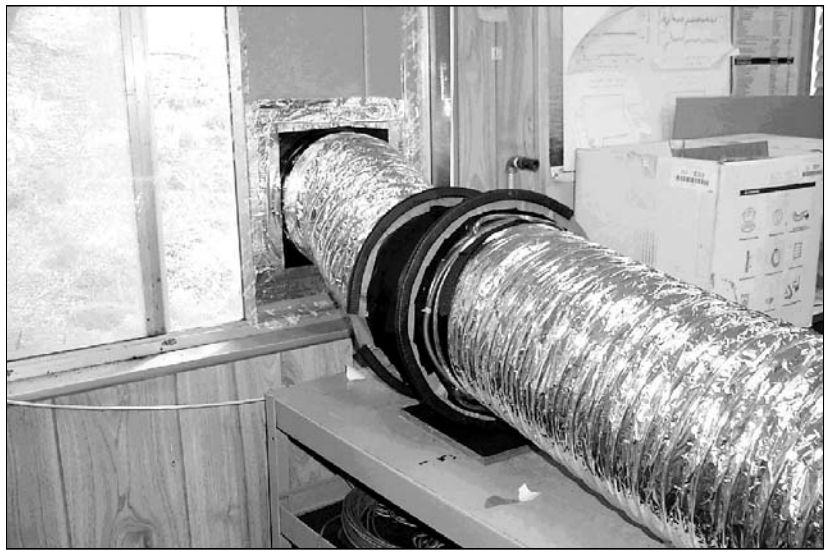
An Easier Way to Measure Duct Leaks

Finally, a duct leakage measurement that HVAC contractors might even love.

by Iain Walker and Max Sherman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Regular readers of *Home Energy* are familiar with the problems associated with duct leakage in residences: heating and cooling energy losses, house pressurization, added infiltration, and indoor air quality (IAQ) problems. (See "Only Testing Will Tell," *HE* Jan/Feb '02, p. 24, and "Chasing Interior Ducts," *HE* May/June '02, p. 24.) Many utility and weatherization programs, together with some new building codes, aim to reduce duct leakage. There are tests that diagnose and measure duct leakage, but these have significant limitations (see "Current Methods").

The most widely used duct leakage measurement techniques involve duct pressurization and differ by the requirement to either pressurize the ducts alone, or to pressurize the ducts and house simultaneously. Our aim was to improve upon these methods by making them more accurate and easier to perform without incurring large time and cost penalties. In particular, we wanted to develop a test that would use existing equipment and test procedures that building scientists and technicians are familiar with. What the home performance community needs is a better estimate of forced air system air leakage for use in energy efficiency calculations and for compliance testing of duct systems.

We developed the DeltaQ test to provide a more accurate measurement of duct leakage. The test is relatively easy to perform, and it uses less time, less equipment, and less labor than the existing tests. The key technical advantage of the DeltaQ test is that it measures air leakage flows at the HVAC system operating conditions, rather than requiring the technician to interpret measurements made at other fixed conditions. The key practical advantage is that preparation time is much reduced and a separate piece of equipment is not needed if technicians are already using a blower door.

The DeltaQ test also determines supply leakage separate from return leakage. This is important because supply leakage represents a direct loss of conditioned air, while return leakage is an increased load and IAQ/filtration problem. The imbalance between supply and return leakage is also of interest when examining the effects of building pressurization or depressurization (when looking for moisture problems, for example), and in estimating the effects of HVAC system operation on house infiltration.

The DeltaQ Approach

For many years, building scientists have known that information on duct leakage can be obtained using blower door tests that include the duct system. However, most efforts have focused on using a single test pressure and some assumptions about converting measured air leakage flow to actual leakage at operating conditions. The DeltaQ test takes a different approach. It measures air leakage flows for the ducts and the building envelope over a large range of pressures, just as normal blower door testing does. We call it DeltaQ because "Q" is the common term used for air flow, and "delta" is the common term used for differences. The test is based on measuring the change in flow through duct leaks as the pressure across those leaks is changed by turning the HVAC system air handler on and off (see Figure 1).

