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Parametrical analysis on characteristics of airflow generated by fabric air dispersion system in penetration mode

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ABSTRACT

Fabric air dispersion system (FADS), as a ventilation terminal, can help create a clean and comfortable indoor environment. Several studies mainly focused on the characteristics of airflow generated by FADS. However, the effects of the configurations on the airflow characteristics were rarely studied. Based on our pervious work, the effects of fiber porosity, fiber diameter and supply air flow rate on characteristics of air velocity and pressure inside FADS were numerically studied and the results were validated by experiments. It is shown that larger porosity or fiber diameter lead to lower pressure inside and poorer distribution of air velocity along the length direction of FADS. Higher supply air flow rate aggravates the non-uniformity of air velocity distribution, and increases the pressure inside. The combined effects of the three factors should be taken into consideration in order to achieve a uniform distribution of air velocity along the length direction and reduce fan energy consumption and noise level. Results of this study would be useful to guide the optimum design of FADS in penetration mode to expand its applications, especially in small enclosed spaces, where air quality, energy conservation and noise level are in high demand.

1. Introduction

It is well known that heating, ventilation, and air conditioning (HVAC) systems are a double-edged sword for human living environment. While it helps improve the temperature and humidity of the living environment, HVAC systems also become one of primary pollution sources causing the deterioration of indoor air quality. Numerous approaches [1] have been adopted to improve indoor environment quality, such as personalized ventilation (PV) [2], displacement ventilation [3] and stratum ventilation (SV) [4].

The fabric air dispersion system (FADS), a new flexible ventilation terminal made of polymer, has many advantages over the conventional ventilation system, such as low air velocity, light weight, convenient installation, etc. [5]. Furthermore, condensation can be effectively avoided when an enclosed space with high humidity air is ventilated by FADS. In addition, most of the pollution sources deposited can be easily removed by routine washing. Therefore, FADS has received more attention by designers and architects around the world. Nowadays, FADS has been used around the world to build high quality indoor environment in many contexts such as the catering and food processing industry, the clean surgeon operation rooms, and the gym centers.

Numerous works have been concerned about the dispersion characteristic of airflow near the local regions of FADS and within rooms ventilated by FADS. Nielsen et al. [6] used the full field measurement method to study the airflow characteristics in a test room ventilated by a textile terminal (FADS), ceiling-mounted air diffusers, and wall-mounted air diffusers. Results showed that an air distribution system based on textile terminals was able to generate comfortable velocity and temperature conditions. The thermal load of the system is the same as that obtained by a mixing ventilation system with a wall-mounted diffuser or a displacement ventilation system with a low-velocity wall-mounted diffuser. Chen et al. [7] used the numerical method to find that draught rate around the ankle and neck within room ventilated by FADS in penetration mode was barely influenced by supply air flow rate and position. Nielsen et al. [8] used two simulated manikins to study the personal exposure between people in a contaminant room ventilated by FADS and found that the personalized ventilation based on FADS can protect the occupants by increasing the personal exposure index. Pinkalla [5] also pointed out that ventilation based on a textile duct system (FADS) could prevent the generation or introduction of pollutants into the occupied space. Fontanini et al. [9] used fully three dimensional computational (CFD) simulations to quantitatively study airflow pattern and thermal evaluation within

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Nomenclature

$\langle u \rangle$	intrinsic velocity, or physical velocity (m/s)
U	macroscopic velocity, or superficial velocity (m/s)
$\langle p \rangle$	intrinsic pressure (Pa)
p	macroscopic pressure (Pa)
D_p	equivalent fiber diameter (μm)
F	modified Brinkman coefficient
x	Cartesian coordinate

Greek symbols

ρ	air density (kg/m^3)
υ	effective viscosity (m^2/s)
ε	porosity
α	permeability (m^2)
μ	kinematic viscosity coefficient (kg/m/s)

Subscript

i, j	directions in Cartesian coordinates

a room ventilated by FADS and ceiling diffuser systems under the steady and transient state, respectively. It was found that FADS heated the room faster, more uniformly than the conventional system (ceiling diffuser systems) did. Indoor airflow pattern is greatly impacted by the location and strength of heat load. Chen et al. [10] numerically studied the influence of four layouts of FADS in penetration mode on indoor airflow pattern, and found that a FADS mounted on the ceiling with exhaust opening on topper sidewalls led to better indoor environment with uniform temperature and lower air velocity than other layouts. Chen et al. [11] validated the feasibility of modeling a FADS based on the porous media model by the comparison of simulation results with experimental measurements. In addition, Chen et al. [11,12] used the numerical and experimental methods to quantitatively study the radial and axial distribution of both air velocity and pressure inside and airflow distribution within a room generated by FADS in penetration mode. Also, flow visualization was conducted using dry ice as smoking material. Simulation results were in good agreement with the experimental results.

