A comparison of the power law to quadratic formulations for air infiltration calculations

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Iain S. Walker*, David J. Wilson and Max H. Sherman***

* Energy Performance of Buildings Group
Energy and Environment Division
Lawrence Berkeley National Laboratory
Berkeley, CA, USA

** Department of Mechanical Engineering
University of Alberta
Edmonton, AB, Canada

1 Synopsis

Although the power law has been broadly accepted in measurement and air infiltration standards, and in many air infiltration calculation methods, the assumption that the power law is true over the range of pressures that a building envelope experiences has not been well documented. In this paper, we examine the validity of the power law through theoretical analysis, laboratory measurements of crack flow and detailed field tests of building envelopes. The results of the theoretical considerations, and field and laboratory measurements indicate that the power law is valid for low pressure building envelope leakage.

2 Introduction

The functional form of the pressure flow relationship for building envelopes has been a topic of debate. Historically, some practitioners supported a power law equation [1] and others a quadratic form [2]. The power law formulation has gained almost universal acceptance for building envelope leakage in:

- measurement standards for building envelopes, e.g., [3], [4], [5],
- ventilation standards, e.g., [6] and [7], and
- many infiltration models.

Many of these standards and calculation procedures use the power law function to extrapolate from data measured at high pressure differences down to the pressures experienced by the building envelope for natural infiltration. This paper will examine how well the power law and quadratic functions can be extrapolated successfully to lower pressures by using theoretical considerations, laboratory and field measurements. In addition, this paper examines how flow through individual leaks combine when determining whole building envelope flows. Test results will be presented for whole house pressurization at the low temperature differences and windspeeds required to reveal the low pressure leakage function. Additional crack flow measurements performed by other authors and flow through furnace flues under controlled laboratory conditions will also be used. The envelope and flue experiments were developed to concentrate on improved measurements at low pressure differences and flow rates.

3 Pressure - flow relationships for crack flow

3.1 Quadratic form

The pressure-flow relationships for fully developed laminar flow and turbulent (orifice) flow give the following limiting cases for crack flow:

$$Q = K_1 \Delta P, \quad Q = K_2 \Delta P^{\frac{1}{2}} \qquad \textbf{1, 2}$$

where Q = flow rate [m^3/s], ΔP = pressure difference across crack [Pa], K_1 [m^3/sPa] and K_2 [$m^3/sPa^{0.5}$] are flow coefficients. Equation 2, for fully turbulent orifice flow, has been used often in ventilation modeling, as early as 1907 [8] and still in use today [9]. The laminar and turbulent equations can be combined into a quadratic form [10] such that,

$$\Delta P = AQ + BQ^2 \qquad \textbf{3}$$

where A [(Pa s)/m^3] is the flow coefficient for fully developed laminar friction losses and B [(Pa s^2)/m^6] is the coefficient for entry, exit and turbulent flow losses. Inconveniently, Equation 3 gives the pressure drop for a known flow rate. For ventilation studies a correlation is needed to give flow rate as a function of the applied pressure difference due to wind, stack and mechanical ventilation effects. Equation 3 can be expressed in a more useful form as

$$Q = \frac{-A + \sqrt{A^2 + 4B\Delta P}}{2B} \qquad \textbf{4}$$

In Equation 4 only the positive root is required because all real flows are positive.
Standard fluid mechanics principles have been used [11] for flow between parallel plates to determine A and B, such that

$$A = \frac{12\mu z}{Ld^3}, \qquad B = \frac{\rho Y}{2 d^2 L^2} \qquad \textbf{5, 6}$$

where μ [kg/ms] is dynamic viscosity, L [m] is the width of the crack, d [m] is the gap thickness, z [m] is the distance in flow direction (crack length), ρ [kg/m^3] is the fluid density and Y is a factor that depends on the crack geometry. The following example values were given in [11], using empirically determined values of Y = 1.5 for a straight crack, 2.5 for an L-shaped crack and 3.5 for a double bend crack. The predictions for A and B were compared to measured data in [11] for various crack geometries with errors typically less than 20%. They found that values of A and B determined by least squares to Equation 4 gave a better fit than the theoretical values to their measured crack flow data for some simple crack geometries over a Reynolds number range of approximately 6000 to 60000.
Additional work for flow in pipes [12] summarized the work of previous authors ([13], [14] and [15]) on linearized Navier-Stokes equations to estimate A and B as:

