Measured Duct Leakage at Operating Conditions in 48 Homes

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ABSTRACT

Duct leakage has long been recognized as a source of energy loss in residential HVAC systems. Unfortunately, for years it has been difficult to accurately measure duct leakage under normal operating conditions. Instead, duct leakage has been measured at an artificially created pressure, which actually measures the airtightness of the ducts rather than the leakage. Recently, two new methods have been developed for estimating duct leakage under normal operating conditions. In the course of a research project evaluating these methods, duct leakage was measured in 48 single-family homes in the Puget Sound region of Washington and was found to average 12% of air handler flow, across the three methods studied, on both the supply and return side when measured at operating conditions.

The purpose of this paper is two-fold. First is a discussion of the validation process of the benchmark method used in this study. Second, the house and conditioning system characteristics for a large sample of homes are presented.

Introduction

Duct leakage in forced-air distribution systems has been recognized for years as a major source of energy losses in residential buildings. Duct leakage can have a variety of impacts. It causes the thermal efficiency of the distribution system to be lower. For heat pumps and air conditioners, return leakage can greatly affect the conditions of the air flowing over the coil, thereby reducing its performance. For heat pumps in heating mode, duct leakage can cause the backup heating to be used more, reducing the efficiency benefits of having a compressor. Further, large or concentrated duct leakage can cause homes to have localized areas that are uncomfortable.

It is reasonable to assume that most houses have some duct leakage, but if the duct system is installed properly, the duct leakage is likely to be relatively small and distributed throughout the duct system. Typically, the leakage in these homes is located primarily at seams and connections, and is often not cost-effective to repair. Thus, quantification of the leakage in an individual house is useful in determining the economic feasibility of duct repair.

Accurate measurement of duct leakage is a notoriously difficult task, and a test with the right combination of simplicity and accuracy has been elusive. Aside from tracer gas tests, which are expensive, difficult, and time-consuming, duct leakage tests for years were done under artificial conditions, with the air handler off and the ducts pressurized or depressurized. This type of test, referred to as a static test, is problematic when trying to assess the actual duct leakage. The duct pressure created in these tests is usually nearly uniform throughout the ducts, and is typically set to approximately the same value for all houses. This differs from the normal operating conditions of the duct system, where the pressures at the plenums can range from 10 Pascals (Pa) to 200 Pa, and the pressures decrease drastically as one gets closer to the registers and grilles. If the majority of the duct leaks are at high pressure locations, such as plenums, static tests may under-represent the actual leakage. If the duct leaks tend to be at lower pressure locations such as registers, the static tests may over-represent the leakage. Static tests actually measure the effective cumulative area of the holes (airtightness), as opposed to the pressure at the holes that is actually causing the leakage.

The following paper is based on a recent study, funded by the National Energy Technology Laboratory, in which leakage tests were performed on 51 homes located in the Puget Sound region (Francisco et al. 2003a). Three of these homes were manufactured homes and were considered separately; the remaining 48 site-built homes are the subject of this paper. All future mention of the "project" or "study" is in reference to this study. The primary purpose of the study was to provide a side-by-side comparison, in real houses, of the performance of various duct leakage tests methods. In this comparative study it was critical to have an independent benchmark measurement of duct leakage against which the other methods would be evaluated. Field assessment of the accuracy of the benchmark estimate was performed in a subsample of five houses. This process and the results will be detailed in this paper.

The project also sought to develop an understanding of the pertinent characteristics of the forced-air heating system and other relevant features of the housing stock in the Puget Sound region. A summary of these findings and the duct leakage results for the 48 site-built homes are also presented in this paper. In addition, the comparative results of the various test methods will be discussed briefly.

Test Methods

The duct leakage tests performed in the study were the nulling test, the Delta-Q test, the fan pressurization test (a static test), and the benchmark estimate. The remainder of this section includes a brief description of the first three methods, as well as the screening process used in the sample selection for this project. The benchmark estimate will be discussed in detail in the following section.

The nulling test. The nulling test (Francisco & Palmiter 2001) is predicated on the idea that, when the air handler is turned on, any change in house pressure is due to unbalanced duct leakage. When there is more supply leakage than return duct leakage, the effect is analogous to an exhaust fan, and the house is depressurized. If the return leakage is greater, the unbalanced duct leakage is like a supply fan, and the house is pressurized. Using a calibrated fan to counter the change in pressure can provide an estimate of duct leakage.

