Measurement of Air Flow Rate Through Perforated Floor Tiles in a Raised Floor Data Center

In a raised floor data center, cold air from a pressurized subfloor plenum reaches the data center room space through perforated floor tiles. Presently, commercial tool “Flow Hood” is used to measure the tile air flow rate. Here, we will discuss the operating principle and the shortcomings of the commercial tool and introduce two other tile air flow rate measurement tools. The first tool has an array of thermal anemometers (named as “Anemometric Tool”), and the second tool uses the principle of temperature rise across a known heat load to measure the tile air flow rate (named as “Calorimetric Tool”). The performance of the tools is discussed for different types of tiles for a wide range of tile air flow rates. It is found that the proposed tools result in lower uncertainty and work better for high porosity tiles, as compared to the commercial tool.

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Keywords: data center cooling, perforated tile, air flow rate measurement, Flow Hood, Anemometric Tool, Calorimetric Tool

1 Introduction

Air cooling is the most common method used in data centers. In raised floor data centers, cooling air is supplied to the server racks from a subfloor pressurized plenum through perforated floor tiles [1–3]. Depending on the rack air requirement, appropriate amount of cooling air is required from the adjacent perforated tile. Many experimental investigations have been reported on effective air flow distribution through an array of perforated tiles [4–8] and it is imperative to measure the tile air flow rates to aid in design of cooling air distribution system. Measurement of air flow rate is also important for validation of numerical models [9–11].

Presently, commercial tool Flow Hood [12] (also known as “Balometer” [13]) is used to measure the tile air flow rate [14–17] based on Pitot-static tubes. The tool air flow resistance is compensated by measuring the air flow rate at two different tool resistance levels to obtain the actual air flow rate (without tool resistance). Here, we show that the necessity for tool resistance compensation results in high uncertainty and ineffective performance at higher tile porosities. To overcome these shortcomings, we propose two tile air flow rate measurement tools, the first having an array of thermal anemometers (Anemometric Tool) and the second based on Pitot-static tubes. The tool air flow resistance is compensated by measuring the air flow rate at two different tool resistance levels to obtain the actual air flow rate (without tool resistance). Hence, tool resistance compensation is not required, resulting in lower measurement uncertainty, and effective operation for high porosity tiles. For Calorimetric Tool, an array of fans, with controllable fan speeds, is used to compensate the tool resistance. The performance characteristics of commercial tool (Flow Hood) and the proposed tools are discussed in the paper.

2 Experimental Setup

Figure 1 shows a section of the Data Center Laboratory at Georgia Institute of Technology, used for experiments. The room has floor area of 56 m² (600 sq. ft) and plenum depth of 0.91 m (3 ft) and houses three computer room air conditioning (CRAC) units, one power distribution unit (PDU), and one chilled water distribution unit (CDU), see Fig. 1(a). A total of 12 standard size racks (none powered) are arranged on either sides of a single cold aisle having six perforated tiles. (size of 0.61 m × 0.61 m (2 ft × 2 ft)), see Fig. 1(b) for the layout of the data center. For testing, same type of tiles are used for a given case. The tile air flow rate is measured for only one tile represented by the cross sign and denoted as “Measurement Tile”, adjacent to the “Server Simulator” rack, see Fig. 1(b).

Hot air return vents are located above the hot aisles, as shown in Fig. 1(a), the vent size is 0.61 m × 0.61 m (2 ft × 2 ft). There are two down-flow CRAC units (“1” and “2”) and one up-flow CRAC unit (“3”), see Figs. 1(a) and 1(b)). In the present investigation, only down flow units, 1 and 2, are used and unit 3 is turned off. Both CRACs 1 and 2 have variable speed drives (VSD) to obtain a wide range of air flow rates through the tiles. Plenum pressure was measured using a Piezoresistive micromanometer (Alnor AXD 610) [13]. Uncertainty in the plenum pressure measurement is estimated to be ±5% of the measured value.

Photographs of different types of tiles and the corresponding tile pressure loss factor (K) and tile porosity (F) are given in Fig. 2. The tiles are commercially available and have different porosities, pore sizes and shapes, and anterior structures. Here, we have tested four types of tiles, namely “Chamfered,” “Circular,” “Generic,” and “Generic (no-damper)” as shown in Fig. 2. The pressure loss factors for these tiles were measured in our previous investigation [17] and the corresponding porosity is obtained from a correlation [18] (also see Fig. 5(b) for the correlation). Anterior dampers from the Generic tile were removed to get higher porosity tile Generic (no-damper).
Section 3 describes operating principle of the commercial tool, Flow Hood.

