

Airflow distribution through perforated tiles in raised-floor data centers

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Abstract

Raised-floor data centers are the most commonly used facilities for housing computer and telecommunication equipment. To adequately cool this equipment, the cooling air through perforated tiles must be distributed properly. The airflow distribution depends on the pressure distribution or the flow field in the space under the raised floor (plenum); it is a complex function of a large number of variables, including the size of the plenum, the open area of the perforated tiles, the locations and flow rates of the computer room air conditioner (CRAC) units, and the size and location of the under-floor obstructions like cables and pipes. In this article, the effect of these parameters on the airflow distribution is studied using an idealized one-dimensional computational model. Within the one-dimensional framework, the airflow distribution is governed by two dimensionless parameters: one related to the pressure variation in the plenum and the other to the frictional resistance. Results, in terms of distributions of pressure in the plenum and flow rates through the perforated tiles, are presented over a range of values of these two parameters. These results provide an understanding of the fundamental fluid mechanical processes controlling the airflow distribution through the perforated tiles. The one-dimensional model is used to calculate flow rates for two possible arrangements of the CRAC units, and these results are compared with those given by a three-dimensional model.

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1. Introduction

Data centers are facilities that house computer servers, data storage systems, and telecommunications equipment. To ensure that these computer systems function reliably, they must be adequately cooled. Each computer unit must receive a certain minimum amount of cooling air, determined by its heat generation rate. Thus, the key to guarantee equipment reliability is to ensure that the cooling air distributes properly throughout the data center, that is, the supplied airflow meets the airflow demand at each location. A successful design of the cooling system requires an understanding of the

fundamental mechanisms governing the distribution of cooling air in data centers.

Most of the current data centers are raised-floor facilities (Fig. 1). These facilities deploy raised (false) floors and use the space (plenum) between the underside of the raised floor and the concrete subfloor to supply cooling air to the equipment. The raised floor typically consists of $0.610\text{ m} \times 0.610\text{ m}$ ($2\text{ ft} \times 2\text{ ft}$) floor panels supported on pedestals on the floor slab. The panels at selected locations are replaced by perforated tiles, and racks containing equipment are placed next to these tiles. Also mounted on the raised floor are the computer room air conditioner (CRAC) units, which push cold air into the plenum and pressurize it. The higher pressure in the plenum forces the cold air to flow through the perforated tiles; this air enters the computer room and provides cooling for the equipment in the nearby racks.

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Nomenclature

A	area
d_h	hydraulic diameter
f	friction coefficient
K	flow loss factor, Eq. (4)
L	plenum length
p	plenum pressure
P	dimensionless pressure, Eq. (8d)
p_0	ambient pressure above the raised floor
u	axial velocity

u_{in}	axial velocity at the plenum inlet
U	dimensionless axial velocity, Eq. (8b)
x	dimensional axial coordinate
X	dimensionless axial coordinate, Eq. (8a)
v	lateral velocity
V	dimensionless lateral velocity, Eq. (8c)
β	fractional open area of perforated tile
η	area ratio, Eq. (3)
ρ	density
Φ	frictional resistance parameter, Eq. (14)
Ψ	pressure variation parameter, Eq. (13)

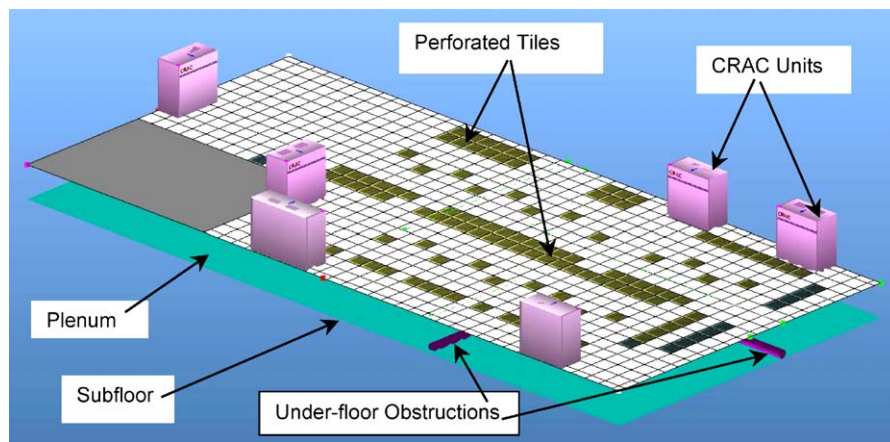


Fig. 1. Schematic of a raised-floor data center, showing perforated tiles, CRAC units, and under-floor obstructions.

Thus, the under-floor plenum of a raised-floor data center serves as the distribution chamber for the cooling air.

The recommended arrangement for the perforated tiles and the equipment racks on the raised floor is the so-called “cold aisle–hot aisle” arrangement [1], shown in Fig. 2. A cold aisle is the region where perforated tiles are placed. On each side of a cold aisle, computer racks are positioned with their intake sides facing the cold aisle. A hot aisle is the region between the back ends of two rows of racks. The cooling air from the cold aisles is drawn in by the fans inside the equipment in the nearby racks; this air heats up and is exhausted from the back of the equipment into the hot aisles. From the hot aisles, the heated air returns to the inlets of the CRAC units. The cold aisle–hot aisle arrangement minimizes the mixing of cold and hot streams and improves effectiveness of the cooling air.

