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# The Delta Q Method of Testing the Air Leakage of Ducts

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## ABSTRACT

The DeltaQ test has been developed in order to provide better estimates of forced air system air leakage for use in energy efficiency calculations and for compliance testing of duct systems. The DeltaQ test combines a model of the house and duct system with the results of house pressurization tests with the air handler on and off to determine the duct leakage air flows to outside conditioned space at operating conditions. The key advantage of the DeltaQ test over other methods is that it determines the air leakage flows directly, rather than requiring interpretation of indirect measurements. The results from over 200 field and laboratory tests are presented. The laboratory tests have shown that the DeltaQ repeatability uncertainties are typically 1% or less of system fan flow and that the accuracy of the test is between 1.3% and 2.5% of fan flow (or 13 cfm to 25 cfm (6 to 12 l/s) for this system).

## Introduction

Duct leakage is a key factor in determining energy losses from forced air heating and cooling systems. Several studies (Francisco and Palmiter 1997 and 1999, Andrews et al. 1998, and Siegel et al. 2002) have shown that the duct system efficiency cannot be reliably determined without good estimates of duct leakage. Specifically, for energy calculations, it is the duct leakage air flow to outside of the conditioned space at operating conditions that is required. Existing test methods either precisely measure the size of leaks (but not the flow through them at operating conditions), or measure these flows with insufficient accuracy. The DeltaQ duct leakage test method was developed to provide improved estimates of duct leakage during system operation, and the supply/return leakage split that is difficult and time consuming to obtain from pressurization tests. In addition, the test uses existing equipment and techniques familiar to building technicians. This test procedure is currently under consideration to be used in the ASTM duct leakage measurement standard E1554-94 (ASTM 1994).

## DeltaQ Development

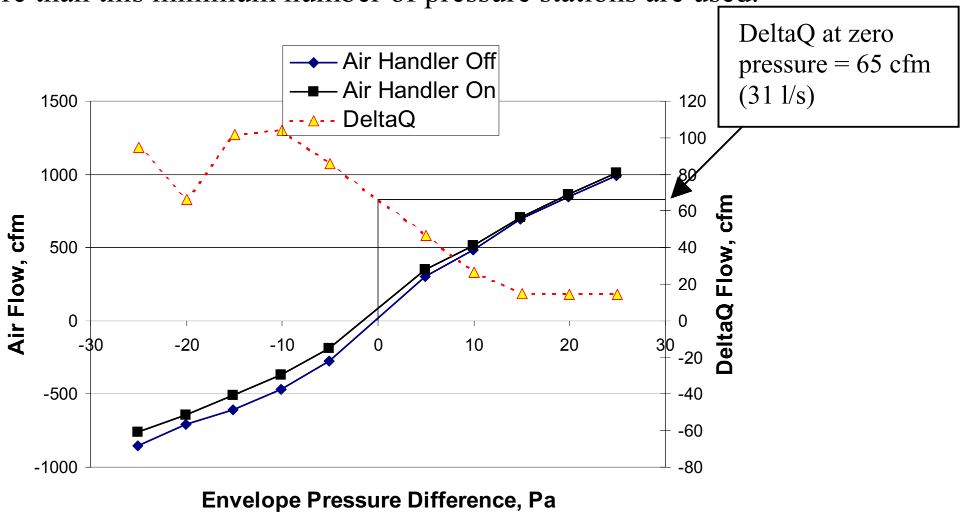
The DeltaQ test is based on measuring the change in flow through duct leaks as the pressure across those leaks is changed. The changes in duct leak pressure difference are created by pressurizing and depressurizing the whole house (including the ducts) using a blower door over a range of pressures. The blower door is used to both create and measure the flows occurring through the duct leaks and the building envelope. The pressurization and depressurization tests are performed twice: once with the air handler off and again with the air handler on. The same pressure stations are used for the air handler on and off tests to form paired data points. The difference between air handler on and air handler off blower door flows gives the DeltaQ ($\Delta Q$) at each corresponding envelope pressure difference ($\Delta P$). Detailed step-by-step instructions of how to carry out a DeltaQ test are given by Walker et al. 2001.

