Experimental Investigation of Air Flow through a Perforated Tile in a Raised Floor Data Center

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Abstract

Raised floor data centers supply cold air from a pressurized plenum to the server racks through perforated floor tiles. Hence, the design of an efficient air delivery scheme requires better understanding of the flow features, through and above the perforated tiles. Different tiles with circular pores in a staggered arrangement and with the same thickness are considered. Tile sheet porosities of 23% and 40%, air flow rates of 0.56 m\(^3\)/s (1,177 CFM), and 0.83 m\(^3\)/s (1,766 CFM), and pore sizes of 3.18 mm (1/8”), and 6.35 mm (1/4”) are investigated. Tiles with 38.1 mm (1.5”) region blocked along the edges is compared to the base case with 12.7 mm (0.5”) blocked edges. Width reduced to 0.46 m (1.5 ft) from standard width of 0.61 m (2 ft) is also examined. Reduced tile width is used to simulate 0.91 m (3 ft) cold aisle instead of standard 1.22 m (4 ft) cold aisle, with potential to save floor space. A case where the rack is recessed by 76.2 mm (3”) from the tile edge is also included in the investigation, as there is a possibility of having racks non-adjacent to the tile edges. Particle image velocimetry (PIV) technique is used to characterize the flow field emerging from a perforated tile and entering the adjacent rack. Experiments suggest that lower tile porosity significantly increases cold air by-pass from the top, possibly due to higher air jet momentum above the tile, as compared to a tile with higher porosity. For the air flow rates investigated here, the flow field was nearly identical and influence of flow rate was non-distinguishable. The influence of pore size was non-negligible, even when the porosity and flow rate for the two cases were same. Larger blockage of the tile edges resulted in higher cold air by-pass from the top. Reduction in the tile width showed improved air delivery to the rack with considerably reduced cold air by-pass. Recessing the rack did not affect the flow field significantly.

Keywords: Perforated tile; Air by-pass; Porosity; Pore size; Particle image velocimetry; Data center

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>B</td>
<td>edge blockage</td>
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<tr>
<td>CDU</td>
<td>chilled water distribution unit</td>
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<tr>
<td>CRAC</td>
<td>computer room air conditioning</td>
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<td>D</td>
<td>tile pore diameter</td>
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<td>F</td>
<td>tile sheet porosity</td>
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<td>Feff</td>
<td>effective tile porosity</td>
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<tr>
<td>F&amp;I</td>
<td>Freid and Idenchik’s correlation [10]</td>
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<td>HACA</td>
<td>hot aisle - cold aisle</td>
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Paper# EP-14-1017
1. Introduction

Air cooling is the most common method used for thermal management of data centers. For energy efficient data center operation, uniform and low air temperature at the rack inlet is desired [1]. However, due to mixing of supplied cold air with the hot room air, higher temperatures, as compared to the supplied air temperature, can be present at the rack inlet, thus lowering the cooling effectiveness [2]. In a raised floor data center, cooling air is supplied from an under-floor pressurized plenum through perforated tiles. Racks are commonly arranged in rows, in hot aisle - cold aisle (HACA) arrangement, where the rack inlets are on the cold aisle and the exits are on the hot aisle. Generally, the cold aisle width corresponds to two standard perforated tiles, where each tile supplies air to the adjacent rack. Hot air from the rack exit moves from the room space directly to the computer room air conditioning (CRAC) units or in some cases exits from the room space via overhead return vents placed above the hot aisle and traveling through the above ceiling plenum to eventually reach the CRAC units. Perforated floor tiles can have different geometrical features such as
size, porosity, pore size and shape, blocked region at the edges (where perforations are absent), and anterior structures (such as flow guiding fins or dampers for air flow control) that can affect the air flow delivery to the adjacent rack.

Until recently, it was believed that the air delivery problem is mostly solved if desired amount of air is supplied through the perforated tiles with careful consideration given to the under floor region only [3]. However, in recent experimental investigations it was observed that even if sufficient amount of air, matching the rack requirement, is delivered through the tile, a significant amount of cold air by-passes from the top [4, 5]. This was attributed to higher momentum of air that prevents it from turning and entering the rack, and thus escaping from the top of the aisle. Hence, to make up the rack air requirement, room air is entrained, leading to higher inlet air temperatures and thus higher cooling energy consumption [2].

