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# Impact of Solar Heat Gain on Radiant Floor Cooling System Design

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## Abstract

*Radiant floor cooling systems are increasingly being used in transition spaces with large glazed surfaces, such as atria, airports, and perimeter areas. For these cases, the cooling capacity can increase significantly according to the scientific literature. However, current design standards and test methods provide only limited guidance on sizing of radiant floor cooling systems and their associated air systems in the presence of solar radiation. The goals of this study are to 1) review current radiant surface cooling capacity estimation approaches; and 2) evaluate the impact of solar heat gain on radiant floor cooling capacity. Sensitivity simulation studies were conducted to investigate the influence of window-to-wall ratio, orientation, building aspect ratio, shading options, and floor material shortwave absorptivity. Review of current radiant system design standards showed that existing radiant cooling capacity estimation methods are insufficient when the system is exposed to solar radiation because shortwave radiation generated by lighting and solar are not considered. Radiant cooling capacity ratio (RCCR), defined as the ratio of the EnergyPlus simulated radiant cooling capacity to the values calculated using ASHRAE Handbooks (2012) and ISO 11855 (2012) methods, were reported to gauge the impact of solar radiation. The simulation results showed that 1) the median of the  $RCCR_{ISO}$  is 1.7 and 1.3 for  $RCCR_{ASHRAE}$ , and the enhancement is attributed to shortwave radiation (both direct and diffuse) absorption; 2) RCCR is most sensitive to shading options and slightly sensitive to shortwave absorptivity of the floor surface material.*

**Keywords – Radiant floor cooling; cooling load and capacity; solar heat gain; Radiant design standards**

## 1. Introduction

Water-based radiant cooling systems are gaining popularity as an energy efficient approach for conditioning buildings [1]. In many countries, hydronic radiant floor systems are widely used for heating (e.g. residential, churches, gymnasium, hospitals, industrial buildings, and commercial, etc.)

[2], and are now increasingly being used for cooling as well [3]. As Olesen [4] pointed out, radiant floor cooling systems provide several potential energy-saving benefits, but also some limitations. Limitations include reduced cooling capacity, caused primarily by condensation concern, relatively small convection heat transfer coefficient, and several comfort factors, such as acceptable floor temperature, risk of radiant asymmetry, vertical air stratification and draft risk. The guideline for standard application of a radiant floor cooling system is a maximum cooling capacity of  $42 \text{ W/m}^2$  [5, 6]. However, many questions arise regarding the system design when the cooling surface is illuminated by sun. For these cases, the cooling capacity can increase significantly, reaching  $80\text{-}100 \text{ W/m}^2$  [7, 8]. For this reason, floor cooling is increasingly designed for those spaces with large glazed surfaces, such as atriums, airports, and entrance halls [3].

Research efforts have been made to understand the solar absorption by radiant systems. Athienitis and Chen [9] have discussed this issue for floor heating, but not cooling. Simmonds [10] looked at longwave and shortwave radiation separately in his calculation of total cooling capacity, and explained that the enhanced cooling capacity was due to absorbed solar radiation reaching the floor. He also investigated water flow and temperature control strategies when the system is subjected to various solar loads using a simple steady-state calculation. However, there was no quantitative evaluation of the magnitude of the solar impact. Causone [11] briefly proposed a fictitious heat transfer coefficient to represent the improvement of heat transfer due to solar radiation without much discussion about this new parameter. De Carli [12] acknowledged the significance of solar radiation in the design process and evaluated different solar radiation modeling approaches for simulation of floor cooling system performance. Overall, there is no comprehensive investigation using dynamic simulation tools on the magnitude of solar impacts under various design/control conditions, let alone the assessment of implications for sizing of radiant and its associated air systems.

The purposes of this paper include: 1) provide a critical review of current radiant surface cooling capacity estimation approaches with an understanding of the fundamental heat transfer at the radiant surface; 2) study the magnitude of the influence of solar load on floor cooling capacity under different design scenarios using full parametric simulations, and this information can provide sizing suggestions on radiant cooled floor systems and their associated air systems when direct solar is present.

## 2. Heat Transfer at the Radiant Surface

The critical issue for understanding radiant cooling systems' behavior is the heat transfer balance at the cooling surface, as shown in Fig 1. The heat balance on the the inside face can be written as follows:

$$q_{conv}'' + q_{lw\_surf}'' + q_{lw\_int}'' + q_{sw\_sol}'' + q_{sw\_int}'' + q_{cond}'' = 0 \quad (1)$$

where,  $q_{conv}''$  = convective heat flux to zone air;  $q_{sw\_sol}''$  = transmitted solar radiation flux absorbed at surface;  $q_{sw\_int}''$  = net shortwave radiation flux to surface from lights;  $q_{lw\_surf}''$  = net longwave radiation flux to surface;  $q_{lw\_int}''$  = longwave radiant exchange flux from internal sources;  $q_{cond}''$  = conduction flux through the cooling surface.

