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A review of methods for calculating radiant air conditioning cooling load

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Abstract
In recent years, radiant air conditioning system has been developed and applied more rapidly because of its remarkable energy-saving effect, high thermal comfort and space-saving advantages. However, the calculation of cold load has always been the biggest constraint on the further promotion and application of radiant air conditioning system, and in recent years, the cold load calculation method of radiant air conditioning system has received extensive attention from researchers and developed rapidly. At present, the cold load calculation method of radiant air-conditioning system is mainly divided into three categories: heat balance method; the simplified calculation method of heat balance method represented by radiation time series method; and the correction coefficient method based on the air system load. This paper will summarize and present the calculation theory and current research status of these three types of methods.
Keywords: *Radiant air conditioning, load theory, heat balance method, radiant time series method, correction factor method, problems and challenges*

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I. 1.INTRODUCTION

In recent years, the radiant air conditioning system because of its unique advantages has been more rapid in development and application. Its advantages are mainly manifested in three aspects: first, radiant air conditioning system is often used with independent fresh air, out of the need to avoid condensation at the end of the radiation and energy saving, the refrigerant temperature at the end of the radiation is relatively high, and at the same time, the ability of the radiation end of the elimination of the indoor load is better, so compared to the existing commonly used form of HVAC system can save 50% of the energy consumption [1, 2];Secondly, studies have shown that radiant air-conditioning systems provide better thermal comfort than conventional air-conditioning systems due to the reduction of cold air movement in the room and the corresponding reduction of thermal comfort problems caused by ventilation [3-5]; thirdly, since the radiant end eliminates most of the room load, the size of the air ducts and some duct accessories used to deliver the eliminated room loads or fresh air to the room can be reduced, thus saving the building space, as compared to the conventional air-conditioning systems [4]. The size of air ducts and some duct accessories can be reduced accordingly compared with conventional air conditioning systems, thus saving building space and initial investment costs [6]. Its energy-saving effect is remarkable, high thermal comfort, saving building space and other advantages, well catered for the dual-carbon policy, people for indoor thermal comfort requirements with the improvement of quality of life and other policy background or social needs, it can be judged that the wide application of radiant air conditioning system is very likely to be the future of the form of HVAC system development of an important trend.

However, there is a key problem in the current application of radiant air conditioning, which is the lack of practical radiant air conditioning cooling load calculation methods [7, 8], while the current standards and guidelines lack practical cooling load calculation methods for radiant systems.The ASHRAE-2016 manual [9], the ISO 18566-2017 standard [10], the ISO 11855-2016 standard [11] and the Chinese standard JGJ 142-2012 [12] all use traditional cold load calculation methods to design and size radiant systems. Feng et al. investigated the design methods of radiant system through a survey study of experienced designers. They found that most of the radiant systems were designed and sized using traditional cooling load calculation methods for air systems [13]. The traditional cooling load calculation method applicable to air systems is based on the fact that all the heat gain in the room is removed by convection form, which differs from the principle of actual radiant air conditioning that removes the heat gain in the room through the combination of radiant and convective heat transfer. Li and Lu established an ideal cooling load calculation model for radiant systems. The results showed that the cooling load of the radiant system was higher than that of the air system at the same indoor air temperature [14].Feng et al. compared the cooling loads between radiant and air systems using EnergyPlus simulations and experimental results. Their results showed that the cooling load of the radiant system was higher than that of the air system. They also suggested the use of different methods of defining and calculating cooling load in the design of radiant systems [15, 16]. It can be seen that the traditional cooling load calculation methods applicable to air system is not practically applicable to radiant air conditioning systems. If the traditional cold load calculation method is applied to the design of radiant air conditioning, improper sizing of equipment selection during the design process, as well as indoor thermal comfort, system operating costs and energy consumption, and owner productivity may be affected [17]. Therefore it is essential to develop a practical cold load calculation method for radiant air conditioning.