In raised-floor data centers, the distribution of flow rates through perforated tiles (lateral flow distribution) is linked to the fluid mechanics in the plenum. The lateral flow rates are proportional to the local pressure drop (pressure in the plenum minus pressure above the raised floor) across the tiles. In real-life data centers, the

pressure variations above the raised floor are small compared to the pressure differentials across the perforated tiles and can be neglected; that is, the pressure above the raised floor is nearly uniform. (This topic has been discussed in detail by Karki et al. [2].) Thus, the lateral flow rates depend directly on the local pressure in the plenum and are, therefore, controlled by the same parameters that govern the plenum flow field. These parameters include the size of the plenum, the layout and open area of the perforated tiles, the locations and flow rates of the CRAC units, and the flow resistance/blockage of the under-floor obstructions like cables and pipes. An understanding of the effect of these parameters on the lateral flow rates is essential for achieving the desired airflow distribution.

The objective of this investigation is to study, using a mathematical model, the relationship between the lateral flow distribution and the governing parameters outlined in the preceding section. As discussed earlier, this study requires examination of the flow field in the data-center plenum. In the present approach, the flow field is calculated using a one-dimensional model. The pressure above the raised floor is assumed to be uniform. This assumption has two ramifications:

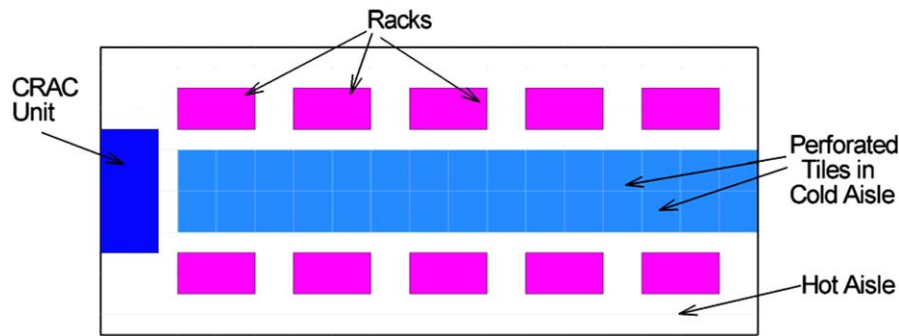


Fig. 2. The hot aisle-cold aisle arrangement of perforated tiles and racks (plan view).

(a) the calculation of lateral flow rates requires only the pressure distribution in the plenum, and (b) this pressure distribution can be obtained by solving the fluid flow equations in a calculation domain comprising just the plenum space, with the boundary condition of uniform pressure above the perforated tiles. The plenum-based model is simpler and computationally more efficient than a model that encompasses the entire data center (plenum and the space above the raised floor).

The fluid mechanics in a data-center plenum is identical to that in a dividing manifold. The role of perforated tiles in a plenum is same as that of exhaust ports in a manifold. The flow in manifolds has been a subject of several prior studies (e.g., [3,4]). These studies, however, are directed towards the process industry, where the main concern is the uniformity of lateral flow through the ports. Our objective is to present results for conditions encountered in data centers and interpret these results from the viewpoint of airflow management.

Three-dimensional counterpart of the plenum-based model adopted here has been the subject of a few recent studies. Karki et al. [2] have applied it to a real-life data center and have shown that the calculated airflow rates are in good agreement with the measured values. Guggari et al. [5] have compared, for a prototype data center, the results from this model with those given by another model that covers the entire data center. The two sets of results are shown to be in excellent agreement. Karki et al. [6] have used the plenum-based model to study various techniques for controlling the airflow distribution in raised-floor data centers.

2. The computational model

2.1. Physical situation

The modeled plenum is shown in Fig. 3. It represents the repeating section of an ideal data center that follows the cold aisle–hot aisle arrangement. Flow enters from the left boundary of the plenum. The right and bottom boundaries are closed, whereas perforated tiles are

placed on the top boundary. (The nature of the right boundary depends on the actual configuration; it can be a solid wall or a symmetry boundary.) The pressure above the perforated tiles is uniform. The sidewalls, parallel to the plane of the paper, are symmetry planes. The cross-sectional area of the plenum and the number of tiles are assumed to be constant along the length of the plenum. The objective is to calculate the distributions of the axial velocity and pressure in the plenum and flow rates (velocity) through the perforated tiles.

The one-dimensional model is appropriate only when the pressure variation in the plenum is primarily along the axial direction. This can be achieved only under the following conditions:

- the perforated tiles are arranged in rows and the CRAC units are located within these rows,
- the plenum height is not too large, and
- there are no discrete obstructions in the plenum.

Although these conditions appear stringent, they are met, at least partially, in many real-life data centers, especially the newer ones that follow the cold aisle–hot aisle arrangement and have a clean plenum. (The presence of obstructions in the plenum leads to nonuniformity in the lateral flow distribution. Therefore, many data center designs now call for a clean plenum.) Thus, the one-dimensional model can be used to design and analyze a certain class of data centers. It is particularly useful at the design stage, where various concepts are evaluated without introducing the complications of obstructions.

2.2. Governing equations

The flow field in the plenum is governed by the continuity and momentum equations. For a one-dimensional situation, these equations can be written as Continuity equation:

$$\frac{d}{dx}(\rho u) = -\rho \left(\frac{\eta}{L} \right) v. \quad (1)$$

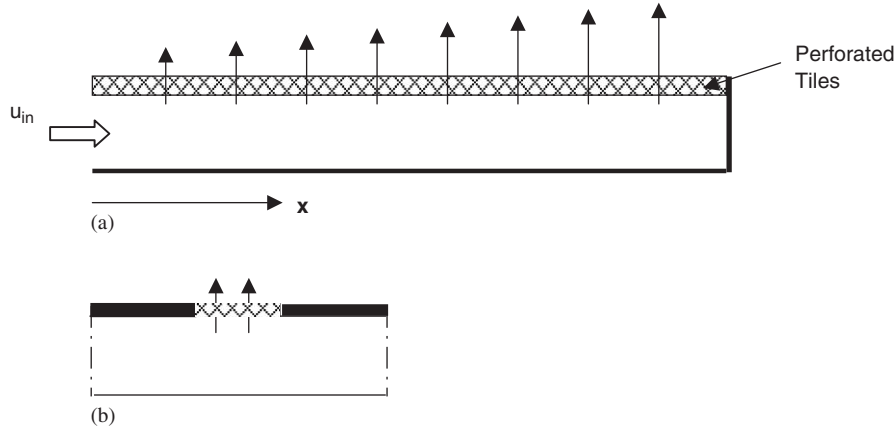


Fig. 3. The modeled plenum. (a) Front view, and (b) end view.

