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New method for the design of radiant floor cooling systems with solar radiation

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ABSTRACT

Impacts of solar shortwave radiation are not taken into account in the standardized design methods in the current radiant system design guidelines. Therefore, the current methods are not applicable for cases where incident solar is significant. The goals of this study are to: (1) use dynamic simulation tools to investigate the impacts of solar radiation on floor cooling capacity, and (2) develop a new simplified method to calculate radiant floor cooling capacity when direct solar radiation is present. We used EnergyPlus to assess the impacts of solar for different design conditions. The simulation results showed that the actual cooling capacities are in average 1.44 times higher than the values calculated with the ISO 11855 method, and 1.2 times higher than the ASHRAE method. A simplified regression model is developed to improve the predictability of ISO methods. The new model calculates the increased capacity as a function of the zone transmitted solar and the characteristic temperature difference between the hydronic loop and room operative temperature.

1. Introduction

Natural lighting and physical connection to our environment are integral to the design of functional residential and commercial buildings. Glass, creating a continuum of space between the outdoors and the living space, is a distinct and pervasive building material in modern architecture. Glass admits solar radiation, and it is usually a challenge for the traditional air-based HVAC systems to maintain thermal comfort in spaces with significant solar radiation. In contrast, water-based radiant floor cooling systems are considered as especially effective for conditioning those spaces. For standard applications of radiant floor cooling systems, the rule of thumb is the cooling capacity can be up to 50 W/m^2 [1,2]. For applications that the sun illuminates the cooling surface, literatures show that the floor capacity can increase significantly, reaching 80–100 W/m^2 [3–5]. For this reason, floor cooling is increasingly designed in spaces with large glazed surfaces, such as atriums, airports, and entrance halls [6,7].

The cooling capacity of radiant floor systems is limited primarily due to a relatively small convective heat transfer coefficient between the floor and air, risk of condensation and concern about discomfort caused by low floor temperature, radiant asymmetry, large vertical air stratification and draft. Researcher have studied the cases with solar radiation. Odyjas and Gorka [4] showed that cooling capacity of radiant systems largely depends on the type of cooling load occurring in the room, but they did not explain the phenomenon from a fundamental heat transfer perspective. Their numerical simulation results showed that with a minimum floor temperature at 20 °C, the cooling capacity of the simulated floor system was 14–22 W/m^2 for pure convective load, 19–30 W/m^2 for mixed radiant/convective load, and 150–226 W/m^2 for 100% direct shortwave solar load at steady-state conditions. The last case, however, would never occur in practice because it requires a supply water temperature of 4.5 °C, which is too low for radiant applications due to condensation and comfort concern.

Simmonds et al. [8] looked at longwave and shortwave radiation separately in his calculation of total cooling capacity, and explained that the enhanced cooling capacity was due to solar radiation reaching the floor. However, in the calculations, he assumed that the amount of solar radiation absorbed by the floor was a known value. This is however hardly true in design practices. The calculations of absorbed solar radiation require not only knowing the transmitted solar through windows, but also floor surface temperature, surface material absorptivity, and room thermal conditions and properties. While the total transmitted solar can be obtained with well-defined calculation method or readily available computer programs, the

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latter factors are either uncertain during design or are variables that cannot be predicted accurately without using a heat-transfer based computer simulation tool. For designers, it would be useful to have a simplified method to estimate the amount of solar radiation absorbed by the radiant floor surfaces.

Causone et al. [9] used a lighting simulation tool to quantify the ratio of the amount of solar radiation that is directly absorbed by radiant ceilings to the total solar heat gain to the space. He studied cases with different aspect ratios, window orientations, surface material absorptivity, and locations. However, his study focused on radiant ceiling applications. Ceilings normally receive a much lower direct solar radiation as compared to floors. In addition, there are limitations in his method: (1) the lighting tool can only figure out the "solar patches", i.e. the amount of radiation that arrives at the surface instead of the absorbed radiation; (2) the calculations were steady-state analysis. At one point in the paper, the authors proposed that a fictitious heat transfer coefficient maybe introduced to characterize the improvement of heat transfer due to solar radiation. The heat transfer coefficient could be a function of directly absorbed solar radiation and the temperature difference between floor surface and room operative temperature. This is a promising idea. However, they did not provide a method to estimate this heat transfer coefficient.

For designers, accurate prediction of radiant system cooling capacity is critical both for designing of the radiant system but also for the associated air system. As radiant systems provide only sensible cooling, air systems work in hybrid mode to provide ventilation, dehumidification and supplemental cooling if needed. The size of the air system depends on radiant system capacity, and underestimation of radiant system capacity can lead to oversizing the air system.