After decades of development, scholars have studied and obtained many radiant airconditioning cold load calculation methods, which can be divided into three categories according to the principle of the method: The first category is the heat balance method, which is the method that most accurately reflects the real physical situation of heat gain and loss in a building, and therefore the industry agrees that the calculation results based on the heat balance method are true and accurate.The second category is the simplified calculation method based on heat balance, represented by the radiation time series method and the room transfer function method, which simplify the heat balance method according to the heat exchange mechanism of radiant airconditioning, of which the radiation time series method is widely studied.The third method is to establish a dynamic heat transfer model based on the principle of radiant airconditioning system or to calculate the cold load of many representative rooms through CFD, EnergyPlus and other software simulation methods, and to compare the cold loads of the air system under the same input conditions, to derive a range of correction coefficients based on the traditional cold load calculation method of the air system, and thus the calculation of the cold load of radiant airconditioning can be obtained by multiplying the calculation results of the traditional air system cold load method by a corresponding range of correction coefficient. For the convenience of the following description, the second type of method will be referred to as the simplified method based on heat balance, and the third type of method will be referred to as the correction coefficient method based on the air system load.

In the following three sections, the principles of the heat balance method, the principles of the radiative time series method in the second category of methods and the current state of research, and the current state of research in the third category of the correction coefficient method based on the air system load, respectively.In the last section, finally the problems with current radiant system cooling loads will also be presented

II. Heat Balance Method

The heat balance method approach is the ASHRAE RP-875 project research to introduce an applicable and complete cooling load calculation method [18], which is a method to solve the cooling load of a room by establishing the heat balance equations for each internal and external surface of the room, the thermal conductivity of the walls, and the heat balance equations on the air side, and ultimately iteratively solving for the cooling load of the room by associating all of the heat balance equations.As mentioned in the introduction, the heat balance method is a method that is not based on transformations and can be solved directly.

The heat balance approach to solving room loads is based on the following six assumptions [18]:

(1) The room air is adequately mixed;
(2) Uniform and consistent temperature on each surface;
(3) Long-wave and short-wave radiation emission ratios are the same;
(4) Surfaces are considered as grey bodies;
(5) Thermal conductivity is one-dimensional;
(6) The solar shortwave radiant heat entering the room is distributed according to the weight of the surface area inside the room

Calculation of hour-by-hour room cooling loads using heat balance requires the establishment of heat balance equations for the outer surface of the wall, the thermal conductivity of the wall, the inner surface of the wall, and the indoor air, the radiant surface for each hour, and the establishment of each of the five parts of the heat balance equations is described in the following section [19]:

2.1Heat balance on the outside surface of the wall

The heat balance equation for the outer surface of the wall is as follows:

$$q_{\alpha sol} + q_{LWR} + q_{conv} - q_{ko} = 0 \tag{1}$$

Where:

$q_{\alpha sol}$ Heat flow density of absorption of direct solar radiation and diffuse solar radiation at the surface of the facade, W/ ㎡;

q_{LWR} Density of long-wave radiant heat flow from surroundings and air, W/㎡;

q_{conv} Heat flow density of convective heat transfer between the outer surface of the wall and the outside air, W/㎡;

q_{ko} Density of thermally conductive heat flow through the façade into the wall, W/ ㎡.

2.2Heat balance of thermal conductivity of walls

In the heat conduction process of the wall, the surface temperature of the outer wall and the density of heat flow into the wall are the input parameters of the process, the surface temperature of the inner wall surface and the density of heat flow through the inner wall surface into the room are the output parameters of the heat conduction process of the wall, these four parameters are functions about time, is changing with time also changes. The conduction transfer function CTF is used in the calculation of heat transfer from the wall for the calculation, the following equation is the annotated heat gain equation for thermal conductivity obtained by heat conduction through the wall [20]:

$$q_e(\theta) = \sum_{6}^{k=0} b_k t_e(\theta - k) - \sum_{6}^{k=1} d_k q_k(\theta - k) - t_{rc} \sum_{6}^{k=0} b_k \tag{2}$$

Where:

t_e Combined outdoor temperature;℃

t_{rc} Indoor Air Setting Temperature;℃

b_k , d_k Coefficients of the conduction transfer function ,can be found by [20];

2.3Heat balance on the inside surface of the wall

The heat balance on the inner surface of a radiant airconditioning room consists of four parts: first, heat conduction through the walls;Second, convective heat transfer with the air; third, absorption or reflection of short-wave radiation and long-wave radiation, short-wave radiation mainly includes solar radiation into the room and hour by hour such as lighting and other heat sources of radiation, long-wave radiation is mainly from the human body, equipment, and other low-temperature heat sources; fourth, the internal surface of the wall and the inner surface of the radiant surface of radiation heat transfer.

