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LABORATORY EVALUATION OF AIR FLOW MEASUREMENT METHODS FOR RESIDENTIAL HVAC RETURNS

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ABSTRACT

This project improved the accuracy of air flow measurements used in commissioning California heating and air conditioning systems in Title 24 (Building and Appliance Efficiency Standards), thereby improving system performance and efficiency of California residences. The research team at Lawrence Berkeley National Laboratory addressed the issue that typical tools used by contractors in the field to test air flows may not be accurate enough to measure return flows used in Title 24 applications. The team developed guidance on performance of current diagnostics as well as a draft test method for use in future evaluations. The series of tests performed measured air flow using a range of techniques and devices. The measured air flows were compared to reference air flow measurements using inline air flow meters built into the test apparatus. The experimental results showed that some devices had reasonable results (typical errors of 5 percent or less) but others had much bigger errors (up to 25 percent). Because manufacturers' accuracy estimates for their equipment do not include many of the sources of error found in actual field measurements (and replicated in the laboratory testing in this study) it is essential for a test method that could be used to determine the actual uncertainty in this specific application. The study team prepared a draft test method through ASTM International to determine the uncertainty of air flow measurements at residential heating ventilation and air conditioning returns and other terminals. This test method, when finalized, can be used by the Energy Commission and other entities to specify required accuracy of measurement devices used to show compliance with standards.

Keywords: Airflow measurement, measurement standards, residential return, grille, forced air.

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EXECUTIVE SUMMARY

Introduction

Current California Building Energy Standards include test procedures for measuring the air flow through forced air heating and cooling systems. These test procedures include using flow hoods to measure flows at return grilles. Research by Lawrence Berkeley National Laboratory (LBNL) and observations from other practitioners has shown that flow hoods can have significant errors when measuring return air flows. This project improved the accuracy of air flow measurements used in commissioning California residential heating and air conditioning systems in Title 24 (Building and Appliance Efficiency Standards), thereby improving system performance and efficiency of California residences. This included developing guidance to use in Title 24 applications as well as a test procedure to determine the errors associated with air flow measurement tools.

Project Purpose

This project addressed the concern that typical equipment used in the field by contractors may not be accurate enough for measuring return flows to use in California Building Energy Code (Title 24) applications. Because manufacturers' accuracy estimates for their equipment do not include many of the sources of errors found in actual field measurements, it is essential for a test method to determine the uncertainty in a specific application. LBNL researchers developed testing methods to improve air flow measurements for residential forced air heating and cooling systems ensuring optimum system performance.

Project Process

The measurement errors from the studied field tools have two components: the air flow through the measurement device, and insertion loss effects of actually performing the measurement. Insertion losses occur because most devices used for air flow measurement introduce additional air flow resistance leading to reduced total system air flows, or, more significantly for multiple branch systems, reduced air flow only through the branch currently being measured. An experimental apparatus was built that could be configured as a one, two or three branch return system. The apparatus used a typical gas furnace with two different blower motors - one Permanent Split Capacitor and one Brushless Permanent Magnet. The different motors were used because they have different responses in terms of changed air flow rate with changing system air flow resistance. The measured air flows were compared to reference air flow measurements using inline air flow meters built into the test apparatus. Laboratory experiments were performed using this apparatus far a range of air flows using several measurement devices to demonstrate the applicability of the test procedure and to give guidance on acceptable test procedures. A draft test method was written and efforts to create an official American Society of Testing and Materials test method began, which included forming a working group that included a range of interested constituents.

Project Results

The experimental results showed that some devices had reasonable results (typical errors of 5 percent, or less) but others had much bigger errors (up to 25 percent) indicating that it is vital to distinguish between air flow measurement devices in Title 24 and other standards that require residential register air flow measurement. A draft test method has been prepared to determine the uncertainty of air flow measurements at residential heating, ventilation and air conditioning (HVAC) terminals and a working group assembled to pursue standardization through ASTM. Until the ASTM test method is available it is recommended that only powered flow hoods or traditional high-capacity (maximum flow rate greater than 500 cubic feet per minute) passive flow hoods be allowed for Title 24 air flow measurements at return grilles.

Project Benefits

This test method, when finalized, can be used by the Energy Commission and other entities to specify required accuracy of measurement devices used to show compliance with standards. This will result in more accurate compliance with Title 24 requirements and improved HVAC performance. Improved compliance with Title 24 will benefit California ratepayers by ensuring that homes and equipment perform as intended, ensuring that energy and financial savings from high efficiency equipment are actually achieved. Homeowners will experience better indoor comfort by having verified HVAC air flows actually match design specifications, increasing the longevity of heating and cooling equipment.

Having the correct air flow in the system leads to savings in natural gas for furnaces and in electricity for air conditioning. For furnaces the avings are about 1 to 2 percent. For air conditioning the savings are significantly greater. Recently published PIER sponsored field research in California found that most systems have too little airflow from a combination of poor duct design and installation and filter implementation. The air flows were about 25% too low on average and correcting this airflow improved field measured Energy Efficiency Ratio (EER) (and therefore energy savings) by 18% on average.

CHAPTER 1: Background

Current California Building Energy Standards include test procedures for measuring the air flow through forced air heating and cooling systems. These test procedures include the use of flow hoods to measure flows at return grilles. Research by Lawrence Berkeley National Laboratory (LBNL)[1] and observations from other practitioners has shown that flow hoods can have significant errors when measuring return air flows. The LBNL study found that some hoods were too restrictive and reduced the air flow by about 17% compared to 5% errors for less restrictive hoods. Some return grilles are too large to be completely covered by flow hoods and this resulted in errors of 24%. These large grilles were measured by separately covering different parts of the grille with each hood, then combining the separate measurements to obtain the total flow.

The preliminary source of measurement error is the uncertainty of the measurement of the actual flow through the flow hood - this includes both calibration errors and errors that occur because the air flow pattern is not the same as under calibration conditions[2]. Another source of error occurs when there are multiple returns for a system and the added flow resistance of the flow hood reduces the air flow through the register being measured. These errors, which have not been fully investigated yet, typically result in a systematic negative bias in the total flow measurement. In this study these sources of error were examined separately. For simplicity, this report will refer to the various devices and measurement techniques evaluated in this study as flowhoods - even though they are not all flowhoods in the traditional sense.

These sources of potential errors raise serious concerns about the use of this measurement technique in the California Building Energy Efficiency standards. Currently, the 2013 California Building Efficiency Standards discuss measurement of total system air flows in Reference Appendix RA 3.1.4.2[3] (California Energy Commission, 2012). The measured return air flows are used for several purposes in the California Standards:

1. To show that minimum air flows are met that ensure acceptable heating and cooling system performance (RA 3.3),
2. In the calculation of fractional duct leakage (RA 3.1.4.3.1),

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[1] Walker, I. S., Wray, C. P., Dickerhoff, D. J., & Sherman, M. H. Evaluation of flow hood measurements for residential register flows. Berkeley CA: Lawrence Berkeley National Laboratory. 2001. LBNL 47382

[2] This is more of a concern when measuring supply air flow because the air flow entering the flow hood may be highly non-uniform. It should be less of an issue for return flows because air enters the flow hood from the room and is likely to be much more uniform.

[3] California Energy Commission. 2013 Reference Appendixes. The Building Energy Efficiency Standards for Residential and Non-Residential Buildings: California Energy Commission. 2012

3. In estimates of blower power ratings (RA 3.3).

In addition to these requirements for measuring air flow that are already in the California Standards, there are other situations that may be included in the future, such as knowing the air flow through filtration systems that use the central forced air system.

There is a need for a test procedure that would exercise the flow hoods in the areas of performance discussed above to ensure that the test methods in the California Building Efficiency Standards give correct information for compliance evaluation, and to provide a method for test equipment manufacturers to show that their equipment performs adequately. Inaccurate flow measurements also lead to improperly balanced HVAC systems that can have implications for health and comfort. Branch return measurements are often summed to determine total system return flow. If the flow measurements are not accurate, it can cause technicians to fail to identify a problem or incorrectly assert that there is a problem when none exists. To address these issues, this study developed a test procedure based on the results of laboratory testing a range of flow hoods and return system configurations.

The effect of the resistance of the flow measurement device on the air flow through a grille is sometimes accounted for by a "K-factor". K-factors are published by manufacturers for some test equipment. However, K-factors are developed for a particular ratio of the air flow resistance of the hood to the rest of the duct system – such that the K-factor may work well for a particular grille or register in a particular system configuration. However, it cannot account for the range of possible impacts that depend on the flow hoods air flow resistance contribution to the overall air flow resistance of the system or the branch being tested, or the degree to which the air flow changes with air flow resistance that depends on the type of blower motor being used to move the air through the system. The contribution of the flow measurement device to the overall air flow resistance of the system or branch depends on duct sizing, the number of elbows and transitions and duct lengths, all of which are highly variable, indicating that a single K-factor is unlikely to be appropriate. In residential furnaces and air handlers there are two types of motors used in blowers: Permanent Split Capacity (PSC) and Brushless Permanent magnet (BPM). The PSC motor is more prevalent and it tends to have decreasing air flow with increasing air flow resistance of the system. BPM motors use controls that tend to maintain air flow through the system so they are expected to show less of the insertion loss effect and would require different K factors. More information on the relative performance of these two types of blowers can be found in previous reports.[4]

The effect of insertion losses can be overcome by powered flow hoods that incorporate a fan to nullify the air flow resistance of the measurement device. There are several commercially available devices that use this technique. Powered flow hoods have proven to also be successful in the measurement of supply air flows in which the non-uniformity of air entering the flow

[4] Walker, I. S. Improving Air Handler Efficiency in Houses. Paper presented at the ACEEE Summer Study 2004, Washington, DC. 2004, and Walker, I. S. Comparing Residential Furnace Blowers for Rating and Installed Performance. ASHRAE Transactions, 114, Pt. 1, 8. 2008

hood due to supply grille geometry is counteracted by the use of the fan coupled with high air flow resistance flow straighteners and measurement methods.[5]

Both powered and non-powered (or passive) methods are described in the current California Title 24 Standards[6]:

> RA3.3.3.1.3 System Airflow Rate Measurement Using Powered Flow Capture Hood
>
> The system airflow measurement shall be performed using the following procedures; all registers shall be fully open, and the air filter shall be installed. Turn on the system fan at the cooling speed and measure the airflow at the return grille(s) with a calibrated powered flow hood to determine the total system return airflow. Operation of the powered flow hood shall conform to the specifications in the manufacturer's product documentation. For multiple return systems, the total system return airflow (Qah, cfm) shall be the sum of the airflow measurements at each of the system's return grilles.
>
> RA3.3.3.1.4 System Airflow Rate Measurement Using Traditional Flow Capture Hood
>
> The system airflow measurement shall be performed using the following procedures; all registers shall be fully open, and the air filter shall be installed. Turn on the system fan at the cooling speed and measure the airflow at the return grille(s) with a calibrated traditional flow capture hood to determine the total system return airflow. For multiple return systems, the total system return airflow (Qah, cfm) shall be the sum of the airflow measurements at each of the system's return grilles.

1.1 Purpose of Study

This project was undertaken to address the concern that typical equipment used in the field by contractors may not be accurate enough for the purposes of measuring return flows for use in Title 24 applications. Because manufacturers' accuracy estimates for their equipment do not include many of the sources of error found in actual field measurements (and replicated in the laboratory testing in this study) there is a need for a test method that could be used to determine the actual uncertainty in this specific application. The goal of this project is to improve air flow measurements for residential forced air heating and cooling systems to ensure optimum system performance. This will result in better energy, Indoor Air Quality and comfort performance, and improved compliance with California Building Energy Standards. The range of air flow rates was chosen to be representative of what is likely to be found in single and

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[5] Walker, I. S., & Wray, C. P. Evaluation of Flow Capture Techniques for Measuring HVAC Grille Airflows. ASHRAE Transactions, 109, Pt. 2, 12. 2003 and Wray, C. P., Walker, I. S., & Sherman, M. H. Accuracy of flow hoods in residential applications. 2002.

[6] California Energy Commission. 2013 Reference Appendixes. The Building Energy Efficiency Standards for Residential and Non-Residential Buildings: California Energy Commission. 2012

multiple branch return duct systems. For individual branches the flows ranged from 90 to 1125 cfm. The total system flows (all branches combined) ranged from 500 to about 1400 cfm.

The study identified which methods of measuring the airflows at the return grilles of residential HVAC systems have acceptable accuracy. The level of accuracy that should be deemed acceptable depends on the purpose of the flow measurements. Previously, LBNL proposed minimum required accuracy for flow hoods for differing objectives that ranged from ±50% for identifying large leaks to ±3% for determining duct leakage, as summarized in Table 1 taken from previous work[7]. These accuracy levels were based on the impacts of the errors on the metric being evaluated and are based on simple uncertainty analyses and expert judgment. An individual authority, such as the Energy Commission may select different acceptability levels depending on the purpose of the measurement. The main concept behind the development of the American Society of Testing and Materials (ASTM) test method was that Title 24 (or other codes/standards entities) could specify the accuracy required for a given measurement and refer to the ASTM test method as the way to evaluate any given measurement device or technique.

Currently, there are no specifications for acceptable accuracy for the measurements in Title 24 or in other codes and standards. This is primarily due to a lack of evaluation data[8] and lack of a test method that could be used to rate different test equipment and methods. This study aims to address both these issues.

Table 1: Minimum Flow Hood Accuracy Requirement for Selected Diagnostic Applications

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

[7] Walker, I. S., & Wray, C. P. Evaluation of Flow Capture Techniques for Measuring HVAC Grille Airflows. ASHRAE Transactions, 109, Pt. 2, 12. 2003

[8] Previous LBNL studies referenced here focused on supply air flows rather than the return air flows in the current study. Energy codes and standards have not required the measurement of supply sir flows - so accuracy issues have not been addressed for that application. The requirements in Title 24 for total system air flows that use measurements at return grilles mean that the issue of measurement accuracy needs to be addressed.

This study assessed the performance of several methods for measuring these air flows by comparing to reference flow meters in a controlled laboratory setting. The results may be used directly to inform potential changes to Title 24. This study also developed a draft ASTM test method that describes how to test flow hoods over a wide range of air flow conditions. This test method could be referenced in the future in Title 24, together with specified accuracy limits, to allow the selection or specification of measurement methods based on performance rather than limiting by individual technique or type of measurement device.

CHAPTER 2: Methodology

The laboratory test method used to evaluate the flow hoods was based on comparing the measurements from the flowhoods to a reference measurement. To best represent a realistic flow rate and air flow pattern, the tests were performed on a full-scale return duct system. The full scale duct system was designed to allow flexibility on the number of return grilles in use so that single and multiple return duct branch effects could be examined. The tests were performed under controlled conditions in the Duct Test Laboratory at LBNL in Berkeley California.

2.1 Devices and Methods Evaluated

A sample of powered and non-powered flow hoods were selected to be evaluated for this study. The flow hoods differ by the way the flow is captured and how the air flow through the device is measured. The flow is captured by directing all the flow through the grille into the flow measuring element of the device. Some measurement methods use large fabric hoods; others use rigid plastic or cardboard. These capturing elements are of varying sizes that rarely match the dimensions of a return grille. If the capture element fully covers the grille and has a good seal around it then we can assume that it captures all the desired air flow. If the grille is larger then there are several potential approaches for capturing the flow. The uncovered portion of the grille may be masked - usually using masking tape or some other seal. Another technique is to measure different parts of the grille and sum the samples to obtain the total air flow. Since the laboratory testing was performed for this study additional powered devices have come to the US market from Europe. These devices arrived after testing began and were too late to be included in our testing, but could be evaluated using the ASTM test procedure.

2.1.1 Description of evaluated Devices

For all the tested devices, the manufacturer's operating instructions were followed. The only exception to this is the testo 417 device. The testo 417 manual's instructions on how to perform a single-point averaged velocity measurement were supplemented by instructions for a multi-point average velocity measurement provided by a Testo representative and are included as Appendix A.

TSI/Alnor® Analog Balancing Tool (ABT) Balometer® (ABT701). The ABT701 is a non-powered flow hood with a standard 24 in. x 24 in. opening hood (other opening sizes are available). The flow is indicated on an analog scale. The flow is measured using a hot-film sensor. The manufacturer's specifications are ±3% accuracy at full scale of the selected range +5 cfm. It has three ranges: 30-250 cfm; 200-500 cfm; 400-1000 cfm[9].

[9] TSI/Alnor. Analog Balancing Tool Owner's Manual. In TSI/Alnor (Ed.). Shoreview, MN

Figure 1: The six flow hoods used in this study

Clockwise from top left they are: TSI/Alnor ABT701, TSI/Alnor EBT721, testo417 (shown with optional capture funnel – not used in our testing), TEC FlowBlaster, Cardboard + Fan/flowmeter, and LBNL Hybrid (uses the capture element from a traditional hood and a fan/flowmeter).

Photo Credit: TSI/Alnor hoods: TSI/Alnor, Testo417: Testo, TEC FlowBlaster: TEC, Cardboard and LBNL Hybrid: LBNL.

TSI/Alnor® Electronic Balancing Tools (EBT) (EBT721). The EBT721 is similar to the ABT701. The differences are that the air flow is measured using a pressure array rather than a hot-film sensor and the flow is indicated on a digital scale that auto-ranges. The manufacturer's specifications are for an accuracy of ±3% of reading ±7 cfm. Its measurement range is 25-2500 cfm. It has been discontinued and in 2013 was replaced by the EBT731.[10]

Testo417. The testo 417 is a 4-inch diameter vane anemometer that provides velocity measurements and can calculate volumetric airflow measurements if the grille open area is entered. Its rated measurement range is 0.3 – 20 feet per minute [11]

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[10] TSI/Alnor. Electronic Balancing Tool Owner's Manual. In TSI/Alnor (Ed.). Shoreview, MN

[11] Testo. Testo 417 Vane Anemometer Instruction Manual. Lenzkirch, Germany.

