LBNL-5982E

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

Measuring Residential Ventilation System Airflows: Part 2 - Field Evaluation of Airflow Meter Devices and System Flow Verification

J. Chris Stratton, Iain S. Walker, Craig P. Wray

Environmental Energy Technologies Division

October 2012

Disclaimer

Acknowledgments

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 and by the California Energy Commission under Pier Contract 500-08-061. The authors would like to thank Woody Delp and Will Turner for their thoughtful review of this report. We would also like to thank the flow hood manufacturers who agreed to participate in this study.

Please use the following citation for this report:

Stratton, J. Chris: Walker, Iain; Wray, Craig. (Lawrence Berkeley National Laboratory). 2012. ***Measuring Residential Ventilation System Airflows: Part 2 - Field Evaluation of Airflow Meter Devices and System Flow Verification.*** California Energy Commission. Publication number: CEC-XXX-2010-XXX.

Key terms: residential, mechanical ventilation, measurement, ASHRAE 62.2, flow hood

ABSTRACT

The 2008 California State Energy Code (Title 24 Part 6) requires that new homes meet ASHRAE 62.2-2007 requirements for mechanical whole-building ventilation and local exhaust. This study evaluates a sample of fifteen new California homes for ASHRAE 62.2-2007 compliance. The flows were measured with six commercially available flow hoods, and the accuracy and usability of these flow hoods were evaluated based on the results of these field measurements. Only two of the fifteen homes tested met all the ASHRAE 62.2 requirements for whole-building ventilation and local exhaust. Because of physical constraints, range hood flows were especially difficult to measure; the flows for only five of the thirteen homes could be evaluated. Consistent with laboratory findings of previous studies, powered flow hoods were found to provide more accurate field measurements than non-powered flow hoods. The errors for the powered flow hood measurements were around 6%, whereas those for the non-powered flow hoods ranged from 11% to 25%. A flow hood measurement standard that takes 'real world' conditions into account should be developed to ensure that residential buildings receive the intended ventilation flows. In addition, specific guidance should be developed with regard to the acceptable methods and equipment used to measure ventilation flows and to evaluate compliance with ASHRAE 62.2.

I. INTRODUCTION

This is the second component of a two-part report on measuring residential ventilation system airflows. The first part (Stratton et al., 2012) discussed their laboratory evaluation of airflow meter devices. The goal of this second component of the study was to evaluate the same devices in the field and to assess compliance with the residential ventilation requirements of ASHRAE Standard 62.2-2007 (ASHRAE, 2007) and the California State Energy Code (Title 24 Part 6) (CEC, 2008). ASHRAE Standard 62.2 requires mechanical whole-building ventilation and local exhaust. ASHRAE 62.2-2007 states that whole-building ventilation and local exhaust flows can be measured or can meet prescriptive ducting and fan labeling requirements, with the latter based on ratings provided by the Home Ventilating Institute (HVI, 2012). The 2013 version of the California State Energy Code will refer to ASHRAE 62.2-2010 (ASHRAE, 2010), which requires that whole-building ventilation airflows be measured with no exceptions. To show compliance with the ASHRAE Standard, we need a reliable way of measuring ventilation system airflows.

ASHRAE Standard 62.2[1] requires that whole-building mechanical ventilation systems provide a minimum airflow of:

$$Q_{fan} = 0.01A_{floor} + 7.5(N_{br} + 1)$$

where
Q_{fan} = fan flow rate, cfm
A_{floor} = floor area, ft^2
N_{br} = number of bedrooms; not to be less than one

For example, to meet ASHRAE 62.2, a 2000 ft^2, three-bedroom home will require a minimum whole-building airflow of 50 cfm.

ASHRAE 62.2 also requires intermittent local ventilation exhaust airflows of 100 cfm for kitchen range hoods and 50 cfm for bathroom exhaust fans. Continuous bathroom exhaust fan flows must be at least 20 cfm, and continuous kitchen exhaust flows must provide the kitchen five air changes per hour.

This study evaluates ASHRAE 62.2 compliance for fifteen California homes both for whole-building ventilation flows and for local exhaust flows. It also evaluates the accuracy of six commercially available flow hoods, based on our field experience using them to measure ventilation flows.

[1] Unless otherwise noted, in this document, 'ASHRAE 62.2' will refer to the 2007 version of that standard.

Homes Measured

Figure 1: Locations of the 15 California homes evaluated (the number of homes evaluated at each location is in parentheses)

The homes included in the study were all within a 100-mile radius of the Lawrence Berkeley National Laboratory (LBNL) and labeled FH1 through 15 (Figure 1). The nine unoccupied homes in Manteca (FH1-4, FH8-10) and Napa (FH14, 15) were in new housing developments. Two of the fifteen homes studied (FH5 and FH6) were built prior to the implementation of California Title 24 2008 which made ASHRAE 62.2 mandatory, but were designed to be compliant with ASHRAE 62.2. Houses FH1-4, 8-10, 14 and 15 were new and unoccupied at the time of the testing.

Table 1: Ventilation characteristics of homes evaluated (exes in bold designate whole-building ventilation fans)

	FH1	FH2	FH3	FH4	FH5	FH6	FH7	FH8	FH9	FH10	FH11	FH12	FH13	FH14	FH15
Out-vented Range Hood	x	x	x	x	x	x		x	x	x	x	x		x	x
Recirculating Range Hood							x						x		
HRV/ERV						**X**	**X**						**X**		
Hole-in-return						x									
Laundry Fan	**X**	**X**	**X**	**X**	**X**			**X**	**X**	**X**	**X**	**X**		**X**	**X**
Bath Fan 1	x	x	x	x	x			x	x	x	x	x		x	x
Bath Fan 2	x	x	x	x	x			x	x	x	x	x		x	x
Bath Fan 3	x	x	x	x				x	x	x	x	x		x	x
Bath Fan 4			x							x					
Occupied					x	x	x				x	x	x		

Twelve of the fifteen homes (Table 1) used the exhaust fan in the laundry room for whole-building ventilation (see Figure 2). The remaining three homes (FH6, 7 and 13) used a fully-ducted energy recovery ventilator (ERV) to provide whole-building ventilation (see Figure 3). In addition to an ERV, FH6 also has a hole-in-the-return ventilation system (see Figure 4). For more information on the different types of whole-building ventilation systems see Review of Residential Ventilation Technologies (Russell et al., 2005).

