Flow Resistance Characteristics for Data Center CFD

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ABSTRACT

Data-center-level CFD simulations require compact models of perforated tiles and other flow resistances that accurately model pressure drop. We discuss the physics of airflow through resistances and compare loss coefficients obtained from commonly used empirical (handbook) correlations, detailed CFD modeling (using four commercial CFD codes), and experimental measurements (using two wind tunnels). Test resistances include square-holed perforated plates with nominal open area ratios of 15%, 25%, 39%, and 56% and one commercial data-center tile of nominal 56% open area. CFD is significantly more accurate than the correlations in predicting resistance characteristics with the added benefit of allowing the modeler to start only from geometry (e.g., CAD) data and precisely control the "experimental" conditions. We also propose a new and simple empirical correlation which fits the measured data better than existing correlations for the perforated plates considered here.

INTRODUCTION

Computational Fluid Dynamics (CFD) is widely used in the design and operation of data centers to ensure compliance to environmental guidelines (e.g., ASHRAE 2021) and minimize cooling-system energy consumption. Data center airflow physics is distinguished from other indoor airflow applications by high heat and airflow loads, intentionally segregated cool supply and warm return airstreams, and populations of repeating elements including IT racks and cooling units. If a raised floor is utilized, perforated floor tiles are generally placed in front of each IT rack and the floor itself will be supported above a concrete slab by stanchions. It is impractical to model many such objects in explicit detail in data-center-level simulations yet physical phenomena such as leakage airflow through racks, flow resistance of stanchions, and discharge airflow patterns from cooling units and perforated tiles should be included for accuracy. Consequently, proper compact modeling techniques are vital - whether included by the CFD vendor or defined manually by the user. An ongoing research project (ASHRAE 2022) will soon deliver guidelines and references related to all these elements. Preceding studies (Hu et al. 2021; Lin et al. 2020) have concluded that compact perforated-tile (flow resistance) models should include straightening (horizontal velocity should not be advected through the tile) and downstream momentum (high velocity/low pressure region just downstream of the resistance should be captured) in addition to the main flow resistance (pressure drop) characteristics. This paper focuses on the latter characteristics which are often obtained from well-known empirical correlations (e.g., Idelchik 2003; Freid and Idelchik 1989) or published manufacturer's data. Manufacturer's data is often provided without sufficient context to assure accuracy. Similarly, there are several limitations associated with the use of handbook

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correlations. First, it may not be clear to the modeler *which* correlation to choose. Additionally, there are very few independent handbook references which allow cross-checking of accuracy and, given the large number of reprintings, it is easy to find errors, typos, and inconsistencies. Finally, even if accurate, many correlations are awkward to use, requiring multiple tables, plots, and interpolation.

One goal of the present paper is simply to explain the physics of airflow through resistances (such as perforated tiles) and, in particular, how to determine the correct resistance characteristics (typically expressed as dimensionless loss coefficients) for data center CFD. These characteristics should be based on a "wind-tunnel" environment because this separates the pure pressure-drop characteristics of the resistance itself from additional pressure drops related to the flow field - which are already explicitly computed by data center CFD. That said, historically, some empirical correlations used in data center CFD have been based on a "open-discharge" environment and may have been chosen to match manufacturer's data which, itself, is of unknown quality and context. For reference, we also include the "open-discharge" environment in our discussion, experimental measurements, and detailed CFD analyses.

Another goal is to show how detailed CFD modeling can more accurately predict pressure-drop characteristics than empirical handbook correlations and manufacturer's data. For this purpose, we experimentally measure four square-holed, perforated plates of nominal open area ratios of 15%, 25%, 39%, and 56%. The test resistances are intentionally simple to model in CFD and allow handbook correlations to be applied unambiguously. To provide greater confidence in our data, we repeated experimental measurements of loss coefficients over two different-sized wind tunnels and four commercial CFD tools. We propose a new and simple correlation which accurately fits the measured flow resistance data. We also demonstrate how detailed CFD can be more accurate than manufacturer's test data in determining pressure-drop characteristics of a commercial data center perforated tile which we also measure experimentally. The geometrically complex tile provides a practical test case for the process of determining flow resistance in detailed CFD starting only with CAD-style geometry.