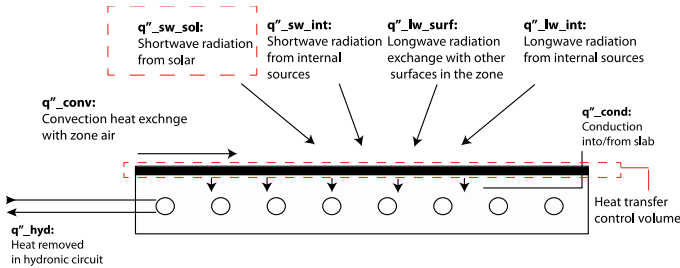


Fig 1: Heat transfer balance at the radiant surface and hydronic loop

The amount of heat removed by the activated cooling surface (cooling capacity) is a combination of convection and radiation, and can be theoretically calculated by (2),

$$q_t'' = -q_{cond}'' = q_{conv}'' + q_{lw\_surf}'' + q_{lw\_int}'' + q_{sw\_sol}'' + q_{sw\_int}'' \quad (2)$$

However, a review of radiant system design standards, in the next section, shows that shortwave/longwave internal load and solar load that directly hit the radiant cooling surfaces and removed by the surface are not considered or considered only partially in calculation and lab measurement of radiant cooling surface capacity. This observation applies not only to radiant floor cooling systems, but actually to all radiant cooling systems.

## 3. Review of Current Cooling Capacity Estimation Methods

To estimate the cooling capacity, there are generally two calculation approaches recommended in the standards: 1) heat exchange is calculated separately for convection and radiation, as is the case in Chapter 6 of *ASHRAE Handbook, HVAC Systems and Equipment* [13]; 2) a combined

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heat transfer coefficient is estimated to calculate a total heat exchange value, as is the case in ISO 11855:2012 [14]. Usually scientists are interested in the first approach, while designers prefer a combined heat transfer coefficient [15]. In this section, a review of current cooling capacity calculation methods is conducted. Different algorithms documented in the literature to calculate convection and radiation heat transfer are compared to the EnergyPlus algorithm to justify the use of this tool for quantitatively studying the phenomenon.

### Convective Heat Transfer

The surface convective heat transfer can be written as:

$$q_{conv}'' = h_c (T_a - T_s) \quad (3)$$

Where,  $h_c$  is the convective heat transfer coefficient,  $W/m^2K$ ,  $T_a$  is the zone air temperature,  $^{\circ}C$ , and  $T_s$  is the radiant surface temperature,  $^{\circ}C$ . Usually for radiant cooling systems, natural convection is assumed. Algorithms for the calculation of the convective heat transfer coefficient of cooled floor/heated ceiling are given in the literature [6, 16-18]. In this simulation study, the algorithm developed by Walton [18] is adopted in EnergyPlus. Numerical comparison of the EnergyPlus algorithm with other algorithms was conducted and confirmed the accuracy of the tool used for this study.

### Radiation Heat Transfer

In the ASHRAE Handbook, *HVAC Systems and Equipment*, the radiation heat flux for surface heating and cooling systems is approximately [13]

$$q_{lw\_surf}'' = 5 \times 10^{-8} [(T_s + 273.15)^4 - (AUST + 273.15)^4] \quad (4)$$

Where,  $AUST$  is area-weighted temperature of all indoor surfaces of walls, ceiling, floor, window, doors, etc. (excluding active cooling surfaces),  $^{\circ}C$ . However, a linear radiant heat transfer coefficient can be defined to express the radiant heat exchange between a specific surface and all the other surfaces in the room.

$$q_{lw\_surf}'' = h_{rad} (T_s - T_{ref}) \quad (5)$$

Where,  $h_{rad}$  is a linear radiant heat transfer coefficient, and it can be considered constant and  $5.5 W/m^2k$  is recommended [6, 13].  $T_{ref}$  is a reference temperature that is not yet clearly defined, and it can be  $AUST$  or  $T_{opt}$  = the operative temperature at a reference point in the room,  $^{\circ}C$ .

Both (4) and (5) are used only for longwave radiation heat transfer between the radiant cooling surface and its enclosure surfaces. However, in

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EnergyPlus, a comprehensive surface heat transfer balance is conducted in the simulation and all types of radiation are considered as long as they are simulated [19].

