A Fundamental Approach in the Use of Whole-House Pressurization Data for Predicting Infiltration Rates

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Introduction

A standard practice among weatherization crews is to report an estimated savings in infiltration using the best estimate of the flow rate through a blower door at a 50 Pa pressure difference between inside and outside the building (Q_{50}). Alternatively, the effective crack area, based on flow rates at pressure differentials much higher than ambient conditions, is used as an indication of savings. In the former case, Q_{50} is divided by a factor determined by the climate, height of building, and wind sheltering.[1] Several studies suggest that Q_{50} is typically correlated to measured infiltration rates using tracer gas techniques to ± 25% at the 75 %tile confidence level. This paper investigates alternative methods of analyzing the blower door data to better predict energy savings.

General Theory

Etheridge[2] has shown that flow (Q) through simulated cracks in buildings for a given pressure differential (P) follows the relationship

$$P = bQ^2 + dQ \qquad (1)$$

where b and d are depend on the geometry of the crack and the density and viscosity of the air. So b and d are crack specific. It follows that the general relationship of flow on pressure difference is:

$$Q(p) = \int f(a)\ ((1+ap)^{1/2} - 1)\,da \qquad (2)$$

The problem is to estimate f(a), where a depends on b and d above. This is a fundamentally difficult mathematical problem. The accepted approximation is a non-physical, semi-empirical model:

$$Q(p) = cp^n \qquad (3)$$

where c and n are estimated by a log-log fit (minimizing an unweighted variance) to typically 6 data pairs in the pressure range of 10 to 50 Pa.

$$Ln(Q) = Ln(c) + n\ Ln(p)$$

"n" is typically .65 which lies between the theoretical limits of .5 (for large holes) and 1 (for very small cracks).

Minimization of Variance

The basic problem with the unweighted minimization of the variance in the log-log fit is that the error in log(Q) is much larger at lower pressures than at higher pressures.

Theory

In practice the error in measuring the pressure differential for a given flow rate is approximately constant (δp) for all data pairs. Therefore,

$$Ln(Q) = Ln(c) + n\ Ln(p \pm \delta p))$$

which can be approximated by:

$$Ln(Q) = Ln(c) + n\ Ln(p) \pm n\delta p/p$$

This means that the error associated with a given data point is distributed with a standard deviation (σ) proportional to the inverse of the pressure. Hence the variance weighting factor is ($1/\sigma^2$) or p^2. A weighted and unweighted variance was used to analyze 63 individual blower door runs for 5 houses before and after weatherization as part of Princeton's Crosslands Study.

Results

The Crosslands Study blower door tests were performed using a typical six data pair analysis. The error in the estimated flow rates, at the 75 %tile confidence level, is typically 1 to 5% for Q_{50} and 20 to 40% for Q_4 (with minimization of the weighted variance). Since Q_4 better represents the conditions during ambient infiltration, it is easy to see why the earlier stated correlation between blower door data and tracer gas measurements of infiltration isn't better.

For the five houses studied the (post/pre retrofit) ratio for infiltration measurements with wind and temperature conditions matched and unmatched are compared with the blower door values for Q_{50} and Q4 are shown in Table 1.

Table 1. Post/Pre Retrofit Blower Door Tracer

ID#	50Pa	4Pa	Gas
H1	.64±.02	.59±.11	.72±.18*
H2	.67±.02	.54±.12	.75±.19
J1	.64±.02	.57±.11	.52±.12
B1	.59±.02	.44±.14	.58±.09
B2	.68±.02	.56±.11	.55±.08

* weather conditions unmatched

The infiltration rates are determined using a decay rate tracer gas (SF_6) methodology which inherently has a large error. Nevertheless the error in Q_{50} is small and does not allow for all the tracer gas measurements, while the range of estimated values for Q_4 does agree with the measured infiltration measurements. That is, even though the mean values for Q_4 do not correlate any better than Q_{50} does with the measured saving in infiltration, the statistical error indicates agreement in the former and not in the latter case. In any case, it appears that the nonphysical nature of the model equation could be creating the large error in Q_4.