Two of the most appealing features of the nulling test are that it directly measures leakage to outside at operating conditions and it is not based on an underlying model, and so has no equations. The primary drawbacks are the setup required for a portion of the test and sensitivity to wind.

The Delta-Q test. The Delta-Q test method (Walker et al. 2001a) utilizes four multi-point blower door tests. Two of these are tests that pressurize the house, and the other two depressurize the house. For each of these pairs of blower door tests, one test is with the air handler off and the other is with the air handler on. Each test is done at several different pressure differences between the house and outside. There are any number of choices that could be made as to what these pressure "stations" are, but at the time that this project started the recommended stations were from 5 to 25 Pa in 5 Pa increments for each of the four blower door tests.

Because of duct leakage to outside, the flow through the blower door required to achieve a certain pressure difference between the house and outside is different with the air handler on than it is with the air handler off. The difference between these flows at each pressure station is called the "Delta-Q" for that station. The basic idea of the Delta-Q test is to regress the set of delta-Qs that are obtained from the test on the measured envelope pressures, using equations for a model derived by Walker et al. (2001a).

The Delta-Q test is most appealing because it can be done relatively quickly and with little setup. It also requires only one major piece of equipment, which is a blower door. It is also done with the air handler and ducts operating normally. It does depend on modeling assumptions and complex equations, so the results are best obtained with a computer and are subject to the accuracy of the assumptions in the model.

The fan pressurization test. The basic principle of the fan pressurization test is that a calibrated fan pressurizes the ducts to a certain pressure with all of the intentional openings (the registers and grilles) sealed. Therefore, the flow through the calibrated fan must be going through the leaks in the ducts. The sealing of the registers and grilles causes the pressure throughout the duct system to be approximately uniform, though large leaks can cause this assumption to fail.

If leakage to outside only is desired, then a blower door is required in addition to the calibrated fan that pressurizes the ducts. The blower door pressurizes the house to the same level that the ducts are pressurized, such that the pressure between the ducts and the house is zero. Then there is no leakage between the ducts and the house, and all of the measured flow through the fan pressurizing the ducts is through leakage to outside. To estimate supply and return leakage separately, an airtight barrier must be placed between the supply and return duct systems, and the test must be done on each portion of the ducts separately. The airtight barrier is typically placed at the filter slot.

Although the fan pressurization test is a simple test to perform, the main drawback is the setup. Isolating the supply from the return, and sealing all of the registers and grilles can be time-consuming.

Sample Selection

The selection of homes for use in the study was unbiased in that homes were not screened for particular leakage levels or style of home. Screening of homes was set up primarily to create a sample of convenience, and any remaining bias in the sample was unintended and mainly attributable to regional construction practices, such as the widespread use of crawl spaces. The primary goal in the screening process was to identify houses which posed insurmountable time constraint problems; homes which were too far away, too large to test in one day (greater than 2500 ft^2), or with conditioning equipment with restrictive access were declined. Additionally, homes were requested which had a considerable percentage of the ducts running outside the conditioned space. It is important to note that the leakage of interest, when energy concerns are primary, are leaks to or from outside; leaks to and from inside are still considered to be contributing to the overall desired conditioning of the home.

A few other characteristics tended to automatically eliminate a house from consideration. Homes were typically not tested with a significant fraction of registers that create a large amount of swirl, produce a jet of air, or without the necessary clearance to use the flow measurement instruments. Homes with air handlers installed in the crawl space or attic were also eliminated from consideration. Dual filters arranged in a “V”- or “A”- orientation, as well as the position of the flue in some furnaces, present problems with installing a barrier at the air handler to isolate the return ducts. Conditioning equipment thought to have these difficulties was considered less desirable but could not to be entirely avoided.

Field Assessment of the Benchmark Estimate

In order to assess the accuracy of any of the leakage test methods, it was necessary to have an independent benchmark leakage estimate to which the results could be compared. For this study, the benchmark estimate was based on the difference between air handler flow and the sum of register flows as measured by flow capture hoods. The air handler flow was measured by creating a surrogate, air-tight return and attaching to it a calibrated fan. With the air handler off, this fan is used to create and measure the air flow required to match the normal operating supply plenum pressure. Static fan pressurization tests were used to adjust the results to account for leakage to inside.

