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Evaluation of Commercially Available Techniques and Development of Simplified Methods for Measuring Grille Airflows in HVAC Systems

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ABSTRACT

This report discusses the accuracy of flow hoods for residential applications, based on laboratory tests and field studies. The results indicate that commercially available hoods are often inadequate to measure flows in residential systems, and that there can be a wide range of performance between different flow hoods. The errors are due to poor calibrations, sensitivity of existing hoods to grille flow non-uniformities, and flow changes from added flow resistance. We also evaluated several simple techniques for measuring register airflows that could be adopted by the HVAC industry and homeowners as simple diagnostics that are often as accurate as commercially available devices. Our test results also show that current calibration procedures for flow hoods do not account for field application problems. As a result, organizations such as ASHRAE or ASTM need to develop a new standard for flow hood calibration, along with a new measurement standard to address field use of flow hoods.

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 have very rarely 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 include using flow hoods to determine if individual rooms are getting the correct airflow, and to estimate total air handler flow and duct air leakage.

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. Previous studies by LBNL (Walker et al. 2001 and Wray et al. 2002) examined the uncertainty associated with using flow hoods to measure residential grille airflows. The results showed 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. This is primarily because of their sensitivity to flow non-uniformities and the difficulty in accounting for insertion losses on multiple low-pressure branch systems.

This paper compiles the results of additional recent studies at LBNL that evaluated commercially available flow hoods and several non-commercialized techniques. The various devices and measurement techniques were evaluated under both laboratory and field conditions. The laboratory testing enabled us to examine detailed performance characteristics and sensitivity to various measurement technique issues such as the critical centering of flow capture devices over registers. We carried out both single and multiple branch system tests. The single branch tests allow us to compare the flow hood measurements to very precise air flow references. These single branch tests are similar to the methods used by manufacturers to calibrate their flow hoods. The multi-branch tests allow the study of the insertion loss effects on flow hood performance. Insertion losses occur when the flow resistance of a flow hood significantly changes the flow through an individual register. Residential systems are particularly sensitive to this issue because registers are placed at the end of short branches – with correspondingly low pressure drops – such that the extra flow resistance of the air flow meter reduces the air flow through the branch and register being measured and the air flow tends to be redirected to other registers in the system. The multi-branch systems and field testing use a powered flowhood as a reference that has been shown to be accurate in broad range of applications in previous studies (Walker et al. 2001 and Wray et al. 2002).

In addition to evaluating performance for residential register measurements we also made some measurements on commercial registers. We had speculated in the previous studies that many of the failings of commercially available devices would be reduced for commercial systems because the registers are larger (they tend to fill the whole cross section of the flow capture device) and they have more uniform flow due to the presence of diffusers on grilles. In order to provide some baseline data on their ability to measure air flows for commercial registers we compared the air flow devices in several field measurements of full scale commercial systems, using the powered flow hood as the reference.

When evaluating the accuracy of the flowhoods we need to keep in mind that there is a range of potential applications for flow hoods requiring different levels of accuracy. Table 1 summarizes typical accuracy requirements for different diagnostic applications. More details about how these accuracy requirements were determined can be found in Walker et al. 2001.

Table 1. Summary of accuracy criteria for register flow measurement applications

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

Summary of Commercially Available Devices

A total of eight commercially available devices for measuring register air flows were tested in this study. All use some sort of time averaging to reduce the influence of flow and pressure fluctuations. For most devices we tested this is on the order of 10 seconds. The flow hoods can split into three broad classifications:

A **standard flow hood** uses a fabric hood that is fixed to a rigid frame that fits over the register. The fabric hood directs the flow over a velocity or pressure-drop sensing element. These devices have built-in electronic signal processing and information displays that include the ability to perform time averaging, temperature compensation and an estimate of insertion loss correction. Five different flow hoods were evaluated in these studies. These flow hoods typically cost between $2000 and $3500.

A **powered flow hood** was originally developed to reduce the effects of backpressure on the flow measurement. The powered flow hood uses a flow capture device connected to a calibrated fan-flow meter. A length of plastic flex duct and a flow straightener placed between the flow capture device and the fan-flowmeter make this device insensitive to non-uniform flows at the register grille. The pressure inside the hood is measured using a soaker hose sewn to the perimeter of the flow capture hood about half way along its length. Laboratory tests using several hood pressure measurement techniques have shown that the precise method and location of hood pressure measurement is not critical. The test results showed a spread of less than 2%, however, all the results presented here used the soaker hose for consistency because it resulted in the least bias on our full scale duct system laboratory. The flow resistance of the capture hood, flexible duct and flowmeter is compensated for by adjusting the fan until there is no pressure difference between the room and the hood. This pressure balancing procedure ensures that placing the flow hood over the register does not reduce the flow out of the register. This device is not commercially available as a complete package; however, many practitioners have the fan-flowmeter device used in these tests. Because laboratory results (Walker et al. 2001) showed this flow hood to be very accurate, it was used as the reference flow hood for the field studies.

The **flow horns** use a formed rigid fiberglass housing to capture the flow and direct the air flow over a thermal anemometer. The housing cross section varies from rectangular at the entry to round at the exit, where the anemometer is mounted. These flow horns came with anemometers that had been specially calibrated for use with these particular flow horns. They were therefore able to provide direct air flow measurements rather than just a velocity measurement. There are also flow horns from other manufacturers (that we did not test) that use vane anemometers in the throats of similar rigid flow capture devices.

Summary of Alternative Techniques

The following alternative techniques were examined because we found in previous studies that many existing measurement techniques and devices performed poorly when measuring residential registers. In addition, the residential HVAC industry needs simple and inexpensive measurement methods in order for diagnostics to be conducted by more practitioners on a regular basis. The following techniques were developed with a focus on reducing the cost and complexity of testing while retaining sufficient accuracy to be useful for most air flow diagnostic applications. Inspired by the Canada Mortgage and Housing Corporation (CMHC) approach (for example: http://www.cmhc-schl.gc.ca/en/burema/gesein/abhose/abhose_ce46.cfm) to have homeowners perform simple self-evaluation of their houses, and in particular, their heating and cooling systems, we selected techniques that could easily be performed using rudimentary equipment and skills. Initially, the idea was to provide tools for homeowners, however, we were able to develop devices that are accurate and robust enough for contractor use, particularly as demonstration tools for illustrating problems to homeowners.

Basket Hoods

The basket hood uses a calibrated flow resistance to measure the flow through HVAC system registers. The Basket Hood measures the airflow by a pressure drop through a set of calibrated holes in the sides of the basket. A good source of baskets with uniform holes is a normal household laundry basket. Most laundry baskets have too many holes (and therefore too little flow resistance) for a pressure difference between the basket and the room to be measured reliably (The pressure resolution is typically 0.1 Pa [1/2500 in. water] for good digital manometers). Therefore we systematically covered the holes in the sides of the basket until a reasonable pressure signal was obtained. The position of the holes has been optimized for the type of registers (supply or return) – holes too close to the flow entry were found to have increased sensitivity to flow non-uniformity. The number and size of the holes have also been optimized to produce a reasonably accurate pressure signal whilst minimizing the backpressure effects. The basket hood uses a couple of innovations to reduce the flow non-uniformity effects. First, the pressure difference between the basket and the room is measured by a "soaker" hose that is fixed inside of the top of the basket. The "soaker" hose has many small holes that effectively average the pressures over the whole length of the hose, and therefore over a large fraction of the basket. Second, a mesh screen is inserted in the entry of the basket that acts as a diffuser to reduce any flow non-uniformities. In order to capture all the flow and have it directed through the holes, a seal of weatherstripping is applied around the edge of the Basket Hood. Our experience in using all the flowhoods in the study (except the powered flow hood) showed that this edge seal is very important because any flow through this edge is not captured by the flowmeter and results in an underprediction of air flow. Different basket hoods have been developed for supplies and returns because return registers are often bigger than supply registers and have larger airflows per return grille.

Residential Return basket hood

The design of the return basket hood (Figure 1) is less critical than for supplies because the flow into the flow meter is relatively uniform and less affected by boot and grille geometry. The dimensions of this return basket flow hood (0.673 m [26.5"] × 0.673 m [26.5"] × 0.216 m [8.5"]) were selected to fit over a wide range of residential return grilles, however in some cases residential systems have return grilles that are larger than this and a larger basket would be required. This particular Return Basket Hood is constructed from a plastic container to which we added 128 holes of 50 mm (2 inch) diameter. The large number of holes optimizes the balance between insertion losses (flow reduction due to the added flow resistance of the flow hood), and the need to provide a large enough pressure signal to avoid pressure measurement resolution limits. As a reasonable compromise, the return basket hood was designed to have a 5 Pa (1/50 in. water) pressure drop at a flow rate of 472 L/s (1000 cfm). A soaker hose is fixed around the inside of the top of the basket, and the pressure difference between the soaker hose and the room is measured using a hand-held digital manometer that takes five second time averages. The time averaging is an important aspect of the pressure measurement due to the turbulent fluctuating nature of the pressure and flows through the flow meter.

Figure 1. Return Basket Hood, front and side views

Residential Supply Basket Hood

The supply basket hood (shown in Figure 2) follows the same design technique as the return basket hood. The two supply basket hood prototypes were made from plastic laundry baskets. A typical residential register is about 150 mm × 300 mm (6 × 12 inches) and the basket hood openings are large enough to fit over a register measuring 190 mm × 390 mm (7.5 × 15.5 inches). Different taping configurations were tested in order to find the optimum configuration that gave a pressure signal that was stable and of a reasonable magnitude (about 5 Pa), and that was insensitive to entering flow conditions. A soaker hose inserted in the inside of the top of the basket is connected to a digital manometer to obtain 5 second time averaged pressures. A diffuser screen (or net) is fixed at the top of the basket hood in order to make the airflow more homogeneous to reduce measurement errors due to flow non-uniformity. For some tests, a honeycomb structure was also added at the inlet of the basket as a flow straightener. Figure 3 illustrates how the basket supply flow hood is used on a wall supply register.

Unlike the return measurements, using the basket hood on a supply register can significantly change the airflow. This is because an individual supply branch has a relatively small pressure drop (typically 5 to 10 Pa) and adding the flow hood effectively doubles the pressure drop. The main consequence is a change in the airflow distribution throughout the duct system. Some of the airflow goes through the other branches and the airflow at the register being measured is significantly reduced. One method of accounting for these insertion losses is to use two different flowmeters each with a different flow resistance. The characteristic change in flow as the backpressure is increased for the duct branch being tested can then be estimated. In these prototype tests two physically separate basket flow hoods were used with different flow resistance achieved by systematically blocking off different holes in the baskets. A total of five supply hoods and a single return hood were tested – each with a different number of open holes (from 4 to 48 holes). Two different baskets were used: a Blue basket with three hole configurations and a white basket with two hole configurations. The baskets were numbered sequentially as they were constructed, however, the Blue and White 2 have less holes than the Blue and White 1 and the Blue 3 has more holes than any of the others. The basket/hole combinations are ordered here in increasing number of holes: Blue 2, White 2, Blue 1, White 1, Blue 3.

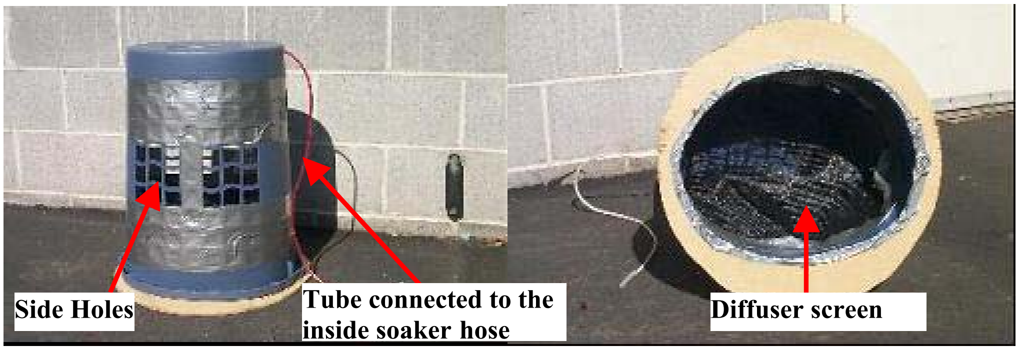


Figure 2. Supply Basket Hood

Figure 3. Residential supply airflow measurement

Basket Flow Meter Calibration

Because the flow resistance of the baskets was unknown they were calibrated using a high accuracy (±0.5%) flow nozzle. The specifications required to measure the pressure difference with sufficient accuracy (0.1 Pa precision and time averaging ability) mean that relatively expensive (about $500) pressure sensors are required. Because of these issues we expect that this flow technique is more appropriate for HVAC or weatherization contractors rather than homeowners. The supply basket flow meters were calibrated using the apparatus illustrated in Figure 4. This same apparatus was used for all the laboratory single branch testing. For returns the fan flow and nozzle direction were reversed and a return grille used instead of a supply register. The setup consisted of a fan, a 0.15 m (6 inch) flow nozzle used as a reference and a register mounted in a plywood panel. The supply register boot used in the calibrations has a 100 mm × 250 mm (4 inch × 10 inch) rectangular exit. The calibrations were done with the supply basket flow meter carefully centered over the register grille. A flow range of 25 to 120 L/s (53 to 250 cfm) for supplies and up to 1,000 L/s (2,000 cfm) for returns was used, which covers most common supply register flows in residential buildings. The calibrations for the supply basket hoods were done using a range of register types. We were successful in developing the baskets so that they are insensitive to grille geometry. As such, we found that all the different register results could be combined into a single calibration equation for each basket. These results are presented later.

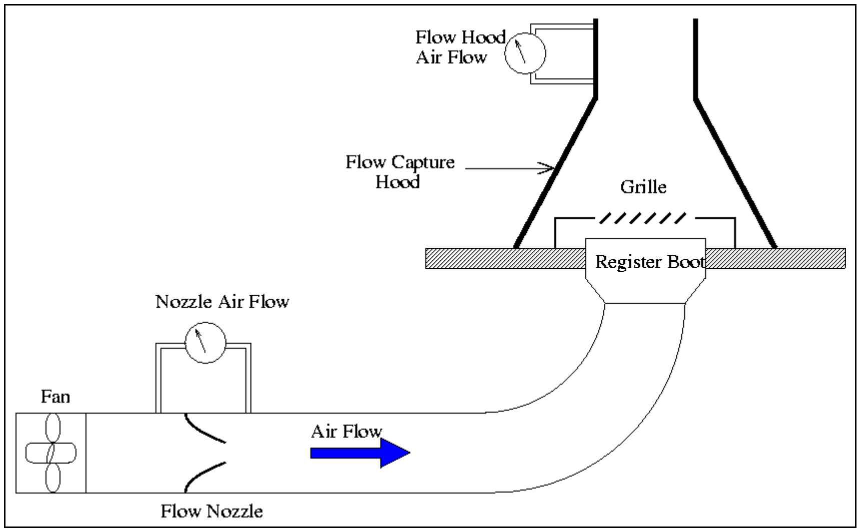


Figure 4. Single branch register measurement apparatus (configured for supply flows)

Commercial Supply Basket Hood

The two main differences between commercial and residential supply registers are the flow range and the size. A typical commercial register is larger – typically 560 mm (22 inches) square and the flow range is from 95 L/s to 240 L/s (200 cfm to 500 cfm). Figure 5 shows how the same plastic laundry basket as for the residential basket flow hood was connected to a fabric hood from a standard flow hood in order to cover the larger square commercial registers. This combination of the basket and the flow capture hood is called the commercial supply basket flow hood. As with the residential measurements, two baskets of different colors (light blue and dark blue) and flow resistances (numbers of open holes) were used to obtain two different flows and their corresponding flow resistances/pressure differences.

