Wind driven flow through building openings

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ABSTRACT

This paper presents internal pressure coeffi-
cients and discharge coefficients in a building
with wind-driven cross-ventilation caused by
sliding window openings on two adjacent walls.
The study found that both coefficients vary con-
siderably with the opening area and the inlet to
outlet ratio.

1. INTRODUCTION

Field experiments carried out in an urban can-
yon have shown that appreciable ventilation
rates can be obtained with natural ventilation,
especially when cross ventilation with two or
more windows is used (Niachou et al., 2005).
However, the modeling of large openings (win-
dows partly open) remains a significant source
of uncertainty in prediction of ventilation per-
formance. In fact, comparisons of simplified
empirical methodologies with respect to airflow
prediction show significant variations when dif-
ferent equations or solution methods are used.

The most common equation describing the
airflow through an opening is the orifice equa-
tion, which is based on Bernoulli's assumption
for steady incompressible flow, and requires
that the discharge coefficient, C_D, and the inter-
nal pressure coefficient, Cp_{in}, are both known.
For typical low-rise residential buildings, the
airflow through ventilation openings (i.e.
openable windows) is mainly wind-driven, es-
pecially during the summer. For wind-driven
ventilation, the discharge coefficient for an inlet
can be determined by:

$$C_{D,inlet} = \frac{Q}{A \cdot V \cdot \sqrt{C_{pw} - C_{pin}}} = \frac{u}{V \cdot \sqrt{C_{pw} - C_{pin}}} \quad (1)$$

in which Q: airflow through the opening, u: ve-
locity in the opening, A: opening area, V: refer-
ence wind speed at the building's height, C_{pw}:
pressure coefficient on windward façade, C_{pin}:
internal pressure coefficient, determined for a
building with two openings by Equations (2)
and (3) for large openings (windows, doors –
turbulent flow) and small openings (cracks –
laminar flow) respectively:

$$C_{pin} = \frac{C_{p2} + \alpha^2 \cdot C_{pl}}{1 + \alpha^2} \quad (2)$$

$$C_{pin} = \frac{C_{p2} + \beta \cdot C_{pl}}{1 + \beta} \quad (3)$$

where C_{p1}: external pressure coefficient in open-
ing 1, C_{p2}: external pressure coefficient in open-
ing 2, $\alpha = A_1/A_2$ and $\beta = ¼$ for uniform distribu-
tion of cracks. Generally, C_{pin} depends on the
external pressure distribution, terrain, shape,
area and distribution of openings on the façade.

This paper presents the results of a series of
experiments carried out in a Boundary Layer
Wind Tunnel (BLWT) for the evaluation of the
internal pressure coefficient in a building with
cross-ventilation. Discharge coefficient values
for different opening configurations with differ-
ent inlet to outlet ratio are presented.

2. DESCRIPTION OF THE MODEL AND EXPERIMENTAL SET UP

A 1:12 gable roof-sloped building model of rec-
tangular plan view 15.3 × 9.8 cm was tested
with an eave height of 3 cm. This corresponds
to a building 61 × 39 m and 12 m high accord-

ing to the 1:400 geometric scale in the BLWT of
Concordia University. The model provides variable side-wall and windward wall openings and
background leakage of 0 and 0.5%. The background leakage was achieved by a series of
holes which could be left open or closed. Five
pairs of closely-located internal and external
pressure taps have been selected for the measurements as indicated in Figure 1. Plastic tubes
connect each tap with a Honeywell 163 PC
pressure transducer. More details on the building model can be found in Wu et al. (1998). A
standard wind profile over open country terrain
was simulated with a power-law exponent equal
to 0.15 and turbulence intensity at the eave
height equal to 22%.

In this study only simple rectangular openings of the same height (1.7 cm) were considered. Differences in opening areas were induced
by different opening width (sliding windows).
The wall thickness is equal to 3 mm. A single-sided ventilation configuration was considered
first for comparison proposes. Experiments
were performed for 0 and 0.5% background
leakage. This was followed by cross-ventilation
experiments with 0.5% background leakage.
Configurations with equal inlet and outlet opening area were tested as well as configurations
with inlet to outlet ratio smaller or larger than 1.
The two rectangular openings were located in
the middle of long wall (windward wall) and
short wall (side wall). Measurements were carried out for a wind angle, θ, equal to 0°. Figure 1 shows the different opening configurations
considered in this study.