$$A = \frac{128\mu z}{\pi D^4}, \qquad B = \frac{\rho Y}{2 d^2 L^2} \qquad \textbf{7, 8}$$

where D is the pipe diameter, and m is a factor to account for the linearization of the Navier-Stokes equations.

The quadratic equation allows the flow to vary from laminar to turbulent over a range of flow rates. However, this equation is based on combining fully developed laminar and turbulent flows and entry and exit losses. This can be physically unrealistic for the convoluted crack geometries typical of building leaks in which the flow is rarely fully developed because the flow has to begin its development after each sharp change of direction. In addition, the pressures across building leaks are not steady because of wind turbulence. This results in changing driving pressures for the flow such that the flow is being accelerated or decelerated almost all of the time. The fluctuations in flow and pressure further reduce the possibility of fully developed flows existing in building leaks.

3.2 Power law form

The power law relationship has the form

$$Q = C\Delta P^n \qquad \textbf{9}$$

where C [m^3/sPa^n] is the flow coefficient and n is the flow exponent. The flow exponent has the limiting values of 0.5 and 1 for fully developed turbulent and laminar flows respectively. A dimensionless pressure has been developed [12] that relates the ratio of total pressure drop to the critical pressure drop that occurs when the pressure drop due to fully developed laminar flow is equal to the pressure drop from combined entry, exit and flow acceleration effects. This parameter, S, has been related to the power law exponent, n , which allows the power law exponent to be related to the crack geometry, such that

$$S = \frac{1}{8}\frac{(1-n)n}{\left(n - \frac{1}{2}\right)^2} \qquad \textbf{10}$$

where A is the cross sectional area of the crack. The flow can then be expressed as a function of S:

$$Q = \frac{16\pi\nu z}{m}\phi S^n \qquad \textbf{11}$$

where ν is the kinematic viscosity and ϕ is a power law factor depending on the exponent, n.

Temperature and pressure corrections for the flow coefficient, C, can be made as follows (some of which was suggested previously [16]). From dimensional analysis it can be shown that

$$C \propto \frac{\rho^{n-1}}{\mu^{2n-1}} \qquad \textbf{12}$$

where ρ is the fluid density and μ the viscosity. If C is evaluated at some reference temperature, T_{ref}, and pressure, P_{ref} at which $C = C_{ref}$, $\mu = \mu_{ref}$ and $\rho = \rho_{ref}$ then

$$\frac{C}{C_{ref}} = \left(\frac{\rho}{\rho_{ref}}\right)^{n-1} \left(\frac{\mu_{ref}}{\mu}\right)^{2n-1} \qquad \mathbf{13}$$

Equation 13 gives the correct behaviour at the flow regime limits with C independent of viscosity for orifice flow (n=0.5) and independent of density for laminar flow (n=1).
For air over the temperature range typically encountered in buildings (-40^{o}C to +40^{o}C) the dynamic viscosity can be assumed to be linearly dependant on temperature to within a few percent so that

$$\frac{\mu_{ref}}{\mu} = \frac{T_{ref}}{T} \qquad \mathbf{14}$$

Assuming air behaves like an ideal gas over this range means that

$$\frac{\rho}{\rho_{ref}} = \left(\frac{P}{P_{ref}}\right)\left(\frac{T_{ref}}{T}\right) \qquad \mathbf{15}$$

Substituting Equations 14 and 15 in Equation 13 gives

$$\frac{C}{C_{ref}} = \left(\frac{P}{P_{ref}}\right)^{n-1} \left(\frac{T_{ref}}{T}\right)^{3n-2} \qquad \mathbf{16}$$