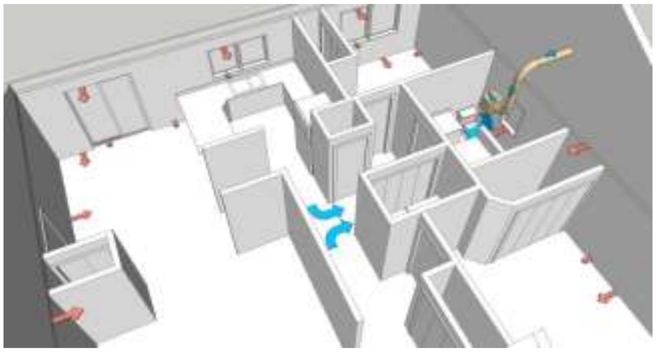

Figure 2: In a home with a single point bathroom exhaust fan, ventilation air enters as infiltration

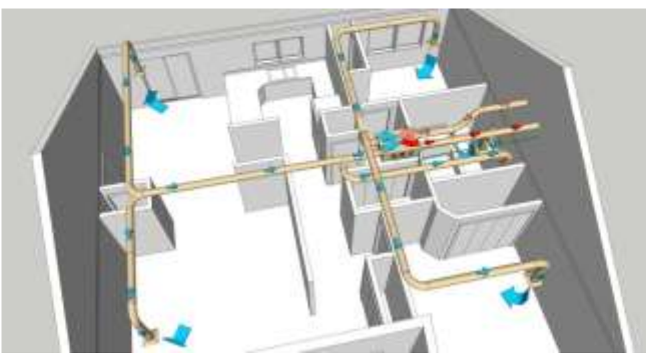

Figure 3: The heat recovery ventilator (HRV) in this home has dedicated supply and exhaust ducting

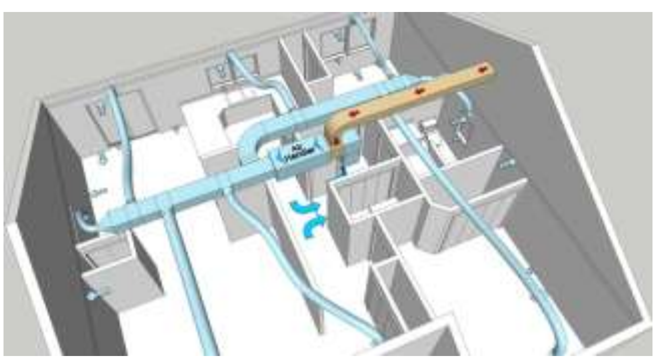

Figure 4: A home with a Central Fan Integrated ventilation system, colloquially known as a 'hole-in-the-return' system

Thirteen of the fifteen homes had range hoods vented to outside. Two of the three homes with ERVs had recirculating range hoods. The recirculating range hoods do not count as kitchen exhaust for compliance with ASHRAE 62.2. Instead, these kitchens need to comply with the alternative to local exhaust ventilation which is five kitchen air changes per hour that would be provided by the ERVs that have pickups in the kitchen.

Flow Hoods

Devices for measuring ventilation (or space conditioning) airflows in buildings are generally referred to as flow capture hoods, or “flow hoods” for short. Typically, these hoods capture the flow entering or exiting a terminal and funnel it through some kind of measurement mechanism. Most flow hoods can measure flows in either direction (both inlet and outlet) and they have the capability to perform time averaging.

Walker et al. (2001) described two categories of flow hoods, which they called non-powered flow hoods and powered (or “active”) flow hoods. Non-powered flow hoods passively measure the flow as it goes through the hood. Flow measurement techniques differ between manufacturers and involve sensing pressure differentials or air velocities, including hot wires, plate deflection, and spinning propellers. Powered flow hoods track the static pressure within the hood relative to the surrounding area and control a fan such that the fan’s flow matches the terminal flow and the static pressure difference across the hood wall is brought to zero. This approach, sometimes called the ‘zero pressure compensation’ method, reduces the effect of the hood on the flow itself and in previous studies (Caillou, 2012; Walker et al., 2001; Wray et al., 2002) has led to more accurate measurements. For a more detailed discussion on flow hoods, see part one of this report (Stratton et al., 2012).

In a previous study, we performed laboratory measurements with six commercially available flow hoods and one flow hood custom-built by LBNL (Stratton et al., 2012). This latter hood is referred to in this study as ‘EPB’, had a previously determined accuracy of ±2%[2] (Walker et al., 2001; Wray et al., 2002). In this study, we used the same devices to record flow measurements in the field. Our sample of commercially-available flow meter devices includes four non-powered devices (ABT701, EBT721, TECEFM, testo417) and three powered, pressure-compensating devices (DIFF, EBT, TECFB). Each of these seven hoods is illustrated in the following figures:[3][4][5]

TSI/Alnor Balometer® Flow Capture Hood ABT701 (ABT701)

Observator DIFF Automatic Air Volume Flow Meter (DIFF)

TSI/Alnor Balometer® Flow Capture Hood EBT721 (EBT721)

The Energy Conservatory Exhaust Fan Flow Meter (TECEFM)

The Energy Conservatory FlowBlaster™ (TECFB)

testo 417 Vane Anemometer (testo417)

Figure 5: The six commercially-available flow hood devices evaluated for this study

---

[2] The laboratory results conducted for this study determined that the accuracy of the EPB to be ±3.2%. This latter study measured lower flows (consistent with ventilation flows), and this may have contributed to the differing accuracy finding between the two studies.

[3] For more information on the devices evaluated, see
Appendix 1: Flow hood specifications

[4] The testo 417 vane probe anemometer is shown with the optional square flow capture funnel, which was used for all measurements

[5] All device images are taken from manufacturers' websites.

Energy Performance of Buildings Group powered flow capture hood (EPB)

Figure 6: The EPB custom-built laboratory grade flow hood device

II. APPROACH

Through recruitment efforts that included email, flyers, social media, and personal communication, we contacted home builders and homeowners asking if they would like to participate in the study. We followed up with each respondent and asked questions about their home to evaluate if it met the criteria for inclusion, as discussed below. After we established that their home(s) qualified and the homeowner indicated their interest in participating, we set up an appointment to take flow measurements.

Aside from geographic proximity, the other criterion for a home's participation in the study was that it must be required to meet California's 2008 Energy Efficiency Standards for Residential and Nonresidential Buildings. This means the building permit had to be submitted to the local enforcement agency for approval on or after January 1, 2010. Exceptions to this were FH5 and 6, which were permitted before 2010, but which were intended to comply with ASHRAE 62.2. FH11 underwent a significant addition and remodel in 2011, including the replacement of all exhaust fans with new ones intended to meet ASHRAE 62.2.