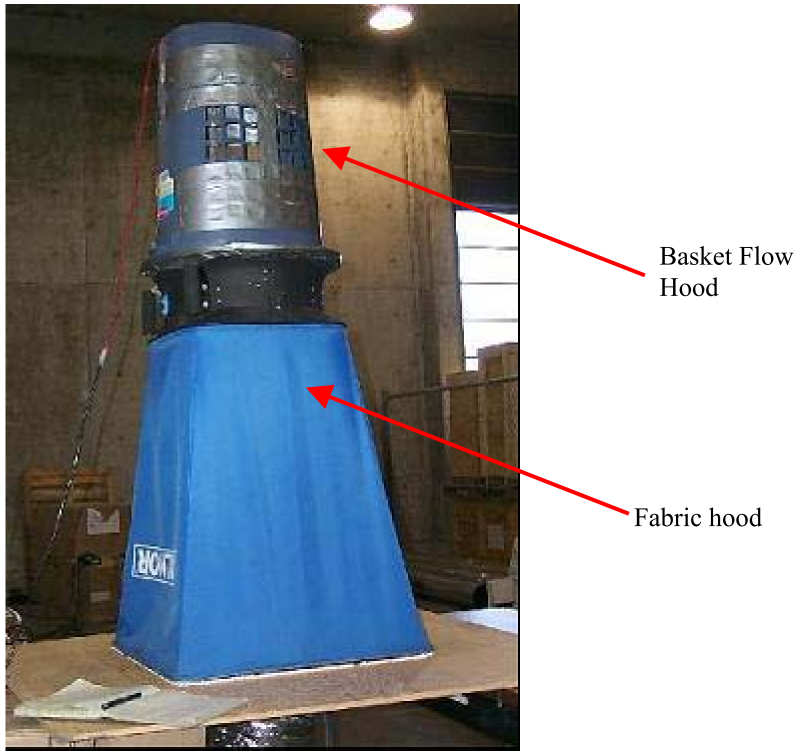


Figure 5. Commercial Supply Basket Flow Hood

Bag Filling

For several years, the idea of filling bags for estimating register flows has been considered as a very cheap and simple alternative to expensive flow hoods when only a rough estimate of flows is required. Originally they were used as a way of quickly checking for HVAC system problems that did not require flow measurement accuracy better than about 30%. For example, the Canadian Home Mortgage Company has instructions on its website: http://www.cmhc-schl.gc.ca/en/burema/gesein/abhose/abhose_ce46.cfm - where they explain in simple terms how to use a garbage bag to measure register flows. This method is much more applicable to homeowner diagnostics because no expensive equipment (like the pressure sensors for the basket hoods) is needed. One of our aims in this study is to quantify the uncertainties associated with this method and find ways to improve the measurement accuracy through simple techniques. This method also has the advantage that it gives a direct volumetric flow without relying on flow measurement techniques that only sample part of the flow or assume a degree of flow uniformity as found with almost all of the other techniques. In addition, as a demonstration of high or low flow to homeowners (or builders/HVAC contractors), the bag filling has a direct visual element that is very appealing. The measurement principle is very simple. A lightweight plastic bag is placed over the register and the time required to fill the bag is measured using a stopwatch. We can then determine the flow by dividing the volume of the bag by the time required to fill it.

After some experimentation we found a good way of making the measurements more accurate and more repeatable. The key issues are: sealing around the edge of the bag (to prevent air leaving the bag before it is full), having the bag keep its shape during filling for consistent filling and picking the correct time to start and stop the time keeping watch. To address these issues, a wood frame was sealed to the bag opening. This wood frame ensured that the bag kept its shape and gave a flat surface for easier edge sealing. In addition, we adopted a consistent technique that helped to ensure consistent timing. The user empties the bag and then places a sheet of cardboard over the bag opening (as shown in Figure 6). This assembly is placed close to the register without blocking the flow. The cardboard is rapidly pulled away, and the frame of the bag opening is pressed around the register. Because the bag introduces little backpressure it is not essential to have a perfect seal around the register – unlike for other flow hoods. The use of the cardboard sheet introduces a rapid bag opening. In addition, the sound of the wooden surround hitting the surface around the register gave a consistent audible signal. The watch is stopped when the bag is full. For most air flows the bag "pops" into its final shape (as illustrated in Figure 7) but for lower flows it is less easy to determine when the bag is "full". Doing multiple tests and averaging them can reduce this problem. Given that we are aiming for the simplest possible test method, not all homeowners may want the additional work of building a wooden frame. In addition, limited access to many registers and the range of register shapes and sizes encountered in a typical home mean that an alternative approach is needed. Therefore, we also used a wire frame (made from coat hangers, and illustrated in Figure 8) and tested it on a range of entry shapes. The same calibration technique was used for the bags as for the baskets. Two different sized garbage bags were chosen for these initial experiments: one clear and one blue. The blue bag was smaller and made of a more lightweight material. We also used the bags for measuring return and exhaust fan flows. These measurements are more difficult because it is hard to place a full bag over the register or fan grille in a consistent manner.

Figure 6. The clear garbage bag before a measurement

Figure 7. Blue garbage bag at the end of a measurement

Figure 8. The blue bag with a wire frame - the edge of the bag opening is wrapped around the wire frame and taped to the wire frame.

Single Branch Test Method

The single branch register air flow tests used the same apparatus shown in Figure 4. All air 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. 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. 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 (Figure 9), 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.

One-way-throw register (G1) Two-way-throw register (G2)

Three-way-throw register (G3) Four-Way-Flow register (G4)

Figure 9. Examples of register grilles used for supply basket hood calibration test apparatus

Multi-branch Test Method

The multi-branch tests used a full-scale duct system that is representative of a typical California house duct system. This duct system is a result of the collaboration between Lawrence Berkeley National Laboratory (LBNL) and California State University at Chico (CSUC). CSUC conducted a site survey at 20 houses selected as representative of present standard practice (O'Bannon 2002). Based on the results of the 20 site surveys and a market review, CSUC developed the specifications for a duct system. It has a single return and eleven supply registers, with a total flow of about 565 L/s (1200 cfm). The ducts are constructed from standard insulated flex duct with duct board splitter boxes at the duct branches. The ducts are suspended below a plywood deck (as if in a crawlspace) as illustrated in Figure 10. More details about this apparatus can be found in Abushakra et al. 2002. All the registers are the same size (but have different flows) and an example is shown in Figure 11. These grilles have a much more uniform and non-directional flow than those shown in Figure 9 because of the design of the grille. This means that the majority of differences between measurements can be attributed to poor centering over the register (for flowhoods sensitive to this effect) and to backpressure/insertion loss issues. The reference flow for each register was determined using the powered flow hood.

Due to small changes in duct and splitter box location as the various experiments were carried out in the facility, we found that the flows through a couple of the registers changed by a few percent. Because the flowhoods were tested over a period of a year on this system, we measured the reference flows before each set of flowhood measurements to ensure that we accounted for these small changes. In addition, a large flow nozzle was used to continuously monitor the total flow for the system in all experiments. This continuous monitoring showed that insertion losses had no measurable (within the ±0.5% accuracy of the flow nozzle) effect on the total flow. This indicates that flow reduction through the register being measured appear at other registers in the system.

Figure 10. Full Scale multi-branch duct system in LBNL Laboratory

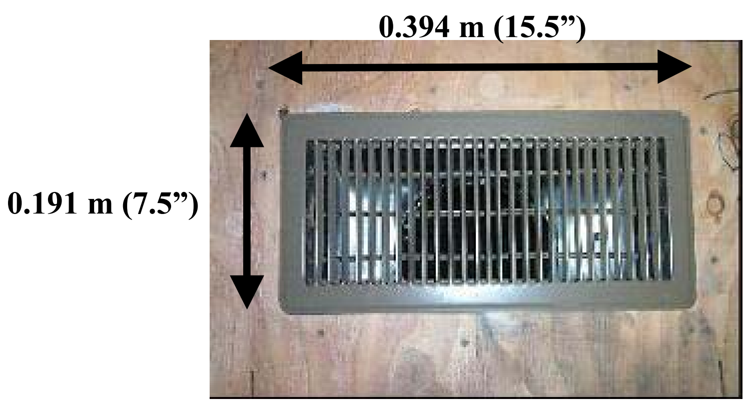


Figure 11. Multi-branch system supply grille

Single Branch Laboratory Test Results for Commercially Available Devices

Flow Horn 1

This small flow horn has a rectangular opening (318 mm × 124 mm (12.5 in × 4.8 in)) that fits over the register and directs the flow over an anemometer placed in the center of a small, 100 mm (4 inch) diameter, round exit opening. This flow horn introduces significant flow resistance to the register flow. On the single branch system, the flow horn reduced the flow from 52 L/s to 33 L/s (110 cfm to 69 cfm) for the open register without a grille, and from 52 L/s to 38 L/s (111 cfm to 81 cfm) for a system with a grille in place. This 30% to 40% reduction in measured flow illustrates the large flow resistance provided by the flow horn. The actual flow horn readings were 49 L/s and 42.5 L/s (103 cfm and 90 cfm) for these two cases. This result indicates that the flow horn does not attempt to measure the actual flow through the flow horn, but has been calibrated to attempt to estimate the flow without the horn in place. The flow horn still underestimates by 7% to 10%, probably because the device it was calibrated on had a different pressure-flow relationship that the one we are using and because of the flow non-uniformities generated by the boot and grille. It should be noted that these attempts to account for insertion losses though calibration only work if the flow being studied has the same pressure-flow relationship as the calibration facility. In particular, calibrations are performed on single branch systems in which all the flow is forced to go through every element of the system. In multi-branch systems (essentially all heating and cooling systems) the added flow resistance to one branch redirects the flow through other branches in the system. This results in much larger flow changes through the register being measured and the calibration would not be able to account for this effect. Flow Horn 1 was used on a couple of registers in the full scale multi-branch system and the underpredictions of flow were so large (on the order of 50%) that no further multi-branch tests were performed because this device was unsuitable for these measurements. We concluded that this device is unsuitable for measuring airflows in multi-branch systems.

Flow Hood 1

This flow hood was tested on the single branch system, with a range of grilles and flow hood locations over the register, including a commercial 610 mm × 610 mm (2 ft × 2 ft) register with its own diffuser. In addition, a diffuser screen inserted into the flow capture hood was evaluated to examine its ability to reduce sensitivity to placement issues. Lastly, tests were repeated with the edges of the flow hood taped to the surface around the register to remove leakage/bypass effects. Each case was repeated between 2 and five times to determine repeatability effects (represented by a calculation of the RMS difference between the individual measurements and their mean value). Note that the reference measurements were made with the flow hood in place so the single branch results do not include flow reduction due to the insertion losses.

The results in Table 2 show that both adding the diffuser screen and taping the edges significantly increased the accuracy of the measurements and reduced the sensitivity to placement. In every individual measurement, the flow hood overpredicted the register flow. In particular, with the register in the corner, the test without the diffuser screen overpredicted by almost 50%, and this was reduced to less than 10% using the diffuser screen. The small changes between the mean difference and RMS difference indicate that these results are biases rather than repeatability errors.

Table 2. Flow Hood 1 Single Branch Results				
Register	**Flow Hood Location**	**Reference Flow L/s (cfm)**	**Mean Difference L/s cfm)**	**RMS difference L/s (cfm)**
No grille	Centered	52 (110)	5 (11)	7 (15)
	Corner	53 (112)	23 (49)	23 (49)
	Centered Edge	53 (113)	8 (18)	9 (19)
No grille	Centered, with diffuser screen	51 (108)	4 (8)	4 (8)
	Corner, with diffuser screen	52 (111)	3 (7)	3 (7)
	Centered Edge, with diffuser screen	53 (112)	4 (8)	4 (8)
Residential grille (damper fully open), edges sealed	Centered	50 (107)	0.5 (1)	0.5 (1)
	Corner	49 (104)	2 (4)	2 (5)
	Centered Edge	50 (106)	1 (2)	1 (3)
Commercial 0.61 m x 0.61 m (2ft×2ft)	Centered	52 (110)	-1 (-2)	-
	Centered	150 (320)	-8 (-17)	-
	Centered	149 (318)	-11 (-24)	-
	Centered, edges sealed with tape	148 (315)	-2 (-5)	-
	Centered, edges sealed with tape	75 (159)	0.5 (-1)	-

Flow Hood 2

This flow meter has two different hood sizes: small 0.41m × 0.41m (16”×16”) and large 0.61m × 0.61m (24”×24”), and has a set of vents that are intended to be opened to extend the measurement range to higher flows. The register grille used for these tests has vanes to direct the air and the flow hood has placed with these vanes facing the front panel of the flow hood and turned 180° so that the air was directed toward the back of the flow hood. The grille was used with the flow control vanes in the fully open position. As with Flow Hood 1, the tests were repeated several times to examine repeatability issues. Lastly, this flow hood was tested in some cases with a diffuser screen. Note that the reference measurements were made with the flow hood in place so the single branch results do not include flow reduction due to the insertion losses.

The results summarized in Table 3 show that the mean and RMS differences are within 0.5 L/s (1 cfm) of each other. This is because the experimental results gave consistent biases with little sample-to-sample variation, indicating good repeatability. The remaining single branch tests with the vents open had unstable readings, so in Table 4 an approximate range of readings is given rather than an RMS value. With the vents closed, the diffuser screen approximately halved the measurement errors from about 7% to 3.5%. Including the results in Table 4, with the vents open and a higher flow rate, the diffuser screen improves the measurements, with the exception of the centered edge case, where the diffuser equipped flow hood significantly underpredicted the air flow. In this case there was visible fluttering of the flow hood material indicating significantly non-uniform flow inside the flow hood. Repeating the tests with the smaller hood gave similar results, with the diffuser screen giving reduced biases and variability: with the air directed to the the front of the flow hood, the errors were reduced from 22% to 3%, and from 14% to 2.5% with the air directed to the rear.

