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MEASUREMENTS AND PREDICTIONS OF THE FLOW DISTRIBUTION THROUGH PERFORATED TILES IN RAISED-FLOOR DATA CENTERS

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ABSTRACT

Data centers are used to house data processing equipment such as servers, mainframes, and storage systems. The equipment, which dissipates a significant amount of heat, needs to be maintained at acceptable temperatures for its reliable operation. A typical cooling arrangement consists of installing the equipment on a raised floor and using several air-conditioning (A/C) units to force cool air into the space under the raised floor. Whereas most of the raised floor is impermeable, perforated tiles are installed at desired locations to provide cool air at the inlets of the data processing equipment.

The distribution of the air flow through the perforated tiles located throughout the data center is governed by the size of the plenum space under the raised floor, the presence of flow obstructions such as cables and pipes in that space, the locations and flow rates of the A/C units, the layout of the perforated tiles, and the tile open area (or their flow resistance). The complex flow in the plenum space under the raised floor sets up a pressure distribution, which controls the flow through the perforated tiles.

The purpose of this paper is to propose a computational predictive model for the problem described and to provide benchmark measurements to test the validity of the model. The measurements were conducted on an actual data center at IBM, Poughkeepsie, New York. It contained two A/C units, which could be activated independently. A large number of different layouts of the perforated tiles were created and the flow rates through them were measured with either one or both A/C units operating. The flow resistance of the perforated tiles was also determined by measuring the corresponding pressure drop.

The measured flow distributions were compared with the predictions of a computational model, which calculated the pressure distribution in the plenum space and the corresponding flow rates through the perforated tiles. The model was correctly able to predict the flow nonuniformity for different tile layouts and different operations scenarios for the A/C units.

Finally, the model was used to study the effect of tile open area and plenum depth on the flow distribution through the perforated tiles. The results provide guidance for choosing these parameters for achieving the desired flow rates through the tiles.

INTRODUCTION

In the 1970’s and 80’s many data centers were constructed to house massive amounts of data processing (DP) equipment including processors and storage devices. The primary cooling method was to supply air throughout the data center with modular air-conditioning units delivering 13–16°C air into a plenum formed by a subfloor and a raised floor. From this plenum the air is then discharged through perforated floor tiles strategically located near the DP equipment. Most data centers constructed during this period were designed to handle heat loads averaged over the entire data center of 500 to 750 W/m^2.

With the ever-increasing amount of heat being dissipated by DP equipment, the current data center designs will have to be carefully upgraded to accommodate the increased heat loads. The heat densities of servers, DASD, and workstations have all increased by a factor of approximately 4 over the last 10 years. The IBM RS/6000 SP system, which occupies about 1.2 m^2, dissipates approximately 10 kW. The Sun UE10000, which occupies approximately 1.24 m^2, dissipates 11.4 kW. The HP V2500 (2 stacked) occupies 0.85 m^2 and dissipates 15 kW. Compaq 8500 system occupies 0.5 m^2 and dissipates 10.3 kW. All of these large servers have heat fluxes in the range of 8000 to 20000 W/m^2. These are but a few examples of the equipment now being marketed. Of course, the equipment will be placed on the raised floor in a manner that will lower the average heat flux relative to the total area of the raised floor. Recent evaluations of some data centers showed that approximately 25% of the floor space was actually populated with DP hardware while the remaining space was made up of aisles, service clearances, modular A/C equipment, power distribution equipment, perforated tiles for exhausting cool air, etc. Other factors that may increase the “hardware packing density” are consolidation of data centers and cost per square foot. Many companies are closing data centers and consolidating to improve the efficiency and to cut the cost of their operation. In addition, many data centers are located in prime locations in large metropolitan areas. These sites, by virtue of their locations, are high priced and tend toward increased packing densities.

Balancing the distribution of the chilled air throughout the data center such that those units that have high heat loads get more chilled air compared to those with lower heat loads is a daunting task. Making changes at one location will change the airflow at all the other locations. In most cases, the equipment is first arranged on the floor and then the facilities engineer is given the layout to find the best cooling solution. Typically, perforated floor tiles are placed in front of systems with the A/C units spaced around the perimeter of the room. Some balancing can be achieved by adjusting the floor tiles or by using baffles at selected locations under the raised floor, but the required modifications have to be determined by an expensive trial and error method.

The archival literature on airflow management in data centers is very scarce. Most of the available work pertains to room thermal and velocity distributions. Quivey [1] have presented results based on a CFD model for a Lawrence Livermore Data Center. Bullock and Phillip [2] presented computational fluid dynamics results for the Sistine Chapel renovation project. Kiff [3] showed results of a CFD analysis of rooms populated with telecommunications equipment. Ambi and Gan [4] used CFD to predict airflow and temperature distributions within offices. Seymour [5] utilizes CFD analysis to show temperature and flow distributions in an atrium. Schmidt [6] presented CFD results compared to measurements of temperature and velocity fields in an office size data processing room. Cinato et al. [7] describe a tool to allow non-CFD users the ability to optimize the energy consumption of the environmental systems that provide cooling to telecommunication rooms. This tool permits optimization of the placement of the telecommunication equipment and cooling systems. Such an approach gives the advantage of evaluating solutions and identifying critical points in advance, in order to choose the best option.

