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ABSTRACT

This study investigates the fluid-modeling techniques used to simulate wind-forced natural ventilation rates of rectangular, single-cell low-rise buildings. A 1:25 scale model of the Texas Tech University Wind Engineering Research Field Laboratory is used in a boundary-layer wind tunnel to evaluate alternative strategies for simulating infiltration into permeable buildings. A new approach is proposed which should permit evaluation of a wide range of leakage situations. In addition data is used to critique standard full-scale tracer gas test methods.

INTRODUCTION

Outdoor air flows through a building either due to intentional ventilation (natural or forced) or unintentionally due to infiltration (and exfiltration). Natural ventilation through intentional openings (windows, doors) and infiltration through cracks, interstices, or porous walls are caused by pressures from wind and/or indoor-outdoor temperature differences. Infiltration due to unintentional openings of as low as 1% porosity can change internal pressure coefficients associated with designed openings alone by orders of magnitude and even revise net internal pressures from positive to negative. Hence, design of building ventilation systems to control internal air pollution, energy exchange, or wind loading must consider both ventilation and infiltration simultaneously.

Net air exchange in buildings is typically modeled by empirical models based on statistical evaluation of pressurization tests or by semi-empirical models which sum contributions from individual building components (ASHRAE, 1993). The local building surface pressures due to wind or thermal effects (stack) are estimated from wind tunnel tests, and the balance of infiltration and exfiltration mass over each building cell determines local internal pressure coefficients, Cp_i. Unfortunately, such methods can not normally account for the effect of wind gustiness, internal pressure fluctuations due to sudden failure of cladding components, unusual sheltering configurations, etc.

Ventilation rates can be determined from model tests in wind tunnels either by measuring the external pressure distributions and using this data for a theoretical prediction or by measurement of ventilation rates directly. The question is whether the ventilation rates are better estimated theoretically or measured directly at a model scale.

A strong argument in favor of direct measurement of ventilation rates during model tests is that the available theory does not account for the effects of wind turbulence and internal air movements. Unfortunately, there are also strong arguments against model measurements of infiltration and natural ventilation. First, it is hard to specify the actual leakage paths on full-scale structures, second, it is generally argued that it is not possible to achieve full-scale Reynolds numbers in model cracks at model scale. Since leakage flows through cracks tend to be laminar, Reynolds number effects will be significant (Etheridge, 1977).

This paper will briefly consider previous wind tunnel infiltration simulations, review physical models proposed for infiltration through cracks, evaluate their implications for proper fluid modeling, and propose an alternative simulation strategy. We will also present some recent data relating to Reynolds number dependence of exterior and interior flows around a model of the Texas Tech University Wind Engineering Field Laboratory (TTU WERFL). Finally we can present some results of model tests of infiltration which occurs through windows and doors on the TTU WERFL.

PREVIOUS FLUID MODELING EXPERIENCE

Shaw and Tamura (1977), Kandola (1978), Vickery et al. (1983)Sherman and Ashley (1984), and Wiren (1984) used wind-tunnel measurements of external pressures to drive a computer program to predict infiltration into homes and high-rise office buildings. Kandola included significant wall porosity on his models, and he reported at no time did the porosity affect the external wall pressure coefficients.

Smith (1951), Caudill et al. (1951) and Van Straaten (1967) used visualization and scale models to examine natural ventilation of buildings, but they limited their studies to dominant opening cases.

Liu (1975), Stathopoulos (1979), Cermak et al. (1982), Bächlin and Plate (19860, Chandra et al. (1986), Ernest et al. (1992), Dutt et al. (1992) and Womble (1994) examined velocity and internal pressure fields for both dominant openings and permeable walls. These studies were primarily directed toward determining internal pressures for severe wind storm situations to better estimate wind loads. Dominant opening to total surface area ratios varied from 0 to 33% and distributed porosity varied from 0 to 3.0%. For zero porosity but distributed dominant openings on the windward, A_W, and nonwindward, A_{nw}, building faces internal pressures agreed with the simple models of Liu (1975) and Saathoff and Liu (1983). Primary conclusions are:

- Internal pressures can be positive or negative depending upon whether upwind or downwind openings dominate, respectively.
- For a windward opening and varied porosity Cp_i can vary from +0.8 to -0.4 depending on open area and porosity. As the porosity decreases Cp_i becomes larger and positive.
- For a given opening ratio, A_W / A_{nw}, porosity tends to decrease the Cp_i range observed. However, the effects only become substantial for small open area ratios (< 5%).
- When there are no dominant openings and porosity is uniform on all sides the internal pressure is insensitive to wind approach angle.