The DeltaQ model for duct leakage is given by the following equation:

$$\Delta Q(\Delta P) = Q_s\left[\left(1+\frac{\Delta P}{\Delta P_s}\right)^{n_s} - \left(\frac{\Delta P}{\Delta P_s}\right)^{n_s}\right] - Q_r\left[\left(1-\frac{\Delta P}{\Delta P_r}\right)^{n_r} + \left(\frac{\Delta P}{\Delta P_r}\right)^{n_r}\right]$$

where the unknowns are: the characteristic pressure difference between supply and house ($\Delta P_s$), and between the return and the house ($\Delta P_r$), the supply leakage flow ($Q_s$) and return leakage flow ($Q_r$). These unknowns are determined using statistical algorithms to determine the values that best fit the measured $\Delta Q$ and $\Delta P$ data. The characteristic pressures, $\Delta P_s$ and $\Delta P_r$, can be fixed at measured pressures, typically from the plenum or some fraction thereof, but in most situations the pressure at the leak site is unknown and it is advantageous to let these pressures be determined by fitting the measurements using a multi-variant least squares technique. The DeltaQ analysis with fitted pressures is referred to as "DeltaQfit" in this paper. Analysis of many DeltaQ and DeltaQfit tests has shown that fitting to the measured data is more robust if the duct leakage pressure exponents ($n_s$ and $n_r$) are fixed. Experiments to characterize the pressure exponent in a wide range of duct configurations have shown that a value of 0.6 is suitable for most duct systems (Walker et al. 1998 and Siegel et al. 2002). However if it is known that the leakage is in the nature of an orifice or a disconnected duct then a pressure exponent of 0.5 is preferred.

The DeltaQ values are measured over a range of envelope pressures (both positive and negative). In theory, only four pressure stations are required in order to determine the four unknowns: $Q_s$, $Q_r$, $\Delta P_s$ and $\Delta P_r$. However, uncertainties are reduced and the procedure is more robust if more than this minimum number of pressure stations are used.



DeltaQ at zero pressure = 65 cfm (31 l/s)

**Figure 1. Example DeltaQ Test Results (l/s = cfm × 0.47)**

An illustrative example DeltaQ test is shown in Figure 1. The DeltaQ vs. envelope pressure difference relationship can have multiple maxima and minima, and be non-monotonic and non-linear. Also, the results are very different for pressurization and depressurization, hence the requirement to test both conditions. The interpolated value of the airflow at a zero pressure difference gives an estimate of the difference between the supply and return leakage under normal operating conditions.

## Sensitivity to the characteristic pressures used in the DeltaQ calculations

By changing the characteristic duct pressures, $\Delta P_s$ and $\Delta P_r$, and reanalyzing the data it was found that even fairly large changes in these pressures did not change the final DeltaQ result a great deal. Typically, the characteristic pressure can be changed by a factor of two and only change the supply and return leakage flow by about 10% to 15%. In addition to work by LBNL (Walker et al. 2001), John Andrews (Andrews 2000) of BNL has performed further uncertainty estimates using monte-carlo simulation techniques. The simulations showed that the DeltaQ results were only weakly dependant on the assumptions about duct operating pressures and duct leakage locations. However, fitting for the characteristic pressures rather than using fixed plenum pressures can better determine the duct leakage in systems where the duct leakage is far from this plenum pressure (e.g. at register boots). Fitting the pressures does not always lead to a precise value for the pressure itself if the leakage is diffuse, however, the leakage itself will still be well defined. The main advantages of fitting the pressures are:

- The time and effort required to perform the test are reduced because the plenum pressures do not have to be measured. This can be a considerable saving for many residential systems whose air handlers are difficult to access. Also, no holes need to be drilled into the plenums (and sealed after the testing is completed).
- It makes use of the measured data from the actual system rather than relying on modeling assumptions about duct pressures scaling with plenum pressures. This has the potential to increase the accuracy of the test method.
- The magnitude of the fitted pressure can be used as a diagnostic tool. If the pressure is low, then leaks are likely at registers and if the pressure is high the leaks are likely at the plenums. Intermediate pressures indicate that the leakage may be diffuse or the leaks are at some intermediate pressure somewhere between the plenums and registers.

The potential drawbacks of DeltaQfit primarily result from the data analysis. Reducing the number of degrees of freedom when fitting to the measured data may reduce the accuracy of the fit to the data. Also, noisy measurements may result in a fit result that is less robust and causes larger errors.

