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Discharge Coefficients for a Dominant Opening in a Building

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Abstract

This paper assesses the discharge coefficient, k for dominant openings in buildings under steady, oscillating and reversing pressure differences. The discharge coefficient is found experimentally as the ratio of the measured flow to the theoretical flow through an orifice. A range of steady pressures were applied in a pressure chamber on two opening configurations of identical area: a sharp edged circular opening and a square opening of 6mm thickness. The measured discharge coefficients were between 0.65 and 0.7 for both opening configurations. Oscillating positive pressures were applied on the pressure chamber for the square opening with a constant amplitude of 1kPa. The discharge coefficients measured were similar to the steady pressure cases, suggesting that the magnitude of fluctuations have minimal effect. However, when the pressure difference alternates between positive and negative, the measured discharge is significantly reduced, resulting in a discharge coefficient of 0.15 to 0.25. This reversing flow is similar to net pressures across a dominant opening, which characterises internal pressure fluctuations due to Helmholtz resonance in buildings. The reduced discharge coefficient supports previous wind tunnel studies that estimated discharge coefficients between 0.15 and 0.5.

Introduction

A dominant opening in the building envelope is typically created by a window or door failure. The critical design case occurs when a breach on the windward wall results in the pressurisation of the internal volume generating large net pressures on the roof, leeward wall and side wall surfaces. The internal pressure fluctuations for a dominant opening have been studied by Holmes (1979), Vickery (1986, 1994), Vickery and Bloxham (1992), Sharma and Richards (1997) and Ginger et al (2010).

Holmes (1979) used the Helmholtz resonator concept to describe internal pressure fluctuations. Idealized conditions, such as steady unidirectional flow through a sharp circular orifice connecting two infinitely large volumes is assumed to estimate the discharge coefficient k. In practice, these conditions are not realised and as a result, theoretical values for k are questionable.

Many studies have been conducted to derive the discharge coefficient for ventilation applications. However, studies for the dominant opening structural design case have been limited. Vickery and Karakatsanis (1987) estimated the discharge coefficient for unidirectional unsteady flow by measuring the flow through a range of opening configurations. They found that for Reynolds numbers greater than about 3000, the discharge coefficient is nominally constant at 0.7. Costola and Etheridge (2008) have studied the effects of changing flow direction on discharge coefficients. However, the forward and reversing directions were considered independently and essentially treated as unidirectional. Few studies have examined the reversing flow condition and its effect on the discharge coefficient.

Oh et al (2007) and more recently Holmes and Ginger (2012) have both presented useful summaries of discharge coefficients, assumed or derived by various researchers in their respective studies. These summaries showed that k has been estimated to be between 0.15 to 1.0. This paper studies the discharge coefficient for steady, oscillating and reversing pressure drop across openings.

Theory

The unsteady mean flow Q, through an opening A, is driven by a pressure difference Δp and can be described by the discharge equation given in Equation 1. Here, ρ is the density of air and $U = Q/A$ the area averaged flow velocity through the opening. The losses through the opening are characterised in the first term, by the discharge coefficient k. The losses are sometimes represented as a loss coefficient $C_L = 1/k^2$. The second term characterises the inertia by the acceleration of the air mass through the opening, defined as dU/dt and the inertial coefficient C_I. Here, $C_I\sqrt{A}$ is the effective length of the slug of air at the opening.

$$\Delta p = \frac{1}{2}\frac{\rho U^2}{k^2} + \rho C_I \sqrt{A}\frac{dU}{dt} \qquad (1)$$

The steady (i.e. time averaged) flow through the opening is given by

$$\bar{Q} = kA\sqrt{\frac{2\overline{\Delta p}}{\rho}} \qquad (2)$$

For the purpose of this study, the discharge coefficient is considered as a constant and does not vary with time. The discharge coefficient for an opening is a function of the velocity coefficient C_v and contraction coefficient C_c:

$$k = C_c \times C_v \qquad (3)$$

where,

$$C_c = \frac{area\ of\ the\ vena\ contracta}{area\ of\ the\ orifice}$$

$$C_v = \frac{velocity\ at\ the\ vena\ contracta}{theoretical\ velocity}$$

The vena contracta is the point where the streamlines first become parallel and where the air jet has the smallest contraction (ie. smallest area). Experimentally locating the exact point of the vena contracta and measuring the contracted area proves difficult.