Upon arriving and entering the home, we first surveyed the fans, identifying their location, flow direction, and whether or not their airflow could be physically measured. We took barometric pressure and indoor air temperature measurements once inside the homes. ASHRAE 62.2 does not specify if flows are at standard or actual conditions and for consistency we needed to compare the results using one or the other basis. We chose to use flow at actual conditions because this is more likely to be used by practitioners. Therefore, we converted measurements given by the flow hoods that measure 'standard' flow into actual flow, using the equations specified by the manufacturer.

The range hoods were measured as outlet flows, because their indoor inlets could not be covered and sealed adequately by any of the commercially available flow hoods. Nine of the thirteen flows from range hoods that vent outside could not be measured because their outlets were in locations (such as rooftops) that were inaccessible or unsafe to access. This is a serious problem for confirming compliance with the standard.

The flow measurement recorded by the EPB flow hood was used as the reference in order to evaluate the accuracy of the commercially available devices. When the flow measurement could not be made with the EPB flow hood, we used the measurements from the TECFB as the reference. The accuracies of the EPB and TECFB hoods, as determined through laboratory measurement, are ±3.2% and ±3.6%[6], respectively (Stratton et al., 2012).

Pass/Fail decisions

A ventilation system was considered to pass if the difference between the measured flow and the flow required by ASHRAE 62.2-2007 was within the accuracy of the reference flow hood. It should be noted that although the 62.2 requirements reflect our current best understanding of the ventilation amount needed for healthy residential environments, meeting 62.2 flow requirements does not guarantee good indoor environmental quality (IEQ) and failing the flow requirements by a few cfm does not necessarily mean poor IEQ. Similarly, ASHRAE 62.2 gives minimum values of airflow and exceeding these values is perfectly acceptable from the point of view of 62.2. However, more airflow can lead to additional energy use in homes and potential benefits from increased dilution of indoor pollutants beyond 62.2 requirements need to be balanced against the potential costs of additional energy use.

[6] The uncertainty of the reference flow upon which this accuracy was based was ±2.3%

III. RESULTS

California homes' ASHRAE 62.2 compliance

Table 2 displays the test homes' compliance with ASHRAE 62.2 requirements for whole-building ventilation and local exhaust.

Table 2: The 15 California homes' compliance with ASHRAE 62.2 requirements for whole-building ventilation and local exhaust – values in green are in compliance, values in red are non-compliant (cells that are marked 'N/A' could not be evaluated)

						ASHRAE 62.2											
						Whole building ventilation		Local exhaust									
						Calculated bedroom-based whole-house ventilation (cfm)		Kitchen		Bath 1		Bath 2		Bath 3		Bath 4	
Home ID	Year built	Area (ft^2)	Volume (ft^3)	#Bed	#Occ	(R)equired	(M)easured	R	M	R	M	R	M	R	M	R	M
FH1	2012	3130	30258	4	0	69	116	100	168	50	46	50	51	50	111		
FH2	2012	2586	24066	3	0	56	94	100	N/A	50	36	50	106	50	48		
FH3	2012	3284	31500	4	0	70	80	100	N/A	50	42	50	43	50	113	50	46
FH4	2012	2902	28466	4	0	67	100	100	N/A	50	55	50	52	50	104		
FH5	2007	3281	34659	4	2	70	32	100	176	50	50	50	51	50	31		
FH6	2009	1776	15984	2	2	40	104	100	N/A	20	57	20	47				
FH7	2012	1860	18615	3	3	49	109	100	N/A	20	35	20	32				
FH8	2012	2586	24066	3	0	56	87	100	N/A	50	43	50	47	50	101		
FH9	2012	2480	22320	3	0	55	86	100	N/A	50	102	50	11	50	46		
FH10	2012	3777	33993	5	0	83	89	100	N/A	50	103	50	42	50	43	50	45
FH11	2011	2499	29988	4	4	55	35	100	N/A	50	32	50	70	50	81		
FH12	2012	1683	15147	3	1	47	82	100	145	50	80	50	73	50	37		
FH13	2012	2400	21600	4	4	62	75	90	17	20	14	20	N/A	20	17		
FH14	2012	2100	21000	3	0	51	52	100	N/A	50	13	50	55	50	105		
FH15	2012	1962	17658	3	0	50	51	100	118	50	56	50	103	50	49		

Whole-Building Ventilation

Thirteen of the fifteen houses included in the study met or exceeded the ASHRAE 62.2 whole-building ventilation requirements. Four of the six occupied homes met the ASHRAE 62.2 whole-building ventilation requirements. However, among these homes, the whole-building ventilation fans were running continuously in only the three homes with ERV/HRV systems.

Local Exhaust

All four of the homes for which kitchen range hood flows were measured met or exceeded the relevant ASHRAE 62.2 requirement. FH13 had a recirculating range hood, and so required 90 cfm of continuous ventilation in the kitchen, as calculated based on the five ACH requirement for kitchens in ASHRAE 62.2 that do not have a range hood vented to outside. However, the ERV return in the kitchen provided only 17 cfm of continuous exhaust, and so FH13 did not meet

ASHRAE 62.2 requirements for kitchen exhaust. It is probable that this was considered just another branch inlet and not sized with the intention of meeting ASHRAE 62.2 continuous kitchen ventilation requirements.

Of the 44 bathroom exhaust fans evaluated for this study, 23 (52%) met or exceeded the ASHRAE 62.2 required airflows for local exhaust. The continuous bathroom exhaust fans in the homes with ERVs were required to be 20 cfm, rather than the 50 cfm required for the other homes' intermittent bathroom exhaust fans. Without further investigation, it is not possible to say with any certainty why the failing fans failed. It is worth noting that in several instances the same fan model in the same house provided flows that differed by as much as a factor of four. This suggests that duct type, length, and condition affect flows considerably, and that installation quality is a factor that determines the flow of an exhaust assembly as much as the fan's HVI rated airflow.

Accuracy of field and laboratory measurements with commercially available flow hoods

Table 3 shows the accuracy of the flow measurement results for each device tested. It includes measurements taken both in the field and in the laboratory.

Table 3: Evaluation of the accuracy of field flow measurements for the six commercially available flow hoods(note: for the TECFB, only measurements that use EPB reference flows were included).