Table 3. Flow Hood 2, Single Branch Results						
Flow Hood Location	**Direction of air flow from grille vanes**	**Hood Size**	**Vents**	**Reference Flow L/s (cfm)**	**Mean Difference L/s (cfm)**	**RMS Difference L/s (cfm)**
Centered	Directed to the front of the flow hood	large	closed	51 (109)	-2 (-5)	2 (5)
Corner				51 (109)	-4 (-10)	4 (10)
Centered Edge				51 (109)	-3 (-7)	3 (7)
Centered, with screen	Directed to the front of the flow hood	large	closed	51 (109)	-1 (-2)	1 (2)
Corner, with screen				51 (109)	-3 (-6)	3 (6)
Centered Edge, with screen				51 (109)	-2 (-3)	-*
Centered, with screen	Directed to the rear of the flow hood	large	open	123 (262)	-4 (-9)	4 (9)
Corner, with screen				118 (250)	1 (2)	1 (2)
Centered Edge, with screen				118 (251)	-12 (-25)**	12 (25)

* No RMS – single reading
**Edge placement had visible fluttering of the flow capture hood fabric

Table 4. Flow Hood 2, Single Branch Results (cases with unstable readings)						
Flow Hood Location	**Direction of air flow from grille vanes**	**Hood Size**	**Vents**	**Reference Flow L/s (cfm)**	**Mean Difference L/s (cfm)**	**Variability L/s (cfm)**
Center	Directed to the front of the flow hood	large	open	119 (253)	5 (10)	9 (20)
Corner				117 (248)	9 (20)	7 (14)
Centered Edge				116 (249)	3 (6)	10 (20)
Center	Directed to the front of the flow hood	small	open	122 (259)	21 (45)	9 (20)
Corner				118 (250)	31 (65)	10 (20)
Centered Edge				118 (250)	21 (45)	9 (20)
Center, with screen	Directed to the front of the flow hood	small	open	119 (252)	-2 (-3)	2 (6)
Corner, with screen				111 (237)	8 (17)	3 (6)
Centered Edge, with screen				113 (240)	6 (12)	4 (8)
Center	Directed to the rear of the flow hood	small	open	118 (251)	23 (49)	11 (24)
Corner				119 (253)	-2 (-3)	5 (10)
Centered Edge				119 (253)	-5 (-11)	4 (8)
Center, with screen	Directed to the rear of the flow hood	small	open	117 (249)	-4 (-8)	3 (6)
Corner, with screen				115 (244)	-4 (-8)	4 (8)
Centered Edge, with screen				115 (245)	-2 (-3)	3 (6)

Multi-branch Laboratory test results for commercially available devices

The multi-branch system was used on two separate occasions. In this first round of testing three devices were evaluated, and in some cases not all registers were tested due to time limitations. In the second round of testing five flow hoods were evaluated. Flow hoods 1 and 2 from the first round were retested. The retested hoods were the same model and manufacturer as the first round, but had different production numbers. In the following test results, the mean difference is an indicator of the bias of the flow hood and the RMS difference indicates how well an individual register is measured. The fractions (%) are the average of the individual fractional errors, not the average or RMS divided by the average register flow. In most cases, these different methods of calculating fractional differences are extremely close for these data.

ROUND ONE

Flow Horn 2

This flow horn is considerably larger than Flow Horn 1, with an inlet of 0.61 m × 0.22 mm (24 in × 8.5 in) and a round exit 0.2 m (8 in) in diameter. This flow horn was used to measure the flows on the multi-branch system only. The air handler flow was continuously monitored during the tests and there was no measurable change (<0.5 L/s out of 548 L/s [< 1 cfm out of 1160 cfm]) in total system flow when this flow horn was placed over a register. Each register was measured with the flow horn centered over the register grille and then with the grille at the corner of the flow horn inlet. In each case, the flow measurements were averaged for ten seconds, and five separate ten-second averages were recorded. These multiple measurements showed that the repeatability for this instrument was good, with standard deviations of about

1 to 2% of flow (0.5 L/s to 1 L/s [1 to 2 cfm]) for the five readings at each register. Compared to the reference powered flow hood, this flow hood showed a bias of –3 L/s (-6 cfm) and an RMS difference of 5 L/s (10 cfm). Expressed as fractions of individual register flow, these correspond to about -6% and 10% of register flow.

The comparison of the flows measured with the flow hood centered over the grille and with the grille in the corner of the inlet showed a mean difference of 0.7 L/s (1.5 cfm), with the corner placement giving higher readings. The RMS difference between the two placements was 4 L/s (8 cfm), or about 8% of measured flow). These results show that although placement is not critical for total flows, individual register flows do show significant differences.

Flow Hood 1

The tests on the multi-branch system were performed with the diffuser screen in place and with the flow hood carefully centered over each register. The reference flow was determined using a powered flow hood. The results for the 11 registers of the multi-branch system are given in Table 5 The mean error is 0.5 L/s (1 cfm) and the RMS error is 2.5 L/s (5 cfm). These results show how the use of a diffuser screen combined with careful placement can give good results for this flow hood.

Table 5. Flow Hood 1, Multi-branch Results – centered, with diffuser screen

Supply Register	Reference Flow, L/s (cfm)	Flow Hood 1 Error, L/s (cfm)
1	68 (145)	-3 (-7)
2	30 (63)	2.5 (5)
3	22 (47)	1.5 (3)
4	64 (136)	-1 (-2)
5	40 (86)	1 (2)
6	71 (150)	0.5 (1)
7	46 (99)	4 (9)
8	78 (165)	-3 (-6)
9	46 (99)	3 (6)
10	65 (138)	-1 (-2)
11	38 (81)	2.5 (5)
Total	568 (1209)	7 (14)

Further tests were performed on selected registers of the multi-branch system that show that the diffuser screen makes the flow hood less sensitive to placement over the register and improves accuracy. Table 6 summarizes these results. The tests without the screen were only performed for four of the six registers.

Table 6. Flow Hood 1, Multi-branch Results for Flow Hood Position Changes							
Supply Register	Reference flow	Difference from Reference, L/s (cfm)					
		Centered with screen	Corner with screen	Centered Edge with screen	Centered no screen	Corner no screen	Centered Edge no screen
1	68 (145)	-3 (-7)	-2 (-4)	-1.5 (-3)	9 (19)	6 (13)	8 (17)
2	30 (63)	2.5 (5)	2 (4)	2 (4)	-	-	-
3	22 (47)	1.5 (30)	1 (2)	1.5 (3)	2.5 (5)	4 (9)	4 (9)
6	71 (150)	0.5 (1)	-2 (-4)	-0.5 (-1)	16 (33)	10 (22)	11 (23)
7	46 (99)	4 (9)	5 (10)	3 (6)	-	-	-
8	78 (165)	-3 (-6)	0.5 (1)	1.5 (3)	1.5 (3)	5 (11)	4 (8)

Flow Hood 2

Table 7 summarizes the test results for Flow Hood 2 with the small hood, and shows how the extra flow resistance of the diffuser screen leads to underpredictions of register flows of 10% to 15%. In the future, it may be possible to reduce these biases through recalibration (note that Flow Hood 1 used a different calibration when the diffuser screen was in place). This flow hood was also tested with the large hood in place. The results in Table 8 show that the large hood has about the same sensitivity to placement over the register as the small hood.

Table 7. Flow Hood 2, Multi-branch Results with Small Hood							
Supply Register	Reference flow	Difference from Reference, L/s (cfm)					
		Centered, with screen	Corner, with screen	Centered Edge, with screen	Centered, no screen	Corner, no screen	Center Edge, no screen
1	68 (145)	-11 (-23)	-10 (-22)	-19 (-22)	-7 (-14)	-6 (-13)	-6 (-13)
2	30 (63)	-3 (-6)	-3 (-7)	-3 (-7)	-3 (-6)	-	-
3	22 (47)	-2.5 (-5)	-2.5 (-5)	-2.5 (-5)	-1.5 (-3)	-2 (-4)	-2 (-4)
8	78 (165)	-7 (-15)	-9 (-20)	-9 (-20)	2 (4)	4 (8)	4 (8)

Table 8. Flow Hood 2, Multi-branch Results Large Hood with Diffuser Screen				
Supply Register	Reference flow	Difference from Reference, L/s (cfm)		
		Centered	Corner	Centered Edge
2	30 (63)	-2.5 (-5)	-1.5 (-3)	-1.5 (-3)
3	22 (47)	-1.5 (-3)	-1.5 (-3)	-1.5 (-3)
7	46 (99)	0 (0)	3 (7)	4 (9)
8	78 (165)	0.5 (1)	3 (6)	2.5 (5)

ROUND TWO

Flow hoods 1 and 2 were retested in the summer of 2002 together with three additional flow hoods. The test results are summarized in Table 9, where the mean difference is an indicator of the bias of the flow hood (of interest when estimating total air handler flows) and the RMS difference indicates how well an individual register is measured. The fractions (%) are the average of the individual fractional errors, not the average or RMS divided by the average register flow. In most cases, these different methods of calculating fractional differences are extremely close for these data. These results are similar to the earlier tests discussed above. The biases range from 1% to 9%, and the RMS errors from 3% to 11%. The diffuser used with Flow Hood 1 is again shown to have significant benefits, particularly for individual register measurements. In all cases, these flow hoods have lower biases than RMS errors indicating that they sometimes overpredict and other times underpredict for an individual register.

The positioning of the flow hoods were evaluated by also measuring the registers with the registers in one corner of the flow hood. Although the registers in this system provide a fairly uniform exit flow, this test should still give an indication of flow hood positioning sensitivity. This is a critical issue in residential testing because the furniture and other house fittings (including intersections of walls, floors and ceilings) often prevent proper centering of a flow hood. The results in Table 9 show that the difference between a properly centered flow hood and a non-centered one are about 2% to 5%. Although these are not particularly large errors, in several cases, the majority of the difference was due to significant variations for just a few of the eleven registers. This indicates that it is more critical to have good centering for individual register flow measurements.

Table 9. Multi-branch Test Results for Commercial Flow Hoods – Air Flow L/s (cfm)

Register	Reference	Flow Hood 1	Flow Hood 1 with diffuser	Flow Hood 2	Flow Hood 3	Flow Hood 4	Flow Hood 5
1	67 (143)	71 (150)	63 (133)	63 (135)	69 (147)	63 (135)	63 (133)
2	28 (59)	34 (72)	30 (64)	27 (57)	29 (61)	27 (58)	26 (55)
3	21 (44)	24 (52)	22 (46)	20 (42)	-*	16 (35)	17 (36)
4	61 (129)	61 (129)	56 (120)	55 (116)	62 (131)	56 (120)	56 (119)
5	39 (83)	45 (96)	40 (85)	36 (76)	41 (88)	38 (80)	38 (80)
6	102 (218)	102 (218)	99 (211)	89 (190)	102 (218)	118 (250)	101 (215)
7	39 (83)	44 (93)	40 (86)	36 (76)	39 (82)	39 (84)	37 (79)
8	72 (153)	72 (154)	70 (148)	64 (137)	71 (152)	68 (144)	67 (143)
9	47 (99)	51 (108)	45 (96)	43 (91)	49 (104)	44 (94)	45 (96)
10	63 (133)	67 (143)	58 (123)	56 (120)	63 (133)	63 (134)	57 (127)
11	37 (79)	39 (84)	37 (79)	34 (72)	37 (79)	35 (74)	35 (74)
Mean Difference	-	**3 (7) [6 %]**	**-1.5 (-3) [-3%]**	**-5 (-10) [-9%]**	**1 (2) [2%]**	**-0.5 (-1) [-1%]**	**-3 (-6) [-6%]**
RMS Difference	-	**4 (8) [11%]**	**3 (6) [5%]**	**6 (12) [9%]**	**1.5 (3) [3%]**	**5 (11) [9%]**	**3 (7) [8%]**
Corner to center differences							
Mean Difference	-	**2 (4) [3%]**	**-0.5 (-1) [1%]**	**1 (2) [2%]**	**1.5 (3) [(2%]**	**-0.5 (-1) [1%]**	**0 (0) [0%]**
RMS Difference	-	**3 (7) [5%]**	**1.5 (3) [2%]**	**1 (2) [2%]**	**3 (6) [4%]**	**4 (9) [5%]**	**1 (2) [2%]**

*Flow Hood 3 could not read below 50 cfm.

Single Branch Laboratory test results for new techniques

Basket Hood

The basket hoods were tested with four different hole configurations (two baskets, each with two hole configurations), and all the calibration results are summarized in Table 10. All the basket hoods used the same calibration equation: $Q = C\Delta P^n$, where Q is the air flow rate and ΔP is the pressure difference between the basket and the room. The example results in Figure 12 show that the kind of grille does not make any significant difference to the results (the coefficients change by only 1%). Therefore, for simplicity the measurements for all four grilles were combined to determine a single calibration equation, to be used in multi-branch laboratory and field testing, for each of the basket flow meters.

Table 10. Supply basket flow hood calibration results					
Configuration name	Number of clear holes on the sides	C, L/sPa^n (cfm/Pa^n)	95% confidence interval for C	n	95% confidence interval for n
Blue 3	48	58.6 (124.8)	58.3, 59.5 (123.5, 126)	0.498	(0.488, 0.508)
White 1	24	31.8 (67.6)	31.3, 32.1 (66.8, 68.4)	0.496	(0.487, 0.5067)
Blue 1	16	16.8 (35.7)	16.6, 17.0 (35.3, 36.2)	0.504	(0.498, 0.509)
White 2	8	10.8 (22.9)	10.7, 10.9 (22.7, 23.1)	0.513	(0.510, 0.515)
Blue 2	4	4.84 (10.3)	4.7, 5.0 (10.0, 10.7)	0.520	(0.511, 0.528)

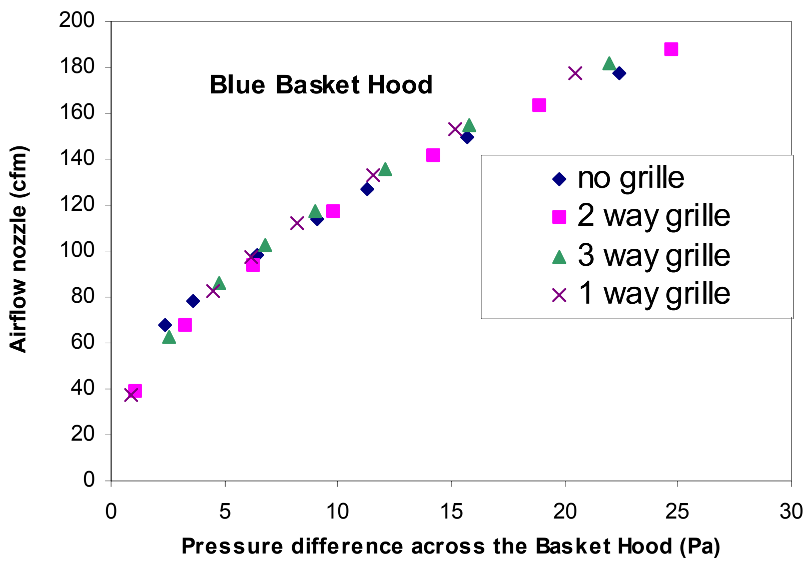


Figure 12. Basket hood test results showing low sensitivity of supply basket hood calibration to grille design for the Blue Basket with 16 open holes

A year after the initial single branch basket testing, the baskets were retested using the same single branch system and range of grilles. Two hole configurations were examined: White 1(with 24 open holes) and a new configuration: Blue 3 (with 48 open holes). In these new tests, the honeycomb flow straightener that had been used in previous tests was removed because we wanted to reduce backpressure insertion losses. Also, this was an effort to simplify the device to make it more like something a broad range of people could use (honey comb flow straighteners are not common outside air flow measurement laboratories). For White 1, the new calibration results were: Q (L/s) = $30.5*\Delta P^{0.506}$ (Q (cfm) = $65*\Delta P^{0.506}$), and for the new Blue 3 hole configuration the results were: Q (L/s) = $59*\Delta P^{0.498}$ (Q (cfm) = $125*\Delta P^{0.498}$). The difference in calibration for White 1 is a reduction in flow resistance of about 5% and is most likely due to the removal of the honeycomb.