Because building envelope leakage is measured with the air handler off as well as with the air handler on, taking the difference between the flows at the blower door cancels out this envelope leakage and leaves us with information about the duct leaks only. In addition, because the test uses the difference between the two blower door measurements, any bias errors in the blower door measurements cancel out.

A link to information about the details and derivation of the DeltaQ model can be found at the end of this article. Simply put, a nonlinear analysis of the data is used to determine both supply and return leakage under operating conditions. The conventional envelope leakage can also be generated from the data. (For detailed instructions on how to carry out a DeltaQ test, see "DeltaQ: Step by Step.")

Bench Testing

We performed two sets of repeatability testing of the DeltaQ test, using a building at Lawrence Berkeley National Laboratory (LBNL). The first round of repeatability testing evaluated the same duct system 20 times over several days. These results showed that repeatability errors were less than 10 CFM, or about 1% of a typical air handler flow.

For the second round of testing, the system was sealed, and known leaks were deliberately added to the duct system. Air flow from registers was ducted directly to outside through combination fan/flow meters (see photo on p. 34) so that the true leakage flow to outside could be measured. We examined four cases of added leakage. (We did not test configurations with more return than supply leakage because it was easier to duct the supplies to outside than the returns, and we ran out of time.) Percentages of added leakage in these four cases were as follows:

- added supply leakage 22%, added return leakage 14%;
- added supply leakage 15%, added return leakage 2%;
- added supply leakage 9%, added return leakage 2%; and
- added supply leakage 4.5%, and added return leakage 1.5%.

The changes in return leakage are due to changing system operating pressures that vary as supply leakage increases. Each leakage combination was tested several times to see if repeatability changed significantly with leakage magnitude and distribution between supply and return.

The test results showed that repeatability was excellent, with a standard deviation of about 0.8% of fan flow (8 CFM) for supply leakage and 0.5 % of fan flow (5 CFM) for return leakage. There were no significant changes in repeatability as the leakage changed. The root mean square (RMS) error between the DeltaQ results and the measured leakage for all the leakage configurations was about 2.5% of fan flow (25 CFM) for returns and 1.3% of fan flow (13 CFM) for supplies. Most of this inaccuracy is due to the overprediction of leakage flows for the case with large supply and return leakage.

If we focus on the errors at low leakage, we find that the RMS error is 0.6% of fan flow (6 CFM) for supplies and 0.8% of fan flow (8 CFM) for returns. These errors are small compared to the leakage specifications found in energy programs or codes, showing that DeltaQ can be used to test for meeting these types of low leakage specifications.

Because extreme fluctuations in envelope pressures would lead to poorer repeatability than these values, we needed a way to estimate some testing limits to ensure this good level of repeatability. In some of our field test evaluations, we collected multiple sets of air handler on and off data together with multiple envelope pressure readings at zero (no pressurization or depressurization with the blower door and the air handler off). Comparing the results of these multiple tests with the

Current Methods

The most popular current techniques (as used in several state energy codes, weatherization, and utility programs) do not measure system flows at operating conditions. Instead they measure air flow at a single imposed pressure. It is then necessary to estimate the pressure difference required to convert to air leakage flows that occur during system operation. Usually plenum and/or register pressures are measured, and are then used in various ways as operating pressures. Measuring plenum pressures requires access to plenums—sometimes located in places with difficult access like attics and crawlspaces—and requires that holes be drilled in the duct system (and later sealed). This addition of holes need not contribute significantly to leakage, but from a homeowner's point of view, adding more holes when determining duct leakage appears counterintuitive.

It is difficult and time-consuming to split supply and return leaks. To do this, a blockage needs to be placed inside the ducts. This must often be done in places that are hard to access or work in, and it is also difficult to ensure a good seal around the blockage. A poor seal leads to overpredictions of leakage.

Measuring the air leakage to outside requires that both a blower door and a duct pressurization device be used, and that they be coordinated. This requires several operators and extra equipment (a duct pressurization fan and flowmeter) that many HVAC or weatherization contractors do not have.

It can be time-consuming to cover all registers. It can also take precious time to ensure that register coverings stay in place and do not damage registers or the surfaces surrounding registers.