3 Flow Hood

A photograph and schematic of the commercial tool, Flow Hood, is presented in Fig. 3. Flow Hood (kit 8400 [12]) measures the tile volumetric air flow rate using a velocity grid, Shortbridge ADM–860 C [12]. Velocity grid calculates the average flow velocity based on the difference between total and static pressures (Pitot static tube principle). In the plane of measurement, it has 16 ports in the direction facing the flow (to measure the total pressure) and 16 ports in the posterior (to measure the static pressure). Air temperature is measured using a thermistor (placed in the air flow path) to calculate the air density. A cloth skirt directs the air flow from the tile through the velocity grid. The inlet of the cloth skirt has same dimensions as that of the perforated tile, to ensure negligible air leakage. To compensate tool flow resistance, two flow rate measurements are acquired in the “Flap Open” and the “Flap Close” conditions, and finally, the “Actual” air flow rate is obtained.

The operating principle and the possible formulation, based on the resistance analysis of air flow through restrictions, to obtain the Actual air flow rate through a tile are shown in Fig. 4. We have assumed that the flow is fully turbulent, which results in pressure loss characteristics independent of the Reynolds number (Re) (independent of the tile air flow rates) [18,19]. In this case, the pressure loss through a restriction is proportional to the specific kinetic energy of the flow and the constant of proportionality is called the pressure loss factor \( \frac{\Delta P}{K} = C_2 \frac{\rho V^2}{2} \) [18,19]. Miller [19] suggested that for \( Re > 10^3 \), the effect of Re is absent.
on \( K \), which is applicable for the present case (for data centers, \( Re > 10^4 \)). Note that \( Re \) is based on pore size and average tile approach velocity.

For Flow Hood, three different resistance levels involved, resulting in three different air flow rates. In Actual condition, the resistance is only due to the perforated tile \((K_t)\) and the corresponding air flow rate is \( Q_t \) which is the desired measurement and is finally displayed, see Eq. (1), Fig. 4. In the Flap Open condition, the resistance is from the tile \((K_t)\) and the tool with open flaps \((K_o)\) and the air flow rate in this condition is reduced and is denoted here by \( Q_{t,o} \) and is displayed first, see Eq. (2), Fig. 4. For the Flap Close condition, the resistance of the tool is further increased \((K_c)\) by closing the flaps, see Fig. 3. This results in further reduction in the air flow rate to \( Q_{t,c} \), but this not displayed, see Eq. (3), Fig. 4.

As the resistances of the tile and the tool are in series, they can be added to get the total resistance for the flow network \([19]\).

Driving potential for all three resistance levels is pressure difference between plenum \( (P_p) \) and room \( (P_m) \). It can be assumed that this differential pressure \( (P_p - P_m) \) is not affected by the tool \([17]\).

From the flow resistance analysis; we have three equations and three unknowns as listed in Fig. 4(c). Note that \( Q_{t,o} \) and \( Q_{t,c} \) are measured and \( K_o \) and \( K_t \) are tool properties (obtained separately), hence, the actual air flow rate \( Q_t \) can be obtained \([17]\). Note that we can also estimate the other two unknowns, namely, differential plenum pressure \( (P_p - P_m) \) and the tile pressure loss factor \( (K_t) \) and this was discussed in our previous publication \([17]\). \( K_o \) was estimated in our previous investigation \([17]\) and the estimation of \( K_t \) is given in the Appendix.