Cocroft and Roberston (1976), Etheridge et al. (1979), Cermak et al. (1982) and Birdsall and Meroney (1995) considered dispersion implications of natural ventilation and infiltration through direct measurements. Primary conclusions are:

- Turbulent pressure fluctuations drives natural ventilation across a single openings. Only about 1/3 of the entering air ever mixes thoroughly with the internal bulk fluid.
- Measurements with the standard concentration decay and constant infection methods are very sensitive to the locations of release and measurement with respect to dominant openings. Hence, the measured values tend to provide lower and upper bounds to actual air exchange rates, respectively.
- The measurements of Cocroft and Robertson suggest strong Re number effects exist; however, their results may reflect experimental errors associated with the concentration decay technique used.

PHYSICAL MODELS FOR BUILDING INFILTRATION

Dimensional analysis suggests a set of dimensionless parameters which govern the behavior of infiltration across slits and holes. For an inviscid fluid:

- $Cp = \Delta p / [\rho (Q/A_s)^2]$, pressure coefficient,
- $A = A_{open} / A_s$ a surface porosity,
- Leak geometry,
- $T = Qt / A$, a dimensionless time for nonsteady flow, and

If the fluid is viscid, then additional parameters are required:

- $Re = Q / [\nu A_s^{1/2}]$, a Reynolds number.
- z / D_h, a slot or hole depth ratio.

Inviscid flows and infinite Reynolds number flows will produce infiltration rates which have constant discharge coefficients such that

$$Q = C_D A_s [\Delta p]^{1/2} \tag{1}$$

where $C_D = 1/Cp^{1/2}$. In such situations only similar building geometry and equal porosities are required for similarity. The fluid modeling dilemma is that viscous effects in cracks scale with crack Reynolds number; hence, we must seek an effective solution to the problem which accounts for the viscous effects on infiltration.

Empirical Correlations

Experimental measurements on full scale buildings using a pressurization method are frequently expressed as:

$$Q = c A_s [\Delta p]^n \tag{2}$$

where $0.5 < n < 1.0$. Both c and n depend upon building construction and type; however, $n = 0.65$ for most configurations. Note that the expression only applies to a limited differential pressure range. Field measurements for overall infiltration for high rise office buildings, supermarkets and shopping centers, schools and houses have been measured (Shaw et al. 1973, 4 office buildings; Tamura, 1975, 6 houses; Teado et al. 1978, 3-bedroom townhouse; Kronvall 1979, 29 houses; Shaw and Jones 1979, schools; Shaw 1981, 5 supermarkets and shopping malls; Wilson 1985, 6 unoccupied houses). Coefficients for individual building components are tabulated by ASHRAE (1993). The problem with this method is that the coefficients are empirical and dimensional and provide no physical incite to the infiltration mechanisms.

One can hypothesize that some effective open area, A_{eff}, exists which produces the same flow rate through equation (1) as was measured in equation (2). This effective or equivalent open area can be specified for a specific reference pressure, Δp_{ref}, and reference discharge coefficient, $C_{D\,ref}$, as

$$K_{eff} = \frac{A_{eff}}{A_s} = \frac{c}{C_{Dref}} [\frac{\rho}{2}]^{1/2} \Delta p_{ref}^{n - 1/2} \tag{3}$$

Investigators commonly set C_{Dref} equal to either 0.65 or 1.0. Given such a reference leak area ratio one can calculate a drag coefficient, C_D, which varies with Δp (or Reynolds number),

$$C_D = \frac{c}{K_{eff}} [\frac{\rho}{2}]^{1/2} \Delta p^{n - 1/2} \tag{4}$$

Crack Flow Equations

If one visualizes the individual leaks as finite dimension rectangular slits or holes, then one can construct a physical model for local flow as a function of pressure difference (Hopkins and Hansford 1974; Etheridge 1977; Chastain et al. 1987). Figure 1 displays a sketch of the rectangular slit dimensions. For either slits or holes the expression becomes,

$$_D = \frac{1}{Cp^{1/2}} = \frac{1}{[K_{ent} + K_{hd} + K_{exit} + \frac{Bz}{Re_l D_h}]^{1/}} \tag{5}$$

where minor loss coefficient subscripts *ent, hd, and exit* denote entrance, hydrodynamic development length, and exit losses, respectively; D_h= 4*(cross-sectional area/wetted perimeter) is the hydraulic diameter. $B = 96 - 106.67\,\alpha$ for a rectangular slot and α is the slot aspect ratio , and $B = 64$ for a circular hole. Re_1 is the slit or hole Reynolds number, and K_{hd} also depends upon $Bz/(D_h Re_1)$ and α.

