Cooling Load of Radiant Systems

Subjects: Engineering, Civil

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The cooling load of systems refers to the heat removed from a room to the outside environment and adjacent rooms, which is based on some parameters such as zone climate data, location, usage, and so on. The cooling capacity of a radiant system represents the amount of cooling required at a specific moment to keep a stable room temperature. It is a basic parameter of radiant systems and an important reference for system design and operation. In addition, The changes of surface heat transfer coefficient also cause changes of cooling load and cooling capacity of the radiant system. Based on above background, current situation of researchers' studies on the cooling load is summarized, cooling capacity and surface heat transfer coefficient of radiant systems.

radiant cooling systems | cooling load | cooling capacity | heat transfer coefficient | building thermal performance

1. Introduction

Cooling load calculation and cooling capacity determination of systems are key steps in sizing radiant systems. When radiant cooling/heating systems stay in a steady state, the cooling load is equal to the cooling capacity. In addition, for a room with an air conditioning system, cooling surfaces alter the heat transfer process in a room, thereby affecting the cooling capacity and the cooling load of the radiant system.

An auxiliary air conditioning system is usually applied for ventilation requirements; these air conditioning systems are also responsible for latent loads [1][2]. Heat gain contains a latent part and a sensible part, and the sensible heat gain can be formed through convection and radiation. The transient cooling load is the cooling rate provided by air conditioning equipment to keep the room temperature steady. Thermal properties of the envelope and types of heat gains determine the relation between heat gain and cooling load, and the cooling load is equal to or lower than the heat gain. In a room with a traditional air conditioning system, latent and convective heat gain can be directly transformed into the transient cooling load, while radiant parts (such as transient solar heat and lighting radiant heat) cannot be immediately turned into the transient cooling load. Moreover, radiant heat is absorbed and conserved by surfaces and then discharged into the air by convection to form a cooling load of air conditioning when the surface temperature rises and is higher than the adjacent air temperature [3]. It is worth noting that in a room with a radiant system, an active surface can directly absorb a part of radiant heat gain through radiation. This could reduce the effect of thermal storage of the envelope on radiant heat gain and strengthen transient space heat exchange. Instantaneous heat exchange on cooling surfaces is not necessarily equal to the heat removed by internal water loops due to structural thermal inertia. The cooling load of a combined system (radiant cooling system + auxiliary air conditioning system) is the sum of heat exchanges in two different terminal circulating water systems, and the value is not necessarily equal to the amount of heat exchange in space.

2. Cooling Load of Radiant Systems

Cooling load calculation is an important step for system sizing and equipment selection. Hu and Niu [4] reviewed the applications of radiant heating/cooling systems in China and emphasized that cooling load calculation is the most urgent problem that needs to be solved during the design and application of radiant systems. The current theory and methods for cooling load calculation are primarily based on traditional convective air conditioning systems, which remove heat from rooms through convective heat transfer. However, these methods do not apply to radiant systems, which primarily remove heat through both radiation and convection [5].

Currently, there are several methods for calculating the cooling load of a radiant heating/cooling system, such as the Total Equivalent Temperature Difference Method [6], the radiant time series method [7], and the heat balance method [8]. Mao et al.[9] compared five methods: the Total Equivalent Temperature Difference/Time Averaging (TETD/TA) method, the transfer function method (TFM), the Cooling Load Temperature Difference/Solar Cooling Load/Cooling Load Factor (CLTD/SCL/CLF) method, the heat balance method (HBM), and the radiant time series method (RTSM)) recommended by the ASHRAE handbook for computing cooling load. They concluded that heat balance method gives more accurate results than other methods.

Niu et al.[10] used software called ACCURACY to calculate the cooling load of a radiant slab system and discovered that the direct cooling rate provided by this system increased the peak cooling load. Using the thermal balance method, Ning et al.[11] created a model of cooling load for a radiant ceiling coupled with a fresh air system. Compared to an all-air system, they found that the radiant ceiling system coupled with a fresh air system was able to remove more heat gain when the indoor air temperature was the same, and the peak load of the combined system increased by 16%.

To quantify the thermal transfer of radiant ceiling systems, Ning and Chen [7] introduced the concepts of radiant time series (RTS) and convective time series (CTS) factors and modified them based on the linear superposition principle. They proposed radiation and convection time series methods to calculate the cooling load. However, this method does not apply to systems with embedded pipes. Considering this limitation, Ning et al. [12] proposed another revised radiant time series method (RTSM) for calculating the cooling load. The results demonstrated that this method achieved higher accuracy compared to the traditional heat balance method.

Feng et al.[13] utilized Energy-Plus, an energy simulation software, to investigate the discrepancies of radiant systems and all-air systems in peak cooling load and 24 h cooling energy. The study revealed that the total energy of the modeled radiant cooling system was 2.7–6.5% higher, with a corresponding increase in peak cooling load ranging from 10–40%. Furthermore, Feng et al. [14]observed that the peak load of a modeled radiant system was 7–35% higher when solar heat gain was not taken into consideration. The finding showed that surfaces of radiant systems could reduce the effect of thermal inertia on radiant heat gain; compared to Response Factor Methods, the heat balance method is more precise in calculating dynamic cooling load [3].

Woolley et al. [15] conducted a comparative experiment to investigate the differences in cooling load between radiant cooling systems and all-air systems while maintaining parallel room temperature (operative temperature). The findings revealed that compared with the all-air system, radiant systems are more effective in removing heat. Additionally, the gap in peak cooling load between the two systems becomes deeper as the radiant heat gain in a room increases [16]. In another study, Hu et al. [17] examined the influence of building thermal mass on the cooling loads of radiant systems in different cities. The findings demonstrated that the peak cooling load and accumulative load of a radiant cooling system coupled with a fresh air system were 9% to 11% and 3% to 4% higher, respectively, compared to an all-air system.