3. RESULTS AND DISCUSSION

3.1 Internal pressure coefficient

The measured mean values of the external pressure coefficients (reference height=building
height) are 0.67 for the windward wall, -0.36 for
the side wall, -0.25 for the leeward wall and -0.4
and -0.74 on taps 7 and 9 of the roof. The measured mean internal pressure coefficient for 0.5%
background leakage (without openings) is -0.36
which is slightly different from the theoretical
value, -0.23, obtained by Equation (3) using C_{p1}
as the representative of the positive external
pressure and C_{p2} as the area-averaged pressure
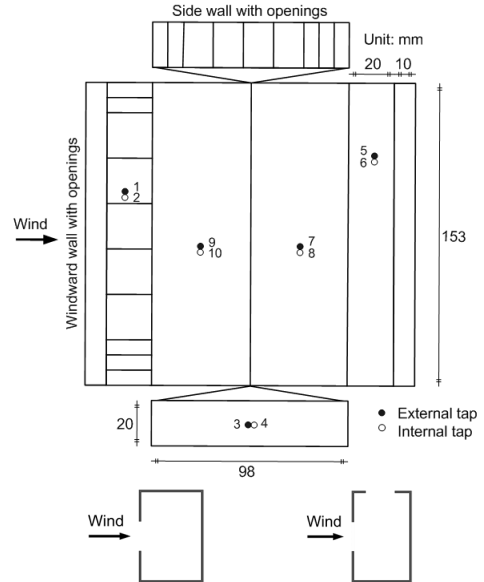on the rest of the building envelope.

Figure 1: Exploded view of building model with pressure
tap locations and opening configurations.
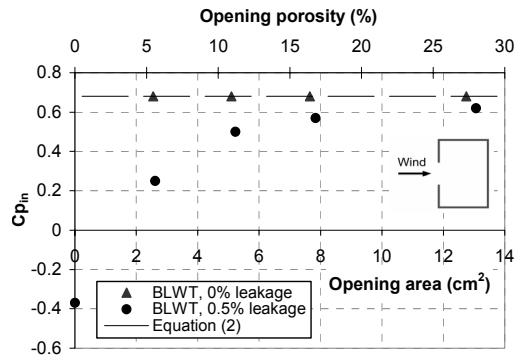
Figure 2: Internal pressure coefficients for single-sided
ventilation and different opening porosity.

The impact of a windward wall opening (single-sided ventilation) on internal pressure was
investigated for 0 and 0.5% background leakage
and results are presented in Figure 2 for different opening area or opening porosity ($A_{opening}/A_{wall}$). The opening is located in the middle
of the long façade. The internal pressure was
measured at different internal taps and it was
found to be uniform, as also previously reported
by Wu et al. (1998). The experimental data is
compared with the values obtained by Equation
(2) for 0% background leakage. For the case of
a single opening, Equation (2) reduces to
$Cp_{in}=Cp_1$, which is equal to 0.67.

Figure 2 shows good agreement between the experimental results and the theoretical values for 0% leakage. In addition, data obtained for 0.5% background leakage shows a similar trend with that observed in previous studies, e.g. Wu et al. (1998). However, Equation (2) cannot be used in this case due to the undetermined character of the flow.

The impact of a windward and a side-wall opening (cross ventilation) of the same area ($A_1=A_2$) on internal pressure was investigated for 0.5% background leakage. The openings were located in the middle of the long and short walls – see Figure 1. Measurements were carried out for opening area up to 10.2 cm^2 (or 22 % opening porosity); which is typically the range in naturally ventilated houses. The external pressure distribution was monitored and found not affected by the presence of openings on the façade (sealed body assumption). The internal pressure was measured on taps 2, 4, 6, 8 and 10. Figure 3 presents the mean value and standard deviation of the internal pressure coefficient as a function of the opening area. The Cp_{in} values by using Equation (2) are also presented. For $A_1/A_2=1$, Equation (2) reduces to $Cp_{in}=(Cp_1+Cp_2)/2$. Note that the background leakage is not considered when using Equation (2). The experimental results show that the average Cp_{in} increases with the increase of the opening area, although Equation (2) provides a constant value. It was found that the internal pressure is not uniform for opening area larger than about 5 cm^2 (which corresponds to approximately 10% opening porosity), resulting in a increase of the standard deviation of the internal pressure coefficient. This is probably due to a virtual flow tube that connects the inlet and

