NATURAL VENTILATION OPENINGS – A DISCUSSION OF DISCHARGE COEFFICIENTS

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ABSTRACT

This paper, in addition to reviewing the current literature in discharge coefficients of natural ventilation openings, presents comparisons among different studies in an attempt to reconcile some of the existing approaches and identify possible discrepancies. The existing information regarding the parameters affecting the discharge coefficient of openings has been summarized and analyzed separately for single-sided and cross ventilation configurations. The discharge coefficient is a result of a multivariable impact and the use of a constant value such as that given in textbooks or works of reference is a simplification, which may cause considerable errors. Large discrepancies in discharge coefficient values were found among the different studies especially at small opening porosities where the fully developed turbulent flow assumption (orifice equation) is incorrect and the impact of building envelope leakage might be important. A significant variation of the discharge coefficient with the wind incidence angle has been found; however, more research is required to clarify this issue so that it can be considered in natural ventilation system design. Several problems with the application of the orifice equation to the calculation of wind-driven cross ventilation rate are pointed out. However, there is disagreement among the different literature sources regarding the proposed solution to the problem. Finally, the review of the literature for buoyancy-driven single-sided ventilation shows considerable variation of the discharge coefficient with temperature difference and lower discharge coefficient values compared to those for cross ventilation.

INTRODUCTION

Integrated multi-zone airflow and thermal models are increasingly popular for detailed simulation of yearly performance of natural ventilation systems and their impact on energy consumption of buildings (Li and Heiselberg 2002). It is therefore necessary to ensure that the fundamental governing equations are correct and that the ventilation rate can be predicted accurately. The most common equation describing the airflow through an opening is the orifice equation, which is based on Bernoulli's equation for steady incompressible flow. This equation can be used for a relatively large opening area (typical dimension larger than 10 mm). In that case, the flow tends to be turbulent under normal pressures and the flow rate, Q (m^3/s), is proportional to the square root of the pressure difference across the opening:

$$Q = C_D \cdot A \cdot \left(\frac{2 \cdot \Delta P}{\rho}\right)^{0.5} \tag{1}$$

where
C_D = discharge coefficient of the opening
A = flow area (m^2)
ΔP = pressure difference across the opening (Pa)
ρ = air density (kg/m^3).

The discharge coefficient is a characteristic parameter for a specific opening; it depends on the geometry of the opening, the Reynolds number of the flow, and includes the influence of contraction and friction. Andersen (1996) provides a thorough discussion of inlet and outlet coefficients. For turbulent flow, C_D is constant at a fixed Reynolds number and therefore, the flow is proportional to $\sqrt{\Delta P}$. For sharp-edge orifice flow the discharge coefficient is almost independent of the Reynolds number. However, in reality the flow through building envelope openings is not fully developed and C_D appears to be variable due to geometry of the openings and the variation in pressure difference with the environmental conditions inside and outside the building. Therefore, C_D is the result of a multivariable impact and it is difficult to analyze simultaneously all the parameters involved. Usually, only limited cases are examined, hence the

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discharge coefficient values should be used within the limits of their applicability. Typical discharge coefficients given in textbooks vary between 0.6 and 0.65 (ASHRAE Fundamentals, 2001) for small square-edged openings and between 0.9 and 0.95 for round edge openings (Andersen 2002). Hence, textbooks and other references provide very limited information considering the variety of typical building openings and their combinations while complex cases such as orientation of openings relative to wind direction, relative shape and sequence of aligned openings are not considered.

Natural ventilation through large openings is distinguished into single-sided and cross ventilation. For single-sided ventilation, airflow through large openings is usually considered to be bi-directional. The total volumetric flow through one-half of the opening for buoyancy-driven flow is given by the following formula:

$$Q = C_D \cdot \frac{A}{3} \cdot \sqrt{\frac{\Delta T \cdot g \cdot H}{T}} \tag{2}$$

where
ΔT = temperature difference across the opening (°C)
g = gravitational acceleration (m/s^2)
H = height of the opening (m).