FlowBlaster (TECFB). The Energy Conservatory FlowBlaster® is an accessory kit for the company's Duct Blaster® fan. The FlowBlaster® kit combines with the Duct Blaster® and a manometer to create a powered flow hood that automatically compensates for its own added air flow resistance. Its rated accuracy is ±5% of indicated flow or ±2 cfm, whichever is greater. It has two flow ranges: 10-120 cfm (ring 3); 80-300 cfm (ring 2) [12]

Cardboard + Fan/Flowmeter (CFF). A common method of testing duct system leakage of forced air systems is to fabricate a seal to cover a return grille and then use a flange to attach a calibrated fan/flowmeter device directly or via a 10-inch diameter flex duct. This method can also be used to measure the flow at a return grille. This powered flow hood approach controls the fan to remove the influence of the flow meter (and, any other restriction imposed by the measurement - such as covering part of the grille) by adjusting the fan to have zero pressure difference between the grille and the room. To measure this pressure difference, a small incision was made on one edge of the cardboard and a pressure probe was inserted that was open to the gap between the cardboard and the grille. The fan/flowmeter used in this study was an Energy Conservatory Duct Blaster that has the following performance specifications: Accuracy of +/- 3% of flow or 1 cfm, whichever is greater (using the DG-700 digital gauge), rated flow range: 10 – 1500 cfm. It should be noted that the Energy Conservatory warns about using the Duct Blaster at the grilles of multi-return systems[13] because of the known issues with changes in individual branch air flow resistance.

LBNL Hybrid. This device combines a 24 in. x 24in. cloth flow capture hood similar to those of the TSI/Alnor devices with a calibrated fan/flowmeter. They are connected by 10" diameter flex duct for ease of use. The LBNL Hybrid has a soaker hose inside the capture hood to obtain an average pressure near the grille that is used to control the fan to zero the pressure difference between the soaker hose and the room. The apparatus is mounted on a wheeled cart to minimize duct bends and to improve its mobility. In previous studies its accuracy compared to reference airflow was ±3% when measuring single branch flows[14].

2.2 Test Apparatus

2.2.1 Apparatus Design

The test apparatus was designed to emulate a residential multi-branch return system. The inlet side of a furnace air handler cabinet was attached to a 16-inch diameter rigid duct via a two-foot long section of duct. The furnace is a Carrier model 58CVA/58CVX and has the capability to be operated with either a PSC or BPM blower. No gas was connected to the furnace but the furnace heat exchanger was retained on the supply side of the blower. The plenum was then connected

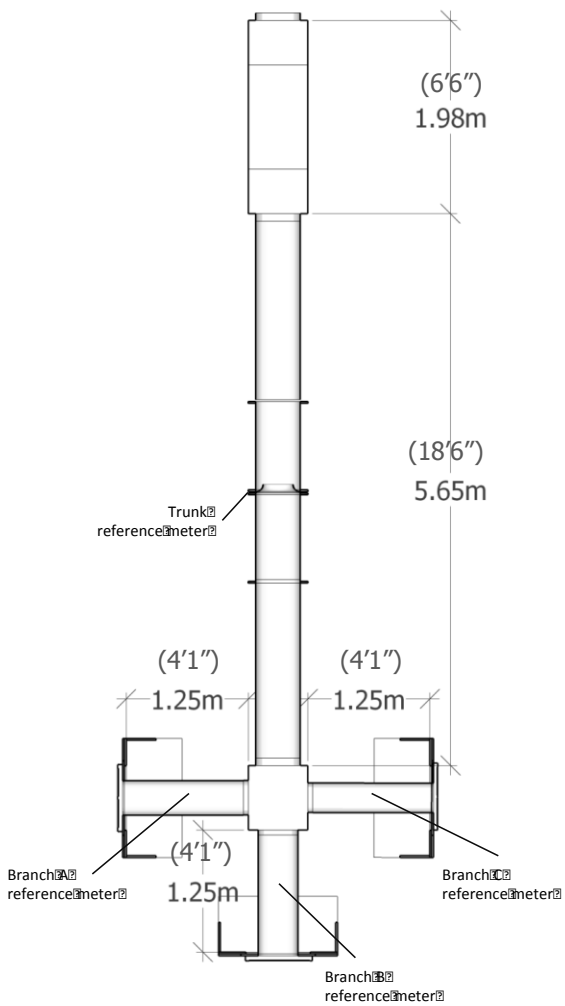
[12] The Energy Conservatory. FlowBlaster® Operation Manual Attachment for the Minneapolis Duct Blaster® Fan and DG-700 Pressure and Flow Gauge Minneapolis, MN. 2012.

[13] http://energyconservatory.com/wp-content/uploads/2014/07/FlowBlaster-Manual.pdf

[14] Wray, C. P., Walker, I. S., & Sherman, M. H. Accuracy of flow hoods in residential applications. 2002

to a nozzle pitot array airflow meter (Thermo Electron Corporation NZP 1000[15]) shown in Figure 2. This differential pressure airflow meter has an upstream and downstream run of 4 diameters, (64 inches) and a rated accuracy of ±0.5% of flow. Its recommended velocity range is 175-6000 feet per minute. There is a flow straightener in the upstream run of the inline airflow meter to minimize turbulence effects and improve the accuracy of the air flow measurements. This flowmeter records the total system air flow and is referred to as the trunk reference flow meter.

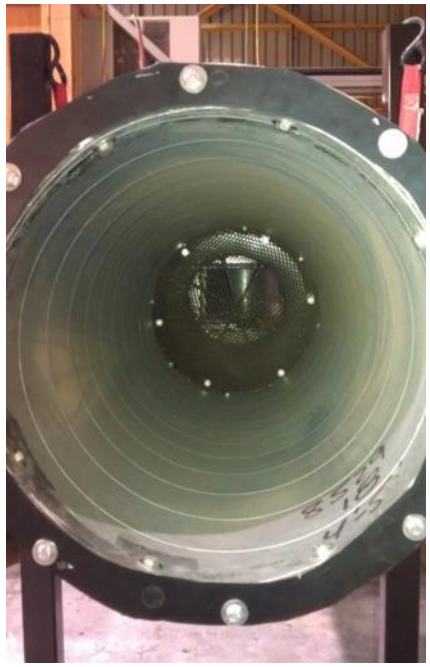
Figure 2: Plan view of apparatus trunk and branches



Location of fan, return terminals, and branch and trunk reference flow meters.
Image Credit: LBNL.

[15] http://www.thermo.com.cn/resources/200802/productpdf_29339.pdf

Figure 3: View inside the main trunk flow meter



Honeycomb-shaped flow straightener shown upstream of flow meter

Photo Credit: LBNL.

Table 2: Test apparatus and grille dimensions

Branch	Diameter (in.)	Pan Depth (in.)	Grille Dimensions (in. x in.)
A	16	4	24x24
B	16	4	20x20
C	14	4	14x24

Upstream of the inline reference airflow meter is a plenum that splits into three branches. Each of the three branches has an iris damper that both controls the flow and serves as the reference airflow meter for that branch. Upstream of the iris damper is a run of rigid duct equal to 2 diameters (32 inches). The three branch reference meters were 16-inch Fantech iris dampers having a rated flow measurement accuracy of ±5%[16]. Upstream of the rigid duct is flex duct that connects each of the branches to an inlet terminal. The branch duct diameters and grille sizes were chosen to give a range of air flows and grille sizes to challenge the flowhoods over a wide range of flows and dimensions similar to those found in new California homes.

[16] http://www.fantech.net/Documentation/Air%20Distribution%20Products/411736%20IR%20Series.pdf

Figure 4: Grille inlets for each branch of the test apparatus

Grille A 24x24in | Grille B 20x20in | Grille C 14x24in

Grille A is taped off to be measured by TECFB. Grille B configured to be measured by CFF. The taping around grille C is for air sealing between the grill perimeter and the mounting plane.

Photo Credit: LBNL.

2.2.2 Apparatus Assembly and Calibration

Figure 5: Multi-branch return flow experimental apparatus

Main trunk on bottom right connecting to central plenum (center), which radiates to the three branches.

Photo Credit: LBNL.

Inlet air temperature, ambient temperature, relative humidity, static duct pressure, and barometric pressure were all monitored during the testing period.

2.3 Test Procedure

The reference airflow is used to determine the accuracy of each flow hood. The reference airflow meter in the main trunk of the system provides a reference total airflow, and the three iris damper orifice flow meters provide reference airflows for each branch inlet.

There are two sources of measurement errors: the direct errors in measuring the flow through the flowhood and indirect errors due to the air flow resistance of the flowhood changing the flow to be measured. To disaggregate these errors, the reference system flows were recorded with and without the flowhood present. The change in system airflows when the flowhood is placed over the grille gives an indication of how the flow hood measurement is affecting the system's airflows and is referred to as the insertion loss. The fundamental normal operating condition error compares the indicated flow from the flowhood to the reference system flow without the flowhood present. This is the error presented here in the body of the report. Appendixes B and C present the results comparing indicated flow from the flow hood to the flow through the system with the flow hood in place that do not include these insertion loss effects.

The accuracy of devices was evaluated in two ways:

1. Individual branch measurements: by comparing the device measurement of the branch flow to the reference branch flow.
2. Total air handler airflow: by summing the device branch measurements to get total system flow and then comparing that total flow measurement to the trunk reference flow.

Tests were performed for:

- six apparatus air flow configurations: single branch, two branches (with two different flow ratios between the branches, or three branches (with three different flow ratios)[17], and
- two motor types; PSC and BPM, and
- two motor speeds (high/low)

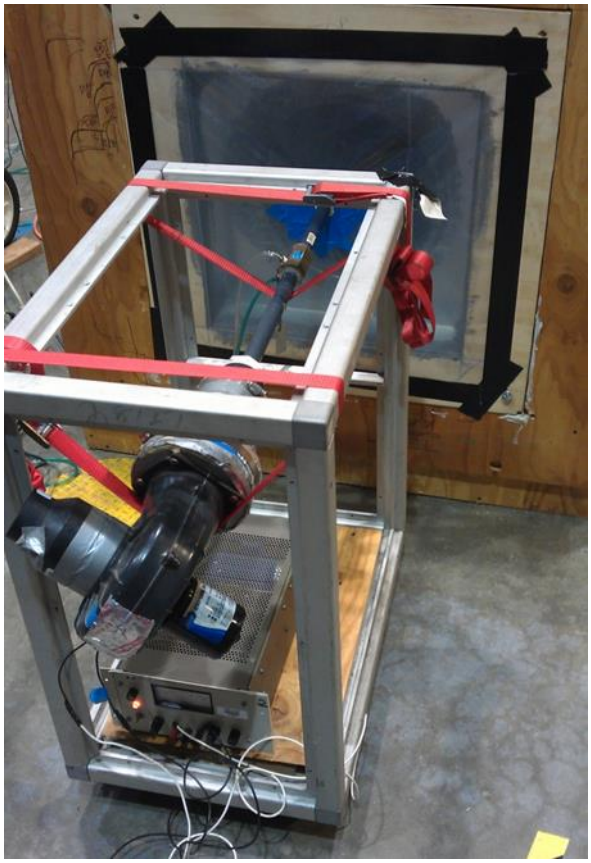
2.3.1 Testing for Apparatus Leakage

Test apparatus leakage is important because any leakage between the flow hood being tested and the reference flow meters is not accounted for in the measurements. For these return flows, the leakage would generally be into the system. This would lead to systematically higher reference flows than flow hood flows. Ideally, the test apparatus would have no leakage, and great lengths were taken to seal the apparatus. These efforts included applying mastic to all the seams and connections, re-testing for leakage flow rate, identifying remaining leaks and sealing them, and repeating the process. The most effective method of leak detection was simply feeling for leaks using our hands. Even after all this air sealing a small amount of leakage remained,

[17] The air flows in each branch for each of the configurations are summarized in Table 3.

and in order to estimate its impact on the test results we measured this leakage. Apparatus leakage was measured by capping the trunk downstream of the trunk reference meter and capping the return grilles of branches A and C.

Figure 6: Pressurizing duct system at grille B to measure system leakage



Terminals A and C as well as the main trunk were sealed and the system was pressurized to levels present during testing.

Photo Credit: LBNL.

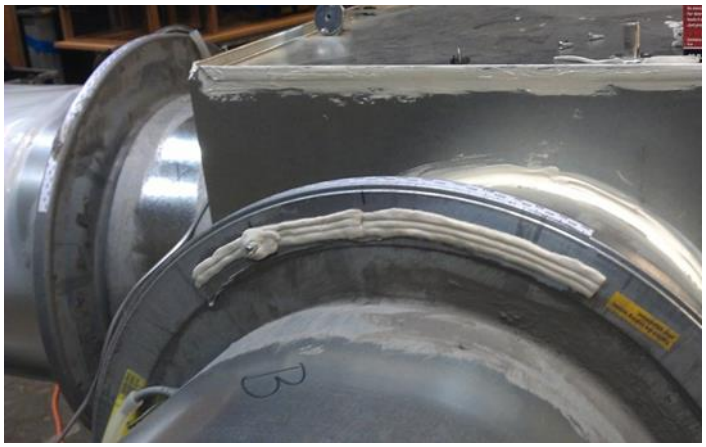
The system was pressurized by attaching a calibrated Venturi flow meter (uncertainty of ±3%, as determined previously using tracer gas methods (Stratton, Turner, Wray, & Walker, 2012)) to branch B. The system leakage for the maximum operating pressure (95.6 Pascals) was 0.77%. A pressure and flow curve was developed for the leakage flow so that we could convert the system static pressures measured during testing into an apparatus air leakage. This pressure and flow curve (details are given in Appendix F) was used to correct reference airflow measurements for system leakage for every measurement. In all cases the leakage correction was less than 1% of flow.

2.3.2 Calibrating Iris Damper Flows

The iris dampers have a rated accuracy of ±5%, however, the test apparatus did not meet the manufacturer's recommended downstream conditions for the iris damper orifice flow calculation, and the airflow measurements generated using the formula provided by the iris

damper manufacturer were inconsistent (a summary of the errors is presented in Appendix E). Therefore, we developed our own calibrations. The flows for each branch reference meter were determined by capping off the other two branches. The iris pressure difference and flow through the trunk reference meter were recorded for a range of flows and pressures and corrected for system leakage. A calibration was developed by least squares fitting to a power law pressure-flow relationship. This relationship for each iris damper (and damper setting) was used together with the iris pressure difference for each test point to determine the flow in each branch of the apparatus. At each test point, the sliding knob that controls the iris aperture was locked into place and the slot it slides in was sealed with rope caulk during the test measurements to minimize leakage.

Figure 7: Detail of system air-sealing measures



Mastic was used to seal duct seams and rope caulking used to seal branch iris damper control slot.
Photo Credit: LBNL.

2.4 Measurement Corrections

Airflow measurements taken with devices that assume standard air density were converted to actual flow per manufacturers' instructions. The reference flows were also corrected for air density following manufacturer's instructions.

2.4.1 Air Density Corrections

All measurements contained in this report are volumetric flows at the measurement conditions of temperature and barometric pressure. Indicated flows that assumed standard air density conditions were converted to actual volumetric flow per manufacturers' instructions using barometric pressure and temperature measurements taken during the test period. These corrections were typically less than 0.5% of the reference flow.

2.4.2 System Leakage Corrections

One half of the leakage was presumed to be in the section of the apparatus downstream of the branch reference meters and before the trunk reference meter. The other half of the leakage was presumed to be distributed equally between the three branches upstream of the branch

reference meter and before the terminal. These leakage corrections ranged from 0.2 – 1.0% of the measured flow.

2.4.3 Other Test Apparatus Uncertainties

The experimental uncertainties for the reference flow meters and related temperature and pressure measurement devices are based on manufacturers' literature.

The rated uncertainty for the meter used for the trunk reference is ±0.5% for the range of flows we tested. The branch reference meters were calibrated for each setting by calculating a linear-fit coefficient to convert the square root of the branch pressure differential to the flow measured by the trunk reference meter, as described above. The uncertainty of each branch measurement was determined by calculating a single variable 95% confidence interval for the measurement as a percentage of the reference flow and adding that number in quadrature to the rated uncertainty of the trunk reference meter. The median of the system uncertainties for each of the reference branch flow measurements was ±0.7% of reading.

2.5 Steb-by-Step Test Procedure

Each test followed the same procedure outlined in the following steps:

1. For each of the six air flow/branch configurations the following steps were performed
2. Adjust branch iris dampers to achieve the desired flows in each branch.
3. Configure the air handler to use motor type 1.
4. Set the air handler to low speed.
5. For each device being tested, measure the flow at each branch return grille.
6. Set the air handler to high speed.
7. Repeat step 5.
8. Configure the air handler to use motor type 2.
9. Repeat steps 4-7.

2.5.1 Test Procedure for Each Device

ABT701

The flow hood performs and auto-zeros every time it is turned on and all measurements were made after the auto-zero was complete. The ABT701 was placed over the inlet grille, taking care that all sections of the rubber seal around the frame's perimeter were in contact with the surface surrounding the inlet grille. This ensured a good seal and channeled the flow through the device. We stood to one side of the ABT701 so as not to obstruct the inlet and potentially make the flow less uniform entering the device.

The needle indicating the flow rate was observed for at least 10 seconds and the observed flow was recorded. Care was required to avoid parallax error (the effect of viewing angle shifting the

location of observed airflow on the scale behind the indicating needle) when interpreting the needle's reading. Reading this analog device requires making a judgment call as to the median location of the needle during the testing period. The movement of the needle and the need to interpret its location can make the ABT701 difficult to read in some field conditions.

A practiced technician can assemble or disassemble the ABT701 in about 3 minutes. Each measurement takes about 20 seconds.

EBT721

The ABT721 was placed over the inlet grille, taking care that all sections of the rubber seal around the frame's perimeter were in contact with the surface surrounding the inlet grille. This ensured a good seal and channeled the flow through the device. During testing, technicians stood to one side of the ABT721 so as not to obstruct the inlet and potentially make the flow less uniform entering the device. The flow was determined by pressing the READ button on the EBT721 user interface and the measurement read from the digital display.

A practiced technician can assemble or disassemble the EBT721 in about 3 minutes. Each measurement takes about 10 seconds.

testo 417

For this application, the testo 417 vane anemometer was used without any funnel attachments. The control interface on the testo417 was used to verify that the units for the measurement read "fpm", meaning velocity measured in feet per minute. To begin the measurements, the anemometer was held perpendicular to – and at the corner of -- the face of the inlet grille about 1 inch away (see APPENDIX A). Once the velocity measurement was stabilized, the "Mean" button was pressed twice so that the display showed "00:00" at top and the velocity measurement in fpm at bottom. The timer was started by pressing the Hold Max/Min button and the device was slowly and smoothly swept device back and forth, "painting" the face of the inlet grille to survey the velocities across all parts of the grille while keeping the anemometer perpendicular to the grille face. The speed of the sweeping motion was adjusted by trial and error such that sampling the entire grille was completed just as the timer reads "00:20" (indicating that 20 seconds have elapsed). At this point the Hold Max/Min button was pressed again to end the sampling period. The "Mean" button was pressed resulting in a clock icon along with the word "Mean" to flash at the top of the display. The bottom of the display showed the average velocity during the test period, measured in fpm.

