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# TECHNIQUES FOR CONTROLLING AIRFLOW DISTRIBUTION IN RAISED-FLOOR DATA CENTERS

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## ABSTRACT

In raised-floor data centers, the airflow rates through the perforated tiles must meet the cooling requirements of the computer servers placed next to the tiles. The data centers house a wide range of equipment, and the heat load pattern on the floor can be quite arbitrary and changes as the data center evolves. To achieve optimum utilization of the floor space and the flexibility for rearrangement and retrofitting, the designers and managers of data centers must be able to modify the airflow rates through the perforated tiles.

The airflow rates through the perforated tiles are governed primarily by the pressure distribution under the raised floor. Thus, the key to modifying the flow rates is to influence the flow field in the plenum. This paper discusses a number of techniques that can be used for controlling airflow distribution. These techniques involve changing the plenum height and open area of perforated tiles, and installing thin (solid and perforated) partitions in the plenum. A number of case studies, using a mathematical model, are presented to demonstrate the effectiveness of these techniques.

## INTRODUCTION

Raised-floor data centers use the under-floor plenum below a raised floor to supply cooling air to the equipment. The computer room air conditioner (CRAC) units push cold air into the plenum, from where it is introduced into the computer room via perforated floor tiles, tile cutouts, and floor grilles. In this configuration, the distribution of the airflow through the perforated tiles is governed by the size of the plenum, the arrangement and open area of the perforated tiles, the location and flow rates of CRAC units, and the under-floor blockages like cables and pipes. The complex flow in the plenum sets up a pressure distribution, which controls the flow through the perforated tiles.

A necessary condition for good thermal management is to supply the required airflow through the perforated tile(s) located at the inlet of each computer server. The heat load can vary significantly across the computer room, and it changes with addition or reconfiguration of hardware. For all computer servers to operate reliably, the data center design must ensure that the cooling air distributes properly, that is, the distribution of flow rates through perforated tiles (airflow distribution) mirrors the heat load pattern on the raised floor.

An easy way to satisfy the above condition is to decide the type of equipment and its location on the basis of the local airflow rates. This is, adapt the heat load pattern to the airflow distribution. This scheme, however, is not practical. It leads to inefficient use of the floor space and imposes restrictions on the type of equipment and the number of units that can be housed in the data center. Further, it lacks flexibility (for example, locations of computer units cannot be fixed) and limits the options for rearrangement and upgrades. For data centers to be flexible and efficient, we must be able to decide the locations of the computer units first, and then produce the desired airflow distribution. That is, we need the ability to control/modify the airflow distribution to match a given heat load pattern.

Data centers offer limited options for modifying the airflow distribution. The available techniques include changing the plenum height, varying open areas of perforated tiles, relocating the CRAC units and perforated tiles, and installation of flow obstructions in the plenum.

The purpose of this paper is to present a computational study of various techniques for controlling the airflow distribution in raised-floor data centers. This study is conducted using the commercial software package TileFlow [1]. TileFlow uses the technique of computational fluid dynamics (CFD) to calculate the three-dimensional velocity and pressure fields in the plenum under the raised floor and the airflow rates through the perforated tiles on the raised floor.

The results of these techniques are illustrated with reference to an idealized configuration deploying the hot aisle-cold aisle arrangement of perforated tiles and computer servers. The findings, however, are general and are equally valid for other configurations.

To authors' knowledge there are no publications dealing specifically with *deliberate control/modification* of airflow distribution in data centers. The prediction and measurement of airflow distribution, however, has been the subject of a number of publications in the recent years. Kang et al. [2] have presented a flow network model in which the plenum is assumed to be at a *uniform* pressure. Schmidt et al. [3] have presented a CFD model based on the depth-averaged (two-dimensional) representation of velocity and pressure distributions in the plenum. This publication also includes a brief discussion of the effect of plenum height and open area of perforated tiles on the uniformity of airflow distribution. Karki et al. [4] have described a three-dimensional CFD model and have reported results for a real-life data center. In these CFD models, the calculation domain is restricted to the plenum space and the pressure above the raised floor is assumed to be uniform. Numerical studies of flow and heat transfer in the computer room are available in Schmidt [5], Schmidt and Cruz [6], and Patel et al. [7].

