002). Currently, they are gaining popularity in cooling applications to deal sensible load as well, since the radiant floors are well protected from moisture condensation by the air system for ventilation and dehumidification (Babiak et al., 2007; Ren et al., 2010). When the floor surface is not lower than 19 °C, the indoor thermal environment conforms well to comfort standards (Babiak et al., 2007; Lim et al., 2006). The application of radiant floor cooling has been extended from the western and northern European where the outside air humidity is relatively low during the summer season, to the regions where the humidity level is much higher, such as Thailand, China, Korea, US (Simmonds et al., 2000; Zhang et al., 2013; Zhao et al., 2011; Song et al., 2008).

With their widespread application, the dynamic performance of radiant floors has continued to improve, e.g., quicker thermal response during the start-up phase of the heating/cooling period, self-adjustment to solar heat gain, etc.

Concrete core radiant floors with pipes embedded in the concrete layer are the most common type of radiant floor (Babiak et al., 2007). Recently, new types of radiant floors with low thermal capacity, known as "light floors," have been developed (Thomas et al., 2011). These two types of radiant floors are considerably different in terms of heat

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**Nomenclature**

| | |
|---|---|
| $a$ | thermal diffusivity ($m^2/s$) |
| $c_p$ | specific heat (J/(kg K)) |
| $C$ | equivalent heat capacity of radiant floor ($kJ/m^2\,K$) |
| $d_1$ | distance from the slab surface to the pipe (m) |
| $d_2$ | distance from the slab bottom to the pipe (m) |
| $h_z$ | heat exchange coefficient of convection and longwave radiation ($W/(m^2\,K)$) |
| $H$ | thickness of radiant floor (m) |
| $k$ | thermal conductivity (W/(m K)) |
| $L$ | pipe spacing of radiant floor (m) |
| $q$ | cooling capacity provided by radiant floor ($W/m^2$) |
| $q_s$ | heat absorbed by radiant floor surface ($W/m^2$) |
| $q_{sr}$ | solar radiation absorbed by radiant floor ($W/m^2$) |
| $q_w$ | heat extraction by chilled water inside radiant floor ($W/m^2$) |
| $Q_{stored}$ | heat stored in the radiant floor ($J/m^2$) |
| $r$ | ratio (dimensionless) |
| $R$ | equivalent heat resistance of radiant floor in steady state ($(m^2\,K)/W$) |
| $R^{sr}$ | dynamic equivalent heat resistance of radiant floor with solar radiation ($(m^2\,K)/W$) |
| $T$ | temperature (°C) |
| $T_s$ | radiant floor surface temperature (°C) |
| $\overline{T}_w$ | mean temperature of chilled water (°C) |
| $T_{w,s}$ | supply temperature of chilled water (°C) |
| $T_{w,r}$ | return temperature of chilled water (°C) |
| $T_z$ | environmental temperature of indoor air and surface (°C) |
| $\delta$ | outer diameter of water pipe (m) |
| $\theta_s$ | excess temperature coefficient of radiant floor surface (dimensionless) |
| $\rho$ | density ($kg/m^3$) |
| $\tau$ | time (s) |
| $\tau_c$ | time constant (s) |

transfer and thermal inertia. According to previous experimental analyses, it took several hours for a measured concrete core radiant floor to reach its steady state during intermittent operation (Liu, 2004); in contrast, the light floor achieved 80% of its maximum emitting power after less than 30 min of operation (Thomas et al., 2011). The different dynamic behaviors of these types of radiant floors during intermittent operation influence when and how these systems can be used before the occupancy period, so understanding these behaviors is of crucial importance to the control and energy conservation of heating/cooling systems.

As for the dynamic heat transfer process, several numerical and simplified models have been constructed to illustrate the heat transmittance among different temperature levels and to determine the heat storage capacity of radiant floors. Usually, a finite difference method or a finite element method is applied to calculate the thermo-active construction with a multi-dimensional heat transfer problem, e.g., TRNSYS component TYPE 160 (Fort, 1987). RC-networks used for the description of heat transfer inside the components were developed to simplify the calculation process (Weber and Jóhannesson, 2005; Liu et al., 2011). In addition, Larsen et al. acquired the analytical solution of the transient bi-dimensional heat transfer in the concrete core layer (Larsen et al., 2010). Nonetheless, simple indicators that can directly reflect the thermal response of radiant floors and discriminate among radiant floor categories based on thermal inertia remain absent from the literature.

Furthermore, when radiant floors are used for cooling in spaces with high-intensity solar radiation (e.g., airports, atriums, etc.), the cooling capacity of the radiant floor will increase dramatically compared to applications without solar radiation. The radiant floor in Suvarnabhumi International Airport in Bangkok, Thailand was dimensioned to remove 70–80 $W/m^2$ of heat, and the radiant floor could absorb up to 50 $W/m^2$ by radiation (Simmonds et al., 2000). The potential for radiant floor cooling systems to achieve higher cooling capacity with solar radiation has been the subject of numerous studies, and certain coefficients representing the improvement of steady-state heat transfer have been proposed (Olesen, 2008; Causone et al., 2010; De Carli and Tonon, 2011). However, the effect of solar radiation is usually a transient process of limited duration (Athienitis and Chen, 2000). The real-time floor surface temperature and cooling capacity of radiant floors with different heat storages are dissimilar; however, this has not been evaluated quantitatively. Moreover, the heat from transient solar radiation that is transferred to and removed by the chilled water, which is different from the surface cooling output due to thermal inertia, is not involved either.

In this paper, typical concrete core radiant floors and light floors are examined. Their variant dynamic behaviors during intermittent operation and the impact of transient solar radiation are illustrated through numerical calculation. The concept of the time constant is used to estimate quantitatively the thermal inertia of the different types of radiant floors in the start-up period of the cooling/heating systems. A simple calculation method for the heat absorption at the floor surface and the heat extraction by chilled water with transient solar radiation is introduced. Dynamic equivalent heat resistance is defined to reflect the thermal behavior of radiant floor further.