Air flow modeling is extensively used in designing and thermally managing data centers. Recently, it has been recognized that the tile’s geometrical features have significant effect on the downstream flow field [6]. For improving predictive capability of the numerical models to simulate air flow in data centers, it is important to understand the effect of geometrical features of the tile on the flow development. Including all the geometrical features of the tile can be computationally prohibitive and hence, rapid turnaround models are desired to simulate the air flow through the tiles in data centers [6-9]. While tile porosity has been taken into consideration for estimating the air flow rate supplied through the tile [3], only few studies consider the effect of porosity on the air flow development downstream of a tile [6-9]. It has been suggested that the restricted openings on the tiles result in higher momentum of air above the tile surface. Consideration of this excess momentum has been observed to improve the flow prediction [6, 7]. In these investigations the influence of pore size, tile edge blockage and any anterior structure, was not included.
In the present study, influence of tile porosity, air flow rate, pore size, tile edge blockage, tile width and rack recess is examined experimentally, with respect to the flow field development above the tile surface in a controlled laboratory environment. There is a possibility of having racks recessed from the tile edges; hence, this is also included in the present study. A single rack and a single perforated tile are used for the investigation. For all the cases, the tile air flow rate is matched with the rack air requirement. The flow field is measured along a vertical plane through the center of the tile, normal to the tile outlet and rack inlet. Measured pressure loss characteristics across the perforated tile are also discussed. Note that the influence of tile geometry as observed for a single tile can be different from a case where multiple tiles are arranged to form a cold aisle. In a cold aisle, the interaction of flow emerging from adjacent tiles will be important and we plan to investigate this in the future. Here, our objective is to identify the influence of different tile geometrical parameters on the downstream flow development for a single tile in a controlled setting. The experimental results can also serve the purpose of facilitating the development and validation of numerical models which capture these effects, and can be useful for air flow prediction through perforated tiles in data centers.

2. Experimental Setup

2.1 Data Center Layout

Figure 1 shows a representation of a section of the Data Center Laboratory at Georgia Tech. The floor area of the data center test cell is 56 m² (600 sq. ft). The data center has three computer room air conditioning (CRAC) units, one power distribution unit (PDU), and one chilled water distribution unit (CDU), see Figure 1(a). The data center has a single cold aisle, with the width corresponding to two standard tiles (1.22 m, 4 ft). For the present study, only one perforated tile is used, with size of 0.61 m × 0.61 m (2 ft × 2 ft), see Figure 1(b) for the
layout of the data center, the perforated tile under investigation is denoted as “Tile” in the figure. A total of 12 racks are arranged on either side of the cold aisle, however, only one rack (“Server Simulator”) is powered. There are two in-row-coolers at the end of the aisle which are also turned off. The hot air return vents are located above the hot aisles as shown in Figure 1(a). The vent size is 0.61 m × 0.61 m (2 ft × 2 ft). There are two down-flow CRAC units (“1” and “2”) and one up-flow CRAC unit (“3”); see Figure 1(a, b). In the present investigation only one down flow CRAC unit, “2”, is used and the CRAC units “1” and “3” are turned off. CRAC “2” has a variable speed drive (VSD), which is used to control the air flow through the perforated tile under investigation. CRAC “1” acts as a by-pass to allow excess air to be circulated in the loop. This is because only one perforated tile is used in the present investigation that can act as a path for air circulation from CRAC “2”. The depth of the plenum is 0.91 m (3 ft). We used standard meshing software (ICEM-CFD from ANSYS) to generate Figure 1(a,b).

2.2 Plenum Setup

Figure 2 shows plenum setup for the tile opening used in the present investigation. The plenum was ducted from all the four sides using four acrylic sheets to allow the air flow to enter the perforated tile normally. The height of the acrylic sheet is 0.61 m (2 ft), thus allowing open height of 0.3 m (1 ft) for air to enter the ducted region (see Figure 2(b)). An Aluminum honeycomb structure with opening size and thickness of 2.54 cm (1”), and width and length of 0.61 m (2 ft) covering the size of the perforated tile was placed 46 cm (18”) below the tile surface (see Figure 2(a, b)). Honeycomb structure was used to straighten the flow, improve the uniformity and remove the large scale eddies from the flow approaching the perforated tile. The opening of the tube connected to a pressure sensor was placed 23 cm (9”) below the tile surface, and along one of the edges as shown in Figure 2(a, b). The tube opening was oriented
to face upwards so as to avoid the effect of dynamic pressure and hence, static pressure measurements can be obtained. It may be noted that in real data centers, ducted air flow is generally not implemented and transverse air flow may also be present. This can be even more pronounced for shallow plenums, where the transverse velocity as compared to normal velocity cannot be neglected. Here, we focus on the case where the air flow approaching the perforated tile is close to normal, which is characteristic of a fairly deep under floor plenums. In the present experimental setup, due to the ducted passage and the honeycomb structure, it is expected that the air flow upstream of the tile is close to normal.