3. Cooling Capacity of Radiant Systems

Radiant system cooling capacity refers to the capacity determined during the system design phase. Generally, the cooling capacity of a metal cooling ceiling can achieve a cooling capacity of up to 100 W/m^2, whereas the cooling capacity of a cooling floor only reaches 40 W/m^2. Olesen [18] concluded that the cooling capacity of a radiant floor system typically ranges from 35 W/m^2 to 50 W/m^2. When direct solar radiation falls on the floor, the cooling capacity increases dramatically, ranging from 100 W/m^2 to 150 W/m^2.

Zhang et al. [19] increased the cooling capacity by 19% by installing inclined aluminum sheets in a metal cooling ceiling system. Jeong and Mumma [20]concluded that the overall cooling capacity of a radiant ceiling system increased by 5% to 35% under mixed convection conditions. And they created an innovative simplified method to assess the cooling capacity of metal ceiling panels. This validated analytical model was then utilized to evaluate the cooling efficiency for various designs [21]. Additionally, Jeong and Mumma [22] presented a more advanced model to compute the cooling capacity of metal ceiling panels under both natural and mixed convection conditions. When computing the cooling capacity of radiant systems, Andrés-Chicote et al. [23] highlighted the importance of considering both radiation and convection separately, rather than relying solely on the operative temperature. Furthermore, Tian er al. [24] analyzed the properties of a radiant ceiling system without mechanical ventilation by conducting experiments in an office subjected to various conditions. They developed a thermal transfer model and found that the internal surface temperature and surrounding wind speed significantly influence the cooling performance, with wind speed accounting for approximately 75% of the impact. Some researchers have established formulas to compute the cooling capacity of systems, but the variables involved are different.

4. Surface Heat Transfer Coefficient

The surface heat transfer coefficient is a crucial parameter utilized in cooling/heating load calculation and radiant system design. It is vital in characterizing the thermal behavior of radiant systems [25]. The radiant heat transfer coefficient of an active surface refers to the radiant heat transfer between a cooling surface and other surfaces in the room. The factors affecting this coefficient are heat flux density, reference temperature, view factor, and so on. The average unheated surface temperature (AUST), which is an average temperature weighted by surface area, is used as the reference temperature for calculating the radiant heat transfer coefficient.

Moreover, the convective heat transfer coefficient signifies the heat exchange between a particular surface and the air in a room. It primarily relies on air velocity and air temperature. The air temperature is used as reference temperature for calculating the convective heat transfer coefficient.

The total heat transfer coefficient represents a combined radiation and convection phenomenon. It is not the sum of the radiant and convective heat transfer coefficients since convection and radiation are different physical phenomena and their reference temperatures used in calculations are different. Currently, a reference temperature for calculating this coefficient has not been definitively determined. However, the operative temperature serves as the most appropriate and widely accepted reference temperature [26].

The total transfer coefficient serves as a significant parameter that quantifies both radiant and convective phenomena simultaneously. Presently, some standards and guidelines adopt this comprehensive heat transfer coefficient as a reference for selecting radiant systems. However, due to variations in reference temperatures and heat flow calculations across different research studies, the surface heat transfer coefficient does not accurately reveal the heat exchange process between active surfaces and their surrounding atmosphere. Typically, the operative temperature is used as the reference temperature to calculate the total heat transfer coefficient. This value is obtained by referencing the Newton cooling formula, while the surface heat flow is measured directly. In terms of calculating the radiant heat transfer coefficient for active surfaces, the reference temperatures usually involve the mean radiant temperature. This temperature represents the average temperature of non-active surfaces, weighted by their respective areas. The radiant heat flux density can be determined using the Stefan–Boltzmann law. The convective heat transfer coefficient of active surfaces can be calculated based on the air temperature in the zone and can be calculated using various methods such as those employed by Khalifa [27][28] and Awbi and Hatton [29][30]. The convective heat flow of surfaces is obtained by subtracting the radiative heat flux from the total heat flow.

Koca et al. [31] investigated radiant cooling walls in residential buildings by experimental study and advised that the total and radiant transfer coefficients of active surfaces should be 7.83 W/m^2·K and 5.14 W/m^2·K, respectively. Cholewa et al. [32] considered that the height and position of the reference temperature should be involved when computing surface heat transfer coefficients in the future. Mustakallio et al.[33]contrasted the effects of internal heat sources and heated surfaces on the heat transfer coefficient and concluded that the ratio of radiant and convective heat transfer from heat sources significantly impacts the cooling capacity of systems. Karadag [34] observed the influences of different room dimensions and heat conditions on the heat transfer coefficient and proposed an equation of the total heat transfer coefficient that includes surface emissivity. Additionally, Karadag [35] also studied the relationship between the convective and radiant heat transfer coefficients of cooling ceilings for different room sizes and temperatures. Zhang et al. [36]examined the changes in indoor parameters during the start-up process of ceiling radiant cooling panels in experiments. The results demonstrated that the surface temperature rapidly decreased when the active surface was activated, while the temperature of other inner surfaces and the indoor air maintained the same trend. The proportion of heat radiation in the total heat transfer of the ceiling decreases with the stability of the indoor thermal environment. Hu et al. [37] surveyed actual systems and discovered that the total heat exchange increased by 48% when the radiant cooling ratio changed from 60% to 74%. This indicates that surface heat transfer coefficients also vary with changes in the radiant cooling ratio.

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