Kang et al. [8] have presented a pressurized plenum model to calculate the flow rates through the tiles in a data center. In this model, the whole volume under the raised floor is assumed to be at a *uniform* pressure. The entire flow system is represented as a network of flow resistances, and a flow network model is used to solve for the flow rates through the tiles. The results from this simplified model agree well with the detailed results from a CFD model. The assumption of uniform plenum pressure is valid, however, only if the pressure drop across the tiles is much larger than the horizontal pressure variations within the plenum. This condition is satisfied if the total tile area is much smaller than the frontal area (area normal to the predominant flow direction) under the raised floor. Otherwise, the horizontal air velocities under the raised floor become significant and introduce pressure variations in the plenum that are comparable to the pressure drop across the tiles. For the sample problem considered by Kang et al., the pressure variation in the plenum happened to be negligible. However, for many other practical configurations, the calculation of detailed velocity and pressure fields under the raised floor becomes necessary.

This paper reports on a combined experimental/modeling effort directed towards quantitative predictions of the airflow distribution through the floor tiles in a data center. The test program was designed to gain a better understanding of the effect of various operating conditions on the airflow distribution and to provide benchmark measurements to test the validity of the computational model. The measurements were conducted on an actual data center at IBM, Poughkeepsie, New York. It contained two A/C units, which could be activated independently. A large number of different layouts of the perforated tiles were created and the flow rates through them were measured with either one or both A/C units operating. The flow resistance of the perforated tiles was also determined by measuring the corresponding pressure drop. The computational model is based on the calculation of the velocity and pressure fields under the raised floor using the two-dimensional (depth-averaged) form of the governing equations. The model can be used to study the effect of parameters like the flow rate for an A/C unit, the floor tile opening, the raised-floor height, and the locations of the under-floor blockages on the airflow rates through the tiles.

THE TEST PROGRAM

Description of Raised Floor

To validate a model for predicting the flow exiting from perforated floor tiles, it is extremely important to obtain actual flow measurements from a data center. In the present program, tests were performed in an actual data center that was not in use. The data center is located at IBM in Poughkeepsie, N.Y. Figure 1 shows the plan view of a portion of the raised floor. The air-conditioning (A/C) units are arranged in two rows across the length of the data center. Since this data center was not in use, no electronic equipment was installed above the raised floor. All floor tiles were 606 mm square with the bottom of the tiles installed 284 mm above the subfloor. Measurements were concentrated in a small section of the floor (6.06 m × 20.0 m), comprising two air-conditioning units, shown in gray in Fig. 1. In order to focus on this test area, and to carefully monitor the flow, the area around the perimeter between the raised floor and subfloor was carefully blocked off with cardboard and then taped at all edges to eliminate any leakage paths. In addition, any other openings, such as pipe or cable openings exiting the subfloor or raised floor tiles, were blocked. This arrangement provided a controlled area where all the air exiting the A/C units would exhaust from the perforated floor tiles arranged in the test area. In all cases, the perforated tiles used for the tests had open areas of 19%. This open area was provided by holes 6.3 mm in diameter located on a staggered pitch of 10.5 mm.

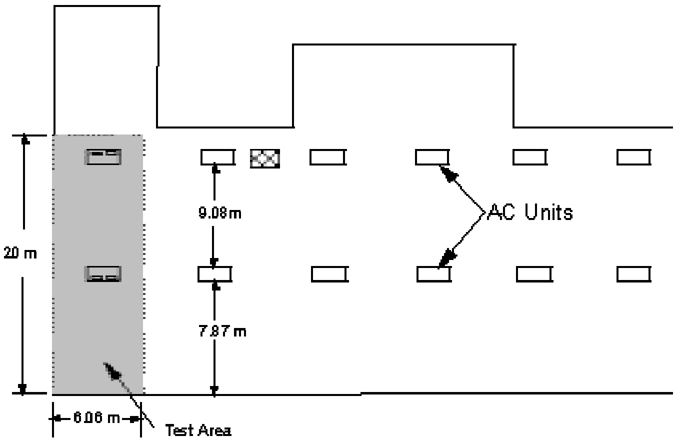

Figure 1. Raised floor test area

A top view of the Liebert A/C unit (Model No. FD411C) showing the exhaust openings is shown in Fig. 2. The units are 890 mm wide, 2510 mm long, and 1835 mm high. Each unit has two large centrifugal wheels 378 mm wide and 391 mm in diameter rotating at a speed of 940 rpm (measured with a strobe light). The sizes of the exhaust areas shown here are less than the typical sizes for these units. This reduction was due to raised floor tiles extending internal to the A/C unit thereby partially blocking the blower exhaust. The blockage resulted in approximately 60% reduction in the volumetric flow rate.