The plenum pressure was measured using a differential pressure sensor, SDP 1000 – L025 (Sensitron). The sensor measures the mass flow rate by measuring the temperature differential across a heated surface with a known power input. The measured mass flow rate is used to determine the differential pressure across the flow path. The pressure drop in the tube, connecting the sensor and the measurement location, was compensated based on the standard pressure drop correlations for a circular tube for laminar flow. The sensor internally compensates for the ambient air temperature variations. The estimated uncertainty in the plenum pressure was found to be ± 5% of the measured value. Data was acquired every 5 seconds and was averaged over a 40 minute period for reporting the pressure for each case.

Pressure loss factor ($K_{\text{eff}}$) was calculated based on the measured differential plenum pressure with respect to the room pressure ($\Delta P$) and the average inlet velocity ($V_{\text{in}}$) based on the tile air flow rate and total tile area (0.61 m × 0.61 m, 2 ft × 2 ft). The expression is given in Equation (1). Air density is denoted here as $\rho$.

$$K_{\text{eff}} = \frac{\Delta P}{\left(\frac{1}{2} \rho V_{\text{in}}^2\right)}$$

(1)
The uncertainty in calculation of $K_{\text{eff}}$ was estimated to be ±11%. For a sharp edged perforated plate, $K_{\text{eff}}$ is mostly affected by three parameters, namely, effective porosity ($F_{\text{eff}}$), pore Reynolds number ($Re_D$), and tile sheet thickness to pore diameter ratio ($T/D$) [10-16].

The measured $K_{\text{eff}}$ is compared with that obtained from correlations available in the literature. The correlation by Freid and Idelchik (F&I) [10] suggests that $K_{\text{eff}}$ is independent of Reynolds number only for $Re_D > 10^5$, representing a fully turbulent case. However, in this investigation $Re_D \sim 10^3$ (see Table 1), hence, there is influence of $F_{\text{eff}}$, $Re_D$ and $T/D$ on $K_{\text{eff}}$ based on the F&I correlation.

Miller (M) [11, 13] and Maynes’s et al. (MHB) [12] suggested that for $Re_D > 1,000$ and 3,000 respectively, the effect of $Re_D$ is absent on $K_{\text{eff}}$. Hence, for the present study only the influence of tile $F_{\text{eff}}$ and $T/D$ will be reflected in the values of $K_{\text{eff}}$, obtained from these correlations. In these two correlations, the sensitivity of $K_{\text{eff}}$ on $T/D$ is much larger, as compared to that suggested by the F&I correlation.

2.3 Rack and Tile

For the present study, air flow emerging from a single tile and entering an adjacent rack is investigated. The rack adjacent to the perforated tile is a standard 42 U (height) (1U = 4.45 cm, 1.75”) rack populated with four server simulators (APC), as shown in Figure 3(a). Each server simulator has a fan speed setting dial to control the air flow rate passing through it. The expanded view of the fan speed setting dial is shown as associated rectangles. For the present study, no heat load is supplied to the server simulators. For details of the server simulator used here, refer to [17].

The rack air flow rate was measured using an array of 45 (3 (along the width) × 15 (along the height)) sensor units, Accusense F900-0-5-0 (Degree Controls Inc.), each having a thermal anemometer. The array is placed at the back of the server simulator rack. A cloth skirt
is used to direct the air flow through the sensor array and to prevent air leakage, refer to [9] for further details of the tool. Average of sixteen measurements was used to compute the rack air flow rate. The uncertainty was estimated to be ± 10% of the measured value. For the present study, all the four server simulators were set to the same air flow rates.

Perforated steel sheets with circular pores, arranged in staggered pattern (holes on corners of an equilateral triangle) are used as tiles, and are shown in Figure 3(b-g). The details of the perforated tiles are given in Table 1. The thickness of all the tiles is 16 gauge (1.59 mm, 0.06”). The perforated sheets used here have porosity of 40% (Figure 3(b, d-g)) and 23% (Figure 3(c)). For tiles shown in Figure 3(b-d, g), due to the support structure used to place them (edge blockage of 12.7 mm, 0.5”), the open area for air delivery is reduced to 0.58 m × 0.58 m (23” × 23”), as compared to the tile dimension of 0.61 m × 0.61 m (24” × 24”), resulting in lower tile porosity as compared to the sheet porosity. For the tile shown in Figure 3(e), the open area is reduced to 0.53 m × 0.53 m (21” × 21”) by using tape along the edges. For the tile shown in Figure 3(f), the open area is reduced to 0.44 m × 0.58 m (17.5” × 23”) due to the support structure as well as because of the tape along one side.

