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Research paper

A simplified analytical model to evaluate the impact of radiant heat on building cooling load

Chengchu Yan, Shengwei Wang*, Kui Shan, Yuehong Lu

Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong

HIGHLIGHTS

- Ignoring the inner radiation may cause significant uncertainty to cooling load.
- We develop a simple analytical model to evaluate the inner radiation effect.
- A simple method is proposed for improving the "air-to-air" conduction method.
- A quantitative analysis of the inner radiation effect is conducted.
- Radiative heat gains and building zoning configurations are two key factors.

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ABSTRACT

In some building cooling load calculation methods, the conductive heat gain is calculated using the "air-to-air" conduction method in which the effect of radiative heat on the outer surface of external envelopes has been considered (e.g., using the sol-air temperature). However, the effect of the radiative heat on the inner surface is ignored, which results in uncertainty of conductive heat gain calculation and may bring significant errors in cooling load calculation under some particular conditions. This paper presents a simple method to consider the radiative heat on the inner surface of external envelopes for improving the accuracy of the "air-to-air" conduction method. A simplified analytical model is developed for evaluating the impact of inner radiant heat effect on cooling load. Five case studies are conducted in EnergyPlus to validate the model and to assess the radiative heat impact under different conditions. An illustrative example is presented to demonstrate the procedures of using the developed method to evaluate the inner radiation effect in a real building in Hong Kong. It is found that the most important factors determining the inner radiation effect are the radiative heat conditions and the building zoning configurations, and oversimplifying the zoning configuration might result in errors of up to 10% in cooling load calculations.

1. Introduction

The accurate calculation of cooling loads is essentially important in building environmental field [1]. ASHRAE has established a series of widely recognized standards and methods for cooling load calculation, including the total equivalent temperature differential/time-averaging method (TETD/TA), the transfer function method (TFM), the cooling load temperature differential (CLTD)/solar cooling load (SCL)/cooling load factor (CLF) method, and the heat balance (HB) method [2]. As Pedersen et al. pointed out, all cooling load calculation methods involve some kind of model and all models are approximate [3]. The degree of approximation significantly determines the accuracy of a cooling load calculation method. When modeling the heat transfer process of cooling load, one should choose the variables and parameters that are significant to the problem and make sure that no significant aspects of the process being modeled are excluded. For instance, uncertainties and errors may be caused by some building cooling load calculation methods in which the radiative heat exchanges on the inner surfaces of a building are ignored or oversimplified.

Among all ASHRAE established cooling load methods, the "heat balance method" is recognized as the most scientifically rigorous and accurate method that formulates fundamental models for the various heat transfer and thermodynamic processes that occur [3].

* Corresponding author. Tel.: +852 27665858; fax: +852 27746146.
E-mail address: beswwang@polyu.edu.hk (S. Wang).

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This method establishes the energy balance equations for each building external surface, wall body, and internal surface and indoor air notes, based on the first principle of thermodynamic [4]. Taking the heat transfer of an external wall for example, various coupled heat transfer components are interrelated with involving three types of heat transfers, i.e. convection and radiation and conduction. In the heat balance method, all radiative and convective heat exchanges on both the outer and inner surfaces as well as the conduction through the external wall are described in detail, as shown in Fig. 1. Particularly, the conductive heat flux through the external envelope is determined by the temperature gradient between the outer and inner surfaces of the external envelope. Using this "surface-to-surface" conduction method for conductive heat gain calculation, the impact from the radiation heat can be reflexed by the surface temperatures.

However, in some building cooling load calculation methods particularly those simplified methods, the conductive heat gain is calculated using the "air-to-air" conduction method. For example, the 2001 ASHRAE handbook proposes a new simplified cooling load calculation method—radiant time series (RTS)—to replace the TETD/TA, TFM and CLTD/SCL/CLF methods [5–7]. Using this method, the conductive heat transfer through external walls and roofs is assumed to be determined by the sol-air temperature and the indoor air temperature by simplification as following [5]:

$$q_{\mathrm{cond,o}} \propto (T_{\mathrm{sol}} - T_{\mathrm{in}}) \quad (1)$$

where, $q_{\mathrm{cond,o}}$ is the conductive heat flux calculated using "air-to-air" conduction method. T_{sol} and T_{in} are the sol-air temperature and the indoor air temperature, respectively. The sol-air temperature is a widely used concept for simplifying the coupled heat transfers on the external surface. It is a fictitious temperature of the outdoor air that in the absence of all radiation changes gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air [8].