$$K_{ent} = 0.5, \; K_{exit} = 1.0 \tag{6}$$

$$K_{hd} = 0.6 \; [B \frac{z}{Re_1 D_h}]^{0.1} \; [1 + \alpha] \tag{7}$$

$$Re = \frac{4 \; Q}{\pi \; D_h^2 \; \nu} \tag{8}$$

For a circular hole K_{bd} values are equivalent to those for a rectangular slit with $\alpha = 1.0$. These expressions are compared to experimental measurements of flow and pressure drop through straight rectangular slits and cylindrical holes in Figure 2. Chastain et al. (1987) data agreed with the predictions of expression (5) within ±2 % except for the very lowest flow rates, and for pressure differences greater than 50 Pa agreement was within ±0.5 %. Etheridge (1977) also measured total minor loss coefficients for a straight slit, a slit with a rectangular bend and a slit with two rectangular bends for which he obtained (B , K_{total}) values of (95.7, 1.5),(91.4, 2.2) and (43.2, 3.4), respectively. Figure 3 displays a plot of the discharge coefficient, C_D, versus $B\,z/(Re_1\,D_h)$ predicted from Equations (5), (6) and (7) for various values of slit aspect ratio, α. We propose the empirical expression Equation (7) which is compared to experimental data compiled by Chastain et al. (1987)

Figure 4 replots the discharge coefficient, C_D, versus a single leak Reynolds number for entrance lengths, z/D_h = 1, 4, and 8 for a cylindrical hole and a square slot. As expected the predicted flow behavior is similar. Figure 5 reveals the influence of entrance length, z/D_h, on rectangular slit discharge coefficients.

Models to Account for Fluctuating Pressures

Measurements by Etheridge and Nolan (1979) demonstrated that flow turbulence can transport fluid across a dominant opening even when there is no net mass flow across the opening. For infiltration only situations, one expects that the viscous effects will damp most pressure fluctuations, and the effective internal pressure coefficient will remain unchange. However, for cases with dominant openings fluctuations in imposed pressures may be expected to result in non-linear changes in air exchange dependent on the empirical coefficient n. Figure 6 demonstrates the nature of this effect. Different infiltration coefficients produce different mean flow rates, and different statistical standard flow rate deviations. Holmes (1979) demonstrated that a building cavity linked to the atmosphere by a finite opening may resonate with a Helmholtz frequency if undamped. Davenport and Surry (1984) calculated that resonance of a typical warehouse would require quite a large and unlikely dominant opening.

Bächlin (1985) suggested that the appropriate criteria for similarity in fluctuations in the pressure field and resultant air exchange might be a Strouhal number parameter like fL/U. This implies that $f_M = LSR*(U_M/U_P)*f_P$. Given a geometrically similar model and prototype building, the Helmholtz frequencies will be related as $(f_{hh})_M = LSR*(f_{hh})_P$ Thus, if one desires $(f_{hh}/f_M) = (f_{hh}/f_P)$ it is required that the mean velocities be equal.

If mean velocities, U, are held equal, and external pressure coefficients are similar , then differential pressures Δp are equal. Given equal differential pressures, building porosity and discharge coefficients, then local instantaneous slit velocities should be equal, ie. $[Q'/(A_s U)]_m = [Q'/(A_s U)]_m$

IMPLICATIONS FOR FLUID MODELING CRITERIA:

Investigators have proposed several methodologies to model building infiltration. Given the lack of specific information about leakage type, area, and geometry for any building structure approximations are unavoidable, alternate strategies include:

a. Measure wind pressure coefficients in a wind tunnel and use these values to drive a numerical infiltration model, (Shaw and Tamura, 1977; Vickery et al., 1983).
b. Use empirical data about the coefficients c and n from equation (2) and equation (3) to specify an effective open area ratio, K_{eff}. Use this value to specify porosity of wind tunnel model.
c. Assume all infiltration and dominant openings behave like orifices (equation (1), group model openings into large enough areas that critical Reynolds number for orifice flow is exceeded. Match open area ratio of dominant openings in model and prototype. (Liu, 1975, Etheridge and Nolan, 1979, Womble, 1994).
d. Model for "worst case" infiltration situations for purposes of design or code preparation, then exact simulation of the infiltration of a particular building is unnecessary. (Womble, 1994)
e. Examine a selection of models with equivalent porosity but different leak dimensions. Vary the leak geometries until the model reproduces anticipated c and n values from field measurements.(Bächlin, 1985).
f. Given Q and Δp from field measurements, model the leakage of a building as a single equivalent opening A_m and an equivalent geometric parameter for a rectangular slit, $\gamma_m = \alpha/[Bz(1+\alpha)^2]$. The parameters are determined by a least squares fit to the flow rate data for alternative choices of the geometric parameter. One then predicts Q vs Δp for each parameter pair and selects the set which gives the minimum average error in Q. (Chastain et al., 1987).