Baskets White 1 and Blue 3 were tested using all the registers shown in Figure 9. The results showed that White 1 has an accuracy of ±3% for grilles 1,2 and 3 but underpredicts the flow by about 5% for Grille 4 that introduces swirl into the flow. Basket Blue 3 has similar results for grilles 1 and 2 (<3% error), but gives errors of about 10% with grilles 3 and 4. The fact that the blue basket has more holes may explain why it doesn't work as well as the white one. In particular, the blue basket has holes that are closer to the opening of the basket and will therefore be more sensitive to the flow pattern in the air entering the basket. As an illustration, imagine a register with flow all directed in one direction. The majority air flow would then be through the holes on only one side of the basket. These results show that these baskets will be less accurate on registers that direct the flow in many directions.

Because these basket hoods are essentially a set of sharp edged holes in parallel, we investigated the possibility of using the open hole area in a standard orifice equation. In practice, many potential users will not have access to calibration facilities, but will be able to measure the area of the holes. In that case, if we can provide a recommended value of orifice coefficient, then a basket with any size hole can be used without needing individual basket calibrations. The calibration data discussed earlier were reanalyzed by fixing the pressure coefficient to be equal to 0.5. This changed the calibration coefficients compared to those in Table 10, but only by a couple of percent. We measured the open hole area for all the basket hoods. Then, a normalized calibration coefficient was calculated by dividing the calibration results by the open area. Table 11 summarizes the results of these calculations. We found that using a single value of orifice coefficient of 0.7 gave only a -0.2% bias averaged over all five supply baskets and the return basket. However, for individual baskets the errors are larger, with a RMS error due to using a fixed value of orifice coefficient of 9%. This result indicates that using a fixed orifice coefficient of 0.7 will produce acceptable results for most potential applications.

Table 11. Evaluation using open area and fixed orifice coefficient for basket hoods, with a fixed pressure exponent equal to 0.5

Basket	Number of holes[1]	Hole Area cm^2	Hole Area in^2	Calibration coefficient L/s·Pa (cfm/Pa^n)	Normalized Calibration Coefficient L/s/Pa^n/cm^2	Normalized Calibration Coefficient cfm/Pa^n/in^2	Equivalent Orifice Coefficient *K*	Error using Orifice Coefficient equal to 0.7
Blue 2	4	55	8.6	5.3 (11.3)	0.096	1.31	0.74	-6
White 2	8	111	17.2	11.3 (23.9)	0.102	1.39	0.79	-11.4
Blue 1	16	222	34.4	17.0 (36.1)	0.077	1.05	0.60	14.0
White 1	24	333	51.6	31.8 (67.3)	0.095	1.31	0.74	-6
Blue 3	48	666	103.2	58.7 (124.4)	0.088	1.21	0.69	1.4
Return	128	2594	402	218 (462)	0.084	1.15	0.65	7.1

1 – Appendix B has illustrations of hole locations

If we average the results in Table 11 for normalized calibration coefficient we get values of: 0.090 L/s/Pa^n/cm^2 and 1.25 cfm/Pa^n/in^2. These can be used to determine the air flow given the hole area (A) and pressure difference (ΔP) in simplified versions of an orifice flow equation (note that if measurements are made at high altitude or with hot or cold air flows then a standard orifice equation should be used that includes density effects):

$$Q = 0.090A(\Delta P)^{0.5}$$ for flow in L/s, area in cm^2 and pressure difference in Pa. **(1)**

$$Q = 1.25A(\Delta P)^{0.5}$$ for flow in cfm, area in in^2 and pressure difference in Pa. **(2)**

Bag Filling

The bags were calibrated using the single branch system. As with the basket hoods, the single branch tests also looked at the sensitivity of the bags to different registers. The time taken to fill each bag was measured for six different flow rates (from 25 L/s to 120 L/s [50 to 250 cfm]) using a two-way register (shown in Figure 9). The effective volume of the bags was determined by a least squares fit to the calibration equation. The uncertainty in the calibrations was estimated from the 95% CI from the fit to determine *V*. Five different sized bags were tested using this procedure. The first two bags were garbage bags that we had in our laboratory. The other three bags were purchased from a hardware store. Because we have the original packaging for these three bags we know the nominal volume claimed by the manufacturer. If bags are to be used by a wide range of people who do not have access to calibration facilities, then we need to know the accuracy of measured air flows if the user uses information they are likely to have, such as the nominal volume based on package labeling. The calibration results are summarized in Table 12.

Table 12. Bag Filling Calibrations

	Nominal Bag Volume L (ft^3)	Calibrated bag Volume L (ft^3)	95% CI for Calibrated Volume L (ft^3)	Time Exponent	95% CI for Time Exponent
Bag 1	not available	170 (6.0)	16 (0.55)	-1.00*	0
Bag 2	not available	306 (10.8)	21 (0.75)	-1.00*	0
Bag 1 – volume and time fit	not available	181 (6.4)	12 (0.42)	-0.97	0.04
Bag 2 – volume and time fit	not available	277 (9.8)	16 (0.57)	-0.94	0.04
Bag 3	147 (5.2)	190 (6.7)	-	-0.98	
Bag 4 – volume and time fit	113 (4.0)	99 (3.5)	14 (0.49)	-1.04	0.16
Bag 5 – volume and time fit	113 (4.0)	110 (3.9)	8 (0.28)	-0.97	0.1
Bag 4	113 (4.0)	99 (3.5)	3 (0.11)	-1.00*	0
Bag 5	113 (4.0)	108 (3.8)	6 (0.20)	-1.00*	0

* Exponent forced to be 1.0

These results show that there can be changes to the calibration if both the bag volume and time exponent are fitted to the data. The variability in time exponent is due to a combination of experimental uncertainty and the fact that the bags do not always fill in a perfectly uniform manner. The calibrated bag volume for Bag 3 is significantly larger than the nominal volume. With this bag it was very difficult to obtain uniform bag filling because the bag material was too light. This led to the bag folding over itself and the bag would only partially fill. Bags 4 and 5 were constructed from a heavier gauge of plastic film and did not have this problem. For Bag 5, the calibrated volume is very close to the nominal value and for Bag 4 the difference is increased to 12.5%. Note, however, that at 47 L/s (100 cfm) air flow out of a register the difference between using nominal (and a fixed time exponent of –1) and calibrated bag volume leads to a change in measured time of 0.1 out of 2.2 seconds. For this reason we can safely recommend the use of bags by homeowners for most airflow measurement diagnostics but can not be used to measure total air handler flow and, by association, duct leakage.

The bags were also tested with the other register grilles shown in Figure 9. For one-way-throw grille the results were within a few percent (less than 5%) of the calibration. However, for the three-way-throw grille at higher flows (>50 L/s (100 cfm)) the errors increase to about 10% for Bags 1 and 2. The problem is that the bags inflate only on one side so that they never fully fill up and it is difficult to visually determine when the bags are full with this highly directed register flow. We performed additional tests with the register dampers inclined at large angle, and found the same problem. We also studied the effects of changing the positions of the bag for one and three throw way registers to check sensitivity to placement over the register. We found that the results for Bag 2 could be improved by deliberately offsetting the bag (rather than centering) placement over the register. The vanes of the registers direct the air flow in specific directions, usually toward one side. The best results for offset placement occurred when the edge of the bag was placed on edge of the register that the flow was directed towards. However this technique did not work for Bag 1. We think that this is because the different material thickness for the bags make them more or less sensitive to the directed flows – with the thicker bag (Bag 2) having better performance.

Another operational issue with the bags is that at higher flows the bags begin to "fly" before they are completely filled. For this reason we recommend either using a heavy frame or having the user hold the frame of the bag so that it does not take off. This flying occurs due to the momentum of the air flowing out of the register under high flow situations. We used the term "flying" because in these laboratory tests the bags were tested on registers in horizontal surfaces, with the bags placed above the registers. The bags would float off the register like a hovercraft if we did not hold them in place.

Because the wooden frame is unlikely to be used by homeowners, we also tested Bag 1 with a wire frame made from a coat-hanger (as recommended in the CMHC literature referenced earlier). We experimented by bending the coat-hanger into different opening shapes to see if the results were affected by opening shape. This is important for a couple of reasons. First, users may not be able to create a uniform opening and we need to know how much uncertainty this creates, and second, some registers in houses are odd shapes and the flexibility of the frame is then useful because it allows us to completely cover each grille. We tested eight opening shapes, using three different registers: the two, three and four-way shown in Figure 9 (G2, G3 and G4 in the legend of Figure 13). Figure 13 shows results of the different grille testing. For grille 2, the results are not very sensitive to the shape of the bag opening. However, for grille 3, there are significant differences – probably due to the more non-uniform flow directions exiting this grille.

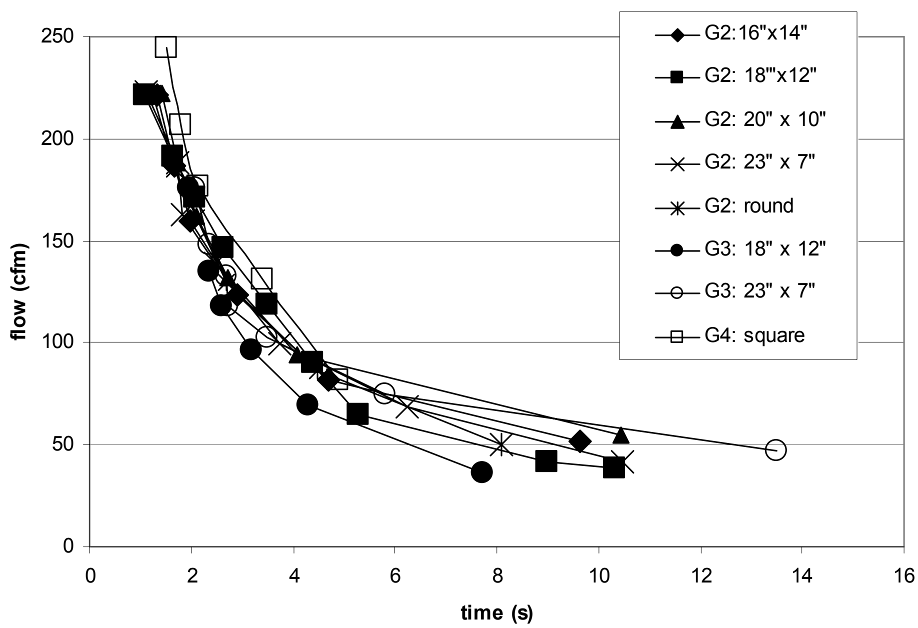
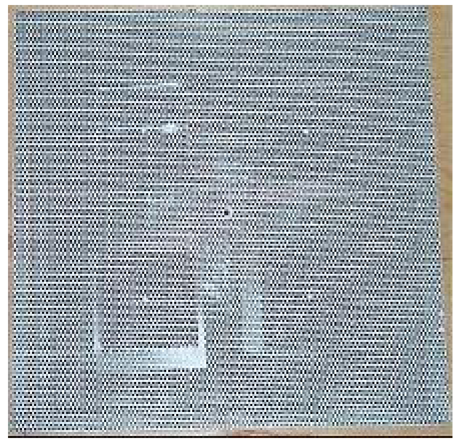


Figure 13. Comparison of bag filling results using different frame shapes and different grilles)

Calibration of the Commercial Supply Basket Flow Meter

The commercial-sized supply basket flow hoods were calibrated using the same single branch apparatus as for the residential flow meters. The small airflow nozzle introduced too much of a flow restriction at higher flows required for commercial operation, so it was replaced with a less accurate (±3%) combined fan/flow measurement device. The calibrations were performed over a range from 95 L/s to 240 L/s (200 cfm to 500 cfm), which corresponds to typical supply register flows in commercial buildings. The effect of different diffuser grilles (shown in Figure 14) was determined by performing independent calibrations with each of the grilles in place in the apparatus. The test results show (in Figure 15) that the kind of the grille does not make any significant difference to the calibration equation. Therefore, in the interest of simplicity, the two data sets (square grille and diffuser) were combined to determine a single calibration equation for each basket hood. The calibration results summarized in Table 13 show how the commercial baskets have less flow resistance (higher value for C) than the residential basket hoods.