For steady flow through a sharp edged circular orifice connecting two infinitely large volumes, steady flow theory gives $C_c = \pi/(\pi + 2) \approx 0.61$ and $C_v \approx 0.99$ or 1. In most internal pressure studies, an approximate k of 0.6 has been used as the generally "accepted" value. This assumption stems from studies by Vickery (1986, 1994) and Vickery and Bloxham (1992) where wind tunnel tests were compared with numerical models.

Holmes' 1979 paper estimated a much lower k value of 0.15 for a dominant opening in a wind tunnel model by comparing wind tunnel results with a numerical simulation. This was attributed to the unsteady highly fluctuating and the reversing flow of the wind through the dominant opening caused by Helmholtz resonance. Wind tunnel studies by Ginger et al (2010) and Kim and Ginger (2012) found that k varies with the ratio of dominant opening and internal volume sizes. For these studies, the discharge coefficients were estimated to range between 0.1 to 0.5.

An alternative method of defining the discharge coefficient was presented by Sharma and Richards (1997), which applies the aforementioned C_c parameter to the opening area A, in the inertial term and an independent loss coefficient C_L in the damping term. In this case C_L includes all losses and is defined as an effective loss coefficient (Sharma, 2010). The C_c was empirically identified using computational fluid dynamics when a contraction was qualitatively observed at the orifice. While the actual vena contracta on the effective length was not measured, a value of 0.6 was heuristically matched using wind tunnel experiments and numerical methods. This form of the governing equation was derived from Liu and Saathoff (1981). For the purpose of this study, the discharge coefficient will be described using the former method.

Experimental Setup

Two types of experiments were performed at the wind tunnel laboratory at James Cook University. The first experiment, was a wind tunnel model building of dimensions 200×400×100mm, with an extended volume of 200×400×600mm below the wind tunnel floor. Six external pressure taps were installed adjacent to a 50×50mm dominant opening located at the centre of the 400mm wall. Internal pressure taps were installed at various locations in the internal volume. A diagram of the wind tunnel model is shown in Figure 1.

The model was tested in a 1:200, open terrain velocity profile. External and internal pressures were combined to give a net pressure across the opening. The pressures were sampled at 1250Hz over a period of 30sec using the Turbulent Flow Instrumentation (TFI) dynamic pressure measurement system (DPMS).

Pressures can be expressed as a non-dimensional pressure coefficient: $C_p = p/\frac{1}{2}\rho\bar{U}_h^2$, where $\bar{U}_h$ is the mean wind speed at a height, h and $\bar{p}, \sigma_p, \hat{p}, \check{p}$ are the mean, standard deviation maximum and minimum pressure respectively. Pressure is considered positive if it acts towards a surface.

For the second experiment, a pressure chamber with a dominant opening was connected to a Pressure Loading Actuator (PLA) with a 4m length of PVC piping. A Cobra Probe was inserted in the pipe to measure the mean velocity profile for each flow condition. A schematic of the test setup is shown in Figure 2. The mean discharge $\bar{Q}$, at the dominant opening was estimated by multiplying the mean velocity by the cross sectional area of the PVC pipe. In the reversing flow case, tests are performed with the Cobra Probe positioned in the positive flow direction followed by a second test in the negative flow direction. The mean flow for both directions are averaged to obtain a mean net flow $\bar{Q}$.