### 4 Tool Resistance Compensation—Flow Hood

Due to resistance imposed by the Flow Hood, the tile air flow rate measured in Flap Open condition \( (Q_{t,o}) \) is lower than the Actual flow rate \( (Q_t) \). The ratio of Actual and Flap Open flow rate is the required tool resistance compensation \( (Q_t/Q_{t,o}) \) and it depends on the tile pressure loss factor \( (K_t) \), see Fig. 5(a). Note that \( Q_t/Q_{t,o} \) increases significantly for high porosity tiles \( (F > 0.5) \), for example, for low porosity tile (say \( F = 20\% \)), \( Q_t/Q_{t,o} = 1.09 \), however, for high porosity tile (say \( F = 60\% \)) the \( Q_t/Q_{t,o} = 2.4 \). Hence, if \( Q_t/Q_{t,o} \) is not determined accurately for high porosity tiles, then there is a possibility of large error in the desired Actual air flow rate. This also suggests that the performance of the Flow Hood may be lower for measurement of air flow rate through high porosity tiles. Note that \( Q_t/Q_{t,o} \) is a function of the tile pressure loss factor \( (K_t) \), hence, in principle if \( K_t \) is estimated accurately, then the performance of the Flow Hood may be higher for measurement of air flow rate through high porosity tiles. Note that \( K_t \) was taken from Ref. \([17]\).

![Fig. 5 Tool resistance compensation required for the commercial tool. \( K_o \) and \( K_t \) taken from Ref. \([17]\).](https://electronicpackaging.asmedigitalcollection.asme.org/doi/abs/10.1115/1.4029797)

![Fig. 4 Operating principle for Flow Hood: (a) Representation of air flow system for three different flow resistances. Knowns: \( Q_{t,o} \) (displayed), \( Q_{t,c} \) (not displayed), \( K_o \) (9.5 \([17]\)), \( K_t \) (19.9 \([\text{Appendix}]\)). Unknowns: \( Q_t \) (displayed), \( P_p - P_m \), \( K_t \); (b) formulation of the air flow system for three different flow resistances; and (c) variables associated with the tile air flow rate measurement system.](https://electronicpackaging.asmedigitalcollection.asme.org/doi/abs/10.1115/1.4029797)
known a priori then the Actual flow rate can be obtained from the measurement of Flap Open flow rate (without requiring the measurement of Flap Close flow rate). However, as an extra input ($K_t$) is required, the applicability of the tool may be reduced and the uncertainty may be large. In any case, large compensation is required for high porosity tiles (see Fig. 5(a)).

In Flow Hood, $(Q/Q_{A,0})$ is calculated by measuring the air flow rate at another (higher) resistance level in the Flap Close condition ($Q_{A,0}$), also refer to Figs. 3 and 4. From the measured flow ratio (Flap Close/Flap Open, $Q_{A,0}/Q_{A,0}$), the $(Q/Q_{A,0})$ can be obtained, and this relation is shown in Fig. 6(a). Note that the $(Q/Q_{A,0})$ depends on $K_t$, see Fig. 6(a) ($K_t$ is related to the tile porosity ($F$) as shown in Fig. 5(b)). From Fig. 6(a), it can be noted that the variation in the $(Q/Q_{A,0})$ is relatively small for a wide range of $F$ (see Fig. 6(a)). The variation of tool resistance compensation $(Q/Q_{A,0})$ with respect to the measured flow ratio $(Q/Q_{A,0})$ shows an interesting trend (see Fig. 6(b)). Note that the sensitivity of $(Q/Q_{A,0})$ increases steeply with $(Q/Q_{A,0})$ for high porosity tiles ($F > 0.5$). This suggests that for high porosity tiles, if there is a small error in the measured flow ratio, it will translate to a large error in the tool resistance compensation and hence in the Actual air flow rate measurement. Hence, this suggests that with Flow Hood, air flow rate measurement for high porosity tiles may lead to large errors.

In Sec. 5, construction and operation of the first proposed tile air flow rate measurement system, Anemometric Tool, is presented to address some of the short comings of the Flow Hood.