To convert velocity into volumetric flow, the velocity was multiplied by the open area of the grille (in square feet). The open area of the grille is equal to the total open area minus the area blocked by the fins and structural members. The open grille area is sometimes expressed as the total area multiplied by a "grille factor" which indicates the fractional percentage of the total area which is open. According to the instructions provided by testo (see APPENDIX A), multiplying the velocity measurement (feet per minute) by the grille open area (square feet) will give the volumetric flow in cubic feet per minute. The grille area and grille factor can be entered into the testo417 and it will convert velocity measurement to volumetric flow.

The testo 417 manual explains the process of correcting for grille factor, and the circumstances under which this correction should be done (p 26):

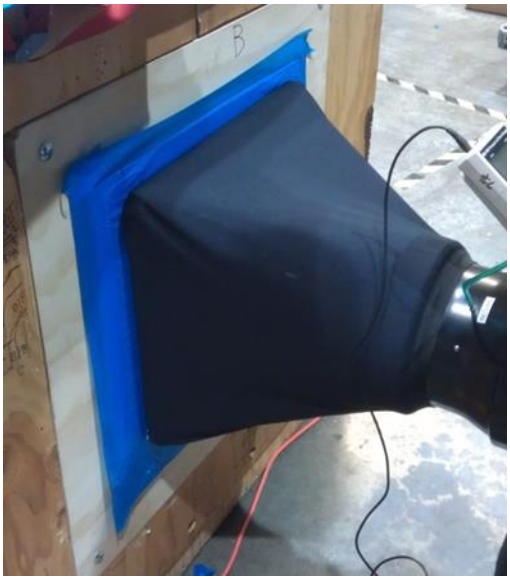
> If parts of the cross-sectional area are covered (e.g., by grill members), this can be corrected via the grill factor. The grill factor indicates the proportion of free space on the cross-sectional area. Example: if 20% of the area is covered, the grill factor must be set to 0.8 (80% free space).

The problem with applying a grille factor is that there is almost always no easy way to know what the grille factor is for a particular grille. For our measurements, a grille factor of 1.0 was applied, as specified for return measurement flows in instructions provided by a representative from testo (See APPENDIX A). Configuring the testo 417 takes about a minute. Each measurement also takes about a minute.

TECFlowBlaster (TECFB)

The FlowBlaster kit was added to the TEC Duct Blaster fan and the TEC DG700 manometer was configured to automate the zero-pressure-compensated flow measurement. The FlowBlaster hood was unable to completely surround the inlet grille so perimeter sections of the grille (keeping the open area in the center) were covered with tape until the hood covered the open area. The process of taping the grille took 10 minutes.

Figure 8: TECFB measuring airflow at a tape-masked grille opening



The perimeter of this duct was masked with tape to a 20-inch square opening to allow the TEC FlowBlaster to capture the return flow.

Photo Credit: LBNL.

With the hood over the grille pushing the BEGIN button on the DG700 started the automated flow measurement. When channel A of the DG700 indicated that the pressure difference between inside and outside the hood was within 0.3 Pa of zero and the flow measurement indicated on channel B was stabilized, the flow (in cfm) was recorded.

An experienced technician can assemble and configure the TEC FlowBlaster in about 10 minutes. Each measurement takes about a minute.

CFF

An extension to the standard TEC Duct Blaster flange was built using a flat piece of cardboard that extended 2-5 inches beyond each edge of the return grille. The flange was connected to the TEC Duct Blaster either directly or via a short length of ducting (less than 5 feet).

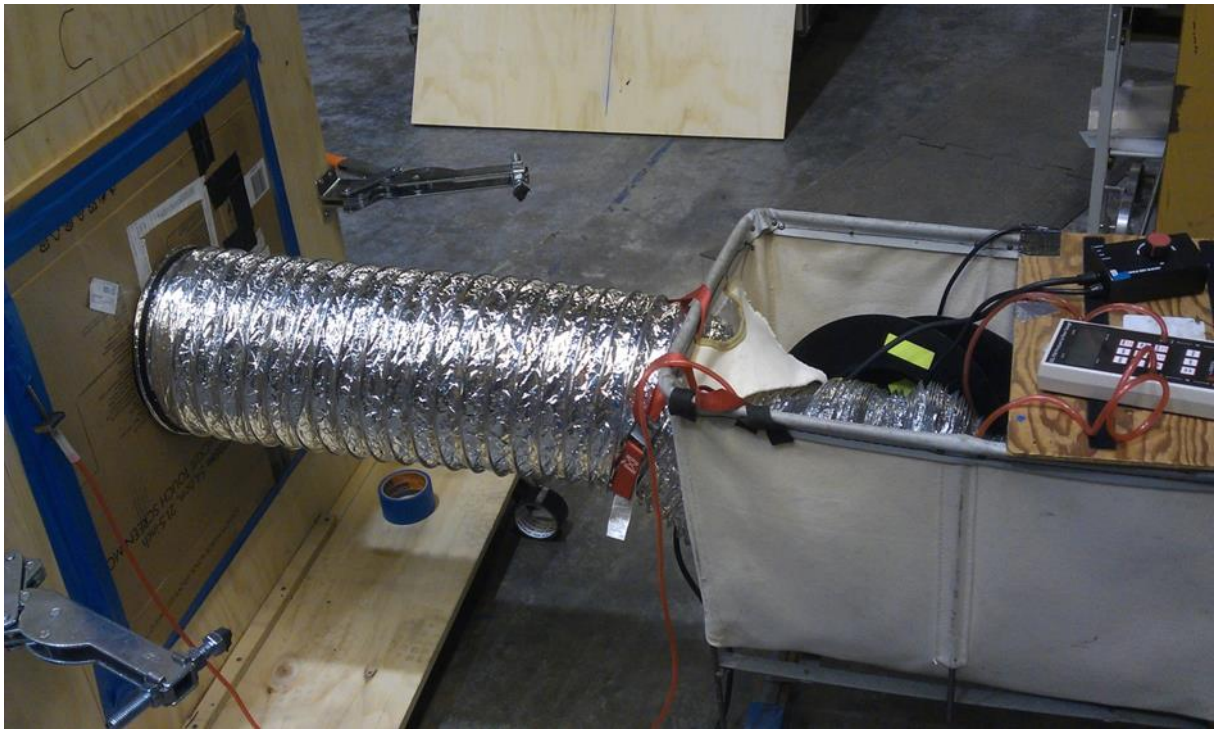
The pressure at the grille was measured using a piece of flexible tubing that was inserted through the cardboard flange and the pressure difference between the room and behind the flange was measured using a DG700 manometer. The TEC Duct Blaster was adjusted until there was zero pressure difference between the room and the grille. The resulting flow through the TEC Duct Blaster was recorded.

If a duct is used to connect the cardboard to the calibrated fan, the duct should be straight and taut. There should be no obstructions impeding the flow through the calibrated fan.

Zeroing out the pressure difference can be done manually or automated. Some manufactures' supply equipment can automatically adjust the fan to maintain zero pressure difference.[18]

Figure 9: CFF measurement device

[18] Refer to chapter 10 of DucTester manual (available at retrotec.com) for instructions on using the Retrotec DucTester to measure flows. Refer to chapter 13 of TEC Duct Blaster manual (available at www.energyconservatory.com) for procedures for using the Duct Blaster to measure flows.



Cardboard was used to ensure that the airflow entering the grille was captured by the fan/flowmeter in card on the right. Notice that the grille is completely covered and the zero pressure tap is inserted on the left side of the cardboard.

Photo Credit: LBNL

LBNL Hybrid

The process for measuring flows with the LBNL Hybrid[19] flow hood was similar to that for the CFF, except that a hood was used to capture the flow and that hood has a built-in pressure tap for zeroing out the pressure.

[19] Earlier reports referred to this device as "EPB".

CHAPTER 3:
Results

The test apparatus was configured in several ways to capture a wide range of flow conditions and branch configurations. Table 3 summarizes all the test configuration flows and system static pressure differences for different motors, through different combinations of branches A, B and C. The fractional branch flow is the target ratio of flow through the branches. So the 1,2, 3 case indicates that branch B has twice the flow of branch A and branch C has three times the flow of branch A. A zero indicates no flow through that branch. Table 4 summarizes the changes in system airflow (insertion effect) due to flow resistance of the measurement devices.

3.1 Individual Branch Flow Measurements

Figures 10 -15 show the accuracy of the individual measurements made at each branch by each of the six devices under test. Each point is coded by color to indicate the motor type (Brushless Permanent Magnet (BPM) – green, Permanent Split Capacitor (PSC) – blue) and by shape to indicate the ratio of the distribution of flow across the branches. Thus "BPM 1_2_3" means brushless permanent magnet motor with roughly 1/6 of the flow going through branch A, 1/3 of the flow going through branch B, and 1/2 of the flow going through branch C.

Because of a variety of factors, there are not an equal number of measurements for all devices. For example, there are only twelve measurements with the TECFB, because it is not rated to measure flows greater than 300 cfm.

The area within ±10% of the reference flow is shaded, and error bars reflect the estimated uncertainty within one standard deviation of the reference flow.

Table 3: Summary of flows and pressures for all flow configurations

Motor	Speed	Branch/Ratio	A/1	B/2	C/3
		Pressure (Pa)			
BPM	Lo	-14.1	91	172	276
	Hi	-89.5	233	445	703
PSC	Lo	-51	170	326	510
	Hi	-94.1	233	447	714
		Branch/Ratio	A/1	B/1	C/2
		Pressure (Pa)			
BPM	Lo	-13.4	129	129	263
	Hi	-86.4	333	333	666
PSC	Lo	-49.8	253	252	501
	Hi	-92.9	347	345	685
		Branch/Ratio	A/1	B/1	C/1
		Pressure (Pa)			
BPM	Lo	-14.1	174	172	174
	Hi	-89.1	450	443	445
PSC	Lo	-50.6	337	333	334
	Hi	-94.7	465	458	459
		Branch/Ratio	A/0	B/1	C/1
		Pressure (Pa)			

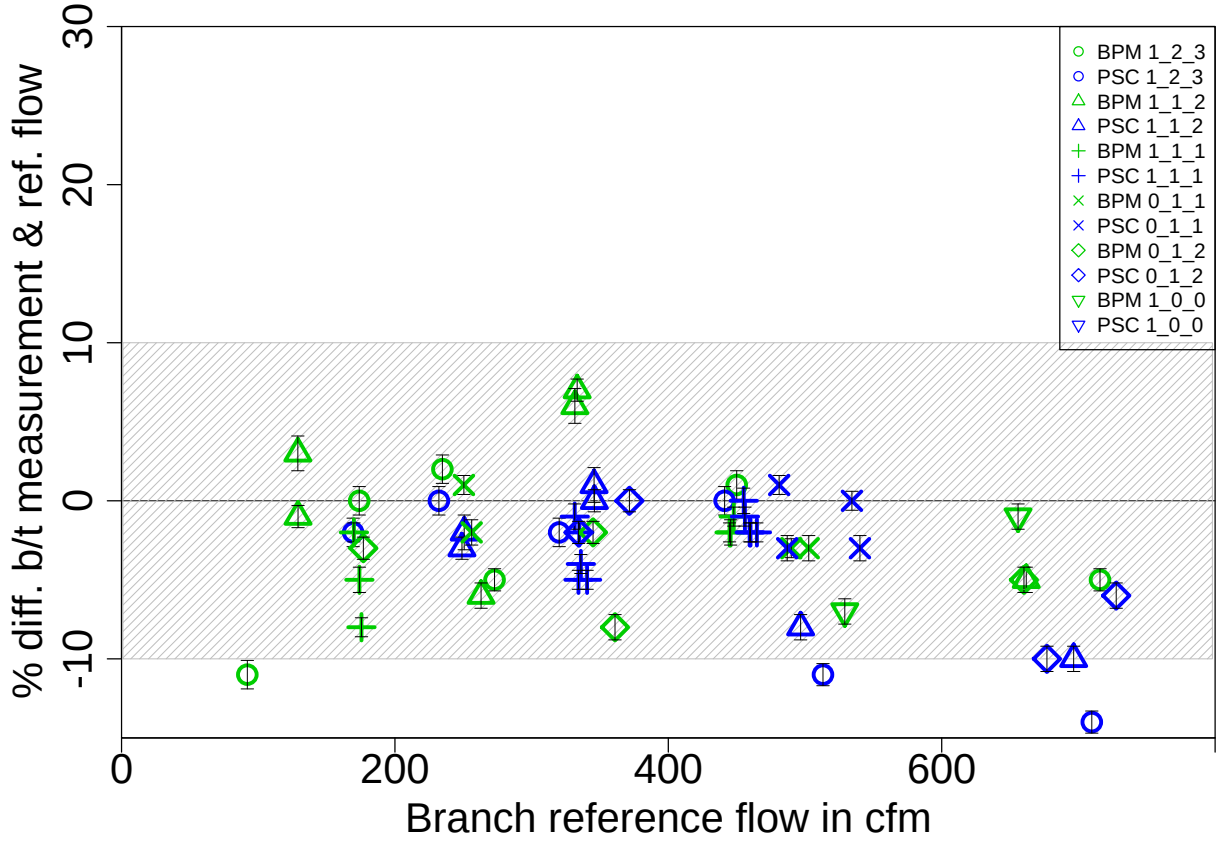
BPM	Lo	-20.4		250	256
	Hi	-76.2		486	502
PSC	Lo	-73.3		478	487
	Hi	-92.2		536	548
		Branch/Ratio	A/0	B/1	C/2
		Pressure (Pa)			
BPM	Lo	-18.5		177	349
	Hi	-59.5		322	639
PSC	Lo	-64.3		316	667
	Hi	-80.4		351	752
		Branch/Ratio	A/1	B/0	C/0
		Pressure (Pa)			
BPM	Lo	-17.1	531		
	Hi	-28.1	683		
PSC	Lo	-59.7	1010		
	Hi	-76.4	1125		

Source: LBNL.

Table 4: Insertion effect caused by each flow measurement device

Percent difference between branch airflow with and without device in place		
	Mean %	RMS %
ABT701 (n=54)	-5.1	6.0
CFF (n=55)	-0.9	6.5
EBT721 (n=56)	-1.8	2.5
LBNL Hybrid (n=55)	-1.9	5.2
TECFB (n=38)	11.3	16.2
Testo 417 (n=56)	0.0	1.7

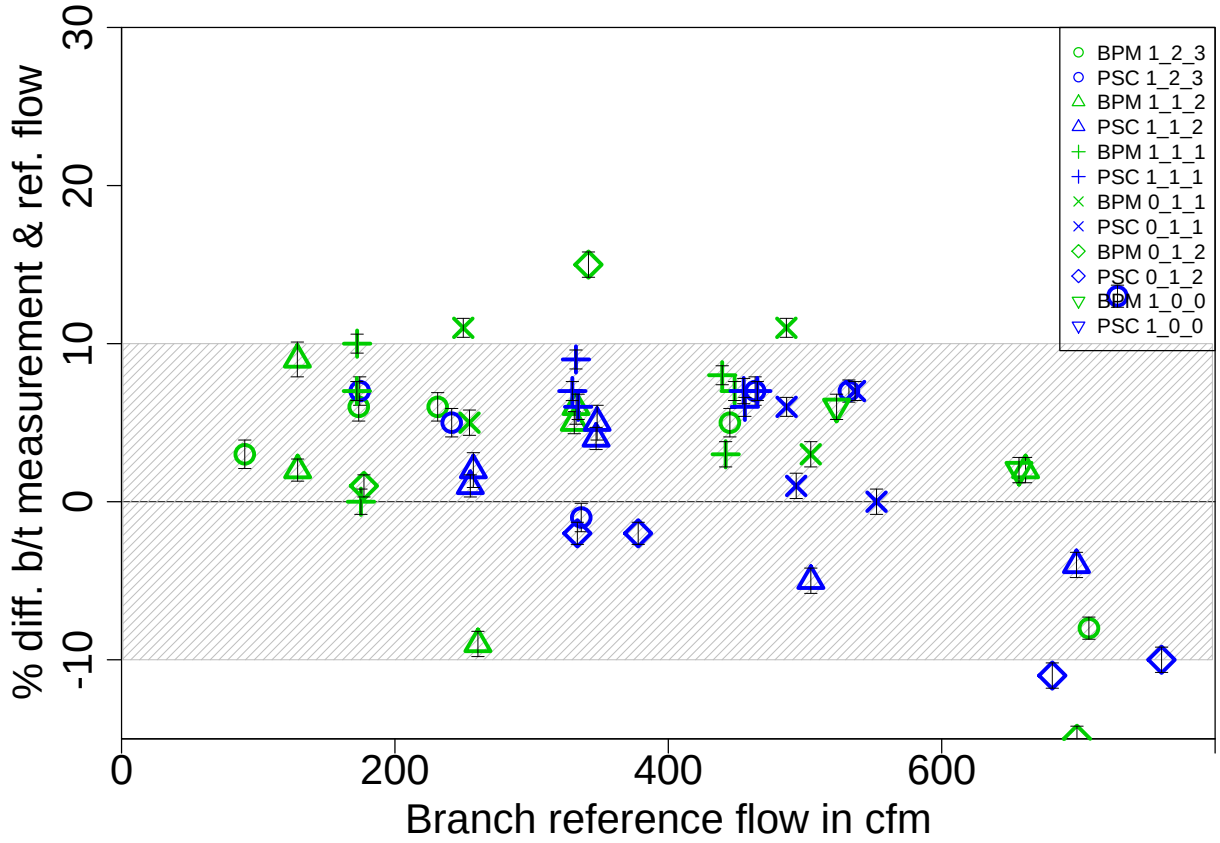
Figure 10: ABT701 percent difference of individual branch measurements



Device-indicated flows are compared to reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL

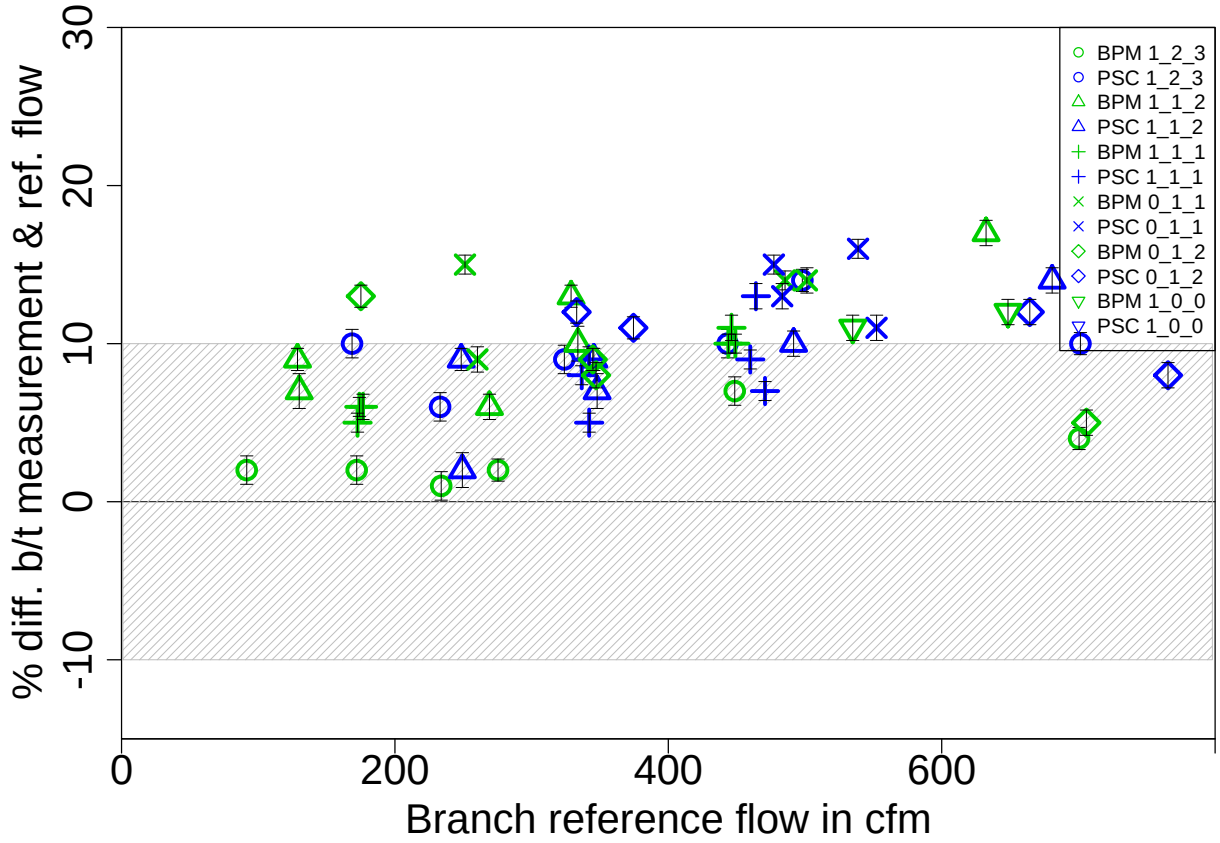
Figure 11: CFF percent difference of individual branch measurements



Device-measured flows are compared to reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

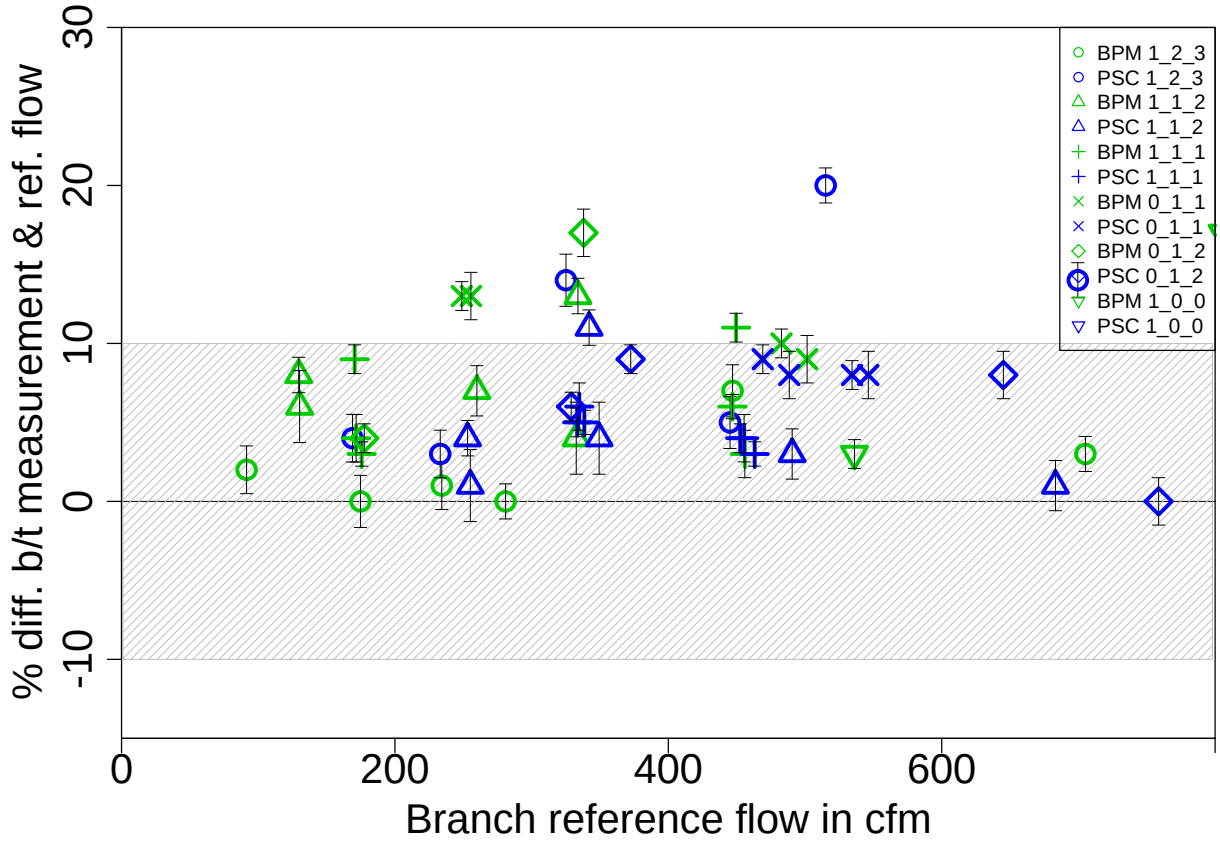
Figure 12: EBT721 percent difference of individual branch measurements



Device-indicated flows are compared to reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

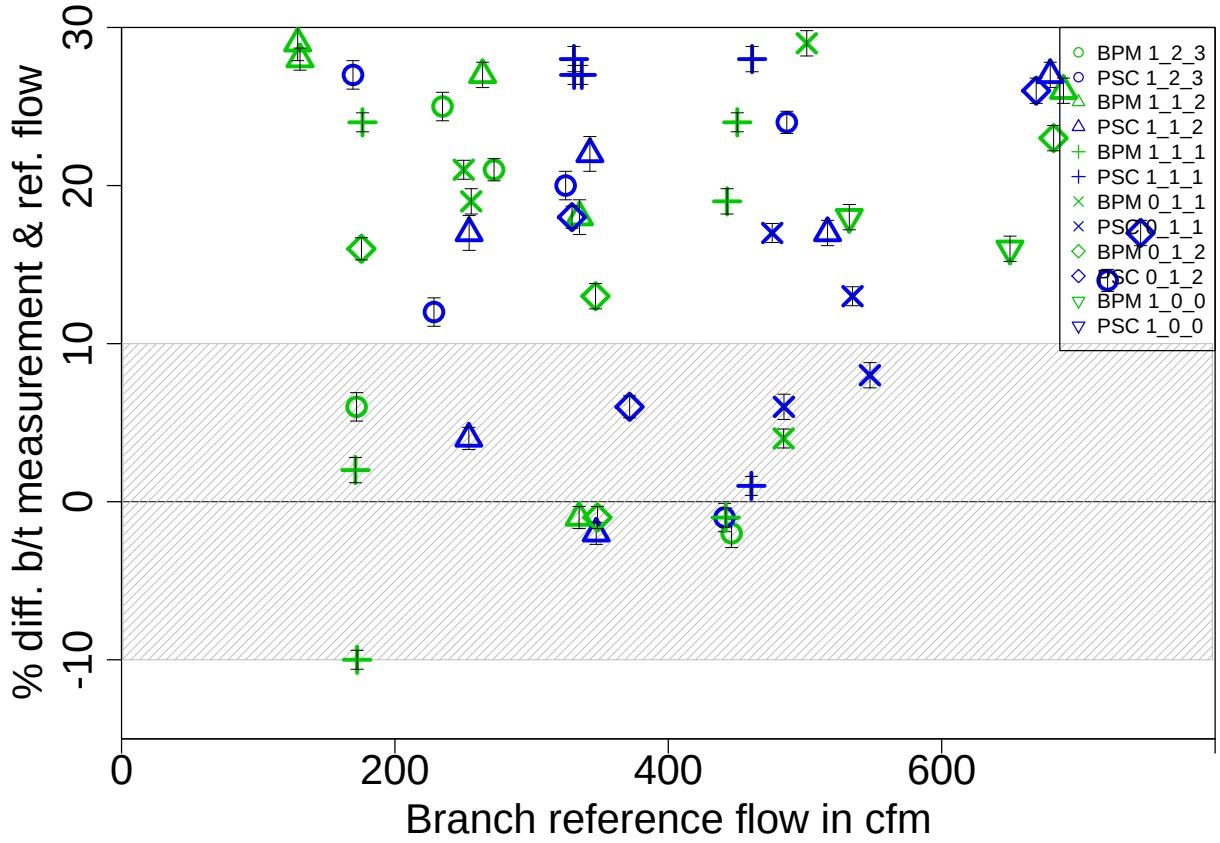
Figure 13: LBNL Hybrid percent difference of individual branch measurements



Device-indicated flows are compared to reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

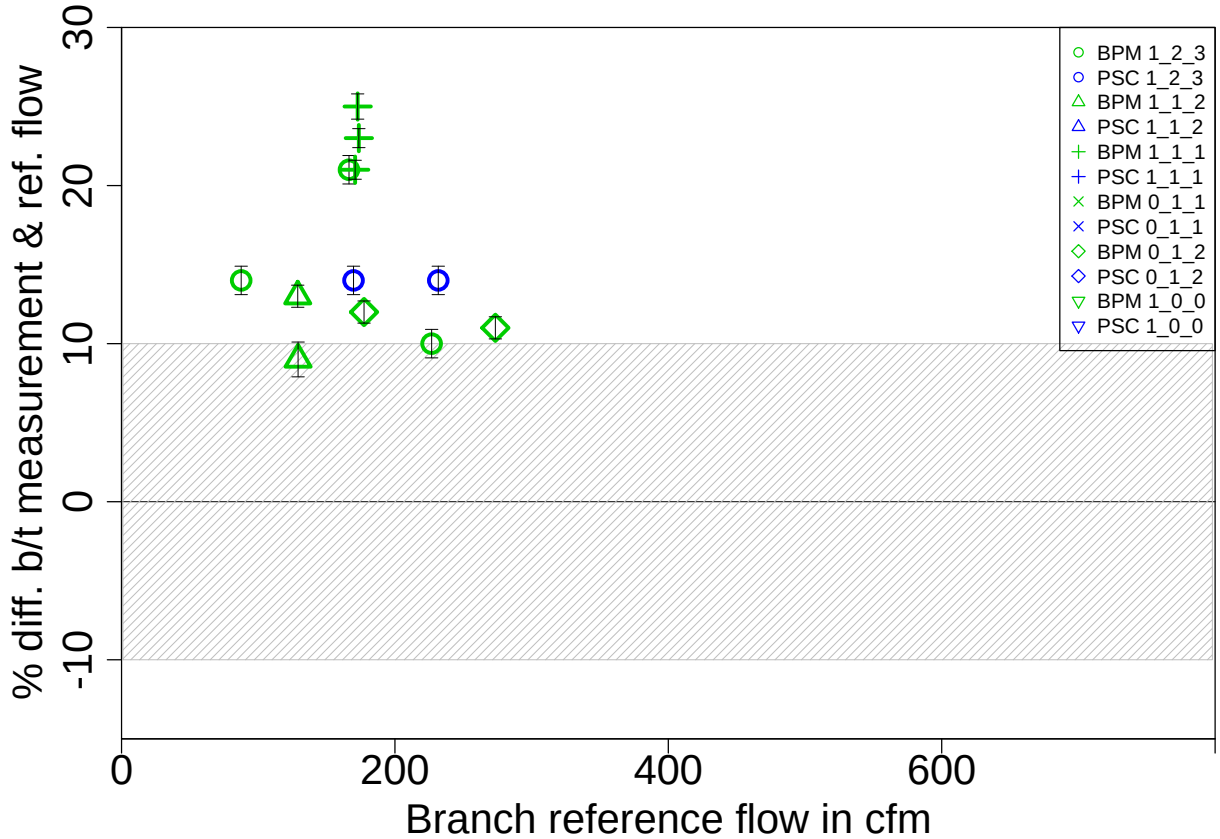
Figure 14: testo 417 percent difference of individual branch measurements



Device-indicated flows are compared to reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

Figure 15: TECFB percent difference of individual branch measurements



Device-indicated flows are compared to reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars. The upper measurement limit of the TECFB is 300 cfm.

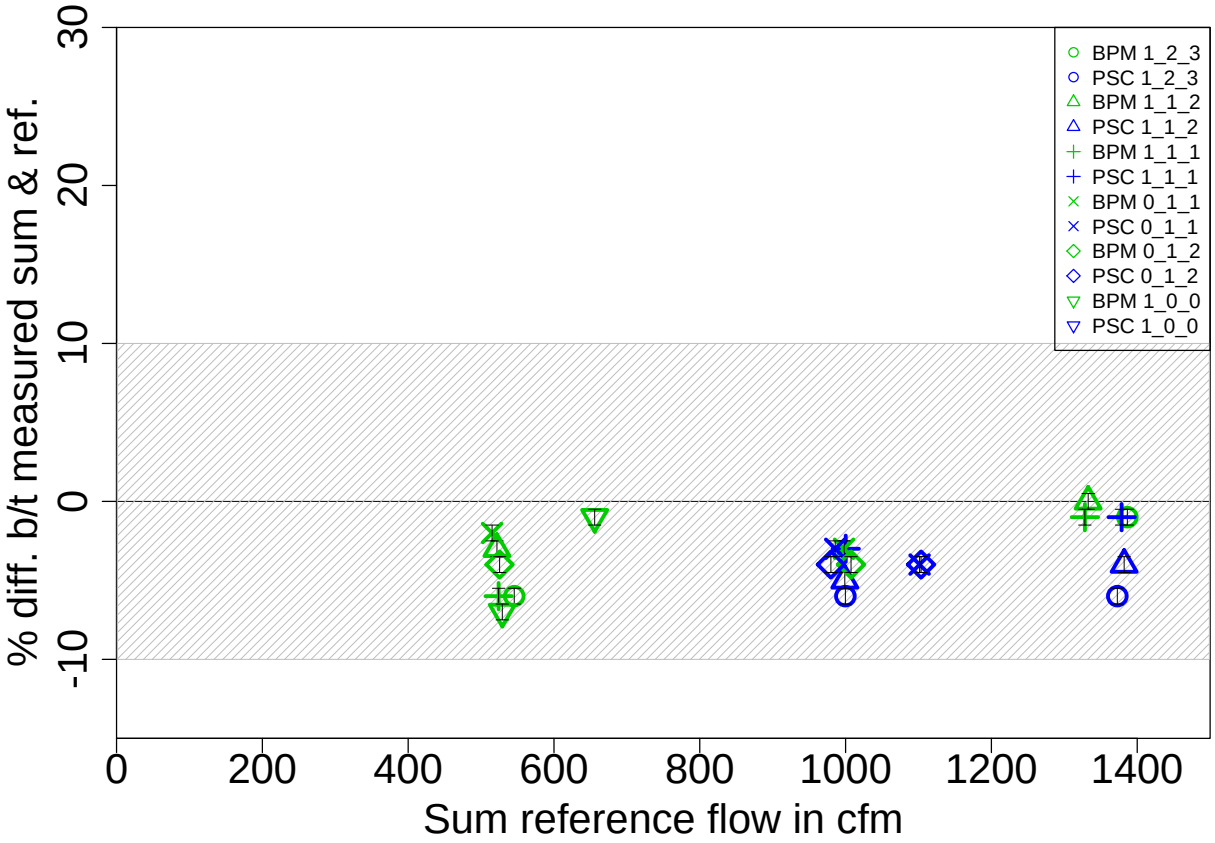
Source: LBNL.

3.2 Total System Flow Measurements

Figures 16-21 show the percentage difference between the device-measured flow and the total system flow for each of the six devices under test. Each point is coded by color to indicate the motor type (Brushless Permanent Magnet (BPM) – green, Permanent Split Capacitor (PSC)– blue) and by shape to indicate the ratio of the distribution of flow across the branches.

The area within ±10% of the reference flow is shaded, and error bars reflect the estimated uncertainty of the reference flow.