Numerical studies have shown that the prediction accuracy of air velocity and temperature distribution is highly influenced by the location and type of air diffusers [13–15]. For instance, Sun and Smith [16] studied the air flow characteristics close to the square cone diffuser, and found that the offset and lips of the diffuser worked together to determine the discharge air angles. FADS also serves the functions of ducts and diffusers as it can transmit and distribute the airflow. Therefore, as a new diffuser, the performance of FADS such as fiber penetrability would affect airflow dispersion characteristics. The performance is, in turn influenced by many factors, e.g. the fiber porosity, fiber diameter and the textile technology, etc. For example, Lekakou and Bader [17] numerically studied the effect of parameters, including fiber volume fraction, fiber tow diameter and injection pressure, on the fluid through woven cloths. They pointed out that the apparent global permeability depended on the injection pressure, and, its variations also depended on the fabric architecture and fiber volume fraction in the regime of relatively low injection pressures. The research by Kwon et al. [18] showed that the decrease in the fiber diameter of the fabric decreased fiber porosity, but increased fiber density and mechanical strength. However, the effects of these factors on the characteristics of air velocity and pressure inside FADS are rarely studied. According to our previous work, the static pressure inside was the main power to overcome the total resistances due to porous fiber and to distribute airflow within a room.

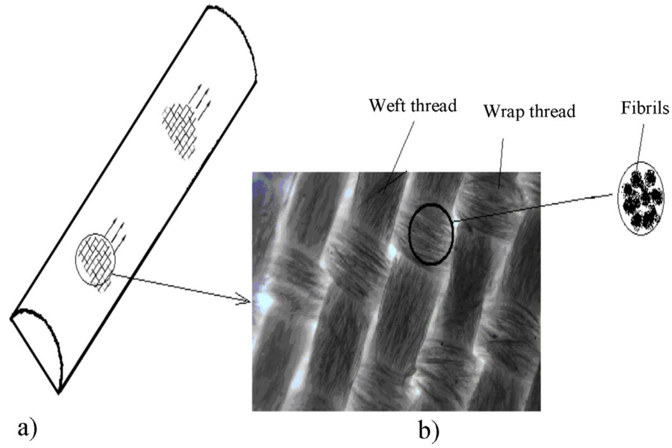

Fig. 1. FADS' geometry: (a) sketch map of air motion; (b) microscopic fiber pictures photographed by the electron microscope.

Since the static pressure inside is related with the supply air flow rate, the higher the supply air flow rate is, the bigger the static pressure inside and the total pressure are. Furthermore, the magnitudes of both the pressure inside FADS and the supply air flow rate are positively related the fan energy consumption and noise level. Hence, the fiber configuration of FADS influences the airflow characteristics as well as the fan energy consumption and noise level.

Therefore, the major objective of the present work is to further numerically study of the effects of configuration (fiber porosity, fiber diameter) and supply air flow rate on the characteristics of airflow generated by FADS, including superficial air velocity, physical air velocity as well as total and static pressure inside FADS along the length direction. Furthermore, the effect of fiber configuration on fan energy consumption and noise level is also discussed.

2. Numerical methods

2.1. Description of FADS

The physical structure of FADS is composed of fiber bundles, which are also called tows. Each tow, in turn, contains several fibrils or filaments. The warp-wise tows are called the warp thread and the weft-wise tows are called the weft thread, respectively. A collection of weft threads and wrap threads form a structure known as a fabric. Various types of fabrics have been designed such as cylinder, half-cylinder, and quarter cylinder which can be dyed with various colors. In present work, a half-cylindrical FADS with nonporous upper facet is taken as an example. The dimension is 0.42 mm in thickness, 305 mm in diameter. The geometry of the FADS in penetration mode is shown in Fig. 1.

2.2. Differential equations for airflow through FADS

With FADS, air is firstly driven into the cavity of FADS (nonporous media zone), and compelled through tiny pores in the porous fiber (porous media zone). The air then exchanges heat and humidity with indoor air. The following assumptions about airflow and fiber material are made in the present work: (a) the airflow is treated to be isothermal, incompressible, and steady with constant physical properties; (b) the fiber material is assumed to be rigid, isotropic, and saturated. Based on the above assumptions, the mass and momentum conservation equations of airflow through FADS are written in tensor notation as follows [11].