Volumetric air flow rate through the perforated tile was measured using ADM – 860C (Shortbridge) “Flowhood”, having a velocity sensor grid. The grid calculates flow velocity based on the difference between the total and the static pressures. It has 16 measurement points in the plane of measurement. The effect of temperature and flow restriction due to the measuring device is compensated. The velocity grid is attached to a cloth skirt, which directs the air flow across the grid. It may be noted that the inlet of the cloth skirt has the same dimensions as that of the tile surface, thus ensuring that there is no leakage of air during measurements. Uncertainty in tile air flow measurement was estimated to be ± 5% of the
measured value. CRAC 2 VSD settings were varied to achieve the desired air flow rate through the perforated tile (see Figure 1 for the location of CRAC 2).

Note that the region between the bottom of the rack and the floor is blocked to disallow air from entering through this gap.

2.4 Cases Investigated

Seven cases are investigated to highlight the effect of tile porosity (F_{eff}), air flow rate, pore size, edge blockage, tile width, and rack recess and these are summarized in Table 1. Case 1, is considered as the base case with air flow rate of 0.56 m$^3$/s (1,177 CFM) corresponding to the rack heat load of 10 kW with air temperature rise of 15 °C, even though no heat load is imposed on the racks in the present study. For the base case, the tile sheet porosity is 40%, and due to edge blockage of 12.7 mm (0.5”) (because of the support structure to place the tile) the effective porosity is reduced to 36.7%. For this case, the pore size is 6.35 mm (1/4”), and the rack is placed adjacent to the tile without any recess as summarized in Table 1 (also see Figure 3(b)). From the base case, a single parameter is varied to investigate its effect. For case 2, the tile sheet porosity is 23%, see Table 1 (also refer to Figure 3(c)). For case 3, the air flow rate is 0.83 m$^3$/s (1,766 CFM) (corresponding to the heat load of 15 kW at air temperature rise of 15 °C) (see Table 1 and Figure 3(b)). For case 4, the perforated sheet pore size is 3.18 mm (1/8”) (refer to Table 1 and Figure 3(d)). For case 5, a region of 38.1 mm (1.5”) along the edges is blocked (see Table 1 and Figure 3(e)). For case 6, the tile width is 0.46 m (1.5 ft). The ducted plenum width (not shown here) is also reduced accordingly (refer to Table 1 and Figure 3(f)). For case 7, the rack is recessed by 76.2 mm (3”) (see Table 1 and Figure 3(g)). Note that the rack recess is the distance from the tile edge to the front edge of the rack base. For cases 2-7, all other parameters are same as the base case 1 (values represented by (-) in Table 1).
Reynolds number is calculated based on the pore diameter \((D)\) and the average pore velocity \((V_{\text{in}}/F_{\text{eff}})\) as shown in Equation (2).

\[
Re_D = \frac{\rho \frac{V_{\text{in}}}{F_{\text{eff}}} D}{\mu}
\]  

(2)

Average inlet velocity \((V_{\text{in}})\) is calculated based on the volumetric air flow rate through the tile and the area of 0.61 m \(\times\) 0.61 m \((2\text{ft} \times 2\text{ft})\). For all the cases, the effective porosity \((F_{\text{eff}})\) of the tiles is calculated based on the area of 0.61 m \(\times\) 0.61 m \((24'' \times 24'')\) and included in the parenthesis. The porosity of the perforated sheet \((F)\) is also included in the table.