The characteristic pressures correspond to inflection points in the DeltaQ relationship that can be interpreted as pressures at which the dominant leaks have the flow through them change direction. In Figure 2, there is a clear jump in the DeltaQ results at around minus 15 Pa. Using this as one reference pressure and 25 Pa as the other results in the best fit line, DeltaQfit, shown in the figure, which reproduces the inflexion point at –15 Pa. The inflection point at 25 Pa is not seen because there is no data past this pressure. (The inflection point at about 0 Pa corresponds to the change in flow direction through the envelope.) Note that the inflection points are only clearly seen for systems where the dominant leakage occurs at a single pressure. In many tests this is not the case, and the smooth, non-inflected (over the test pressure range) relationships give very good fits. This is also the case if the pressures across the majority of the leaks are greater or less than the pressures used in the tests; e.g., when the dominant leaks are at the high pressures usually measured at the plenums.

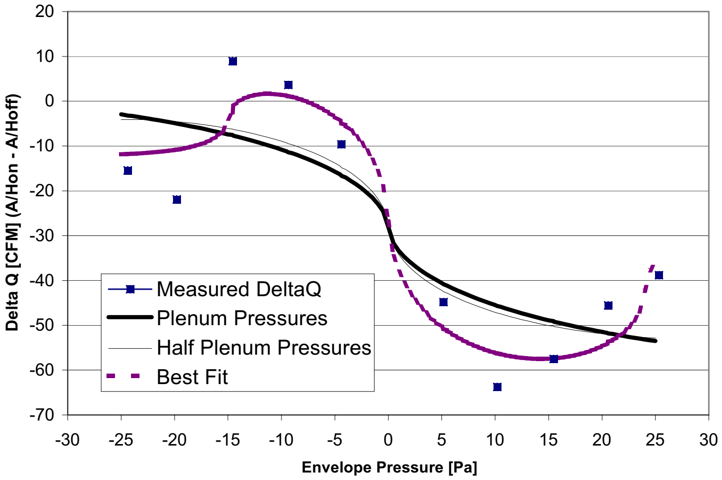


**Figure 2. Adjusting the Pressures Used in the DeltaQ Relationship to Better Fit Measured Data (l/s = cfm × 0.47)**

## Uncertainty and Repeatability analyses

Two sets of repeatability testing of the DeltaQ test have been performed using a building at LBNL. The first round of repeatability testing evaluated the same duct system 20 times over several days. These results showed that the repeatability errors were similar to values obtained in repeatability studies for direct duct pressurization (Walker et al. 1998). Table 1 summarizes these repeatability testing results for DeltaQ. Rather than analyze the repeatability results in absolute terms (cfm), it can be instructive to look at them in terms of the fraction of fan flow. This is because the leakage test results to be used in either energy calculations or verification of low leakage compliance will express the leakage as a fraction of fan flow. The air handler flow was approximately 1000 cfm, so the standard deviation of the multiple measurements was less than 2% of the air handler flow., The small building where the tests were performed had an envelope leakage of 1000 cfm50 (ELA 80 in$^2$). This is relatively large compared to the small amount of duct leakage in these repeatability tests. Low duct leakage in combination with a leaky envelope is the situation that we expect to be most difficult for the DeltaQ test due to the resulting small envelope pressure changes. The different wind characteristics on different days of repeatability testing led to a range of envelope pressure variability, characterized by the standard deviation of the envelope pressures with the air handler off. It is expected that the repeatability of the test results should decrease as this standard deviation increases. However, for this data set, the test variability did not increase with the measured envelope pressure standard deviation. (Walker et al. 2001) This is an important result, because it indicates that the DeltaQ test is relatively insensitive to these pressure fluctuations so that it will provide accurate results under a wide range of weather conditions.

**Table 1. Repeatability Results for DeltaQ Testing**

| | Average Leakage Flow (cfm) [% of fan flow] | Standard Deviation (cfm) [% of fan flow] |
|---|---|---|
| Supply Leakage ($Q_s$) | 19 [1.9] | 11 [1.1] |
| Return Leakage ($Q_r$) | 66 [6.6] | 16 [1.6] |

For the second round of laboratory testing, leaks were added to the duct system. The added leaks were carefully installed so that the leakage flow could be accurately monitored with an orifice or nozzle. Air flow from the registers was ducted directly to outside through flow meters so that the true leakage flow to outside could be measured. The only other study we are aware of that has used a similar procedure to determine true leakage flow was by Andrews (2002) for a laboratory mock-up of a duct system that was used to evaluate pressurization testing to estimate characteristic pressures (that he called DeltaQPlus). Andrews found that the average error in supply or return leakage for the fan-pressurization test was 6.4% of system fan flow. For the Delta Q test using half plenum pressures it was 3.4% of fan flow, while for DeltaQPlus it was 1.9% of fan flow.