Momentum equation:

$$\frac{d}{dx}(\rho u u) = -\frac{dp}{dx} - \frac{2f}{d_h} \rho u^2 - \rho \left(\frac{\eta}{L} \right) v u. \quad (2)$$

The momentum equation expresses the balance between the change in momentum, pressure force, frictional resistance, and the momentum carried away by the fluid exiting through the perforated tiles.

In the above equations, η is the ratio of the total area of perforated tiles A_{Tile} and the cross-sectional area of the plenum (width $\times$ height) A_{cs} , that is,

$$\eta = \frac{A_{\text{Tile}}}{A_{\text{cs}}}. \quad (3)$$

The hydraulic diameter d_h is taken as twice the plenum height. The friction coefficient f includes contributions from wall shear stress and the flow resistance of support structures and other distributed obstructions in the plenum.

The outflow velocity v is related to the local pressure drop across the perforated tiles:

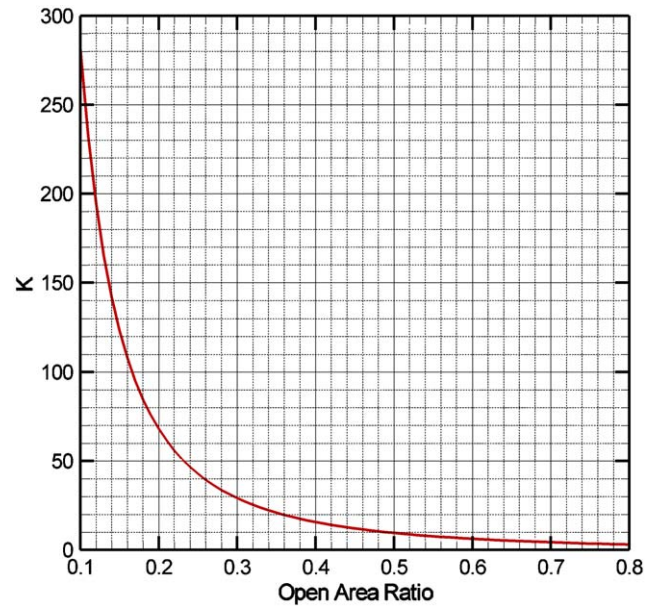
$$p - p_0 = \frac{1}{2} K \rho v^2, \quad (4)$$

where p is the pressure in the plenum, p_0 is the pressure above the perforated tiles (ambient pressure), and K is the flow loss factor (flow resistance) for the perforated tiles.

The flow exiting a perforated tile breaks up into a number of small high-velocity jets, which coalesce into a small-velocity stream. The loss of kinetic energy of these high-velocity jets is primarily responsible for the pressure loss across a perforated tile. An empirical formula for K , supported by a large number of measurements, is [7]

$$K = \frac{1}{\beta^2} (1 + 0.5(1 - \beta)^{0.75} + 1.414(1 - \beta)^{0.375}), \quad (5)$$

where β is the fractional open area of the perforated tile. The pressure drop given by this formula agrees well with

Fig. 4. Variation of K factor with open area.

the data available from the manufacturers of perforated tiles. Fig. 4 shows the variation of K with the open area.

Eqs. (1), (2), and (4) can be manipulated, by eliminating v , to obtain the governing equations for the plenum flow field in terms of u and p only. The resulting equations are

$$\frac{d}{dx}(\rho u) = -\rho \left(\frac{\eta}{L} \right) \left(\frac{2}{\rho K} \right)^{1/2} (p - p_0)^{1/2}, \quad (6)$$

$$\rho u \frac{du}{dx} = -\frac{dp}{dx} - \frac{2f}{d_h} \rho u^2. \quad (7)$$

Eqs. (6) and (7) describe the velocity and pressure fields in the plenum. Eq. (4) provides the distribution of outflow velocity (lateral flow rate) from known pressure field in the plenum.

2.3. Boundary conditions

At the inlet ($x = 0$), the axial velocity is known from the specified flow rate into the plenum. At the closed end ($x = L$), the velocity is zero. The latter condition implies that all the fluid entering the plenum is discharged before the closed end of the plenum is reached. The ambient pressure p_0 is also known. These boundary conditions are sufficient to solve the above set of equations.

