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Accuracy of Flow Hoods in Residential Applications

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ABSTRACT

To assess whether houses can meet performance expectations, the new practice of residential commissioning will likely use flow hoods to measure supply and return grille airflows in HVAC systems. Depending on hood accuracy, these measurements can be used to determine if individual rooms receive adequate airflow for heating and cooling, to determine flow imbalances between different building spaces, to estimate total air handler flow and supply/return imbalances, and to assess duct air leakage. This paper discusses these flow hood applications and the accuracy requirements in each case. Laboratory tests of several residential flow hoods showed that these hoods can be inadequate to measure flows in residential systems. Potential errors are about 20% to 30% of measured flow, due to poor calibrations, sensitivity to grille flow non-uniformities, and flow changes from added flow resistance. Active flow hoods equipped with measurement devices that are insensitive to grille airflow patterns have an order of magnitude less error, and are more reliable and consistent in most cases. Our tests also show that current calibration procedures for flow hoods do not account for field application problems. As a result, a new standard for flow hood calibration needs to be developed, along with a new measurement standard to address field use of flow hoods. Lastly, field evaluation of a selection of flow hoods showed that it is possible to obtain reasonable results using some flow hoods if the field tests are carefully done, the grilles are appropriate, and grille location does not restrict flow hood placement.

Introduction

For many years, the HVAC industry has used flow hoods to measure grille airflows in non-residential buildings, usually as part of a testing and balancing procedure; residential HVAC systems very rarely have been tested (usually by the research community). Now, utility programs, weatherization programs, and codes and standards such as California's Title 24 are beginning to consider the need to commission residential HVAC systems. Such efforts could include using flow hoods to determine if individual rooms are getting correct airflow, and to estimate total air handler flow and duct air leakage.

Flow hoods have two basic parts: a flow capture device and a measurement device. The flow capture device is usually a fabric hood mounted over a rigid frame (often collapsible for storage and transportation). It directs the airflow over a sensing element in the measurement device. The hood has a larger open end, usually sized to fit a standard commercial grille of 560 mm × 560 mm (22×22 inches); many manufacturers also offer other hood sizes. Flow measurement techniques differ between manufacturers and include pressure difference, thermo-anemometry, plate deflection, and spinning propellers. Most flow hoods can measure flows in either direction (for supply and return grilles). Some hoods have a system of user operable openings and flaps that reduce backpressures at higher flows.

A few studies have evaluated flow hood measurement uncertainty in commercial applications (Choat 1999); they found that flow hoods are poor at measuring commercial grille flows. However, there are no published studies about uncertainty associated with using flow hoods to measure residential grille airflows. Our paper discusses residential applications of flow hoods and the accuracy requirements in each case. It then discusses our laboratory tests and field study of several flow hoods, which show that some commercially available hoods can be inadequate for measuring flows in residential systems, and that powered flow hoods equipped with measurement devices that are insensitive to grille airflow patterns give reliable and consistent results.

Residential Applications for Flow Hoods and Accuracy Requirements

Flow hoods have several residential applications that may require different levels of accuracy in order to be acceptable. Applications can be split into two subsets: those based on individual grille flows, and those based on the total of all supply or return grille flows.

Subset 1: Individual Grille Flows

Measurements of individual grille flows can be used to identify parts of a system with large leaks (e.g., disconnected ducts), to determine flow imbalance between different spaces in a building, and, when combined with temperature and humidity measurements, to determine if enough heating or cooling is delivered by a grille to the space it serves. For identifying large leaks or disconnected ducts, the airflow changes are large and the accuracy of the measurement is not critical: being within ±50% of the correct flow is reasonable. Similarly, imbalances in residential airflows between different spaces in a building are only critical at higher flow rates and an accuracy of ±25% is probably reasonable.