THE PHYSICS OF AIRFLOW THROUGH RESISTANCES

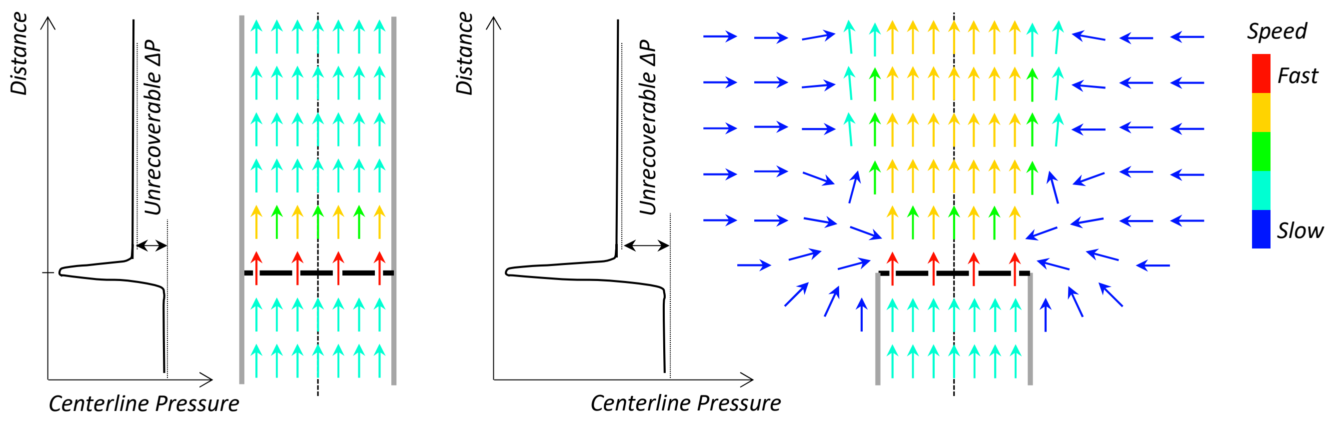
Consider the ideal (frictionless-wall) wind-tunnel and open-discharge environments depicted in Figure 1. In both cases, high velocity jets downstream of each small opening in the resistance create a low-pressure region. As the jets recombine, the pressure partially recovers. It is the net unrecoverable pressure drop across the tile that we seek for room-level CFD and which is typically published in handbooks. The open-discharge environment typically results in a larger overall pressure-drop due to the complex flow pattern downstream of the resistance. In real data center applications, perforated tiles are typically surrounded by other tiles, IT racks, containment panels, etc. Consequently, the airflow is confined in a manner more like the wind-tunnel than the open-discharge environment; the latter environment allows surrounding airflow to be entrained while the former does not. Regardless, detailed CFD modeling should simulate the resistance in a wind-tunnel environment as this excludes pressure drop which is associated with the neighboring flow field. In detailed CFD, the wind-tunnel walls can be specified as frictionless. Real wind tunnel walls have friction; however, the contribution to pressure drop is small for relatively large-cross-section wind tunnels and more restrictive resistances.

The pressure-drop across a (relatively thin) resistance is often expressed in dimensionless form as a loss coefficient f defined by:

$$\Delta P = f \frac{1}{2} \rho V^2 \tag{1}$$

where ρ is the density of air and V is the average (approach) velocity over the entire cross-section of the resistance. For data-center-level CFD, the loss coefficient is typically determined from well-known correlations or manufacturer's data. As discussed above, it depends on the test environment and is theoretically dependent on velocity (Re) at low

Reynolds Number. Conveniently, most data center scenarios involve high-Re flow; indeed, f was found to be practically constant for all scenarios considered in the present study.



a) Wind tunnel b) Open discharge

Figure 1 Physics of airflow through a resistance.

As noted above, the compact resistance model for data-center-level CFD should include a momentum source just downstream of the tile (Hu et al. 2021) to properly model the high-velocity/low-pressure region. This momentum source adds energy to the flow which effectively reduces the net unrecoverable pressure drop. Hu et al. (2021) explain how to compensate for this in the compact model for data center CFD. Again, the present study focuses on accurately characterizing flow resistances themselves; this is a prerequisite for creating an accurate compact model for data center CFD.

DETERMINING LOSS COEFFICIENTS

Experimental Measurements

Two wind tunnels were constructed with inner cross-sectional dimensions as indicated in Figure 2. In both cases, airflow is supplied by a speed-controlled fan and passes through a long flexible duct and flow straighteners which help deliver uniform airflow to the entrance of the wind tunnels. The 10 in (254 mm) and 24 in (610 mm) wind tunnels consist of two 30 in (762 mm) and 8 ft (2.44 m) sections, respectively – one upstream and one downstream of the resistance. Wind-tunnel and open-discharge measurements were made with and without the downstream sections of tunnel, respectively. For the open-discharge scenario, the entire tunnel was supported approximately 1 ft (300 mm) above the floor to allow unconfined airflow on all sides.