Square grille



Diffuser

Figure 14. Two different commercial register grilles used in the calibration process

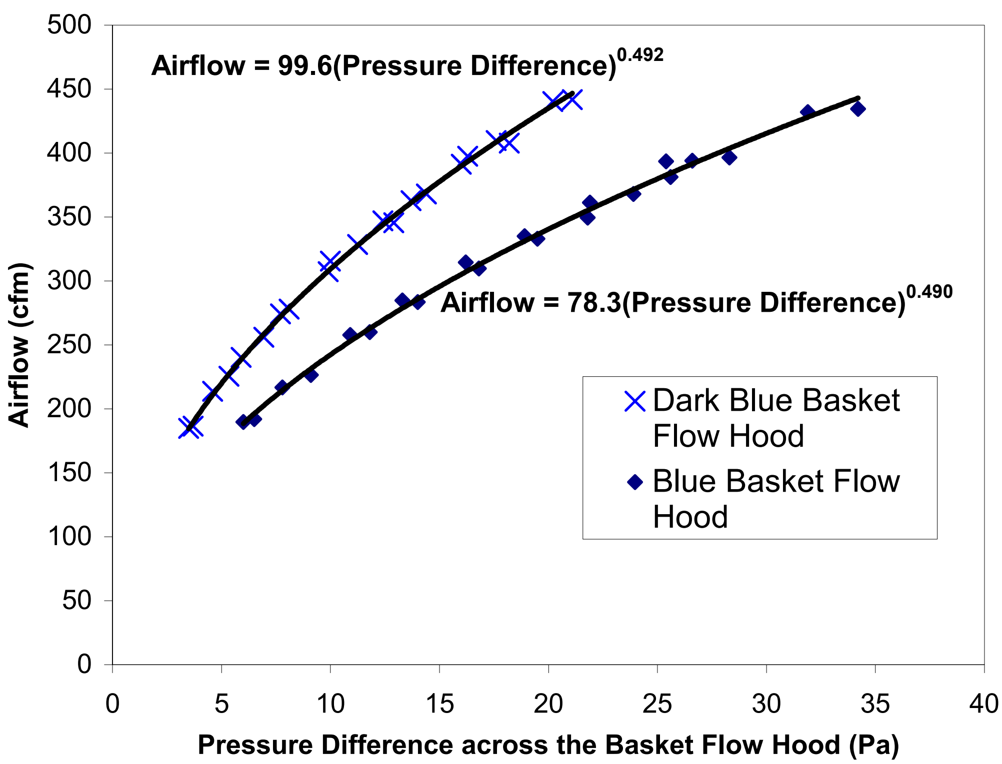


Figure 15. Commercial Supply Basket Flow Hood Calibration Results

Table 13. Commercial register supply basket flow hood calibrations				
Configuration name	C, L/sPa^n (cfm/Pa^n)	95% confidence interval for C	n	95% confidence interval for n
Blue	36.8 (78.3)	35.3, 38.4 (75.1, 81.7)	0.490	(0.476, 0.505)
Dark Blue	46.8 (99.6)	45.8, 47.8 (97.5, 101.7)	0.492	(0.483, 0.501)

Multi-branch System Laboratory Test Results for New Techniques

Return Basket Hoods

Figure 16 shows the dimensions of the return register of the multi-branch system that was used to calibrate the return basket hood. The return basket hood calibration used the same power law relationship as the supply basket hoods: $Q= C\Delta P^{n.}$ To determine the flow coefficient (C) and pressure exponent (n), the pressure difference must be measured over a range of air flows. Because the air handler fan used in the calibration apparatus was not designed to provide different airflows, the airflow was modified by blocking the return register with tape using a uniform grid pattern. Figure 17 shows the calibration data for the return basket hood. C and n were determined by a least squares fit to these data (C = 229 L/s [484 cfm], n = 0.469). The 95% confidence interval (C.I.) for C was 217/240 L/s (460/509 cfm) and for n it was 0.434/0.505.

Figure 16. Laboratory calibration system test return register

These laboratory tests also included measurements of air flow through the system with and without the flow meter in place using a large flow nozzle of ±0.5% accuracy. These tests showed that he added flow resistance of the return basket hood decreases the system flow by only 0.5%. Because this small change was the same as the accuracy of the reference flow meter it was neglected in the calibration procedure and does not need to be accounted for in field measurements of single returns. For multiple branch return systems, this effect would be further reduced because only part of the return duct system would be affected. However, in these cases, the insertion loss problem that we have examined for supply flow hoods would then occur for returns. The return with the basket on it would have lower flow and the other returns higher flow – thus resulting in an underestimate of return flows. We have not yet investigated this effect because we only have a single return on our laboratory system. It requires further research.

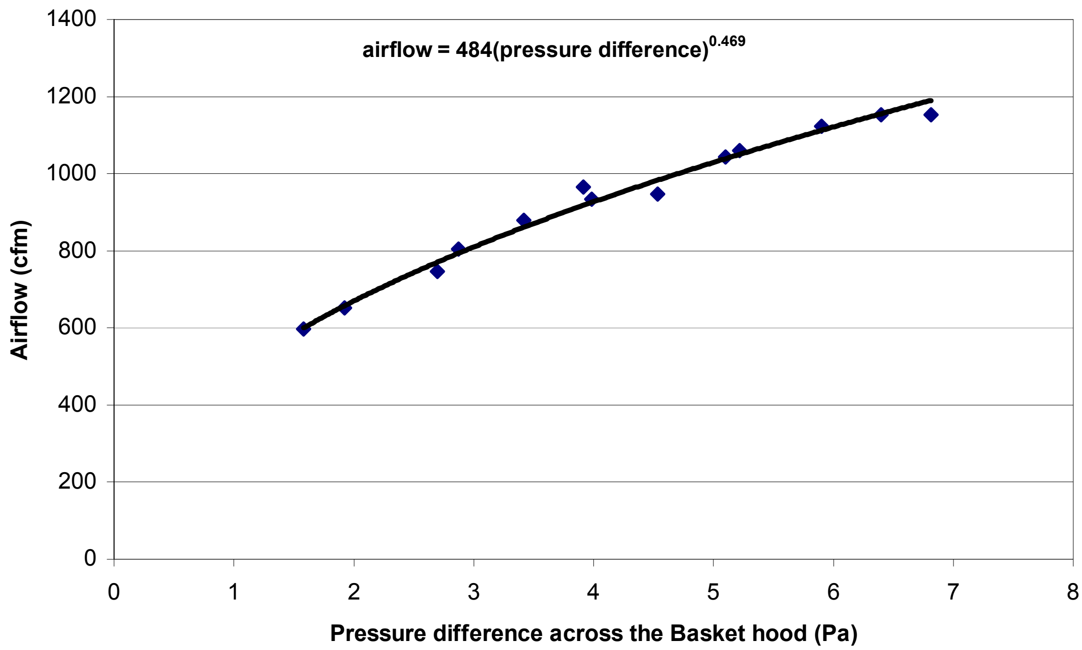


Figure 17. Return Basket Hood calibration results

The basket hood was also tested for its sensitivity to centering over the register. A second set of measurements were taken with the basket hood deliberately off-centered as shown in Figure 18. The results showed the fact that the return basket hood is not very sensitive to centering over the register, with less than 1% difference compared to the centered results.

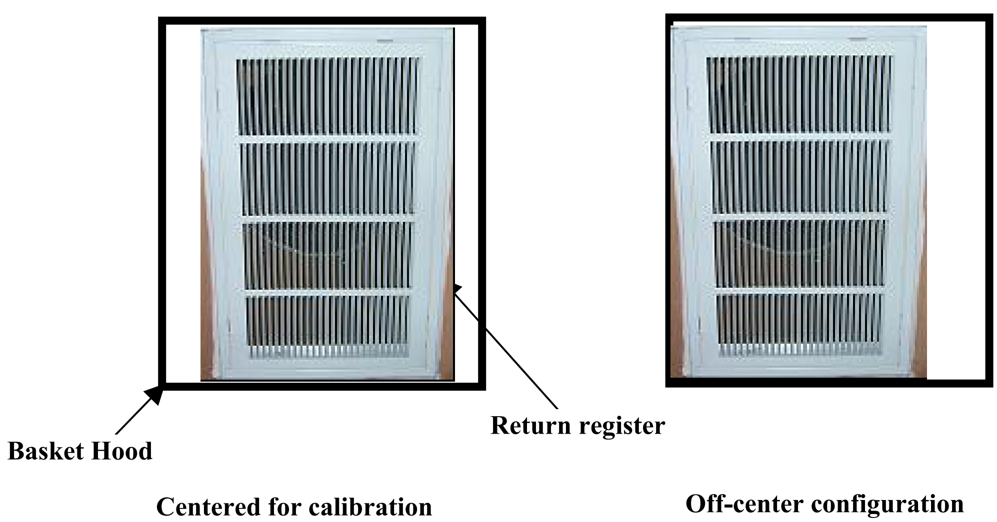


Figure 18. Comparison of basket hood edge location for centered and off-centered tests

Supply Basket Hoods

We found that the baskets significantly underpredicted the multi-branch system flows due to insertion losses: typically by about 20% for a 5 Pa basket pressure difference to 60% at higher pressures. Figure 19 illustrates the field testing results for an uncorrected basket hood. The figure clearly shows how the uncorrected basket generally underpredicts the individual register flows, with the underprediction tending to increase as the basket flowmeter pressure difference increases. This is the expected result since higher flowmeter pressure difference implies a greater flow resistance added to the branch of the system being measured. Figure 19 also includes the results from the multibranch laboratory system for comparison.

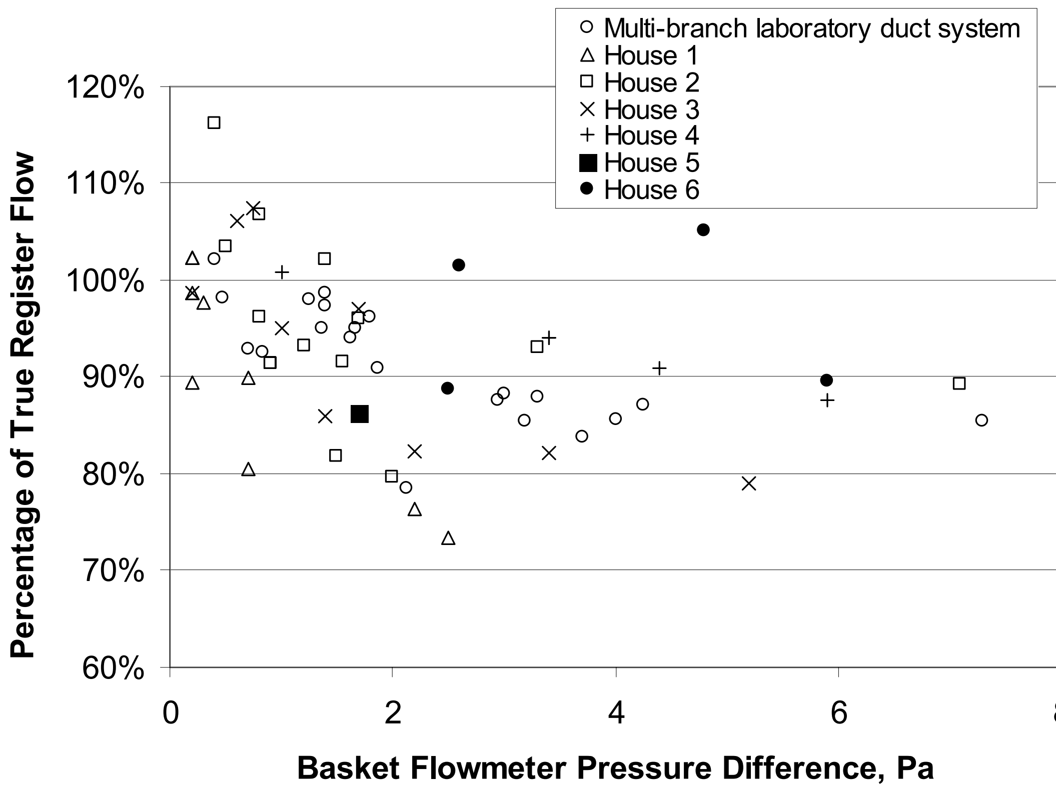


Figure 19. Basket White 1 indicated flow as fraction of true flow in seven different systems

We examined two potential correction methods for accounting for these insertion losses: single point and two-point. The single point correction is empirical and is based on measurements on the multi-branch laboratory system and tests in three houses from a previous study (Sherman and Walker 2002). The two-point correction uses two baskets of different flow resistances combined with analytical and empirical correction terms. A total of 88 register flows from eight houses and the multi-branch laboratory apparatus (used twice) were used to determine the correction factors. Not all flow hoods were tested with all the baskets, therefore different subsets of these 88 measurements were used for each correction evaluation.

The single point correction uses Equation 1, with the value of k determined from the field and laboratory measurements. The value of k ranged from 0.03 to 0.09 depending on which of the five tested baskets was being evaluated, and the use of a honeycomb flow straightener for some of the testing. Using this single value of $k=0.055$ results in bias errors less than 3% and RMS errors of about a 10%. These results indicate that using a single value for k gives reasonable results for most flow hood applications.

$$Q_{reference} = Q_{calibration}\left(1 + k\Delta P\right) \quad \textbf{(3)}$$

where $Q_{calibration}$ is the flow rate calculated using the calibration and $Q_{reference}$ is the flow measured using the reference flow meter. The results also showed that this single point correction works most reliably for flow hoods that have low flow resistance. For example, restricting the application of Equation 3 to a single low flow resistance flow meter resulted in a value of $k=0.045$, with a bias less than 1%. For comparison, the highest resistance basket had k=0.066, a bias error of –3% and and RMS error of 24%.

The two-point correction was developed for a two-branch system. An analysis (given in detail in appendix A) has been performed to examine the system effects of adding flow resistance (the flow meter) to one branch of a duct system. Note that analysis for more branches tends to add complexity without improving flow estimates because of the additional unknowns that each branch brings to the analysis. The pressure drop (without the flowmeter in place) through both branches is the same and the total flow is assumed to be constant. Additional laboratory tests performed for this study have shown that the adding of a flowmeter to a register changes the total air handler flow by about 0.1%, which is substantially less than the ±0.5% accuracy of the nozzle used to measure total air handler flow. Equation 4 gives the method of calculating a corrected flow based on the flow resistance of the two system branches:

$$Q_{correct} = Q_{flowmeter}\left(\frac{C_1 C_{fm}}{C_1 + C_{fm}}\right)\frac{\left(C_1 + C_2\right)}{C_1\left(\dfrac{C_1 C_{fm}}{C_1 + C_{fm}} + C_2\right)} \quad \textbf{(4)}$$

where:

$Q_{correct}$	=	flow through branch 1 (L/s, cfm)
$Q_{flowmeter}$	=	flowmeter measured flow (L/s, cfm)
C_1	=	flow coefficient for branch 1 (L/s/Pa$^{0.5}$, cfm/Pa$^{0.5}$)
C_2	=	flow coefficient for branch 2 (L/s/Pa$^{0.5}$, cfm/Pa$^{0.5}$)
C_{fm}	=	flow coefficient for flow meter (L/s/Pa$^{0.5}$, cfm/Pa$^{0.5}$)

Using this relationship it is possible to examine how the flowmeter branch flow changes with flowmeter resistance and measured pressure difference. In practice, these coefficients are generally not known, instead the system flows and pressures are known (or measured). In the following examples, the branch flow coefficients C_1 and C_2 are determined from the imposed total flow (472 L/s [1000 cfm] in these examples) and the branch pressure differences. A higher branch pressure difference for the same flow implies a higher branch flow resistance and a lower branch flow coefficient. The flowmeter pressure difference is determined from the flows and the flowmeter flow coefficient, assuming that the flow is proportional to the square root of the pressure difference. A couple of cases are examined: in the first case the total flow is split evenly between two branches; the other case is more typical of residential systems, with 10% of the total flow through the branch being measured.