The raised floor tiles were supported by 25 mm-diameter stanchions at the intersection corners of tiles and were mounted to the subfloor. In addition to the stanchions, several other restrictions existed in the plenum formed by the raised floor tiles and the subfloor. Adjacent to the A/C unit A, a 100 mm diameter chilled water pipe was installed horizontally and parallel to the A/C unit. The centerline of the pipe was located 125 mm in front of unit A. In addition, coils of cable were located under some of the tiles, occupying roughly 10% of the volume underneath these floor tiles. These cables were, however, not in the primary airflow paths and were ignored in the model.

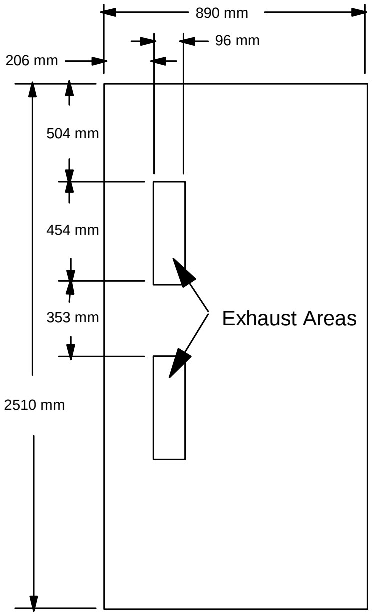

Figure 2. AC unit plan form

Calibration and Verification Studies

Several calibration and verification studies were performed to provide support for the accuracy of the measurement data to be described. The airflow exhausting from the raised floor tiles was measured by an Alnor Velometer measurement tool. Figure 3 shows this tool positioned for a typical measurement of flow from a perforated floor tile. Two ranges are available on the tool for measuring low (6.94 m^3/min) and high flow rates (13.88 m^3/min), and both scales were used in these tests. The tool was calibrated in a wind tunnel and, at the same time, its impedance was also measured. This measurement was made to compare the flow impedance of the tool with the flow impedance of the floor tile. If the two flow impedances were comparable, the reported flow rates would be inaccurate. This condition (of comparable flow impedances) was met when the tool was set on the low range. The reason for the increased tool impedance in this (low) range was that a perforated plate needed to be installed internal to the flow tool for these measurements. In order to correct the measured flow rates on the low scale, static pressure measurements were taken underneath the raised floor for the case with and without the measurement tool in place. It was found that the static pressure did not change for the two cases.

Figure 3. Flow measuring tool

Therefore, the flow across the floor tile could be corrected by using the following relationships:

$$\Delta p = k_{tile} V_{actual}^2 \tag{1}$$

$$\Delta p = \left(k_{tile} + k_{instrument}\right) V_{measured}^2 \tag{2}$$

Solving for V_{actual}

$$V_{actual} = \left(\frac{k_{tile} + k_{measured}}{k_{tile}}\right)^{1/2} V_{measured} \tag{3}$$

The correction factor for the volumetric flows measured on the low range turned out to be 1.19. A spot check of this correction was made with the flow tool on the high range compared to the corrected measurements made on the low range. The two flow rates agreed to within 2%.

As a verification of the total flow as measured from the floor tiles, the pressure drops across the various elements of the flow path internal to the A/C unit and through the perforated tiles on the raised floor were also measured. The total pressure drop was then compared to the blower performance curve operating at 940 rpm. The comparisons showed very good agreement.

Test Results

Five arrangements of perforated tiles, shown in Fig. 4, were investigated. Tests were performed with either one or both A/C units operating. For each test, flow rates were measured for every perforated floor tile. Although some flow oscillations occurred at some tile locations most readings were stable. In case of oscillations, an average of the high and low readings were recorded. The measured flow rates through tiles for selected tests are shown in Figs. 5 through 8. These results show that for some tiles air is actually flowing in the downward direction, i.e., towards the subfloor. In all the figures in the paper, the tile numbers increase from unit A towards unit B.

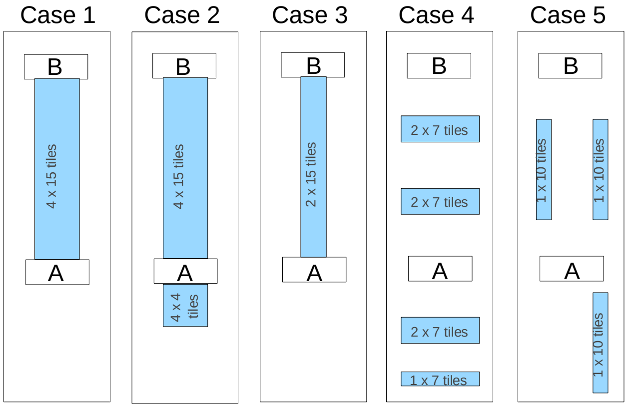

Figure 4. Perforated tile arrangements for tests

For tests where only one A/C unit was operating, the inlet of the other (nonoperating) A/C unit was blocked such that all the air exhausting from the operating A/C unit exited the floor tiles. However, several comparison runs were performed in which the nonoperating A/C unit was not blocked. The results showed less than 5% change in the total flow leaving the floor tiles. This suggests that the flow impedance through the A/C unit is very large compared to the floor tile impedance.