Methods a, b, c, and d fail to consider the influence of viscous effects on infiltration and ventilation on the pressure coefficients.. Methods e and f require iterative experiments, and f presumes some knowledge about the depth of the leak passages, z, in the prototype.

AN ALTERNATIVE INFILTRATION MODEL STRATEGY

Although the leak geometry in a typical full size building structure is unknown, it is possible to prescribe the geometry of such leakage paths in a wind tunnel model. Thus, the proposed approach is to systematically select a model leakage geometry which approximates the Q/A_s variations with Δp. Consider the following procedure:

- Estimate the appropriate value of c and n [see equation (2)] for the full scale building type from tabulated data (ASHRAE, 1993; etc.).
- Calculate the effective open area ratio, K_{eff}, of the full scale building from equation (3).
- Calculate the field discharge coefficient, C_D, over a range of pressures from equation (4).
- Assume a convenient model hole diameter (1-3mm), d, and calculate the number of equivalent holes to reproduce the full scale effective open area, $N = A_{eff}/(\pi d^2/4)$.
- Calculate the equivalent single hole Reynolds number, $Re_1 = Q/A_{eff} * (A_{eff}/N*4/\pi)^{1/2}/\nu$ and plot C_D versus Re_1.
- Superimpose results on single hole discharge coefficient curves calculated from equation (5) as shown in Figure (4). Select the z/D_h for model construction which best approximates field data.
- Construct scale model with the selected d, z/D_h and K_{eff} (porosity) values. Operate wind tunnel with model reference wind speed equal to the anticipated full scale wind speed, $U_M = U_P$.

Laminar flow is expected to occur in leakage cracks, slits or holes only up to Re_1 = 2,000, and the field parameters c and n are only appropriate for a finite Δp range; hence, the field and model discharge coefficient curves may not superimpose at large Reynolds numbers (Re_1 > 1,000). Given equivalent geometry and dominant opening area ratios, this method should simulate the instantaneous flow rate parameter Q/(AU) for both infiltration and dominant opening flows.

REYNOLDS NUMBER DEPENDENCE OF EXTERIOR BUILDING SURFACE CONCENTRATIONS

The flow field and concentration distribution over a model building in a wind tunnel will depend upon turbulence intensities, turbulent scales, and the separation and reattachment of streamlines from the building surface. These properties are known to vary with Reynolds number, but Golden (1967) performed measurements of dispersion over a cube mounted in a uniform flow, and he concluded similarity exists if $Re = U_H h/\nu > 11,000$, where h is cube height. Snyder (1992) extended this study for shear flows oriented perpendicular to a cube face for a source released at the downwind base of the cube. He concluded that Re > 4,000 would limit perturbations to twice the minimum inherent concentration standard deviation, S, where

$$S = [\frac{1}{N}\sum_{i=1}^{N} (\log K_{i1} - \log K_{i2})^2]^{1/2} \tag{9}$$

where K_{ij} is the dimensionless concentration coefficient measured at port I during situation 1, situation 2 is selected to be a case which definitely exceeds the critical Reynolds number. Snyder chose a minimum S of 0.1 and a minimum discrimination level in K of 0.001.

Recently, staff at Colorado State University have extended such measurements to another building geometry (TTU WERFL model) for three roof source locations, two model scales (1:25 and 1:50) and two wind approach angles (0° and 30°). Minimum discrimination levels in K of 0.001 were specified. Minimum inherent S values were 0.05-0.15 for concentrations on the building surface and 0.05-0.1 in the wake (Figure 9). Given the additional complexities of roof source location, orientation, and intermittent reattachment of streamlines on the building surface , we recommend that Re > 15,000.