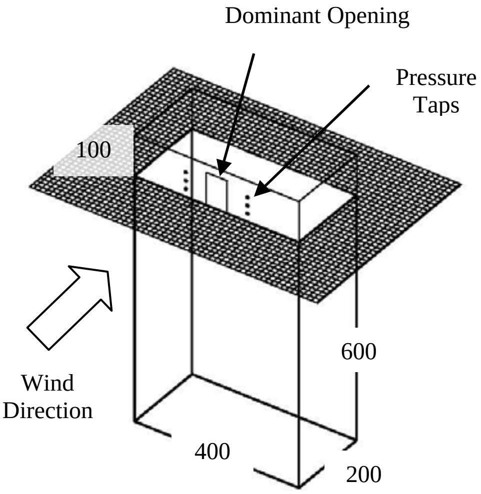

Figure 1: 200×400×100mm model with a 600mm extension below the wind tunnel floor, with test wind direction, dominant opening and external pressure tap locations

Pressure taps were installed in the pressure chamber and measured simultaneously with the Cobra Probe using the TFI integrated DPMS to obtain the pressure difference. The discharge coefficient can then be measured using Equation 2.

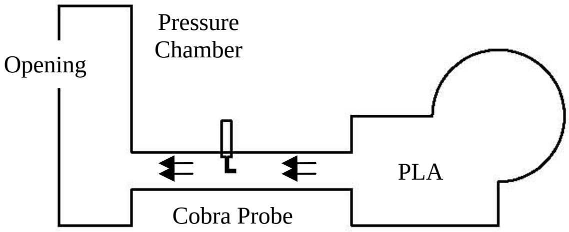

Figure 2: Setup for measuring the discharge coefficient, with the opening shown in the pressure chamber and arrows indicating positive flow direction

Two opening configurations with equal areas were used to simulate a dominant opening in the pressure chamber: a sharp edged, 56mm diameter circular opening, shown in Figure 3 and a 50×50mm, 6mm thick square opening shown in Figure 4. Test configurations are summarised in Table 1.

The PLA is able to simulate static, oscillating and reversing pressure conditions, by a feedback system with a pressure transducer installed in the pressure chamber (Kopp et al, 2010). For all oscillating and reversing flow tests, an amplitude of 1kPa and frequency of 5Hz were maintained. Samples of steady, oscillating and reversing pressure traces are shown in Figure 5.

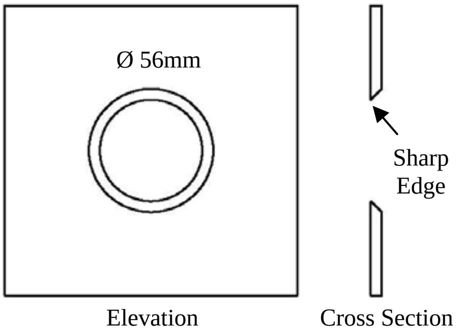

Figure 3: Sharp edged, 56mm diameter circular opening

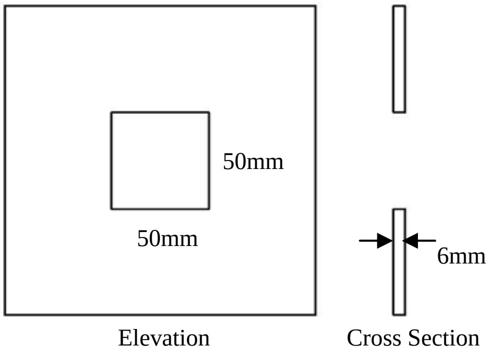

Figure 4: 6mm thickness, 50×50mm square opening

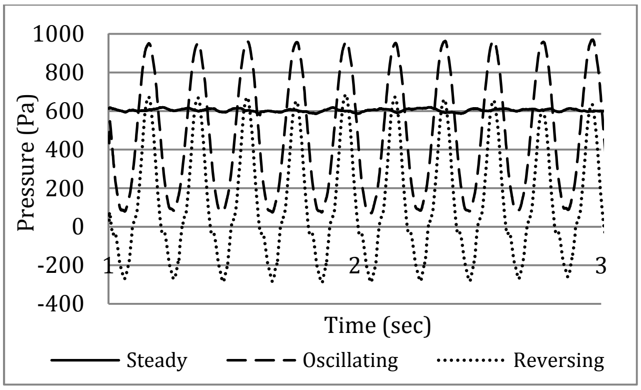

Figure 5: Sample pressure traces for steady ($\bar{p} = 600Pa$), oscillating ($\bar{p} = 500Pa$) and reversing pressure ($\bar{p} = 200Pa$) conditions

