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On the characteristics of airflow through the perforated tiles for raised-floor data centers

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ABSTRACT

Perforated tiles are widely used in raised-floor data centers. The cooling air across the perforated tiles must be distributed properly to adequately cool the equipment. This paper aims at investigating the dependence of the pressure loss coefficient across perforated tiles with respect to the geometrical factors and flow parameters. Numerical simulations of flow distribution of perforated tiles were performed for different pore-type and flow parameters. The pressure loss coefficient upon the Reynolds number, the tile area, the porosity, the diameter of the hole, the thickness of the hole and the arrangement is studied. The fitting equation was provided to calculate the pressure loss coefficient. And experimental tests were taken to verify the validity of the model, comparison with the other empirical equations is provided. Based on the comparison, the fitting equation is more applicable to study the pressure loss coefficient for perforated tiles in data center.

1. Introduction

Generally, perforated tiles are used to remove swirl and correct a distorted flow profile [1,2]. In data centers, perforated tiles are installed on pedestals as an outlet of the plenum or a disturbance device in the plenum. Most of current data centers are raised-floor facilities and use the space between the underside of the raised floor and concrete subfloor (plenum) to supply cooling air to the “cold aisle”. Patankar [3] suggested that the flow field in the under-floor plenum holds the key to the distribution of airflow across the perforated tiles. The perforated tiles in data centers typically consist of floor panels size of 2 ft×2 ft, they are supported on pedestals on the floor slab. The panels at selected locations are replaced by perforated tiles to supply air into the “cold aisle” to cool the equipment [4,23].

Computational fluid dynamics (CFD) have been an important tool for examining the flow fields in data centers. Several models (porous jump and body force model) have been used in perforated tiles simulations. But it's important to consider the geometrical parameters and some other details in these porous media models to improve the accuracy.

A fluid flow across a porous media has attracted increasing attention, being encountered in extensive engineering applications such as mechanical, aeronautics, energy, architecture, chemical, and nuclear industries. Idelchik [5] investigated the perforated tiles with different hole geometrical shape and open area ratio. Relevant empirical equations are proposed to predict the pressure loss coefficient. The friction resistance is also considered in his study. Wang [6] analyzed the Stokes flow through a perforated plate with holes arranged in a regular manner, indicating that the pressure drop is primarily dependent on the porosity and hole geometrical shape, but depends only slightly on the flow pattern. A similar investigation from Malavasi et al. [2], the influence of the hole geometrical parameters on the pressure losses at a high Reynolds number have been investigated experimentally. They reported that the pressure drop primarily depends on the ratio of plate thickness to hole diameter (equivalent diameter ratio) and the porosity, while the impact of hole arrangement is insignificant. Zhao et al. [19] studied the multi-hole plate and provide an empirical equation to study the pressure loss coefficient. Tio [7] studied the stokes flow through the porous membrane of zero thickness. In their report, the pressure difference is directly proportional to the velocity, and the coefficient is a function of the open area ratio (porosity). Guo et al. [8] performed numerical simulations of a turbulent flow through a thin perforated plate with cylindrical holes, considering the effects of surface roughness and plate inclination angle, and proposed that the pressure loss is determined by the flow structure in the downstream side.

However, few investigations deal with the air characteristics through the perforated tiles in data centers and a simplified model is important for the study of perforated tiles in data centers. Karki and Patankar [4] proposed an idealized one-dimensional computational

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Nomenclature

β	equivalent diameter ratio
f	porosity
t	thickness(depth) of the hole
p	pitch, the distance between two adjacent pore
e	length of the edge
P_U, P_D	upstream and downstream pressure
k	pressure loss coefficient
ρ	fluid density
v	bulk-mean velocity (superficial average velocity)
ΔP	average pressure difference based on each hole
D_p	pipe (upstream) diameter
V_p	pipe (upstream) bulk mean velocity
Re_p	pipe Reynolds number
D_h	hole diameter
V_h	hole bulk-mean velocity
Re_h	hole Reynolds number
Re_{h-p}	Reynolds number based on D_p and V_h
k'	pressure loss coefficient achieved in region (1)
ε_{Re}	correction factor of pressure loss coefficient
F_U	upstream area
ε	area correction coefficient
E	relative erro
$C_{1,T}$	single-tile and multiple-tile pore-type coefficient
n_t	number of perforated tiles