## TECHNIQUES FOR CONTROLLING AIRFLOW DISTRIBUTION

### Relationship Between the Flow Field in the Plenum and Flow Rates Through Perforated Tiles

The flow rate through a perforated tile depends on the pressure drop across the tile, that is, the difference between the plenum pressure just below the tile and the ambient pressure above the raised floor. Pressure variations within the computer room are generally small compared to the pressure drop across the perforated tiles. Thus, relative to the plenum, the pressure just above the perforated tiles can be assumed to be uniform. The flow rates, therefore, depend primarily on the pressure levels in the plenum, and the nonuniformity in the airflow distribution is caused by the horizontal pressure variations under the raised floor.

For the nonuniformity in the airflow distribution to be significant, the horizontal pressure variations (or change in velocity heads) must be comparable to the pressure drop across the perforated tiles. This condition is satisfied if the area available for horizontal flow in the plenum is comparable to or less than the total open area of the perforated tiles.

### Techniques Considered

The key to controlling the airflow distribution is the ability to influence the pressure distribution (or the flow field) in the plenum. For specified (horizontal) floor dimensions and total flow rate, the pressure distribution is governed by the following parameters:

- Plenum height
- Open area of perforated tiles
- Distribution of open area on the floor
- Relative positions of CRAC units and perforated tiles
- Presence of under-floor blockages

The techniques for controlling the airflow distribution vary one or more of these parameters to effect the desired change in the pressure distribution. Among these techniques, those involving changes in plenum height and open area influence the degree of nonuniformity in the airflow distribution; they provide very limited control over individual airflow rates. The remaining techniques are more flexible; they allow for selective modifications in the airflow distribution and can be used, for example, to obtain specified flow rates in designated regions.

The locations of CRAC units and perforated tiles in a data center are usually determined by factors unrelated to airflow distribution and cannot be changed. Thus, the rearrangement of CRAC units and perforated tiles is not a viable option for controlling airflow distribution and is not considered in this study.

The use of under-floor blockages for airflow control requires further explanation. Blockages influence the flow field in the plenum by introducing additional flow resistance and by reducing the area and volume available for the airflow. A blockage can be classified as thick or thin, depending on its volume, relative to the plenum volume. The pressure nonuniformities caused by the presence of a thick blockage are difficult to control. Further, because of the associated reduction in the plenum air space, there is a limit on the number and sizes of thick blockages that can be introduced in the plenum. Because of these considerations, installation of thick blockages in the plenum is not a practical option for modifying the airflow distribution.

A data center plenum usually contains a number of thick blockages, such as, pipes and cables, which are associated with CRAC units and computer equipment. Although the local pressure distribution can be modified by changing the location and orientation of these blockages, they do not provide enough flexibility to serve as useful means of controlling the overall airflow distribution.

In this work, we propose the use of thin perforated partitions or plates for modifying the pressure distribution in the plenum. Partitions offer several advantages. The flow resistance of a thin partition can be controlled precisely by varying its open area. Unlike thick blockages, the installation of thin partitions has negligible effect on the space available for airflow in the plenum. Partitions are especially well suited for existing data centers, where very limited options are available for controlling the airflow distribution.

We now discuss, in qualitative terms, the influence of various parameters on the airflow distribution; support for these remarks will be presented through case studies in the next section.

**Plenum Height.** The plenum height has significant influence on the horizontal velocity and pressure distributions in the plenum. As the plenum height increases, the velocities reduce and the pressure variations diminish, leading to a more uniform airflow distribution.

**Open Area of Perforated Tiles.** As the open area of perforated tiles is reduced, the pressure drop across the tiles increases and, at some point, becomes much larger compared to the horizontal pressure differences under the raised floor. Under these conditions, the entire plenum is essentially at a uniform pressure, and the airflow distribution is nearly uniform.

**Distribution of Open Area on the Floor**. Further flexibility for modifying the airflow distribution can be achieved by varying the open area (flow resistance) of perforated tiles according to the local pressure under the raised floor. The flow rate through a perforated tile depends on the flow resistance of the tile and the local pressure difference across it. When all perforated tiles have the same open area, flow rates are simply proportional to the local pressures under the raised floor. The flow rate distribution can be changed by varying the flow resistance of perforated tiles, according to the local pressure levels under the raised floor. The flow rates in the high-pressure regions can be reduced by increasing the flow resistance, that is, by installing perforated tiles with less open area. Likewise, flow rates in low-pressure regions can be increased by placing perforated tiles with larger open area (less flow resistance) in these regions.