Equation 16 allows correction of the flow coefficient, C, for changes in barometric pressure and temperature. The fan pressurization tests discussed later have had the measured values of C corrected to a reference temperature of 20^{o}C and a barometric pressure of 90 kPa (This barometric pressure is lower than a standard atmosphere because the tests were conducted in Edmonton, Alberta which is about 700 m above sea level). These corrections allow direct comparison of fan pressurization test results measured under different ambient conditions.
The temperature correction is usually small for the distributed envelope leakage of a building because typical values for the flow exponent are close to 2/3. Using this value of n makes Equation 16 independent of temperature which means that the flow coefficient, C, is independent of temperature. **This makes the power law formulation simpler to use than other formulations at different conditions from those at which flow coefficients were measured.** For larger individual leakage paths, such as fireplaces and furnace flues, the flow exponent is typically 0.5, in which case the temperature correction in Equation 16 is significant. For example, if T_{ref} = 293 K and T = 253 K, then the flow coefficient is reduced by about 7%. This becomes more important for heated flues (e.g., when furnace burners are on) where the operating temperature is about 100K greater than the reference temperature.

4 Developing flow for a single crack

Given typical building crack geometries and flow rates the flow in building leaks is likely to be developing flow. Some researchers suggest that the flow exponent, n, is constant over a wide range of flow rates and pressure differences for cracks similar in geometry to building leaks. For example, for laminar flow in the entrance region of smooth circular tubes [17]. It has been proposed [18] that the results in [17] imply an exponent of n = 2/3 for this entrance region developing flow regime. This is also a typical value for n found from pressurization testing of houses. Although tempting, this does not prove that flow in cracks in building envelopes is undeveloped laminar flow because the developing flow regime in [17] was only dominant over an entry length of less than one diameter. It remains an intriguing coincidence, however, and requires further research. Experiments on parallel flat plates [19] have shown that n is constant over a very wide range of flow rates and pressures for a given crack geometry. The tests were performed from 1 to 50 Pa, encompassing the typical values experienced by a building envelope.

Other work has found that the power law exponent, n, may vary with flow rate. Tests of circular capillary tubes with length to diameter (aspect) ratios ranging from 0.45 to 17.25 found that n depends on aspect ratio for laminar flow where $Re_D < 2000$ (Re_D is Reynolds number based on tube diameter, D) [20]. Most building leakage sites fall into this category. For example, a 1 mm diameter crack with orifice type flow will have a $Re_D \approx 85$ for 1 Pa pressure drop and $Re_D \approx 400$ for 10 Pa pressure difference. The capillary tube measurements showed that at high aspect ratios the flow became more laminar and n approached 1, while at low aspect ratios the entrance effects were more dominant and n approached 1/2.

5 Flow through arrays of cracks

Previous work [11], [19] and several other researchers has concentrated on flow through an individual crack or cracks in series. However, in a real building the total leakage is the sum of many individual cracks of differing flow characteristics in series and parallel with each other that are distributed over the building envelope.

5.1 Parallel Cracks

The flow may be modeled as a parallel array of cracks. For laminar flow

$$\Delta P_L = R_L Q_L \qquad \textbf{17}$$

where ΔP_L is the pressure drop across the laminar flow crack, R_L is the flow resistance and Q_L is the flowrate. Similarly, for orifice like cracks

$$\Delta P_O = R_O^2 Q_O^2 \qquad \textbf{18}$$

where ΔP_O is the pressure drop across the orifice flow crack, R_O is the flow resistance and Q_O is the flowrate. For cracks in parallel an electrical analogy is to have the flow resistances in parallel such that

$$Q_{total} = Q_L + Q_O \text{ and } \Delta P_{total} = \Delta P_L = \Delta P_O \qquad \textbf{19, 20}$$

Substituting Equations 17 and 18 in Equation 19 and using Equation 20 gives

$$Q_{total} = \frac{\Delta P_{total}}{R_L} + \frac{\Delta P_{total}^{\frac{1}{2}}}{R_O} \qquad \textbf{21}$$

Equation 21 expresses the relationship between total flow and total pressure drop in terms of combined laminar and orifice type leaks in parallel.