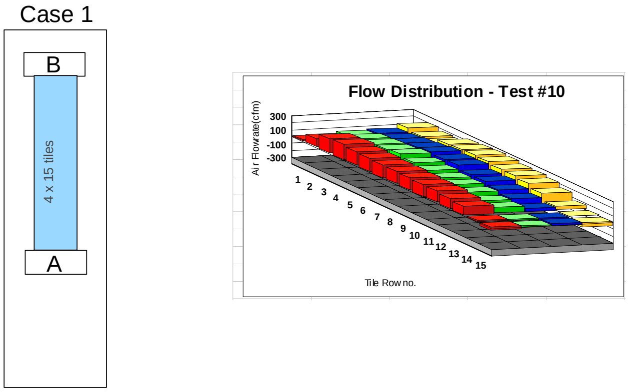

Figure 5. Measured flow distribution for Test 10
(Both AC units operating)

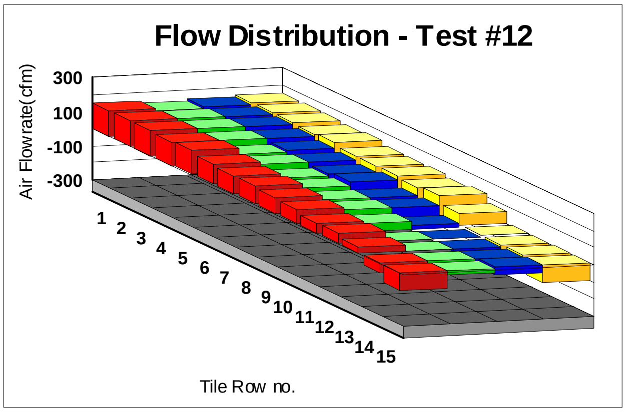

Figure 6. Measured flow rate distribution for Test 12 (AC unit A off)

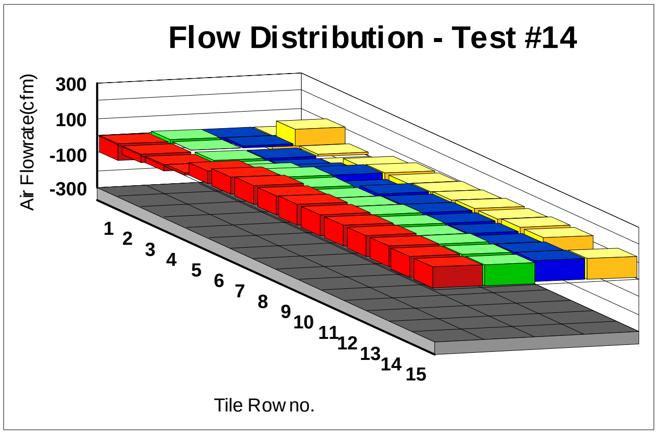

Figure 7. Measured flow distribution for Test 14 (AC unit B off)

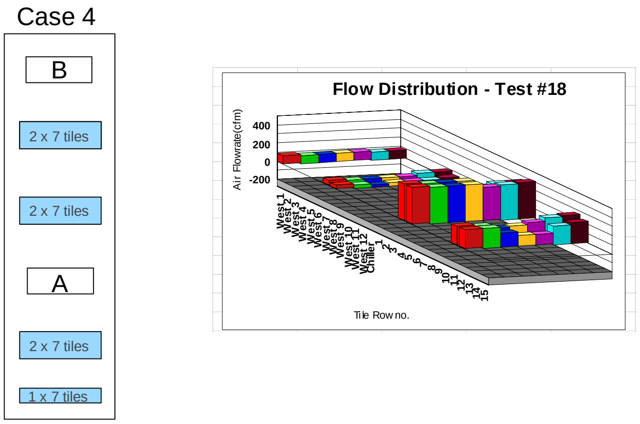

Figure 8. Measured flow distribution for Test 18 (Both AC units operating)

THE COMPUTATIONAL MODEL

In a typical data center the height of the raised floor is much smaller compared to the two horizontal dimensions, and the variations along the height are relatively unimportant. Thus, while the actual flow is three dimensional (3D), predictions of adequate accuracy can be made using a two-dimensional (2D), depth-averaged, model. This 2D model is derived by integrating the 3D form of the equations over the height of the air space. In this model, the calculation domain comprises the plan view of the data center raised floor. Compared to a full 3D model, the 2D model offers significant advantage in terms of the computational time and ease of use. Due to its extremely short turn-around times, this model is ideally suited as a tool that can be used in a routine manner by designers and analysts.

Governing Equations and Boundary Conditions

The governing equations in the 2D model are the depth-averaged continuity and momentum equations. These equations are identical in form to the corresponding standard 2D equations, except that the momentum equations involve additional dispersion terms due to depth averaging. These equations are supplemented by an additional model that represents the effects of turbulence; in the present model, the turbulence effects are represented via an eddy viscosity model.

The various flow obstructions between the subfloor and raised floor are represented as flow resistances in the momentum equations. The flow exiting the A/C unit outlets is specified as an inflow. The flow through the perforated tiles is calculated using the following relationship

$$\Delta p = R\left|Q\right|Q \tag{4}$$

where Δp is the pressure drop, Q is the volumetric flow rate, and the factor R is related to the flow resistance offered by the perforated tiles.