### 2.5 Particle Image Velocimetry (PIV) Setup

Velocity field is measured in the middle plane covering the width of the tile and height of the rack using a particle image velocimetry (PIV) system, as shown in Figure 4 (also see Figure 1(b)). The origin of the measurement plane is at the tile edge and at the floor. “X” is along the tile width and “Y” is along the rack height, as shown in Figure 4(b). The edges of the measurement plane are denoted as “Tile”, “Rack”, “Top”, and “Aisle”, as shown in Figure 4(a, b). The plane of measurement is located at the centerline of the tile. Air emerging from the perforated tile is seeded with the water based fog particles from a theatrical fog generator (F-100, High End Systems). The fog generator is placed in the plenum upstream of the tile inlet. Here, we have a deep plenum \((0.9\text{m}, 3\text{ft})\) and the fog generator is placed about 1.8m \((6\text{ft})\) away from tile inlet. Hence, the influence of fog generator on the flow field emerging from the tile is expected to be minimal. The plane of measurement is illuminated with a laser light sheet and the scattered light is captured on two Flow Sense (Dantec Dynamics) cameras adjacently placed, so as to cover the width of the tile, see Figure 4(a, b). The laser and the cameras are fixed on a vertical traverse system and the entire system is moved along the height of the rack to measure the velocity field at multiple heights. Finally, the obtained velocity field is stitched.
together to obtain a complete velocity field in the measurement plane. At each location 30 image pairs are used to obtain the average velocity field. The interrogation window size is $64 \times 64$ pixels with 50% overlap, resulting in spatial resolution of about 7 mm. Note that the spatial resolution is larger than the small length scales present from the jets ($<D$) emerging from the tiles, and hence only large scale flowfield features will be discussed here. The particle size was $\sim 10\mu m$ and the corresponding Stokes number was $<< 1$, thus ensuring that the seeding particles follow the air flow field satisfactorily [4, 5].

Air flow rate from the four edges of the measurement plane was calculated, assuming same velocity profile for the depth of the perforated tile (0.61 m, 2 ft), and was scaled with the air flow rate through the tile/rack. Note that there might be velocity variation along the depth of the tile and the calculated air flow rates might be different from the actual flow rates. However, to get a physical feel of the flow rates from different sides, we have scaled it with the inlet flow rate and as we had information in only the middle plane (see Figure 4(a)) we assumed same profile across the depth. The objective here was not to report the actual flow rates from different sides, but to identify trends for the influence of tile geometry on flow field development in the measurement plane. The flow rates are calculated 60 mm above the tile surface (“Tile”), 1,840 mm above the tile surface (“Top”), 20 mm from the aisle center (“Aisle”) and 590 mm from the aisle center (“Rack”), see Figure 4(b). Flow rate is positive along the direction of the arrow. The scaled flow rates are presented along the four sides of the measured velocity field.

3. Results

3.1 Effect of Tile Porosity

Stream traces corresponding to case 1 ($F_{\text{eff}} = 36.7\%$, Figure 5(a)) and case 2 ($F_{\text{eff}} = 21.1\%$, Figure 5(b)) shows that even though the tile air flow rate is same for both the cases,
higher velocity of air above the tile surface is observed for case 2 (lower porosity), as compared to the case 1 (higher porosity). For both the cases, significant amount of air by-pass is observed from the top, and this is similar to the trend observed previously [4, 5]. With decrease in porosity, significantly higher air flow rate is observed from the top (100.1% vs. 67.7%). This may be attributed to the higher momentum of air above the tile surface for lower porosity case due to higher acceleration of air as it passes through a more restricted area. The air exiting from the aisle is observed to reduce for the lower porosity case (-7.0% vs. -17.5%). This may be due to air entrainment from the aisle side (also observed from the profile of streamtraces near the aisle side) which is absent for the case with higher tile porosity. From Figure 5(b), we also note that the value of pressure loss factor ($K_{eff}$) is significantly higher for the lower effective tile porosity case 2. With higher value of $K_{eff}$, higher excess momentum of air is expected above the tile surface, which can lead to higher cold air by-pass from the top [6-8], as also observed here.

The longitudinal velocity above the tile surface is shown in Figure 6(a). From the figure it can be inferred that for case 2 with lower tile porosity, higher velocity of air flow is observed near the tile edges (also see Figure 5(b)). The velocity profile for case 1 with higher tile porosity is nearly uniform with relatively smaller peaks near the tile edges. This can be attributed to higher momentum of air above the tile surface for lower porosity case.

Figure 6(b) shows the longitudinal velocity at the top for the two tile porosity levels. Due to higher momentum of air above the tile surface for lower porosity, significantly higher velocity is observed at the top as compared to the higher porosity case. This can also be inferred from the higher cold air by-pass from the top and reduced efficacy of air to bend and enter the adjacent server rack (refer to Figures 5(a) and (b)). On the other hand, the result also suggest that for an under-provisioned case, where the supplied air flow rate is lower than the
rack air requirement, tile with lower porosity can allow air to reach near the top of the rack and possibly improve the cold air delivery.

It may be noted that the air flow distribution for multiple tiles, in a cold aisle is also significantly affected by the tile porosity. It has been observed that higher non-uniformity in the tile air flow rate is present for higher tile porosities [3, 18, 19]. Hence, on one side higher tile porosity can result in lower cold air by-pass, on the other hand it can lead to non-uniform supply air flow rate distribution in the cold aisle. Hence, important factors and their effects needs to be considered while designing an air flow delivery scheme.