**Under-Floor Partitions**. Under-floor partitions act as flow obstructions and can have significant effect on the pressure distribution in the plenum. When an air stream impinges on a partition, a high-pressure region is created on the upstream (impingement) face of the partition, and a low-pressure region is produced on the downstream face. The pressure drop across a partition depends on its open area and the flow conditions in its vicinity. Using perforated partitions with appropriate open areas and placing them at appropriate locations, almost any desired pressure distribution, and thus airflow distribution, can be achieved.

Partitions can also be used as “flow guides,” that is, they can be used to create channels within the plenum to direct the flow to specified regions. The cross-sectional area of the channel can be varied to influence the velocity and pressure distributions.

## CASE STUDIES

### Mathematical Model

The computational study reported here is conducted using the commercial software package TileFlow™, a customized CFD package designed specifically for airflow distribution in raised-floor data centers. TileFlow solves the three-dimensional form of the equations governing turbulent airflow. The calculation domain is restricted to the plenum under the raised floor, with the assumption that the pressure above the raised floor is uniform. The turbulence effects are represented using the standard $k$-$\varepsilon$ model [8]. The governing equations are discretized on a Cartesian grid using the finite-volume method described by Patankar [9]. Geometries that do not fit neatly into this coordinate system are represented by a series of rectangular steps.

The flow from the CRAC units is taken as inflow into the plenum, and the flow rate through a perforated tile is related to the pressure drop across the tile via its flow resistance (e.g., loss factor). The formulation allows for the possibility of reverse flow—flow from above the raised floor entering the plenum—when the pressure under a tile is below the ambient pressure above the raised floor. The treatment of boundary conditions at walls and internal fluid-solid interfaces is based on the wall function approach [8].

The airflow rates predicted by TileFlow have been validated using measurements in prototype and real-life data centers. Further details of TileFlow and its validation are available in publications by Schmidt et al. [3] and Karki et al. [4].

The results presented here were obtained on a nonuniform grid. The horizontal plane, the control volume width was 0.5 ft (0.1524 m) under and near the CRAC unit openings and 1 ft (0.3048 m) elsewhere. In the depth direction, the control-volume width was 3 in (0.0762 m). Our initial explorations indicated that the calculated flow rates on this grid are accurate within 2%. This level of accuracy is considered satisfactory for the present study, where the emphasis is not so much on the quantitative accuracy, but on the qualitative trends.

### The Base Configuration

The use of various techniques for controlling the airflow distribution will be illustrated with reference to the idealized configuration shown in Fig. 1. This layout uses the conventional hot aisle-cold aisle arrangement, with the CRAC units in the cold aisles. The perforated tiles are placed in the cold aisles. The computer servers are arranged on both sides of the cold aisles, with their intake sides facing the cold aisles. The hot aisles divide the back ends of two rows of equipment. The cooling air exiting the perforated tiles is sucked in by the internal fans of the equipment, heats up as it picks heat generated by the equipment, 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 CRAC units.

The base configuration considered here consists of a CRAC unit and two rows of perforated tiles, each containing 15 tiles with 25% open area. The CRAC unit delivers 10,000 CFM (4.72 $m^3/s$) of cold air. The plenum height is 12 in (0.3048 m).

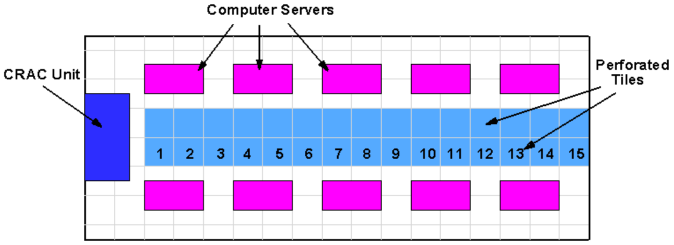


**Figure 1. Base configuration**

The distribution of airflow rates for this configuration is shown in Fig. 2. The flow rates are smaller near the CRAC unit and increase towards the opposite wall. There is reverse flow through the perforated tiles next to the CRAC unit. Thus, computer servers cannot be placed in this area.

