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Stratified air distribution systems in a large lecture theatre: A numerical method to optimize thermal comfort and maximize energy saving

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ABSTRACT

Complaints on thermal comfort and confusions on cooling load calculation are still two main issues for the design of stratified air distribution (STRAD) system. This paper investigated these two issues for STRAD systems applied in a large space lecture theatre. The simulation results revealed that best satisfied thermal environment was obtained when supplied air from floor level, terrace and desk-edge mounted grilles simultaneously. A new method for the calculation of the occupied zone cooling load, which is based on CFD (computational fluid dynamics) simulation was proposed and tried. The effective cooling load factor concept was further clarified, which can be conveniently used to calculate the occupied zone cooling load and then determine the supply airflow rate. The concepts of occupied zone cooling load reduction and the associated but different cooling coil load reduction were differentiated, and it was illustrated that cooling coil load reduction up to 16.5% of the space cooling load can be achieved with split location of return and exhaust grilles. These simulation works provide a good basis for full-scale experimental validation of the key energy saving features of a well-designed stratified air distribution system.

1. Introduction

Stratified air distribution (STRAD) systems have been developed rapidly in recent years for their better performance in energy efficiency and thermal comfort [1]. A well-designed STRAD system has vertical thermal stratification and may prevent convective heat from upper zone being transferred to occupied zone. The complexity of the air distribution in STRAD system demands modification of existing cooling load calculation methods [2], which is based on the assumption that all the convective heat in the space contributes to the space cooling load. According to the results of numerical study for 56 displacement ventilation (DV) cases, Chen and Glicksman [3] proposed a method to calculate the required flow rate. This method can be applied to design the optimal combination of supply airflow rate and temperature to avoid large head-to-foot temperature difference in design stage. Loudermilk [4] split the space sensible heat gains into convective and radiant components in under floor air distribution (UFAD) system. The entire radiant gain must be considered in calculation of the supply airflow, while the convective heat gains that originate outside the occupied zone should be neglected. The effective heat gain factors (EHGFs) for individual space heat sources were defined to quantify their impact on the occupants in the space. The space sensible heat gain (ESHG) was obtained based on the EHGFs and was used to determine the supply airflow rate. However, the values of EHGFs were empirically estimated. Bauman [1] proposed the separation of occupied zone and unoccupied zone, and correspondingly the space cooling load can be artificially distributed into $Q_{occupied}$ and $Q_{unoccupied}$. Then, the supply airflow rate can be calculated by using $Q_{occupied}$ as the cooling load. But this method was conceptual for information on how to obtain $Q_{occupied}$ was not provided. Later, they developed a practical design tool for determining the required cooling airflow rate in UFAD system [5]. The design tool predicts the room air temperature profile through empirical correlations based on the fraction of the cooling load assigned to the room and the designed parameters of the room, such as the room set-point temperature and the diffuser discharge temperature. The cooling load assigned to the room was calculated by using a fixed value of 0.7 for room cooling load ratio (RCLR), which defined as the percentage of the total system heat gain (including 100% of lighting) that is to be assigned to the room in the UFAD system. The simple temperature profile was used to derive the two comfort parameters, the average occupied zone temperature $T_{OZ,avg}$ and the head-ankle temperature difference ΔT_{OZ}, and then determines the airflow that matches most closely the design conditions. Recently, they improved the design tool with much more flexibility and proposed a simplified calculation method for designing cooling loads in UFAD systems [6]. The space cooling load in an UFAD system was calculated based on the cooling load ratio (UCLR), which defined as the ratio of the cooling load calculated for UFAD to the cooling load calculated for a mixing

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ventilation system. The space cooling load was divided between the supply plenum, the zone and the return plenum, i.e. the supply plenum fraction (SPF), the zone fraction (ZF) and the return plenum (RPF). Regression models to predict the UCLR and the split of space cooling load have been developed based on 87 EnergyPlus Simulations, with the consideration of different room floor levels, and different position and orientation of the room located. The applicability of the developed models is limited to the tested conditions with combined locations of return and exhaust grilles and may overestimated the cooling coil load when separate the locations as illustrated in Appendix A of this paper. Xu [7] developed a convenient cooling load calculation method based on the effective cooling load factors ($ECLF_i$) for each heat source, which was defined as

$$ECLF_i = \frac{Q_{i\text{-}occupied}}{Q_{i\text{-}space}} \quad (1)$$

where $Q_{i\text{-}occupied}$ (W) and $Q_{i\text{-}space}$ (W) are the cooling load in the occupied zone and the space cooling load caused by a heat source i (W), respectively. If $ECLF_i$ and $Q_{i\text{-}space}$ for each individual heat source are known, the total effective cooling load in the occupied zone $Q'_{occupied}$ originating from different indoor heat sources can be calculated conveniently as:

$$Q'_{occupied} = \sum_{i=0}^{n} ECLF_i Q_{i\text{-}space} \quad (2)$$

It was proposed that the space cooling load $Q_{i\text{-}space}$ can be obtained through current standard space cooling load calculation procedures for a well-mixed system, and $ECLF_i$ can be obtained by using a CFD method. It was also suggested that to enable the method widely applied in design practice, a comprehensive database of $ECLF_i$ for different heat sources at different room spaces is needed.