3.2 Effect of Tile Air Flow Rate

Two air flow rates corresponding to the heat load of 10 kW (0.56 m³/s, 1,177 CFM) (case1) and 15 kW (0.83 m³/s, 1,766 CFM) (case 3) at bulk air temperature rise of 15 °C are investigated and the results are shown in Figures 5(a, c) and 6(c, d). From the figure it can be noted that the velocity field scaled with the average inlet velocity \( V_{in} \) is nearly identical. Also, minimal influence on the pressure loss factor \( K_{eff} \) and the flow rates from the four sides of the measurement plane are observed. This suggests that the influence of air flow rate in the investigated range is minimal.

Figure 6(c, d) shows the scaled longitudinal velocity above the tile surface and near the top end. The scaled velocity at both tile and top ends shows very similar profiles, which further confirms that the influence of air flow rate is minimal in the range investigated here. For fully turbulent flow emerging from a perforated sheet, the flowfield is independent of \( Re_\theta \) [10-13]. Hence, it appears that the flow field for the air flow rate range studied is in the fully turbulent regime. This observation can be useful while implementing numerical models that are valid for fully turbulent flows.
Note that ReD can be varied via change in either the pore diameter or the pore velocity (or tile air flow rate), refer to Equation 2. In this study, ReD is varied by increasing the flow rate through the tile, while preserving the same pore diameter. Change in pore diameter may not result in similar flow field, if other length scales (such as tile thickness, width and length, and rack height) are not scaled proportionately. This will be investigated next, where the flowfield development for the two pore sizes is compared.

3.3 Effect of Tile Pore Size

The effect of two pore sizes of 3.18 mm (1/8”) (case 4) and 6.35 mm (1/4”) (case 1) is investigated in Figures 5(a, d) and 6(e, f). Stream traces for the cases 1 and 4 are shown in Figure 5(a, d) and it can be observed that there is non-negligible difference between the two cases. For the smaller pore size (1/8”), air is not observed to be leaving the measurement plane from the aisle side (Figure 5(d)), as seen with the larger pore size (1/4”) (Figure 5(a)) and this resulted in air entrainment from the aisle (5.7%), as compared to air exiting from the aisle side (-17.5%). With smaller pore size, the number of pores is larger and the pore to pore center spacing is smaller (refer to Table 1), resulting in a greater number of closely spaced jets. Smaller pore size will also result in faster decay of the jets, as the jet decay length varies linearly with the pore diameter [15], and thus reducing the region of influence of entrainment and flow development above the tile surface. This may be the reason for different flow profiles near the aisle for the two cases. Minimal influence on pressure loss factor (K_{eff}) for the two pore sizes is observed.

Figure 6(e, f) shows the longitudinal velocity profile near the tile surface (Figure 6(e)) and near the top end (Figure 6(f)) of the measurement plane. From Figure 6(e) it can be observed that the velocity profile is slightly different for the two cases near the tile surface. For the smaller pore size case, slightly higher velocity is observed near the rack end of the tile (X ~
600 mm). This may be due to faster decay of the jets with smaller pore size, resulting in smaller region of influence of higher momentum. As the rack is adjacent to the tile, the air sucked by the rack may result in acceleration of air emerging from the tile in the region adjacent to the rack. This effect is slightly delayed with higher pore size case. Note that the velocity profile is plotted at a distance of 60 mm from the tile surface, which corresponds to ~19D for the smaller pore size case (3.18 mm, 1/8”), and at ~9D for the larger pore size case (6.35 mm, 1/4”), where D is the pore diameter. Note that the region of influence for excess momentum above the tile surface was considered to be 12D [8].

Figure 6(f) shows the longitudinal velocity profile at the top, which seems very similar for the two pore sizes investigated here. It is possible that the influence of pore size on the flow at the top may not be evident from these measurements as the two pore sizes are very small as compared to the tile size. Investigation with larger pore sizes may provide more insight for the same.