Figure 3 shows the velocity vectors and the pressure distribution on the horizontal plane just under the raised floor. The cold air exiting the CRAC unit impinges on the subfloor and expands horizontally. In the impingement region, the pressure levels are high, and they decrease rapidly as the fluid rushes out of these regions. Under the perforated tiles, as we move away from the CRAC units, cold air is exiting the plenum, causing the horizontal velocity components to diminish and the pressures to increase. Note that the pressure under the perforated tiles next to the CRAC unit is negative and produces reverse flow through these tiles.

## Varying the Plenum Height

To illustrate the effect of plenum height on the airflow rates, the height for the base configuration is varied from 6 in (0.1524 m) to 30 in (0.7620 m).

The flow rates for plenum heights of 6 in, 12 in, and 30 in are shown in Fig. 4. It is seen that the nonuniformity in flow rates is most pronounced for plenum height of 6 in and diminishes as the height is increased. The intensity of reverse flow through the perforated tiles next to the CRAC unit also weakens as the plenum height is increased. Note that there is no reverse flow at the plenum height of 30 in.

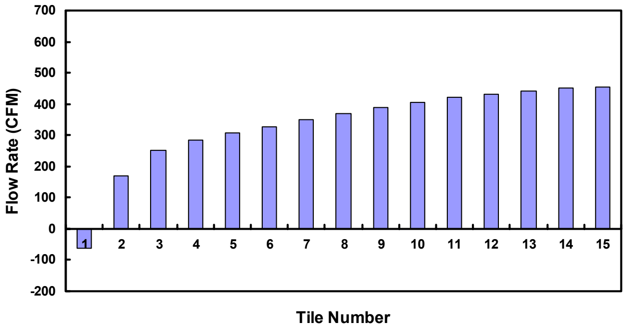


**Figure 2. Flow rates through perforated tiles for the base configuration**

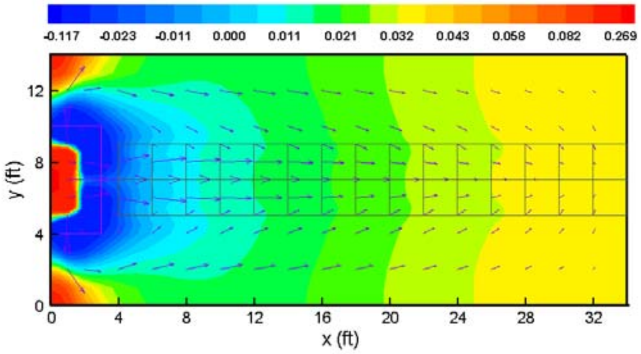


**Figure 3. Pressure distribution (inch of water) and velocity vectors under the raised floor for the base configuration**

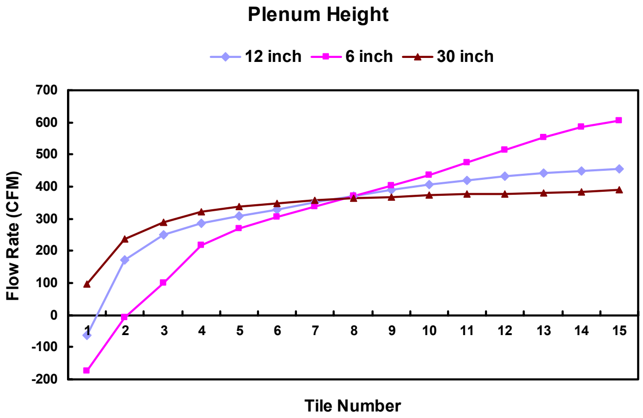
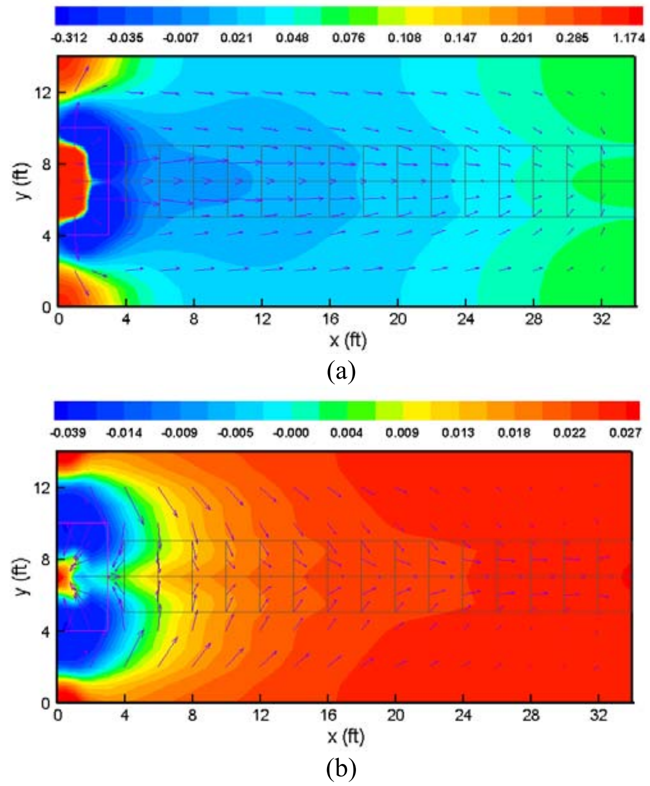