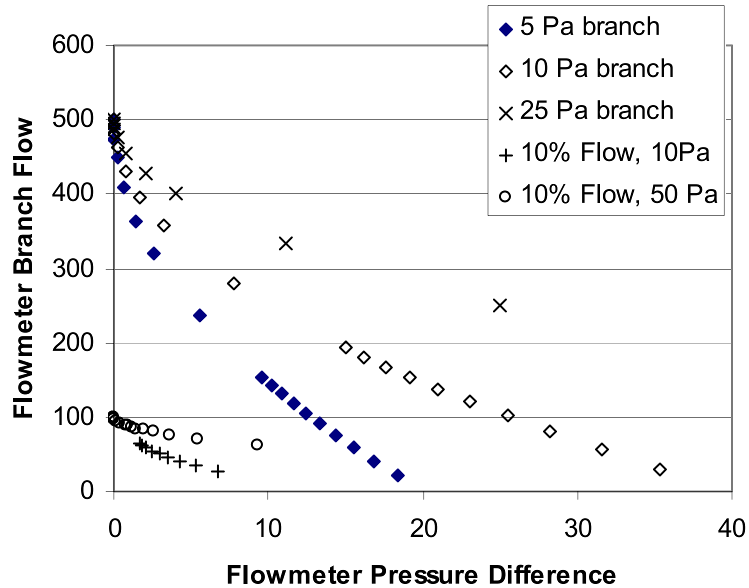


Figure 20a. Flowmeter Effect on Branch Flow

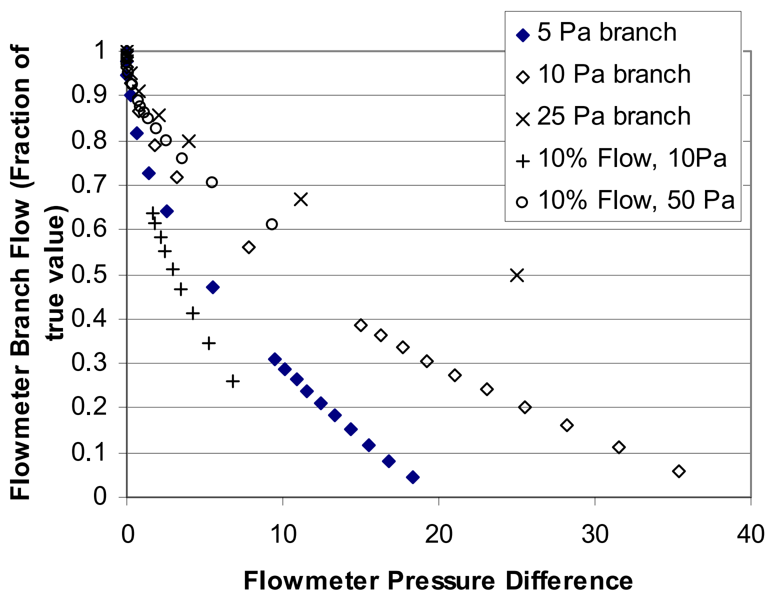


Figure 20b. Example Calculations for Flowmeter Effect on Branch Flow expressed as a fraction of true flow

Figures 20a and 20b show how the slope of the pressure/flow relationship increases with decreasing flowmeter pressure difference (this is the opposite trend to that of a single branch system with added flow resistance). This figure also illustrates how the flowmeter has a greater effect on branches with lower pressure differences under normal operating conditions. Analysis of the results shows that the "error" term, i.e., the difference between the measured flowmeter flow and the true flow is proportional to the square root of the measured flow meter pressure. Using a two-point measurement technique allows for evaluation of the error coefficient and therfore a good prediction of the true flow. If the two points are labelled "hi" and "lo" for high and low flow resisitance respectively, then the error at low flow resistance is:

$$Q_{error,lo} = C_{error}\Delta P_{lo}^{0.5} \quad \textbf{(5)}$$

and at high resistance is:

$$Q_{error,hi} = C_{error}\Delta P_{hi}^{0.5} \quad \textbf{(6)}$$

where, ΔP_{lo} and ΔP_{hi} are the pressure differences across the flowmeter. The equation for the true flow ($Q_{1,a}$) can be written:

$$Q_{1,a} = Q_{lo} + C_{error}\Delta P_{lo}^{0.5} = Q_{hi} + C_{error}\Delta P_{hi}^{0.5} \quad \textbf{(7)}$$

where Q_{lo} and Q_{hi} are the flowmeter flows. After some algebraic manipulation, Equation 5 yields a relationship for the error coefficient, C_{error}:

$$C_{error} = \frac{Q_{lo} - Q_{hi}}{\Delta P_{hi}^{0.5} - \Delta P_{lo}^{0.5}} \quad \textbf{(8)}$$

Substituting back into Equation 7, the lo or hi flow can be corrected. The lo flow will be closest to the correct flow, but have the greater precision errors, whereas the hi flow will have improved precision but a greater extrapolation uncertainty. For example, for the lo flow case:

$$Q_{1,a} = Q_{lo} + \frac{Q_{lo} - Q_{hi}}{\Delta P_{hi}^{0.5} - \Delta P_{lo}^{0.5}}\Delta P_{lo}^{0.5} \quad \textbf{(9)}$$

The next step is to apply these corrections to some measured field and laboratory data on real duct systems. We took field and laboratory data on 19 registers in 3 systems (one laboratory and two houses), where each register had three or four different flow/pressure measurements that can be plotted to examine the trend of pressure and flow changes. The fraction of true flow was calculated for each individual measurement and flow meter pressure difference. The individual flow and pressure combinations are illustrated in Figure 21. The data trends in Figure 21 are less clear than the idealized system plots shown in Figure 21. However, each individual register does show a definite trend.

Figure 22 combines the results of Figure 21 with measurements of 2 additional houses. Figure 22 identifies the variation as a function of flow meter rather than by register as seen in Figure 21. This figure shows that the trends for an individual register become less clear when all the results are examined. The first issue is that there is significant "scatter" in the field data from a single ideal relationship. This is due to a combination of experimental uncertainties (e.g., how well the flow hood seals against the wall/register and low pressure resolution) and each measurement point being on a different branch of the tested duct systems and having a different set of defining branch flow resistance characteristics. This implies that any correction factor we develop for general use will still have significant uncertainties.

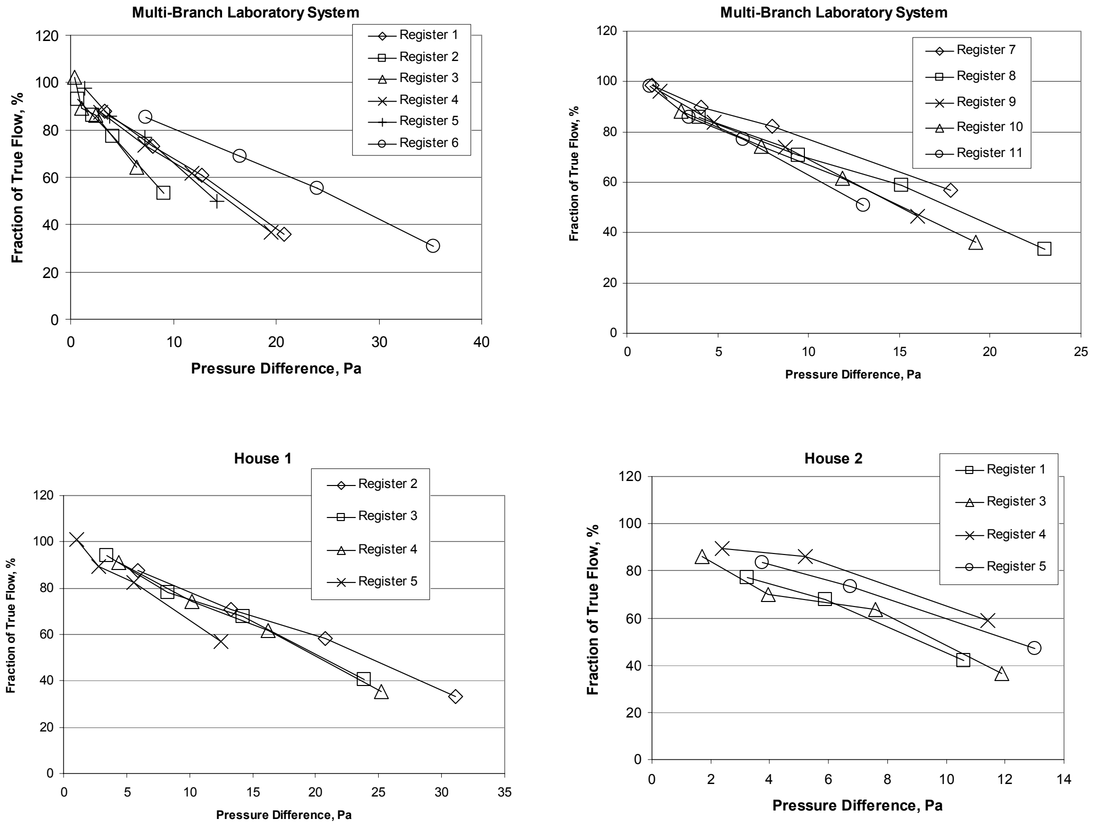


Figure 21. Multiple resistance basket flow meter measurements on individual registers

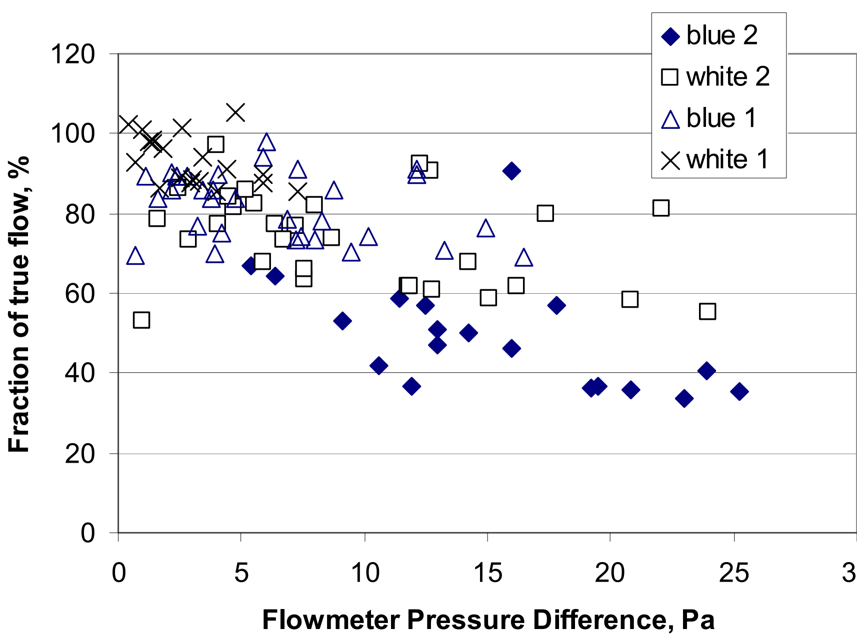


Figure 22. Field Test results for four flow hoods of different resistances

Applying the corrections from Equation 9 to these data results in predicted flows averaging 7 L/s (15 cfm, 13%) too high, with an RMS error of 9 L/s (19 cfm, 17%). This result indicates that further study is required (including field testing of more duct systems) in order to further evaluate the applicability of these relationships. Another possibility is that the flowmeter pressure drop is not the same as the static pressure differences assumed in the multi-branch analysis above. This is because the soaker hose mounted in the flowmeter may allow some velocity pressure as well as static pressure to be included in the flowmeter pressures. This would result in the pressure differences used in Equation 9 being too high. To investigate these effects, the standard assumption that the velocity pressure would be proportional to the square of the velocity was used. Furthermore, it was also assumed that the velocities inside the flow hood were proportional to the volumetric airflow through the flowmeter. However, if the same velocity pressure coefficient is used for high and low flow resistance cases then the coefficient would cancel out in Equation 9 and have no effect. This implies that the correction factors need to have different values for the high and low flow cases.

After some experimentation we found that using the same offset pressure (as opposed to the same velocity pressure coefficient) gave good results. The offset pressure was calculated using the lo flow resistance pressure. Equation 10 includes the empirical velocity pressure corrections and is used to calculate the corrected flow based on the two flowmeter flows and pressures. Using this equation with the two-point correction factor, k_2, equal to 0.67 reduced biases to -0.1% and the RMS errors to 7%, i.e. about the same improvement as the simple linear empirical relationship.

$$Q_{corrected} = Q_{lo} + \frac{\left(Q_{lo} - Q_{hi}\right)\left(\Delta P_{lo} - k_2 \Delta P_{lo}\right)^{0.5}}{\left(\Delta P_{hi} - k_2 \Delta P_{lo}\right)^{0.5} - \left(\Delta P_{lo} - k_2 \Delta P_{lo}\right)^{0.5}} \quad \textbf{(10)}$$

Bag Filling

Each register was tested three times in order to study both the accuracy compared to the reference flow hood and the repeatability of the results. The results are summarized in Table 14. The bias is less than 1% for Bag 2 and 4% for Bag 1. This indicates that these bags have sufficient accuracy for all applications using the sum of register flows (total fan flow and duct leakage). The RMS errors range from 5% to 7%, but are still accurate enough for any diagnostic requiring individual register measurements to be known. The repeatability uncertainties averaged about 3% for these two bags on this system. Compared to the errors found earlier looking at highly directed flows out of individual registers, these results are partly due to the registers used for the multi-branch testing having relatively uniform flow out of them.

Table 14. Accuracy of bags on the multi-branch system

	Bag 2		Bag 1	
	%difference	Difference, L/s (cfm)	%difference	difference, L/s (cfm)
RMS	5.4	4.1 (8.8)	6.9	3.1 (6.7)
BIAS	0.7	0.7 (1.4)	-4.1	-1.6 (-3.3)

Field Evaluation of Commercially Available Flow Hoods on Commercial Registers

In previous LBNL studies (Walker et al. 2001 and Wray et al. 2002) commercially available flow hoods were field tested on a residential system. The results of those tests showed considerable differences between different flow hoods. In the current study, we want to see if the same differences are also present when testing commercial registers. The current field tests were done on four different multi-branch subsections of a large VAV system, using one supply grille on each system (there were two to five grilles for any one subsection). We selected four grilles to cover a range of nominal grille airflows from 50 to 200 L/s (100 to 400 cfm). The grilles were all 0.41 m (2 ft) square, 4-way throw, with a perforated face (4.8 mm (3/16") holes, 6.3 mm (1/4") on center). The VAV system was set to provide constant flow during the test period (supply air handler at full flow, all VAV box primary air dampers wide open, system set to full recirculation). On each grille, all five hoods were used in sequence with 0.41 m × 0.41 m (2ft × 2ft) capture hoods to measure the flows. The reference grille flow was measured using a powered flow hood that uses a fan to balance insertion losses and a flow meter that is not sensitive to incoming air flow patterns (for more details on the powered flow hood see Walker et al. 2001 and Wray et al. 2002). Manufacturer's instructions for hood operation were followed in each case (e.g., the use of relief vents or low-flow plates). We found that it was essential to follow instructions properly because it was easy to use the wrong operating mode and get large errors. For example, we found an error of 38% by using incorrect vent modes for one of the flow hoods.

The results of these field tests are summarized in Table 15 and shown graphically in Figure 23. The results showed that the flow hoods exhibited similar trends – with underprediction of low flow rates. Overall Flow Hood 1 had the best performance. Flow hoods 3 and 5 were a little worse, with RMS errors approaching 5%. Flow Hoods 2 and 4 exhibited significant biases and underpredicted by more than 10%.