In our study, the system was sealed and measured before the leaks were added to determine the background leakage (less than 2% of fan flow). This background leakage was added to the directly measured leakage flows to obtain the total leakage for comparison to the DeltaQ results because the DeltaQ test includes all the leakage, not just the added leakage. Four combinations of added leakage were examined:

1. **High supply and return leakage**: 22% supply leakage, 14% return.
2. **High supply and no added return leakage**: 15% supply leakage, 2% return.
3. **Moderate supply and no added return leakage**: 9% supply leakage and 2% return.
4. **Small supply and no added return leakage**: 4.5% supply leakage and 1.5% return (the changes in "no added return" leakage are due to changing system operating pressures that vary as the 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 the repeatability was excellent: the average standard deviation for the five cases in the second round of testing (background leakage plus the four added leak cases) was 0.8 % of fan flow (8 cfm) for supplies and 0.5 % of fan flow (5 cfm) for the return leaks). In addition, there were no significant changes in repeatability as the leakage changed. Figure 3 illustrates supply leakage repeatability results for the four different leakage levels for DeltaQfit. The difference between the results shown in Figure 3 and the directly measured leakage listed above is due to inaccuracies in the DeltaQ test and data analysis.

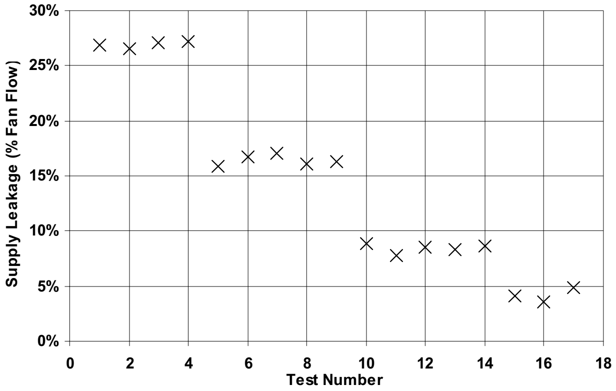


**Figure 3. Supply Leakage Repeatability Results for Four Leakage Configurations**

The accuracy of DeltaQ and DeltaQfit, as well as other options for selecting the characteristic system pressures were examined. DeltaQ uses the pressures measured at the plenum for these characteristic pressures, while DeltaQfit allows the fitting routine to determine these pressures. Using half the plenum pressures and fixing the pressures at 25 and 100 Pa for the supply and return respectively were also investigated.

From these controlled laboratory tests, with carefully measured duct leakage, it was found that the fitted pressures gave the best results, followed by the measured plenum pressures. Table 2 summarizes the error estimates for each characteristic pressure technique. The RMS error between the DeltaQfit results and the measured leakage for all the leakage configurations was about 2.5% of fan flow (25 cfm (12 l/s)) for returns and 1.3% of fan flow (13 cfm (6 l/s)) for supplies. Most of this inaccuracy is due to the over prediction of leakage flows for the case with large supply and return leakage. This over prediction may be due to the asymmetric nature of the added leaks because DeltaQ assumes that duct leaks have the same flow coefficients and exponents regardless of flow direction.

**Table 2. RMS Errors in Predicted Supply and Return Leakage for Four Different Characteristic DeltaQ Pressure Estimates**

| | Plenum Pressure, cfm (% of fan flow) | Fixed Pressures at 25 and –100 Pa, cfm (% of fan flow) | Half Plenum Pressure, cfm (% of fan flow) | "Fitted" Pressure, cfm (% of fan flow) |
|---|---|---|---|---|
| Supply | 17 (1.7) | 57 (5.7) | 33 (3.3) | 25 (2.5) |
| Return | 29 (2.9) | 14 (1.4) | 34 (3.4) | 13 (1.3) |

Field tests have shown that when the duct leakage is small the DeltaQ analysis can sometimes yield negative numbers for supply or return leakage. Generally, when negative numbers result from the test this shows that the duct system is not leaky and the test result should be interpreted to mean that the leakage is less than the precision of the test procedure. The precision of the test is limited to about 10 to 20 cfm (5 to 10 l/s) based on the resolution of the envelope pressure measurements (roughly 0.1 Pa, although this can be effectively reduced by taking many data points) and the corresponding envelope flows. Typically, these leakage flows are about 1% of fan flow and therefore not significant in terms of energy losses or poor thermal distribution. Also, any system with this little leakage is going to pass any of the existing (and probably future) leakage limits found in energy codes (e.g. CEC (1998) gives a 6% of fan flow limit) or voluntary programs (EPA Energy Star ducts have a 10% of fan flow limit).