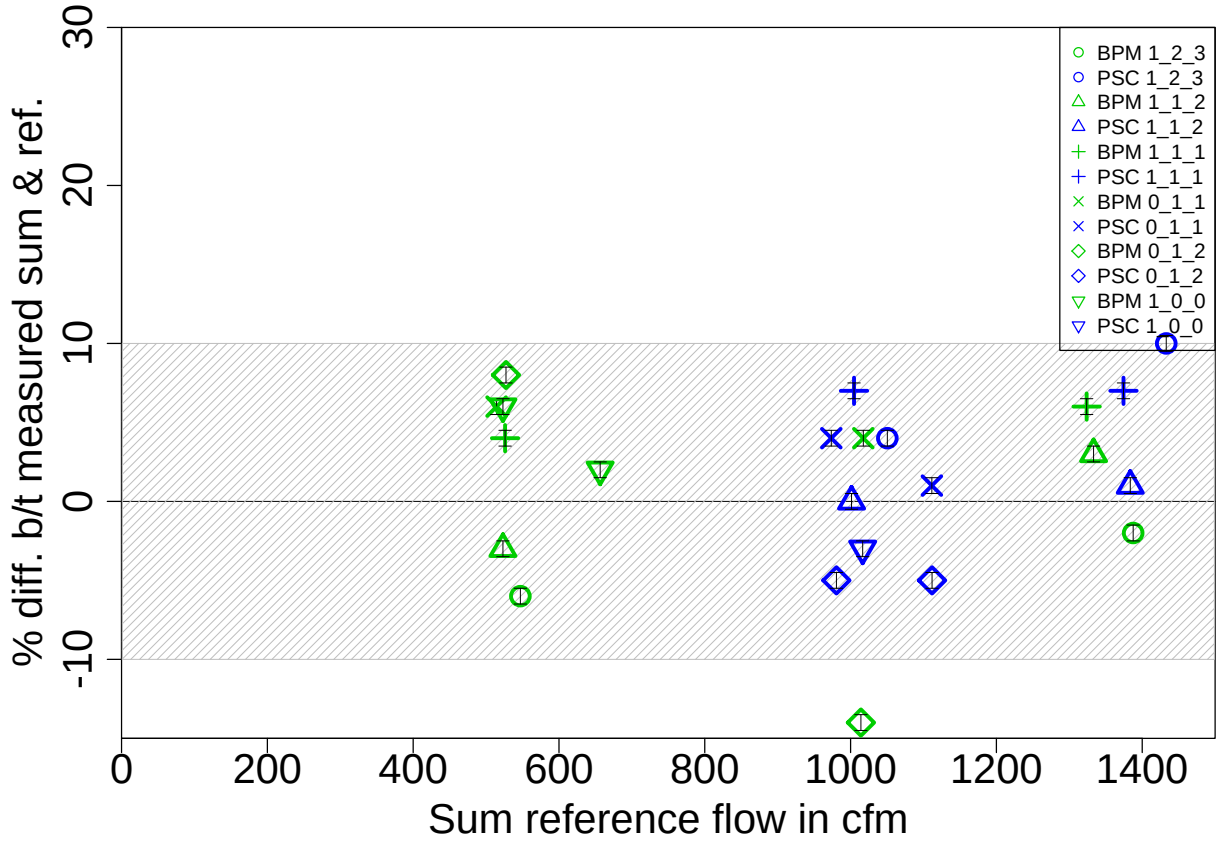
Figure 16: ABT701 percent difference of summed branch measurements and total flow



Device-indicated branch flows summed and compared to total reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

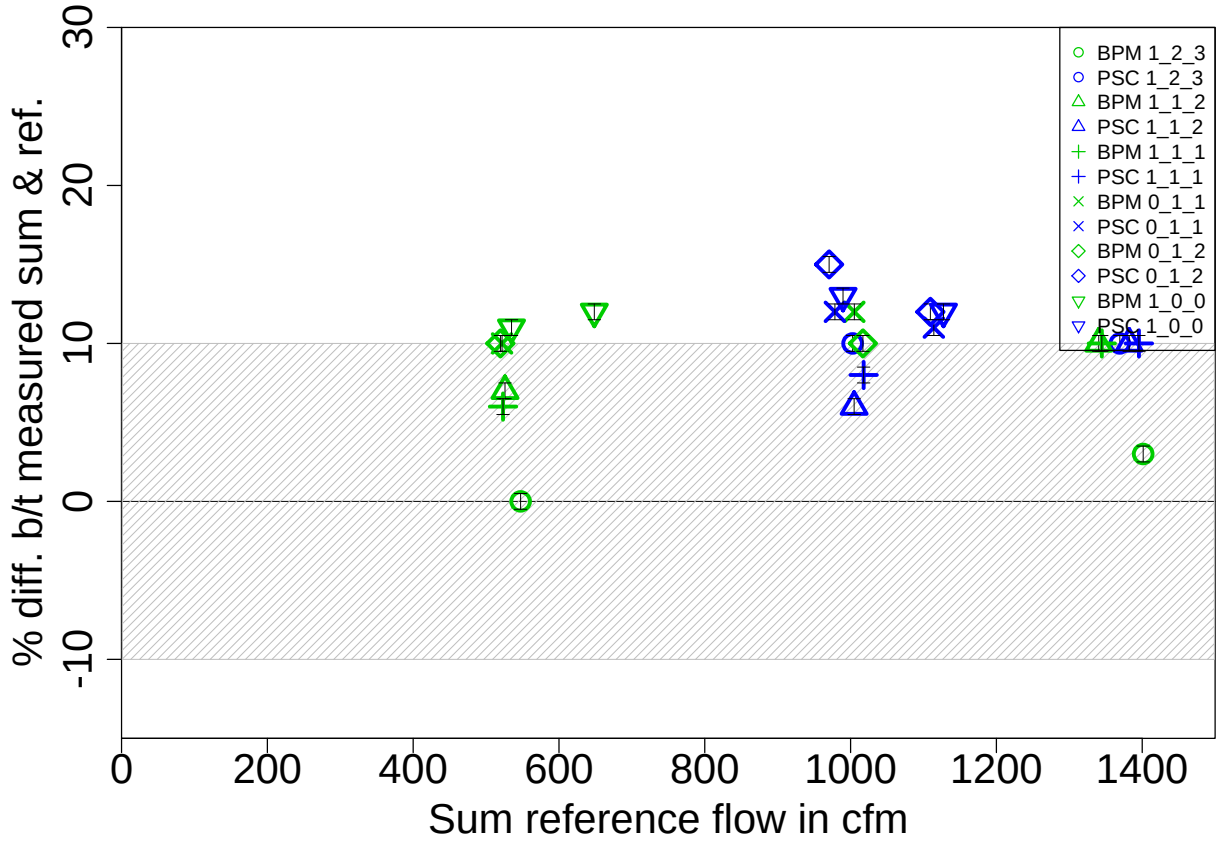
Figure 17: CFF percent difference of summed branch measurements and total flow



Device-indicated branch flows summed and compared to total reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

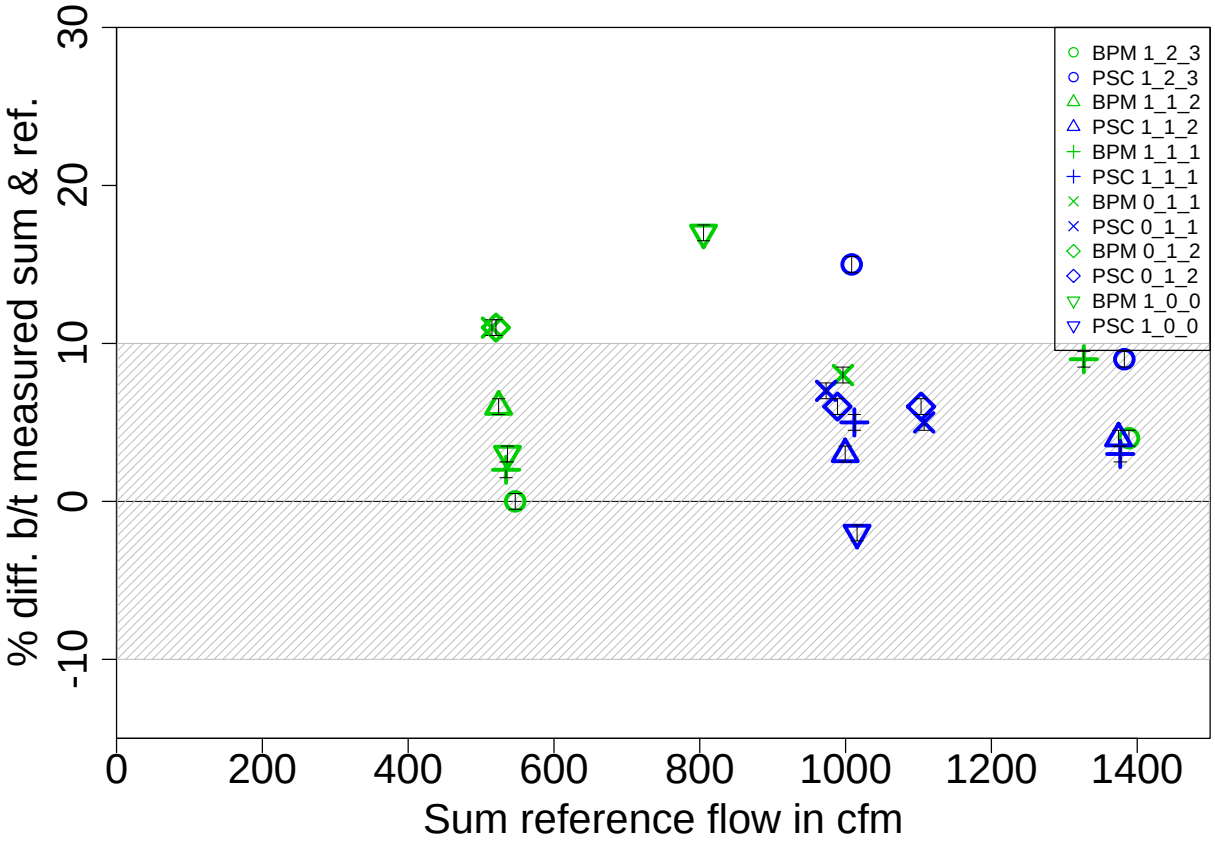
Figure 18: EBT721 percent difference of summed branch measurements and total flow



Device-indicated branch flows summed and compared to total reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

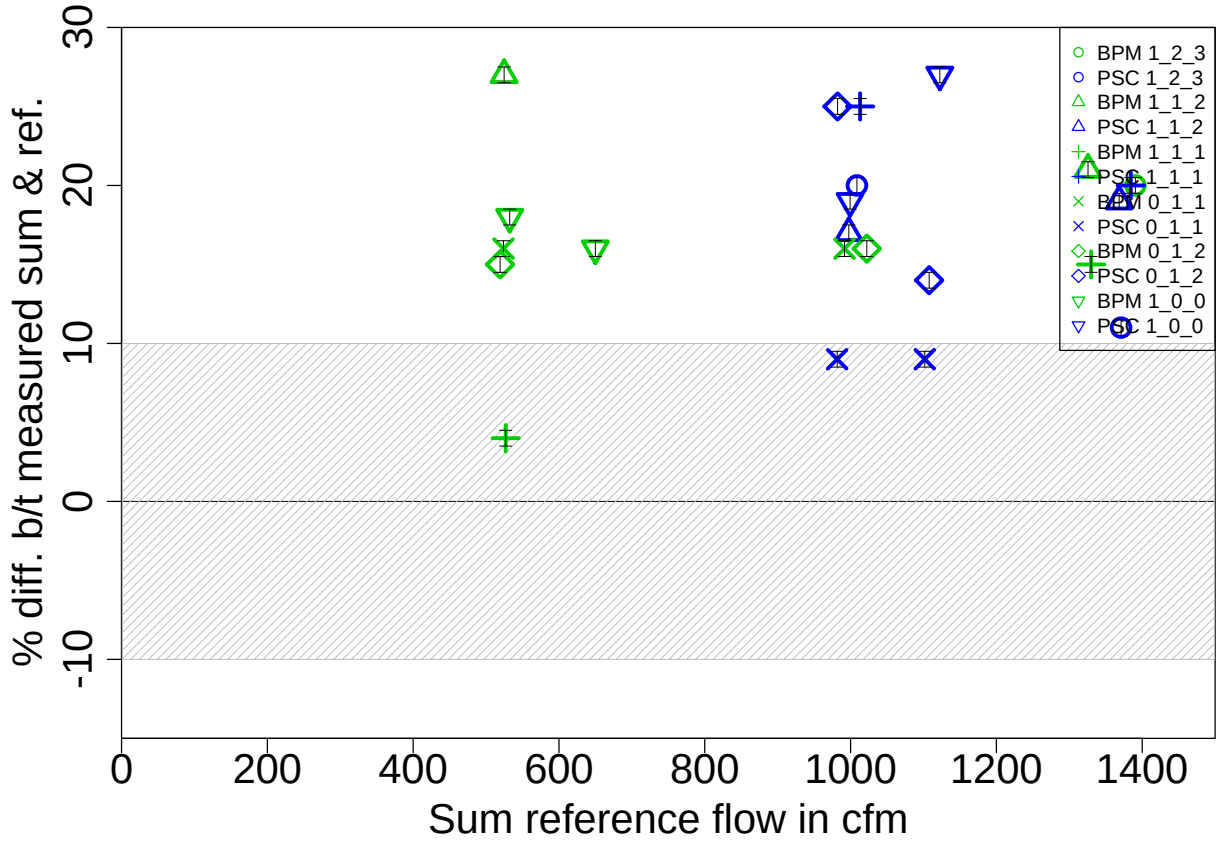
Figure 19: LBNL Hybrid percent difference of summed branch measurements and total flow



Device-indicated branch flows summed and compared to total reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

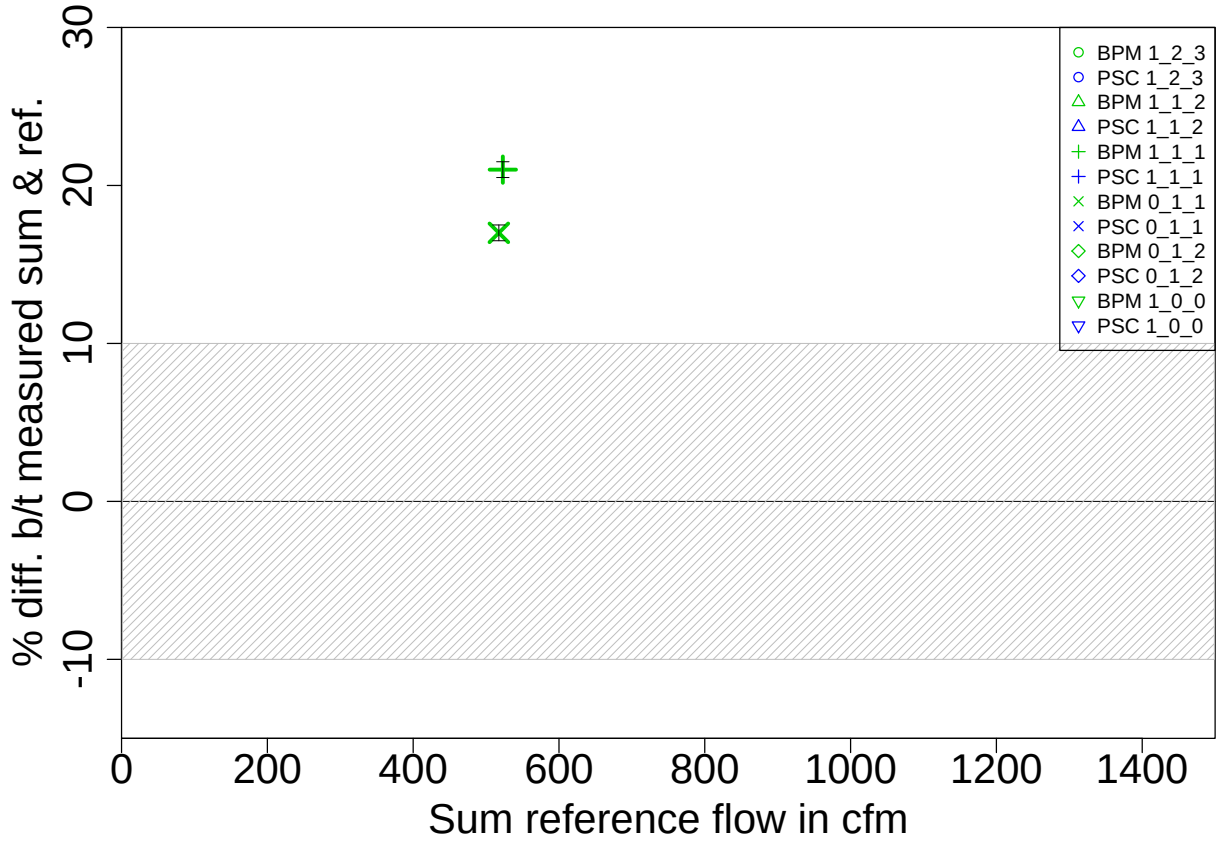
Figure 20: Testo 417 percent difference of summed branch measurements and total flow



Device-indicated branch flows summed and compared to total reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL.

Figure 21: TECFB percent difference of summed branch measurements and total flow



Device-indicated branch flows summed and compared to total reference flow. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars. For total flow evaluations for the TECFB, each of the three branch flows for the fractional flow configuration must be less than 300 cfm, which is the device's upper measurement limit. There were only two configurations for which this was true.

Source: LBNL.

3.2.1 Results Summary

Table 5: Difference between measured and reference flow for individual and summed measurements for each device under test

	Individual Branch Air Flow						Total System Air Flow					
	mean (bias)			RMS (accuracy)			mean (bias)			RMS (accuracy)		
Flow hood	perc.	cfm	L/s	perc.	cfm	L/s	perc.	cfm	L/s	perc.	cfm	L/s
ABT701	-2.8%	-13.1	-6.2	4.8%	24.9	11.7	-3.6%	-32.6	-15.3	4.2%	39.0	18.3
CFF	2.5%	6.8	3.2	7.5%	34.4	16.2	1.7%	17.6	8.3	5.7%	58.1	27.3
EBT721	9.3%	42.3	19.9	10.1%	52.1	24.5	9.6%	95.5	45.1	10.1%	104.5	49.1
LBNL Hybrid	7.5%	30.3	14.3	10.1%	46.1	21.6	6.3%	59.2	27.9	7.7%	73.1	34.3
TECFB	15.6%	27.1	12.7	16.4%	28.9	13.6	21.4%	112.1	52.7	21.4%	112.1	52.7
Testo417	16.5%	73.6	34.6	19.7%	98.8	46.4	17.3%	147.4	69.3	18.3%	174.6	82.1

Device-measured branch flows are compared to branch reference flow for that configuration. Summed branch flows are compared to trunk reference flow for that configuration. The mean difference indicates the device's bias error compared to the reference flow. The root mean square (RMS) represents the absolute difference between the device measurement and reference flow (irrespective of valence) and indicates the device's overall accuracy compared to the reference flow.

Source: LBNL.

For each device the mean and RMS differences between indicated air flow and actual air flow were calculated for all the testing configurations. The results were split into individual branch measurements that are useful when assessing system balance or comfort issues, and the total system air flow that is used in Title 24 HVAC system assessments and are summarized in Table 5. The bias indicates the uncertainty expected over a wide range of homes and is useful for programmatic assessments where the results of many homes are combined. The RMS is more useful for the assessment of individual homes and is the metric that is most important for Title 24 compliance testing and is the focus of the following discussion.