2.4. Governing parameters

To identify the parameters governing the fluid flow in the plenum, Eqs. (6), (7), and (4) and the boundary conditions are rewritten in terms of dimensionless variables:

$$X = \frac{x}{L}, \quad (8a)$$

$$U = \frac{u}{u_{\text{in}}}, \quad (8b)$$

$$V = \frac{v}{u_{\text{in}}}, \quad (8c)$$

$$P = \frac{p - p_0}{(1/2)\rho u_{\text{in}}^2}. \quad (8d)$$

The resulting governing equations and boundary conditions are

$$\frac{dU}{dX} = -\frac{\eta}{\sqrt{K}} P^{1/2}, \quad (9)$$

$$\frac{d}{dX}(U^2) = -\frac{dP}{dX} - \frac{4fL}{d_h} U^2, \quad (10)$$

$$P = KV^2 = \frac{K}{\eta^2} (\eta V)^2, \quad (11)$$

$$U(X=0) = 1, \quad (12a)$$

$$U(X=1) = 0. \quad (12b)$$

These equations involve two dimensionless governing parameters

$$\text{Pressure variation parameter, } \Psi = \frac{\eta}{\sqrt{K}}. \quad (13)$$

$$\text{Frictional resistance parameter, } \Phi = \frac{4fL}{d_h}. \quad (14)$$

Note that the quantity ηV , Eq. (11), is the dimensionless lateral flow rate *per unit axial length*. When the lateral

flow rate is expressed in this form, the loss factor K does not appear as an independent parameter.

The parameter Ψ characterizes the extent of pressure variation in the plenum relative to the pressure drop across the perforated tiles. It controls the degree of nonuniformity in the lateral flow distribution; an increase in the value of Ψ increases the nonuniformity. The parameter Φ characterizes the strength of the frictional resistance relative to the flow inertia.

When f is taken as constant, the dimensionless equations do not explicitly involve the inlet velocity or the Reynolds number. Thus, the flow field in the plenum (hence the lateral flow distribution), expressed in terms of dimensionless variables, is independent of the flow rate into the plenum. The corresponding dimensional variables simply scale with the inlet flow rate. Since, for typical flow conditions in data centers, f has a relatively weak dependence on the Reynolds number, this scaling property is valid for most practical situations.

2.5. A limiting case

When all perforated tiles are identical (same K values) and the frictional resistance is negligibly small ($\Phi \approx 0$), Eqs. (9) and (10) can be combined to obtain a single equation with U as the only unknown:

$$\frac{d}{dX}(U^2) + \frac{1}{\Psi^2} \frac{d}{dX} \left(\frac{dU}{dX} \right)^2 = 0. \quad (15)$$

Eq. (15) can be solved analytically under the condition $dU/dX \neq 0$; the resulting distributions of the axial velocity and the lateral flow rate, derived from Eq. (11), are

$$U(X) = \frac{\sin \Psi(1-X)}{\sin \Psi}, \quad (16)$$

$$\eta V(X) = \Psi \frac{\cos \Psi(1-X)}{\sin \Psi}. \quad (17)$$

2.6. Range of applicability of the model

The one-dimensional model requires that the pressure in the plenum be higher than the ambient pressure above the raised floor; it does not admit as valid solution negative plenum pressures, i.e., reverse flow through the perforated tiles ($V < 0$). Thus the model is appropriate only up to the limiting condition of incipient reverse flow ($V = 0$), which depends on Ψ and Φ . It will give erroneous results when applied for conditions that in reality would produce negative plenum pressures. For situations where Φ is small, Eq. (17) shows that reverse flow begins at $\Psi = \pi/2$; hence, for such conditions, the one-dimensional model is appropriate if $\Psi < \pi/2$. (The actual geometric conditions at which this limit is reached are discussed later.)

3. Results and discussion

3.1. Numerical details

The governing equations were solved using one-dimensional variant of the finite-volume method for calculation of the flow field [8]. The loss factor K and the friction coefficient f were taken as constant. The numerical results were obtained on a uniform grid comprising 160 control volumes. Use of finer grid spacing produced negligible changes ($<0.5\%$) in the local values of velocities and pressures. The results, in the form of axial distributions of dimensionless pressure (P) and lateral flow rate per unit axial length (ηV), are presented over a range of the values of Ψ and Φ . (Note that the quantity ηV represents local lateral flow rate per unit axial length. It must be integrated over the axial length covering a tile to obtain the *total* volumetric flow rate through perforated tiles at a *given* axial location. This total flow rate must be divided by the number of tile rows to obtain the flow rate *per tile*.)

3.2. Remarks on the values of Ψ and Φ

To get a feel for the values of the two governing parameters and how they are affected by changes in the plenum dimensions and the number and open area of perforated tiles, consider a plenum with the specifications given in Table 1.

The perforated tiles are assumed to cover the entire length of the plenum. Thus, there are two rows of perforated tiles, each with 15 tiles.

With these specifications, we have:
cross sectional area of plenum = 1.30 m^2 ;

total area of perforated tiles = 11.16 m^2 ;

area ratio, $\eta = 11.16/1.30 = 8.58$;

$$\Psi = \frac{\eta}{\sqrt{K}} = \frac{8.58}{\sqrt{42.8}} = 1.31;$$

$$\Phi = \frac{4fL}{d_h} = \frac{4 \times 0.005 \times 9.144}{2 \times 0.3048} = 0.3.$$

Let us now briefly discuss how these reference values of Ψ and Φ are affected when certain quantities are

changed.

- A change in the number of perforated tiles or their open area (loss factor) causes Ψ to change without affecting Φ . For example, if there are only 15 tiles (just one row of tiles) with 25% open area, $\Psi = 0.65$; if there are 30 tiles with open area of 20% ($K = 68$), $\Psi = 1.04$.
- A change in the plenum length causes Φ to change without affecting Ψ . For example, if the plenum length is changed to 18.29 m (60 ft) with just one row of 30 tiles, $\Phi = 0.6$.
- A change in the plenum height, however, affects both Ψ and Φ . For example, if the plenum height is changed to 0.457 m (18 in), $\Psi = 1.03$ and $\Phi = 0.2$.