The accuracy requirement related to providing enough heating or cooling airflow to a space for occupant comfort depends on how well the space, the rest of the building, and outside are thermally connected. For most typical residential rooms, there is little thermal resistance to other parts of the building; this reduces the sensitivity of room temperature to deviations in individual supply grille airflows. A simple steady-state heat balance for a room with an insulated exterior wall containing a window and uninsulated partitions for its other surfaces shows that a reasonable limit is to have supply grille airflows within ±20% of their design specification to keep the room temperature within approximately ±1°C (2°F) of the adjoining room temperatures. Therefore, the accuracy of the flow measurement device needs to be better than this ±20% requirement. It is important to note that the sensitivity depends on building loads and therefore climate. The larger the load, the more precisely one needs to know the grille flow in order to maintain reasonable temperature limits. In addition, if transient performance is an issue (how fast a particular room is heated or cooled by the system), then the supply grille airflows need to be better defined.

Subset 2: Total Supply or Return Flows

One can sum individual grille measurements to find the total supply or return airflow, which in turn can be used to estimate air handler flow (if leakage is well known), duct leakage to outside (if air handler flow and leak location are well known), and supply/return imbalances (e.g., determining the degree of house depressurization in backdrafting investigations). From a residential commissioning perspective, the key uses are determining the air handler flow and duct leakage, because residences are generally not deliberately pressurized or depressurized.

For air handler flows, the desire to have the correct air handler flow is most critical for cooling systems, because inadequate air handler flows can reduce cooling capacity and efficiency, and can sometimes lead to coil icing. The effects of air handler flow become significant if the flow is about 15% lower than desired. For example, Rodriguez (1995) found an 8% reduction in equipment efficiency for a 15% flow reduction. If the grille flow measurements are to be used to estimate the effect of air handler flow on equipment performance and a reasonable limit for changing the equipment performance is about 5%, then the total of all grille flows needs to have an accuracy better than about ±10%.

The requirements are more restrictive for using the results to calculate duct leakage. The current low leakage limits for the whole duct system are between 6% (CEC 1998) and 10% (State of Oregon and proposed EPA Energy Star ducts). Because these limits include both supply and return leaks, and because the supply and return grille flows are determined separately, the measurement technique needs to determine leakage flows on the order of 3% to 5% of air handler flow (assuming leakage flows are split evenly between supply and return). If duct leakage testing needs to verify these low leakage levels or provide reasonable estimates of the energy penalty of leakier ducts, then the duct leakage measurement accuracy needs to be better than ±3%. Assuming there is no uncertainty in the air handler flow measurement, this implies that the total of all supply or return grille flows needs to have an accuracy better than ±3%. Note that this implies an uncertainty almost the same as the measurement when verifying low leakage ducts and it would be preferable to have a much tighter specification in this case (about ±1% of air handler flow). In addition, this does not address the uncertainty in measuring air handler flow or in estimating what fraction of the total leakage (the difference between air handler and grille flow) is to outside (as required for energy loss calculations).

Table 1 summarizes the accuracy criteria for using flow hoods in residential applications, in order of increasing accuracy requirements.

Table 1. Summary of Accuracy Requirements for Residential Flow Hood Applications

Application	Required Minimum Accuracy
Identifying large leaks/disconnected ducts	±50%
Identifying room to room pressure imbalances	±25%
Ensuring room load and comfort requirements are met	±20%
Determining air handler flow for cooling equipment performance estimation	±10%
Determining duct leakage	±3%

Experimental Assessment of Accuracy

Measuring residential airflows with a flow hood developed for commercial systems is a challenge for the following four key reasons:

1. Residential supply grille airflows are typically much lower than non-residential ones. Usually, residential flows range from 25 to 120 L/s (53 to 250 cfm), with many in the lower half of this range and some substantially lower: some small interior bathrooms have design flows in the 5 L/s (10 cfm) range. For comparison, commercial system flows typically exceed 120 L/s (250 cfm). Manufacturers of commercially available hoods indicate their equipment is capable of measuring the lower flows; however, they provide no data to support using their measurement techniques for these flows.
2. Residential grilles do not have diffusers that make the flow spatially homogeneous. For supply grilles in particular, the vanes that direct the flow in a particular direction to control the throw of air from the grille into the room lead to highly non-uniform flows entering the flow hood.
3. Residential supply grilles are often physically smaller than those used in commercial systems. A typical residential supply grille is 150 mm × 300 mm (6 × 12 inches) rather than the 560 mm (22 inches) square grille used in commercial systems. This size difference introduces measurement errors, because the flow is non-uniform over the inlet of the flow hood.
4. Some residential systems have single return grilles that are closer to commercial grilles in terms of size and airflow; however, they often have dimensions larger than the 560 mm (22 inch) square standard flow hood. In these cases, it is necessary to combine several individual measurements over the face of the grille. There are substantial potential errors with this technique. For example, some flow hoods add resistance at the grille (insertion loss). This increases the airflow that bypasses the flow hood when it only covers part of the grille. As a result, the airflow measured by the flow hood is too low.

To determine the potential magnitude of errors associated with using flow hoods to measure flows at residential grilles, we conducted detailed laboratory tests on five hoods specifically intended for residential systems. These five hoods were comprised of two "standard" hoods from major manufacturers, one "prototype" hood that is currently being developed, one propeller hood, and a state-of-the-art "active" hood. We also performed a field test using eight hoods in a single house. Of these eight, two were for residential use, four were primarily for commercial use, and the remaining two were active flow hoods. Only the propeller hood and our active flow hood were common to both laboratory and field evaluations, because the flow hoods that we tested belonged to other organizations and we were restricted to the ones available to us at the time of testing. Characteristics of these hoods are described in the following section of this paper.

Our laboratory tests systematically varied potential sources of uncertainty and compared the flow hoods (numbered 6 though 10) to a very accurate standard. These tests evaluate the factory calibration and the sensitivity of the results to changes in entering flow pattern (which can be thought of as the robustness of the measurement technique/device);

they do not evaluate insertion loss effects. In the field study, the flow hoods were used in one house with nine supply grilles and a single return. Hoods numbered 1 through 5 and 9 through 11 were used on the supply grilles; Hoods numbered 2 through 5, and 10, were used on the return grilles. Due to limited airflow capacity, not all of the available flow hoods could measure return flows.

Flow Hoods Tested

Hoods 1 through 7 are **standard** flow hoods from three manufacturers; Hoods 2, 6, and 7 were specifically developed for measuring residential flows. The standard hoods measure flow across a flow element within the throat of the hood. The element samples the flow at several fixed locations and combines the samples together in a manifold that contains a thermo-anemometer or that is connected to a pressure transducer. With fixed sampling locations, it is possible that non-uniform flows will not be sampled with sufficient spatial resolution, or that incorrect weighting might be applied to some samples.

Hood 8 is a **prototype** flow hood that uses a flow capture device like a "standard" flow hood, but uses a proprietary flow sampling and sensing technology. This hood is still under development and is not generally available.