5 Anemometric Tool

The proposed Anemometric Tool for tile air flow rate measurement is shown in Fig. 7. The tool has a simple design with Plexiglas walls on all four sides and open top and bottom. Sixteen low profile thermal anemometers (UAS 1200LP [20]) are attached on a stainless steel wire mesh to form a velocity grid (4 × 4), see Fig. 7(b). The thermal anemometers are nondirectional and they measure the velocity magnitude. The number of sensors was chosen appropriately to minimize the measurement error due to velocity field nonuniformity. The measured velocity magnitude at discrete points (16 in the present case, see Fig. 7(b)) are number averaged and this may be different from the desired area-weighted average velocity (normal to the measurement plane) for computation of the volumetric flow rate. The difference may be due to nonuniformity in the flow-field including the wall boundary layer effect, flow emerging from complicated pore pattern and blocked edges. To quantify the difference, flow-field computations were reported in our earlier publication [21]. It was found that the number of sensors and their positioning is critical to achieve (number averaged) velocity that closely represents the area-weighted average (normal) velocity across the measurement plane. With more sensors, the errors pertaining to nonuniformity in the measurement plane can be reduced. For example, using one sensor (placed at the center of measurement plane), four sensors (placed at the center of four quadrants of the measurement plane), and 16 sensors (present design), the volume flow rate is over-predicted by 39%, 24%, and 6%, respectively. Hence, the present design was found to be satisfactory. Operating range of the anemometers is between 0.5 and 5 m/s, resulting in tile air flow rate measurement range of 0.24–1.89 m$^3$/s (500–4000 CFM). The manufacturer specified accuracy for the anemometers is ±5% of the measured value and the anemometers are internally compensated for variation in air temperatures range of 0–70 °C (32–158 °F). The anemometers are connected to a data acquisition hub (ATM 2400 [20]) and the acquired data is finally transferred to a personal computer. The volumetric air flow rate is computed from average velocity and open area. The porosity of the tool is estimated to be 84% ($F = 0.84$) and the outer dimensions of the tool base are same as that of a standard tile (0.61 m × 0.61 m, 2 ft × 2 ft).

The velocity grid is placed 46 cm (18 in.) above the tile surface to allow reasonable development of the flow field emerging from a perforated tile. Note that significant decay of free jet is observed at an axial distance of ~18D (even faster decay for symmetric jets ~8D) [22]. Considering tile pore size of 1.27 cm (0.5 in), the jet decay distance will be 23 cm (9 in.). This suggests that at the velocity grid, the flow field is reasonably developed.

![Anemometric Tool](image_url)
with temperature rise of 15°C. The test setup is shown in Fig. 1. Note that this range of air flow rate measurement was obtained by changing the CRAC fan speed (experiments). The tool resistance compensation factor \( F \) is estimated to be negligible. The tool resistance compensation \( (Q_t/Q_{\text{measured}}) \) variation with respect to tile porosity \( (F) \) for the Anemometric Tool is shown in Fig. 8. Pressure loss factor for the Anemometric Tool, \( K_t = 0.28 \), corresponding to \( F = 0.84 \) from correlation (see Fig. 5(b) \[18\]).

For the Anemometric Tool, the tool resistance compensation is not considered and the air flow rate measured with the tool \( (Q_t) \) is considered as the Actual tile air flow rate \( (Q_a) \). In this aspect, \( (Q_t/Q_{\text{measured}}) \) gives an estimate of the error induced by the tool for tile air flow rate measurement. Figure 8, shows that the tool can be used even for high porosity tiles \( (F = 60\%) \) with reasonably low error \((\sim 7\%)\).

The tool resistance compensation \( (Q_t/Q_{\text{measured}}) \) variation with respect to tile porosity \( (F) \) for the Anemometric Tool is shown in Fig. 8. Pressure loss factor for the Anemometric Tool, \( K_t = 0.28 \), corresponding to \( F = 0.84 \) from correlation (see Fig. 5(b) \[18\]). The tool resistance compensation factor \( (F) \) ranging from 20 to 32% (see Fig. 2). For corresponding tile pressure loss factor \( (K_t = 53.5 - 15.9, 17) \) for these three tiles, the error induced because of tool resistance for the Anemometric Tool is estimated to be negligible \((<1\%)\), see discussion for Fig. 8.

Figure 9(a) shows the comparison of air flow rate measurements from Flow Hood (Actual) and Anemometric Tool. From the figure, we note that both the tools agree well (within \( \pm 10\%) \) in the measured range. Figure 9(b) shows the measurement uncertainty for the two tools. The uncertainty was calculated based on 15 readings at a particular condition (tile air flow rate of about \( 0.57 \, m^3/s, 1200 \, CFM \)) for 95% confidence level \[23\] using student-t distribution. Note that nonuniformity in the velocity field can also result in measurement errors. Flow field computations were reported in our earlier publication to quantify the effect of flow-field nonuniformity \[21\]. However, due to large variation in tile geometrical structures and different operating conditions as well as unknown fidelity in the computational results, it may not be possible to include this error as systematic error and we have only reported the estimates of uncertainty based on the repeatability of measurements. Figure 9(b) suggests that the uncertainty for Anemometric Tool and Flow Hood in Flap Open condition is low \((<2\%)\), whereas the actual air flow rate reading from Flow Hood is higher \((<5\%)\). This may be because the Actual reading is based on two measurements at Flap Open and Flap Close conditions (refer to discussion for Figs. 3–6). This also suggests that the proposed Anemometric Tool can result in lower measurement uncertainty as compared to the commercial Flow Hood, possibly because it requires single reading.