For the specifications in Table 1, the limiting condition of $\Psi = \pi/2$, which marks the onset of reverse lateral flow when frictional effects are small, can be achieved by changing the plenum height to 0.254 m (10.0 in) or by using perforated tiles with open area of 30% ($K \approx 30$). In this manner, this simplified one-dimensional analysis allows us to determine the conditions that would lead to reverse flow through the perforated tiles.

In the following sections, results are presented in terms of dimensionless variables with either Ψ or Φ as the parameter. To interpret these results, it is useful to relate changes in the values of Ψ and Φ to changes in a single variable related to the plenum geometry or the perforated tiles. For this purpose, a change in the value of Ψ at a fixed Φ is best thought of as a change in the open area of perforated tiles (or the loss factor) with the plenum dimensions and total area of perforated tiles remaining fixed. Similarly, a change in the value of Φ at a fixed Ψ can be interpreted as varying the plenum length keeping fixed the remaining plenum dimensions and the open area and loss factor of perforated tiles.

3.3. Comparison with analytical solution

To verify the accuracy of the computed solution on the chosen grid, simulations were made for flows with no frictional resistance, and the results were compared with the analytical solution, given in Eqs. (16) and (17). Fig. 5 shows a representative comparison; the two sets of results are in excellent agreement. Note that in this simulation the value of $\Psi (= 1.5)$ is very close to the limiting value of $\pi/2$, beyond which reverse flow occurs. Here the inlet pressure is slightly above zero; at $\Psi = \pi/2$, it will become zero. For $\Psi > \pi/2$, the one-dimensional model would give zero pressure over a finite length starting at the inlet. However, under these conditions, the real flow usually produces negative pressure and reverse lateral flow.

Table 1
Specifications for reference plenum

Variable	Value
Plenum length	9.144 m (30 ft)
Plenum width	4.267 m (14 ft)
Plenum height	0.3048 m (12 in)
Side dimensions of a perforated tile	0.610 m (2 ft)
Total number of perforated tiles	30
Open area of perforated tiles	25% ($K = 42.8$)
Coefficient of friction (f)	0.005

3.4. Distributions of lateral flow and plenum pressure

Figs. 6–9 show the distributions of pressure and lateral flow rate for a range of values of the parameter Ψ , with the friction parameter Φ fixed at 0.4, 2.0, 4.0, and 10.0, respectively. A quick glance at these results shows that, although the distributions depend strongly on the values of Ψ and Φ , the effect of varying Ψ at a fixed Φ is qualitatively similar at all values of Φ . As discussed earlier, the parameter Ψ is a measure of the pressure variation within the plenum, relative to the pressure drop across the perforated tiles. When Ψ is small, a large pressure drop is required to force the fluid out through the perforated tiles. For these conditions, the pressure levels in the plenum are large, and the pressure variations in the plenum are small compared to the

pressure drop across the perforated tiles. Thus, the plenum behaves like a constant-pressure chamber, and the lateral flow distribution is nearly uniform. As the value of Ψ is increased, the pressure levels in the plenum drop and the pressure variations become comparable to, or even larger than, the pressure drop across the perforated tiles. Consequently, the lateral flow distribution becomes more nonuniform.

At low values of Φ ($\Phi = 0.4$), Fig. 6, the frictional resistance is small compared to the rate of change in momentum, and the pressure distribution is controlled by the flow inertia, irrespective of the value of Ψ . Thus, a decrease in axial velocity is accompanied by an increase in pressure and vice versa. Because the fluid is being extracted through the perforated tiles, the axial velocity decreases continuously along the length of the plenum, causing the pressure to increase. Consequently, the lateral flow rate, which is proportional to the local plenum pressure, is lowest near the inlet ($X = 0$) and increases monotonically along the length of the plenum, reaching a maximum value at the closed end.

As the value of Φ is increased ($\Phi = 2.0$), Fig. 7, frictional effects begin to influence the pressure distribution and tend to cause a *pressure drop* along the length of the plenum. The degree to which friction modifies the pressure distribution depends on the local axial velocity (frictional resistance) and the local pressure gradient. The effect of friction is first felt near the inlet, where the axial velocities are large, and at large values of Ψ , which represent conditions that result in smaller pressure gradients. It is evident at $\Psi = 1.5$, where the pressure *decreases* near the inlet for some distance and then begins to rise. In contrast, for $\Psi = 1.5$ at $\Phi = 0.4$, the pressure increases all along the plenum length. The maximum pressure at $\Phi = 2.0$, however, still occurs at the closed end. (The lateral flow distribution mimics the pressure distribution.) At lower values of Ψ , the pressure

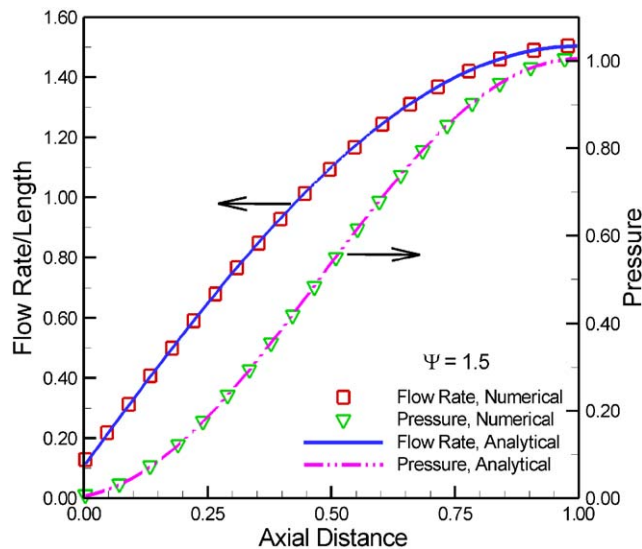


Fig. 5. Comparison of numerical and analytical solutions for a flow without frictional resistance.