	Field Tests											
	TECFB		DIFF		TECEFM		testo417		ABT701		EBT721	
Flow Direction	in	out	in	out	in	out	in	out	in	out	in	out
Number of Measurements	32	14	44	2	76	N/A	76	16	63	7	63	10
% Within Acceptable Accuracy (±5 cfm, 10%)	97	93	100	100	79	N/A	45	56	95	86	97	0
Mean Difference (%)	6	-6	-3	-6	-12	N/A	-25	-20	-9	1	0	34
(cfm)	3	-11	-3	-2	-7	N/A	-20	-26	-6	-3	0	57
Mean Absolute Difference (%)	8	6	5	6	13	N/A	27	22	11	11	6	34
(cfm)	4	12	4	2	8	N/A	20	27	7	14	4	57
	Laboratory Tests											
	TECFB		DIFF		TECEFM		testo417		ABT701		EBT721	
Flow Direction	in	out	in	out	in	out	in	out	in	out	in	out
Number of Measurements	45	75	45	78	39	N/A	39	78	36	63	36	78
% Within Acceptable Accuracy (±5 cfm, 10%)	100	100	100	96	100	N/A	92	54	100	84	100	19

Mean Difference (%)	5	2	4	2	0	N/A	6	-6	-1	6	2	41
(cfm)	2	1	2	0	0	N/A	3	-4	0	4	2	32
Mean Absolute Difference (%)	6	2	5	6	4	N/A	6	16	4	7	4	41
(cfm)	2	1	3	3	2	N/A	3	9	2	4	3	32
	Manufacturer's Specification											
	TECFB		DIFF		TECEFM		testo417		ABT701		EBT721	
	±5% of reading, or 2 cfm, whichever is greater		±3% of reading + 0.6 cfm		±10% of reading	N/A	Velocity ± 0.33ft/s (flow: 1.3cfm) + 1.5% of reading		±3% of full scale selected (7.5 cfm) + 5 cfm		±3% of reading + 7 cfm for flows > 50 cfm	

Table 3 characterizes the accuracy of the field measurements and the previously recorded laboratory measurements (Stratton et al., 2012) for each of the six commercially available flow hoods evaluated. Each flow hood was evaluated separately for inlet (in) and outlet (out) flows. The field measurements listed and evaluated for the TECFB are only those for which the EPB was used as a reference flow. Listed in the "Within Acceptable Accuracy" row is the percentage of each flow hood's measurements that are within an acceptable accuracy range of 5 cfm and 10%, whichever is greater. For the field measurements, the uncertainty of the reference flow is also considered in this evaluation.[7] As such, this metric provides a conservative (i.e., inclusive) account of the percentage of flow measurements that are within an acceptable accuracy range for each flow hood.

The mean difference (MD) of the measurements is displayed for each device, listed as a percentage of the reference flow and as the cfm difference from the reference flow. Mean difference provides an indication of whether a flow hood's measurements tend to be positively or negatively biased. Finally, the mean absolute difference (MAD) is shown for a flow hood's measurements, listed as a percentage of the reference flow and as the cfm difference from the reference flow. Mean absolute difference provides an indication of the overall accuracy of a flow hood's measurements, as evaluated against a reference flow.

IV. DISCUSSION

Comparison of Laboratory and Field Results

The results in Table 3 show that, for all of the flow hoods besides the TECEFM and the testo417, the laboratory and field results were similar. Both the TECEFM and the testo417 provided less accurate field measurements than laboratory measurements, especially for inlet flows.

Although Stratton et al. (2012) did not report static pressure changes due to flow hood insertion losses during their laboratory measurements, it is worth noting that these two devices produced the largest static pressure changes during

[7] Uncertainty of the reference flow is the sum of the accuracy of the reference flow hood as determined by laboratory measurements and the uncertainty of the laboratory reference flow meter upon which that accuracy is based.

those measurements. This suggests that these two hoods had the greatest effect on the flow during the measurement. In the laboratory, this effect was corrected by the fan settings, which adjusted to maintain a constant flow. However, the fans we measured in the field, with few exceptions, did not adjust to maintain a constant flow, potentially leading to larger discrepancies between reference field flow measurements and the field measurements taken by the TECEFM and testo417.

Accuracy and Usability of Commercially Available Flow Hoods

Energy Conservatory FlowBlaster (TECFB) - powered

Key Issues

Heavy weight; Long, complicated setup; No measurement button on handle; Must reconfigure device when switching between flow directions

Accuracy

97% of inlet flow measurements and 93% of outlet flow measurements made with the TECFB were within acceptable accuracy range for measuring ventilation flows when compared to reference flow measurements made by the EPB. The TECFB's inlet measurements had a slight positive bias (MD of 6%) and its outlet measurements had a slight negative bias (MD of -6%). Its accuracy was similar for measuring inlet (MAD of 8%) and outlet (MAD of 6%) flows. The TECFB measures flow based on assumed standard air density conditions.

The TECFB's field measurement results were slightly less accurate than its rated accuracy, but generally still well within our acceptable accuracy range.

Figure 7: The FlowBlaster™ add-on kit for the Energy Conservatory's Duct Blaster®

Note: The TECFB was used as a reference flow hood when the EPB flow hood could not be used. However, all the accuracy figures discussed above were based on measurements for which the EPB was used as a reference hood.

Usability

The TECFB is an add-on kit for The Energy Conservatory's Duct Blaster®, so its setup is similar to that of the Duct Blaster (see Figure 7). The blower is attached to one of three rings, based on the flow being measured. The fan's orientation must be changed when switching between inlet and outlet flows. Attached to the fan is a capture hood made of a fabric that is both flexible and airtight. The fabric is stretched over a frame supported by the kind of thin plastic rods that might come with a camping tent, and kept in place with hook-and-loop fasteners. Pressure tubes must be run from the DG-700 manometer to the combined blower and capture hood. The configuration of the tubes changes slightly when switching from inlet to outlet flow measurement, and care must be taken to ensure that the correct configuration is used. The TECFB is powered by a dedicated lithium-ion battery pack that sits in a holster strapped to the user's waist.   There are cables that run from the battery pack to the blower and from the blower to the DG-700. Based on our testing, it takes an experienced user five to seven minutes to set up the TECFB.

The DG-700 must be configured for the flow ring being used and the direction of the flow. The configuration process requires pressing specific buttons on the 12-button keypad in a specific sequence. In this way, the versatility of the DG-

700 is also a shortcoming, as it introduces to the setup process a complexity that can be intimidating to novices and tedious to even experienced users.