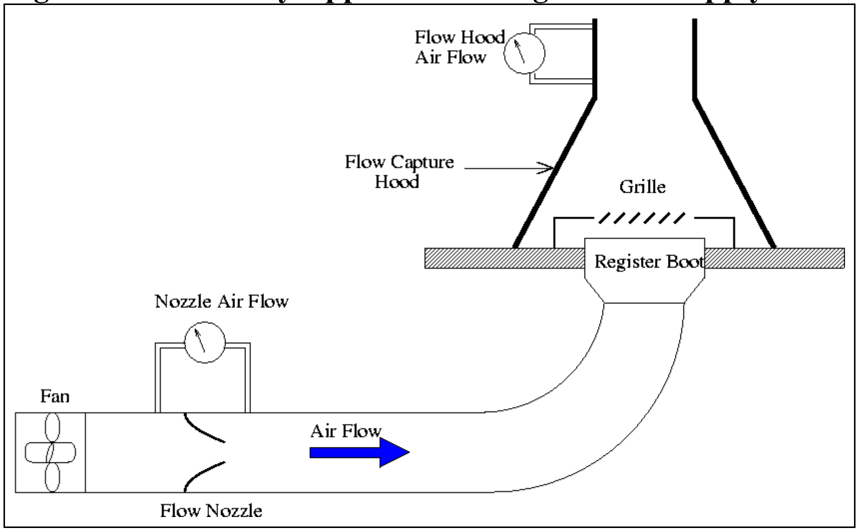
Although Hood 9 (**propeller** flow hood) is no longer in production, some residential airflow practitioners still use it. This hood is intended for the smaller grilles and flows in residential systems. The sensing element is a freely spinning propeller, whose speed indicates the flow through the hood. A possible advantage of this hood is that it samples the whole flow (the propeller tip clearance to the flow capture housing is very small). However, it does not eliminate problems of non-uniform flow, because of inertial effects of the propeller and non-linear interactions between local airflow velocity and the rotational force applied to the propeller. In addition, it is possible that swirl in the flow will cause the propeller to spin either too fast or too slow, thus biasing the measurements.

Hoods 10 and 11 are **active** flow hoods (also known as fan-assisted or powered flow hoods), which were developed for research use to reduce the effects of backpressure on flow measurement. For a flow capture device, these hoods use a fabric capture hood from a standard flow hood (Hood 10) or a cardboard box (Hood 11). The outlet of the capture device connects to a calibrated fan and flow meter through a length of flex duct and a flow straightener. By adjusting fan speed until there is no pressure difference between the room and hood interior, one can compensate for the flow resistance of the capture hood, flexible duct, and flow meter. This pressure balancing ensures that placing the flow hood over the grille does not reduce the grille flow and minimizes the effects of air leakage between the flow hood edges and the surfaces they are pressed against.

Laboratory Test Apparatus

Figure 1 shows a schematic of our laboratory test apparatus. It represents a "single branch" system in which all flow passes through the reference nozzle and the flow hood. The reference nozzle combines a flow straightener, a nozzle, and a pitot-averaging-array to form a flow meter that is less sensitive to flow asymmetry than other flow meters. It has an accuracy of ±0.5% of the flow reading. We used an adjustable fan to produce a range of typical residential grille flows through the apparatus: 25 to 120 L/s (53 to 250 cfm) for supplies and up to 1,000 L/s (2,000 cfm) for returns. Figure 1 shows the apparatus configured for supply flows; we reversed the nozzle and fan for return flows.

Figure 1. Laboratory Apparatus Configured for Supply Flows



We changed the flow pattern entering the hoods by varying hood lateral placement relative to the grille (center, corner, and center edge), and by using different grille styles (one-way and four-way throws), different grille damper settings, and different boot types. To examine grille-induced swirl effects, we used two different four-way grilles with vanes in opposite directions. We positioned the dampers at a “full open” setting and, for the one-way throw grille, also with the damper blades partially closed (parallel with the outlet vanes). The rectangular boots had different entry conditions: from the long side or from the short side.

Test Results

Figures 2 through 6 show detailed results from our laboratory tests for the different test configurations. The legend differentiates between test configurations. Center/Edge/Corner refers to the location of the hood relative to the grille. The term “w/damper” means that the damper in the grille was partially closed. Lastly, the CW/CCW designation refers to the use of a four-way throw grille that introduces swirl in either the Clock-Wise (CW) or Counter-Clock-Wise (CCW) sense.

Table 2 summarizes our laboratory test results. The fractional errors listed here are the average of the individual fractional errors for each measurement and not the average error divided by the average flow rate. The average error is an estimate of the bias in the flow hood. The RMS errors do not let positive and negative errors cancel out and are a better indicator of the uncertainty in an individual grille measurement.

Tables 3 and 4 summarize the field test results relative to the reference active flow hood for supply and return flows respectively.