This benchmark estimate procedure has been used previously with apparent success (Francisco & Palmiter 1999; 2000; Francisco et al. 2002a; 2002b; 2003b). However, it was deemed important to do a direct assessment of the method in the field in order to provide greater confidence in the results. The importance of this was heightened as a result of a recent study on the accuracy of flow hoods (Walker et al. 2001b; Wray et al. 2002). That study focused on registers that generated outlet conditions that were essentially “worst-case” flow patterns (swirls and jets), and included considerations of poor placement of the flow hood over the register. Though these conditions were avoided in this field study, and the flow hood used on supply registers in this study (though no longer commercially available) was found in Walker et al. (2001b) to perform better on residential supplies than other hoods, it was still considered critical to address the concern.

Methodology

To assess the adequacy of the benchmark estimate technique additional tests were performed on a subset of five homes. The approach was to locate homes with very low leakage, and then to introduce a known leak that could be directly measured. The flow through the added leak could then be compared to the change in leakage estimated by the benchmark estimate, as well as by the other measurement methods. Low initial leakage was desired, because introducing a large leak has the potential to change the pressure distribution throughout the duct system, potentially changing the leakage at other leakage sites. Therefore, minimizing the initial leakage reduces the chances for a significant bias in the comparisons due to changing pressures within the ducts.

Added leaks were usually created by disconnecting a duct. On the return side, the leaks were sometimes added by cutting a large hole in a duct or junction box. Measurement of the flow through the added leak was done using a flow station at the end of the disconnected duct. This flow station was calibrated in the laboratory using a factory calibrated Duct Blaster®. Supply disconnects were done at the end of branch runs and before the elbows, such that the flow station would be placed after many diameters of straight upstream duct, often 20 or more. The flow station was calibrated in this configuration prior to use in the field. On the return side, the flow station was placed at the end of a long straight section of duct prior to the added leak, again providing many upstream diameters of duct. When measuring the supply leakage an effort was made to seal holes in the air-handler cabinet (temporarily, with tape) so as not to attribute to supply leakage what would be return leakage in normal operation.

Assessment Results

The discussion that follows refers to house identification numbers from the full project. The identification numbers are followed by an "S" or "R", corresponding to added supply leak and added return leak, respectively. It should also be noted that there were cases where the air handler flow changed when a leak was added. This is especially the case if a hole was added to the return side, since this makes it much easier for the air handler fan to draw air. In order to simplify the analysis, all of the air handler flow and leakage estimates were adjusted to the air handler flow measured in the as-found case. These air handler flow results are shown at the top of Table 1. Leakage estimates were adjusted by maintaining the same percentage leakage.

The upper portion of Table 1 compares the flow station measurement of the added supply leak to the measurements from the benchmark estimate. The measurements from all of the methods are the estimated amount of leakage above the as-found leakage, so they are directly comparable to the flow station leakage. This portion of the table shows that the benchmark estimate worked extremely well, indeed better than expected. The maximum difference in terms of actual flow was less than 7 cubic feet per minute (cfm), at N04S, and the average difference was about 3 cfm. Taking the mean of the absolute values of the differences gives an average discrepancy of about 4 cfm. When expressed as a percentage of the flow station leakage, the maximum discrepancy was less than 6%, at N12S, with an average difference of about 2% of flow station leakage. All cases were within 1% of the air handler flow, with a mean absolute difference of about 0.5% of air handler flow on the supply side.

Table 1. Results of the Field Assessment of the Benchmark Estimate

	N04	**N12**	**N17**	**N33**	**N36**	**Mean**	**Mean Abs.**
Air Handler Flow (cfm)	949	697	1114	733	1122	923	923
Supply	**N04S**	**N12S**	**N17S**	**N33S**	**N36S**		
Leakage (cfm)							
Flow Station	151.3	110.5	108.4	101.4	127.4	119.8	119.8
Benchmark Estimate	158.1	116.8	112.3	97.9	127.6	122.6	122.6
Difference (cfm)	6.8	6.3	3.9	-3.4	0.2	2.7	4.1
Difference (% Flow Station Leakage)	4.5	5.7	3.6	-3.4	0.2	2.1	3.5
Difference (% Air Handler Flow)	0.7	0.9	0.3	-0.5	0.0	0.3	0.5
Return	**N04R**	**N12R**	**N17R**	**N33R**	**N36R**		
Leakage (cfm)							
Flow Station	139.0	91.1	156.1	99.6	158.6	128.3	128.3
Benchmark Estimate	155.3	59.5	149.0	50.5	176.0	118.0	118.0
Difference (cfm)	16.3	-31.7	-7.1	-46.2	17.4	-10.2	23.7
Difference (% Flow Station Leakage)	11.7	-34.8	-4.5	-47.8	11.0	-12.9	22.0
Difference (% Air Handler Flow)	1.7	-4.5	-0.6	-6.3	1.6	-1.6	2.9

