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Design configuration for a higher efficiency air conditioning system in large space building

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ABSTRACT

The full air conditioning and the stratified air conditioning designs in large space buildings were investigated based on air flow measurement that pertains to an in-patient hall of a hospital building. We compared and analyzed the indoor comfort parameters such as temperature and air velocity. On the basis of the measurements, we calculated the theoretical load index by solving the model for inner surface temperature of the building envelope based on the modified radiant heat transfer method. Using flow fields and parameters that are generated by computational fluid dynamics (CFD), the indoor thermal comfort when adopting the full air conditioning and the stratified air conditioning designs can be effectively analyzed. And the respective energy saving rate of the two air conditioning design loads in the hall at different storey heights, window-wall ratios, and air supply heights can be compared. Finally, the recommendation for usage of the stratified air conditioning design was put forward in large space buildings.

1. Introduction

In general, a large space building is defined as one that spans a floor height of over 5 m and has an occupancy volume of over 10,000 m^3. Examples of such buildings are theaters, concert halls, auditoriums, exhibition halls, gymnasiums, workshops, etc. This type of building is characterized by a high storey, large ratio of the outer wall area to the floor area, large volumes, small ventilation rates, complicated functions, and special air conditioning load that demands a considerable energy consumption in terms of air conditioning [1]. Nevertheless, the proportion of air cooling or heating load for the thermal comfort in the occupied area is quite small in terms of total load as most of the cold or heat load is wasted in the non-occupied area. As a result, the energy saving of the air conditioning in large space buildings is attracting increasing attention in building research. For energy conservation and to achieve a more efficient air conditioning system, the stratified air conditioning system is suggested for large space buildings [2]. In recent years, the stratified air conditioning systems have developed rapidly due to the advantages of energy conservation and thermal comfort.

We introduced the development and described the history of the technology by regions in the order starting with USA, Japan, and then China. In the early 1960s, the stratified air conditioning technology was first applied in the plasma laboratory of a foundry in Philadelphia, United States. During the 1970s, the stratified air conditioning cooling load calculation methods were discussed theoretically [3,4]. For instance, Beier and Ball [5,6] investigated the load and air distribution of the stratified air conditioning by using simple mathematical methods. The research results did not come from the practical conditions due to the assumption they made, thus it was difficult to apply the research results to the design and calculation of the practical engineering. By the 1980s, researchers such as Gorton and Sassi [7,8] started working on the problems such as the stratification, cold load calculations, and minimum-energy consumption procedures for stratification cooling of the large enclosures. Since the beginning of the 1970s, the stratified air conditioning technology has been used in Japan and some experimentation on air distribution in large space buildings were performed. For example, the model and site testing of the stratified air conditioning was implemented in a large precision machinery processing and assembling workshop in Kobe in 1974. By comparing the experimental and the test results, the energy saving was reported to increase by 38% when stratified air conditioning systems were implemented [9]. Since the 1970s, Chinese universities and research institutions have began to perform research on the application of stratified air conditioning technology. In 1979, the Chinese Academy of Sciences organized its second, sixth and seventh Design Institute of Ministry of Machinery and other design

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institutes to participate in the study of the stratified air conditioning design in large workshops and had many important achievements [10]. After the 1990s, with the development of construction technology, more large space buildings were emerging in China, and the study of temperature and air flow distribution has received even more attention since then [11–13].

To the best of our knowledge, there are two kinds of methods for investigating the stratified air conditioning design. One is the simulated experiment according to the Similarity Theory, which can verify the small scale or field test results of air flow [14,15]. The other is the numerical model analysis based on computational fluid dynamics (CFD). With the rapid development of computer technology, CFD has been looked upon as a prediction tool in the design and assessment of the indoor building environment [16–18]. A significant number of scientific papers exists and they dealt with the application of CFD models in various indoor environments with considerable success existence. They focused on models of apartments, offices, classrooms, lecture theatres, industrial premises, stadiums, etc., [19–24]. Among these buildings, large space buildings are very important application targets for computational models; and CFD has been applied widely in the research of air distribution and thermal comfort of stratified air conditioning in large space buildings [25–27].