## Field Experience

The DeltaQ test was first used in several pilot studies. Thirteen houses were tested by LBNL, BNL and Davis Energy Group (DEG). These houses covered a range from new to old (zero to 100 years), a large range of sizes (up to about 3700 $ft^2$ (344 $m^2$)) and a large range of duct system sizes and configurations. These pilot tests showed that the DeltaQ procedure gave reasonable results based on other knowledge about the system performance. For example, duct pressurization tests were also performed in these houses to determine duct leakage to outside. The pressurization calculations used half the plenum pressures as the operating pressure to which the leakage flows were converted. On average, total leakage (supply plus return) for the pressurization tests were 2% of fan flow higher than the DeltaQ tests (about 10% of the measured total). The RMS difference was considerably higher at 9% of fan flow, indicating that the tests do not show good agreement for individual houses.

California State University at Chico (CSUC) and LBNL have recently completed a program of field testing over 100 duct systems in California that were between 5 and 20 years old (Walker and Sherman 2002). The field testing included using the DeltaQ test, duct pressurization and measurement of air handler flows. At several houses the pressurization test was not performed because the house or the ducts were too leaky. For example, more than one house had completely disconnected ducts that could not be pressurized to 25 Pa. In some houses the pressure sensors were placed in the blower door air flow, which led to very large measured pressure fluctuations and unusable DeltaQ data. These factors reduced the number of systems available for analysis to 87. These CSUC/LBNL tests had multiple air handler on and off tests for each house. These multiple tests allowed the identification of problems with specific tests and to examine repeatability and maximum allowable wind pressure fluctuation issues, but they would not be required in standard production testing.

Testing over a wide range of envelope leakage is important because the DeltaQ test uses the change in flow through the envelope caused by duct leakage imbalances to calculate the duct leakage. Our field experience with the DeltaQ test has shown that for the houses in this study, the automated DeltaQ test produced reasonable results, even with leaky envelopes. This is because many data pairs are used in the analysis over a range of envelope pressures which are greater in magnitude than the weather induced envelope pressure fluctuations. In addition, a data acquisition system was used to provide time averages to reduce weather induced fluctuations.

Detailed measurement data recorded by the computer program are being used to examine the uncertainties and test results from each individual test. In windy conditions, or houses with leaky envelopes (when it is expected that the test may have problems), individual test points can show large variation during the test. However, these large variations for individual points do not necessarily lead to large variations in the test results.

The reason that the DeltaQ test does not have these sensitivities is because it uses multiple pressure stations so that an individual poor measurement does not corrupt the entire test.

To provide guidance for the user of the DeltaQ procedure, an estimate has been made of the envelope pressure difference limits that yield acceptable test results. This recommendation is based on the results of the protocol used in the CSUC/LBNL tests, where the DeltaQ air handler on and off tests were repeated until a pair of tests gave envelope flow coefficients that differed by less than 2%. For the houses tested in this study the limit for a good test was that the standard deviation of each envelope pressure measurement should be less than 1 Pa.

Because both the DeltaQ and duct pressurization tests were performed for the CSUC/LBNL study, it is possible to compare the test results to look for possible biases and how individual houses compare. The average leakage for these houses is typical of those seen in previous surveys and Table 3 summarizes a comparison of the duct pressurization and the DeltaQ results. In Table 3 the % of air handler flow values are based on the % of air handler flows for each individual house. It is not the leakage flow divided by the average air handler flow for all the houses. The duct pressurization results are for duct leakage to outside at 25 Pa. Averaged over all the houses, the two test methods give very close results for the sum of supply and return leakage, with an average difference of only 2% of fan flow (or about 20 cfm (9 l/s)). However, the average difference for an individual house is estimated by the RMS difference and is about 12% of air handler flow. This is a significant discrepancy: about half of the average leakage.