Walker et al. (2001) describe our test results in more detail.

Figure 2. Laboratory Results for Standard Hood 6

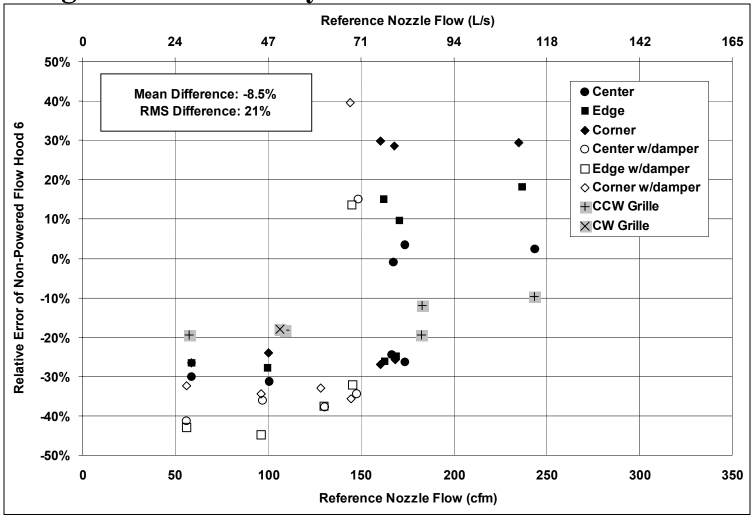


Figure 3. Laboratory Results for Standard Hood 7

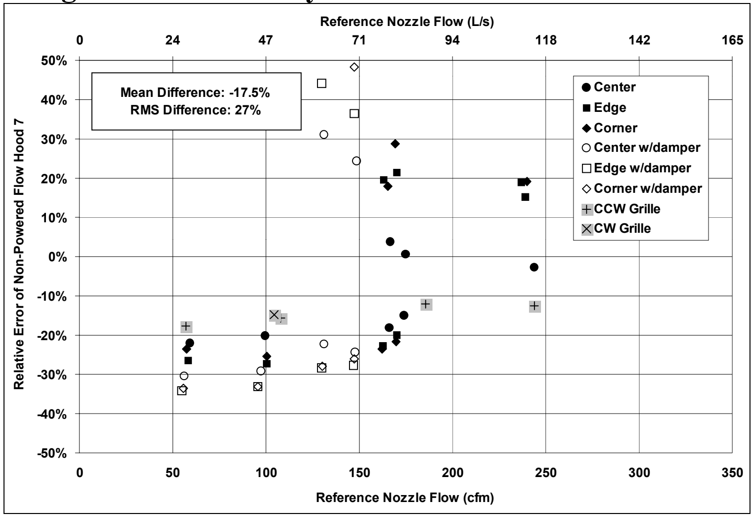


Figure 4. Laboratory Results for Prototype Hood 8

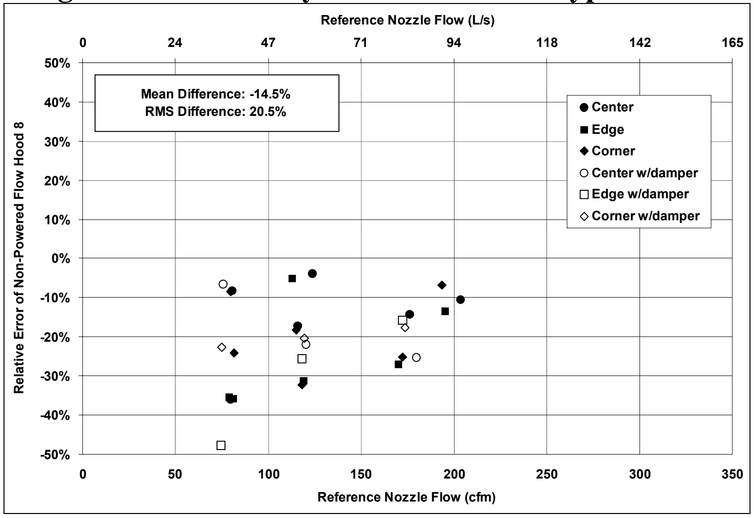


Figure 5. Laboratory Results for Propeller Hood 9

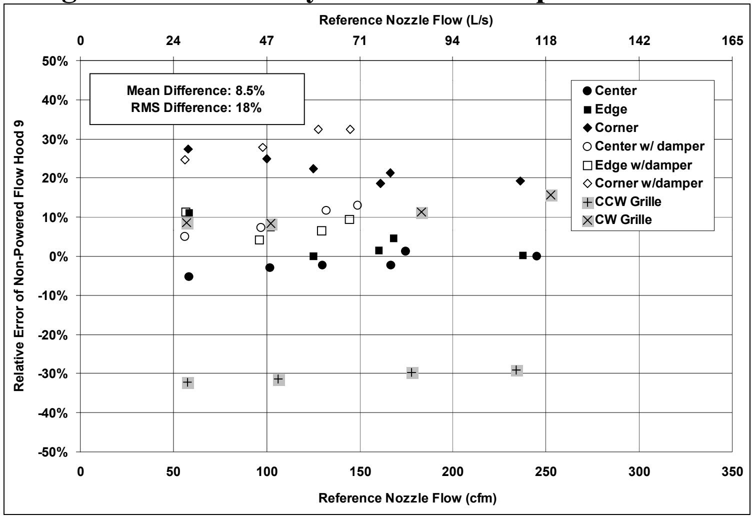


Figure 6. Laboratory Results for Active Hood 10