The TECFB's 18"x18" capture hood fit over nearly all the terminals we encountered. Only the flow hood's 30-inch height precluded its use to measure terminals in tight spaces, such as laundry exhaust fans over an appliance or cabinet, or a bathroom exhaust fan above a shower curtain bar.

At 12 lbs., the TECFB was the heaviest of the flow hoods that we included in the study. Ascending and descending ladders to reach terminals was made difficult by the battery holster's tether to the flow hood. To initiate the measurement process, the user must press the 'Begin Cruise' button on the DG-700 that is mounted to the side of the TECFB. This button cannot be reached while holding the flow hood with both handles. This situation requires the user to make a choice: either hold up the TECFB using one hand while pressing the 'Begin Cruise' button with the other, or press the 'Begin Cruise' button before placing the TECFB's capture hood over the terminal. If the user chooses the latter option, he risks an aborted measurement. If he chooses the former, he risks back strain and loss of balance. The addition of a dedicated 'Begin Cruise' button to one of the TECFB's handles would eliminate this conundrum and improve the flow hood's usability.

<u>Observator DIFF Automatic Air Volume Flow Meter (DIFF) - powered</u>

Key issues
Short battery life; No measurement button on handle; Long setup time

Accuracy
100% of the field measurements taken with DIFF were within the acceptable accuracy range for ventilation flow measurement.[8] Both the DIFF's inlet (MD of -3%) and outlet (MD of -6%) measurements had a slight negative bias. The accuracy of the DIFF's inlet (MAD of 5%) and outlet (MAD of 6%) flow measurements was nearly identical. The DIFF measures actual volumetric flow.

The DIFF's field measurements were slightly less accurate than its rated accuracy, but all of them were within our acceptable accuracy range.

Figure 8: With the capture hood attached, the DIFF is more difficult to support with one hand

Figure 9: The DIFF's digital interface, with click wheel.

Usability
The DIFF can be used alone or with any of various hoods available from the manufacturer. We primarily used the DIFF with the 24"x24" hood because we found that the DIFF alone (which measures 10"x10") didn't fit over some bathroom exhaust grilles. The fabric and supports for the DIFF hoods resembled camping

[8] Note: because of availability constraints, only 2 outlet flow field measurements were taken with the DIFF.

tent equipment. The setup process required some practice to learn and took five to seven minutes for even an experienced user. The DIFF has adjustable handles that click into place and allow the user to configure the display for easy viewing while taking the measurement. To ensure a proper measurement, the DIFF has to be held in place over the terminal when the ‘measurement’ button is pushed. At 6.4 lbs., the DIFF is by far the lightest powered flow hood included in our evaluations. Without the optional hood, it’s manageable to push the button while holding the DIFF with one hand (Figure 8). But when the weight and size of a capture hood is added (Figure 8), it becomes a strain to hold the device with one hand while pressing the ‘measurement’ button with the other. Also, the ‘measurement’ button is actually an all-in-one multi-purpose click wheel, with an interface similar to an early-generation Apple® iPod® (See Figure 9). Sometimes when holding the device with one hand while attempting to push the button with the other, the wheel turned before the button was pushed, and a selection other than ‘measurement’ was made. The addition of a dedicated ‘measurement’ button integrated into the handle would prevent this error and improve the DIFF’s usability.

Unlike the two other powered flow hoods included in this study, the DIFF automatically detects the direction of the flow and does not require reconfiguration when switching between inlet and outlet flow measurements. The DIFF is powered by four AA batteries. The product manual states that “the DIFF is designed for modern rechargeable NiMH batteries with a capacity of 2700mAh as a minimum.”(Nasveld, 2010) In the course of our measurements, we found that the DIFF’s batteries had to be charged and replaced more frequently than was indicated by the manual, which stated that fully charged batteries should last “8 hours fan in continuous operation at 75 m^3/h”. We used new rechargeable 2700mAh NiMH batteries as indicated, but still found that the DIFF needed freshly charged batteries after as few as ten flow measurements.

The DIFF can take 20 seconds or more to make small fan adjustments to settle on a flow measurement, which it then displays in tenths of a cfm. Some users might be willing to trade getting a slightly less precise result – say, rounded to the nearest cfm – in exchange for a quicker measurement; the addition of a setting that would allow users to trade off speed for precision would be a welcome option for some users.

Energy Conservatory Exhaust Fan Flow Meter (TECEFM) - passive

Key issues

Only measures inlet flows up to 124 cfm; Sensitive to flow location; Can cause insertion loss

Accuracy

79% of the measurements recorded by the TECEFM were within the acceptable accuracy range for ventilation flows (inlets only). The TECEFM’s flow measurements had a moderate negative bias (MD of -12%). The MAD of the of the TECEFM’s measurements was 13% relative to the reference flow. The TECEFM measures flow based on assumed standard air density conditions.

The TECEFM’s field measurements were slightly less accurate than its rated accuracy, and most were within our acceptable accuracy range.

Usability

Setting up the TECEFM entails attaching a tube to the pressure tap and to a manometer such as an Energy Conservatory DG-700. If desired, a painter’s pole can be attached to the metering box to more easily reach terminals. This setup process takes less than a minute, and makes the TECEFM the easiest of the flow hoods tested to set up and use.

Using the TECEFM, the DG-700 can be configured to calculate flows automatically using the EXH setting, or the pressure recorded by the DG-700 or by another manometer can be looked up in a flow table printed on the side of the metering box. The TECEFM has a flap that slides into one of three positions, depending on the flow range and induced pressure being measured. The position of this flap must be taken into consideration when calculating the flow using either the DG-700 or the lookup table. We typically took measurements by taking 5-second-averaged pressure measurements with the DG-700 and then using the lookup table to find the flow.

The TECEFM is light (3 lbs.) and small, and was able to cover nearly all the inlet terminals that we encountered. Its shallowness (8 inches) and breadth (13" x 16") made it the most physically versatile flow hood included in the study. However, this physical flexibility comes at a cost in terms of the kinds of flows it can measure. The TECEFM is only intended to be used to measure inlet flows between 10 and 124 cfm. This means it is limited to measuring bathroom and laundry exhaust inlet flows and measuring inlet flows for a fully-ducted HRV/ERV.

<u>testo 417 Vane Anemometer (testo417) - passive</u>

Key issues
Funnel too small for some bathroom exhaust terminals; Insertion loss leads to negatively-biased measurements

Accuracy
45% of the inlet flow measurements and 56% of the outlet flow measurements made with the testo417 were within the acceptable accuracy range for ventilation flow measurements. Both inlet (MD of -25%) and outlet (MD of -20%) measurements had a significant negative bias. Possible contributors to these negative biases were a poor seal around the terminal and insertion loss caused by the testo417. The accuracies for inlet (MAD of 27%) and outlet (MAD of 22%) measurement were similar.