Results and Discussion

A net pressure time history trace was created by taking the difference between the simultaneously measured external and internal pressure time histories measured in the wind tunnel model test. A portion of the net pressure time history is shown in Figure 6. The highly fluctuating nature of the pressure signal is clearly observed as well as the pressure changing from positive to negative numerous times. The rapid change from positive to negative pressure causes a mass of air to move in and out of the opening. The mean, standard deviation, maximum and minimum $C_{p\,net}$, were measured to be -0.07, 0.16, 0.57 and -0.88 respectively. A $\bar{C}_p$ that was very close to 0 was observed. The large $C_{\sigma p}$ of 0.16 is due to the highly fluctuating signal observed in Figure 6. The large $\hat{C}_p$ and $\check{C}_p$ indicate, that sizeable flow is still possible even with a small mean pressure coefficient.

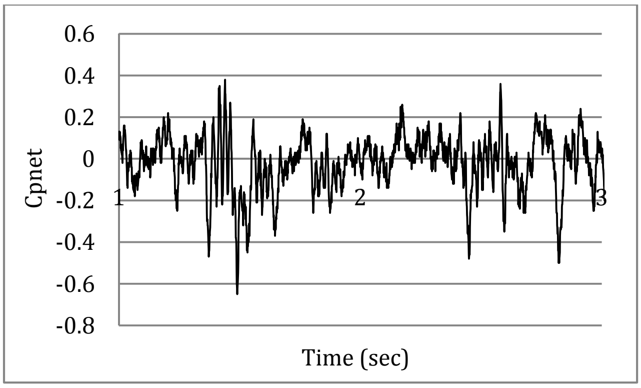

Figure 6: Sample net pressure across the dominant opening time history trace

Equation 2 was used to estimate k by measuring the mean flow and the mean differential pressure for the circular and square openings. The resulting discharge coefficients and corresponding mean pressure drops are presented in Table 1. The results show that the discharge coefficients for circular and square orifices are between 0.65 and 0.7. As the mean pressure drop is increased, there is minimal variation in the discharge coefficient for both circular and square openings. This is similar to results found by Vickery and Karakatsanis (1987), where the discharge coefficient remained constant for Reynolds numbers larger than 3000. In this test program, Reynolds number at openings were much larger than 3000. In general, the discharge coefficients for the square openings were slightly smaller than the circular openings but, the differences can be considered negligible. Similarly, when the flow is oscillating or highly fluctuating but still unidirectional, the discharge coefficient appears to remain unchanged and fall within the range of 0.65 to 0.7. This suggests that the discharge coefficient for highly fluctuating unidirectional flow is similar to the steady flow cases.

Table 1: Opening shape, pressure signal patterns and mean test pressures with resulting discharge coefficients

Opening	Pressure Pattern	Mean Pressure Difference (Pa)	Discharge Coefficient
Circular	Steady	25	0.649
		150	0.680
		600	0.688
		1300	0.694
Square	Steady	25	0.675
		150	0.679
		600	0.672
		1300	0.662
Square	Oscillating	1000	0.659
		500	0.674
Square	Reversing	200	0.255
		100	0.162
		20	0.186

When the pressure in the chamber alternates between positive and negative, the flow direction at the opening also changes direction. Under these reversing flow conditions, the discharge coefficient is reduced to between 0.16 and 0.25. Table 1 also shows that when the mean pressure is increased to 200 Pa, the discharge coefficient also increases. This is due to the majority of the flow being in the direction of the positive pressure drop and only a small part of the flow in the reversing direction, causing a larger net flow in the positive direction. However, as the mean approaches 0 Pa, the positive and negative pressures become similar and the net flow is reduced. When the mean pressure is almost 0 Pa (i.e. 20 Pa) the discharge coefficient is slightly larger than when the mean pressure is 100 Pa. This is because as mean approaches 0 Pa, any observed pressure fluctuations will amplify the discharge coefficient, since the net flow is expected to be very small. Equation 2 implies that there is always a differential pressure and a net flow. It should be noted that these trends are for constant amplitude and frequency in pressure. If the amplitude and frequency are varied, the results could differ.