The lower portion of Table 1 shows the corresponding results for the return side. These results paint a very different picture for the benchmark estimate. All of the estimates are further from the flow station measurement than the largest error on the supply side. Overall the errors are about 5-6 times greater on the return side than were seen on the supply side. Note that different flow hoods were used to measure supply and return flows, but this result goes against the conventional perception that, in general, flow hoods will work better on the return side. An in-house evaluation of the performance of the return flow hood after the conclusion of the field study failed to identify the exact cause of the problem, but found that the accuracy across measurement ranges varied as much as 5% of the flow. This discrepancy was also found to be orientation dependent.

The primary conclusion from the results on the return side is that the benchmark estimate is probably not as reliable as would have been desired, especially considering that the primary concern of this method had been on the supply side.

Results

This section summarizes the house characteristics, the results of the duct leakage tests for all 48 homes, and a brief comparison of the three operating condition test measurement methods.

House and Conditioning System Characteristics

Although the primary goal of the study was to compare the duct leakage test methods, it was hoped the sample would be large enough to be roughly representative of the single-family housing stock in the Puget Sound region. Previously, very little was known about the distribution of leakage and related variables in the housing stock.

The following is a statistical summary of selected home characteristics and test results in a format that allows one to assess the statistical distribution of the characteristics across the sample of homes. The first entry in each data row is the variable label. This is followed by the sample mean. The seven remaining columns present selected quantiles of the data: the sample minimum, followed by the 10th percentile, the 25th percentile, the 50th percentile (the median), the 75th percentile, the 90th percentile, and the sample maximum. This allows easy assessment of some of the distributional properties. For instance, the central half of the sample lies between the 25th and 75th percentiles. The difference of the 75th and 25th percentiles is the interquartile difference, a robust measure of spread.

The discussion of the tables is limited to the summary of median results, however many interesting observations can be made with respect to the range of values and comparisons of other quantiles. Although the tables do not include separate summaries for single- and multi-story homes, some notes on the differences in the relative distributions for a few variables are included.

Table 2 presents information on the homes including the ducts, envelope leakage, and furnace information. The first four lines of the table present the floor area, volume, ceiling height, and supply duct surface areas found in the study, but it should be noted that these should not be considered representative of the region on a whole as the size of the home was a screening factor. The median floor area in this study was 1668 square feet for the sample as a whole. The median area for single-story homes was 1541 square feet versus 1812 square feet for the multi-story homes.

Physical information about the portion of the supply ductwork that was located in unconditioned zones is included in Table 2. Due to time constraints and lack of suitable access in some homes, it was not always possible to gather this information, so the sample size is only 39 instead of 48. The surface area of the supply ductwork is one of the physical characteristics that determine the conductive heat loss from the ducts; the other is the R-value of the duct walls. The unit of duct R-values is ($ft^2 \cdot hr \cdot F / Btu$).

Table 2. House and Furnace Characteristics (n=48 Unless Otherwise Noted)

Variable	Mean	Min	10%	25%	50%	75%	90%	Max
House Floor Area (ft^2)	1647	707	1071	1268	1668	1914	2400	2683
House Volume (ft^3)	13753	5036	8583	10632	13592	15819	19200	27549
Ceiling Height (ft)	8.29	7.12	7.58	7.67	8.00	8.48	9.42	11.32
Supply Duct Area (ft^2), n=39	285	81	207	222	296	342	409	451
Supply Duct Area, % Floor Area	17.8	7.2	10.0	13.7	17.5	20.9	25.5	29.8
Supply R-value, n=39	4.0	1.5	1.7	2.0	4.0	5.1	7.4	8.1
Envelope Leakage, CFM50	2376	969	1191	1631	2162	2952	3829	4921
Envelope Leakage, ACH50	11.40	4.17	5.88	7.18	9.43	13.71	21.88	29.03
Envelope Leakage, ACHnatural	.57	.21	.29	.36	.47	.69	1.09	1.45
Furnace Size (kBtu/h), n=35	74.4	39.0	46.0	66.0	75.0	80.0	100.0	125.0