The testo417's rated accuracy is listed in terms of velocity, not volumetric flow. To translate velocity accuracy to flow accuracy, we measured a flow with the testo417 and displayed the results in both feet per minute and cubic feet per minute. We then divided the flow measurement by the velocity measurement to determine the aperture opening area used by the device. This area was then multiplied by the rated velocity accuracy figure to convert it to a flow accuracy rating. The testo417 measures actual volumetric flow.

The testo417's field measurements were considerably less accurate than its rated accuracy, and around half of them were within our acceptable accuracy range.

Usability
The testo417 vane anemometer is first removed from its case and snapped into one of its two funnels. The testo417 can be set up and ready to take flow measurements in less than a minute.

According to its manual, the testo417 can be used to measure volumetric flow without the use of its optional capture funnels, but we found this method impractical, and opted to use the testo417 exclusively with its capture funnels. Using the testo417 to measure volumetric flows without the capture funnels requires 'sweeping' the anemometer across the terminal face while taking an average velocity measurement. This average velocity is then multiplied by the terminal's open area, as measured -- or approximated -- by the user, to produce a volumetric flow. In our findings, the measurement inaccuracies and uncertainties associated with this method rendered its results meaningless.

The testo417 is light (3 lbs., including funnel) and small (12"x12"x8" tall), making it among the easiest-to-use flow hoods included in this study. The capture funnel is placed over the terminal and a button is pressed to start and stop the timer.

We took 20-second average measurements. The testo417 automatically detects the direction of the flow. The shallow depth of the testo417 allowed it to be used to take measurements in spaces that were too tight for every other flow hood tested. However, its opening was too small to fit completely over many of the bathroom exhaust covers that we encountered. This prevented the testo417's capture funnel from making a good seal against the wall or ceiling surface, and resulted in flows that were too low. In addition, just as in the laboratory measurements, the testo417 introduced significant airflow resistance to the terminals and reduced the flow being measured. The testo417 takes air temperature measurements as well as air velocity measurements.

<u>TSI/Alnor ABT701 (ABT701) - passive</u>

Key issues
Flow screen and edge seal; Ambiguity of measurement; Large size prevents use in small spaces*;* Unable to measure flows <30 cfm

Accuracy
95% of the inlet flow measurements and 86% of the outlet flow measurements taken by the ABT701 were in the acceptable accuracy range for ventilation flow measurements (Table 3). The ABT701's rated accuracy is ±12.5 cfm for the setting we used, meaning that its rated accuracy is within our acceptable accuracy range only for flows greater than 125 cfm. Yet, the device performed significantly better than its rated accuracy across all flows tested. The ABT701 had a moderate negative bias when measuring inlet flows (MD of -9%) and a very slight positive bias when measuring outlet flows (MD of 1%), meaning that its measurements were, respectively, on average 9% lower and 1% higher than the reference flow measurement. The accuracy of the ABT701's inlet (MAD of 11%) and outlet (MAD of 11%) measurements was identical. The ABT701 measures flow based on assumed standard air density conditions.

Figure 10: The ABT701's analog needle requires interpretation by its user so is susceptible to parallax error

Figure 11: As this range hood outlet measurement shows, the ABT701's height requires the user to be well away from the terminal

The ABT701's field measurements were more accurate than its rated accuracy, and nearly all of them were within our acceptable accuracy range. It was the only flow hood that performed better than its rated accuracy for both laboratory and field measurements.

Usability
Setting up the ABT701 is relatively quick and straightforward. It can be transformed from an unzipped case to a measurement-ready flow hood in about 3 minutes.

The ABT701 is large for residential applications. Its width (24 inches) and height (40 inches) make it difficult to get through residential doorways. The aluminum frame at the hood face is prone to scuffing walls and door frames. We combatted this by covering the frame with painter's tape and by using care when crossing through narrow thresholds. The size of the ABT701 prevented us from taking measurements in some instances because it couldn't fit in the space available. At 7 lbs., the weight of the ABT701 is manageable.

The height of the ABT701 is convenient in that it allows the user to measure ceiling terminal flows without using a step ladder. However, this height becomes a liability when using the ABT701 to measure wall terminals, because it requires the user to extend well away from the wall – a position that is potentially hazardous when standing on a ladder (Figure 11), and difficult to do in smaller rooms, such as bathrooms.

The ABT701 has a mesh fabric flow-conditioning screen that is attached by hook-and-loop fasteners to the frame at the flow hood's face. The screen covers the face of the hood and makes it difficult to measure terminals that protrude from the surface of the wall, such as exterior exhaust hoods for ventilation, dryer, and range hood flows. The protruding rain hood pushes against the screen and prevents the flow hood from making a good seal against the wall. Previous studies have found that flow conditioning screens can significantly improve flow hood measurements (Walker et al., 2003).

The ABT701 has an analog needle that displays the flow being measured (Figure 10). The needle moves during the measurement, requiring the user to interpret the results indicated. The ABT701 measured continuously, which obviated the need to simultaneously support the device and push a 'measure' button. During the measurement, the user could focus on getting the best seal possible and interpreting the measurement from the needle.

The ABT701 cannot measure flows less than 30 cfm; it can be used to measure most bathroom exhaust fan flows, but cannot be used to measure most flows for fully-ducted HRV/ERV systems.

<u>TSI/Alnor EBT721 (EBT721) - passive</u>

Key Issues
Inaccurate outlet flow measurement; Large size prevents use in small spaces; Problem with input jack; Unable to measure flows less than 25 cfm

Accuracy
97% of the inlet and 0%[9] of the outlet flow measurements made by the EBT721 were within the acceptable accuracy range for ventilation flows. The EBT721 had no bias (MD of 0%) when measuring inlet flows, but had a strong positive bias (MD of 34%) when measuring outlet flows. The EBT721 measured inlet flows (MAD of 6%) much more accurately than outlet flows (MAD of 34%).

Although it has a shape and size identical to the ABT701, the EBT721 does not come equipped with the ABT701's flow conditioning screen. The experimental addition of the screen significantly improved the EBT721's outlet flow measurements in the laboratory, and we suspect that it would similarly improve the EBT721's outlet flow measurements in the field. However, because the EBT721 does not come equipped with the screen, we chose to make its field measurements without the screen. The EBT721 measures actual volumetric flow.