5.2 Series cracks

This flow is equivalent to inlet and exit turbulent flow losses in series with fully developed laminar flow. This is the same as the quadratic flow discussed earlier and advocated by some researchers [2]. The laminar and orifice type flows are described by Equations 17 and 18. In this case the flows are the same and the pressures add so that

$$Q_{total} = Q_L = Q_O \quad \text{and} \quad \Delta P_{total} = \Delta P_L + \Delta P_O \qquad \textbf{22,23}$$

and the pressure drop can be written in terms of the two types of flow

$$\Delta P_{total} = R_L Q_L + R_O^2 Q_O^2 \qquad \textbf{24}$$

Equation 24 can realistically only be applied to a single crack whereas Equation 21 can be applied to an array of cracks.

The different behaviour of power law, series resistance and parallel resistance crack flow equations is shown in Figure 1. The logarithm of pressure and flowrate are plotted in Figure 1 to better distinguish between the different equations. The power law equation plotted in Figure 1 appears as a straight line with a constant slope due to its constant exponent (in this example the exponent value was chosen to be n = 2/3). R_O and R_L for the resistance crack flow equations were found by fitting to the power law relationship at 1 Pa and 10 Pa because this is the typical pressure range experience by building envelopes due to natural wind and stack effects. For the parallel cracks: R_O = 51.0 and R_L = 184.9 and for the series cracks: R_O = 24.65 and R_L = 19.45. Figure 1 shows how the series cracks become more like laminar flow (slope = 1 on this log-log plot) at low flow rates and orifice flow (slope = 0.5) at higher flowrates. For parallel cracks the reverse is true with orifice flow dominating at low flow rates and laminar flow at higher flowrates. Over the range of interest for air leakage (1 Pa to 10 Pa) there is very little difference between the three methods. This is partly because all three methods were chosen to be equal at 1 Pa and 10 Pa. If the methods had been equated over a different range larger differences over the range of interest would be observed.

The relationships illustrated in Figure 1 show that a combination of series and parallel leaks in an experiment may result in a pressure-flow relationship that fits a power law type equation even though the dominant flow regimes in each individual leak may change over the range of experimental pressures and flow rates.

6 Low pressure fan pressurization tests

In a real building there are cracks of many geometries that include both series and parallel leaks. To determine which crack flow method is the best for describing real building leakage, experiments have been performed on full size buildings using the method of fan pressurization testing. The buildings were tested with the large holes (e.g., furnace flues) sealed to observe pressurization test results for arrays of parallel and series cracks. The tests were repeated with flues open to look at combining the small cracks in the building envelope with large holes.

Standard methods for fan pressurization exist [3] and [4]. Both standards have recommended values for the pressure differences at which to take measurements. These pressure differences cover a range of 15 to 50 Pa for CGSB tests and 12.5 to 75 Pa for ASTM tests. Most of the time the actual pressures caused by wind and temperature difference (stack) effects on a building will be considerably less than 10 Pa. It is a fair question to ask if test results from high pressures may be extrapolated to the lower pressures that a building envelope usually experiences, because at lower flow rates the flow characteristics of the leaks may be different. This would imply that a different flow coefficient, C, and flow exponent, n, apply at the low pressures that a building experiences due to natural conditions than at the elevated pressures of a fan pressurization test.

For this study, fan pressurization tests were conducted at the Alberta Home Heating Research Facility (AHHRF) located south of Edmonton, Alberta, Canada. The houses were unoccupied and the fan pressurization test system was automated, which allowed over 5,000 fan pressurization tests to be performed. Windspeed, wind direction, and ambient temperature data were taken from meteorological towers at the test site. Pressure and flow rate measurements were taken over 15 seconds (at about 10 samples per second) and averaged for each data point. The uncertainty in the measured flows is estimated to be 0.001 m^3/s.