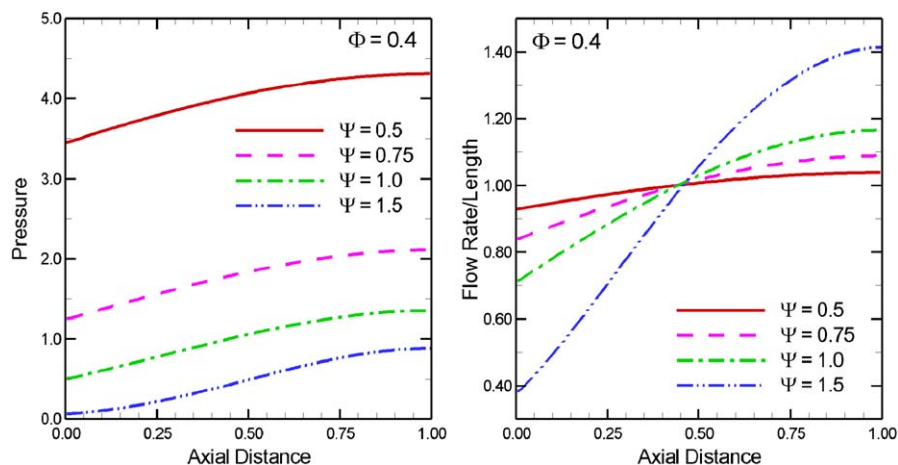


Fig. 6. Distributions of pressure and lateral flow rate for various values of Ψ at $\Phi = 0.4$ (short plenum).

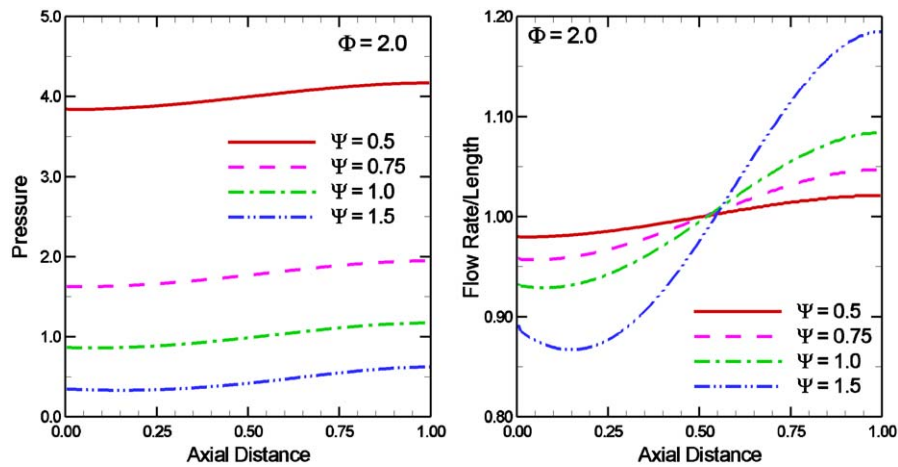


Fig. 7. Distributions of pressure and lateral flow rate at various values of Ψ at $\Phi = 2.0$ (plenum of moderate length).

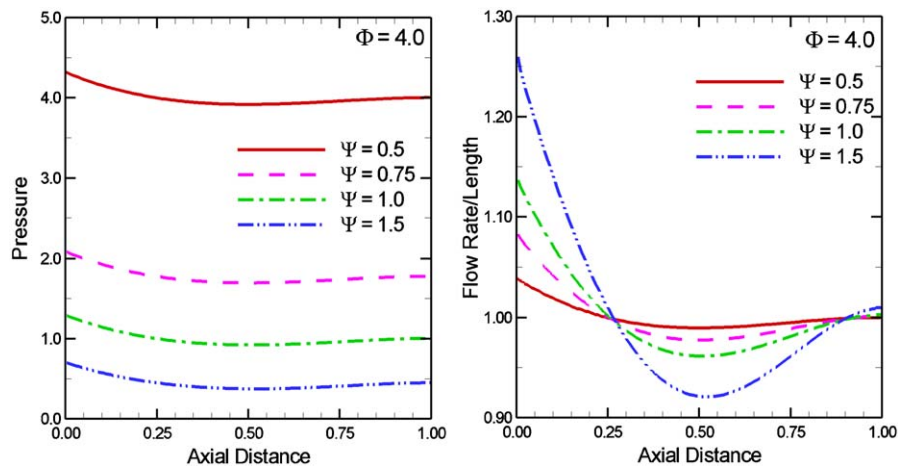


Fig. 8. Distributions of pressure and lateral flow rate at various values of Ψ at $\Phi = 4.0$ (plenum of moderate length).

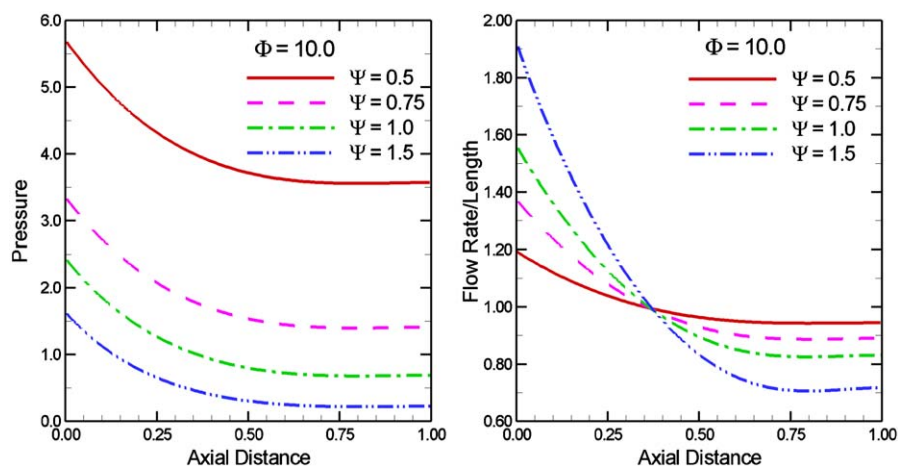


Fig. 9. Distributions of pressure and lateral flow rate for various values of Ψ at $\Phi = 10$ (long plenum).