Compared with commercial and residential building, school building has its own features, such as high occupancy density, resulting in large internal heat gain, and multiplicity of daily activities and occupants, leading to complicated thermal conditions. Indoor thermal environments of school buildings have great impact on not only the attendance and learning potential of students, but also their health [8,9]. On the other hand, the draught discomfort and too large temperature gradient in the occupied zone are two problems frequently associated with STRAD system. However, the applications of STRAD in school classrooms or lecture theatre were rarely reported. Karimipanah et al. [10] tested four types of air distribution systems in a sample classroom with a fixed ceiling height of 3 m. The results indicated that system with air directly supplied into the occupied zone has higher ventilation effectiveness than other systems. Fong et al. [11] conducted human subject tests in a classroom with different ventilation methods. They found that the stratum ventilation could maintain comfortable thermal environment at a temperature of up to 27 °C, which is higher than mixing ventilation and displacement ventilation. These two researches were focused on general classroom with flat floor and the findings may not be applicable for large lecture theatres. With terraced floor, cool air coming out from floor level supply with low-velocity tends to move downwards the terraced floor, leading to undesirable temperature stratifications from front to back rows of seating and causing overcooling in the front row and inadequate cooling in the back row [12]. Thus, in order to obtain satisfied thermal environment for students, special considerations have to be given, when applied the STRAD system to a terraced lecture theatre.

In this paper, different designs to realize STRAD for a large-space lecture theatre with terraced-floor were evaluated by using numerical simulation technique. A novel approach [13] was first applied to evaluate the possible discomfort due to vertical temperature stratification and near-body airflow effects, on the basis of meeting thermal comfort requirements. Then, the cooling load calculation method proposed by Xu et al. [7] was tested as well with different approaches to obtain the occupied zone cooling load. Energy saving potential caused by STRAD design was also estimated and the reduction of cooling coil load due to vertically separating exhaust and return air grilles was analyzed. In this study, it was first clarified in Appendix A that occupied zone load is useful for determining the supply airflow rate and temperature, but should not be simply considered as an equivalent of reduced cooling load for the air conditioning system. It was illustrated that reduced AHU cooling load is reversely related to the exhaust air temperature and that separate return and exhaust grilles may help to further raise the exhaust air temperature and therefore generate further energy savings in STRAD system.

2. Methodology

2.1. CFD model validation

The standard k–ε model is capable to simulate convective heat transfer of buoyancy-driven airflow as long as reasonable value of y+ is achieved [14]. Hence, it was adopted in present simulation together with buoyancy term and differential viscosity model to account for low Reynolds number effect. The discretization schemes used for all variables except the pressure term were second-order upwind scheme to ensure the computational accuracy. The pressure was discretized by a staggered scheme in FLUENT named PRESTO. The SIMPLE algorithm was applied to couple pressure and velocity. The radiant heat transfer between different surfaces was calculated using the Discrete Ordinates (Do) radiation model.

An experiment carried out by Zhang and Chen [15] in a full-scale environmental chamber with under floor air distribution (UFAD) system was selected to validate the computational model. Fig. 1 displayed the comparison of vertical temperature and velocity profiles between the numerical simulation and experiment. It can be seen that for most points, the velocity and temperature distributions were in good agreements.

2.2. Classroom configurations

As shown in Fig. 2(a), a large classroom in terms of dimension, occupant density and lighting layout referred to an existing classroom in university campus is selected. There are 130 seats arranged in 10 rows on a terraced floor in the classroom and the height from ceiling to floor of the classroom varies from 3 m to 5 m. 20 lamps are installed at the ceiling level and simplified as rectangle panels. The existing air-conditioning system is a fan-coil unit (FCU) + primary air-handling unit (PAU) design, with ceiling supply and ceiling returns. In this numerical study, several hypothetical STRAD air distribution methods are simulated. As indicated in Fig. 2(b), air is supplied into occupied zone directly, i.e. from floor-level, terrace or desk edge. Part of the air is exhausted from three grilles located at ceiling-level. What should be noted is that different from conventional design, the rest four returns grilles are distributed on surrounding walls at middle-level, as indicated in Fig. 2(a).

2.3. Mesh generation and boundary conditions for CFD simulation

Taking advantage of the symmetrical characteristic of the classroom, half of the room was selected as the simulation domain in order to save the computational time. Computational domain was divided into several sub-regions and most regions were meshed by structured grid with high quality. In the occupied zone, the local airflow information and heat transfer between air and human body