the outlet – see also Murakami et al. (1991), Sawachi et al. (2004). In fact, small Cp_{in} values were measured in taps 2 and 10 that are in the flow tube, while high Cp_{in} values were recorded in taps 4, 6 and 8 that are not in the flow tube. These variations should be considered in the selection of the measurement points. The non-uniformity of Cp_{in} distribution in the room was not observed in the case of single-sided ventilation and it is not predicted by the theory – Equation (2). Variation in Cp_{in} values along the flow tube have been reported by Sawachi et al. (2004). In the same study, the average Cp_{in} in a cross ventilated room with two rectangular openings with 9% inlet and outlet opening porosity was about 0.52, while in the study by Murakami et al. (1991) varied from -0.33 to 0.18 for different configurations and opening areas ranging from 5 to 36 cm^2.

The internal pressure coefficient was also investigated for inlet opening area equal to 2.6 cm^2 ($A_1=2.6$ cm^2), 0.5% background leakage and different inlet to outlet ratio (outlet opening area, A_2, varied from 0.9 to 12 cm^2). The experiments were repeated for inlet opening area, A_1, equal to 5.2 cm^2. The internal pressure was measured on taps 2, 4, 6, 8 and 10. The mean and standard deviation of the internal pressure coefficient as a function of inlet to outlet ratio (A_1/A_2) for $A_1=2.6$ cm^2 is shown in Figure 4 and for $A_1=5.2$ cm^2 in Figure 5. The results are compared with data from Murakami et al (1991) for the case of a side-wall outlet (model 1) and a leeward wall outlet (model 2). The Cp_{in} values by using Equation (2) are also presented. The experimental results indicate that the average Cp_{in} increases with the increase of inlet to outlet ratio. For $A_1/A_2<1$ (i.e. large outlet area, A_2) the standard deviation of Cp_{in} is higher due to differences among the various internal pressure taps; these differences are even higher for larger inlet area, $A_1=5.2$ cm^2. This internal pressure coefficient variation is again due to the flow tube connecting the inlet and the outlet. The Cp_{in} values predicted by Equation (2) are overestimated compared to the experimental data, particularly for higher inlet to outlet ratios. This might be due to the impact of the background porosity that is more important for small opening areas and high A_1/A_2 ratios. Comparison of Figures 4 and 5 shows that there are no substantial differences among average Cp_{in} values for
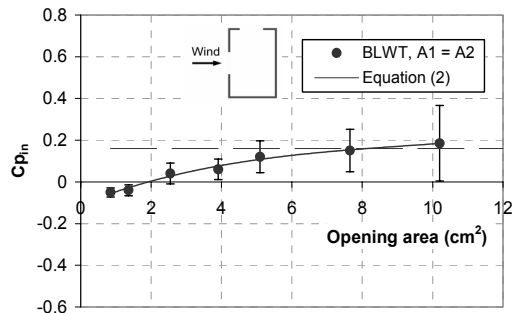

Figure 3: Internal pressure coefficients for cross- ventilation, $A_1=A_2$ ($\alpha=1$) and 0.5% background leakage.

the same A_1/A_2 ratio but different A_1 and A_2, as opposed to Cp_{in} values for configurations with $A_1=A_2$ (Figure 3). However, the internal pressure coefficient varies considerably (from -0.26 to 0.47) for configurations with $A_1/A_2>1$ or $A_1/A_2<1$ compared to configurations with $A_1/A_2=1$ (from -0.05 to 0.19). This might be important to be considered in natural ventilation design.