The accuracy of the EBT721's field measurements depended on the type of flow being measured. Its inlet flow field measurements were consistent with its rated accuracy, and nearly all of them were within our acceptable accuracy range. Its outlet flow field measurements were far less accurate than its rated accuracy, and none of them were within our acceptable accuracy range.

Usability
Setting up the EBT721 is quick and straightforward. It can be transformed from an unzipped case to a measurement ready flow hood in about 3 minutes. Its setup is identical to the ABT701 except that it does not have a flow conditioning screen.

[9] 10 outlet flow measurements were made with the EBT721.

With a few exceptions, the EBT721 has the same usability advantages and disadvantages as the ABT701. Like the ABT701, the EBT721 is large for residential spaces and one must take care to prevent scuffing walls when navigating doorways and narrow hallways. The absence of a flow conditioning screen allows the EBT721 to make a good seal when taking flow measurements over protruding rain hoods, but also likely contributes to the inaccuracy of outlet flow measurements. The EBT721 provides a digital flow measurement and temperature readout approximately 5 seconds after pressing the 'Read' button.

We encountered an electromechanical problem with one of the input jacks on the unit that we tested, and worked with the manufacturer to resolve the problem. The EBT721 is not rated for measuring flows below 25 cfm. However, during the course of our measurements, its digital readout displayed flow measurements as low as 19 cfm.

Impediments to making flow ventilation flow measurements

A good air seal is necessary for a flow hood to make an accurate measurement. When taking flow measurements, we made every effort to ensure that there was a good seal between the terminal and the flow hood being tested.

<u>Bathroom fan and ERV/HRV terminals</u>

In some cases, physical impediments make it difficult or impossible to measure a terminal's flow with a particular flow hood. None of the flow hoods that we evaluated were able measure every terminal that we encountered. The smallest instruments – the TECEFM and testo417 – were the most versatile in terms of getting into tight spaces. However, sometimes these devices were too small, and either couldn't fit over the terminal to be measured or could not reach the flow that was being measured, or both. The largest hoods – the ABT701 and EBT721 – could read higher flows and fit over even the largest terminals, but were too big for many of the smaller spaces in the homes. The DIFF and the TECFB were of a moderate size and could fit over most terminals, but still had the ability to measure both high and low flows.

Figure 12: None of the flow hoods would fit into the space adjacent to this bathroom ERV inlet; it went unmeasured

Figure 13: Only the smallest flow hoods could measure this ERV outlet set between floor joists

Figure 14: The refrigerator has to be pulled out to measure this kitchen ERV inlet, and even then, the uneven surface prevented measurement with most of the flow hoods

Figure 15: The ledge and uneven surface adjacent to this ERV outlet terminal made its flow difficult to measure

<u>Range hoods</u>

Range hood flows cannot usually be measured from inside because it is rarely possible to get a good seal between the flow hood and the range hood inlet (Figure 17). To measure a range hood flow from inside, a custom-sized capture box or hood must be constructed and connected to a fan/flowmeter combination such as the Energy Conservatory DuctBlaster® or Retrotec DucTester. Building a custom apparatus for each home's range hood is not practical for home contractors, and the aesthetics of the resulting device may not inspire confidence among clients, despite its accuracy. An alternative is to measure range hood flows at the outlet on the outside of the house. If the range hood outlet is on the side wall of the house, and that outlet can be reached, the flow can be measured there (subject to the practicability of establishing a good seal, which may not be possible for homes with certain types of siding). If the range hood outlet is on the roof or some other inaccessible location, it becomes difficult or to measure because fall protection measures for safety might be needed (Figure 16).

Figure 16: We located FH6's range hood outlet (circled) on its roof, but for safety reasons did not try to measure its flow

Figure 17: The dimensions and irregular surface of this typical microwave-integrated range hood in FH2 makes inlet flow measurements difficult

V. CONCLUSIONS AND RECOMMENDATIONS

ASHRAE 62.2 Compliance

Thirteen of the fifteen homes that we tested met the ASHRAE 62.2 whole-building ventilation requirements, but only two of fifteen met ASHRAE 62.2's local exhaust requirements for all bathroom exhaust fans. Because range hood flows are difficult to measure, the ASHRAE 62.2 local kitchen exhaust requirements were evaluated for only five of the thirteen homes with out-venting range hoods, with four passing.

All three ERV homes – FH13, FH14, and FH6 – met the ASHRAE 62.2 whole-building ventilation requirements and had one or more bathroom exhaust fans fail to meet the local exhaust requirement.

These results suggest that a significant proportion of new California homes fail to meet one or more components of the ASHRAE 62.2 requirements.

Eight of the thirteen homes that met the ASHRAE 62.2 whole-building ventilation requirements were 'over ventilating' at a flow that averaged 82% more than their required flow. However, the phrase 'over ventilating' may be a misnomer, as there is currently no consensus that the ASHRAE 62.2 ventilation requirements in all cases represent the ideal balance between energy and health costs (Logue JM, 2011; Turner et al., 2012). Simulations by Turner et al. (2012) suggest that in some instances these higher ventilation rates may be appropriate.

Recommendations

1. <u>Establish Standard for Flow Hood Accuracy</u>

At present, there is no industry consensus standard for assessing flow hood accuracy. For several of the hoods, there was little resemblance between the manufacturer's claimed accuracy and the accuracy that we determined in the course of our laboratory and field measurements. To ensure that hoods are evaluated uniformly on their ability to measure flows in the field, there needs to be a standard method of testing for accuracy evaluation that incorporates 'actual use' considerations, such as terminal type, flow direction, and flow location.

Establishing an industry consensus standard for assessing flow hood accuracy would give practitioners more confidence in their flow hoods and help them verify that homes are receiving ventilation flows consistent with ASHRAE 62.2 requirements. Until this standard is completed we can only give broad recommendations for acceptable methods of showing compliance with ASHRAE 62.2:

1. For inlet flows, use any hood except a rotating vane type
2. For outlet flows, use only powered flow hoods[10]

2. Establish Guidance for Range Hood Flow Measurements

Range hood flows are difficult to measure. Previous studies (Fugler, 1989; Kuehn et al., 1989) have discussed laboratory range hood flow measurements, but little guidance exists for field measurement of range hoods. The dimensions and configuration of range hood inlets vary, making it difficult to get a good seal between a range hood inlet and a flow hood. Custom-designed measurement boxes or capture hoods can be constructed to fit over individual range hood inlets, but it is not reasonable to expect a practitioner to do this for every home.