**Table 3. Comparison of DeltaQ to Duct Pressurization Results in 87 California Houses**

| | Average DeltaQ | Average Duct Pressurization | Average Difference | RMS Difference |
|---|---|---|---|---|
| Sum of supply and return leakage to outside | | | | |
| cfm (l/s) | 206 (97) | 183 (88) | -19 (9) | 110 (52) |
| Fraction of air handler flow | 22% | 20% | -2% | 12% |
| Supply Leakage to Outside | | | | |
| cfm (l/s) | 97 (46) | 103 (49) | 6 (3) | 67 (32) |
| Fraction of fan flow, % | 10% | 11% | 1% | 7% |
| Return Leakage to Outside | | | | |
| cfm (l/s) | 105 (50) | 80 (38) | -25 (12) | 72 (34) |
| Fraction of fan flow, % | 12% | 9% | -3% | 8% |

The above results looked at the combined supply and return leaks. For many duct systems, supply and return leaks can have significantly different effects on the duct system losses. The results in Table 3 show that the fractional differences between the two tests are greater when the supply and return are looked at individually than when they are combined into the total leakage shown above. The individual supply and return results are illustrated in Figure 4. The trend in the figure shows that the DeltaQ test tends to predict higher values of leakage compared to pressurization as leakage increases. In Figure 5 the pressure fitting technique, DeltaQfit, has been applied to the data from 87 houses measured by /LBNL. Fitting for the pressures results in lower leakage rates (by about 0.8% of air handler flow) compared to using plenum pressures (as with the laboratory tests presented earlier), and would reduce the trend shown in Figure 4. The RMS difference between the fitted and plenum pressure leakage flows is about 3% of air handler flow for supplies and 2.5% for returns. This represents significant fractional changes in supply and return leakage flows of about 30%.

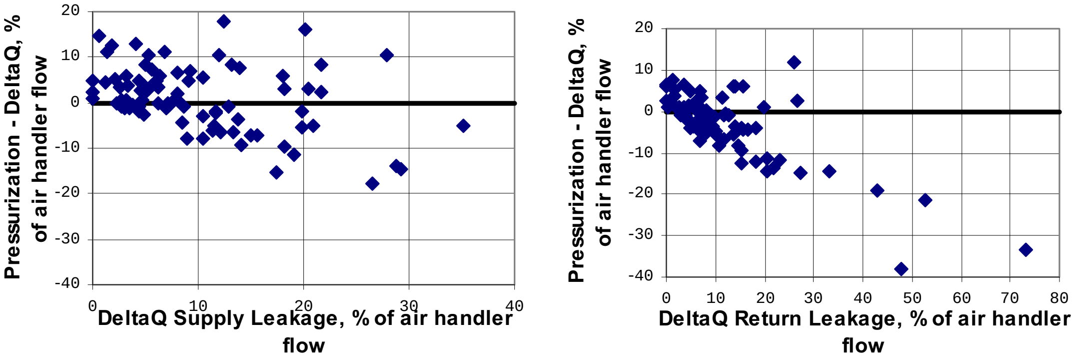


**Figure 4. Comparison of DeltaQ Supply and Return Leakage to Duct Pressurization Supply and Return Leakage to Outside at 25 Pa.**

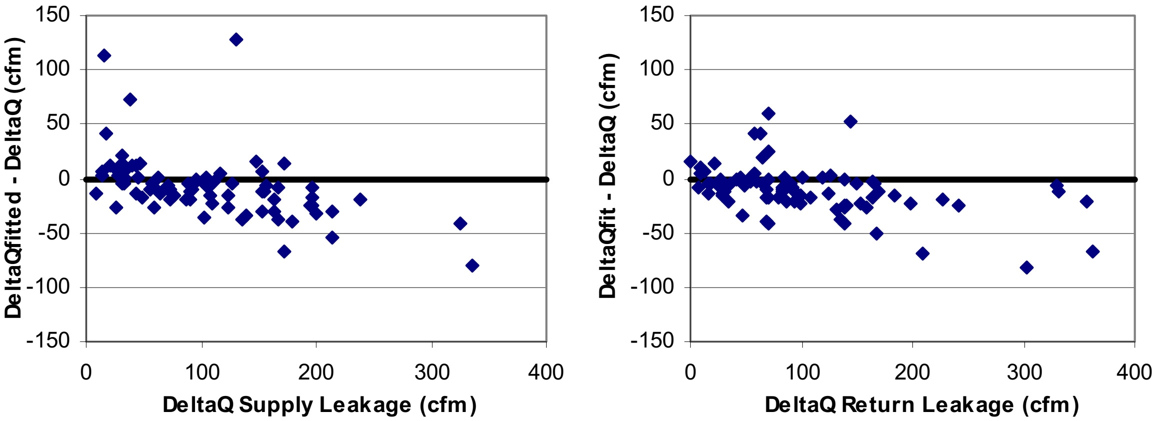


**Figure 5. Change in Duct Leakage Flows Predicted by DeltaQ by Using Fitted Characteristic Pressures (l/s = cfm × 0.47)**