Two Parameter Physical Models

In order to better estimate the flow at lower pressures more typical of ambient conditions, it is important to have a physical model capable of reliably projecting into this lower pressure range.

Theory

In addition to the semi-empirical model analyzed above several approximations can be made to the Etheridge equation. In particular:

model 1. $Q = c\ p^n$
Standard semi-empirical model

model 2. $Q = r\ p^1 + s\ p^{1/2}$
All holes small or large

model 3. $Q = b\ ((1 + ap)^{1/2} - 1)$
All holes the same size - a

model 4. $Q = t\ p^1 - u\ p^2$
All holes very small

model 5. $Q = -v + w\ p^{1/2}$
All holes are very large

Results

Eighty sets of blower door measurements representing 25 buildings were analyzed for these five models. A best fit was determined by the model with the smallest variance. The results are shown in Table 2:

Table 2. Best Model Fit

Model #	Crosslands Brdtn (73)*	SSC (7)*
1.	12%	-
2.	52%	-
3.	36%	-
4.	-	-
5.	-	100%

* number of blower door tests

To further test the hypothesis that more careful measurements at lower pressures will result in better predictions 6 blower door tests before and one after weatherization of a student housing unit were taken with twelve data pairs.

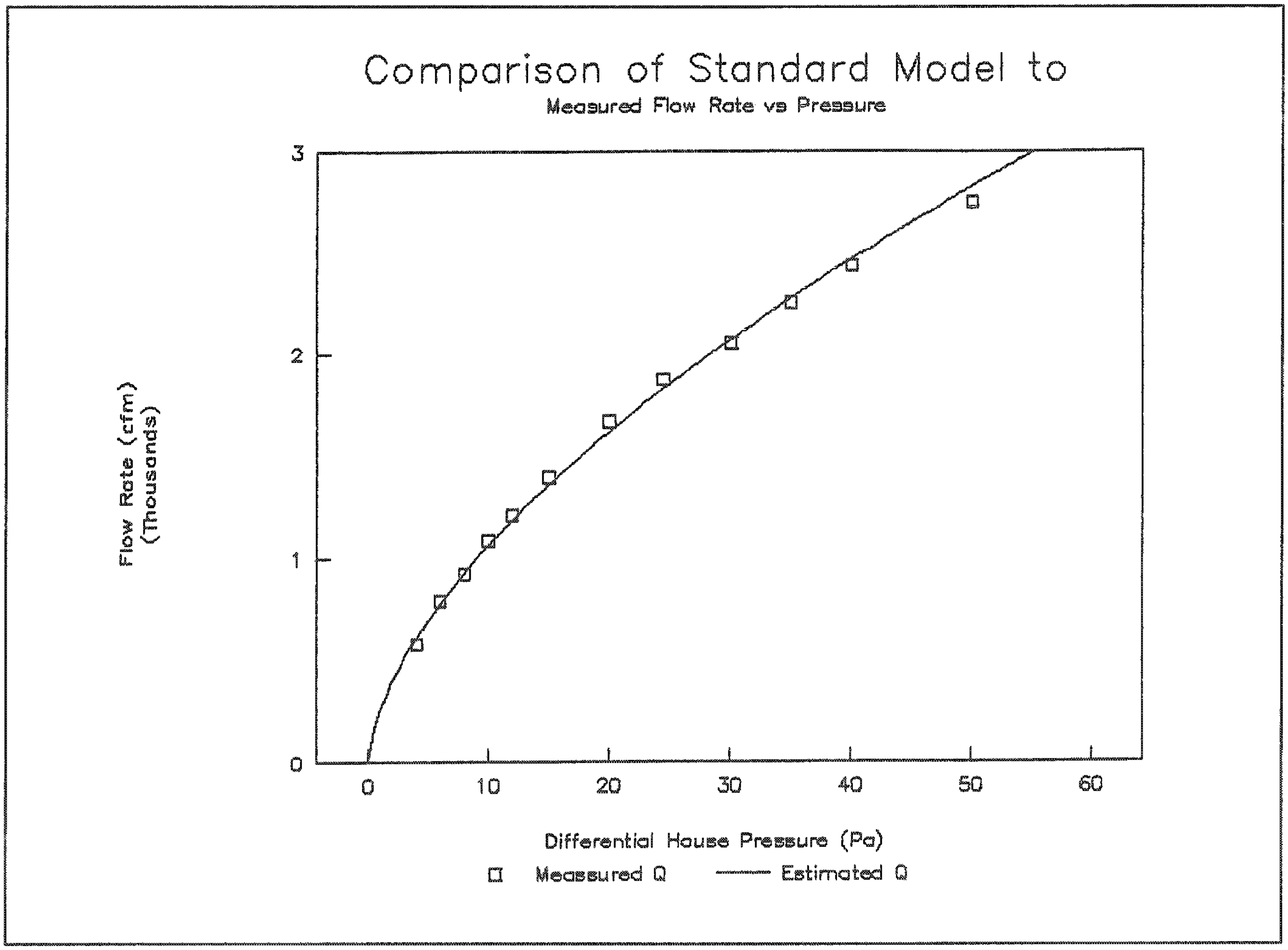

Figure 1. Best Fit of Blower Door Data of SSC Housing Using Standard Model (#1)

The best fit consistently was model 5 (all holes are very large) with the standard model second. The data is displayed above:

The end points in the fits are the critical region to study, showing that extending data over a large pressure range is important in estimating physical parameters. It should be noted that Models 2-5 are all physically based approximations. Unfortunately, Models 1, 2 & 5 all are unreliable in their projections into the lower pressure region since the assumptions in the development of these approximations are not valid at low pressures.

Three Parameter Model

A model which captures the essence of all potential behavior and can be reliably projected into the lower pressure region is needed. This involves incorporating aspects of several of the above models. The simplest would necessarily contain three parameters.

Theory

Starting with the exact physical model (Equation 2), f(a) can be considered as a distribution function which can be approximated by three definite values -- corresponding to large, intermediate and small holes. Three parameters requires more than the standard six or so data pairs normally taken by a weatherization crew.

Results

The results of this analysis for the SSC student housing caulking project shows an equally good fit to the data and also has the physical result of going through the origin unlike Figure 2. The distribution function pre and post caulking is shown in Figure 3 50 Pa. It is seen that the