For the full and stratified air conditionings, the corresponding load calculation methods are implemented [1]. The indoor load changes with different air supply and return flow organizations in large space buildings, and affects the refrigeration capacity, the selection of terminal equipments and water pumps. Different large space buildings result in various indoor environment parameters of air conditioning. It is worthwhile mentioning that the interior decoration and air distribution schemes are related to the optimal technical and economic analysis. Therefore, the calculation and analysis of the energy saving rate in different air distribution has a great significance on the energy saving design of the air conditioning systems in large space buildings. With the theoretical calculation, as well as the experimental and computational field measurement, we obtained the load distribution of the full air conditioning and the stratified air conditioning and evaluated the energy saving rate between the stratified air conditioning load and the full air conditioning load under various working conditions. Most importantly, we are able to harness the CFD results that can evidently provide the recommendation for the stratified air conditioning application.

2. Methods

2.1. Theory of computational fluid dynamics

The presence of turbulent flow and heating are common in nature and are studied by various engineering fields and these flow process and heat transfer process are all subordinate to three basic physical laws based on the conservation of the mass, momentum, and energy. The experimental results show that the indoor airflow of air conditioning is generally non-laminar [28]. Therefore, the turbulence model is used for numerical calculation of three dimensional incompressible flows of indoor air. By numerical technique, we pay more attention to mathematical expression of the conservation laws, i.e., partial differential equations, which are commonly known as the fluid flow heat transfer control equations [29–31].

For the numerical analysis of indoor thermal environment in large space buildings, the k–ε two-equation model is the most widely used and also has got successful results. The basic k–ε model is relatively simple, and is effective in simulating isothermal flow, but there is a large error for non-isothermal and mixed convection situation [32]. In most projects, there are always a variety of flow existing simultaneously. In 1998, Nielsen pointed out that for the thermal plume, the wall jet and thermally stratified flow, the different turbulence models were needed to be simulated to achieve the accuracy results [33,34]. The RNG k–ε model is derived from the standard k–ε model based on the renormalization group theory, and is similar to that of the standard k–ε model. But after improvement, the RNG k–ε model is more accurate and reliable as compared to the standard k–ε model in the simulation of air distribution in large space buildings. Based on our above rationale, the RNG k–ε eddy viscosity turbulence model is selected here.

2.2. Experimental verification

The in-patient hall of a hospital building was selected for field measurement and model validation. The theoretical and numerical calculation results were compared with the experimental results to demonstrate its effectiveness. The investigated model is an entrance hall in the in-patient department with an area of 446 m^2, a length of 30 m, a width of 15 m and a height of 7.5 m. The stratified air conditioning is implemented. The central air conditioning system with primary return air is chosen and one horizontal air conditioning unit is located in the air conditioner chamber on the first floor in constant operation. The air conditioning unit also undertakes the load of the aisle connecting to the hall. The parameters of the air conditioning unit are as followings: air volume is 18,000 m^3/h, refrigerating capacity is 106 kW, heating capacity is 167 kW, external residual pressure is 600 Pa, and power is 11 kW. There are 12 spherical nozzles with diameter of 174 mm each, and the design air output of single nozzle is 1,166 m^3/h. The air supply height is 3.7 m, the airflow sprays down in 10 degree angle from the spherical nozzles, and the distance between the nozzles is 2.5 m. The return air inlets are located on the right side of the wall in the hall, and the exhaust system is set at the top of the hall.

The main measured parameters are temperature, humidity, air velocity, electric current, and voltage of the air conditioning unit. From these parameters we can obtain the distribution of indoor temperature field and air velocity field, air conditioning electric power, which can assist in analyzing the load, and energy consumption. The experimental instruments include data acquisition (DAQ), thermocouple temperature sensor, intelligent environment tester, power meter, infrared thermometer, etc; and specific parameters of these experimental instruments are shown in Table 1.

We arranged 26 horizontal temperature field measuring points (three columns, the number of each column is respectively 8, 9, 9) on the left side of the hall and 14 horizontal temperature field measuring points (two columns, the number of each column is 7) on the right side. The distribution of the measuring points can be seen in Fig. 1(a). There is a temperature point with interval 0.2 to 1.0 m in vertical height, and with the height increases, the interval increases. There are 192 temperature measuring points in the space.

The numerical model of the in-patient hall is shown in Fig. 1(b), which is simplified to facilitate the calculation. There are a total of 12 air supply nozzles. The air supply velocity is 9 m/s and the temperature is 18 °C. There are a total of 4 air return inlets. The air return velocity is 0.8 m/s and the temperature is 26 °C.

2.3. Case study of numerical models

2.3.1. Description of numerical models

Two types of numerical models are selected, a full air conditioning design and a stratified air conditioning design. Both of them are in the halls with external windows in the south, north, and west directions. For each of the model designs, different building heights are adopted. The size of