Table 6 shows the percentage of each device's measurements that were within ±10% of the reference branch or total airflow. In parentheses next to the percentage is the number of data points for each device.

Table 6: Percentage of individual branch and total flow measurements within 10% of reference flow for each device under test

	Individual Branch	Sums
	Percent within ±10% of reference flow	
ABT701	98% (n=58)	100% (n=22)
CFF	96% (n=55)	96% (n=23)
EBT721	38% (n=56)	42% (n=24)
LBNL Hybrid	64% (n=55)	74% (n=23)
TECFB	83% (n=12)	0% (n=2)
Testo 417	26% (n=55)	13% (n=23)

CHAPTER 4:
Test Results Discussion

The total system RMS uncertainty results indicate that there is a significant range of performance between the devices, with all but the ABT701 tending to over predict airflows. This is despite the overall effect of the devices being to reduce flow through the system as shown in Table 4. The only flowhood with a negative overall bias in air flow measurements also had the biggest insertion loss effect of 5%. The LBNL Hybrid and CFF pressure compensating methods lead to insertion losses that are small (about 1% or less on average). The EBT721 has a lower air flow resistance design and also had a small insertion loss.

The TECFB is really not intended to measure the high air flows associated with central forced air system returns, but even with that device removed the results indicate that there is a clear need to evaluate these devices for suitability in the Title 24 applications: with an acceptable accuracy requirement of +/-10%, three of the six hoods were not acceptable. This indicates the need for some sort of performance testing and evaluation – such as the ASTM test method developed in this study. Both the powered flow hoods and the tradition large passive flow hoods (if we allow the EBT721 error of 10.1%) had acceptable performance and, in the absence of ASTM rated hoods could be recommended for total air flow measurement applications. The testo suffered from the large uncertainty inherent in its measurement technique largely from how the flow is sampled.

For the individual branch flows, the applications (except for duct leakage estimates) require less accuracy and all the tested devices would be acceptable. With duct leakage limits of 6% of total flow (and further restricted if we assume 3% supply and 3% return leakage) the approach of using measured grille air flows will generally not have sufficient accuracy with any of the tested devices With the additional uncertainty of the air handler flow measurement we recommend that this technique not be used for measuring duct leakage.

The ABT701 and CFF methods were the most accurate for measuring total airflows, measuring 100% and 95.7%, respectively, of summed reference flows to within ±10% accuracy. In previous studies, the ABT701 measured inlet flows with acceptable accuracy (±3.6%), but was slightly less accurate when measuring outlet flows (±6.7%)[20]. The ABT701 is well suited for measuring single or multiple return inlets, though its 1000 cfm maximum range may prohibit it from being used to measure some single return system flows. The CFF also provided reliable airflow measurements for multiple return systems, but its flow limit for the largest ring is 800 cfm may limit its applicability to smaller capacity systems.

[20] Stratton, J. C., Turner, W. J. N., Wray, C. P., & Walker, I. S. Measuring Airflows in Residential Mechanical Ventilation Systems: Part 1 - Laboratory Evaluation of Commercially Available Devices LBNL-5983E. Berkeley, CA: Lawrence Berkeley National Laboratory. 2012

The TECFB is somewhat limited for use on central forced air system returns because its rated flow limit is 300 cfm. It could be used for low capacity systems or for systems with multiple smaller returns.

Among the remaining five devices, there was a distinct separation in terms of the percentage of total airflow measurements that fall within 10% of the reference flow. The EBT721 tended to overestimate the flow (median is +9.6% for total flow measurements), and fewer than half of its total airflow measurements were within 10% of the reference flow. This phenomenon is consistent with previous findings for this device[21], which was recently discontinued and replaced with the EBT731.

Only one in seven of the Testo 417 vane anemometer total airflow measurements were within 10% of the reference flow. The measurements for the device were both imprecise and had low accuracy (±18.3% for total flow measurements). Several factors combine to hinder the reliability of this instrument's measurements. It can yield acceptable results if the measurement process is performed precisely and an appropriate grille factor is applied when translating its velocity measurement into a volumetric flow measurement. The problem is that it is difficult to perform the velocity measurement correctly and that there is no good way to know what grille factor to apply for a given inlet grille.

The LBNL Hybrid is representative of what a contractor could do if they already have a fan/flowmeter. Its return flow measurements were less accurate than indicated in a previous study22, in which its accuracy was determined to be within ±3.2% . There were times when its pressure compensation seemed to be adversely affected by the multiple branch inlets. At times, with the zero pressure compensation automated, the device seemed to overcompensate for the flow, in some cases even reversing flow in one or both of the branches not being measured, turning them from return to supply grilles. We also encountered this behavior with the TECFB. Further investigation would be required to make a more conclusive determination, but there may be some issue with the zero pressure compensation when the flow at the branch being measured is increased by the powered flow hood fan overcompensating. This issue has been raised with the manufacturer of the TECFB and they are investigating the control algorithm for potential future improvements.

To overcome this concern with the zero pressure compensation method for multiple return systems, perhaps an alternative powered flow hood method could be used to identify a "normal" operating pressure downstream of the grille and match that pressure during the flow measurement. This proposed airflow measurement method could be evaluated in future investigations.

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[21] Stratton, J. C., Turner, W. J. N., Wray, C. P., & Walker, I. S. Measuring Airflows in Residential Mechanical Ventilation Systems: Part 1 - Laboratory Evaluation of Commercially Available Devices LBNL-5983E. Berkeley, CA: Lawrence Berkeley National Laboratory. 2012

CHAPTER 5: Recommendations

The total system RMS uncertainty results indicate that there is a significant range of performance between the devices. With an acceptable accuracy requirement of +/-10%, three of the six hoods were not acceptable. This indicates the need for some sort of performance testing and evaluation – such as the ASTM test method developed in this study. It is therefore recommended that the ASTM method continue to be developed and completed so that future Title 24 test methods can require the use of devices that are evaluated using the ASTM method.

Both the powered flow hoods and the traditional large passive flow hoods (with standard 24 in. x 24 in. openings and flow capacities greater than 500 cfm) had acceptable performance for current Title 24 testing of air flows at return grilles, and could be recommended for total air flow measurement applications until ASTM rated devices are available. The rotating vane velocity averaging technique was found to have too much uncertainty for use in Title 24 compliance testing.

The tested devices gave acceptable results for other applications, such as air flow balancing and comfort, therefore it is recommended that their use be restricted to these applications.

Some devices are limited in their maximum airflow and thus restrict the systems they can be applied to. Users need to be aware of these limitations before testing, and engagement is needed with test equipment manufacturers to determine if they can produce test equipment with higher maximum flow capability.

When measuring air flows at larger grilles, the technique of masking uncovered areas with tape proved to be an acceptable method for testing.

Based on the apparatus and test procedure developed during the laboratory testing a draft ASTM test procedure has been prepared and is included in Appendix D. We have formed an ASTM Task Group representing equipment manufacturers, other researchers and entities likely to refer to the test method and set requirements for testing uncertainty. The current task group members are listed in Table 7.

Table 7: Membership of ASTM working group to prepare flow hood measurement standard

Task Group Member	Organization
Iain Walker (Chair)	LBNL
Charlie Wright	TSI
Gary Nelson	TEC
Mark Alatorre	CEC
Dean Gamble	EPA
Mike Lubliner	WSU energy center and ASHRAE TC63
Kristin Heinemeier	UC Davis
Lieko Earle	NREL
Glenn Hourahan	ACCA
Kristof Irwin	Positive energy

GLOSSARY

This is an example of Body (Normal) Text. It is Palatino Linotype, 11 point, and aligned left.

A glossary is required.

Below is an example of terms and definitions in a table format.

Term	**Definition**
ASTM	ASTM International is an international standards organization that develops and publishes voluntary consensus technical standards
BPM Motor	Brushless Permanent Magnet DC Motor
cfm	Cubic feet per minute, a measure of volumetric air flow
IAQ	Indoor Air Quality
LBNL	Lawrence Berkeley National Laboratory
Passive Flow Hood	A device that captures and measures airflow using means other than the zero pressure compensation method employed by a powered flow hood
Powered Flow Hood	A device that captures and measures airflow by using a fan to match the flow being measured and zero out the pressure difference between inside and outside the capture hood
PSC Motor	Permanent Split Capacitor AC Motor

APPENDIX A:
Measuring average face velocity and calculating volumetric flow with Testo 417

Making a measurement with the Testo 417
Large vane Anemometer

1) Determine the **OPEN AREA** as follows:
On **RETURNS**, the **OPEN AREA** is the 100% of the full measured area of the grille, as the air is flowing first through the 417 measuring vanes, then into the return duct.
On **SUPPLIES**, the **OPEN AREA** is the fraction or percentage of the grille that the air passes through, before moving through the 417 measuring vanes.
See grille manufacturers product info for open area data **.
Then **Multiply** the **Duct dimensions** (Height and width) in inches by multiply of the **OPEN AREA** factor.

FOR EXAMPLE:
We have a supply grille that is 6x10 inches with 65% open area. The open area is 6 x 10 x 0.65 = 39 sq inches open area

2) **ENTER** the **OPEN AREA** into the 417.
Turn ON the 417, after a few seconds the display comes up. **PRESS AND HOLD** the **RETURN ARROW** (Hold/Max/Min Key) until a number appears on the display and the in2 label is blinking.
Use the **UP** or **DOWN** arrows (VOL and MEAN keys) to adjust the number in the display your open area.
I*N THE EXAMPLE ABOVE* adjust it to ***39.0***

3) **EXIT** to measuring mode by pressing the **RETURN ARROW** (Hold/Max/Min Key) **5** times

4) **MEASURE**: Place the 4" vane into the air stream in front of the grille position it at one corner of the grille, perpendicular to the grille surface.
a) Press the MEAN key TWICE to enter the timed average mode.

b) Press the RETURN key (Hold/Max/Min Key) when you want to start collecting data.

c) Keep the 417's measuring head about 1" away from the face of the grille. Move the 417 head across the grille at a rate of about 1 foot (12") over 4 seconds. (note the timer on the 417's screen)

d) Be sure to "paint" the entire grille face with head of the 417 to account for total flow through the grille. DO NOT paint any area more than once!

e) When you are done covering the entire grille area, press the RETURN key (Hold/Max/Min Key) again to pause the reading on the display.

OPTIONAL: You can measure again (re-paint the ***entire*** area) to improve the reading. Just start at step 4b.

5) **DISPLAY** the average values by pressing the **MEAN** key. The Timed MEAN icon will flash and the average Feet Per Minute (FPM) will be displayed.

Tap the VOL key once to see the Average CFM for this test.

Tap the VOL key again to see the Average Temperature for this test.

Tapping the VOL key continues rotating thru these three results.

NOTE *BE SURE to record the data, as there is NO memory storage in the 417. Once you tap the MEAN key again, the data is gone.*

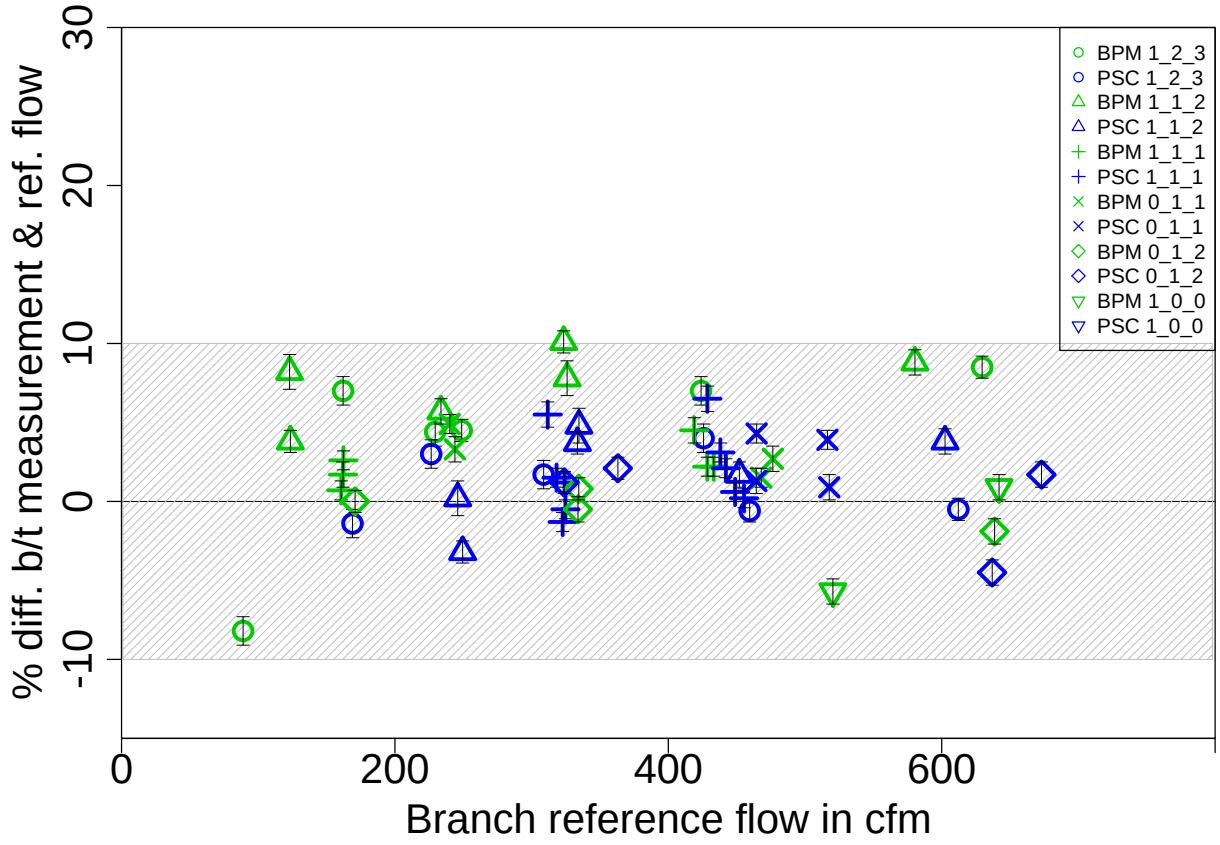
6) **CLEAR** the data and prepare for another measurement by tapping the **MEAN** key

** One manufacturer's data books give open area factors of from 71% to 75% for one type of floor diffuser (depending on size), 66% to 75% for another model and 65% to 75% for another model.

While a heavy duty, dual shutter floor grille from the same manufacturer has a range of 48% to 52% open area factor.

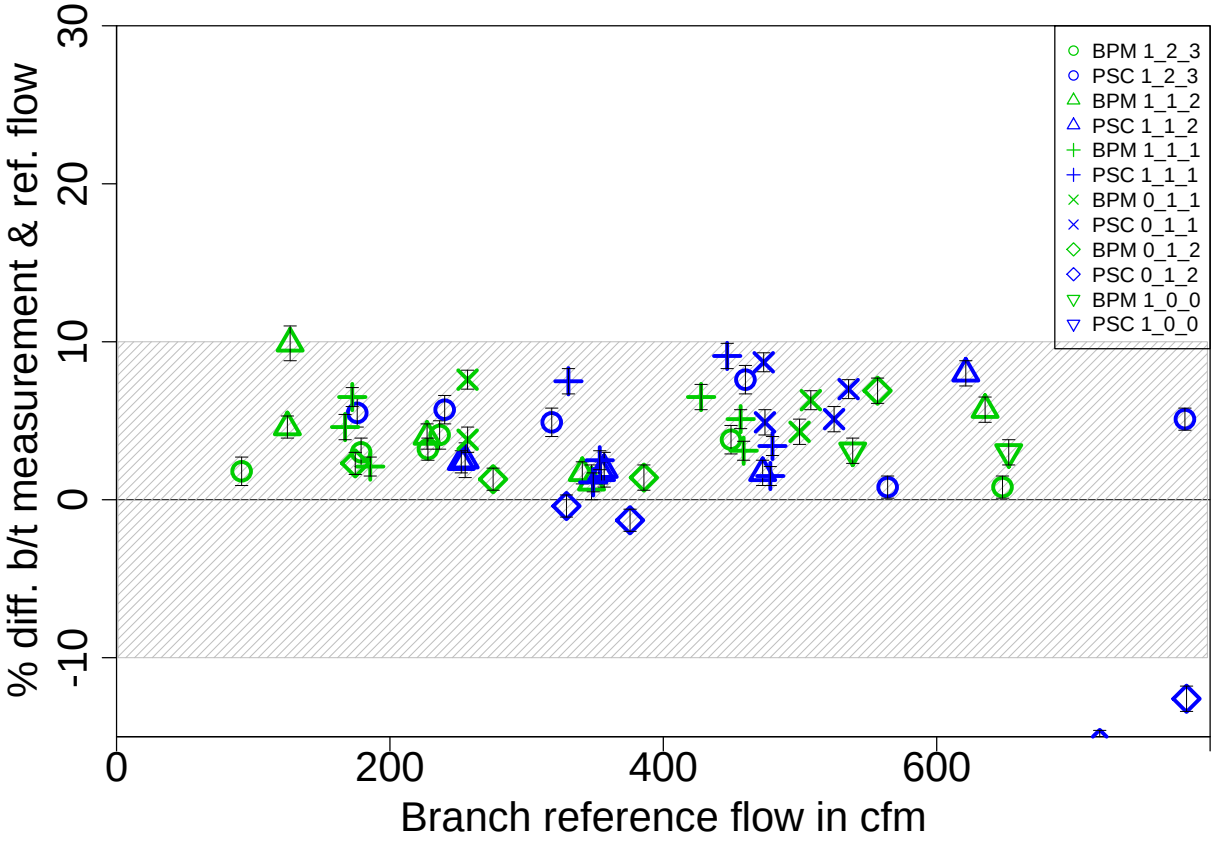
Generally speaking, the larger the grille dimension, the small the open area factor.