continues to increase along the length, but the rate of increase is much reduced compared to that when friction is small; compare, for example, the curves for $\Psi = 0.5$ in

Figs. 6 and 7. Thus, at low values of Ψ , an increase in the strength of frictional resistance makes the flow distribution more uniform. For example, for the

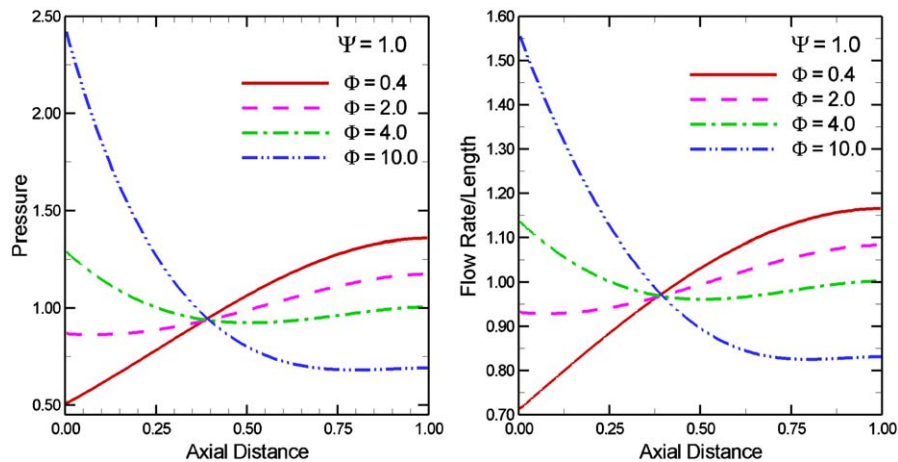


Fig. 10. Distributions of pressure and lateral flow rate at various values of Φ .

conditions corresponding to $\Psi = 1.0$ and $\Phi = 0.4$, the flow rates vary from 0.7 to 1.17 (Fig. 6); when Φ is increased to 2.0, the range becomes narrower—0.93–1.08 (Fig. 7).

As Φ is increased further, the effect of friction becomes significant even at low values of Ψ . At $\Phi = 4.0$ (Fig. 8), the pressure distributions are nonmonotonic for all values of Ψ . Further, largest pressures (lateral flow rates) now occur at the inlet. In contrast, at $\Phi = 2.0$, the largest pressures (lateral flow rates) always occur at the closed end of the plenum.

At large values of Φ ($\Phi = 10.0$), Fig. 9, frictional resistance overwhelms the inertia forces and controls the pressure distribution over the entire length. For these conditions, the pressure and lateral flow rates decrease monotonically along the length. This trend is opposite of that observed at low values of Φ . (The results for $\Phi = 10$ have been included for completeness. This value of Φ corresponds to a 1000 ft long plenum, under reference conditions, fed by a single CRAC unit. It is unlikely that such a configuration will be employed in reality.)

Fig. 10 summarizes the effect of friction on the pressure and flow distributions at $\Psi = 1.0$. At low values of Φ , the flow rate is lowest near the inlet and increases monotonically along the length. As Φ increases, the flow distribution tends to become uniform. For certain intermediate values of Φ , the flow distribution becomes nonmonotonic, where the flow rates decrease near the inlet for some distance and then increase towards the closed end. At large values of Φ , the flow rates decrease over the entire length.

4. An application of the one-dimensional model

In this section, we present a design application of the one-dimensional model. An important factor that

determines the lateral flow distribution in raised-floor data centers is the location of the CRAC units. The one-dimensional model is used to predict the flow distributions for two possible arrangements of the CRAC units. To assess the appropriateness of the one-dimensional model, its results are compared with those given by a three-dimensional model.

The three-dimensional model is described by Karki et al. [2]. Like the one-dimensional model, the three-dimensional model also solves the governing equations in the plenum space only. It uses a finite-volume method, the k - ϵ turbulence model, and a multigrid method to solve the coupled continuity and momentum equations.

4.1. The arrangements considered

The arrangements considered are shown in Fig. 11. In the back-to-back arrangement, two CRAC units are placed next to each other, with no perforated tiles between them. That is, perforated tiles are placed on only one side of a CRAC unit. In the distributed arrangement, perforated tiles are placed on both sides of a CRAC unit.

The two arrangements have the same number of CRAC units and perforated tiles. In the back-to-back arrangement, there are 48 tiles (24 tiles per row) between two CRAC units; in the distributed arrangement, there are 24 tiles between two CRAC units. Each CRAC unit supplies a flow rate of $4.72 \text{ m}^3/\text{s}$ (10,000 cfm). The side dimension of a perforated tile is 0.6096 m (24 in) and the open area is 25% ($K \approx 43$). The width of the data center is 4.27 m (14 ft) and the plenum height is 0.3048 m (12 in). There are no under-floor obstructions. The friction factor is taken as 0.005. The effect of frictional resistance is expected to be small, because the lengths involved are short.