The median surface area for supply ducts outside the conditioned space is 296 ft^2, or about 17.5 percent of the floor area. It is interesting to note that the multi-story homes actually had a somewhat smaller supply duct surface area in unconditioned spaces than the single-story homes: 257 versus 312 ft^2 respectively. Correspondingly, the duct area as a percentage of floor area drops from 20.6% for single-story homes to 15.0% for multi-story homes. One possible explanatory factor for this is the fact that multi-story homes tend to have smaller footprints than single-story homes. For example, a 2200 ft^2 multi-story home may have a footprint of only 1100 square feet, compared to the single-story median of over 1500 ft^2. Much of the ductwork serving second stories and the two-story portions of split level homes are located within interior walls, so they are not counted in these surface areas.

The level of supply duct insulation in these homes was fairly low, with medians of R-3.1 for the single-story and R-4 for the multi-story homes. It should be noted that all uninsulated ductwork was assigned an R-value of 1.5, which is the effective R-value for uninsulated, galvanized steel ductwork.

The leakage of the home envelope was measured using a blower door with all supply and return registers sealed in order to exclude the duct leakage. The next three lines of Table 2 present the house leakage test results. It is customary to state the house leakage as CFM50 (flow in cfm at a 50 Pa pressure difference) and ACH50 (air changes per hour at a pressure difference of 50 Pa). The row labeled ACHnatural is a rough estimate of the heating season natural infiltration rate. It is calculated as ACH50 divided by 20. The median CFM50 is 2162 cfm, the median ACH50 is 9.43 ACH and the median natural infiltration rate is 0.47 ACH.

The final line of Table 2 shows the nominal input capacities of gas furnaces tested in this study. The median gas furnace nominal size is 75 kbtu/h.

Duct Pressures and Air Flows

The pressures in the duct system play a very important role with respect to air leakage into or out of the duct system. Table 3 displays pressures in the duct system in Pa. Return plenum pressures were measured upstream and supply plenum pressures downstream of any filters or coils throughout the duration of the various duct leakage tests. The values in the table are those pertaining to normal operation of the system. The median plenum pressures were 38.2 Pa on the supply side and 53.2 Pa on the return side. The sum of these two pressures provides a rough estimate of the external static pressure, which was not otherwise measured. This estimate is actually somewhat low because the pressures were measured in the plenums, and not external to the air-handling unit. The median external static was 101.4 Pa. It is of interest to compare this with 0.2 inches of water or about 50 Pa, which is the standard rating external static pressure used by residential equipment manufacturers.

The fan pressurization test data was used in combination with register and air handler flows to estimate an apparent leak pressure separately for the supply and return systems. These leak pressures are for leaks to or from outside only. This procedure is discussed in more detail in the full report (Francisco et al. 2003a). The apparent leak pressures are summarized in Table 3. The median leak pressure on the supply side was only 10.2 Pa or about 27% of the supply plenum pressure, versus 20 Pa or about 38% of the plenum pressure on the return side. Using the mean values puts the supply leak pressure at 35% of the plenum pressure and the return leak pressure at 55% of the plenum pressure.

Table 3. Duct Pressures in Pa (n=48)

Variable	Mean	Min	10%	25%	50%	75%	90%	Max
Supply Plenum, Measured	44.9	11.7	19.1	25.0	38.2	59.2	83.3	113.3
Return Plenum, Measured	58.8	8.1	20.2	37.2	53.2	74.4	115.9	143.8
External Static, Calculated	103.8	31.0	52.5	68.2	101.4	139.8	165.9	186.3
Supply Leak, Calculated	15.6	0.3	1.7	4.6	10.2	22.9	36.0	67.5
Return Leak, Calculated	32.8	0.0	5.6	10.9	20.0	33.8	119.0	147.1

The results of the fan pressurization test are presented in Table 4. While this test is not performed at operating conditions, it is a method which is widely used and its results can be interpreted by a wide audience. Table 4 is included as a reference for comparison with the results of the other tests used in the study. It should also be noted that the mean leakage to outside plus mean leakage to inside equals the mean total leakage but that does not hold true for the medians and other quantiles. Also notice that the means for return leakage are skewed in Table 4 by the presence of one home with huge leakage due to a very large panned joist return run. The last two rows of the tables give the leakage to inside as a fraction of the total leakage.