REYNOLDS NUMBER DEPENDENCE OF INTERIOR BUILDING CONCENTRATIONS

As noted above infiltration discharge coefficients will be dependent upon Reynolds number based on crack dimensions. Similarly, discharge coefficients for sharp edged dominant openings should be invariant if Reynolds number based on opening dimensions are greater than about 400. But the internal building pressure coefficients which govern air exchange are sensitive to the distribution of external pressures; hence, simulated air exchange will also be dependent upon $Re = Uh/\nu$. Womble (1994) found that internal pressure coefficients are sensitive to approach flow turbulence intensity, which demonstrates the need to properly simulate terrain exposure.

Birdsall (1993) examined the TTU WERFL 1:25 scale model for variation in Cp_i for zero, one and two dominant openings for three wind orientations. Significant perturbations in pressure coefficient occurred when Re < 30,000. This suggests that lower velocity circulations within the model building may result in variations in internal flow patterns that affect air exchange.

APPLICATION OF MODELING STRATEGY TO TTU WERFL MODEL

Measurements of the porosity of the full scale Wind Engineering Research Field Laboratory at TTU were performed by Yeatts (1993). Using the procedure suggested in equation (3) he determined the effective open area porosity of 0.025%. The measured discharge coefficients found at the field site are plotted versus overall leakage Reynolds number in Figure 8.

Also plotted on this figure are data from pressurization tests performed on 1:25 scale models of the building with 6 and 57 holes of diameter 1.59 mm and z/d = 4. Analytic curves based on equation (5) include finite and zero values for K_{bd}. Based on total open area the curves are displaced over many order of magnitude in Reynolds number.

About 36,000 holes of 1.59 mm diameter are required to produce an open area of 0.025% on the TTU WERFL building. Thus the equivalent values of $Re_1 = Re_{open}/190$. The field values for discharge coefficient, C_D, are replotted on Figure 9 versus Re_1. Also included is equivalent data for the CSU 6-hole and CSU 57-hole experiments. All the data are superimposed on the values from equation (5) assuming a hole diameter of 1.59 mm and z/d = 4. It appears that model leakage paths of this size will simulate the field behavior over a wind range of conditions. To obtain an equivalent model porosity of 0.025% at a model scale of 1:25 one calculates $N_M = N_P/ LSR^2 = 36,000/(25)^2 = 57$.

Womble (1994) also constructed a porous model of the TTU WERFL building at a scale of 1:50 to investigate internal pressure effects on wind loading. He used 0.79 mm leakage holes, plastic walls such that z/d = 7.6, and stipulated 62 holes. Fortunately, these choices produce discharge coefficients which also approximate the recommended conditions. Womble compared model internal pressure coefficients to field measurements for 0, 1, 2 and 5% defined open area conditions. Measurements agreed within inherent experimental error.

TRACER GAS RESULTS FOR TTU WERFL MODEL TESTS

Continuous release concentration tests were run with the 1:25 scale TTU WERFL model for situations with no discrete openings, window open, and window and door open. Concentration samples were taken at multiple points within the interior to adjust calculations for incomplete mixing (see Birdsall and Meroney, 1995). Make up volumes of air were bled into the model during sampling to correct air volumes for any removed by sample suction. Estimates of average, median, minimum and maximum mean concentrations were made from the set of internal sampling ports. From this data average , Q_{avg}, and median, Q_{med}, ventilation rates were calculated based on known source strengths and source flow rates.

Figure 10 displays the variation of model building concentrations and ventilation versus wind orientation for the window open configuration of the TTU WERFL building. Ventilation is maximum when wind approaches the open window directly (orientation 180°). Since only a single opening exists ventilation is solely due to turbulent fluctuations since mean mass exchange must be zero. The wide variation of the maximum mean concentration sampled suggests the danger of implying ventilation rates from a single sample point.

Figure 11 displays the variation of model building concentrations and ventilation versus wind orientation for the case when both window and door are open. Ventilation rates are maximum and concentrations are minimum when the wind is aligned with the window or door (orientations 0° and 180°). In this case air can pass directly through the building, turbulent exchange plays a smaller role, and ventilation magnitudes increase by an order of magnitude.

Figure 12 compares the average ventilation rates normalized by reference wind speed at building height, Q/U (cm/s^2). All model tests were performed at 0.53 m/s. Window and door openings results in ventilation rates 10 times greater than window open only situations, and the same condition exceeds infiltration rates by a factor of 10,000. One should note that the porosity value of 0.025% represents an extremely tight structure; hence, the relative role played by porosity in this situation is not typical. Full scale values for Q/U are obtained by multiplying model values by the square of the length scale ratio.