APPENDIX B:
BRANCH AIRFLOW MEASUREMENTS COMPARED TO TEST CONDITION REFERENCES



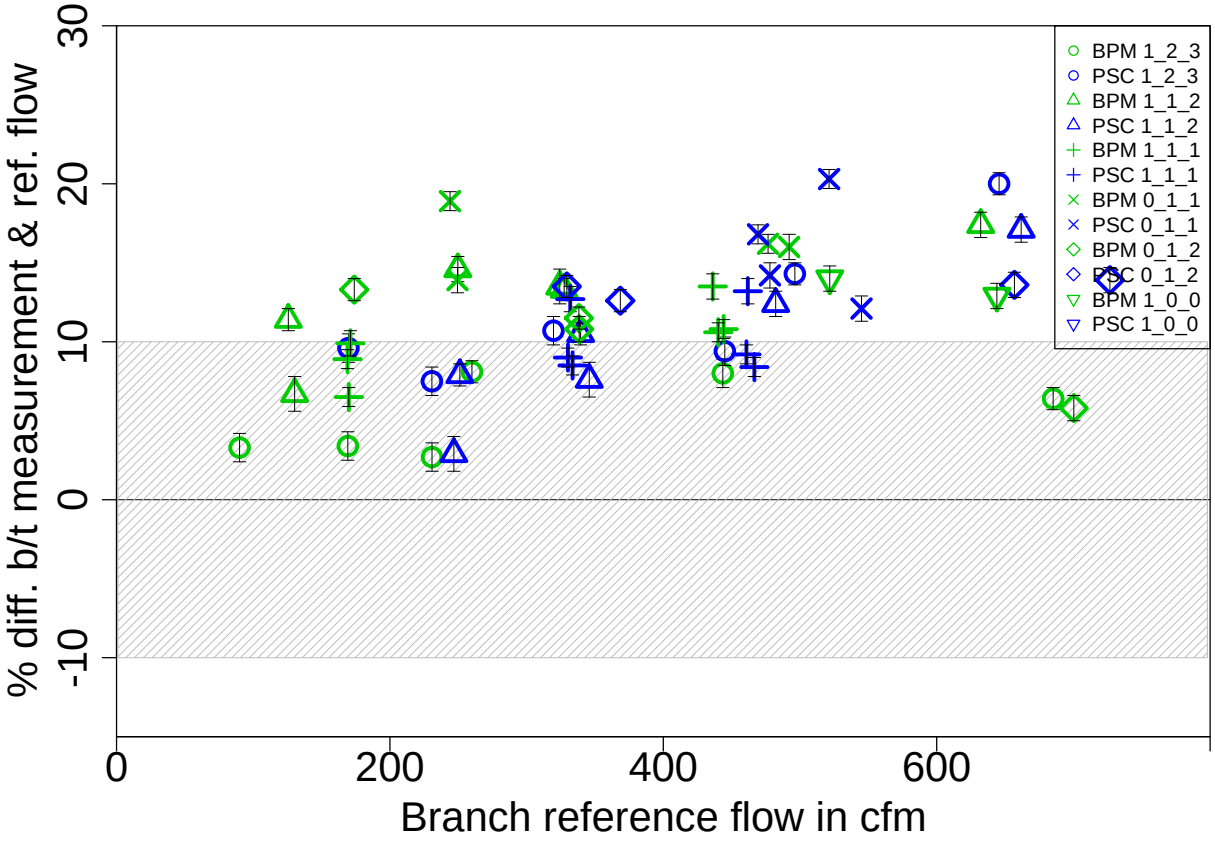
Device-measured flows are compared to reference flow under test conditions. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL



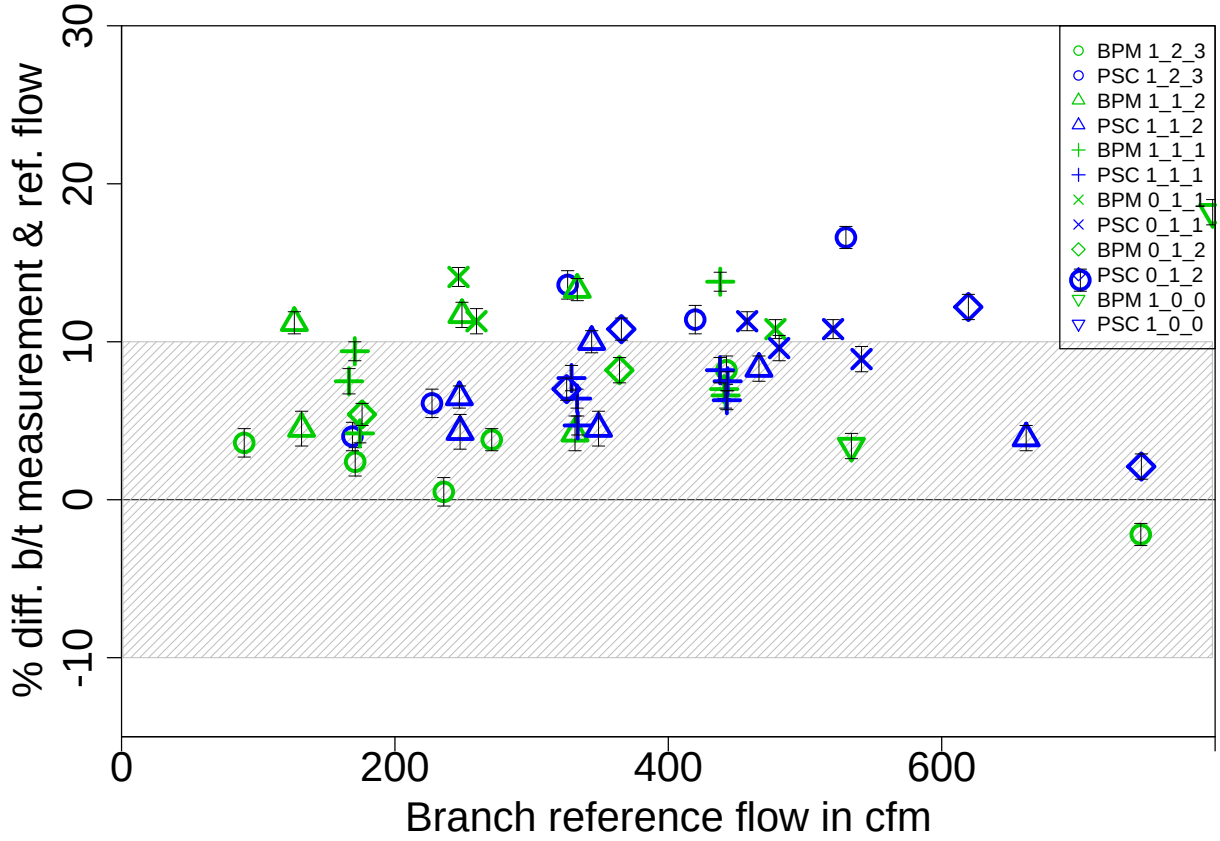
Device-measured flows are compared to reference flow under test conditions. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL



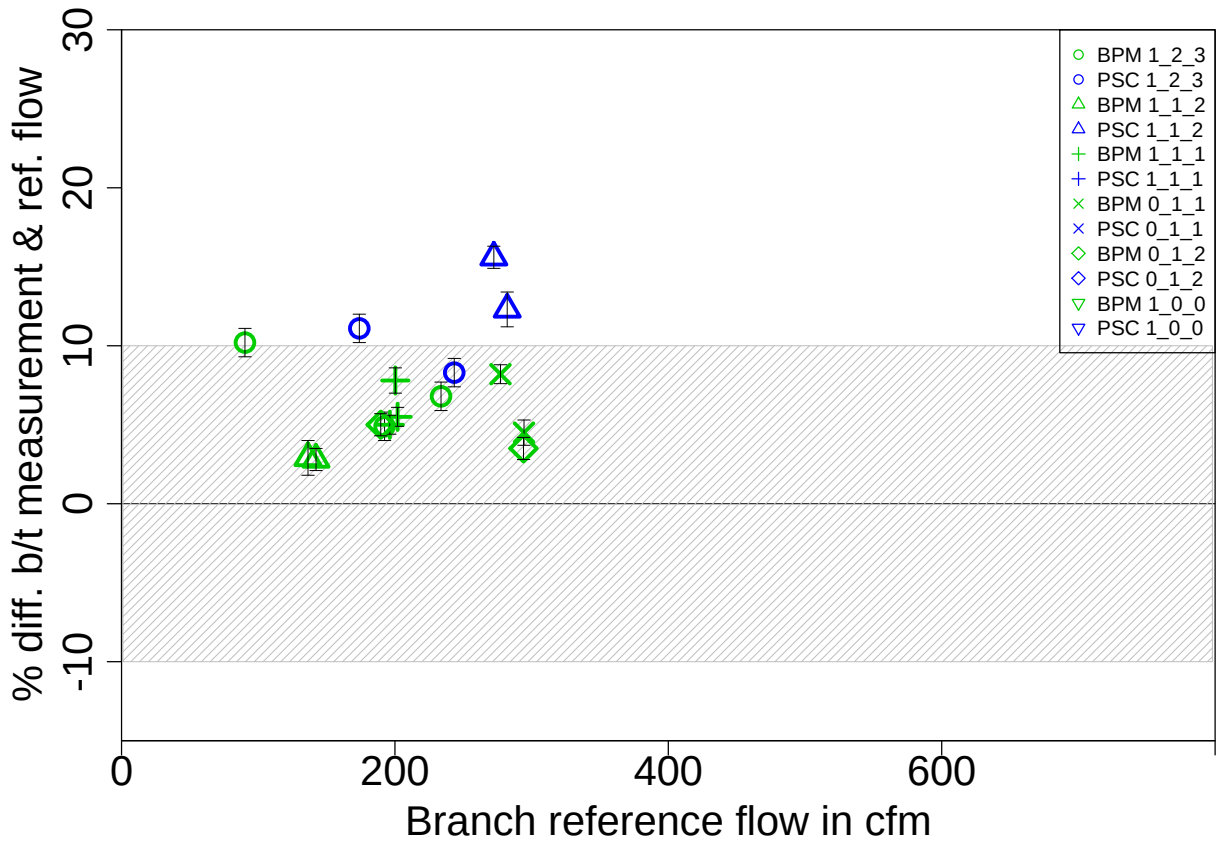
Device-measured flows are compared to reference flow under test conditions. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL



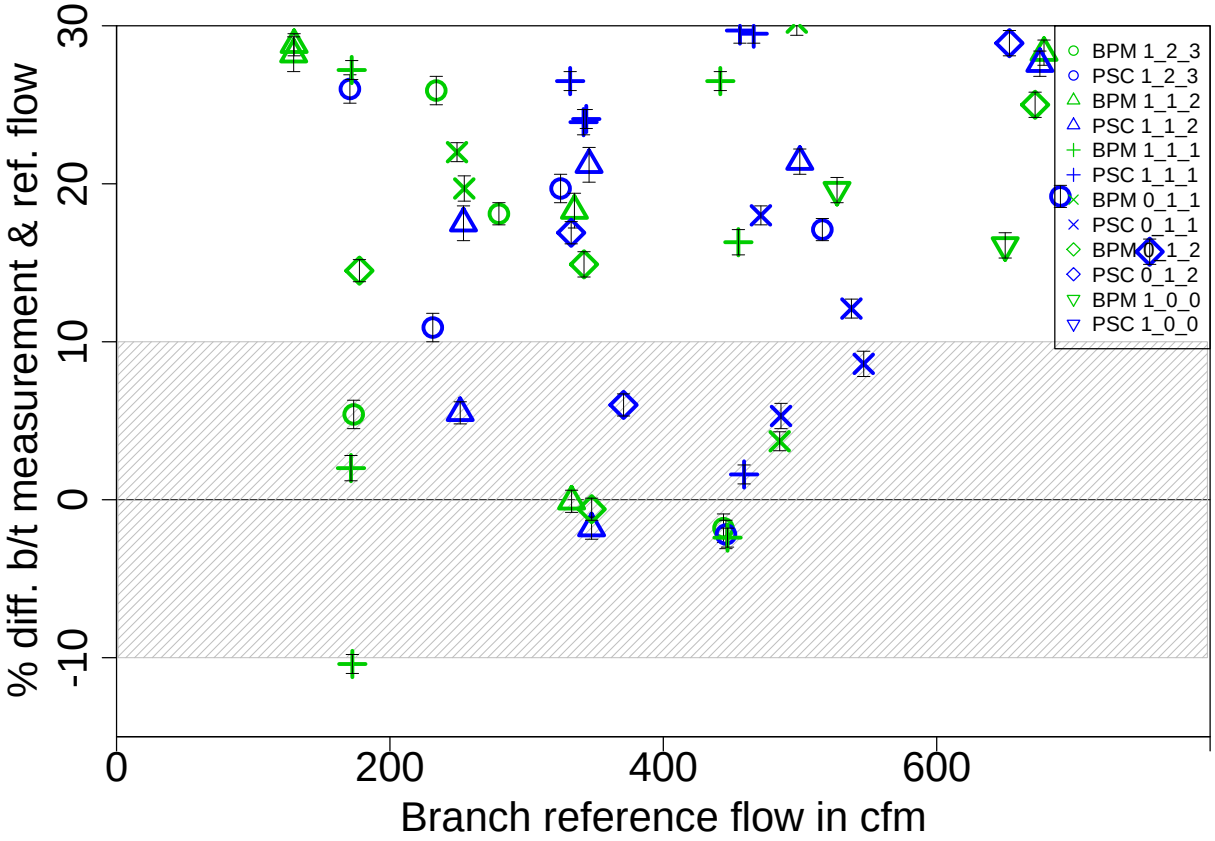
Device-measured flows are compared to reference flow under test conditions. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL



Device-measured flows are compared to reference flow under test conditions. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL



Device-measured flows are compared to reference flow under test conditions. Test configuration indicated by symbol color and shape, uncertainty of reference flow indicated by error bars.

Source: LBNL

APPENDIX C:
Bias and Accuracy for Individual Measurements Compared to Test Condition Reference Airflow

	Individual					
	mean (bias)			RMS (accuracy)		
Flow hood	**perc.**	**cfm**	**L/s**	**perc.**	**cfm**	**L/s**
ABT701	2.3%	8.4	4.0	4.2%	16.4	7.7
CFF	3.3%	11.0	5.2	5.3%	28.0	13.2
EBT721	11.4%	49.7	23.4	12.1%	60.1	28.3
LBNL hybrid	10.8%	45.5	21.4	16.0%	78.3	36.8
TECFB	6.4%	11.7	5.5	6.9%	12.8	6.0
testo417	16.6%	74.1	34.8	19.9%	99.8	46.9

APPENDIX D:
Draft ASTM Test Procedure

Method of Test for Determining the Measurement Uncertainty of Devices Used to Measure Airflow through Residential HVAC Terminals

1. Purpose

1.1 This standard provides a method of test for determining the measurement uncertainty of devices used to measure airflows through air inlets and outlets that terminate ducted systems for air distribution in buildings.
1.2 This standard establishes performance specifications for equipment required to test measurement devices, defines methods of calculating and reporting the results obtained using the test data (including accounting for the effects of air density on airflow measurements), and establishes an accuracy reporting system that can be applied to devices covered by this standard.

2. Scope

2.1 This standard applies to the testing of airflow measurement devices that are intended for field application to residential heating, cooling, and ventilation air distribution systems.
2.2 This standard is for use in the laboratory and is not intended for use in field calibration of airflow measurement devices.
2.3 This standard applies to measurement devices for flows less than 500 L/s (1060 cfm).

3. Definitions (TBD)

4. Summary of Test Method

4.1 The test method compares the airflow rates reported by measuring devices to a reference flow meter in a laboratory test apparatus. The comparison is performed for a range of residential HVAC terminals and system air flows characteristic of residential HVAC systems. The testing also includes the effects of placement of the device under test relative to each register. Some tests include the evaluation of insertion loss effects using multi-branch systems. In addition to reporting the errors for individual test configurations, this test method also reports the bias and root mean square error over all tests. The errors are reported separately for air flows into and out of the device under test.

5. Significance and Use

5.1 The measurement of air flows in residential heating and cooling systems has several applications: measuring total air flow of the system to ensure good equipment performance and

measuring the air flows in and out of rooms to ensure individual room loads are met. Some building energy codes are requiring the measurement of total system airflow as part of code compliance.
5.2 The measurement of ventilation system airflows is required to demonstrate compliance with standards, such as ASHRAE 62.2-2013.
5.3 The measurement of ventilation, and heating and cooling system airflows is required in energy and indoor air quality related standards, such as RESNET 301 (2013) and BPI Standard 1100 (2012) and ACCA Standard 5 (2010).

6. Laboratory Test Apparatus

6.1 Two test apparatus configurations are required: one for single-branch testing (see Section 6.2) and one for multi-branch testing (See Section 6.3). The apparatus components in section 6.1 are common to both configurations and shall meet the following specifications.
6.1.1 A reference air flow meter capable of measuring the air flow through a terminal with an accuracy of +/- 3% or +/- 0.5 L/s (1cfm). Flow straighteners shall be used upstream and downstream of the reference flow meter. A straight undisturbed duct run meeting the reference flow meter manufacturers specifications (but at least 2m (6 ft.) in length) shall be installed upstream and downstream of the reference flow meter. Some flow meters are unidirectional. For flow meters of this type they shall be installed following manufacturer's instructions and shall be configured correctly for each flow direction.
6.1.2 An air leakage flow meter that can measure air flows with an accuracy of ±10% or ±0.1 L/s (0.2 cfm).
6.1.3 A differential pressure gauge capable of measuring pressure to an with an accuracy of +/- 1% or +/- 0.1 Pa (0.004 in. water) – whichever is greater. The pressure in the duct shall be measured within 100 mm (4in.) of the terminal.
6.1.4 A fan or blower with a flow control mechanism that can be adjusted to provide specified air flows through the apparatus. It is possible that two fan or blower devices may be needed – one for the air leakage testing and one for air flow testing.
6.1.5 The terminals used for testing as shown in Table 1. Terminals 1 to 5 are used for ventilation applications. Terminals 6 to 9 are for heating and cooling applications.
6.1.6 Air temperature measuring equipment with an accuracy of +/-1°C (+/-0.5°F). Air temperatures in the duct shall be measured upstream and downstream of the reference flow meter within 1m (3 ft.) of the reference flow meter. Room air temperatures shall be measured not more then 3 m (9 ft.) from the terminal at the same height above the floor as the terminal.
6.1.7 A barometric pressure measuring device with an accuracy of +/-250 Pa (+/- 1.00 in. water).
6.1.8 All temperature, pressure, and flow measurements shall be a one minute average of points taken at least once every five seconds.
6.1.9 Sheet metal air ducting, boots and collars required to connect the fan, reference flow meter and the terminals.