3.2 Inlet discharge coefficient

3.2.1 Theoretical background

The discharge coefficient (Equation 1) is determined by applying the Bernoulli equation on a horizontal stream line between a point in front of the building opening with stagnant air and pressure and the vena contracta (minimum cross section area of the flow with parallel stream lines, uniform velocity and static pressure equal to the surrounding air pressure) – see also Andersen (1996) and Karava et al. (2004). Hence, in case an opening separates two regions with still air boundary conditions, the discharge coefficient can be assumed to be constant ranging from 0.6 to 1, depending primarily on the shape (geometry) of the opening. Bernoulli equation assumes two points that are not affected by the opening and the pressure if uniform. Thus selection of the measurement point should not be a problem.

For wind-driven cross-ventilation the velocity and pressure fields at the inlet are unsteady, creating difficulties with the selection of C_D and, more fundamentally, its definition (Etheridge, 2004). Experimental results confirm the previous statement, particularly in the case of cross-ventilation with large opening areas (see Figures 3, 4 and 5). Thus, care should be taken in the selection of the measurement point. For wind-driven cross-ventilation, the discharge coefficient depends on the geometry of the opening but also the external (surrounding and building) and the internal flow field (background leakage, leeward/side wall openings). In fact, for large opening area, there is significant air movement in the room due to the flow tube and the flow might no longer be considered as pressure driven. Therefore, discharge coefficient values might be outside the standard range i.e. from 0.6 to 1.

3.2.2 Experimental results

In order to determine the inlet discharge coefficient, the velocity ratio u/V - see Equation (1) - was evaluated using a hotfilm anemometer. The results are presented in Table 1 along with data from other similar wind tunnel studies reported in the literature. The ratio u/V is about 0.6-0.63 in the present study and it varies between 0.45 and 0.83 in other literature sources. A more precise method to evaluate this ratio might be to consider velocity field measurements (PIV technique), as opposed to point measurement techniques.

In the present study, the velocity in the opening is assumed equal to the velocity just before the opening, i.e. for two inlet openings with dif-

Table 1: Velocity ratios (u/V) for different studies.

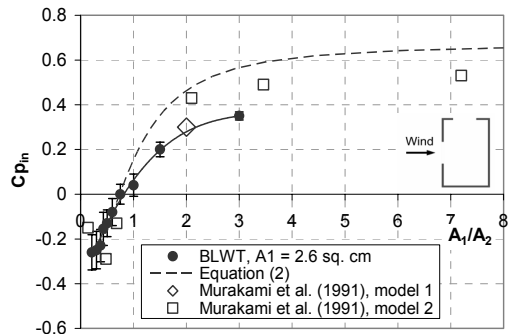| Reference	u/V	U_{ref} (m/s)
Present study	0.6-0.63	7.2
Hu (2005)	0.45	7.0
Etheridge (2004)	0.60	4.0
Sawachi et al. (2004)	0.50	3.0
Murakami et al. (1991)	$0.62-1.0$	Not reported

Figure 4: Internal pressure coefficients for cross- ventilation and different inlet to outlet ratios (A_1=2.6 cm^2).
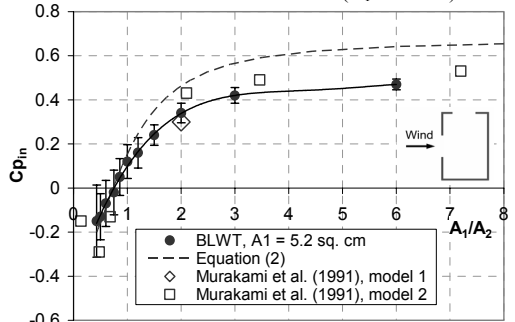

Figure 5: Internal pressure coefficients for cross- ventilation and different inlet to outlet ratios (A_1=5.2 cm^2).

ferent areas the velocity ratio (u/V) is assumed to be the same. Consequently, the difference in the discharge coefficient between the two openings is due to Cp_{in} variation with the opening area. Velocity profile measurements carried out by Jensen et al. (2002) show that for opening porosity from 2 to 20 % (porosity range considered in the present study), the ratio of the velocity in the opening and the velocity just before the opening is about 0.9-1.0 (except for measurement points close to the edge). This confirms that the assumption made in the present study is reasonable.