From Figs. 5 and 6, it was noticed that the Flow Hood may not work effectively for high porosity tiles \( (F > 0.5) \). Operation of both Flow Hood and Anemometric Tool was examined for a high porosity Generic (no-damper) tile (see Fig. 2) \((F = 53\%, K_t = 3.2)\). The pressure loss factor \( (K_t) \) for this tile was obtained from the measured differential plenum pressure (see Fig. 1(b) for the test setup) and the measured tile air flow rate using the Anemometric Tool.

Figure 10(a) shows the comparison for a wide range of measured air flow rates from the high porosity tile using both the tools (Actual air flow rate for Flow Hood) and it can be noticed that the two tools don’t agree well. From Fig. 9, we can estimate that the error from Anemometric Tool for the corresponding tile porosity \( (F = 53\%) \) will be \(<5\%). This suggests that the Anemometric Tool will measure reasonably correct air flow rates and the Flow Hood is not working properly for this high porosity tile.

Figure 10(b) shows the measurement uncertainty for the two tools. The uncertainty was calculated based on 15 readings at a particular condition (tile air flow rate of about \( 0.94 \, m^3/s, 2000 \, CFM \)) for 95% confidence level using student-t distribution \[23\]. It can be noted that the uncertainty for Actual measurement from the Flow Hood is unacceptably high \((>25\%)\), whereas the uncertainty for the measurements from Anemometric Tool is very low \((<2\%)\). This further shows that the Anemometric Tool can work reasonably well even for high porosity tiles.

The degree of nonuniformity, quantified as the ratio of standard deviation and the mean of the measured velocity across the grid (measured at 16 points, see Fig. 7(b)), for the generic tile (see Fig. 2) at tile air flow rate of 0.85 \, m^3/s (1800 CFM) is found to be 43\%. The errors caused by nonuniformity in the velocity field in the measurement plane are expected to be lower with the use of multiple sensors (16 was found satisfactory) \[21\].

In Sec. 6, construction and operation of the second proposed air flow rate measurement system, Calorimetric Tool, is presented.

**Fig. 8** Tool resistance compensation required for Anemometric Tool

The air flow rate was measured for a wide range of air flow rates from 0.24 to 1.18 \, m^3/s (500–2500 CFM) for Chamfered, Generic, and Circular tiles shown in Fig. 2. Tile air flow rate variation was obtained by changing the CRAC fan speed (experimental test setup is shown in Fig. 1). Note that this range of air flow rate can cool server racks with heat load range of 4.5–22.5 kW with temperature rise of 15°C. The three tiles investigated here have porosities \( (F) \) ranging from 20 to 32% (see Fig. 2). For corresponding tile pressure loss factor \( (K_t = 53.5 - 15.9, 17) \) for these three tiles, the error induced because of tool resistance for the Anemometric Tool is estimated to be negligible \((<1\%)\), see discussion for Fig. 8.

**Fig. 9** Experimental evaluation of the Anemometric Tool: (a) Measured tile air flow rates and (b) measurement uncertainty

**Fig. 10** Air flow rate measurement for high porosity tile: (a) Measured tile air flow rates and (b) uncertainty for high porosity tile
The Calorimetric Tool is compared with the previously discussed Anemometric Tool as the later was found to perform well for different tiles, including the high porosity tile.

6 Calorimetric Tool

Figure 11(a) shows a photograph and Fig. 11(b) shows a schematic of the proposed Calorimetric Tool. The tool has Plexiglas walls on the four sides and open bottom and top, similar to the Anemometric Tool. Nine electric resistance heaters (3 × 3 array) are placed in the path of the air flow. To compensate the flow resistance (or pressure drop) across the heaters, fans are placed below the heaters and the fan speed is adjusted so as to achieve near zero pressure differential across the heaters. Thermocouple (T-type, 321 μm wire diameter) grids (4 × 4 thermocouples) were placed before (upstream) and after (downstream) the heaters to measure the temperature rise of air flow through the heaters. Distance of the downstream thermocouple grid from the heaters was large (0.61 m, 2 ft), to allow reasonably good thermal mixing in the measurement plane.