Velocity and pressure measurements were made 6.5 in (165 mm) and 16 in (406 mm) upstream of the resistance in the small and large wind tunnels, respectively. In a virtual CFD wind tunnel, pressure would normally be measured at the entrance of the tunnel (relative to room ambient). However, with the experimental setup, the airflow was more uniform closer to the resistance; additionally, measuring pressure closer to the resistance minimizes the contribution of wall friction – which can be conveniently excluded in CFD but not in the lab. Velocity was measured with a (Testo 405i) hot-wire anemometer following duct-traverse locations prescribed in ASHRAE 2017. Pressure was measured with a pitot probe connected to a (Energy Conservatory DG-700) digital pressure gauge. Measurements were made at approximately 25 different velocities in the range of 0-3.5 m/s (0-700 fpm) for each test resistance. Finally, other than minor differences due to wall friction, loss coefficients obtained for the small and large wind tunnels should be theoretically identical.

a) 10 x 10 in (254 x 254 mm) wind tunnel

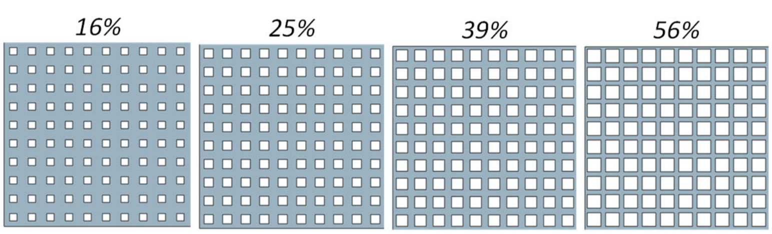
b) 24 x 24 in (610 x 610 mm) wind tunnel

Figure 2 Experimental setup.

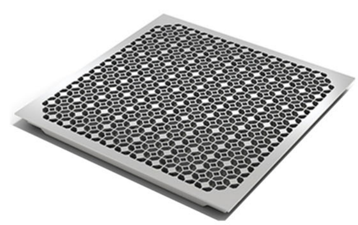
Finally, North (2011) published pressure-drop data for similar square-holed perforated resistances of 40%, 56%, 64%, and 80% open area as measured on a flow bench. This provides some overlap with our data and extends it to larger open-area ratios. However, reported pressure drops are somewhat lower than determined by our measurements and CFD, especially at larger open areas.

Flow Resistances Evaluated

Test resistances include four perforated plates (Figure 3a and Table 1) and one commercial perforated tile for data center applications (Figure 3b). Perforated plates with square holes simplify CFD-modeling. All plates have identical hole-to-hole pitch such that the inner cross section of both the 10 in (254 mm) and 24 in (610 mm) wind tunnels evenly covers a repeating symmetric portion. The 16%, 39%, and 56% plates are off-the-shelf items with cleanly punched square holes. The 25% perforated plate was fabricated specifically for this project – and sized only for the smaller wind tunnel; the holes were milled and, therefore, slightly rounded in the corners. The commercial perforated floor tile (GrateAire 2021) was selected because it is popular, geometrically complex, and a CAD model was available.



a) Square-holed perforated plates



b) Commercial tile, 68% nominal open area

Figure 3 Flow resistances evaluated.

Table 1. Perforated-Plate Characteristics

Description	% Open Area	Thickness in (mm)	Opening Side Length in (mm)	Opening Center-to-Center Spacing, in (mm)
16%	16.0000	0.0500 (1.270)	0.2000 (5.080)	0.5000 (12.700)
25%	25.0000	0.0625 (1.588)	0.2500 (6.350)	0.5000 (12.700)
39%	39.0625	0.0478 (1.214)	0.3125 (7.938)	0.5000 (12.700)
56%	56.2500	0.0598 (1.519)	0.3750 (9.525)	0.5000 (12.700)