### Total Heat Transfer

To size HVAC systems, and especially radiant systems, a combined coefficient is convenient. The key concept to determine the cooling capacity in ISO-11855:2012 is to “establish a basic characteristic curve for cooling and a basic characteristic curve for heating, for each type of surface, independent of the type of embedded system.” This means that a constant total heat transfer coefficient, depending on system type (floor/wall/ceiling and heating/cooling), is used to calculate the surface heat flux.

$$q_{t,flr}'' = h_{t,flr}(T_s - T_{ref}) \quad (6)$$

where,  $h_{t,flr}$  is the combined convection and radiation heat transfer coefficient, and its values are reported in Table 1. Again, only convection and longwave radiation between surfaces are included in the total heat transfer calculation, and solar/lighting/equipment radiation are not reflected.

Table 1. Summary of floor cooling total heat transfer coefficient

$h_{t,flr}$	$T_{ref}$ : reference temperature	Source
7	operative temperature	ISO 11855 (2012)
7.5	operative temperature	Olesen (2000)

## 4. Impact of solar heat gain

Even though the internal radiative heat gain is also not properly considered in the cooling capacity calculation, this simulation study focused only on the impact of solar. A single zone model was developed for this study primarily based on ASHRAE Standard 140 [20]. System and design parameters for the radiant system were adopted from RADTEST [21]. A full matrix of simulation runs was conducted to study the magnitude of the impact and investigate key parameters using cooling capacities estimated by both the ASHRAE and ISO standard methods as baselines. The parameters and their variations investigated include: shortwave absorptivity of floor surface material (0.4/0.6/0.8), shading options (Interior blinds/Exterior shading/No shading), window-to-wall ratio (40/55/70), radiant system type (ESCS/TABS), zone orientation (east/west/south) and building aspect ratio (1.3/2). The interior blinds were controlled to be active when the incident solar on window is higher than 50 W/m<sup>2</sup>. The total number of simulation runs was 323.

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EnergyPlus v7.2 was used for the study because it performs a fundamental heat balance on all surfaces in the space, can capture both longwave and shortwave radiation heat transfer and has been extensively validated [22]. Detailed solar simulation algorithm employed in EnergyPlus can be found in its Engineering Reference, and basically a “ray tracing” method is used to track the paths of the beam and diffuse solar coming from the fenestration systems.

The test case model is a rectangular single zone with no interior partitions. For the cases with aspect ratio at 1.3, the model dimension is 8 m wide  $\times$  6 m long  $\times$  2.7 m high, and for the aspect ratio 2, the width increased to 12 m. The base building is of heavy weight construction. The construction is based on case 900 (heavyweight) [20], except that the floor construction has been modified so that water tubes can be embedded in the concrete layer when radiant floor systems are simulated. There is one window with an overall U-value of 2.721 W/m<sup>2</sup>K and SHGC of 0.788 and the total area of the window varies for each window to wall ratio. The TMY3 Denver weather data was used. No internal load or infiltration was modelled. Two types of radiant systems were modelled: the hydronic embedded surface cooling systems (ESCS) and the thermally activated building systems (TABS) [14].

## 5. Results and Discussion

A total of 323 runs were conducted to study the impacts of solar heat gain on radiant floor cooling capacity for the 99.6% cooling design day.

### Design Day Heat Flux

Simulation results confirmed that radiation is the dominant heat transfer mechanism, and is the main interest to this study, so we concentrated our analysis on radiation heat transfer rate. Figure 2 is a plot of the 24-hour radiation heat flux at the floor surface, including the total radiation and its breakdown into longwave and shortwave radiation. For each hour, a box-plot displays the range of floor surface heat flux for the 323 runs. The maximum peak heat flux is around 50 W/m<sup>2</sup>, smaller compared to the number (80-100 W/m<sup>2</sup>) reported in the literature that only occurs at extreme operation conditions. Those conditions did not happen in the simulation runs in this study. Because no internal load has been simulated, shortwave radiation consists of pure solar load, and the longwave radiation includes envelope load and part of the solar load that has been absorbed by building mass and reemitted toward the radiant floors. As discussed before, the current standard methods have taken into account surface longwave radiation. From now on

we will focus on radiation heat flux during the period from 8am to 5pm when the shortwave radiation is present.