**Figure 4. Effect of plenum height on the airflow distribution**

Figure 5 shows the velocity vectors and pressure distribution on a horizontal plane just under the raised floor for plenum heights of 6 in and 30 in. (Note that the pressure scales are different in the two plots.) At smaller plenum heights, the



(a)

(b)

**Figure 5. Pressure distribution (inch water) and velocity vectors under the raised floor. (a) Plenum height = 6 inch, (b) Plenum height = 30 inch**

pressure variations are significant, with negative pressures near the CRAC units. The pressure distribution becomes more uniform as the plenum height is increased.

Although the plenum height can be varied to influence the uniformity of airflow rates, this option is not feasible for existing data centers. For a given plenum height, the nonuniformity in flow rates increases as more flow is introduced into the plenum (for example, to meet the cooling demands of new higher-heat-dissipation equipment). Thus, a plenum height that was satisfactory in the initial design may become inappropriate after rearrangement/retrofitting of the data center.

A change in the plenum height produces a global change in the flow rate distribution, that is, it affects flow rates at *all* locations. This technique cannot be used for controlling airflow rates in selected section of the floor.

## Varying the Open Area of Perforated Tiles

To illustrate the effect of the open area of perforated tiles, the open area in the base configuration is varied from 10% to 40%. The open area is same for all perforated tiles.

The flow rates at three open areas (10%, 25%, and 40%) are shown in Fig. 6. For a fixed layout and plenum height, the nonuniformity in flow rates diminishes as the open area is reduced. A reduction in the open area also reduces the likelihood of reverse flow near the CRAC units. Note that there is no reverse flow for open area of 10%.

The airflow distribution becomes more uniform as the open area is reduced. However, at smaller open areas, the pressure levels in the plenum increase, and a large proportion of cold air escapes through extraneous openings on the floor, e.g., openings around the cables and pipes. (The flow resistance of these openings now becomes comparable to the flow resistance of the perforated tiles.) This wasted air will not be available for cooling of equipment and may lead to other undesirable effects like short-cycling of the CRAC units. The higher plenum pressures also increase the total resistance (external static) that must be overcome by the CRAC unit blowers and may reduce the flow rates supplied by the CRAC units

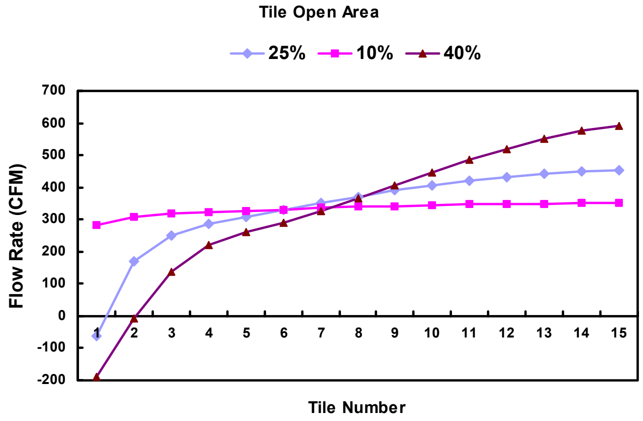


**Figure 6. Effect of open area of perforated tiles on the airflow distribution**

A change in open area of perforated tiles, like a change in the plenum height, also produces a global modification to the flow rate distribution and cannot be used to modify airflow rates in selected regions.