Detailed CFD Modeling

CFD simulations were created to match the 10 in (254 mm) wind-tunnel and open-discharge experimental configurations. For the latter, the CFD domains include a portion of the room environment extending 30 in (762 mm) downstream and 10 in (254 mm) in the lateral directions with "open" ($P = 0$) boundary conditions. Wall friction was included to match the experiment and all simulations assumed a uniform supply velocity of 1 m/s (200 fpm). Four commercial CFD codes were employed to model the perforated plates: two data-center-specific tools (6SigmaRoom 2021; EcoStruxure IT Advisor CFD 2021), one electronics-thermal tool (Simcenter Flotherm 2021) and one general-purpose tool (ANSYS Fluent 2020). Starting from a CAD model, 6SigmaRoom and ANSYS Fluent were also used to model the commercial tile. ANSYS Fluent employs a collocated grid scheme while all others a staggered scheme. Predictions were found to be fairly insensitive to turbulence model, discretization scheme, and velocity-pressure coupling technique. However, results were quite sensitive to grid size and distribution. Ultimately, it was necessary to model the perforated plates as 3D (thick) objects with, at least, approximately 12-16 cells across each perforated opening with 4 or more cells across the thickness of the plate to obtain reasonable grid independence.

Empirical Correlations

This popular and convenient "high Re, thin" correlation (Freid and Idelchik 1989) estimates loss coefficient as a function of only the open-area ratio β for wind-tunnel environments:

$$f = \frac{1}{\beta^2}\left[1 + \sqrt{\frac{1-\beta}{2}} - \beta\right]^2 \tag{2}$$

The indicated range of applicability of this correlation is Reynolds Number > 10^5 and t/d_h < 0.015 where t and d_h are the thickness of the plate and hydraulic diameter of a single perforated opening, respectively. We follow the handbook authors' terminology; however, note that the transition to turbulence for internal flows characterized by a transverse length scale (e.g., flow in a pipe), occurs at about 2,300 - much lower than 10^5. Further, given the observation that f varies only a few percent down to Re of 2,000 or smaller (based on measurements, CFD, and all correlations considered here), we conclude that the Re > 10^5 condition is not strictly necessary.

Other wind-tunnel-environment correlations evaluated here include "low Re, thin" (Freid and Idelchik 1989) and "any Re, thick" (Idelchik 2003). Unlike the "high Re, thin" correlation of Equation 2, these correlations cannot be written as single equations but rather rely on additional parameters from charts or tables - the latter typically requiring interpolation. With both the "low Re, thin" and "any Re, thick" correlations, f depends on Re - and also t/d_h in the latter case. Because of these added complexities, they are less convenient for CFD users and developers.

Analogous correlations are available for the open-discharge environment (Freid and Idelchik 1989). Again, the simplest "high Re, thin" correlation conveniently depends only on open area ratio and may be written explicitly:

$$f = \frac{1}{\beta^2}\left[1 + \sqrt{\frac{1-\beta}{2}}\right]^2 \tag{3}$$

The corresponding "low Re, thin" and "any Re, thick" correlations for the open-discharge environment also depend on Re - and t/d_h in the latter case - and require the calculation of various intermediate parameters and interpolation.

RESULTS

Loss coefficients determined from measurements, detailed CFD, and empirical correlations for the perforated plates with the 10 in (254 mm) wind tunnel are shown in Figure 4. For reference, measurements made with the 24 in (610 mm) wind-tunnel were within 4.2% and "10.3%" of the smaller wind tunnel for the wind-tunnel and open-discharge environments, respectively. Note that the "low Re" and "any Re" correlations predict a different f at each measured flow rate so values reported in Figure 4 are a least-squares fit of constant f over the entire flowrate range. An excellent fit is obtained with $R^2 \geq 0.999$ in all cases.