### 3.4 Effect of Blocked Tile Edges

Generally, commercially available perforated tiles do not have perforations extending till the tile edges and they have solid edge strips that do not allow air passage through them. The effect of blocked tile edges is investigated by sealing the edge strips for width of 38.1 mm (1.5”) (case 5) and the results are shown in Figure 7(b). As compared to the base case 1, with 12.7 mm (0.5”) of edge blockage due to support structure, the flow field is significantly altered due to larger edge blockage. Higher velocity is observed above the tile surface and this can, in part, be attributed to the reduced effective porosity with larger blocked tile edge (30.6% vs. 36.7%). This results in higher pressure loss factor (K_{eff}) (15.0 vs. 9.7). From the calculated flow rates it can be observed that, significantly higher air by-pass from the top (109.3% vs. 67.7%) is present for the case with larger blocked edges. Note that the effective
porosity for this case (5) is higher (30.6% vs. 21.1%) than that for lower porosity case (2). Still, higher amount of air by-pass is observed from the top for this case (109.3% vs. 100.1%). This highlights the importance of tile geometry on the flow features above the tile. The results also suggest that having higher tile edge blockage can be detrimental for a fully provisioned case. On the other hand, for an under provisioned case the edge blockage may be helpful for air to reach near the top end of the rack, resulting in improved air delivery.

Note that with larger blockage at the tile edges, the calculated air flow rate near the tile surface is significantly higher (123.3% vs. 110.9%). This is due to the consideration that same flow profile is present for 0.61 m (2 ft) depth. In reality, the region near the blocked edges will have significantly lower velocity, and hence would contribute lower to the total calculated flow rate. For the case with blocked edges, the air escaping from the aisle side is also reduced (4.9% vs. 17.5%) and this can be observed from the profile of stream traces near the aisle side (Figure 7(b)), where air entrainment is observed near the tile surface from the aisle side.

The longitudinal velocity profile at the top and tile for the effect of blocked edges is shown in Figure 8(a, b). From the figure it is observed that the velocity is significantly higher at the top for the case with larger edge blockage (Figure 8(b)). This can be attributed, in part, to the lower effective porosity with blocked edges, which results in higher air momentum above the tile surface, and hence higher cold air by-pass from the top. At the tile surface, higher velocity and smaller width of air entry for the case with blocked edges can be observed, see Figure 8(a).

3.5 Effect of Tile Width

Generally, data centers have 1.22 m (4 ft) wide cold aisle composed for two standard 0.61 m (2 ft) tiles placed adjacenty. However, the aisle width can be reduced to 0.91 m (3 ft)
by using only one 0.91 m (3 ft) wide tile instead of two standard (0.61 m, 2 ft long) perforated tiles to save the floor space. Here, the 1.22 m (3 ft) cold aisle is simulated (case 6) by reducing the width of the tile from 0.61 m (2 ft) to 0.46 m (1.5 ft) (case 1) and the stream traces for this case are shown in Figure 7(c). The stream traces shows that most of the air exiting the perforated tile enters the adjacent rack which results in considerably lower (39.1% vs. 67.7%) air by-passing from the top. Note that in this case 6, the effective tile porosity is lower than the porosity corresponding to the base case 1 (28.0% vs. 36.7%); even then there is reduction in the cold air by-pass from the top. This suggests significantly improved air delivery, as compared to the base case 1 with standard 0.61 m (2 ft) wide tile (see Figure 7(a)). This further emphasizes the importance of choosing appropriate tile geometry to achieve desired air flow field above the tile surface. The stream traces in Figure 7(c) also shows air entrainment from the aisle (10.5% vs. -17.5%) and the entrained air escaping from the top.

The longitudinal velocity profile for the case with reduced tile width is shown in Figure 8(c, d). The velocity profiles show significantly reduced air velocity at the top for the reduced tile width case, especially near the aisle center. Though, the velocity is higher near the rack as compared to the base case 1, the overall effect is reduced air by-pass from the top (39.1% vs. 67.7%) (also see Figure 7(a, c)). At the tile, higher velocity is observed as the effective porosity for this case 6 is 28.0% as compared to 36.7% for the base case 1. Reduced porosity will result in higher momentum of air above the tile surface, for the same flow rates; however, in this case, smaller tile width resulted in significantly reduced air by-pass from the top.
Note that, reduction in aisle width may not be practically feasible in some cases and reducing the tile width by blocking a portion of the standard tile (as done here) can be used to achieve improved air delivery.

3.6 Effect of Rack Recess

Stream traces for the case 7 with 76.1 mm (3”) rack recess are shown in Figure 7(d). Note that rack recess is the distance from the tile edge to the front edge of the rack base. The flow field looks very similar to the base case with no recess (Figure 7(a)). Air by-pass from the top (72.0% vs. 67.7%) and air escaping from the aisle (-18.8% vs. -17.5%) are similar with and without rack recess. This suggests that the effect of rack recess is minimal on the flowfield above the tile surface. The calculated air flow rate from the rack side is lower (89.6% vs. 105.9%) for the case with rack recess and this may be due to larger distance from the rack inlet and the flow calculation line.