As seen in Table 4, the median supply leakage to outside at 25 Pa was much greater than the return leakage to outside: 180.0 cfm versus 83.6 cfm. This reflects the fact that for many of these homes the return runs were rather short and had few connections, as is common for homes with central returns. The median supply leakage to inside was larger than that for the return side: 53.9 versus 31.3 cfm. Return leakage to inside was typically found to be very small, except when building cavities were used. This is evident in the mean and especially at the upper quantiles which show return leakage to inside greater than supply leakage to inside. When expressed as a fraction of the total duct leakage the medians for the two sides are more similar:

25.9% leakage to inside for the supply side versus 28.5% for the return side. For both sides the leakage to inside was much smaller than the leakage to outside. The median total leakage at 25 Pa on the supply side was also much greater than that on the return side: 228.2 versus 130.7 cfm.

Table 4. Fan Pressurization Duct Leakage Test Results at 25 Pa, in cfm unless noted (n=48)

Variable	Mean	Min	10%	25%	50%	75%	90%	Max
Supply Out	171.8	11.4	87.1	113.6	180.0	214.4	281.0	332.4
Return Out	136.4	16.5	23.1	40.8	83.6	197.5	270.5	1014.0
Supply In	70.3	4.2	20.2	30.2	53.9	88.4	143.4	312.5
Return In	115.2	0.4	5.5	10.5	31.3	98.4	271.1	1533.3
Supply Tot	242.1	111.7	124.9	185.2	228.2	285.6	369.7	467.7
Return Tot	251.6	23.2	36.9	74.4	130.7	301.7	491.8	2547.3
Supply %In	28.1	3.0	8.8	15.3	25.9	34.2	50.7	95.9
Return %In	32.4	1.2	4.7	11.8	28.5	45.6	73.8	96.0

Table 5 summarizes air handler flow and total register flows as measured under normal operating conditions as well as the number of supply and return registers and the average flow per register. The unbalanced register flow (total supply register flow minus total return register flow) is also of interest.

The median air handler flow was 930 cfm. The median supply flow was slightly larger than the median return flow: 754 versus 729 cfm. Although on average the return and supply flows are about the same, this does not imply that the supply and return flows were nearly balanced on each individual home. The row labeled Unbalanced Flow shows the degree of discrepancy. The median unbalanced flow was supply dominated at 28.7 cfm, but the unbalanced flow ranges from about -123 to +215 cfm at the 10th and 90th percentiles respectively.

Table 5. Air Handler and Register Flows in cfm, and Register Count (n=48)

Variable	Mean	Min	10%	25%	50%	75%	90%	Max
Air Handler Flow	929	425	621	767	930	1099	1224	1423
Total Supply Flow	774	307	518	622	754	922	1088	1234
Total Return Flow	733	261	421	588	729	883	1005	1157
Unbalanced Flow[1]	40.3	-199.2	-122.9	-46.6	28.7	83.2	214.8	498.8
Supply per Reg.	81.0	37.0	51.4	63.0	79.4	94.3	117.5	159.0
Return per Reg.	485.9	74.3	140.2	323.0	445.2	703.7	863.6	1085.7
No. Supply Reg.	10.1	3	7	8	10	12	15	16
No. Return Reg.	1.98	1	1	1	2	2	3	7

1. Supply Flow minus Return Flow through registers only. Negative numbers mean that more air is going through return registers than through supply registers.

The median number of supply registers was 10 and the median number of return registers was 2. For each individual home the flow per register was calculated on both the supply and return sides. The median supply flow per register was 79.4 cfm while on the return side the median flow per register was 445.2 cfm.

Test Method Comparison

The primary goal of the study was to compare three different methods for measuring duct leakage under normal operating pressures. These results are summarized in Table 6 in terms of leakage as a fraction of the air handler flow. More extensive discussion of these results can be found in the full report (Francisco et al. 2003a) and a discussion of the sources of error in these test methods are presented in Francisco et al (2004).