Table 15. Summary of field test results for commercially available flow hoods on commercial registers

Flow Hood	Bias Error, L/s (cfm)	Bias Error, %	RMS Error, L/s (cfm)	RMS Error, %
1	1.3 (2.7)	0.7	1.9 (4.1)	1.6
2	- 13.8 (-29.3)	-10.8	17.0 (36.1)	11.1
3	5.6 (11.9)	3.5	7.2 (15.4)	4.8
4	-9.2 (-19.5)	-11.3	9.9 (21.0)	13.6
5	-3.1 (-6.5)	-2.0	5.8 (12.3)	3.6

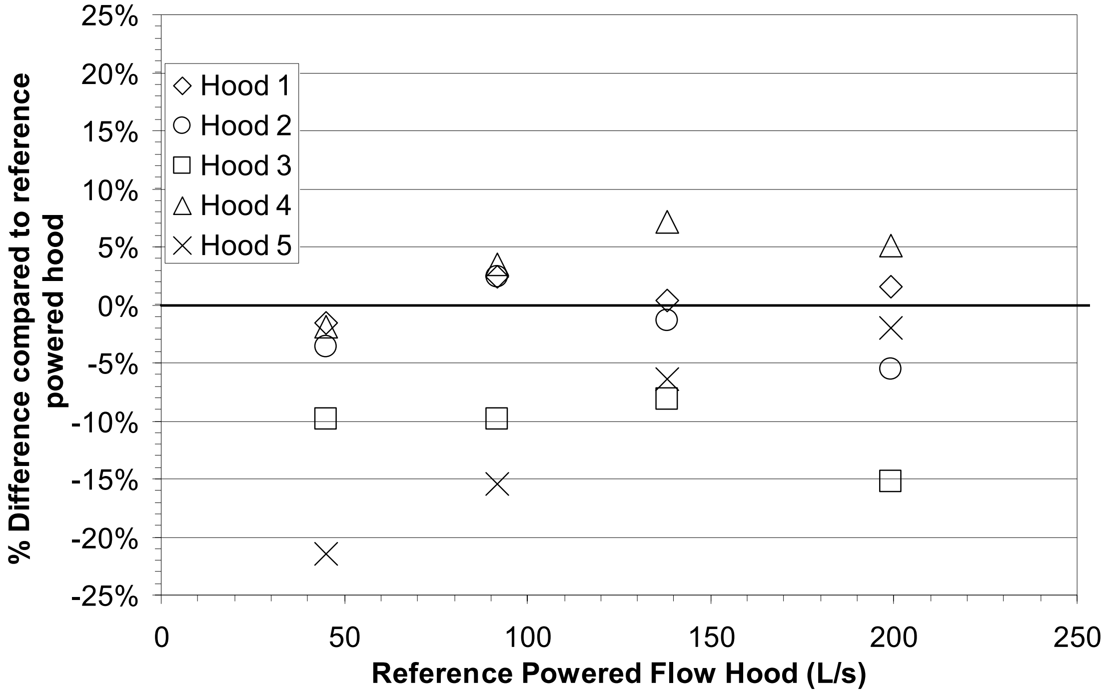


Figure 23. Results of field testing commercially available flow hoods on commercial registers

Field Evaluation of New Techniques

Return Basket Hood

The return basket hood was field tested on five residential and three commercial buildings in California. A powered flow hood was used as the reference for these tests. In some systems, a single fan-flowmeter powered flow hood could not produce enough flow to match the large flows through a single return. In these cases a device was constructed (shown in Figure 24) that allowed the flows from several fan-flowmeters to be combined using a mixing box. Table 16 summarizes the test results for these systems and shows that the return basket hood gives excellent results. The average difference over all these systems was –0.2 % and the RMS difference was 2.4 %. This RMS difference is close to the accuracy of the powered flow hood itself, which shows that the return basket hood gives the same results as our reference device within the uncertainty specification of the reference.

The field evaluation also looked at ease of use issues. To use the Basket Hood the operator has to put the device on the register and hold it tight over the register in order to maintain a seal. The field testing demonstrated that this is easier to do with the basket hood than the other flow meters because of its light weight. Figure 24 is a particularly good illustration of the difficulties in applying powered flowhoods in the single large return flow application. In practice, powered flow hood measurements are normally performed with a single fan-flowmeter and measured system pressures are used to extrapolate from the measurement condition to the return flow at operating condition. This introduces extrapolation errors to the calculations. Because the powered flow hood is being used as the reference measurement technique in this study, it was important to reduce the potential errors and so the extrapolation method was not used, and the complex and time consuming multiple fan-flowmeter technique illustrated in Figure 24 was used.

Figure 24. Multiple fan-flowmeter return powered flow hood

Table 16. Return Basket Hood field tests results			
Building	"Powered flow hood" airflow, L/s (cfm)	"Basket Hood" airflow, cfm (L/s)	Difference (%)
Beauty salon (Sacramento)	463 (981)	467 (990)	+0.9
Bicycles store (Sacramento)	190 (402)	193 (409)	+1.8
Dance studio (Sacramento)	357 (757)	351 (744)	-1.7
One-story house (Fresno)	490 (1039)	490 (1039)	0.0
Dance studio (Sacramento)	293 (620)	301 (637)	+2.7
One-story House (Berkeley)	233 (494)	239 (506)	+2.4
Two-story House (Berkeley)	111 (235)	107 (227)	-3.4
Two-story House (Albany)	322 (683)	330 (700)	+2.5
Two-story House (Alameda)	268 (568)	258 (547)	-3.7

Field testing of commercial supply basket flow hood

The commercial supply basket flow hood was field tested on 11 registers from three commercial building systems located in Sacramento, California. The reference flow hood for these commercial registers was the same powered flow hood used for the residential field testing. Table 17 shows the detailed results of these tests. The test results show that flow resistance of the basket flow hoods introduce significant underpredictions averaging 33% for the blue flow hood and 27% for the dark blue flow hood. The underprediction is greater at higher flow rates, when the backpressure of the flow hood is highest. Using the same two point velocity pressure corrections used for residential registers reduces the errors to a bias of 6%

and an RMS uncertainty of 14%. This required the use of a velocity pressure fraction (k_2) of 0.1 in Equation 10, substantially less than for the residential flowmeter. This difference is probably because the construction of the commercial flowmeter places the soaker hose pressure sensing element far away form the direct register flow.

Table 17. Commercial basket hood field test results

Register	Blue Basket flow, L/s (cfm)	Dark blue basket flow, L/s (cfm)	Reference Airflow, L/s (cfm)	Blue Difference (%)	Dark Blue Difference (%)	Two Point Flow, L/s (cfm)	Two Point Difference, %
Beauty Salon 1	117 (248)	126 (268)	187 (397)	-38	-33	176 (373)	-6
Beauty Salon 2	105 (223)	114 (242)	165 (349)	-36	-31	164 (348)	0
Beauty Salon 3	108 (230)	124 (263)	195 (413)	-44	-36	257 (545)	32
Dance Studio 1	109 (231)	120 (254)	159 (338)	-32	-25	185 (392)	16
Dance Studio 2	105 (222)	114 (240)	158 (336)	-34	-28	161 (341)	1
Dance Studio 3	76 (162)	81 (171)	97 (205)	-21	-17	101 (214)	5
Bicycle Store 1	195 (413)	216 (457)	340 (721)	-43	-37	343 (727)	1
Bicycle Store 2	190 (404)	205 (434)	313 (664)	-39	-35	278 (589)	-11
Bicycle Store 3	160 (338)	169 (357)	229 (486)	-30	-27	210 (445)	-8
Bicycle Store 4	136 (288)	147 (311)	170 (360)	-20	-14	202 (429)	19
Bicycle Store 5	127 (270)	137 (290)	162 (344)	-22	-16	187 (397)	15

The individual flows errors and corresponding pressure differences for the commercial register measurements are illustrated in Figure 25. The flow to pressure drop relationship is even less clear than for the residential supplies shown in Figure 22. Because the commercial results did not show definite flow to pressure difference trends, the one point analysis performed for the residential registers was not repeated for commercial registers.

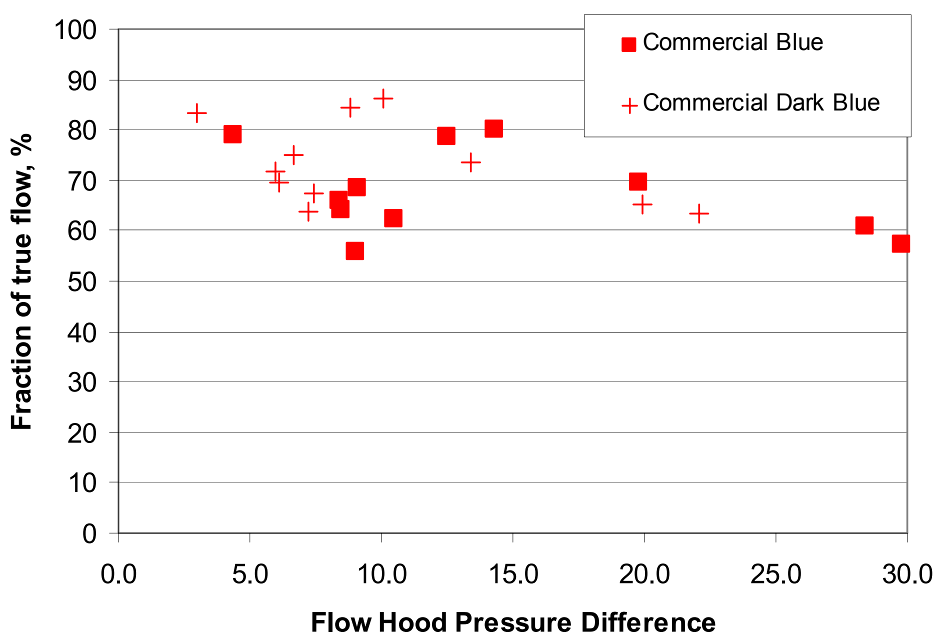


Figure 25: Individual pressure and flow measurements from commercial supply basket hood field test results

Bag Filling

Bag 1 was used on thirty registers in three houses. Compared to the reference flow hood, the bias was about –5% and the RMS uncertainty was 11%. These results indicate that although the bag filling method appears crude, the results of bag testing can be used for almost all register air flow diagnostics, with the exception of the requirement for duct leakage estimates (but even for that test, the 5% bias is very close to being acceptable). We found that the largest errors are for registers whose flows are lower than about 20 L/s (40cfm). At these small flows the influence of leakage around the edge of the bag is increased because it takes a long time to fill the bag, and at the low flow registers the small backpressure required to fill the bag becomes more significant.

Variability from user to user needs to be evaluated because the bag filling tests requires an individual to interpret when the bag filling starts and stops. A total of 5 people (including LBNL staff, a homeowner and their son – none of whom had any previous experience with this measurement technique) measured the same register in a house 3 times. Each person was given simple instructions on how to perform the testing and observed an experienced LBNL staff member perform the test. The results were that the five flow measurements were in a narrow range between 29 and 30 L/s (61 and 64 cfm). Compared to the reference flow measurement there was an RMS error of 1.1 L/s (2.4 cfm), or about 4% of the measured flow. This result indicates that repeatability does not introduce significant errors into the test procedure.

Discussion and Conclusions

Based on our test results, flows measured using commercially available flow hoods can vary widely, with some devices performing much better than others. Some devices exhibited enough sensitivity to placement over the grilles and the extremes of flow non-uniformity that their applications are severely limited. In particular, Flow Horn 1 produced such large backpressure that it was essentially useless for any branched system. All the tested flow hoods had good repeatability (less than 5% variability) if well centered over the grille. In general, the results showed that most of the errors are biases rather than random errors. The diffuser screen reduced sensitivity to placement and flow direction, but recalibration may be required to account for the extra insertion loss. The diffuser screen is particularly useful in removing the extreme (on the order of 50%) errors and reducing them below 10% for some individual grille measurements. Finally, testing on a small number of commercial grilles shows less variability than for residential applications, mostly because the flow hood size matches the grille size (meaning the hood is well centered) and the tested grilles had built-in diffusers. However, there was still a significant range of biases from 1 to 10% depending on the individual flow hood, with two of the five being significantly worse than the others. These results indicate that there is a potential for flow hoods to be accurate enough for a wide range of residential HVAC system diagnostic applications, as long as they are well designed to account for the issues of centering and non-uniform flow, and they do not introduce large backpressures. Combined with the observed range of performance on commercial grilles, this implies that standards are needed to ensure consistent and realistic calibration and testing of flow hoods.

The results of the basket hood and bag filling tests are discussed in the context of the lower expectations of these devices compared to commercial equipment. In other words, a 10% error from bag-filling or an adapted laundry basket is more acceptable than a 10% error from a much more expensive commercial device because we do not expect the simple home-made device to work as well. The basket hood combines sufficient accuracy for most applications while being cheap and easy to use. The development of the basket hoods has shown that it is important to balance the need to have hoods that introduce small flow resistances with the precision limits of measuring pressures. Extrapolation errors from the intrinsic flow resistance can be effectively reduced by simple empirical correction factors that result in biases of about 3% and RMS errors of about 10%. Our experience showed that, for best results, extrapolation should be limited to about a 20% change in flow. There is a small added uncertainty (<5%) if we simply measure the hole size and assume an orifice coefficient of 0.7 and use a standard orifice equation rather than specifically calibrating individual devices.

These basket hoods all proved to be very easy to use due to their light weight compared to other flow meters. The only significant issue for the operator is the need to have a good seal around the base of the flow hood where it surrounds the register. The component cost is minimal – only a few dollars. However, the accurate results obtained in this study require a good time averaging pressure sensor that costs about $600. In addition, as with most measurement instrumentation there is the need to calibrate the basket. This would add to the cost. However, there remain significant potential cost savings compared to commercially available flow hoods that cost $2000 to $3000 or powered flow hoods that cost about $1500 to $2000.

Bag filling is a good method to measure the flows for situations where the necessary accuracy does not have to be better than 10%. The test results showed that the volume indicated by the manufacturer can be used, rather than a sophisticated calibration, and only introduces an additional error of about 5 to 10%.

All these results are based on a limited set of measurements. Future work needs to expand on these evaluations, in particular by performing more field testing of basket hoods and bag filling to confirm their potential as alternative measurement techniques.