Calorimetric tool measures the air flow rate based on the temperature rise across a known heat load in the path of the air flow, i.e.,

\[
Q = \frac{H}{(\rho cp(T_d - T_u))},
\]

where, \(Q\) is the volumetric air flow rate, \(H\) is the sum of powers supplied to heaters and fans, \(\rho\) is the air density, \(cp\) is the specific heat capacity of air at constant pressure, \(T_d\) and \(T_u\) are the number (16 in the present case) averaged temperatures at downstream and upstream of the heaters, respectively. The uncertainty in temperature measurement was estimated to be ±0.5°C. Note that, we have not measured velocity at the thermocouple locations, hence, the mass weighted average temperature is not reported.

Heater power was measured by a power meter [24]. The manufacturer reported accuracy for the power meter is ±1.5%. The total heater power was 12.8 kW. The total fan power was obtained by measuring the input voltage (current was constant and equal to 2.5 A). Power for all the heaters was kept constant and uniform. The fan controller adjusts (and also displays) the input voltage to the fans to control its speed. Hence, the fan power depends on its operating speed. The fan speed was uniform for the present investigation.

The pressure drop across the resistance heaters was compensated by controlling the fan speed (installed in series to the resistance heaters, see Fig. 11). The principle of tool resistance compensation could be understood from the flow resistance diagrams shown in Fig. 12. When the pressure head provided by the fans equals the pressure loss across the resistive heaters, then the measured air flow rate would correspond to the actual air flow rate.

That is, if

\[
P_n(Q_{t,a}) = \frac{Q}{(2A^2)}K_h Q_t^2,
\]

then: \(Q = Q_{t,a}\), where \(P_n(Q_{t,a})\) corresponds to the fan curve. Note that for this condition the pressure drop across the tool (∆P) tends to zero. Depending on the air flow rate through the tiles, the corresponding fan speed to compensate for the pressure drop is different. The fan speeds were controlled manually to achieve near zero pressure drop across the tool (∆P) (∆P ≤ 0.1 Pa). Note that with better feedback control of fan speed the performance of the tool can be enhanced and the operation can be simplified.

Figure 13(a) shows the measured air flow rate from the two proposed tools (Anemometric and Calorimetric) for the Generic tile and Generic tile (no damper). The data from the two tools agree well with each other (within ±10%) for a wide range of air flow rate (0.57–1.13 m³/s, 1200–2400 CFM). For air flow rate above 1.13 m³/s (2400 CFM), the fans are not able to compensate...
the pressure drop and for air flow rate lower than 0.57 m³/s (1200 CFM), the air flow is not able to cool the heaters sufficiently (heaters get overheated and tripped). Thus, the above mentioned practical limitations govern the air flow rate measurement range for the Calorimetric Tool. Note that the Calorimetric Tool is able to measure the air flow rate for high porosity tile (Generic (no-damper)), see Fig. 13(a), where the commercial Flow Hood was found to perform inadequately, see Fig. 10.

The uncertainty for both the proposed tools for generic tile, with and without dampers, is shown in Fig. 13(b). The uncertainty was calculated based on 15 readings at a particular condition (tile air flow rate of about 0.94 m³/s (2000 CFM)) for 95% confidence level using student-t distribution [23]. The figure shows that the uncertainty for the Calorimetric Tool is slightly higher as compared to the Anemometric Tool. This may be because of the manual feedback control used for the tool resistance compensation for the Calorimetric Tool. However, the uncertainty is acceptable (<5%) for both high and low porosity tiles. Recall, that the uncertainty for Flow Hood was unacceptably high (~25%) for the high porosity tile (see Fig. 10(b)).

The degree of nonuniformity, quantified as the ratio of standard deviation and the mean of the measured temperature difference across the grid (measured at 16 points both upstream and downstream, see Fig. 11(b)), was obtained for the generic tile (see Fig. 2) at tile air flow rate of 0.85 m³/s (1800 CFM) and was found to be 29%. The errors caused by nonuniformity in the temperature field in the measurement plane are expected to be lower with the use of multiple sensors [21].