Table 6 gives the results of each of the duct leakage tests. Comparing the median supply leakage as a percent of air handler flow for the three methods gives: 8.9% for the nulling test, 10.5% for the benchmark estimate method, and 12.3% for the Delta-Q method. Comparing the median return leakage for the three estimates gives 8.3% for the nulling test, 10.3% for the benchmark estimate method, and 10.2% for the Delta-Q test. However, the benchmark estimate results for return leakage may be suspect, as suggested by the consistent overestimation shown in the benchmark validation. The final column of Table 6 gives the mean duct leakage value in cfm for each method to facilitate comparison with the fan pressurization test results of Table 4.

Table 6. Duct Leakage, as % of Air Handler Flow (n=48)

Variable	Mean	Min	10%	25%	50%	75%	90%	Max	Mean[1]
Supply Nulling	11.5	-0.2	4.7	6.9	8.9	15.0	24.6	30.5	104.4
Supply Benchmark	11.8	0.1	2.7	8.4	10.5	14.3	25.0	29.8	111.1
Supply Delta-Q	13.1	-2.3	3.8	7.5	12.3	19.4	23.0	31.9	119.2
Return Nulling	10.4	-3.9	1.0	4.6	8.3	15.4	23.7	36.8	97.2
Return Benchmark	12.9	0.8	4.3	7.7	10.3	15.3	22.6	41.8	125.4
Return Delta-Q	12.5	-5.2	1.9	5.4	10.2	20.3	26.0	40.5	120.6
Unbalanced Nulling[2]	1.1	-28.2	-14.2	-4.0	1.7	5.8	15.2	32.8	7.3
Unbalanced Benchmark[2]	-1.1	-32.7	-17.5	-6.5	0.1	4.0	10.8	20.3	-14.3
Unbalanced Delta-Q[2]	0.6	-27.3	-16.0	-3.7	1.3	8.2	14.1	25.0	-1.4

1. This column in cfm, not as percent of air handler flow.
2. Supply minus return leakage to outside. Negative numbers indicate greater return than supply leakage.

The last three rows of the table show the unbalanced leakage (calculated as supply leakage minus return leakage) for each of the three methods. The nulling method and the Delta-Q method have similar median unbalanced leakage: 1.7% and 1.3% respectively. The benchmark estimate method has a median unbalance very close to zero. This general pattern persists across quantiles with the Delta-Q and nulling methods being somewhat more positive than the reference method.

Table 7. Distribution Efficiency Estimate, Duct Leakage to Outside at Operating Conditions, Duct Insulation, and Surface Areas

Site	Distribution Efficiency (%)	Duct Leakage (% Air Handler flow)		Ave. Supply Duct R-value	Supply Duct Surf. Area (ft^2)
		Supply	Return		
N01	78.0	13.5	7.6	6.0	302
N07	93.1	1.7	1.9	5.1	107
N08	84.2	9.7	9.0	4.0	296
N10	78.3	10.2	9.8	3.1	213
N17	75.3	3.4	11.7	2.3	424
N18	82.3	8.7	5.0	1.9	311
N23	81.8	11.2	18.5	2.5	319
N36	81.1	8.5	8.8	5.0	315
Avg.	81.8	7.4	9.0	3.3	254

As part of analysis of the project data, distribution efficiency estimates were generated using the model in ASHRAE Standard 152 for a subsample of 8 homes. As seen in Table 7, the modeling produced distribution efficiencies as low as 75.3%. The first column in Table 7 refers to house identification numbers from the full project.

Conclusions

The benchmark estimate, on the supply side, was shown to be more accurate than expected in those houses in which validation testing was performed. When comparing the benchmark estimate results on the supply side to the added known leak, the maximum error was less than 7 cfm, and no error in these houses was greater than 1% of the air handler flow. However, the benchmark estimate validation tests found that on the return side this method of estimating leakage did not perform as well. Much of the reason for this may be the discrepancies across measurement ranges and indications of position dependency found after the field study.

The study found average leakage levels in homes less than about 2500 ft^2 in the Puget Sound Region of 10 to 12% of air handler flow on both the supply and the return side. The houses tested also showed fairly low duct insulation levels. Although 10% may not seem to be an excessive amount of leakage, the energy impacts are large when considering the combined effect of leakage and low insulation levels on distribution efficiency. It is also important to note that while the various methods agree to within a few percent of the air handler flow, this typically results in a much greater percentage difference in the leakage estimate. For instance, on average the Delta-Q test on the supply side is 1.3% of air handler flow greater than the benchmark estimate, but this difference is 11% of the supply leakage.

Disclaimer

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