model to study the influencing parameters of pressure distribution. Within the one-dimensional framework, they proposed two dimensionless parameters to describe the flow field. Arghode and Joshi [9] considered several models and reported that realizable k-e model is more appropriate for modeling airflow through holes, they also reported the effects of the Reynolds number, the tile thickness and the tile porosity. Arghode [10] also provided a modified body force model based on the prescribed pressure loss across the tile surface to increase the accuracy. Fulpagare [11] et al. studied the influence of obstructions on rack cooling with CFD method, they reported that the obstructions in plenum will reduce the airflow rates and increase the occurrences of hot spots, the influence of boundary condition is also investigated in their study. Some investigations have reported modeling of plenum with improved models [12–14]. But some of these researches considered the influence factors with single-pore model, microscopic flow or unit cell model to determine the macroscopic flow. And in some papers, no consideration was given to the hole geometrical parameters in models. And most of them failed to provide the function of specific parameters which is specific to perforated tiles in data centers, so it is hard to apply it in models such as porous jump model in plenum simulations.

The purpose of the present work is to investigate the dissipation characteristic of multi-hole tiles for data center. Various variables influencing the flow field are described. The fitting function for data centers multi-hole tiles is worked out to describe the influence of specific parameters. Good agreement is observed between the current simulations and empirical equation. Relevant experiment work is finished to check the validity of the function. Compared with recent published empirical equations, the fitting equation shows a high accuracy to calculate pressure loss coefficient for generally used perforated tiles in date centers.

2. Model condition

Three-dimensional steady-state turbulent flow is studied using commercial software ANSYS FLUENT 14.5, which is based on the finite volume method [15]. Pressure-velocity coupling is calculated by the SIMPLE algorithm [16]. It has been proved that the Realizable k-e model has a better performance for modeling flow through pores, as compared with the generally used standard k-e model [8,9,17,18]. A second-order upwind method is chosen for discretization. Instead of the unit cell model, a complete tile model is chosen to study the tile level flow structure. A uniform velocity along the y axis is set for the inlet and a pressure boundary for the outlet. Periodic conditions with zero pressure gradient are applied on the side boundaries of the domain. In the flow path (perpendicular to the perforated tile surface) direction, the length of the downstream side is longer than the upstream side. Both sides should not be too long and 50 mm is chosen for the upstream side. In this way, the total pressure loss is sole dependent on the perforated tile. Typically, each case has about half a million mesh nodes. Air at room temperature and pressure are chosen for the fluid in the chamber.

A mesh sensitivity study was performed to access the accuracy of the calculation. The optimized computational mesh (which was considered to produce a good trade-off between accuracy and computational time) was employed for the tile model. The optimized mesh consisted of more than two hundred and fifty thousand nodes. The minimum grid spacing was 0.002 m, and the maximum grid spacing was 0.01 m.

The porosity values (open area ratio, range from 0.78% to 50.3%) f, the hole diameters (range from 14 mm to 300 mm) D_h, the tile thickness (range from 2 mm to 10 mm) t, are varied from case to case to study the common used perforated tiles in data centers. In Refs. [2,6], it has been proved that the effect of hole arrangement is insignificant. In this case, the pores are modeled by cylindrical holes of diameter D_h and depth t, which are distributed in a rectangular manner. The distribution is shown in Fig. 1. The value of p (the distance between two adjacent pores) is constant. The length of the edge section is e, which is the distance between the edge of the pore and the adjacent edge of the tile. The correlation is shown as follows:

$$\sum_{i}^{n-1} p = L - 2e \tag{1}$$

$$e = p - D_h \tag{2}$$

The flow characteristics of perforated tiles are usually quantified by means of the resistance coefficient (pressure loss coefficient) [5],

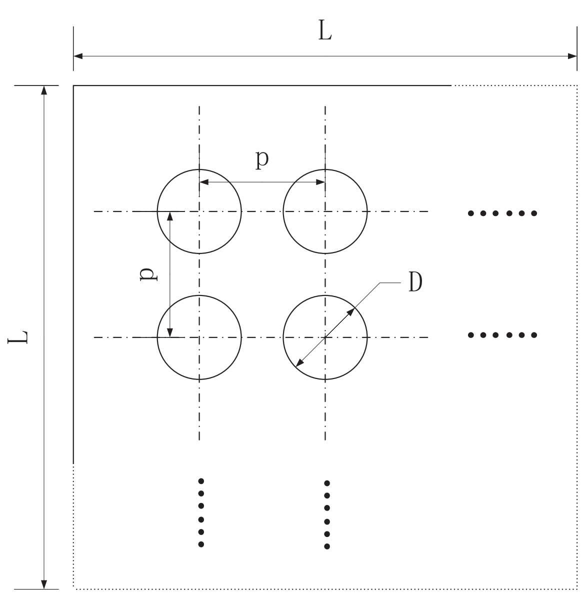

Fig. 1. The unit cell of the perforated tile.