Lastly, application of the alternative test methods in the current ASTM standard (ASTM E1554 1994) often leads to large measurement uncertainties. This is because the standard is based on the difference between two large numbers whose uncertainty is often as great as the difference that we are trying to measure.

envelope pressure fluctuations allowed us to develop the following criterion for acceptable repeatability for the results based on the measured envelope pressures: The standard deviation of the envelope zero pressures should be less than 1 Pa.

Field Experience

About 200 HVAC systems have been tested using DeltaQ by a variety of researchers, building scientists, and contractors. The tests have been carried out in a wide range of house styles and HVAC system types, installations, and locations. The houses ranged from new to 100 years old and from less than 1,000 ft² to 4,000 ft² of floor area. The time required to perform the test was recorded in over 100 cases; it averaged about 30 minutes. When the DeltaQ test is performed as part of a program that also requires envelope leakage measurements, the additional time required for measuring duct leakage using DeltaQ should be shorter, because the blower door is already set up.

The field personnel who used the DeltaQ test liked it because they didn't have to perform the more difficult aspects of pressurization testing. Registers do not have to be covered; a seal does not have to be placed between supply and return ducts; and plenum pressures do not have to be measured. Because the test does not require the registers to be covered, it avoids the associated drawbacks: possible damage to registers and surrounding finishes; the difficulty of finding all the registers; the need to move furniture to gain access to all the registers; and the need to ensure that all the register covers remain airtight during testing. Because access to air handlers and plenums is not required, field testers do not have to go into attics and crawlspaces that are dirty, cramped, and uncomfortable to work in. Nor do they have to clean up loose insulation that falls from attic access, or mud tracked in from crawlspaces. Lastly, testers who were familiar with blower door envelope leakage testing found it easy to do the DeltaQ test because it uses the same equipment and measurement techniques.