Therefore, the goals of this the paper are to: (1) verify and quantify the dynamic impacts of solar radiation on radiant system capacity, (2) develop a simplified method to calculate radiant floor cooling capacity, and (3) investigate the implications for sizing the associated air systems. In the first part of this paper, we theoretically analyze the limitations in existing design methods, and explain why they fail to take into account solar shortwave radiation and radiation from internal load in the calculation process. Even though the internal radiative heat gain is also not properly considered, this paper focuses on the solar radiation because the impacts of internal load were evaluated to be less significant (5–10% for studied simulation cases).

The following sections present the methods and results that quantify the dynamic impacts of solar radiation on radiant system capacity. Based on the simulation results, a simplified method is developed for predicting the radiant system capacity when there is solar load. The last section of the paper demonstrates how the designers may use the new method to size the associated air system.

2. Background

There are two primary types of water-based radiant systems: (1) suspended metal ceiling panels with copper tubing attached to the top surface (radiant ceiling panel, RCP); (2) prefabricated or installed-in-place systems consisting of embedded tubing in radiant layers (embedded surface system, ESS). Depending on pipe position and radiant layer constructions, ISO 11855, the standard titled *Building environment design – Design, dimensioning, installation and control of embedded radiant heating and cooling systems*, further classifies the embedded system into seven types, from type A to G (Table 2 of part 2 of the standard) [10]. Radiant floor system can be one type of the ESS systems.

Table 1
Floor cooling convective heat transfer coefficient correlations.

Correlation	Source	Range[b]
$h_c = 0.87(T_a - T_s)^{0.25}$	ASHRAE recommendation: A. Kollmar [24]	0.8–1.46
$h_c = 1.0$	Olesen, B [25]	1.0
$h_c = 0.948$	Walton [23]: EnergyPlus *Simple* option	0.948
$h_c = 0.7589(T_a - T_s)^{1/3}$	Walton [23]: EnergyPlus *TARP*[a] option	0.75–1.51
$h_c = \frac{0.704}{D^{0.601}}(T_a - T_s)^{0.133}$	Awbi [26]	0.46–0.61

[a] We adopted this algorithm for the EnergyPlus simulations.

[b] The heat transfer coefficients are calculated with $T_a - T_s$ varied fom 1–8 °C.

Table 2
Summary of floor cooling total heat transfer coefficient.

h_t	Reference temperature (T_{ref})	Source
7	Operative temperature	ISO 11855 [22]
8.29	AUST	Chapter 6 ASHRAE HVAC Systems and Equipment [20]
7.5	Operative temperature	Olesen [25]

Designing a radiant system generally involves the determination of the following parameters: system specifications (tube diameter, spacing, surface finishing, insulation, total tube length, etc.), and design operating conditions (design surface temperature, flow rate, supply temperature, and pressure drop). The goal is to make sure the system capacity can satisfy the heating/cooling demand.

According to ISO 11855, design Cooling Capacity is defined as the thermal output at a cooling surface at design conditions. In practice, there is no standardized way to obtain the radiant system capacity. A survey of leading designers indicated that the design approaches include the direct use of numbers from manufacturer's product catalog, the use of designers' in-house calculation tools, which are developed mostly for steady state analysis, or conducting finite element or finite difference analysis which allows the evaluation of system dynamic performance. Occasionally, the most experienced designers use whole building simulation software, such as EnergyPlus or TRNSYS to assist in the design [11]. Dynamic simulation tools allow an evaluation of dynamic impacts of the thermal environment on system performance and an assessment of control sequences. For the panel systems, steady-state analysis method might be adequate because of the relatively small delay of the heat exchange between the environment and hydronic loop. For the embedded systems with thermal delay, dynamic solution is desirable for improved prediction accuracy. However, it is not always practical due to reasons such as lack of available skills or financial/time constraints. Simplified methods that are developed based on steady state calculations are still the most widely adopted practice.

There are two standardized ways to represent system capacity. The first one directly correlates surface heat flux to the temperature differences between room operative temperature and radiant surface(s), and this method explicitly requires the knowledge of the surface heat transfer coefficients. The second approach represents system capacity with a lumped thermal resistance and a mean temperature difference between the cooling medium and the space. In the design guidelines, there is no information about the application or differences between the two approaches. However, it appears that designers like to use the first approach as a quick way to check the feasibility of radiant system and as a basis for detailed design of system configuration and design operating conditions [7,12]. The second approach uses product performance data from manufac-