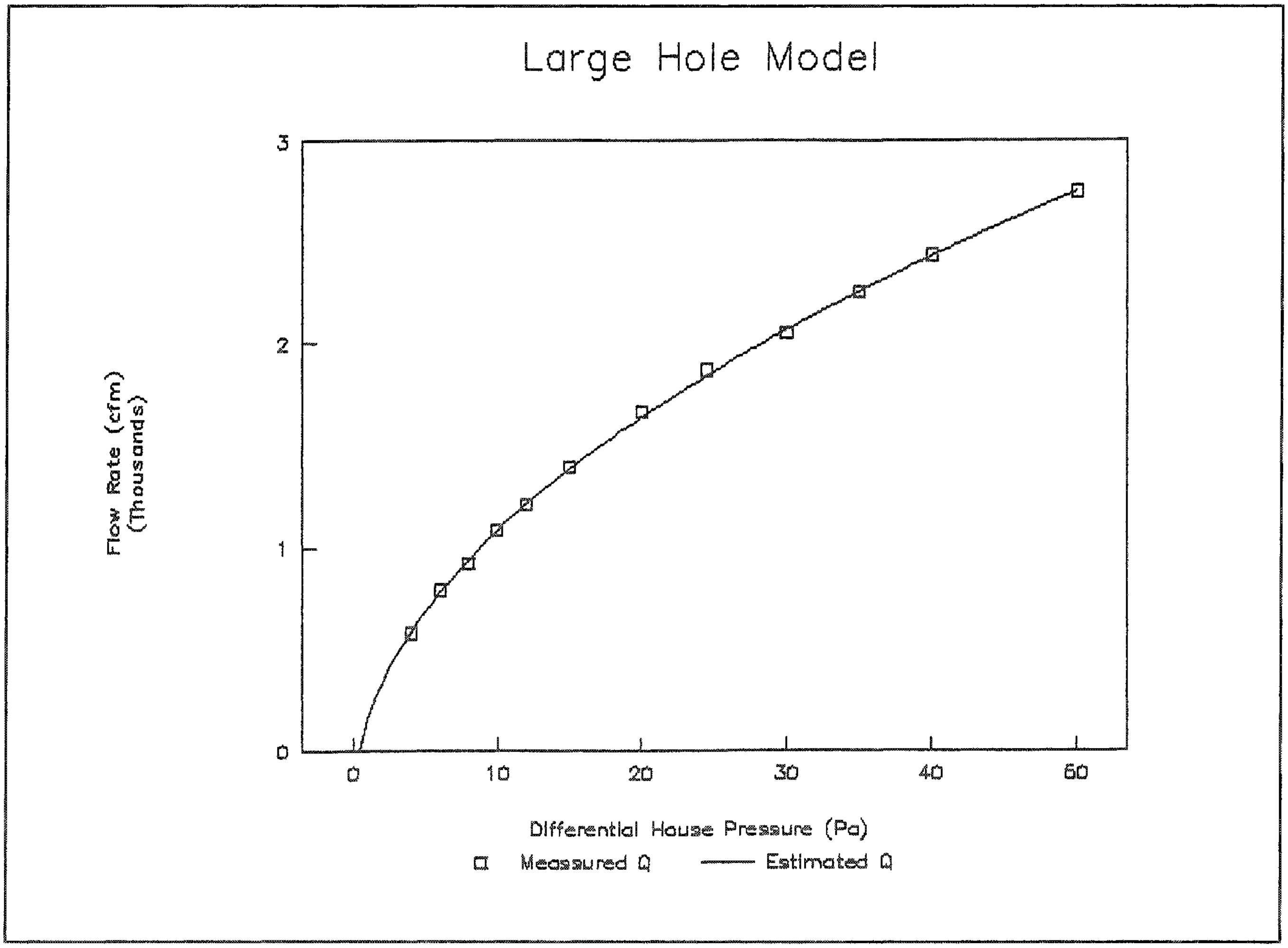

Figure 2. Best Fit Using All Large Hole Model (#5)

dominant holes are quite large -- corresponding to our observation that there were large leaks in the air duct system and an uncapped vent to the roof. Caulking clearly cut down on the leakage through intermediate size holes. The second observation to make is that the reduction at 50 Pa is larger than at 4 Pa since the large holes have more persistent leakage at low pressures.

Conclusion

There are several conclusions from this work. Firstly, a minimization of the weighted variance should be used to fit the data and a statistic should be reported for both Q_4 and Q_{50}. Secondly, for a two parameter fit there are better physical models available than the standard model given by Equation 3. And thirdly, more careful data acquisition, and a three parameter distribution function can lead to realistic projections of flow into the low pressure region. Only then can a reasonable assessment of the correlation of blower door data with tracer gas measurements be made.

Acknowledgements

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Endnotes

1. For example, Energy and Auditor Retrofitter July/Aug, 1986

2. Etheridge's results are applied assuming there is no turbulence. In fact, wind could cause turbulent behavior under ambient conditions.