Range hoods come in standard widths, (a 30-inch width is most common), and their depths and surrounding conditions vary. Although it would not be difficult to imagine a commercial capture hood versatile enough to establish a good seal with a majority of range hoods inlets, no such product currently exists to the knowledge of the authors.

In some cases, range hood flows can be measured at the outlet terminal on the outside of the home. If the outlet is in a location that can be accessed safely, such as a side wall with a relatively smooth surface (e.g., stucco rather than clapboard siding), the flow can be measured there. However, among the thirteen homes with out-vented range hoods that we encountered in this study, only four had outlet terminals that could be safely accessed and measured.

If range hood flows are to be measured to verify compliance with the ASHRAE 62.2 local kitchen exhaust requirements, guidance needs to be established with regard to the methods and flow hoods that are to be used to make these measurements.

3. Ensure that Bathroom Exhaust and ERV/HRV Terminals are Measureable

Because they are usually installed on the face of continuous flat surfaces such as walls and ceilings, flows at terminals for bathroom exhaust fans and fully-ducted HRV/ERV systems tend to be more readily measureable than range hood flows. However, these terminals present their own measurement challenges. Tight spaces or obstructions immediately in front of the terminal face can make flow measurement difficult or impossible. If the wall or ceiling surface surrounding the terminal is inadequately sized or irregular, it may not be possible to create a seal with the flow hood and make an accurate measurement.

Given that ASHRAE 62.2 requires measurement of the ventilation flows at these terminals, it is imperative that efforts are made to ensure that flows at these terminals are in fact measurable. Possible strategies for ensuring the measurability of these flows may include a building code stipulation requiring an adequately-sized flat surface bordering the terminal and a requirement that flow hoods have an adjustable flow capture mechanism that can establish a good seal under a range of common terminal conditions.

[10] To date, no non-powered flow hood has been able to measure outlet flows with an acceptable level of accuracy.

REFERENCES

ASHRAE. (2007). ASHRAE Standard 62.2-2007: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.

ASHRAE. (2010). ASHRAE Standard 62.2-2010: Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings.

Caillou, S. (2012). *Flow Rate Measurement at Air Terminal Devices: Comparison Study of Common Methods for Residential Applications*. Paper presented at the Ventilation 2012, The 10th International Conference on Industrial Ventilation, Paris, France.

CEC. (2008). 2008 Building Energy Efficiency Standards for Residential and Nonresidential Buildings *California Title 24, Part 6*. Sacramento, CA, USA.

Fugler, D. W. (1989). Canadian Research into the Installed Performance of Kitchen Exhuast Fans. *ASHRAE Transactions, 95(1)*, 6.

HVI. (2012). Certified Home Ventilating Products Directory: Certified Ratings in Air Delivery, Sound and Energy for Accurate Specifications and Comparisons. In H. V. Institute (Ed.), (Vol. HVI Publications 911).

Kuehn, T. H., Ramsey, J., Han, H., Perkovich, M., & Youssef, S. (1989). A Study of Kitchen Range Exhaust Systems. *ASHRAE Transactions, 95(1)*, 9.

Logue JM, M. T., Sherman MH, Singer BC. (2011). Hazard Assessment of Chemical Air Contaminants Measured in Residences. *Indoor Air*, *21*(2), 17.

Nasveld, C. W. (2010). Observator Instruments Manual DIFF Automatic Retrieved 10/18/2012, from http://www.houm.no/filestore/PDF/MeteorologiKlima/Observator/DIFFManualV10.02-ENG.pdf

Russell, M., Sherman, M., & Rudd, A. (2005). Review of Residential Ventilation Technologies.

Stratton, J. C., Turner, W. J. N., Wray, C. P., & Walker, I. S. (2012). Measuring Airflows in Residential Mechanical Ventilation Systems: Part 1 - Laboratory Evaluation of Commercially Available Devices *(LBNL # Pending)*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Turner, W. J. N., Logue, J. M., & Wray, C. P. (2012). A Combined Energy and IAQ Assessment of the Potential Value of Commissioning Residential Mechanical Ventilation Systems *(LBNL # Pending)*. Berkeley, CA, USA: Lawrence Berkeley National Laboratory.

Walker, I. S., Wray, C. P., Dickerhoff, D. J., & Sherman, M. H. (2001). Evaluation of flow hood measurments for residential register flows (E. P. o. B. Group, Trans.) *LBNL#-47382*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Walker, I. S., Wray, C. P., Guillot, C., & Masson, S. (2003). Evaluation of Commercially Available Techniques and Development of Simplified Methods for Measuring Grille Airflows in HVAC Systems *LBNL#-51551*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Wray, C. P., Walker, I. S., & Sherman, M. H. (2002). Accuracy of Flow Hoods in Residential Applications (E. E. T. Division, Trans.) *LBNL#-49697*. Berkeley, CA: Lawrence Berkeley National Laboratory.

APPENDICES

Appendix 1: Flow hood specifications

Manufacturer	Model	Dimensions in inches			Weight (lbs.)	Stated accuracy	Rated flow range (cfm)	Cost ($)	Powered by	Notes
		length	width	depth						
TSI/Alnor	ABT701	24	24	40	7.4	±3% of full scale selected, + 5 cfm	30-1000	2375 - 3632	4 AA batteries	
Observator	DIFF	10	10	18	6.4	±3% of reading + 0.6 cfm	6-235	3800 (does not includes optional hoods)	4 AA Sanyo 2700 mAh NiMH batteries	Multiple hoods available. Tested with 24"x24" hood. Dimensions without optional hood.
TSI/Alnor	EBT721	24	24	40	7.4	±3% of reading, ±7 cfm for flows greater than 50 cfm	25 -2500	2645 - 3784	4 AA batteries	
The Energy Conservatory	Exhaust Fan Flow Meter	16	13	8	3	±10% of reading, when used with DG700	10 -124	975 (includes flow meter and DG700 manometer)	9v battery	Price includes flow meter and DG700 manometer
The Energy Conservatory	FlowBlaster	18	18	30	12	±5% of reading, or ±2 cfm, whichever is greater	10 - 300	2975 (includes Duct Blaster and FlowBlaster kit)	Dedicated Li-ion battery pack, 9v battery.	FlowBlaster kit and Duct Blaster can be purchased seperately
Testo	417	12	12	8	3.6	velocity: ±3.3 ft/s + 1.5% of reading	0 - 99,999	686 - 728 (includes vane anemomenter and funnel kit)	9v battery	Dimensions include rectangular funnel (kit also comes with conical funnel)