Figure 7 shows the variation of the inlet discharge coefficient with the opening area for cross-ventilation with two rectangular openings of the same area ($A_1=A_2$) located on the windward and side wall of the building model for 0.5% background leakage. Wind tunnel data from Murakami et al. (1991) (for cross-ventilation with openings located in the long façade of the building) and Jensen et al. (2002) are also included. Most previous studies have found that the discharge coefficient increases with the increase of the opening area. However, Sawachi et al. (2004) has reported that C_D is not affected by the opening area. Heiselberg et al. (2002) found that C_D might decrease, increase or remain almost constant depending on the configuration, regardless of opening area. Karava et al. (2004) reviewed the current literature and concluded that no clear trend can be established. The results of the present study show that the inlet discharge coefficient varies from 0.74 to 0.9 for opening area from 0.1 to 10 cm^2 (corresponding to 2-20% inlet opening porosity) and u/V=0.63 and from 0.6 to 0.71 for
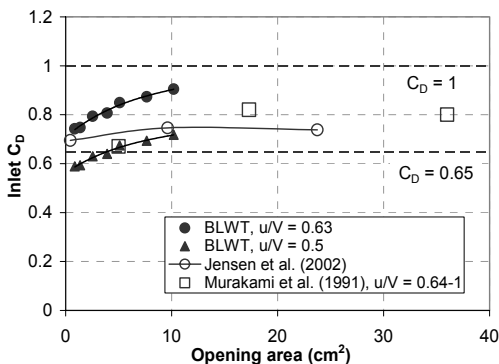
u/V=0.5. Different C_D values are observed in the various studies especially for u/V=0.63 due to different external flow conditions, opening and building configurations considered. A 0.5% background leakage was considered in the present study as opposed to impermeable models used in other studies. Hence, the results of a study can only be used within the limits of their applicability. For the opening and building configurations considered in Figure 7, the discharge coefficient is higher than 0.65, which is the typical value given in textbooks, e.g. Etheridge and Sandberg (1996). For u/V=0.5 the BLWT results of the present study are in good agreement with the other literature sources. Therefore, C_D=0.65 might be a good approximation for velocity ratio u/V=0.5. However, further experimental work is required considering different building and opening configurations as well as more precise measurement techniques such as PIV before any generalization is to be made.

Figure 8 shows the variation of inlet discharge coefficient with the inlet to outlet ratio (A_1/A_2) for A_1=2.6 cm^2. Data from Murakami et al. (1991) were also considered for the case of cross ventilation with a windward wall inlet and a side wall outlet. Generally, the discharge coefficient varies from 0.65 to 1.15 for u/V equal to 0.63 and from 0.52 to 0.9 for u/V equal to 0.5. For $A_1/A_2<1$ there is smaller variation of C_D compared to that for $A_1/A_2>1$. A similar observation was made by Sandberg (2004) for the catchment area Ac, defined as Q/Uo for "relative large" opening area. Non–standard discharge coefficients (i.e $C_D>1$) are observed for $A_1/A_2>>1$. This can be justified by the unsteady external and internal flow field in the case of

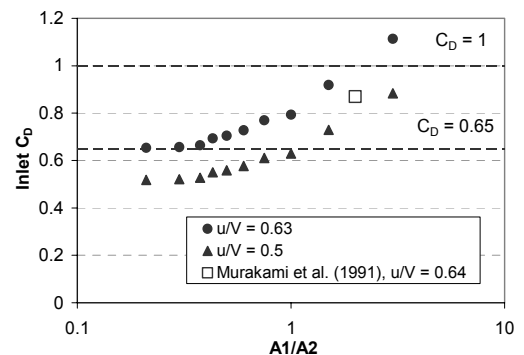Figure 7: Inlet C_D as a function of the opening area for equal inlet to outlet ratio.

Figure 8: Inlet C_D as a function of inlet to outlet ratio for A_1=2.6 cm^2.

cross ventilation particularly for large opening area, as previously discussed.

4. CONCLUSIONS

The internal pressure coefficient varies considerably for cross-ventilation configurations with unequal inlets and outlets. This is particularly important for natural ventilation design. The inlet discharge coefficient varies with the opening area and inlet to outlet ratio, particularly for $A_1/A_2 > 1$.

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