Numerical Solution Procedure

The governing equations are solved using the computational fluid dynamics software package COMPACT [9]. COMPACT is based on the finite-volume method described by Patankar [10]. In the finite-volume method, the calculation domain is divided into a number of finite or control volumes. A grid point at the center of each control volume denotes the location of the unknown dependent variable (e.g., velocity components and pressure). The partial differential equation for the dependent variable is integrated over the control volume, and the resulting integrals are approximated in terms of grid geometry and values of variables at surrounding grid points to obtain an algebraic equation. The solution of these algebraic equations, one for each grid point, provides the values of the dependent variables at all grid points in the calculation domain.

In the present model, a staggered grid arrangement is used in which pressure is located at the center of a control volume and the velocity components are located at the control-volume faces. This arrangement helps in maintaining the coupling between the velocity and pressure fields. The pressure field is calculated using the SIMPLER algorithm. The algebraic equations are solved using the TriDiagonal Matrix algorithm, supplemented by a block-correction procedure to enhance convergence. Complete details of the computational method are given in the Reference Manual for COMPACT [9].

RESULTS

To verify the correctness of the model, it was used to simulate a large number of tests, and the predictions were compared with the measurements. Next the model was used to study the effect of various parameters on the flow rates through the tiles. This section is divided into two parts. In the first part, comparisons for selected tests are presented. The cases considered are variations of Case 1 shown in Fig. 4. (The agreement between predictions and test data for the remainder of the tests is very similar to that seen in the results included here.) For these cases, in addition to the flow rates through the tiles, the predicted velocity and pressure fields are also shown. This detailed information provides an insight into the factors that influence the airflow distribution through the tiles and gives guidance for modifying this distribution. In the second part, the results of the parametric study are presented. These results illustrate the use of the model to provide guidance for choosing parameters (e.g., tile opening and floor depth) to achieve the desired flow rates through the tiles.

Comparisons with Measurements

Test 10. In this test, both A/C units are on. The test data shows some back flow near unit B. Figure 9 shows the comparison of predicted and measured tile flow rates for the four tile rows. (In this and subsequent figures, the row number increases in the direction of increasing y.) The predicted flow rates are in fair agreement with the measured values, except in the immediate vicinity of the A/C units. Figure 10 shows the predicted velocity vectors and distributions of pressure and airflow velocity though the tiles. The flow exiting the A/C unit A splits into two streams: one moving in the forward direction (toward unit B) and the other in the reverse direction. The fluid in the forward stream exits from the tiles close to unit A. The stream flowing in the reverse direction impinges on the left wall (at x = 0), turns 180 deg., and exits from the tiles in the middle. Most of the fluid exiting the unit B is discharged as a jet towards unit A. A small amount of fluid impinges on the east wall (at x = 20 m), turns around, and is also exhausted through the tiles in the middle. As expected, pressure is higher near the