The reversing flow direction in and out of a dominant opening in a building closely resembles the reversing flow case in the pressure chamber. This change of flow direction causes the C_v to become smaller since the mean velocity at the vena contracta implies a unidirectional flow across the opening.

The actual magnitude of the C_v from wind tunnel results have not been estimated in this study and remains to be determined. However, if the area of the vena contracta C_c is reduced as suggested by Sharma (1997) and the velocity at the vena contracta is also reduced then this would result in discharge coefficients much smaller than the "accepted" value of 0.6 used in many studies.

Conclusions

A study was conducted to assess the discharge characteristics of a dominant opening in a building envelope that results in air flow in and out of the building. The study assessed the discharge coefficients for steady, oscillating and reversing pressure drops across an opening. The results showed that when the flow is unidirectional, the discharge coefficient k, is between 0.65 and 0.7 regardless of whether the pressure is steady or highly fluctuating.

As the fluctuating pressure drop across the opening changes sign, the resulting air flow across the opening changes direction similar to that in buildings with a dominant opening. In this case the discharge coefficient k, is reduced to a value less than 0.6 due to the reduction in the velocity coefficient. The resistance of the air inside the building volume prohibits the wind to flow freely in to the volume and results in a smaller C_v. The smaller C_v causes the discharge coefficient to reduce. This smaller discharge coefficient supports studies which have estimated discharge coefficients in the range 0.1 to 0.5.

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References

Costola D, Etheridge D. (2008) Unsteady Natural Ventilation at Model Scale – Flow Reversal and Discharge Coefficients of a Short Stack and an Orifice, Building and Environment, 43:1491-1506.

Ginger J, Holmes J, Kim P (2010) Variation of Internal Pressure with Varying Sizes of Dominant Openings and Volumes, Journal Structural Engineering ASCE, 136:1319-1326.

Holmes J (1979) Mean and Fluctuating Internal Pressure Induced by Wind, Proceedings of the 5th International Conference on Wind Engineering, Fort Collins, USA.

Holmes J, Ginger J (2012) Internal pressures – The dominant windward opening case – A review, Journal of Wind Engineering and Industrial Aerodynamics, 100:70-76.

Kim P, Ginger J. (2012) Internal Pressure in Buildings with Dominant Openings and Background Porosity, Wind and Structures Journal, under review

Kopp G, Morrison M, Gavanski E, Henderson D, Hong HP. (2010) "Three Little Pigs" Project: Hurricane Risk Mitigation by Integrated Wind Tunnel and Full-Scale Laboratory Tests, Natural Hazards Review ASCE, 11:151-161.

Liu H, Saathoff P. (1981) Building Internal Pressure: Sudden Change, Journal of Engineering Mechanics Division, 107:309-321.

Oh J, Kopp G, Inculet D (2007) The UWO Contributions to the NIST Aerodynamic Database for Low Buildings Part 3: Internal Pressures, Journal of Wind Engineering and Industrial Aerodynamics, 95:755-779.

Sharma R, Richards, P (1997) Computational Modelling of the Transient Response of Building Internal Pressure to a Sudden Opening, Journal of Wind Engineering and Industrial Aerodynamics, 72:149-161.

Sharma R, Mason S, Driver P (2010) Scaling Methods for Wind Tunnel Modelling of Building Internal Pressures Induced Through Openings, Wind and Structures, 13:363-374.

Vickery B (1986) Gust Factors for Internal Pressures in Low-Rise Buildings, Journal of Wind Engineering and Industrial Aerodynamics 23:259-271.

Vickery B (1994) Internal Pressure and Interactions with the Building Envelope, Journal of Wind Engineering and Industrial Aerodynamics 53:125-144.

Vickery B, Bloxham, C (1992) Internal Pressure Dynamics with a Dominant Opening, Journal of Wind Engineering and Industrial Aerodynamics 41:193-204.

Vickery B, Karakatsanis C (1987) External wind pressure distributions and induced ventilation flow in low-rise industrial band domestic structures. ASHRAE Transactions 93:2198-2213.