## Varying Perforated Tile Open Area According to Local Conditions

The use of perforated tiles with different open areas is illustrated via the layout shown in Figure 7. It is identical to the base configuration, except that the open area of perforated tiles varies with location. The open area is largest for the perforated tiles near the CRAC units and decreases towards the opposite wall. As explained earlier, this arrangement will lead to lower

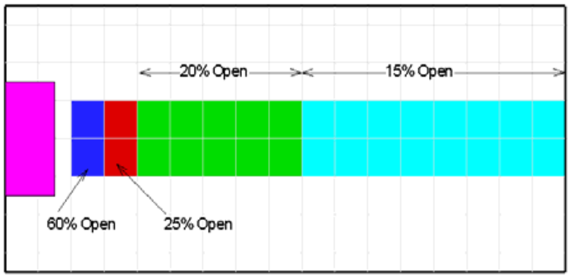


**Figure 7. Variable open area across the floor**

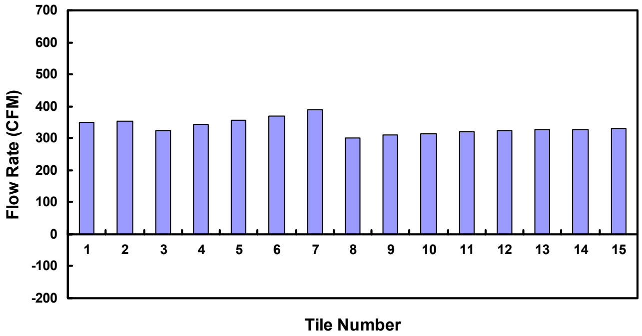


**Figure 8. Airflow distribution for the layout shown in Fig. 7**

flow rates away from the CRAC unit and higher flow rates near the CRAC unit, producing an airflow distribution that is more uniform than that produced by the base configuration, where all tiles are 25% open.

The flow rate distribution for the modified configuration is shown in Fig. 8. As expected, it is significantly more uniform compared to the distribution for the base configuration (see Fig. 2). In the basic configuration, the space near the CRAC unit is unusable due the presence of reverse flow. In the modified layout, the reverse flow has been eliminated and this space becomes usable. Thus, the modified layout allows for better space utilization.

In this example, the open areas were adjusted to achieve a nearly uniform airflow distribution. This technique can also be used for modifying airflow rates in designated sections of the floor.

## Installing Under-Floor Partitions

Here we illustrate the use of inclined solid partitions and perforated partitions for modifying the airflow distribution.

**Use of Solid Partitions as Flow Guides**. In this example, shown in Fig. 9, inclined, solid partitions are used to create a converging channel, with its area decreasing away from the CRAC unit. In the base configuration, the velocities decrease and pressures increase as we move away from the CRAC units. In the modified configuration, the horizontal velocities within the converging channel remain nearly constant; the reduction in area compensates for the reduced flow rate, to produce constant velocity. Consequently, the pressure under the perforated tiles is nearly uniform, producing a near-uniform distribution of airflow rates, as shown in Figure 10.

The airflow distribution can be modified further by varying the angle of inclination of the partitions and by creating channels of other shapes.

**Use of Perforated Partitions**. In this example, results are presented for a number of configurations, showing how the airflow distribution can be modified by changing the open area of partitions.