The heat balance equation for the inner surface is as follows:

$$q_{lwx} + q_{sw} + q_{lws} + q_{ki} + q_{sol} + q_{conv} + q_{lw\_surf} = 0 \tag{3}$$

Where:

q_{lwx} Heat flow density of net longwave radiative heat transfer between wall surfaces in a room, W/㎡;

q_{sw} Heat flow density of short-wave radiative heat transfer between the light and the surface, W/ ㎡;

q_{lws} Heat flow density of long-wave radiation heat transfer between equipment and surface, W/ ㎡;

q_{ki} Heat flow density of thermal conductivity through the envelope, W/ ㎡;

q_{sol} Heat flow density of solar radiation absorbed by the surface into the room, W/ ㎡;

q_{conv} Heat flow density of convective heat transfer with area air, W/ ㎡;

q_{lw_surf} Heat flow density of radiant heat transfer between the surface and the surface of the radiant surface, W/㎡.

2.4 Heat balance of air

In a conventional convective air conditioning system, the heat balance equation of the air determines the cooling load of the room, but in a radiant air conditioning system convective heat transfer is only one of the ways of removing heat from the room, and the heat in the air is removed by both convection and radiation.
The air heat balance equation for a radiant-conditioned room is as follows:

$$q_{conv} + q_{CE} + q_{IV} + q_{sys} = 0 \tag{4}$$

Where:

q_{conv} Convective heat transfer between the air and the internal surface of the wall, W/ ㎡;

q_{CE} Convective heat transfer with internal heat source, W/ ㎡;

q_{IV} Significant heat load due to infiltration air, W/ ㎡;

q_{sys} Convective heat transfer between air and radiant surfaces, W/ ㎡.

2.5 Heat balance on radiant surface

The heat balance equation for the surface of the radiant plate is as follows:

$$q_{conv} + q_{lw\_surf} + q_{lw\_\text{int}} + q_{sw\_sol} + q_{\text{sw\_int}} + q_{\text{cond}} = 0 \tag{5}$$

Where:

q_{conv} Convective heat transfer between the surface of the radiant panel and the air, W/ ㎡;

q_{lw_surf} Net longwave radiation received by the surface of the radiant plate from other surfaces in the room, W/ ㎡;

q_{lw_int} Heat exchange of long-wave radiation from the internal heat source, W/ ㎡;

q_{sw_sol} Solar radiation absorbed by the surface of the radiant plate, W/ ㎡;

$q_{\text{sw\_int}}$ Short-wave radiation absorbed by the surface of the radiant plate from the internal heat source, W/ ㎡;

q_{cond} Short-wave radiation absorbed by the surface of the radiant plate from the internal heat source, W/ ㎡;

The heat balance method is an iterative calculation that combines all the heat balance equations for the indoor and outdoor areas to solve the hourly cooling load. The advantage of the heat balance method is that the results are more accurate than those of the simplified calculation methods; secondly, the method not only calculates the cold load but also calculates some additional parameters, such as the surface temperature of the enclosure that varies over a 24-hour period; and thirdly, the heat balance method calculates the cold load of a room where the indoor temperature is constant as well as the hour-by-hour cold load of a room where the indoor temperature varies over a period of time. The disadvantages of the heat balance method are also quite obvious, that is, there are a lot of parameter inputs and all the heat balance equations of indoor and outdoor need to be linked together and then solved, so that it is necessary to carry out repeated iterative calculations, and the whole process of calculation will be more complicated.

III. The simplified method based on heat balance

There are many simplification methods based on heat balance, such as the radiation time series method, the room response coefficient method, and the room transfer function method. Among them, the study of the radiation time series method is considered to be the best choice to replace the heat balance method, and in recent years there have been more studies on the radiation time series method for radiant air conditioners. In this section we focus on the calculation principle and research status of the radiation time series method.