Supply and Return Pressures with Air Handler On and Off

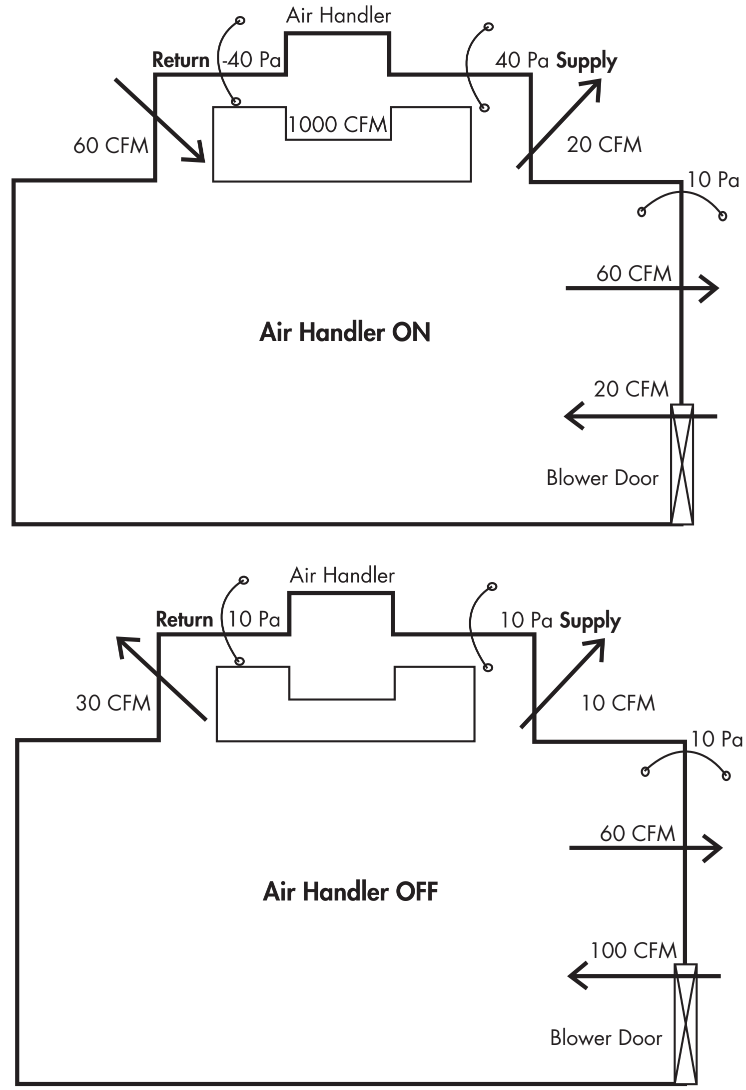

Figure 1. When the air handler is on, the pressures are increased across the supply leaks, leading to increased flow out of the supply leaks. The return section is at a lower pressure than the duct surroundings (and the house). The flow through the blower door that is required during a test to maintain the same envelope flow and pressure difference is then reduced from 100 CFM to 20 CFM. This change in flow at the same envelope pressure is the "DeltaQ".

The only significant limitation we found in field-testing the DeltaQ was that large envelope pressure fluctuations associated with high winds led to increased uncertainty in the test results, and more significantly, made it difficult to control the blower door at a fixed pressure difference. This limitation is similar to high wind speed restrictions for envelope leakage testing.

To better match air handler on and off pressures and perform the DeltaQ equation fitting calculations, and also to make record keeping easier, we used an automated software program to control the blower door equipment, record all

DeltaQ: Step by Step

Instructions for performing the DeltaQ test are as follows:

1. Connect the blower door to the building envelope using a window or door opening.

2. Install an envelope pressure difference sensor. The outside pressure measurement location should be sheltered from wind and sunshine. (Wind and sunshine can have a significant effect if the pressure tube has significant vertical travel.) The inside pressure measurement location should be as far away as possible from the localized air flows induced by the blower door. We recommend attaching a tube to the indoor pressure port of the pressure measurement sensor and extending this tube into another room far from the blower door location. All the envelope pressures use the outside pressure as the reference.

3. With the blower door opening blocked, air-moving fan off, and air handler fan off, measure the pressure difference across the envelope with the blower door off (ΔP_{zero}). We recommend that multiple pressure and flow readings be recorded for the zero reading at each subsequent operating point and averaged (over about ten seconds) for use in the calculation procedure. The (ΔP_{zero}) offset pressure shall be added to all target pressures. For example, if (ΔP_{zero}) is 2 Pa, then the first target pressure for pressurization is 7 Pa, and for depressurization -3 Pa. All the air-moving device flows are positive out of the house and negative into the house.

4. With the air handler fan off, turn on the blower door and adjust the flow until there is 5 Pa envelope pressure difference, with the house at a higher pressure than outside (for pressurization testing). Record the envelope pressure difference (ΔP_{env}) and flow rate (Q_{off}) through the blower door at this pressure level. Only record pressure and flow readings when the pressure reading is within 0.5 Pa of the 5 Pa operating point.

5. Repeat step 4, but with the envelope pressure difference, ΔP_{env}, incremented by 5 Pa each time until the envelope pressure difference is 50 Pa. Record the envelope pressure difference with the air handler fan off, ΔP_{off}, for each pressure level. Because the tightness of the building and the weather conditions affect leakage measurements, the full range of the higher values may not be achievable. In such cases substitute a partial range encompassing at least five data points, with the size of pressure increments suitably adjusted. At each pressure level, the air handler fan on and off conditions must both have the same target pressure.

6. Turn on the air handler fan and repeat the measurements in steps 4 and 5, recording Q_{on} and ΔP_{on} on at each pressure level.

7. With the air handler fan kept on, repeat steps 4 and 5, but with the house depressurized. That is, adjust the flow through the blower door for envelope pressure differences of -5 Pa through -50 Pa in 5 Pa increments, with the house at a lower pressure than outside.

8. Turn off the air handler fan, and repeat steps 4 and 5 with the house depressurized.

These steps can be summarized as follows: House pressurized with air handler off, house pressurized with air handler on, house depressurized with air handler on and finally house depressurized with the air handler off. This order minimizes the number of times the air handler has to be switched on and off (waiting for the air handler to turn on and off can be very time consuming).

Calculations:

Subtract ΔP_{zero} from the measured envelope pressures at each pressure level (ΔP_{env}) to determine the corrected envelope pressures (ΔP).