CONCLUSIONS

Since building infiltration can play a dominant role in the design of buildings for ventilation, energy control, and even wind loading, it is valuable to be able to include its effects during physical simulation in meteorological wind tunnels. This paper has reviewed the nature of infiltration, simple analytic models which explain the physical processes present during leakage, and previous experience modeling building ventilation and infiltration. A simple method to accommodate the simulated effects of infiltration during fluid modeling is proposed. This approach leads to definitive suggestions for model construction.

The modeling approach is demonstrated for the case of the TTU WERFL facility. Coefficient of internal pressure measurements confirm the method.

Concentrations and ventilation rates are presented for tests performed over a 1:25 scale model of the TTU WERFL including infiltration through distributed leaks and ventilation through discrete openings.

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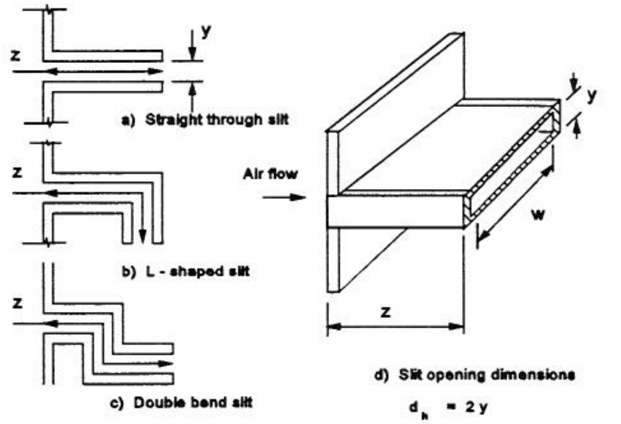

Figure 1: a), b) & c) Common crack types (Etheridge, 1977), and d) slit dimension (Chastain et al., 1987).

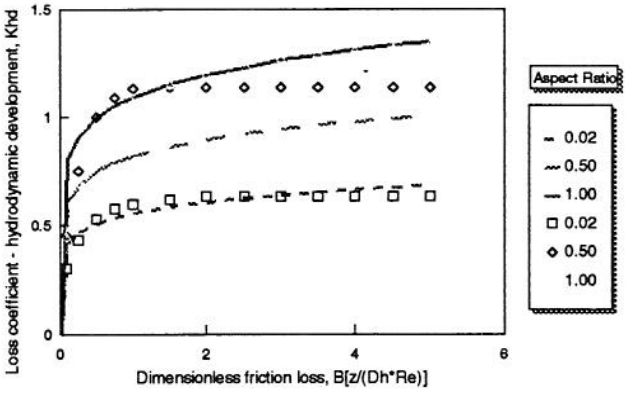

Figure 2: Variation of minor loss coefficient for slit or hole development length with Reynolds number and slot aspect ratio. Cylindrical holes follow $\alpha = 1.0$. Data is from Chastain et al. (1987).

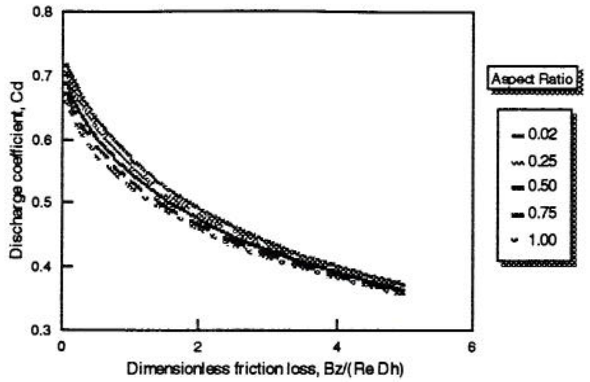

Figure 3: Leakage slit or hole discharge coefficient versus dimensionless friction loss. The discharge coefficient for a cylindrical hole is equivalent to a slit with $\alpha = 0$.

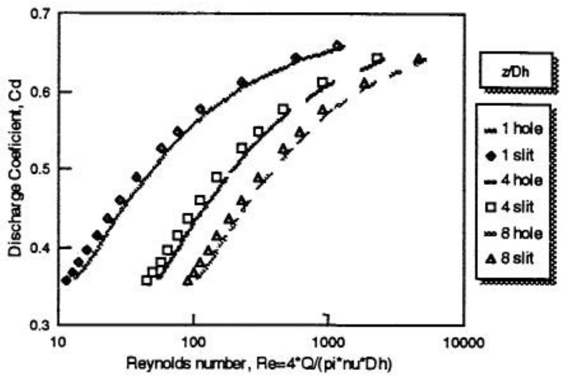

Figure 4: Discharge coefficient versus slit or hole Reynolds number, $\alpha = 1.0$, $B_{hole} = 64$, $B_{slit}(\alpha=1) = 57$.

