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Investigation on the thermal comfort and energy efficiency of stratified air distribution systems

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ABSTRACT

A stratified air distribution (STRAD) system is a feasible air conditioning design for large space buildings that satisfies the energy conservation and thermal comfort requirements. In this paper, a novel energy efficiency index for STRAD systems is developed using theoretical analysis to properly evaluate the system's energy saving potential. Using a validated numerical model, two typical stratified air distribution designs in a hypothetical terminal building are evaluated based on thermal comfort and energy savings. The influence of supply and return diffuser distributions on the ventilation performance of these two ventilation designs is studied. When the air is supplied at mid-height, the local thermal comfort is greatly improved without sacrificing the energy efficiency due to additional return grilles located at exterior walls. When the air is supplied at floor level, installing additional return grilles at exterior walls slightly alleviates the local draft risk, but doing so largely impairs the energy saving capacity of the ventilation system. To achieve better thermal comfort and higher energy efficiency, a more uniform distribution of supply diffusers surrounding the occupied zone is suggested. When the air is supplied at the floor level, increases in solar radiation intensity can be mitigated by utilizing external shading designs, which are particularly important in preventing too large of a temperature gradient in the region exposed directly to the solar radiation.

Introduction

Modern buildings with high ceilings and large spaces, such as airport terminal buildings and international conference halls, are usually enveloped with large areas of transparent glass curtain walls, which serve the purpose of providing architectural esthetics and natural lighting (Gordon, 2008). However, large areas of fenestration admit extensive solar heat gains and significantly increase the space-cooling load. Furthermore, in these types of buildings, the internal heat gains are always substantial due to high occupant densities and illumination intensities. As a result, considerable energy consumption is spent on air conditioning to maintain a satisfactory thermal environment for the occupants (Parker et al., 2011). A survey study revealed that the average annual energy consumption of air conditioning systems in 29 Greek airport terminals was approximately 120 kWh/m^2, which accounted for a large proportion of the total building energy consumption and was highly energy-intensive (Balaras et al., 2003). Nevertheless, thermal comfort issues still exist in these large space buildings. For example, occupants may frequently feel overheated due to a large amount of direct solar radiation that is caused by a large ratio of window area to wall area (Kim et al., 2001). On the other hand, in large space buildings with traditional mixing ventilation system design, the air cooling for thermal comfort in the occupied zone is quite a small proportion of total load, most of the cold load is wasted in the un-occupied zone. Thus, increasing the energy-efficiency of air conditioning while also improving thermal comfort in large space buildings is attracting considerable attention in building research.

The stratified air distribution system (STRAD) is an applicable air distribution design for large space buildings. In recent years, STRAD systems have developed rapidly because of their better ventilation efficiency and energy saving capacity compared with traditional mixing ventilation systems (Bauman, 2003). In a numerical study of the air conditioning system in the International Airport of Bangkok, Simmonds (1996) demonstrated that the STRAD system was a feasible energy-conserving design for terminal buildings. In a following study, they clearly revealed that the application of a hybrid conditioning system consisting of a variable-volume displacement ventilation system and a radiant cooled floor to a terminal building was able to reduce the energy consumption of the air conditioning system (Simmonds et al., 1999). Han and Gu (Han and Gu, 2008) numerically studied the thermal environment in the third terminal building of the Beijing Capital International Airport. They found that by using a stratified air distribution in the terminal building, a satisfactory thermal environment was achieved in the occupied zone. Similarly, Li et al. (Li et al., 2009) investigated different air distribution designs to optimize the thermal environment in a

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train station building with a high ceiling level. The numerical results indicated that satisfactory thermal comfort in the occupied region was realized using a stratified air distribution design and supplying air at mid-height horizontally.

However, such limited research conducted on the application of STRAD systems in large space buildings offers little insight into their aspects of energy conservation and thermal environment optimization. Further in-depth research is required to solve the problems that continue to confuse design engineers, including energy saving principles, the organization of air supply and return flow, the occupied zone cooling load calculations and the size determinations of refrigeration equipment. In this paper, the energy saving potentials for STRAD systems adopted in large space buildings are clearly illustrated using theoretical analysis. Based on this analysis, a novel energy efficiency index that is able to quantify the energy saving capacity of different stratified air distribution designs in large space buildings is also developed. Then, using a validated computational fluid dynamic (CFD) model, two typical and practical air distribution designs that can realize thermal stratification in a hypothetical terminal building are numerically evaluated based on thermal comfort and energy saving. The influence of diffuser location and solar radiation on the indoor thermal environment of the building and the energy consumption of the air conditioning in both designs are studied. Most importantly, we aim to harness the CFD results that provide sufficient evidence in order to make a recommendation for an effectively designed STRAD system in large space buildings.