The indoor-outdoor pressure difference was measured using a pressure averaging manifold that had a pressure tap on each wall of the building. Offset pressures due to stack and wind effects with the fan not in operation were measured at every data point. A damper was closed over the fan opening for each offset reading because the fan opening can change the pressure distribution of the building significantly. The data shown in the following figures were chosen from tests with low windspeeds because increasing windspeed tends to increase the scatter in the measured data due to differences in the wind induced envelope pressures between the offset and measurement. For these tests, the uncertainty in the envelope pressure measurement is estimated to be 0.1 Pa.

Figure 2 shows the results of a typical test in a house with very little envelope leakage both with and without an open 15 cm diameter furnace flue with a 7.5 cm diameter orifice at the bottom (House #1 at AHHRF). The value of flow exponent (n = 0.56) with the flue open is lower than with the flue closed (n=0.73) because the flue flow exponent is about 1/2, and performing a test with the flue open will bring the value of the flow exponent for the whole building closer to 1/2.

Figure 3 shows the results of a test performed in House #2 at AHHRF with a 15 cm diameter furnace flue with a 7.5 cm diameter orifice at the bottom. Curves showing the least squares fitted power law and the quadratic leakage function are also shown in Figures 2 and 3. The quadratic was matched to the least squares power law at 1 and 100 Pa to determine A and B for Equation 3. Matching at these extreme values (rather than, for example, 5 and 50 Pa or by least squares) minimizes the differences between the extrapolations of the two methods to higher and lower pressures. The results shown in Figures 2 and 3 show that the power law formulation works well for houses with an array of small cracks as well as in houses with additional large holes (in this case a furnace flue).

A significant observation to be made from the results of these tests is that the relationship between flow rate and pressure difference does not change over the range of values tested. There is no observable trend towards more laminar flow at low flow rates and pressures (i.e. n approaches 1) or more turbulent flow at higher values (i.e. n approaches 0.5) or vice-versa. This shows that the C and n derived from blower test results in the range of 10 to 50 Pa are true constants describing the building leakage for the purposes of ventilation calculations. The power law fits the data well because the leaks are relatively short and convoluted for the building envelope. This means that the flows are never fully developed. In addition, a building envelope is a combination of parallel leaks and series leaks that when combined can result in power law behaviour (as shown above). On the other hand, the quadratic function attempts to make the leakage function more laminar at low flow rates and more turbulent at high flow rates and this trend is not observed in the data. These results also imply that tests at higher pressures of the CGSB and ASTM standards can be safely extrapolated to determine the leakage characteristics of a building for the pressure range that a building actually experiences.

7 Furnace flue leakage - a single well known leak

Except for open doors and windows, the furnace flue is usually the largest single leakage site in a building envelope. It is also the easiest to define in terms of size, shape and location. Laboratory tests were performed on a furnace flue typical of Canadian housing, consisting of 5 meters of 15 cm I.D. double walled pipe (Class B vent), with a raincap at one end of the pipe and a sharp edged inlet at the other. The laboratory tests were performed under controlled conditions to reduce external temperature and pressure fluctuation effects on the measurements. The flue was tested horizontally to eliminate any contribution to the flow due to buoyancy caused by temperature differences in the laboratory. When furnaces, boilers or fireplaces are in operation, the temperature (and composition) of flue gasses are changed. Section 3.2 discusses how the flow coefficient changes with temperature so that flue flows can be estimated under operating conditions.

A settling chamber consisting of a one meter cube partially filled with filter material was placed at each end of the flue. The pressure difference between these chambers was the driving pressure for flow through the flue. An ASME standard orifice flow meter with flange taps was placed upstream of the flue to measure the flow rate. Because a large range of flow rates was covered, several different orifices were used to reduce errors due to low Reynolds number effects. Air was drawn through the flue using a centrifugal fan on the outlet to reduce fan turbulence effects.

In order to obtain reasonable results below 1 Pa it was necessary to use sensitive pressure transducers (the ones used in these experiments had a range of only 75 Pa or about 0.25 inches of water), make very careful calibrations, and to correct for the offset pressures measured at zero flow. The offset pressures were measured at each data point to account for any zero drift in the instrumentation. A purpose built integrating voltmeter was used to time average the pressure and flow measurements. An averaging time of 100 seconds was found to remove any unsteady contribution and produce repeatable results.