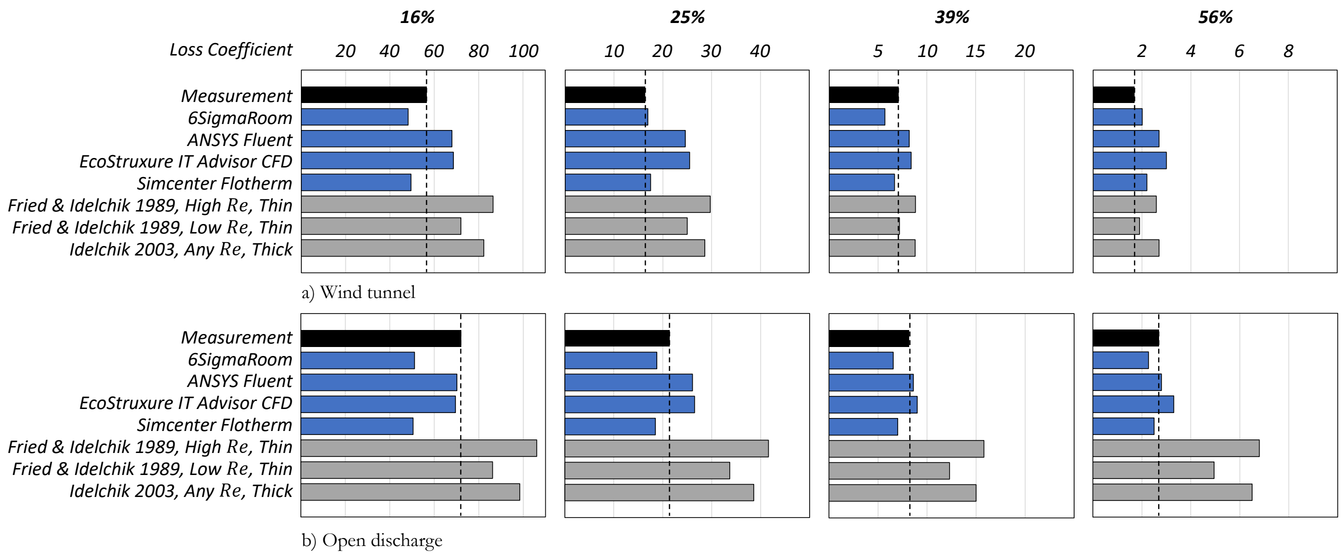


Figure 4 Perforated plate loss coefficients.

Overall, CFD predictions are closer to the measured data than the empirical correlations. The latter tend to over-predict loss coefficients in general and to a greater extent in the open-discharge environment. Out of the empirical correlations, the "low Re, thin" correlation is best. Variations in loss coefficients predicted by the CFD codes were determined to be due primarily to grid scheme and how momentum-equation boundary conditions are implemented. The differences between CFD-predicted and measured loss coefficients for the 16% perforated plate under open-discharge conditions seem large in light of the other results. It is noted that this was the scenario with the largest variation between small (f=72.1 – shown in Figure 4) and large (f=64.7) wind-tunnel measurements. The latter value better fits the trend of the results from other scenarios.

Figure 5 is an alternative presentation of the measured and CFD-predicted loss coefficients of Figure 4. The CFD data points are shown in aggregate – with data from all CFD codes. Superimposed on the data points are curve fits to both the measured and CFD data. The form of the curve fit is suggested by Equations 2 and 3 which have the desired limiting characteristics of $f \rightarrow \infty$ as $\beta \rightarrow 0$ and $f \rightarrow 0$ as $\beta \rightarrow 1$. A least-squares-error fit of the constant C to the functional form $f = \frac{1}{\beta^C}(1-\beta)$ for the wind-tunnel-environment measured data leads to:

$$f = \frac{1}{\beta^{2.29}}(1-\beta) \tag{4}$$

Equation 4 provides a simple (though not analytically invertible) relationship between open area ratio and loss coefficient for the square-holed perforated plates considered here. It may also apply to plates with holes of different size and shape though this is yet to be verified. A similar fit to the aggregate CFD wind-tunnel-environment data results in C=2.32. Similar curve fits are shown for the open-discharge environment in Figure 5b with C=2.43 and C=2.34 for measured and CFD, respectively. Although not quite as good a match as in the wind-tunnel-environment scenario, aggregate CFD results are still quite close to the measured values.