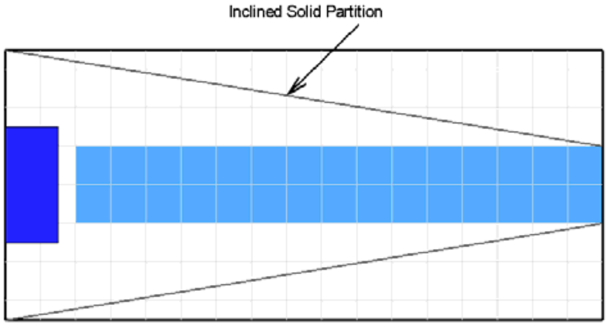


**Figure 9. Configuration with inclined partitions**

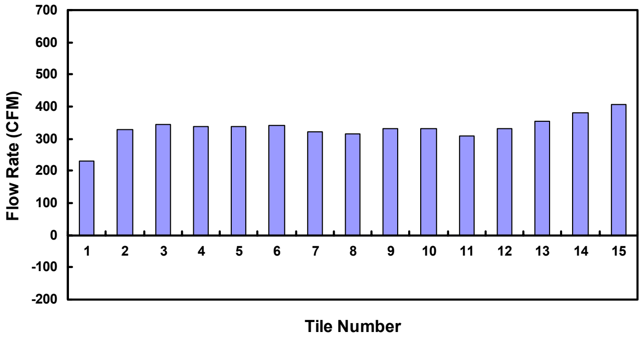


**Figure 10. Airflow distribution for the layout with inclined partitions**

The configuration considered includes two perforated partitions and is shown in Fig. 11. Results are presented for three combinations of the open areas of the partitions. The open areas are listed in Table 1.

**Table 1. Open areas of perforated partitions in different configurations**

| Configuration | Open Areas (%) | |
|---|---|---|
| | *Partition 1* | *Partition 2* |
| A | 70 | 30 |
| B | 75 | 50 |
| C | 80 | 65 |

Figure 12 shows the flow rates for these three configurations. The corresponding velocity and pressure distributions are presented in Fig. 13.

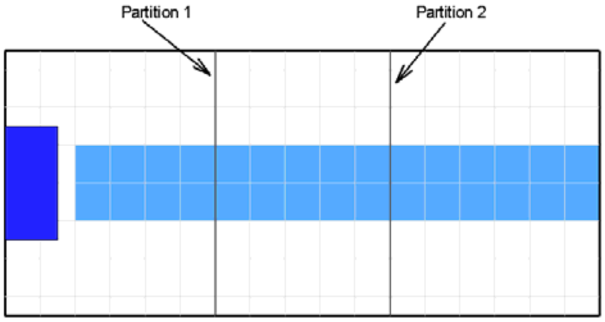
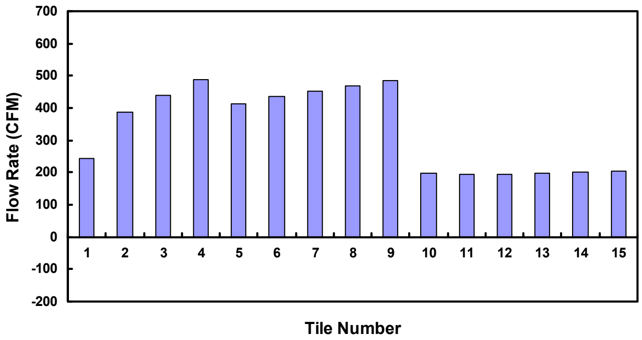


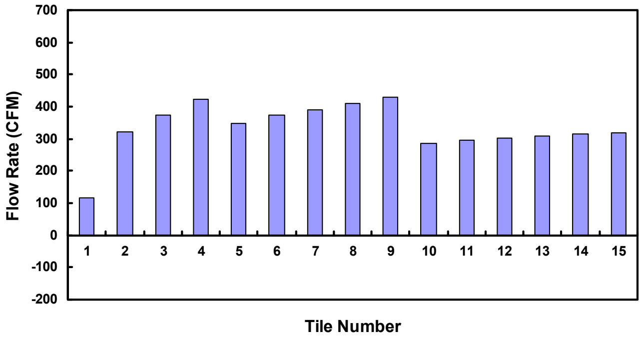
**Figure 11. Configuration with perforated partitions**

The partitions have effectively divided the data center into three sections. The impingement of flow on the partition produces higher pressures on the upstream side, and there is a drop in pressure across the partition. For the base configuration, the pressure continuously increases as we move away from the CRAC unit. This behavior has now being altered. In the presence of partitions, the pressure is still increasing, but the pressure levels across a partition depend on the open area of the partition. As the partition open area is reduced, the pressure level on the upstream side and the pressure drop across the partition both increase. These quantities also depend on the local velocities upstream of the partition, that is, on the partition location.