Although the impact of radiative heat on the outer surface has been considered and corrected by using the concept sol-air temperature, the impact of the radiative heat on the inner surface of the external envelope is ignored which will result in uncertainty to the conductive heat gain calculation and may bring significant errors for cooling load calculation, under some particular conditions. Rees

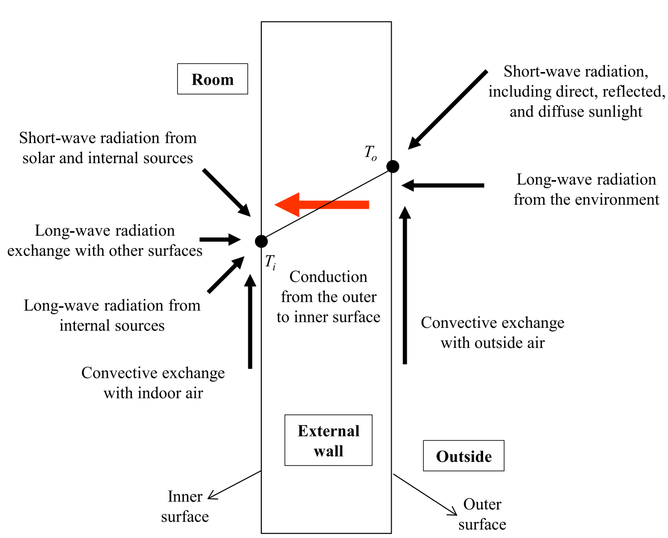

Fig. 1. Heat transfers of an external wall described by heat balance method.

and Iu et al. found that the RTS (the radiant time series method) that uses the "air-to-air" conduction method can over predict the peak cooling load by as much as 37% for cases with a high percentage of glazing and low internal heat gains [6,9]. Yik and Wan found that ignoring the radiation among different surfaces for OTTV (overall thermal transfer value) calculation may result in significant errors [10]. For example, using the pre-calculated coefficients that do not consider radiation effect on inner surfaces for estimating the OTTV of the buildings with different WWR (window-to wall area ratio), the relative errors can range from −41% to +16%. Corrado et al. investigated the applicability of the ISO 13790 quasi-steady state method to determine the energy needs for cooling. They found that the effect of zoning configuration, which is closely related to the inner radiation effect, plays an important role in determining building cooling energy need [11].

The studies on radiative heat transfer and cooling load calculation have been attracting increasing attentions in recent years due to the extensive application of radiant cooling/heating systems in recently designed/constructed buildings. Many researchers focused on the development and application of new approaches and models for heat transfer coefficients, which are a fundamental characteristic parameter for radiant systems [12]. For instance, Tian et al. established a dynamic heat transfer model for concrete radiant cooling slab based on reaction coefficient method [13]. Zhang et al. proposed a heat transfer model for evaluation of lightweight radiant floor heating system [14]. Ploskić and Sture proposed a hydronic radiant baseboards whose mean heat transfer coefficient was about 50% higher than the mean heat transfer coefficient of five conventional panel radiators [15]. Different from the case of air systems where the cooling load is purely convective, the cooling load for radiant systems consists of both convective and radiant components. Feng et al. investigated the magnitude of the cooling load differences between the radiant systems and air systems over a range of design configurations through simulation and experimental studies [16]. Lv et al. presented a calculation method of radiant time factors for radiant cooling load calculation [17].

There are three different approaches available for calculating radiative heat transfers and considering the inner radiation effect from existing literature. The first approach is to calculate the radiant heat exchanges among different inner surfaces in detail using the fundamental principles of heat transfer theory [4,18]. A good example is the aforementioned "heat balance method" [3]. Han and Yang also proposed a detailed dynamic model for analyzing the transient heat transfer through the roofs considering both the inner and outer radiations [19]. Fonseca et al. developed a dynamic model of radiant ceiling panels in heating or cooling modes coupled to various heat exchangers with its environment (fenestration, walls, internal loads and ventilation system) [20]. The second approach is to calculate the radiant heat exchanges using the radiative transfer coefficients and reference temperatures based on empirical or semi-empirical equations [21–24]. When radiation heat exchange involving, the heat transfer coefficient may be expressed separately for radiation and convection or as one total parameter [25]. Karadağ proposed a new approach to calculate the total heat transfer coefficient including the effect of radiation and convection at the ceiling in a cooled ceiling room [26]. The commonly used reference temperature for the calculation of the radiant heat transfer coefficient is the average unheated surface temperature (AUST) [25]. The operative temperature is also a convenient solution as reference for calculating the total heat transfer coefficient, which is also suggested for cooling/heating load calculations in EN Standard 12831 [27]. The third approach is to allocate the total radiation heat among difference surfaces according to distribution ratios. Lian and Zhang found that the distribution ratio of radiation heat has an important effect on the