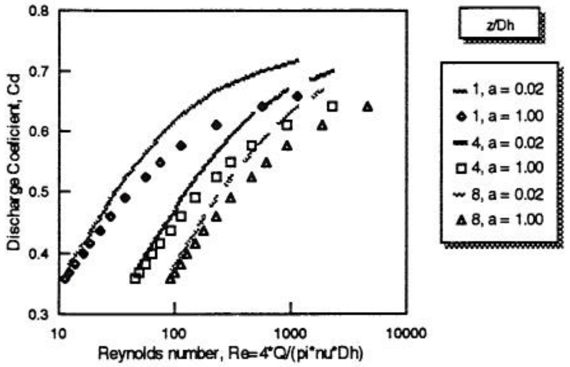

Figure 5: Discharge coefficient versus Reynols number for slit aspect ratios, $\alpha = 0.02$ and 1.00, $B(0.02) = 93.9$ and $B(1.00) = 57$.

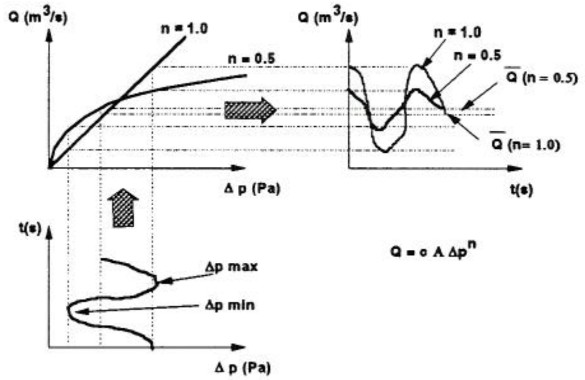

Figure 6: Influence of the exponent n on the average and fluctuating values of infiltration after Bächlin (1985).

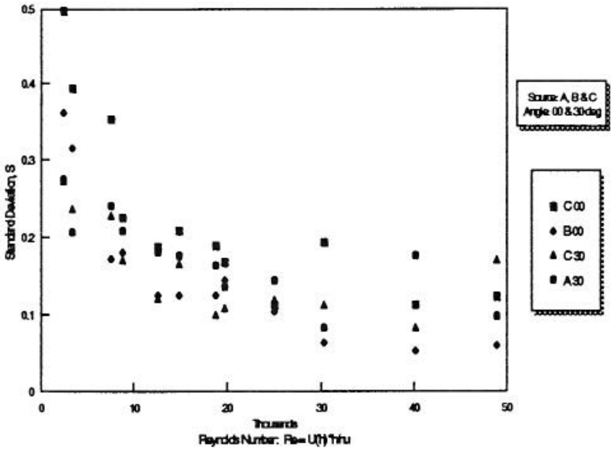

Figure 7: Standard deviation meaures of the similarity of concentration fields as a function of building Reynolds number. Model scales of 1:25, roof source locations and wind orrientations of 0° and 30°.

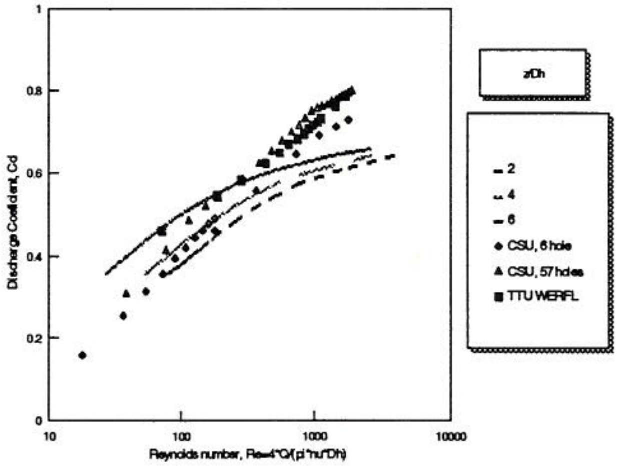

Figure 9: Discharge coefficient versus normalized one-hole Reynodls number, where $Re_1 = Re_{all} / N^{1/2}$. Assumed leakage is through cylindrical holes with $\alpha = 4.0$.