Methodologies

Energy conservation of STRAD systems

In a STRAD system, cold air is delivered directly to the occupied zone and is normally returned at or near the ceiling level. Thermal plumes that are generated by heat sources within the room draw air from the surrounding space and direct it upward. The upward movement of air in the room takes advantage of its natural buoyancy and produces a vertical temperature gradient. Because only the lower occupied zone needs to be cooled, the STRAD system is inherently energy saving, and this benefit is even more likely to be realized in buildings with high ceilings (Lin et al., 2006; Hashimoto and Yoneda, 2009). A significant number of studies have been conducted on the energy conservation of STRAD systems and have achieved considerable success. One of the most important findings is that the energy efficiency of a STRAD system highly depends on the stratification height (Yuan et al., 1998), which refers to the height in the room where the combined airflow rate of the thermal plumes is equal to the total air supply volume entering the room. Previous researchers have demonstrated that for a certain building ventilated by a STRAD system, the stratification height is mainly determined by several design parameters, including the heat load distribution in space (Nielsen, 1996; Gladstone and Woods, 2001; Kaye and Hunt, 2010), the supply diffusion characteristics (Lin and Linden, 2005; Lee et al., 2009), the designed air flow rate and the organization of indoor air flow (Mundt, 1995; Webster et al., 2002). A schematic diagram showing the primary relationship between these key design parameters and the stratification height is presented in Fig. 1, which is based on a review of the studies mentioned above.

To evaluate the energy conservation of a STRAD system, the ventilation effectiveness for heat distribution ε_t was defined by Awbi (Awbi, 1998), as:

$$\varepsilon_t = \frac{t_e - t_s}{tave - t_s} \tag{1}$$

where $t_s$is the supply air temperature, t_e is exhaust air temperature, and *tave* is the mean value for the occupied zone. This index is effective in the comparison of the energy efficiency of different STRAD systems with combined locations of return and exhaust grilles. However, this index may underestimate the energy saving potential of STRAD systems with separated locations of return and exhaust grilles because there is an additional energy saving potential (Lau and Niu, 2003; Xu et al., 2009). Taking this into account, efforts towards developing a new energy efficiency index for STRAD systems are conducted here. A cooling coil load Q_{coil} calculation method for a typical STRAD system has been developed (Cheng et al., 2013). The required Q_{coil} is calculated by the following equation:

$$Q_{coil} = Q_{Space} + Q_{vent} - C_p \times \dot{m}_e \times (t_e - t_{set}) \tag{2}$$

where Q_{Space} and Q_{vent} are, respectively, the space cooling load and the ventilation load in the classical sense, $\dot{m}_e$ is the exhaust air flow rate, t_e is the exhaust air temperature, and t_{set} is the room set-point temperature. It is obvious that the cooling coil load in a STRAD system is smaller than that in a mixing ventilation system by the quality of $C_p\dot{m}_e(t_e - t_{set})$, identified as the cooling coil load reduction ΔQ_{coil}. The larger the exhaust air temperature, the more cooling coil load reduction is achieved and the more energy is saved by the refrigerating unit. By installing the exhaust grille at ceiling level and the return grille at a middle height, as shown in Fig. 2, the convective heat generated in the upper zone can be discharged by exhaust air directly and excluded from the cooling coil load. Correspondingly, the exhaust air temperature is able to be further increased and extra energy is saved for the cooling coil. To evaluate the energy saving potential of a STRAD system, an energy efficiency index ε is defined as:

$$\varepsilon = \Delta Q_{Coil} / Q_{Space}. \tag{3}$$

When the return and exhaust grilles are combined, the return air temperature is equivalent to the exhaust air temperature and the space cooling load can be described as:

$$Q_{Space} = m_s (t_e - t_s). \tag{4}$$

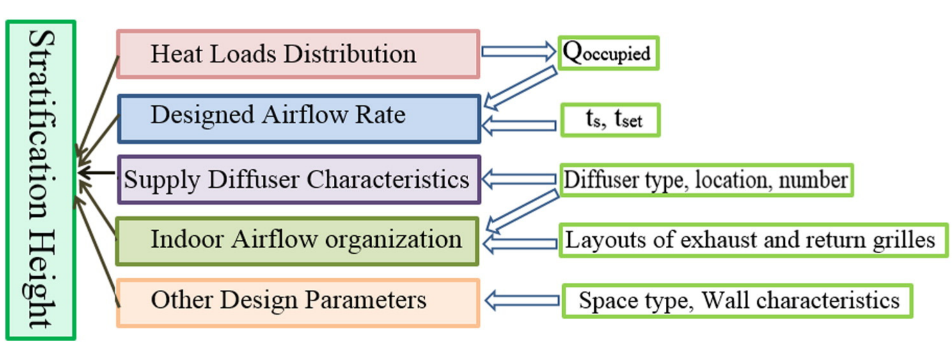

Fig. 1. Primary relationship between key design parameters and the stratification height.