The effect of fitting pressures and changing pressure exponents was further investigated by examining the results of testing eight houses by ECOTOPE (2001). These measurements were made with the duct system in the "as-found" condition and with added leaks. The added leakage was mostly accomplished by disconnecting ducts. In these cases of massive duct failure (e.g. a big hole or a disconnected duct), the assumption of 0.6 for the ducts leak pressure exponent is not valid. In these cases it is better to perform the calculation with a lower exponent of about 0.5. It should be noted that the ability to quantify massive duct failure accurately is not particularly relevant because knowing that there is massive failure is the important thing. Figure 6 shows the changes in the DeltaQ flows caused by using a lower exponent, where appropriate, and fitting for the characteristic pressures. Using fitted pressures and a lower pressure exponent results in an average decrease in supply leakage of 23% and return leakage of 20% compared to fixed plenum pressures and pressure coefficients of 0.6. The majority of this change was due to the change in pressure exponent rather than the pressure fitting.

Under normal test conditions of a leaky system, the user of the test would not know if the duct leakage was due to distributed leaks or single large leaks with a known pressure exponent, and the above corrections could not be applied. However, the corrections are mostly significant when the leaks are individual large holes. In addition, these large hole leaks will tend to have low pressure differences. In these cases a secondary diagnostic component of the DeltaQ test can be utilized. If the DeltaQ results are plotted as shown in Figures 1 and 2, large leaks at low pressures are manifested as large jumps in the DeltaQ results at low pressures. Upon observing such characteristics for a leaky system the DeltaQ or DeltaQfit calculations should be repeated with changed pressure exponents for a more accurate result.

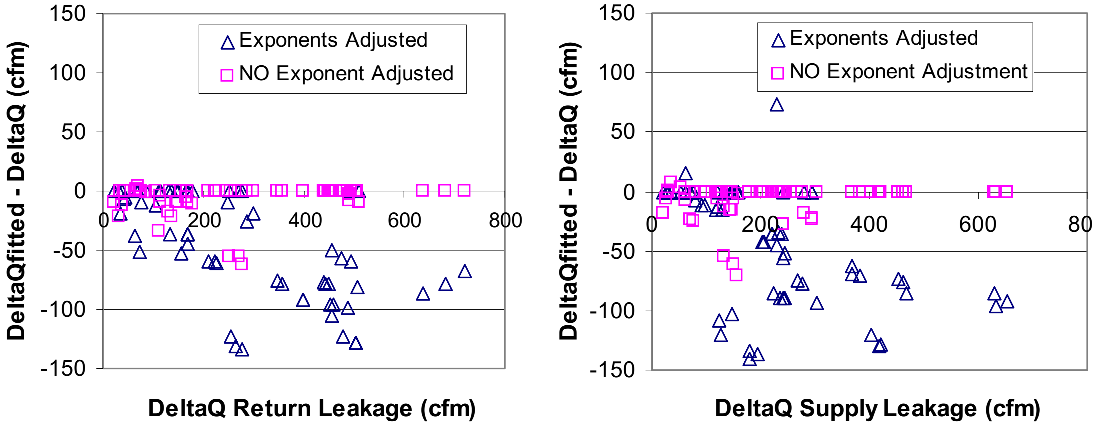


**Figure 6. Comparison of DeltaQ Supply and Return Leakage to DeltaQfit with Adjusted Flow Exponents (l/s = cfm × 0.47)**

## Conclusions

- The DeltaQ test provides accurate (the RMS error better than 2.5% of air handler flow in our test facility) measurements of duct leakage to outside at operating conditions.
- Recent advances in the DeltaQ technique that allow characteristic pressures to be fitted to measured data increase the accuracy of the test and reduce the time and effort required to perform the test by eliminating the need to measure plenum pressures.
- The DeltaQ test can be performed with existing equipment using techniques that building diagnosticians are familiar with, and does not require access to plenums or any system preparation.
- The DeltaQ test offers the advantage of determining envelope leakage at the same time as duct leakage.

## Acknowledgements

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