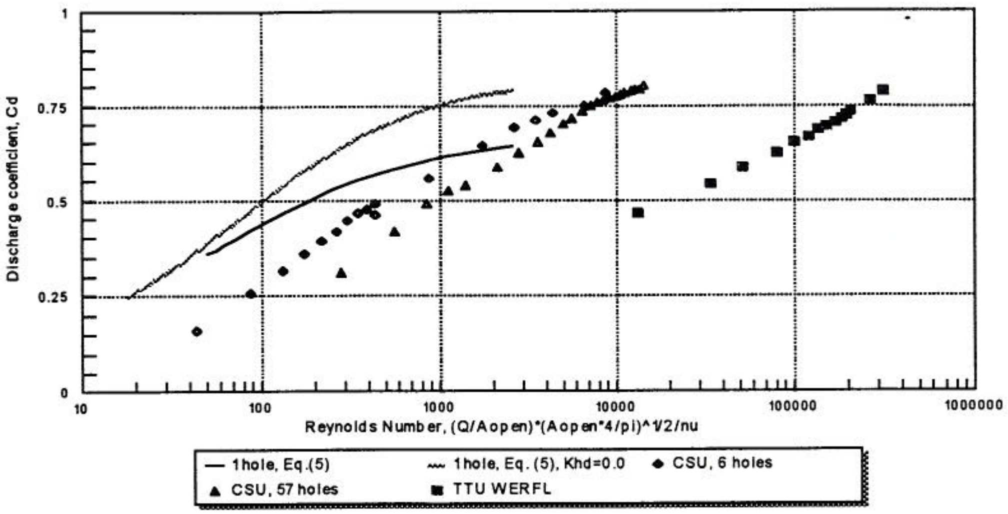

Figure 8: Discharge coefficient versus total flow Reynolds numbers. CSU experiments on 1:25 scale model of TTU WERFL with cylindrical holes and $z/D_h = 4.0$.

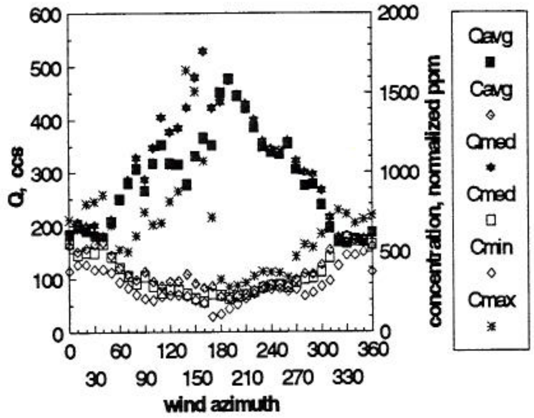

Figure 10: Ventilation into 1:25 scale model TTU WERFL building with open window. Continuous flow method using 16 internal sample ports.

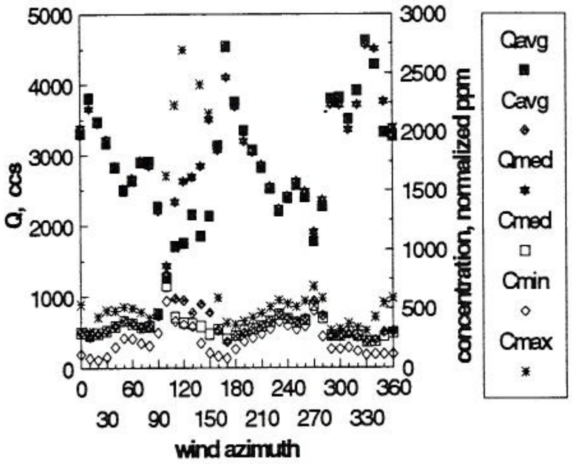

Figure 11: Ventilation into 1:25 scale model TTU WERFL building with open window and door. Continuous flow methods using 16 internal sample ports.

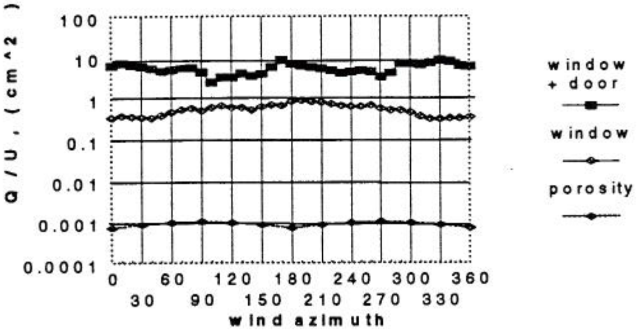

Figure 12: Comparison of average ventilation rates for infiltration alone, one window open, and a window and door open on the 1:25 scale model TTU WERFL building.