The flue was tested for both regular operation and backdraughting i.e. forward and reversed flow. The results are shown graphically in Figures 4 and 5. The power law relationship was fitted by least squares to the data and is indicated by the straight line in each figure. Both data sets show that single values of C and n describe the flow over a wide range of pressures and flow rates. A least squares fit to the data gives values of C and n:

$C = 0.0137$, $n = 0.54$ forward flow

$C = 0.0118$, $n = 0.54$ reversed flow

The exponent, n, is the same in both cases, but the leakage coefficient C, is 13% less for backdraughting (reversed flow) most likely due to the change in flow geometry through the raincap. Using this measured value of n, together with the appropriate values of ν, z, m and ϕ, Equations 10 and 11 predict C = 0.0127. This shows that the theoretical power law formulations are good at estimating the flow coefficients.

Figures 4 and 5 also include a curve representing the quadratic relationship, where the flow coefficients A and B were found by calculating flow rates at 0.1 and 10 Pa and solving the two resulting equations. The tendency of this quadratic relationship to describe the flow as more laminar at low flow rates and more turbulent at higher flow rates can be seen by comparison with the reference lines indicating a slope of 1.0 (laminar flow) and a slope of 0.5 (turbulent flow). There is no clear transition from laminar to turbulent flow (like that suggested by the quadratic equation) in the measured data. This transition may have been expected because the Reynolds number has a range from approximately 600 at a flow rate of 0.001 m^3/s to over 30,000 at 0.05 m^3/s. This change in exponent is not seen because the flow is never fully developed for the whole flue and the entry and exit losses have a square root of pressure relationship. For Re $\approx$ 600 the length of pipe required is 18 pipe diameters (2.7 metres) for fully developed laminar flow. Therefore approximately one half of the flue length could contain fully developed laminar flow. Similarly at higher Reynolds numbers (Re $\cong$ 30,000) the flow in the flue is not all fully developed turbulent flow.

At flow rates less than 0.002 m^3/s there appears to be a small change in slope where the slope is increasing with decreasing flow rate, indicating that the friction factor loss term is significant and not constant with flow rate i.e. there is more laminar flow friction factor contribution. This situation occurs with flow in either direction. It should be noted that this occurs at a pressure difference of less than 0.1 Pa (which is extremely difficult to measure) and is somewhat obscured by uncertainty in the measurements, and that steady flows of this magnitude do not occur in building ventilation due to fluctuations in wind induced pressures. In addition, any mean flow generated by a 0.1 Pa pressure difference would be insignificant in an air infiltration analysis.

These results show that the power law can be applied to a single large leak over a wide range of pressures, particularly the pressures driving natural ventilation in houses.

8 Conclusions

The power law has been compared to the quadratic formulation for field and laboratory measurements of flows though building envelopes, and the theoretical backgrounds have been discussed. The power law was found to better represent the relationship between pressure and flow for buildings with small cracks only, combinations of the small building envelope cracks and large holes (a furnace flue) and laboratory measurements of furnace flues.

The following are key points developed in this paper:

- The quadratic formulation of laminar flow ($Q \propto \Delta P$) at low flows and turbulent flow ($Q \propto \Delta P^2$) at high flows is not valid for combinations of series and parallel leaks (as found in real building envelopes) and the power law is a balance between the two possible extremes of all series and all parallel leaks.
- Experimental and theoretical evidence shows that a power law function is appropriate for developing flow in cracks. Because the flow in building leaks is mostly developing flow, this evidence therefore shows that the power law should work well for building envelope leakage.