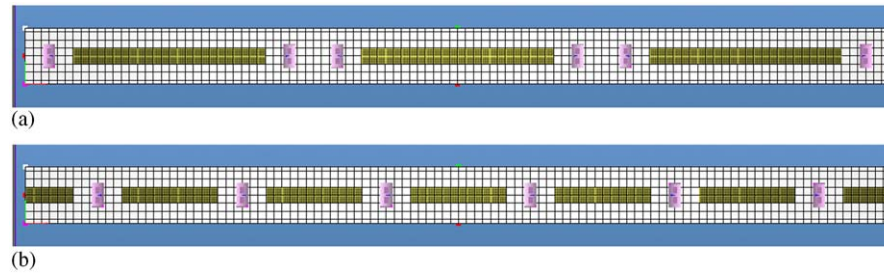


Fig. 11. Two possible arrangements for CRAC units. (a) Back-to-back arrangement, and (b) distributed arrangement.

Table 2
Governing parameters for the two configurations

Quantity	Back-to-back arrangement	Distributed arrangement
Total area of the perforated tiles, A_{Tile} (m ²)	8.92	4.46
Plenum cross-sectional area, A_{cs} (m ²)	1.30	1.30
Plenum length, L (m)	7.32	3.66
Hydraulic diameter, d_h (m)	0.61	0.61
Pressure-loss ratio, Ψ	1.05	0.52
Frictional resistance parameter, Φ	0.24	0.12

4.2. One-dimensional representations

In the back-to-back arrangement, one CRAC unit supplies air to 24 perforated tiles (12 tiles per row). The one-dimensional representation of this arrangement consists of one CRAC unit with flow rate of 4.72 m³/s (10,000 cfm) supplying air to two rows of perforated tiles, each containing 12 tiles. In the distributed arrangement, the flow from a CRAC unit splits into two equal streams; each stream feeds two rows of perforated tiles, each with six tiles (total of 12 tiles). Thus, the one-dimensional representation of the distributed arrangement consists of a CRAC unit with flow rate of 2.36 m³/s (5000 cfm) supplying air to 12 perforated tiles, equally distributed in two rows.

The values of the governing parameters for the two configurations are given in Table 2.

4.3. Lateral flow distributions

The values of Ψ indicate that the lateral flow distribution would be more uniform for the distributed arrangement. Further, since the values of Φ are small, the flow rates for both arrangements are expected to increase monotonically from the inlet towards the closed end of the plenum.

Fig. 12 shows the flow rates through perforated tiles calculated by the two models. For both arrangements, the two sets of results are nearly identical. As expected, the flow distribution is more uniform for the distributed

arrangement. In either arrangement, the plenum flow field is governed mainly by the flow inertia; consequently, the flow rates are lowest near the inlet and increase monotonically along the plenum.

Note that in these configurations, the region between two CRAC units is like the cold aisle shown in Fig. 2, which is subject of the parametric study described in the preceding section. From the results presented in Fig. 12, it can be concluded that the one-dimensional model also produces accurate results for the simpler configuration comprising a single cold aisle.

The results presented here show that the one-dimensional model can be an effective design tool. It is especially useful for obtaining qualitative trends and for evaluating alternative designs.

5. Concluding remarks

The flow field or the pressure distribution in the under-floor plenum of a raised-floor data center determines the lateral flow distribution through perforated tiles. In this study, we have examined the fluid mechanics in the plenum using a one-dimensional computational model. Within the one-dimensional framework, various variables influencing the plenum flow field—and hence the lateral flow distribution—can be combined into two dimensionless parameters: (a) the pressure variation parameter, which characterizes the extent of pressure variation in the plenum relative to the pressure drop across the perforated tiles, and (b) the frictional resistance parameter, which characterizes the strength of frictional resistance relative to flow inertia. The pressure variation parameter controls the degree of nonuniformity in the lateral flow distribution; an increase in the value of this parameter increases the nonuniformity. The frictional resistance parameter, on the other hand, controls the pattern of the lateral flow distribution. When the frictional resistance is small, the lateral flow rates are lowest near the inlet and increase monotonically along the length of the plenum, reaching a maximum at the opposite end. For intermediate values of frictional resistance, flow rates decrease for some distance near the inlet, with the

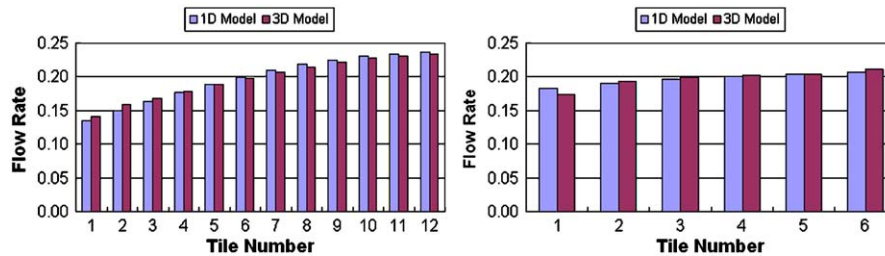


Fig. 12. Flow rates (m^3/s) through perforated tiles given by the one-dimensional (1D) and three-dimensional (3D) models. (a) Back-to-back arrangement, and (b) distributed arrangement.

length depending on the relative strength of flow inertia, and then start increasing. When the frictional resistance becomes large, the flow rates are largest near the inlet and decrease monotonically along the length.

The one-dimensional model is used to predict the lateral flow distributions for two possible arrangements of the CRAC units, and these results are compared with those given by a three-dimensional model. The two sets of results are in excellent agreement. This case study shows that the one-dimensional model can be an effective design tool, especially for obtaining qualitative trends and for evaluating alternative designs.

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