Acknowledgements

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Appendix A. Derivation of backpressure correction equation for multi-branch flow hood operation

The pressures and flows are defined as follows:

Q_1	=	flow through branch 1 (cfm, L/s)
Q_2	=	flow through branch 2 (cfm, L/s)
Q_{total}	=	total flow through the system (cfm, L/s)
C_1	=	flow coefficient for branch 1 (cfm/$Pa^{0.5}$, L/s/$Pa^{0.5}$)
C_2	=	flow coefficient for branch 2 (cfm/$Pa^{0.5}$, L/s/$Pa^{0.5}$)
C_{fm}	=	flow coefficient for flow meter (cfm/$Pa^{0.5}$, L/s/$Pa^{0.5}$)
C_{comb}	=	combined flow coefficient for branch and flow meter (cfm/$Pa^{0.5}$, L/s/$Pa^{0.5}$)
R_1	=	flow resistance of branch 1 ($Pa^{0.5}$/cfm, s$Pa^{0.5}$/l)
R_{fm}	=	flow resistance of flow meter ($Pa^{0.5}$/cfm, s$Pa^{0.5}$/l)
R_{comb}	=	combined flow resistance of branch and flow meter ($Pa^{0.5}$/cfm, s$Pa^{0.5}$/l)
ΔP	=	pressure difference across both branches (Pa)

Addition subscripts ",a" and ",b" refer to pressures and flows during normal operation and with the flowmeter inserted respectively, such that $Q_{1,a}$ is the true register flow to be measured.

Under normal operating conditions:

$$Q_{total} = (C_1 + C_2)(\Delta P_a)^{0.5} \quad \textbf{(A3)}$$

With the flowmeter added the flow resistance of branch 1 is changed. The flow resistance of the branch and the flowmeter are inversely proportional to their flow coefficients.

$$R_1 = \frac{1}{C_1}; R_{fm} = \frac{1}{C_{fm}} \quad \textbf{(A4)}$$

The total flow resistance of the branch and flowmeter, R_{comb}, is given by the sum of these resistances. The flow coefficient for the branch plus the flowmeter is then:

$$C_{comb} = \frac{1}{R_{comb}} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_{fm}}} = \frac{C_1 C_{fm}}{C_1 + C_{fm}} \quad \textbf{(A5)}$$

Then, the total flow with the flow meter added is:

$$Q_{total} = (C_{comb} + C_2)(\Delta P_b)^{0.5} = \left(\frac{C_1 C_{fm}}{C_1 + C_{fm}} + C_2\right)(\Delta P_b)^{0.5} \quad \textbf{(A6)}$$

With the total flow the same in each case, the change in driving pressures is:

$$Q_{total} = (C_1 + C_2)(\Delta P_a)^{0.5} = \left(\frac{C_1 C_{fm}}{C_1 + C_{fm}} + C_2\right)(\Delta P_b)^{0.5} \quad \textbf{(A7)}$$

which can be rearranged:

$$(\Delta P_b)^{0.5} = \frac{(C_1 + C_2)}{\left(\frac{C_1 C_{fm}}{C_1 + C_{fm}} + C_2\right)}(\Delta P_a)^{0.5} \quad \textbf{(A8)}$$

Next the pressure difference under normal operating conditions is replaced with flow and flow coefficient terms. From

$$Q_{1,a} = C_1 \left(\Delta P_a\right)^{0.5} \quad \textbf{(A9)}$$

ΔP can be expressed as:

$$\left(\Delta P_a\right)^{0.5} = \frac{Q_{1,a}}{C_1} \quad \textbf{(A10)}$$

Substituting Equation A10 in Equation A8:

$$\left(\Delta P_b\right)^{0.5} = \frac{Q_{1,a}\left(C_1 + C_2\right)}{C_1\left(\frac{C_1 C_{fm}}{C_1 + C_{fm}} + C_2\right)} \quad \textbf{(A11)}$$

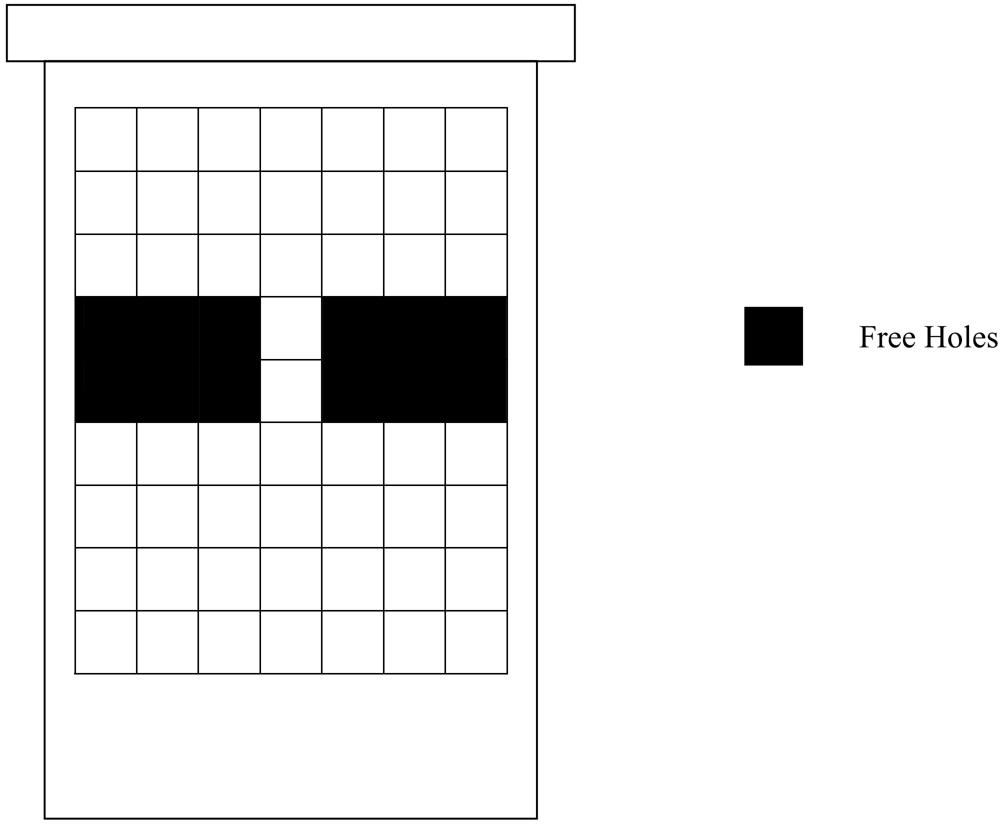
The flow through branch one and the flowmeter is given by:

$$Q_{1,b} = \left(\frac{C_1 C_{fm}}{C_1 + C_{fm}}\right)\left(\Delta P_b\right)^{0.5} \quad \textbf{(A12)}$$

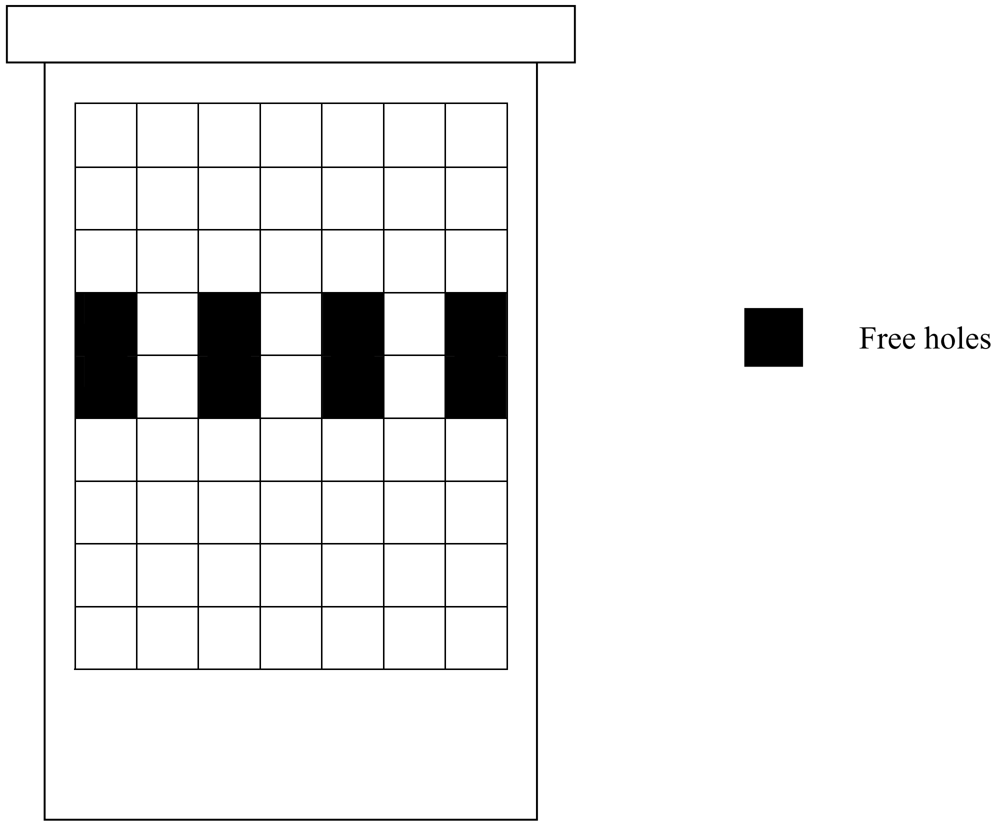
Substituting Equation A11 in Equation A12 then given the flow through the flowmeter as a function of the flow under operating conditions, $Q_{1,a}$ and the flow coefficients for each branch and the flowmeter:

$$Q_{1,b} = Q_{1,a}\left(\frac{C_1 C_{fm}}{C_1 + C_{fm}}\right)\frac{\left(C_1 + C_2\right)}{C_1\left(\frac{C_1 C_{fm}}{C_1 + C_{fm}} + C_2\right)} \quad \textbf{(A13)}$$

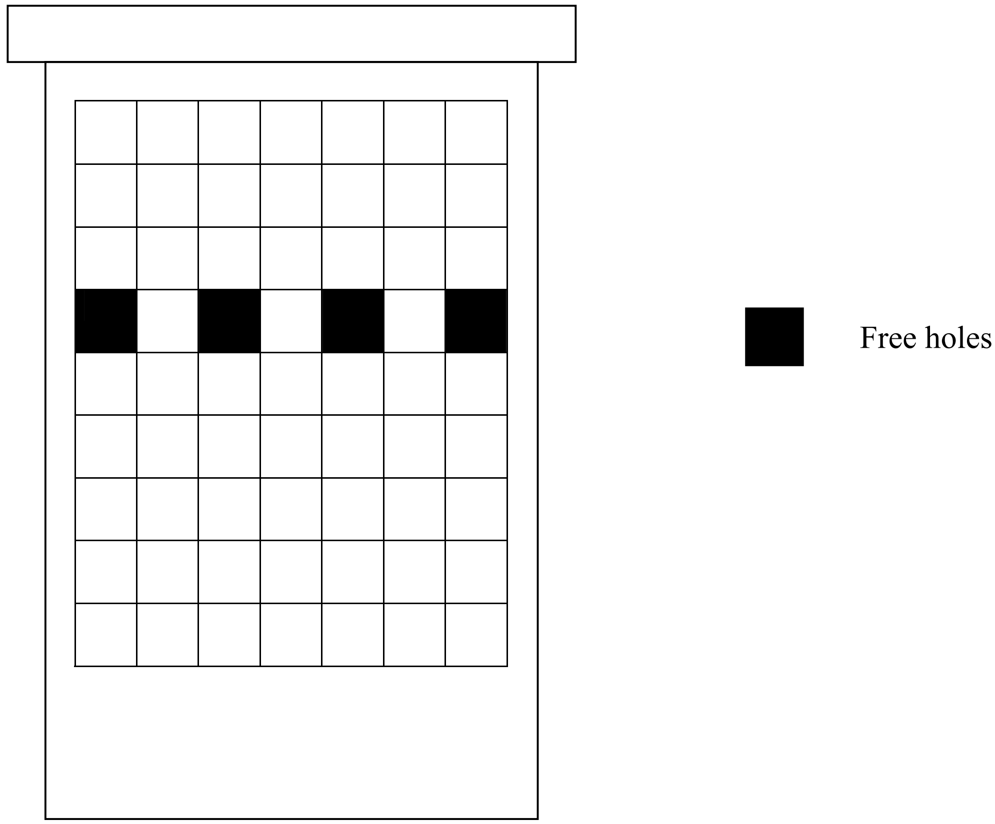
Appendix B. Illustrations of basket hole locations



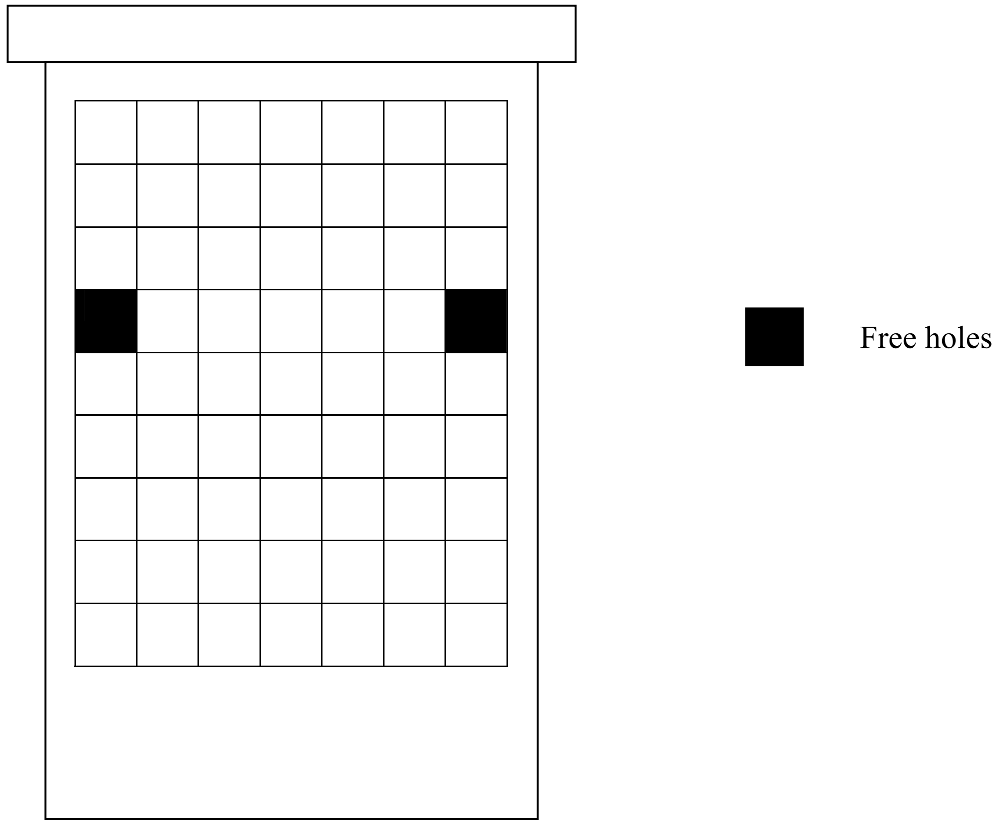
Residential Basket Hood , Configuration : White 1 (24 holes)



Residential Basket Hood , Configuration : Blue 1 (16 holes)



Residential Basket Hood , Configuration : White 2 (8 holes)



Residential Basket Hood , Configuration : Blue 2 (4 holes)