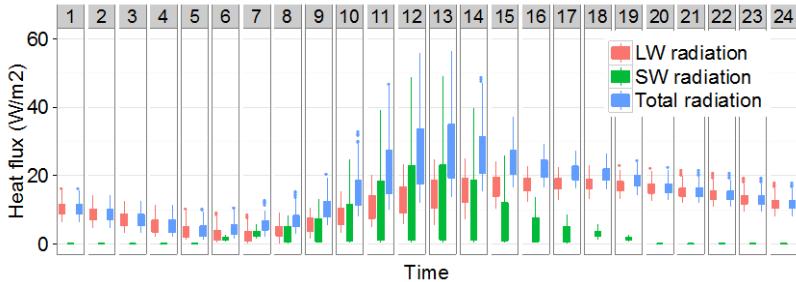


Figure 2: Cooling design day floor radiation heat flux breakdown for the 323 simulation runs

### Radiation Heat Flux

Table 2 lists the parameters studied in this section. Radiation cooling capacity ratios are defined for a direct comparison of EnergyPlus simulated radiation heat flux and the values calculated using ISO and ASHRAE methods.

Table 2. Parameters analyzed

	Compared to ISO	Compared to ASHRAE
Radiation cooling capacity ratio (RCCR)	$RCCR_{ISO} = \frac{\dot{q}_{rad,EPPlus}}{q_{rad,ISO}}$ $\dot{q}_{rad,ISO} = 5.5 \times (T_s - T_{opt})$	$RCCR_{ASHRAE} = \frac{\dot{q}_{rad,EPPlus}}{q_{rad,ASHRAE}}$ $\dot{q}_{rad,ASHRAE} = \text{Eq. (4)}$
Longwave radiation cooling capacity ratio (LW RCCR)	$LW\_RCCR_{ISO} = \frac{\dot{q}_{rad,lw,EPPlus}}{q_{rad,ISO}}$	$LW\_RCCR_{ASHRAE} = \frac{\dot{q}_{rad,lw,EPPlus}}{q_{rad,ASHRAE}}$



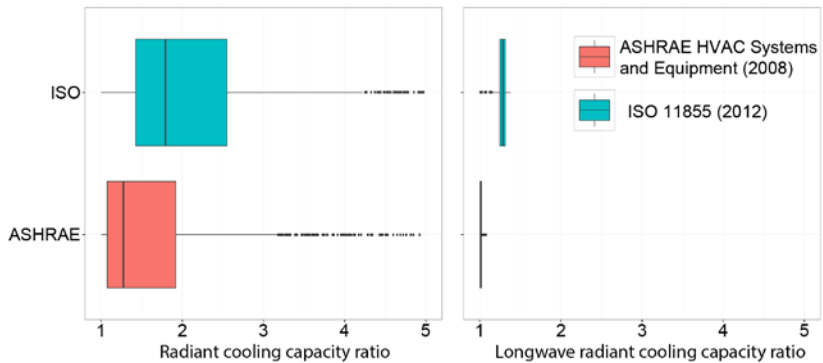


Fig 3: Comparison of radiation heat flux at radiant surface between Energyplus and ISO/ASHRAE method using box-plot of the 323 simulation runs

The hypothesis is that with the presence of solar heat gain, the actual cooling capacity of a radiant floor cooling system is higher than the values estimated using either ISO or ASHRAE methods. The enhancement is caused purely by shortwave radiation heat transfer at the cooling surface for the simulated cases and this is demonstrated in Fig 3. The plot on the left shows the range of total radiation cooling capacity ratio (RCCR) using boxplot. If the ratio is higher than 1, that means the simulated total radiation heat flux is higher than calculated values. The right plot shows longwave radiation cooling capacity ratio (LW\_RCCR), defined as the ratio of simulated longwave radiation heat flux at the cooling surface to the radiation calculated in ISO and ASHRAE. The scale of x-axis is adjusted to achieve better resolution for the interquartile range. The box plot shows that LW\_RCCRs are very close to 1. This result demonstrates that the cooling capacity calculated using the standard methods is almost the same as that simulated for longwave radiation alone; therefore the increase of cooling capacity in EnergyPlus can be attributed to shortwave radiation. Fig 3 demonstrates that the median of the simulated cooling capacity is 1.7 times higher than the ISO 11855 method and the interquartile range (IQR) is from 1.2 to 2.7, and when compared to ASHRAE, the simulated cooling capacity is at median 1.3 times higher and the IQR of  $RCCR_{ASHRAE}$  is 1.1 to 2.1. Cooling capacity estimated using ASHRAE method coincides better with the results from EnergyPlus.

### Sensitivity Study of Percentage Enhancement

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A sensitivity study was conducted to investigate the impact of key parameters on the magnitude of the enhanced cooling capacity. Among the parameters investigated (shortwave absorptivity of floor surface material, shading options, window-to-wall ratio, radiant system type, orientation, and building aspect ratio), only results for shading options and shortwave absorptivity of floor surface material are reported because radiant cooling capacity ratio is most sensitive to these two parameters.