7 Conclusions

Two tile air flow rate measurement tools are proposed. The first tool is based on multipoint velocity measurements using thermal anemometers (Anemometric Tool). The porosity of the tool was designed to be high enough to result in minimal impact of tool resistance on the measured tile air flow rates. This also allowed single point measurement as compared to two point measurement for the commercial tool, Flow Hood. The second tool is based on bulk temperature rise of air flow across a known heat load (Calorimetric Tool). For this tool, the flow resistance compensation is provided by the fans, which are placed in series with the resistance heaters, so as to achieve near zero pressure drop across the tool. Both Anemometric and Calorimetric Tools resulted in lower measurement uncertainty and acceptable performance for high porosity tiles for which Flow Hood does not work properly. These tools could be further, automated and refined for practical applications and could be developed to allow their use as general purpose tile air flow measurement tools.

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Nomenclature

Symbols

\[ A = \text{area} \]
\[ c_p = \text{specific heat capacity of air at constant pressure} \]
\[ F = \text{open area ratio or porosity} \]
\[ H = \text{sum of fan and resistance heater power} \]
\[ K = \text{pressure loss factor} \]
\[ P = \text{pressure} \]
\[ Q = \text{air flow rate} \]
\[ Re = \text{Reynolds number} \]
\[ V = \text{air velocity} \]
\[ \rho = \text{air density} \]

Subscript/Superscript

\[ c = \text{tool in Flap Close condition} \]
\[ d = \text{downstream} \]
\[ h = \text{resistance heater} \]
\[ in = \text{inlet} \]
\[ m = \text{room} \]
\[ n = \text{fan} \]
\[ o = \text{tool in Flap Open condition} \]
\[ p = \text{plenum} \]
\[ t = \text{tile} \]
\[ u = \text{upstream} \]

Appendix: Estimation of \( K_c \)

The pressure loss factor for Flow Hood in Flap Close condition \((K_c)\) was estimated using the setup shown in Fig. 14(a). From Fig. 13 Experimental evaluation of the Calorimetric Tool: (a) Measured tile air flow rates and (b) uncertainty estimation

from Degree Controls, Inc. and Triad Tiles, Inc. is gratefully acknowledged.

\[ K_c = \left( \frac{1}{\left( \frac{Q_{t,c}}{Q_{t,o}} \right)^2} - 1 \right) K_t + \left( \frac{1}{\left( \frac{Q_{t,c}}{Q_{t,o}} \right)^2} \right) K_o \]

Fig. 14 Estimation of \( K_c \) (\( Q_{t,c} \) and \( Q_{t,o} \) were measured using the Anemometric Tool, \( K_t = 9.5 \) [17] and \( K_o = 24.7 \) [17]): (a) Setup to estimate \( K_c \) and (b) formula to obtain \( K_c \)
Eqs. (2) and (3) (see Fig. 4) we can obtain the expression for $K_t$ and the same is given in Fig. 14(b). Note that we have assumed that the differential plenum pressure ($P_p - P_m$) is same in both the conditions (Flap Open and Flap Close) [17]. The Flow Hood was placed over the Anemometric Tool as shown in Fig. 14(a) and the edges were sealed at the interface of the two tools to avoid air leakage. With this setup, the air flow rate through the Flow Hood in Flap Close (sealed at the interface of the two tools to avoid air leakage. With this setup, the air flow rate through the Flow Hood in Flap Close ($Q_{a,\text{Cl}}$) and Flap Open ($Q_{a,\text{O}}$) conditions can be measured using the Anemometric Tool and the measured air flow ratio ($Q_{a,\text{Cl}}/Q_{a,\text{O}}$) can be obtained. For this measurement, we have used Generic tile (see Fig. 2) with known tile pressure loss factor ($K_t = 24.7$) [17]. The pressure loss factor in the Flap Open condition ($K_o = 9.5$) was estimated previously [17]. Note that $Q_{a,\text{O}}$ can also be measured directly from the Flow Hood itself and for the present case this value was within ±5% of that measured using the Anemometric Tool. Also, note that the Flow Hood does not display the air flow rate in the Flap Close condition and directly displays the Actual flow rate [17]. Using this method, $K_t$ was estimated to be 19.9.

References