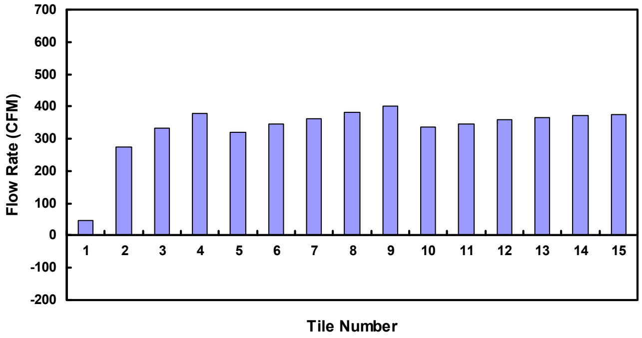
This example illustrates that thin, perforated partition provide unlimited flexibility for controlling the airflow distribution. These partitions are ideally suited for modifying the flow rates in specific section of the floor.



**(a) Configuration A**



**(b) Configuration B**

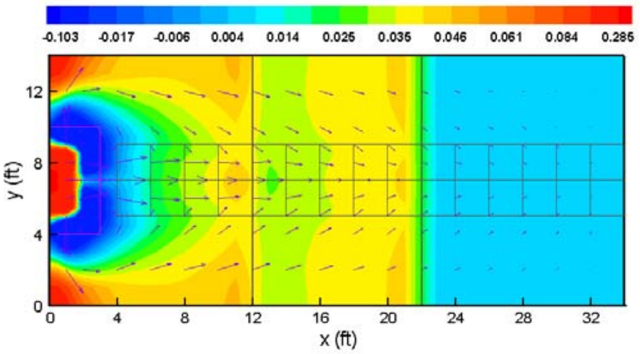


**(c) Configuration C**

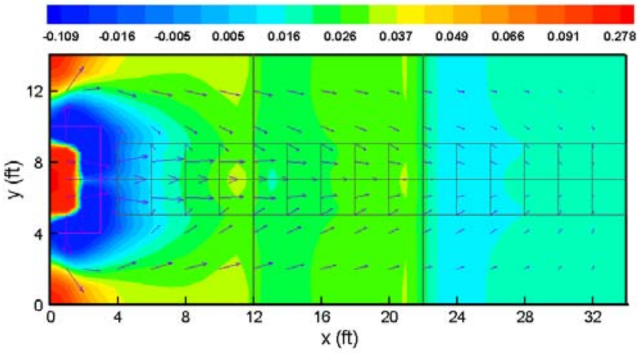
**Figure 12. Airflow distributions for the three configurations with perforated partitions (See Table 1 for open areas of partitions)**

## CONCLUDING REMARKS

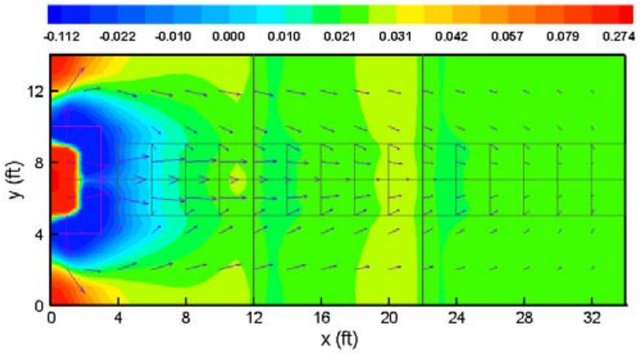
In this paper, we have discussed a number of techniques for modifying the airflow distribution in raised-floor data centers. These techniques involve changing the plenum height, open area of perforated tiles, and the distribution of open area on the floor; and installing solid and perforated thin partitions in the plenum. A number of case studies are presented to illustrate the effectiveness of the selected techniques. The case studies are performed using a mathematical model based on the computational fluid dynamics. The results indicate that the thin partitions offer significant flexibility for controlling the airflow distribution, especially in existing data centers.



(a) Configuration A



(b) Configuration B



(c) Configuration C

**Figure 13. Pressure distribution (inch water) and velocity vectors for the three configurations with perforated partitions (See Table 1 for open areas of partitions)**

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