Table 1. Terminals to be tested

Terminal Number	Terminal Description	Flow Direction	Air flow test points (L/s)	Single or Multi-Branch	Duct diameter
T1	Bathroom exhaust fan with face dimensions of at least 380 mm by 380 mm (15 in. by 15 in.)	Into terminal	15, 20, 30, 40, 50	Single	100 mm (4 in.)
T2	HRV/ERV return	Into terminal	5, 15, 25, 40, 50	Multi	100 mm (4 in.)
T3	HRV/ERV supply	Out of terminal	5, 15, 25, 40, 50	Multi	100 mm (4 in.)
T4	Exterior wall #1 – 100 mm duct – with backdraft damper	Out of terminal	15, 25, 50, 100, 150	Single	100 mm (4 in.)
T5	Exterior wall #2 – 150 mm duct – with backdraft damper	Out of terminal	15, 25, 50, 100, 150	Single	150 mm (6 in.)
T6	Fixed vane 1 – way supply grille (400 mm × 190 mm, 15.5” × 7.5”)	Out of terminal	10, 20, 30, 40, 50	Multi	100 mm (4 in.)
T7	Fixed vane 2 – way supply grille (400 mm × 190 mm, 15.5” × 7.5”)	Out of terminal	10, 20, 30, 40, 50	Multi	100 mm (4 in.)
T8	Fixed vane 3 – way supply grille (400 mm × 190 mm, 15.5” × 7.5”)	Out of terminal	10, 20, 30, 40, 50	Multi	100 mm (4 in.)
T9	Fixed vane 4 – way swirl-inducing supply grille	Out of terminal	10, 20, 30, 40, 50	Multi	100 mm (4 in.)

6.2 Single-branch apparatus

For the single-branch apparatus all the air shall flow through a single terminal. The single-branch test apparatus shall be constructed such that the fan or blower moves air through a duct containing the reference flow meter that terminates in the terminal used for each test configuration. The terminal shall be mounted in a flat surface with dimensions of at least 1m x 1m (3 ft. x 3 ft.). Figure 1 is an illustration of a typical single-branch test apparatus.

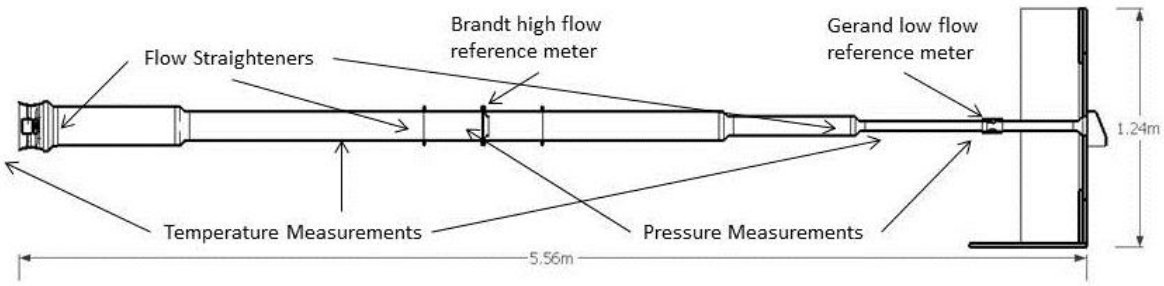


Figure 1. Test Apparatus for Single-Branch Testing

6.3 Multi-branch apparatus.

The multi-branch test apparatus shall be constructed such that the fan or blower moves air through a duct containing the reference flow meter and then through three equal length ducts – each of which has a terminal attached. For multi-branch testing the air shall flow through the terminal being measured by the device under test and two other terminal(s) that are not measured by the device under test. Each branch shall have the same terminal. Each terminal shall be mounted in a flat surface with dimensions of at least 1m x 1m (3 ft. x 3 ft.). Each branch shall be 3 m (9 ft.) in length and have ducts of the same diameter (either 100 mm or 150 mm (4 in. or 6 in.)). Figure 2 is an illustration of a typical single-branch test apparatus.

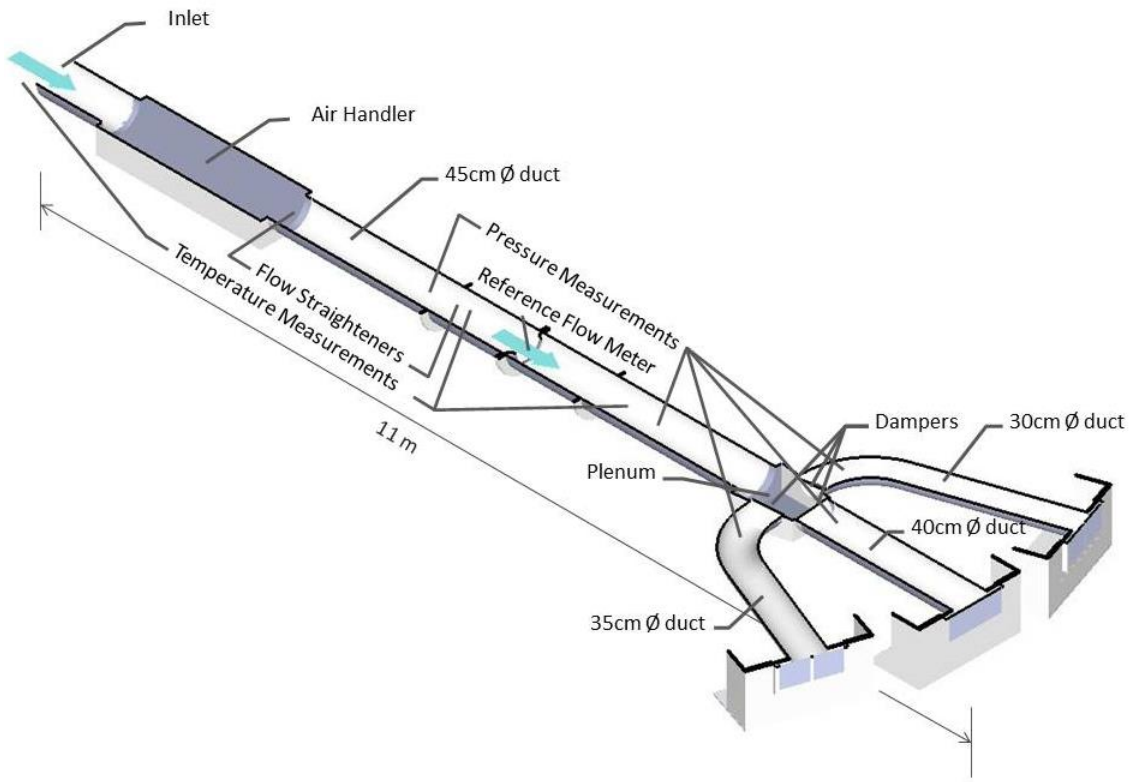


Figure 2. Test Apparatus for Multi-Branch Testing

6.4 Air Leakage of Test Apparatus.
6.4.1 The test apparatus shall be tested for air leakage after initial construction and any time a configuration change is made to the apparatus that could affect its airtightness – such as changing air terminals or reference air flow meters.
6.4.2 Seal all the terminals.
6.4.3 A differential pressure gauge shall be connected to the test apparatus to measure the pressure difference between inside the test apparatus and the room.
6.4.4 A fan or blower and air flow measurement system meeting the specifications of 6.2.1 shall be attached to the test apparatus so as to pressurize the apparatus.
6.4.5 The fan or blower shall be adjusted to maintain a 25 Pa (0.1 in. water) test pressure between the inside of the test apparatus and the room.
6.5.5 The air flow required to maintain the test pressure shall be recorded.
6.5.6 The maximum allowable air flow shall be 0.5 L/s (1 cfm).
6.5.7 If the air leakage is above the maximum, then the apparatus shall be further air sealed and retested until the above maximum allowable air leakage level is met.
6.5.8 After air leakage testing is complete the terminal seals shall be removed.

7. Hazards

7.1 Eye Protection—Some tests may require the use of high airflows that may result in airborne debris. Adequate precautions, such as the use of eye protection shall be taken.

7.2 Safety Clothing—Use safety equipment required for general laboratory work, such as safety shoes.
7.3 Equipment Guards—The air-moving equipment shall have a proper guard or cage to house the fan or blower and damper to prevent accidental access to any moving parts of the equipment.
7.4 Noise Protection—Exposure to the noise level generated by fans can be hazardous to the hearing of involved personnel and hearing protection is recommended.

8. Procedure

8.1 Single Branch Testing. The single branch test apparatus shall be used. The single-branch test procedure shall be repeated for T1, T4, and T5 with the air flow direction through the apparatus matching the requirement in Table 1. For each terminal the test shall be repeated for each air flow test point in Table 1. For each air flow test point the test shall be performed for three relative locations of the terminal and device under test: centered over the terminal, with the terminal on one edge of the device under test and with the terminal in one corner of the device under test. The barometric pressure shall be recorded for each test.
8.1.1 The following procedure shall be followed for each, terminal, air flow test point and relative location of terminal and device under test.
8.1.1.1 The device under test shall be placed over the terminal.
8.1.1.2 The fan or blower shall be adjusted such that the flow though the reference flow meter is within 1 L/s (2 cfm) of each test point.
8.1.1.3 The following shall be recorded: air flow through the reference flow meter (Qref), the flow through the device under test (Q), the temperature of air flowing through the device under test, and the pressure difference between the apparatus downstream of the flow meter and the ambient (Ptest).
8.2 Multi-Branch Testing. The multi-branch test apparatus shall be used. The multi-branch test procedure shall be repeated for T2, T3, T6, T7, T8, and T9 with the air flow direction through the apparatus matching the requirement in Table 1. For each terminal the test shall be repeated for each air flow test point in Table 1. For each air flow test point the test shall be performed for three relative locations of the terminal and device under test: centered over the terminal, with the terminal on one edge of the device under test and with the terminal in one corner of the device under test. The barometric pressure shall be recorded for each test.
8.2.1 The following procedure shall be followed for each, terminal, air flow test point and relative location of terminal and device under test.
8.2.1.1 Without the device under test in place, the fan or blower shall be adjusted such that the flow though the reference flow meter is within 1 L/s (2 cfm) of each test point. Record the air flow through the reference flow meter (Q_{ref}). The blower or fan and dampers shall not be adjusted when the device under test is placed over the terminal.
8.2.1.2 The device under test shall be placed over the terminal.
8.2.1.3 The following shall be recorded: the flow through the device under test (Q), the temperature of air flowing through the device under test, and the pressure difference between the apparatus downstream of the flow meter and the ambient (P_{test}).

9. Data Analysis and Calculations

9.1 Convert the device-measured airflows (Q and Q_{ref}) to actual volumetric flow using manufacturers' instructions and the measured temperatures and barometric pressures.
9.2 The difference (Q_{diff}) between the corrected device-measured airflow and the reference airflow shall be calculated for each terminal, test flow rate, and relative position of the terminal and device under test. The square of the difference (Q^2_{diff}) between the corrected device-measured airflow and the reference airflow shall be calculated for each terminal, test flow rate, and relative position of the terminal and device under test.
9.2.1 The errors for all tests shall be calculated using 9.2.1.1 through 9.2.1.4.
9.2.1.1 The bias for the device under test shall be calculated using Equation 1.

$$Q_{bias} = \frac{\sum_{all\ tests} Q_{diff} N}{} \tag{1}$$

where N is the total number of tests.
9.2.1.2 The RMS error for the device under test shall be calculated using Equation 2.

$$Qrms \quad = \sqrt{\frac{\sum_{all\ tests} Q^2_{diff}}{N}} \tag{2}$$

9.2.1.3 The fractional bias shall be calculated using Equation 3.

$$Q_{bias,\%} = 100 \times \frac{\sum_{all\ tests} Q_{diff}}{\sum_{all\ tests} Q_{ref}} \tag{3}$$

9.2.1.4 The fractional RMS error shall be calculated using Equation 4.

$$Q_{rms,\%} = 100 \times \frac{N \times Q_{rms}}{\sum_{all\ tests} Q_{ref}} \tag{4}$$

9.2.2 The errors for each individual terminal shall be calculated using 9.2.2.1 through 9.2.2.4.
9.2.2.1 The bias for the each terminal shall be calculated using Equation 5.

$$Q_{bias,terminal\ i} = \frac{\sum_{n\ tests} Q_{diff}}{n} \tag{5}$$

where n is the number of air flow test points for the ith terminal.
9.2.2.2 The RMS error for each terminal test shall be calculated using Equation 6.

$$Q_{rms,terminal\ i} = \sqrt{\frac{\sum_{n\ tests} Q^2_{diff}}{n}} \tag{6}$$

9.2.2.3 The fractional bias for each terminal shall be calculated using Equation 7.

$$Q_{bias,\%,terminal\ i} = 100 \times \frac{\sum_{n\ tests} Q_{diff}}{\sum_{n\ tests} Q_{ref}} \tag{7}$$

9.2.2.4 The fractional RMS error for each terminal shall be calculated using Equation 8.

$$Q_{rms,\%,terminal\ i} = 100 \times \frac{n \times Q_{rms,terminal\ i}}{\sum_{n\ tests} Q_{ref}} \quad (8)$$

10. Report

10.1 The report shall contain the following information:
10.1.1 The date, time, and location of the test.
10.1.2 The make, model number and calibration date for the reference meter.
10.1.3 The make and model number of the device under test.
10.1.4 A list of the terminals used to develop the rating and the test air flows used for each terminal.
10.1.5 The test results: Qbias, Qbias,%, Qrms, Qrms,% for all tests and for each individual terminal.

11. Precision and Bias

11.1 The primary source of uncertainty in the reported airflows is the +/-3% accuracy specification for the air flow meter. Assembly leakage is a secondary source of uncertainty, on the order of +/- 1-2% of the reference flow.

12. Keywords

Flow hood, calibration, terminal, register, air inlet, air outlet

13. References

ACCA Standard 5-2010. HVAC Quality Installation Specification. Air-conditioning Contractors of America. Arlington, VA.

ASHRAE Standard 62.2-2013, "Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential Buildings, ASHRAE, Atlanta, GA.

BPI-1100-T-2012. Home Energy Auditing Standard. Building Performance Institute, Inc.

BSR/RESNET 301-2013: Standard for the Calculation and Labeling of the Energy Performance of Low-Rise Residential Buildings using the HERS Index. Residential Energy Services Network,

APPENDIX E:
Iris Damper Branch Measurement Accuracy

Table 8: Difference between iris calculated airflow and reference calibrated airflow

Mean (bias) (n=1120)	11.6%
RMS (accuracy) (n=1120)	1.1%

Mean and root mean squared (RMS) differences between iris airflows calculated using manufacturer's formula and airflows calculated using calibrated reference meter.

Source: LBNL

APPENDIX F:
Test Apparatus Leakage Measurements

Figure F1. Pressurized test apparatus leakage measurements

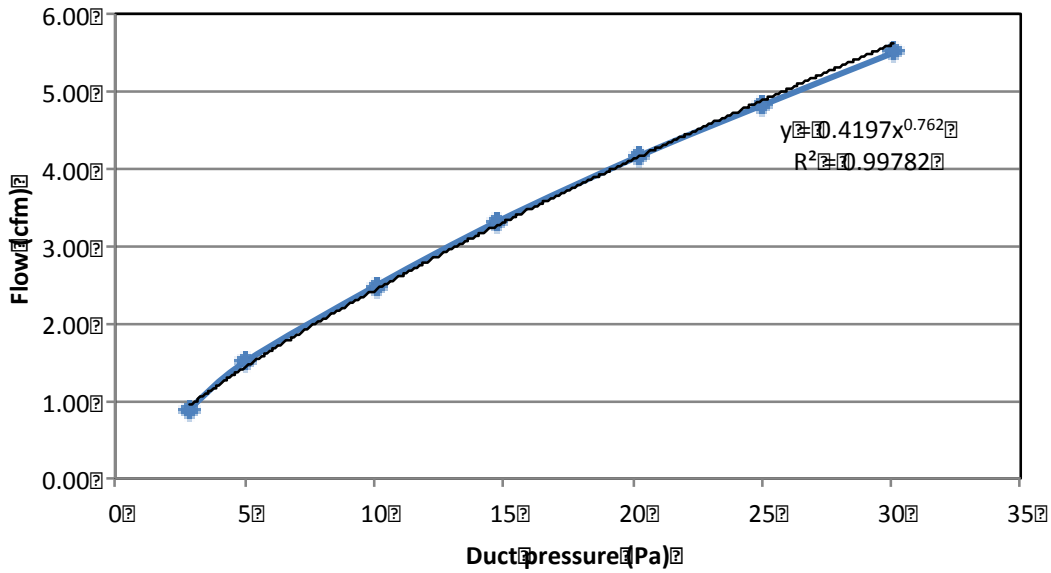
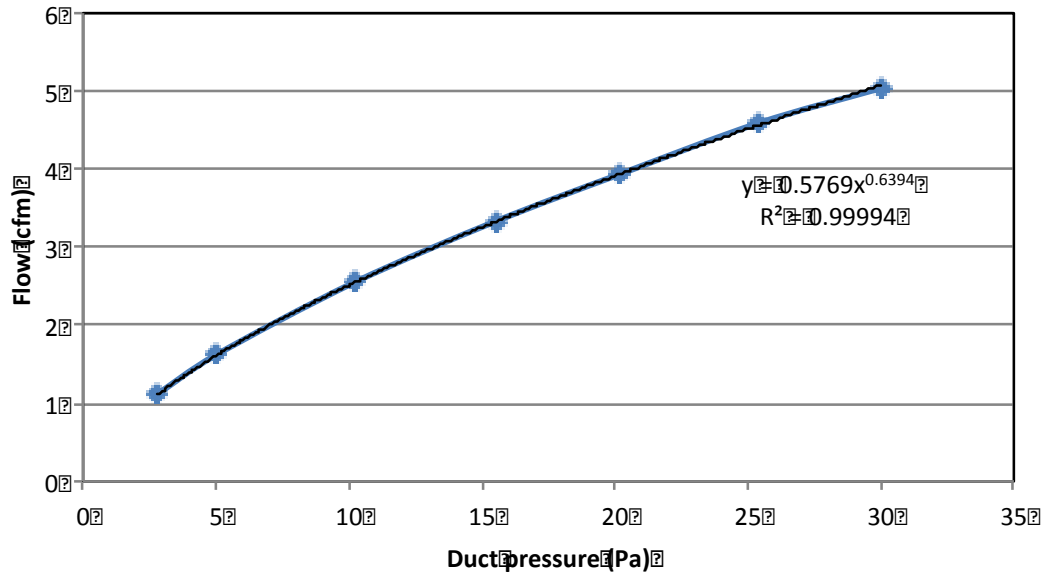



Figure F2. Depressurized test apparatus leakage measurements