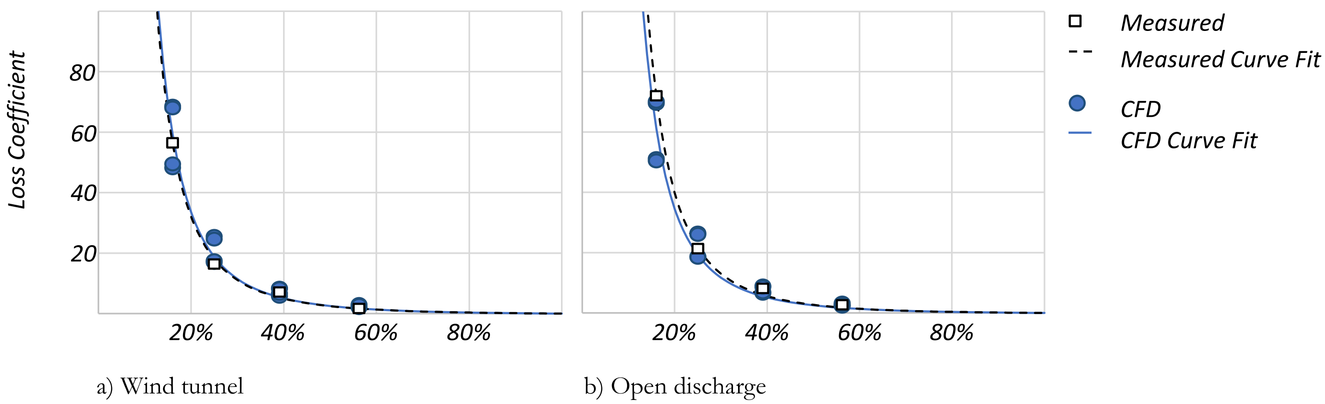


Figure 5 Perforated plate loss coefficient with curve fits.

Figure 6 compares loss coefficients for the commercial perforated tile (GrateAire 2021) obtained from measurements, detailed CFD, and the manufacturer's published data. Measurements and CFD simulations are for the 24 in (610 mm) wind tunnel - which corresponds to the tile size. Manufacturer's data is shown for reference; however, we do not know the environment in which these measurements were made. The CFD predictions are closer to the measured values than manufacturer's data for both environments. The manufacturer's data is closer to the measured data in the open-discharge scenario suggesting that this may be more representative of the manufacturer's actual test environment. In any case, we again note that it is the wind-tunnel data that should be used in data-center-level CFD.

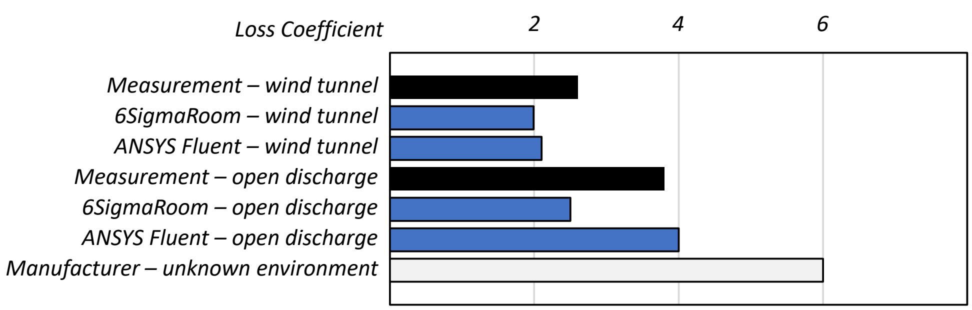


Figure 6 Commercial perforated data center tile loss coefficient.

SUMMARY AND CONCLUSIONS

Accurate compact models of perforated floor tiles and other resistances are required for data-center-level CFD. We discussed the physics of airflow through flow resistances and explained why the wind-tunnel environment should be used when determining loss coefficients with detailed CFD. We determined loss coefficients of square-holed perforated plates through physical measurement, detailed CFD, and empirical handbook correlations. We also compared loss coefficients obtained from measurement, detailed CFD, and manufacturer's data for a commercial perforated tile. To assure high quality, we repeated experimental measurements over two wind tunnel sizes and employed four different commercial CFD codes.

For the square-holed perforated plates, loss coefficients were found to be practically constant across the Reynolds Number range considered and more accurately predicted by detailed CFD than well-known empirical correlations. We proposed a new correlation which predicts loss coefficient as a function of open area ratio; this fits the measured data quite well for the perforated plates and may apply to other resistances as well. For the commercial perforated floor tile, detailed CFD more accurately predicted loss coefficient than the manufacturer's data.

Detailed CFD was more accurate than all empirical handbook correlations and manufacturer's data in determining loss coefficients. Further detracting from the usefulness of the empirical correlations, the simplest and most convenient of which was found to be the least accurate. In detailed CFD, test conditions were precisely controlled, random measurement errors were avoided, and no physical lab space was required. In summary, we found that the best method by which to obtain accurate flow resistance data for data-center-level CFD is to perform a detailed CFD simulation of the resistance in a (virtual) wind tunnel, for example, starting from CAD-style geometry.

NOMENCLATURE

β	Open-area ratio	P	Pressure
ρ	Fluid density	R^2	Coefficient of determination
C	Constant	Re	Reynolds Number
d_h	Hydraulic diameter	t	Thickness
f	Loss coefficient	V	Velocity

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