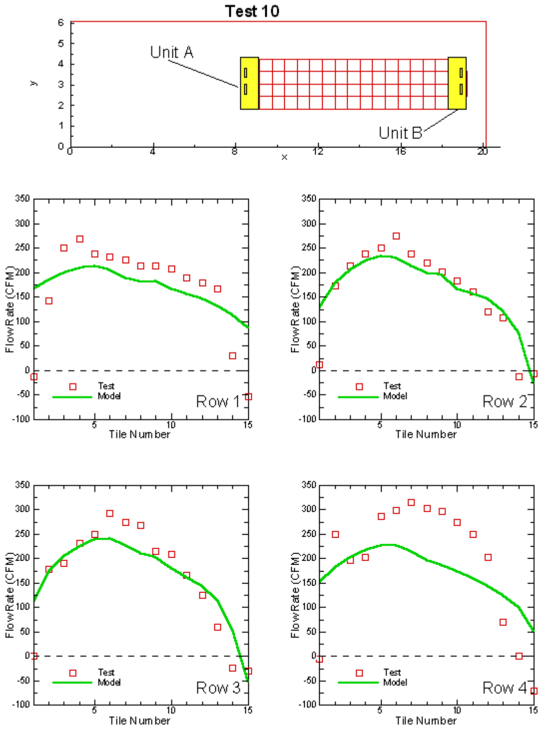

Figure 9. Tile airflow rates for Test 10

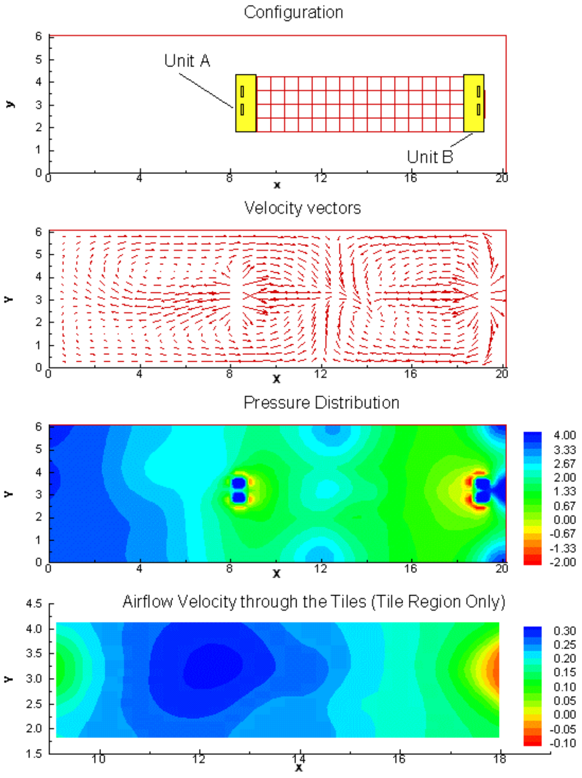

Figure 10. Predicted distributions of under-floor velocity, pressure, and air velocity through tiles for Test 10

outlets of the A/C units and within the stagnation point regions on the walls. The longitudinal velocities (directed along the x axis) are larger near unit B, causing large pressure variation in this region, which leads to back flow. The peak in the airflow velocity distribution is located closer to unit A and corresponds to the location where the two opposing streams meet. In accordance with the volumetric flow rates shown earlier, negative velocities are seen near unit B.

Test 12. In this test, A/C unit A is off. The test data shows back flow near unit B. Figure 11 shows the comparison of predicted and measured tile flow rates. The predicted flow rates are in good agreement with the measured values. Figure 12 shows the predicted velocity vectors and distributions of pressure and tile airflow velocity. A large portion of the flow from the A/C unit exits as a jet directed along the length of the tiles and is exhausted from the tiles close to unit B. The remaining fluid impinges on the right wall (x = 20 m), turns around, and is exhausted from the tiles located near unit A. The longitudinal velocities (directed along the x axis) are largest near unit B, causing large pressure variation, which leads to back flow. As expected, pressure is higher near the outlet of the A/C unit B and within the stagnation point region on the right wall. The tile airflow velocities conform to the volumetric flow rate variations shown in Fig. 11.

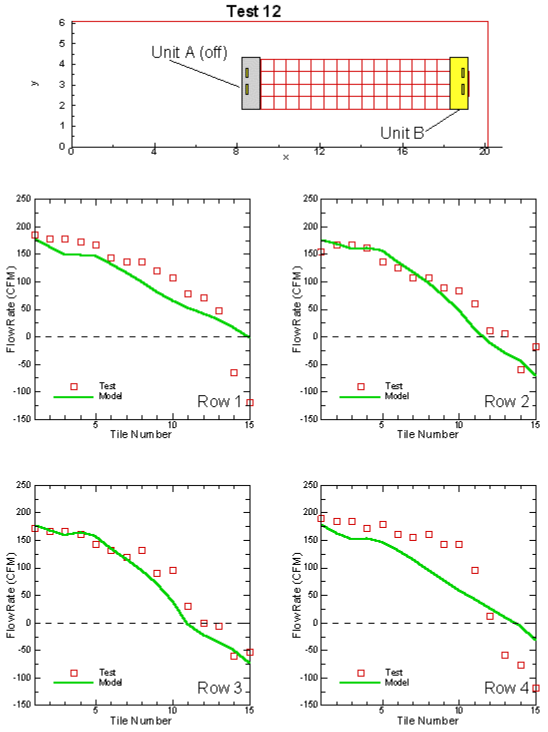

Figure 11. Tile airflow rates for Test 12

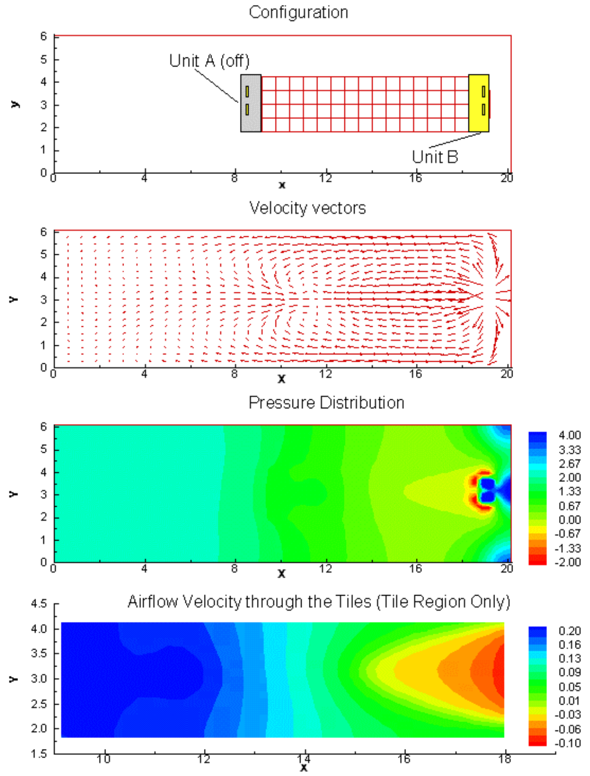

Figure 12. Predicted distribution of under-floor air velocity, pressure, and velocity through the tiles for Test 12

Test 14. In this test, the A/C unit B is off. The test data shows back flow near unit A. Figures 13 and 14 show the results for this test. Again, the predicted and measured flow rates are in fair agreement. As in Test 10, the flow exiting the unit A splits into two streams. The fluid in the forward stream is exhausted from the tiles close to unit A. The reverse stream turns 180 deg. and is exhausted from the tiles near unit B.