The radiant cooling capacity ratio is very sensitive to shading options as can be seen from Fig 4. With interior blind design option, there is little enhancement on cooling capacity, while for the cases without any shading the enhancement is largest, with the median of the  $RCCR_{ISO}$  at 2.9 and  $RCCR_{ASHRAE}$  at 2.2. This is because interior blinds absorb incoming solar and re-emit the heat to the space in the form of longwave radiation, which is well taken into account using the ASHRAE and ISO standard methods. Buildings without shading systems admit a large amount of solar heat gain, and therefore have the greatest enhancement. When exterior shading systems are installed so that direct solar is blocked, the median of  $RCCR_{ISO}$  is 2.0 and  $RCCR_{ASHRAE}$  is 1.6. The enhanced cooling capacity is caused by diffuse solar (also shortwave radiation) that hits the floor surface. The radiant cooling capacity ratio is also slightly sensitive to shortwave absorptivity of floor surface material. Shortwave absorptivity of common floor materials can be found in the handbooks [23]. Solar radiation is full spectral light, but it is treated as shortwave. Building interior materials can have relatively small shortwave absorptivity (for example, light colored plaster has shortwave absorptivity of 0.3 to 0.5). And in these cases, a significant portion of incident solar is reflected back to the space or the outdoor environment instead of being absorbed directly by the cooled floor.

Even though the actual cooling capacity of a radiant floor is higher than the standard recommended values when it is illuminated by either direct or diffuse solar, in general, a successful radiant system design will minimize the amount of solar admitted to the building. However, for those cases such as atria, airports, and perimeter areas when solar radiation is desirable or inevitable, the impact of solar should be properly considered to achieve optimal sizing of radiant floor cooling systems and their associated air systems.

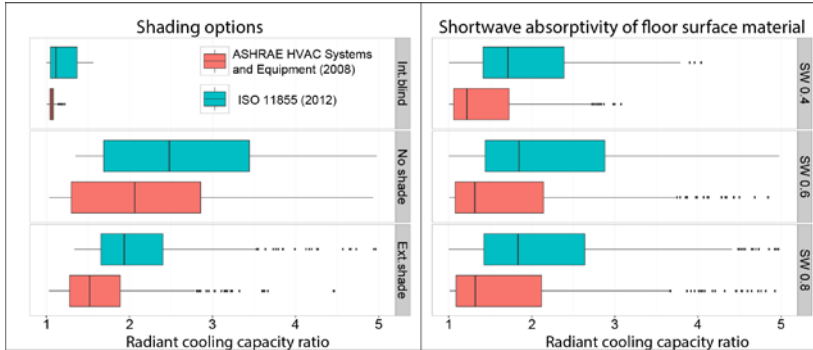


Fig 4: Sensitivity study of various design parameters using box-plots of radiant cooling capacity ratios for all simulated cases

## 6. Conclusions

Radiant floor cooling systems are increasingly being used in transition spaces with large glazed surfaces, such as atria, airports, and perimeter areas. A literature review and preliminary simulations indicate that the radiant floor cooling performance depends very much on the solar radiation that enters a room. Detailed heat transfer analysis conducted between the space and the radiant cooling surface reveals that the existing radiant cooling capacity estimation methods are insufficient when the system is exposed to solar radiation because only convective heat transfer and heat from standard temperature heat sources (longwave radiation), not lighting or solar, are considered in the calculation and lab measurement.

A full parametric simulation study was conducted to study the impact of incident solar radiation on radiant cooling capacity. The simulation results for a total of 323 runs showed that instantaneous radiant cooling capacity is at median 1.7 times higher than the values calculated with ISO 11855 method and the interquartile range (IQR) is from 1.2 to 2.7. Compared to ASHRAE, the simulated cooling capacity is at median 1.3 times higher and the IQR of  $RCCR_{ASHRAE}$  is 1.1 to 2.1. The difference is caused by absorption of shortwave radiation.

Among the parameters investigated, radiant cooling capacity ratio (RCCR) is most sensitive to shading options and shortwave absorptivity of floor surface material. When interior blinds are installed to block solar gain, the RCCR is close to 1, and when exterior shading (overhang) is installed, the median of the  $RCCR_{ISO}$  is 2.0 and  $RCCR_{ASHRAE}$  is 1.6 due to diffuse

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solar. When there is no shading system, the median RCCR is 2.9 times ISO standard values and 2.2 times ASHRAE values.

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