The calculation process of the radiant time method is shown in Fig. 1, where the first step is to calculate the heat gain of each item. In this case, the wall thermal conductivity heat gain needs to be calculated by a 24-term period response factor (PRF), which can be obtained by equation6, which relates the heat gain at the current moment to the wall heat gain in the previous 23 hours. There are two main methods for the calculation of the 24 PRF: the first method is obtained through the PRF RTF generator software calculation, which only requires the input of the building thermal parameters to be calculated; the second is obtained through the conduction transfer function matrix transformation, which will not be described in detail here. The other heat gain terms are calculated in a similar way to the general method. The second part is to separate the heat gains into convective and radiative heat gains, and specific allocation ratios are given in the ASHRAE Handbook. The third part is the calculation of the hour-by-hour radiative cooling load, which in this method is related to the cooling load at the current moment to the radiation heat gain at the current moment as well as in the previous 23 hours using a 24-item radiative time-series (RTS) as shown in equation 7. The 24 RTS can be calculated using the PRF RTF generator software or the transfer function coefficients.

$$q_\theta = \sum_{23}^{j=0} Y_{Pj} T_{e,\theta-j\delta} - T_{rc} \sum_{23}^{j=0} Y_{Pj} \tag{6}$$

Where:

q_θ Thermal conductivity of the wall at the current moment, W/㎡;

Y_{Pj} PRF for the first j time steps;

$T_{e,\theta-j\delta}$ Combined outdoor temperature at the first j time steps,℃.

$$q_{r,\theta} = r_0 Q_{r,\theta+} r_1 Q_{r,\theta-1} + r_2 Q_{r,\theta-2} + \ldots + r_{23} Q_{r,\theta-23} \tag{7}$$

Where:

$q_{r,\theta}$ Cooling load converted from radiation heat gain at the current moment at the current moment, W/㎡;

r_i RTS for the first i time steps;

$Q_{r,\theta-i}$ Cooling load formed by radiation heat gain at the first i time steps, W/ ㎡.

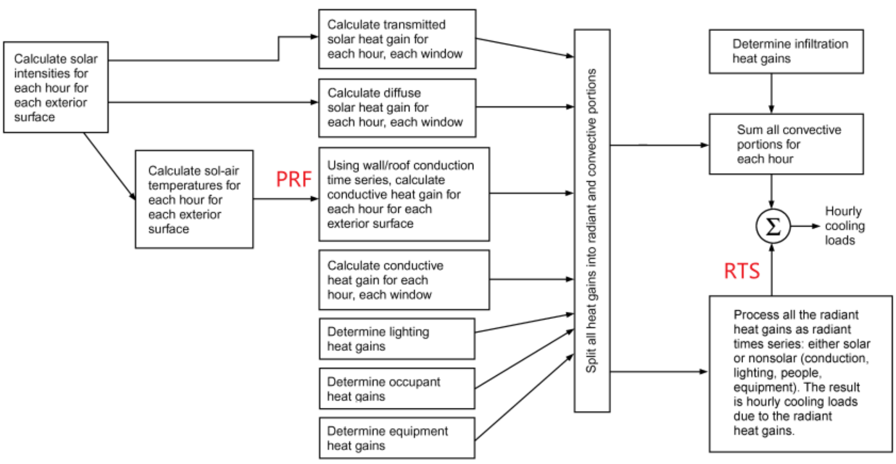

Fig. 1Overview of Radiant Time Series Method

Finally, the cooling load formed by convection plus the radiation cooling load is the current total cooling load, as shown in equation 8. Where it is considered that convective heat gain is immediately converted into convective cold load without decay and delay.

$$q_\theta = q_{c,\theta} + q_{r,\theta} = q_{c,\theta} + r_0 Q_{r,\theta +} r_1 Q_{r,\theta-1} + r_2 Q_{r,\theta-2} + \ldots + r_{23} Q_{r,\theta-23} \quad (8)$$

Where:

q_θ Total cooling load at the current moment, W/㎡;

$q_{c,\theta}$ Cooling load converted from convective heat gain at the current moment, W/㎡;

In previous studies, Bai [21] and some other scholars have suggested that convective heat gain is also converted to indoor cooling loads by radiation as in the case of radiative heat gain, and not only by convection. Similarly, radiative heat gain is also considered to be converted into radiation cooling load through convection.And the heat absorbed by the radiation surface also affects the calculations of the existing radiation time series method.