Parametric Studies

The validated model was used to study the effect of various parameters on the airflow distribution through the tiles. In this section, we present results from three case studies. These studies are concerned with the effect of the raised-floor height (plenum depth), tile open area, and tiles with variable openings. The physical configuration considered is very similar to that for Test 14 (Case 1 in Fig. 4), except that there are only three rows of tiles. The results presented here are for the center row. Note that these examples are presented to illustrate certain concepts and the quantitative information is not relevant.

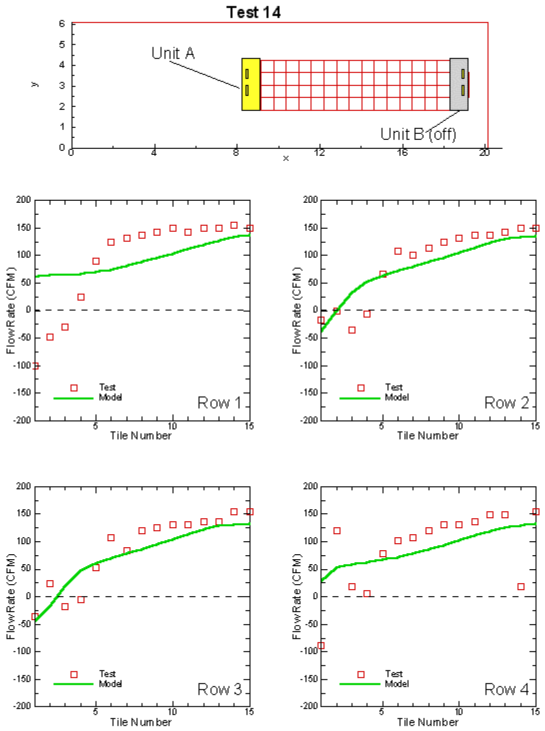

Figure 13. Tile airflow rates for Test 14

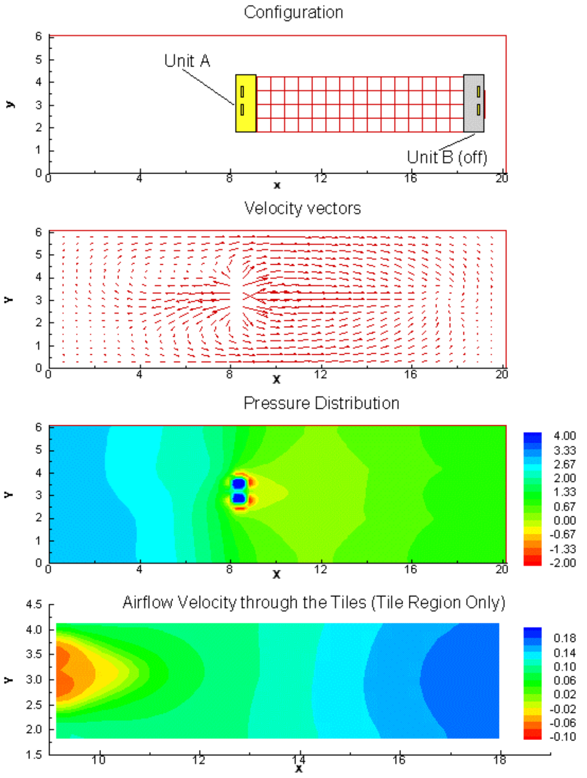

Figure 14. Predicted distribution of under-floor air velocity, pressure, and velocity through the tiles for Test 14

Effect of Raised-Floor Height. The airflow rates through the tiles become nonuniform when the horizontal pressure differences under the raised floor are comparable to the pressure drop across the tiles. The horizontal velocity and pressure distributions are significantly influenced by the height of the raised floor. As this height is increased, the airflow in the horizontal planes weakens and leads to reduced nonuniformity in the pressure distribution and, therefore, in the flow rate through the tiles. Figure 15 shows the variation of flow rate through the tiles for various heights.

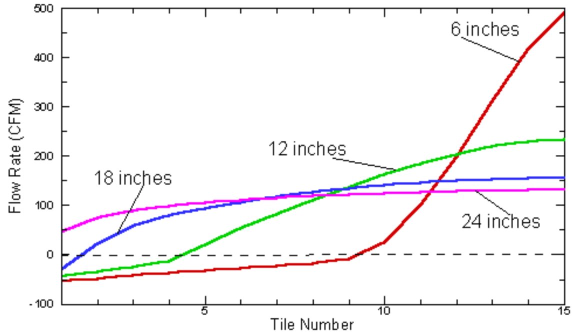

Figure 15. Effect of raised-floor height on airflow rates through tiles

Effect of Tile Open Area. As the open area 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. Thus, at low open areas, the entire plenum is essentially at a uniform pressure, and the flow rates through the tiles are nearly equal. Figure 16 shows the effect of tile open area on the airflow rates through the tiles.