- House pressurization tests have shown that the power law is valid over the range of pressures typically experienced by a naturally ventilated house.
- Laboratory experiments on a furnace flue have shown that the leakage coefficient, C, and leakage exponent, n, can be considered independent of flow rate, Q, and pressure difference, Δ P, for a single large leak as well as the array of smaller cracks in the building envelope. Below 0.1 Pa the measurements showed a slight trend to wards more laminar flow, however, these low flows are insignificant in air infiltration calculations, and the measurement uncertainties are large.
- Dimensional analysis shows that the power law formulation has simple temperature and pressure corrections, and gives flow coefficients that are insensitive to air temperature for most building envelopes. This makes the power law easier to use than other methods for air infiltration calculations at temperatures different from the measurement conditions.

These results imply that the assumption of a power law relationship used by many standards and measurement procedures is valid. In addition, extrapolation of results from tests at high pressures to those typically experienced by a building envelope does not introduce a bias in infiltration predictions.

9 References

[1] Liddament, M.W., (1987), "Power Law Rules - OK?", Air Infiltration Review, Vol. 8, No.4.

[2] Etheridge, D.W., (1987), "The Rule of The Power Law - An Alternative View", Air Infiltration Review, Vol. 8, No.4.

[3] ASTM Standard E779, (1982), "Measuring Air Leakage by the Fan Pressurization Method", Annual book of ASTM Standards, part 18, pp.1484-1493.

[4] CGSB Standard 149.10-M86, (1986), "Determination of Airtightness of Building Envelopes by the Fan Depressurisation Method", Canadian General Standards Board.

[5] ISO Standard 9972, (1995), " Thermal insulation - determination of building air tightness - Fan Pressurization Method", International Organization for Standardization.

[6] ASHRAE Standard 119 - 1988, (1988), "Air Leakage Performance for Detached Single-Family Residential Buildings", ASHRAE, Atlanta, Georgia.

[7] ASHRAE Standard 136 - 1993, (1993), "A Method of Determining Air Change Rates in

[8] Shaw, Sir W.N., (1907), "Air Currents and Laws of Ventilation", Cambridge University Press.

[9]ASHRAE, (1989), Chapter 23 ASHRAE, Fundamentals Handbook, ASHRAE, Atlanta, Georgia.

[10] Etheridge, D.W., (1977), "Crack Flow Equations and Scale Effect", Building and Environment, Vol.12, pp. 181-189, Pergamon Press.

[11] Baker, P.H., Sharples, S., Ward, I.C., (1987), "Air Flow Through Cracks", Building and Environment, Vol.22, No.4, pp.293-304, Pergamon Press.

[12] Sherman, M.H., (1992), "A Power Law Formulation of Laminar Flow in Short Pipes", Journal of Fluids Engineering, Vol. 114, pp. 601-605, (LBL report 29414, Lawrence Berkeley Laboratory, University of California).

[13] Boussinesq, J., (1891), Mem. Pres. Acad. Sci. Paris, 23:46.

[14] Shiller, L. and Agnew, Z., (1922), Math. Mech., 2:96.

[15] Langhaar, H., (1942), “Steady Flow in the Transition Length of a Straight Tube”, J. Appl. Mech. 9:A55.

[16] Kiel, D.E., Wilson, D.J., and Sherman, M.H., (1985), "Air Leakage Flow Correlations for Varying House Construction Types", ASHRAE Trans. 1985, Vol. 91, Part 2.

[17] Shapiro, A.H., Siegel, R., and Klein, S.J., (1954), "Friction Factor in the Laminar Entry Region of a Small Tube", Proc. Second U.S. National Congress of Applied Mechanics, Michigan, 1954, ASME, pp. 733-741.

[18] Jones, W.R., (1987), private correspondence with D.J. Wilson (U. of A.), M. Modera and W.J. Fisk (L.B.L.).

[19] Honma, H., (1975), "Ventilation Of Dwellings and its Disturbances", Tekniska Meddelanden No.63 1975:2 (Vol.3) of Institutionen För Uppvärmings-och Ventilation Steknik, Teknika Högskolan.

[20] Kreith, F., and Eisenstadt, R., (1957), "Pressure Drop and Flow Characteristics of Short Capillary Tubes at Low Reynolds Numbers", ASME Trans., July 1957, pp. 1070-1078.