The longitudinal velocity profiles at the tile and the top are shown in Figure 8(e, f). From the figure, it can be inferred that the velocity profiles are very similar at both tile and the top surface, which further confirms minimal effect of rack recess on the flowfield above the tile surface. It may be noted that for larger rack recess the flow field may get affected and this needs to be investigated further.

For all the cases, the measured value of $K_{eff}$ is higher than that suggested by correlations, see Figures 5 and 7. Note that these correlations are developed for ducted flows, where there is a possibility of pressure recovery in the downstream, however, in the present case the flow downstream of the tile is not ducted and this may result in higher value of $K_{eff}$ as compared to ducted flows. Note that for all the cases, the calculated air flow rate from the tile and rack are similar.
4. Conclusions

Air flow development above a perforated tile and its entry into an adjacent rack are investigated. With decrease in effective tile porosity from 36.7% to 21.1%, significantly higher air by-pass from the top is observed, possibly due to higher momentum of air above the tile surface for the lower porosity case. Increase in tile/rack air flow rate from 0.56 m$^3$/s (1,177 CFM) to 0.83 m$^3$/s (1,766 CFM) resulted in nearly identical flow profile, suggesting fully turbulent flow regime. Reduction in pore size from 6.35 mm (1/4”) to 3.18 mm (1/8”) had small but non-negligible effect on the flow field, especially, near the tile surface at both rack and aisle ends. This is possibly due to smaller flow development region for smaller pore size. The results also suggest that the influence of pore size cannot be neglected and should be included in the numerical models for improved predictive capability.

Edge blockage of 38.1 mm (1.5”) resulted in significantly higher air by-pass from the top as compared to the base case with 12.7 mm (0.5”) of edge blockage. The air by-pass was even higher than the case with lower effective tile porosity of 21.1%, even though the effective porosity for the case with edge blockage was higher (30.6%). Reduction in the tile width to 0.46 m (1.5 ft) from 0.61 m (2 ft) resulted in significantly improved air delivery with considerably lower air by-pass from the top, even though the effective porosity was lower than the base case porosity (28.0% vs. 36.7%). These two cases show the importance of appropriately considering the tile geometry apart from porosity and pore size to achieve the desirable result. For the case with rack recess of 76.1 mm (3”) from the tile edge, the flow field did not reveal significant difference in the air by-pass or entrainment characteristics as compared to the case without rack recess. Overall, present investigation suggests significant influence of porosity and tile geometry on flow development and the parameters can be appropriately chosen to improve air flow delivery to the adjacent rack.
Acknowledgments

This research is supported by the National Science Foundation Industry/University Cooperative Research Center on Energy Smart Electronic Systems (ES2). Additional support from Degree Controls, Inc. and Triad Tiles, Inc. is acknowledged.

References


List of Table Captions

Table 1. Cases investigated, supply air temperature = 20 °C (68 F), no heat load from the racks, tile width (W) and length (L) = 0.61 m (2ft), tile thickness (T) = 1.59 mm (1/16”). (-) shows value same as the base case.
List of Figure Captions

Figure 1. Data Center Laboratory at Georgia Tech.

Figure 2. Plenum setup for the perforated tile under investigation.

Figure 3. Rack and the tiles under investigation.

Figure 4. Particle image velocimetry (PIV) setup.

Figure 5. Streamtraces along the middle plane, colored with scaled velocity magnitude and pressure loss factors for cases 1-4.

Figure 6. Longitudinal velocity (a,c,e) 60 mm above the tile surface and (b,d,f) 1840 mm above the tile surface at the top for cases 1-4.

Figure 7. Streamtraces along the middle plane, colored with scaled velocity magnitude, and pressure loss factors for cases 1, 5-7.

Figure 8. Longitudinal velocity (a,c,e) 60 mm above the tile surface and (b,d,f) 1840 mm above the tile surface at the top for cases 1, 5-7.
Table 1. Cases investigated, supply air temperature = 20°C (68 F), no heat load from the racks, tile width (W) = 0.61 m (2 ft), tile length (L) = 0.61 m (2ft), tile thickness (T) = 1.59 mm (1/16”). (-) shows value same as the base case.

<table>
<thead>
<tr>
<th>Case #</th>
<th>Tile porosity (F) (Effective porosity, Feff)</th>
<th>Air flow rate (tile &amp; rack) (Q)</th>
<th>Tile pore size (D)</th>
<th>Pore-pore center spacing (P)</th>
<th>T/D</th>
<th>ReD</th>
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Paper# EP-14-1017