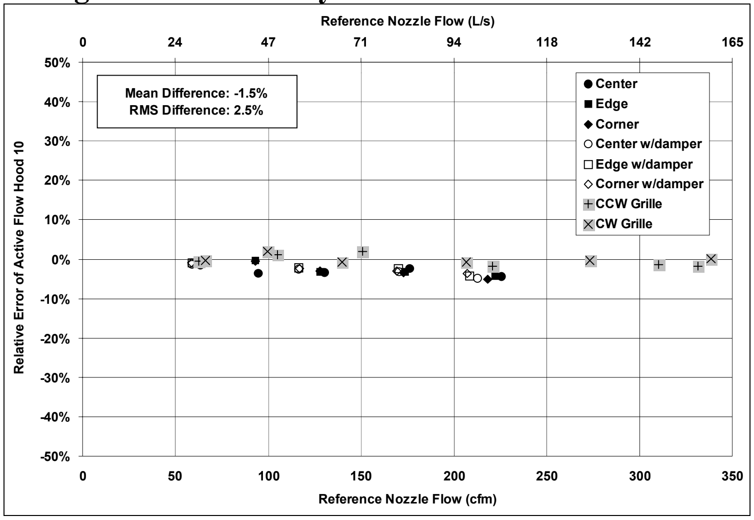


Table 2. Summary of Laboratory Test Results: Supply and Return Flows

Hood ID	Hood Type	Average Difference	RMS Difference	Number of Tests
		Supply Flows		
6	Standard	-8.5% (-8 cfm)	21% (28 cfm)	90
7	Standard	-17.5% (-19 cfm)	27% (36 cfm)	74
8	Prototype	-14.5% (-18 cfm)	20.5% (25 cfm)	43
9	Propeller	8.5% (10 cfm)	18% (25 cfm)	75
10	Active	-1.5% (-3 cfm)	2.5% (5 cfm)	87
		Return Flows		
8	Prototype	33% (488 cfm)	33% (511 cfm)	3
10	Active	2.5% (25 cfm)	3.5% (38 cfm)	9