Determine the envelope leakage coefficient and pressure exponent, n_{env}, by fitting the pressure and flow data with the air handler fan off to a power law function.

Adjust the flows to exactly match pressures. The measured flow with the system off is corrected to the flow at the same pressure as when the system is on at each pressure level, using Equation 1:

$$Q_{off,\ corrected} = Q_{off}\left(\frac{\Delta P_{on}}{\Delta P_{off}}\right)^{n_{env}}$$

Calculate the flow difference (ΔQ) at each pressure level by subtracting $Q_{off,corrected}$ from Q_{on}.

Do a multivariate nonlinear least squares fit of the ΔP and ΔQ pairs from each pressure level to determine supply leakage (Q_s) and return leakage (Q_r), and the characteristic pressures (ΔP_s and ΔP_r) using Equation 2:

$$\Delta Q\,(\Delta P) = Q_s\left(\left(1+\frac{\Delta P}{\Delta P_s}\right)^{0.6}-\left(\frac{\Delta P}{\Delta P_s}\right)^{0.6}\right) - Q_r\left(\left(1-\frac{\Delta P}{\Delta P_r}\right)^{0.6}+\left(\frac{\Delta P}{\Delta P_r}\right)^{0.6}\right)$$

Because this type of fitting requires complex and repetitive calculations, these calculations should be done using commercial statistical software. Note that some of the pressure ratios (and 1± the pressure ratios) will be negative. In these cases, take the absolute values to the power 0.6 in Equation 1 (because it is not possible to calculate a negative number to a noninteger power without resorting to complex number arithmetic) and carry the sign outside the exponent term.

This building at LBNL was used to bench test the DeltaQ method. Taking the difference between flows at the blower door with the air handler on and off cancels out the building envelope leakage, leaving information about the duct leaks only.

the data, and perform all the required calculations. (We are currently rewriting this software to make it easier to use.)

DeltaQ Compared to Duct Pressurization Test

Duct pressurization tests were also performed in many of the field test houses for comparison purposes. (For the duct pressurization tests, we measured duct leakage at a fixed pressure of 25 Pa.) The results showed that differences averaged over all the tested systems were reasonable, at about 2% of air handler flow (with average leakage of about 10% of air handler flow). This shows that the measured leakage of the housing stock (and almost all duct leakage tests done up until now have been pressurization tests) is not biased. However, the difference for individual houses was large: 9% of air handler flow RMS difference for one study of 13 houses and 12% of air handler flow RMS difference for another study of 87 houses. These represent differences between the two tests of about one-half to two-thirds of the measured leakage. These large differences indicate that the two tests measure different system attributes. The DeltaQ test measures air leakage flows at operating conditions—and therefore more accurately reflects real leakage—and the pressurization test measures air leakage flows at a fixed pressure.

These large differences are a concern when establishing performance criteria—like the lower leakage limits given by some codes and standards—because they imply that using different tests will change which houses will pass or fail. More detailed investigations have shown that the DeltaQ test tends to pass more houses than pressurization testing at these low limits, indicating that the pressurization tests currently used are conservative. Systems with little leakage tend to have well-sealed plenums and plenum connections, so that the leaks are at the lower pressure parts of the duct system, such as at boots and register grilles. This makes the fixed 25 Pa pressurization results give values that are too high. This is good from a codes/standards body perspective, because it means that houses that pass a pressurization test are unlikely to have excessive air leakage at operating conditions. Conversely, from a builder or contractor perspective, the DeltaQ test may be preferable, because more systems will pass.

It is important to remember that duct pressurization and DeltaQ measure quite different quantities. Duct pressurization does for ducts what a blower door does for the envelope—it measures the size of the holes (or flow at a fixed pressure). DeltaQ does for ducts more what a tracer gas test does for the whole building—it measures the airflow under actual conditions. If we know the pressure distribution in the duct system, we can calculate the flow under normal conditions from the size of the holes, just as we can use the LBNL infiltration model to estimate ACH from blower door data.

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For more information:

More details on DeltaQ development are available on-line at http://epb.lbl.gov/Publications/lbnl-47308.pdf.