IV. The correction coefficient method based on the air system load

Among the existing studies, this correction factor method obtains the exact value of the acquired load in two main ways.

The first is to simulate the cooling load of radiant and conventional air systems under the same conditions through Energy Plus and compare them to obtain the correction factor.Feng [16] et al. compared the cooling loads of radiant and air systems using EnergyPlus simulation and experimental results. The results showed that the cooling load of the radiant system was higher than that of the allair system. However, there was no quantitative statistics on the difference in cooling loads between the two systems for different types of rooms under the same input conditions. They also suggested that different cold load definitions and calculation methods should be used in the design of radiant systems. Ni Peng [23] selected three representative rooms on the middle floor of an office building in Wuhan City as the object of study. Energy Plus software based on the heat balance method was used to establish the room model and the traditional air conditioning system model, and the results of the cold load calculation were compared and analyzed.

The second is to simulate the cooling loads of radiant and conventional air systems under the same conditions through CFD and compare them to obtain the correction factor.A lot of work has been done in this area by Gong et al. Their study of the air system load-based correction factor method is mainly applicable to air-carrying energy-radiating air-conditioning system [24] (ACERS), they firstly obtained the corresponding indoor and outdoor parameters through the experimental test, these indoor and outdoor parameters for the CFD simulation to provide the necessary boundary conditions, and then used the traditional load calculation method and CFD simulation method to derive their respective load values and to carry out comparison. The respective load values were then derived and compared using traditional load calculation methods and CFD simulation methods respectively, and the corresponding range of correction factors for the thermal and cooling loads were obtained. The study shows that the summer and winter cooling and heating loads of this form of radiant air-conditioning system are 75 % and 80 %, respectively, of the air system loads under the same conditions, with corresponding energy savings of 25 %and 20 %.

V. Conclusions and Outlook

In the past two decades, with the rapid development and application of radiant airconditioning calculations, the method of calculating radiant air-conditioning cold loads has also been more rapidly developed and updated. However, there are still many problems and challenges in the calculation of radiant airconditioning cooling loads.

Although the heat balance method is the most accurate, it requires constant iterations, and software based on the heat balance method, such as EnergyPlus, is not suitable for engineering applications due to the complexity of its operation. The radiation time series method does not require iterative calculations, but it is relatively difficult to obtain RTS. The load correction factor method based on the air system is relatively simple and convenient for load calculation, but its accuracy in calculating cold loads for different types of buildings needs to be further verified.

In addition, the effect of direct solar radiation on the increase in cooling load and the cooling capacity of indoor radiant surfaces cannot be ignored if the radiant airconditioning cooling load calculation is not obtained by the heat balance method [25]. It is generally assumed that the increase in the indoor cooling load by direct solar radiation is comparable to the increase in the cooling capacity of the indoor radiant equipment, that is, the radiant air conditioning system is self-regulating, but the applicability of this conclusion to other forms of radiant systems such as floors and built-ins, where the thermal mass is large, is currently controversial and needs to be further investigated.

Finally, radiant airconditioning systems are usually used with DOAS systems, but there are relatively few studies on the calculation of cooling loads for composite systems of radiation combined with DOAS. Bai et al [21, 22] proposed in the past years for the radiation time series method and correction coefficient method for the composite system of radiation combined with DOAS, there is still a large error, and at the same time, the theory of these two methods may not be fully applicable to the form of radiant airconditioning represented by radiant floors with a slower thermal response. Therefore, the calculation method for the cooling load of the radiant airconditioning system with DOAS needs further research.

As mentioned above, the calculation of cold load of radiant airconditioning system still faces greater difficulties and challenges, which requires researchers in related fields to continuously optimize the research and provide essential load theory support for the promotion and application of radiant airconditioning.

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