Table 3. Summary of Field Test Results: Nine Supply Flows

Hood ID	Hood Type	Difference Relative to Active Hood 10	
		Sum of all grille flows	RMS for individual grilles
1	Standard	-1% (-9 cfm)	8% (8 cfm)
2	Standard	3% (31 cfm)	10% (14 cfm)
3	Standard	7% (78 cfm)	15% (12 cfm)
4	Standard	48% (519 cfm)	58% (65 cfm)
5	Standard	45% (484 cfm)	56% (61 cfm)
9	Propeller	-1% (-7 cfm)	8% (6 cfm)
11	Active	-1% (-10 cfm)	6% (4 cfm)

Table 4. Summary of Field Test Results: One Return Flow

Hood ID	Hood Type	Difference Relative to Active Hood 10
2	Standard	-17% (-177 cfm)
3	Standard	-4% (-42 cfm)
4	Standard	-1% (-9 cfm)
5	Standard	2% (18 cfm)

Key Findings

Our laboratory test results for the reference active flow hood (Hood 10, summarized in Table 2 and shown in Figure 6) show it is clearly better than the non-powered flow hoods: all its results fall in a narrow band (RMS error of only 2.5%, 5 cfm), with a small negative bias (-1.5%, -3 cfm). A comparison of these results to the criteria presented in Table 1 shows that this hood can be used in all applications.

Table 2 indicates that the non-powered flow hoods we tested in the laboratory (Hoods 6 through 9) do not necessarily meet the accuracy criteria for many residential applications. RMS errors are in the 20% to 30% range, which is much larger than the 10% or better accuracies that are required for most distribution system diagnostics. In particular, the measurement accuracy is poor for individual grilles, as well as over the sum of many grilles. This means that these hoods can be inadequate for use in estimating duct leakage and air handler flow, and for assessing individual grille flows for room load and comfort. However, most of the flow hoods can be used in applications that require less accuracy (finding big leaks/disconnected ducts and estimating room-to-room pressure imbalances). The provision made by some manufacturers to change the flow resistance of the flow meter by opening or closing vents did not offer any advantages in improved accuracy.

Flow hood errors shown in Figures 2 through 5 are mostly due to non-uniformity of incoming flow from typical residential grilles. The non-uniformity has two sources: the duct system itself (including the grille) and the opening of the flow hoods being larger than the grilles. The duct system contributions include the effects of the flow pattern generated by the grille, the changes in flow pattern because of the use of grille dampers, swirl in the flow (either generated by the grille or upstream ducts), and the boot entry type. Because grille area is only a fraction of the total entry area of the flow hood, this guarantees non-uniform flow entering the flow hood; it also allows flexibility in the flow hood positioning over the grille. Positioning of the flow hood over the grille was found to be critical: the flow hood needs to be centered for best results. Because the results are sensitive to positioning (errors as much as ±40% due to poor centering), this is a key issue in the field application of flow hoods. In field applications, our experience indicates that the user often has little choice over flow hood placement, because grilles are located near the intersection of walls, floors, and ceilings (or other obstructions); the ability to center the hood is probably limited more by these physical constraints than by visual acuity.

Figure 5 shows that the propeller flow hood (Hood 9) has considerable variation with inlet flow conditions. It is sensitive to swirl in the entering flow, to location of the hood over the grille, and to damper position. CW swirl is in the same direction as propeller rotation and results in the propeller spinning too fast, and produces an average 11% over estimate of flow. Conversely, CCW swirl acts in opposition to propeller rotation, and produces an average 30% under estimate of flow. Even though this flow hood has a small range of positioning movement, it is still sensitive to positioning over the grille. Flow hood position relative to the grille changes the relative error by about 25%, with corner placement giving the greatest sensitivity. The effects of damper position are also significant for Hood 9: compared to the results with the damper fully open, the dampered results are 11% higher on average and have about three times the RMS error. In field applications where occupants have set dampers to control airflow (and do not want them changed), this means that the flow hood errors could change from grille to grille.