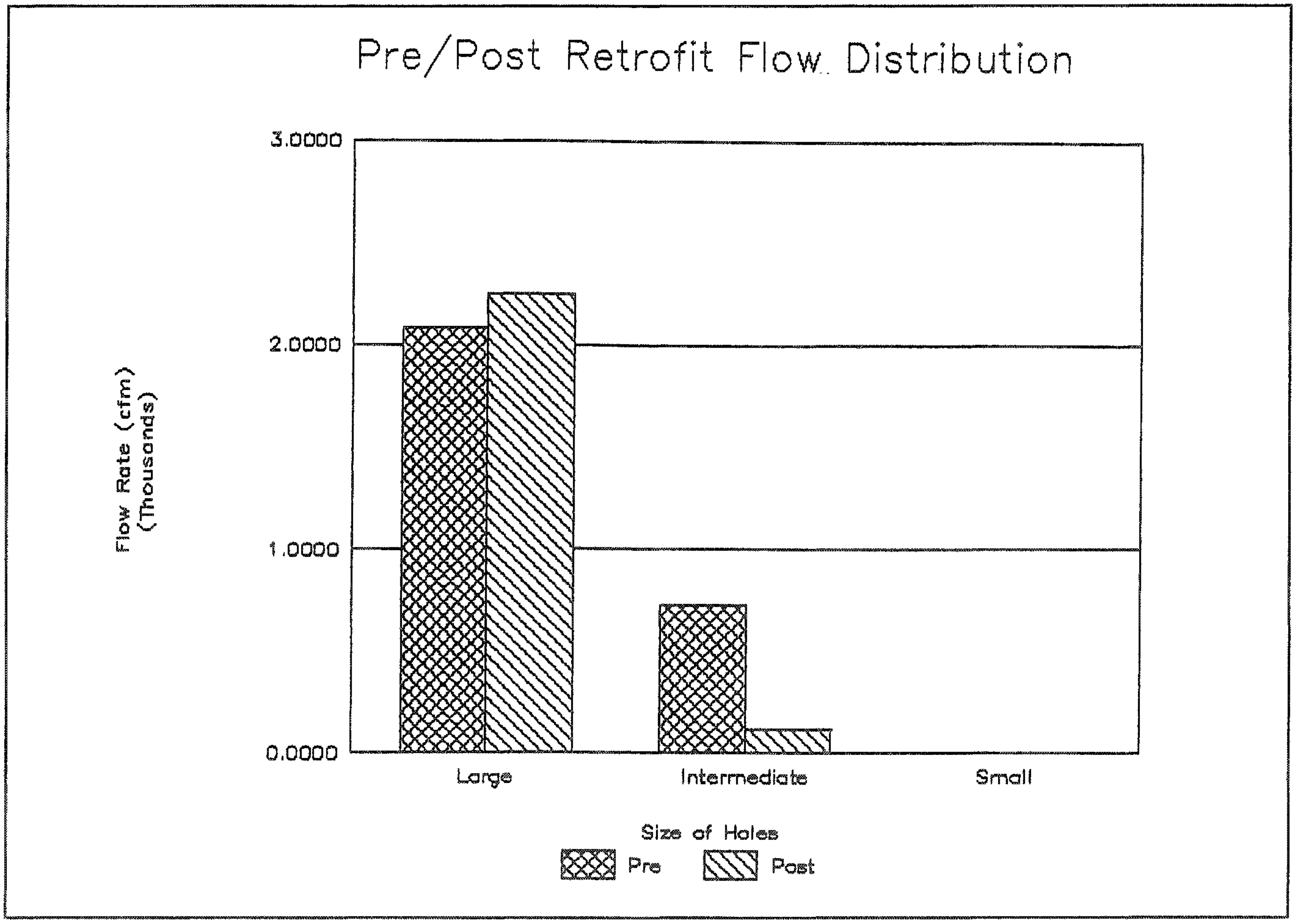

Figure 3. Comparison of Flow Through Three Different Size Holes Before and After Caulking of SSC Housing Unit

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