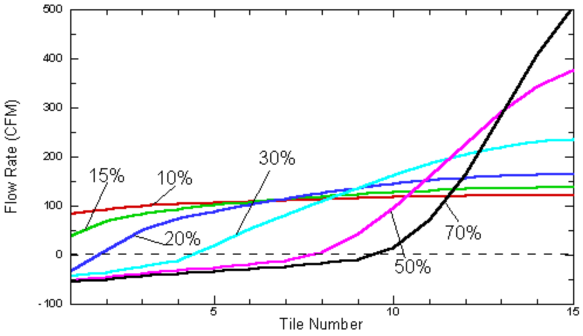

Figure 16. Effect of tile open area on airflow rates through tiles

Effect of Variable Tile Open Area. An important consideration in the design of a data center is the uniformity of flow rates through the tiles. As seen in Figs. 15 and 16, two possible ways of making the flow rate distribution uniform are to increase the plenum depth or reduce the tile open area. For an existing data center, it is not feasible to increase the floor height. Similarly, although the flow rate distribution can be made uniform by reducing the tile open area, this option leads to significant loss of chilled air from other openings in the raised floor (e.g., open areas around cables and pipes), which offer lower flow resistance. Thus, other methods for achieving uniform airflow distribution must be sought. One possible way of achieving a uniform flow rate distribution is to use tiles of different openings at different locations. As seen in the previous examples, the flow rates are largest in the regions of high pressure. These flow rates can be reduced by installing tiles with reduced open areas in these regions. The flow rates through tiles above the low-pressure regions can be increased by using tiles with larger open areas. Figure 17 shows a possible arrangement with variable tile openings and the corresponding flow rate variation. It is seen that the arrangement with variable open area leads improved flow rate distribution.

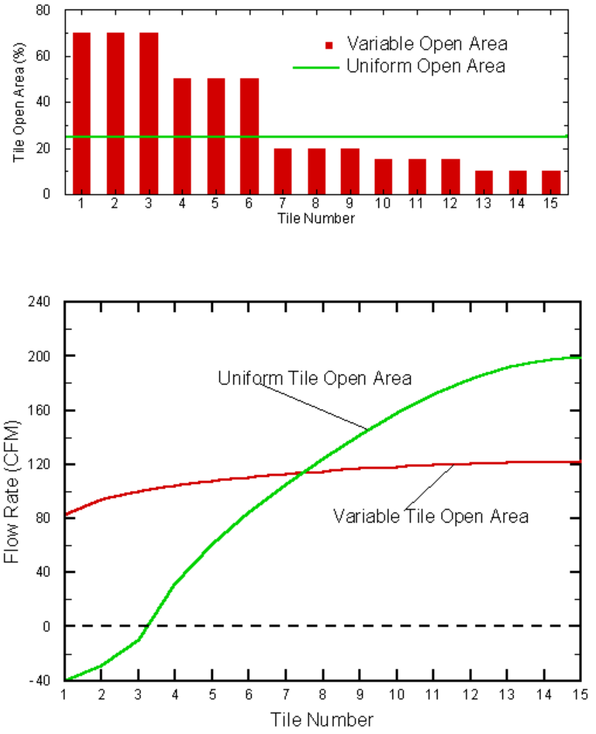

Figure 17. Flow rates through tiles for a variable tile open area arrangement

Scaling of Results

In this paper, we have covered total flow rates up to 10,000 cfm and individual tile flow rates around 200 cfm. In actual data centers, however, even larger flow rates may be encountered. The pressure variation under the raised floor is caused primarily by the change of momentum (the flow inertia). The pressure drop across the perforated tiles is proportional to the square of velocity. Thus, all pressure differences will scale identically with the square of the velocity, and the predicted flow patterns will remain independent of the flow rate or the air velocity. Thus, the computational model is expected to produce similar results even at higher flow rates.

CONCLUDING REMARKS

In this paper, we have presented the results of a joint experimental/modeling project focused on the prediction of airflow distribution through tiles in data centers. The computational model is based on the solution of the depth-averaged equations governing the velocity and pressure distributions for airflow under the raised floor. The model is very general and allows for variations in the raised-floor height, tile open area, air-conditioning unit flow rate, and under-floor flow blockages.

The test program provided reliable data to check the validity of the computational model. The measurements were conducted on an actual data center at IBM. It contained two A/C units, which could be activated independently. A large number of different layouts of the perforated tiles were created and the flow rates through them were measured with either one or both air-conditioning units operating. The flow resistance of the perforated tiles was also determined by measuring the corresponding pressure drop.

The predicted airflow rates are in fair agreement with the test data. After establishing the validity of the model, it was used to perform a number of parametric studies involving variations in the raised-floor height and tile open area. These results provide valuable guidance for selecting parameters that will leads to uniform airflow rates through the tiles.

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