Because our laboratory tests and field experience have demonstrated the accuracy of active flow hoods and their insensitivity to non-uniform flows, we used the active Hood 10 as the **reference** flow hood for our field studies. The field test results in Tables 3 and 4 show that some flow hoods gave acceptable results and others did not. For example, differences for the sum of all supply grille flows were less than 10% compared to the active reference (Hood 10) for five of the tested hoods (Hoods 1, 2, 3, 9, and 11). However, Hoods 4 and 5 gave supply flows that are much too high for most applications (these were two identical flow hoods from the same manufacturer). The results for Hoods 1, 9, and 11 indicate that they are acceptable for all the potential grille flow tests outlined in Table 1. The return flow uncertainty for Hood 2 (-17%, -177 cfm) and the individual grille uncertainties for Hood 3 indicated by its RMS error (15%, 12 cfm) mean that these two hoods are acceptable for all the potential grille flow tests outlined in Table 1, except for determining air handler flow and duct leakage.

The findings based on our field tests apply only to the tested system; we expect that the errors reported for these field tests are lower than those from a typical HVAC diagnostic application. Experienced researchers conducted all the field tests on a system with grilles that were well placed, had fully open dampers, and did not introduce swirl or other extreme flow non-uniformities. They took as much time as necessary to achieve the best possible results for each flow hood (e.g., taking particular care to center the flow hoods). A field test survey involving more houses and typical flow hood users is needed to estimate the error distribution related to system type and hood usage.

Calibration versus Application

As with other instrumentation, flow hoods are susceptible to large errors in field applications that are not apparent in manufacturers' accuracy specifications. Flow hoods are calibrated in a fixed position with uniform flow, resulting in typical accuracy specifications of about ±3%. Instruction manuals for flow hoods often warn of the possibility of errors due to airflow patterns from grilles differing from those during calibration (e.g. Alnor 1998). However, no estimates of the related error are given. Our laboratory and field tests show that the change in airflow pattern between calibration and application creates large flow measurement errors.

ASHRAE Standard 111 (ASHRAE 1988) also discusses flow hood accuracy issues. For example, Section 8.6.4.4 states: " System Effects: Perhaps the most important result of these tests has been to demonstrate that errors as great as 15% to 30% may be caused by neglecting the effect of approach conditions." This agrees closely with our laboratory test results. ASHRAE Standard 111 also indicates in Section 8.6.5 that one should "…consider most diffuser measurement as not reliable for certifiable accuracy". Current testing and balancing reporting procedures do not emphasize these issues.

Manufacturer's instructions and ASHRAE Standard 111 discuss the use of pitot-tube traverses to field calibrate the flow hood to account for the problems discussed above. However, this is not a practical solution in residential systems because:

- there will rarely be duct access so that a traverse can be performed,
- ducts are often made from flexible plastic duct that cannot be used for pitot-tube insertion and mounting (unlike sheet metal ducts),
- almost no duct system has a long enough uninterrupted flow to meet the requirements for an accurate pitot-tube traverse, and
- most ducts are unique (in terms of fittings, length, and layout) and a traverse would be required for every grille, thus obviating the need for a flow hood.

Recommendations

Of the flow hoods that we tested in the laboratory (i.e., ones that are reasonably available), active flow hoods are the most reliable and consistent for measuring distribution system airflows if the measurements are to be used in estimating duct leakage, air handler flow, and individual grille flows for room load and comfort. This does not mean that active hoods are the only ones that can work. There is no fundamental problem with passive hoods, and our field test results showed that some passive hoods can obtain good results when they are used with appropriate care on the right set of grille types and locations. Laboratory and field tests of a wider range of flow hoods should be pursued, in addition to evaluating improvements for residential flow hoods. Because the active flow hood is the most accurate, it can be used as a reference in field evaluations of other hoods.

A new flow hood measurement standard should be developed to address how flow hoods are operated in the field. This standard should have some standard grille sizes, types, and placements that would cover most common geometries found in residential systems. The laboratory tests we used are a prototype for this standard test procedure. Possible agencies for development of this standard are ASHRAE and ASTM.

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