For wind-driven cross ventilation the so-called total pressure loss coefficient ζ is often used instead of the discharge coefficient (i.e. Murakami et al. 1991; Vickery and Karakatsanis 1987). The following equation given by Andersen. (1996) can be used to calculate C_D values based on total pressure loss coefficient values:

$$\zeta = \Delta P_t \cdot \frac{2}{\rho} \cdot \left(\frac{A_o}{Q}\right)^2 = \frac{1}{C_D^2} \tag{3}$$

where
ΔP_t = total pressure difference across the opening (Pa)
A_o = opening area (m^2)
Q = airflow (m^3/s)
ρ = air density (kg/m^3).

There are several problems with the application of Equation 1 to the calculation of wind-driven cross ventilation rate. Murakami et al. (1991) found that the conventional method based on the application of Bernoulli's law (approximation of the airflow through small openings, such as thin orifices of sufficiently large Re) for cross ventilation can lead to unrealistic results. Similar studies have been carried out by He et al. (1991) and Ishihara (1969). Sandberg (2002) pointed out the need for a more elaborate model than the orifice equation. A better approach might be to regard the flow through openings as a flow catchment problem.

Since the validity of the "traditional" orifice equation remains questionable for large openings, the selection of an appropriate equation to represent the flow characteristics of openings is problematic. This paper, in addition to reviewing the current literature in discharge coefficients of natural ventilation openings, presents comparisons among different studies in an attempt to reconcile some of the existing approaches and identify possible discrepancies. The existing information regarding the parameters affecting the discharge coefficient of openings has been summarized and analyzed separately for buoyancy-driven single-sided ventilation and cross ventilation configurations.

REVIEW OF CURRENT LITERATURE RESULTS

Table 1 summarizes existing information regarding the parameters affecting the discharge coefficient of openings. The first column gives the bibliographical reference. Since all the experiments were not carried out under the same conditions, it is necessary to define the experimental set up (i.e. wind tunnel, field measurements). Columns 2 and 3 give the ventilation strategy (single or cross ventilation) and the method (i.e. analytical, experimental or numerical) used. Column 4 gives the opening type and columns 5 to 12 give all the parameters affecting the pressure difference across an opening and therefore, the C_D.

TABLE 1. Literature sources regarding the evaluation of discharge coefficients.

Source	Ventilation Type	Method	Opening Configuration	A	T	V	θ	P_{fan}	Opening Location	Internal Partition	Building Envelope Leakage Area	C_D
Aynsley et al. (1977)	cross vent.	empirical	rectangular	✓								
Vickery and Karakatsanis (1987)	cross vent	wind tunnel	rectangular and holes	✓		✓						
Riffat (1989)	single-sided	full-scale, real building	internal doorways		✓						✓	$C_D = 0.0835\left(\frac{\Delta T}{T}\right)^{-0.313}$
Kiel and Wilson (1989)	single-sided	full-scale, real building	exterior doorways		✓						✓	$C_D = (0.4 + 0.0075\Delta T)$
Pelletret et al. (1991)	single-sided	full-scale test building	doorways 1.5m≤h≤2m	✓	✓							$C_D = 0.21 \cdot H$ or C_D about 0.43
Murakami et al. (1991)	cross vent.	wind tunnel	windows	✓		✓			✓	✓		power balance model
Flourenzou et al. (1998)	cross and single vent.	real building	windows and doors							✓		$C_D = 0.6 \pm 0.1$
Heiselberg et al. (1999, 2001, 2002a and 2002b)	cross vent.	laboratory experiment	side and bottom hung windows	✓	✓			✓	✓		✓	no constant value of C_D
Sandberg (2002)	cross vent.	wind tunnel	holes in circular disk or cylinder	✓		✓			✓			0.7 at large porosities or flow catchment problem
Jensen et al. (2002a)	cross vent.	CFD	holes in circular disk or cylinder	✓		✓			✓			
Jensen et al. (2002b)	cross vent.	CFD	rectangular				✓					
Kurabuchi, et al. (2002)	cross vent.	wind tunnel	rectangular			✓	✓		✓			local similarity model P_R^*
Ohba et al. (2002)	cross vent.	wind tunnel	rectangular and circular	✓		✓			✓			local similarity model P_R^*
Sawachi (2002)	cross vent.	full scale wind tunnel	window openings	✓		✓	✓			✓		
Andersen (2002)		empirical	vents with movable flaps	✓								

These variables are the opening area (A), temperature (T), wind speed (V), wind incidence angle (θ), mechanical pressure (P_{fan}), location of the opening on the façade, internal partitions and building envelope leakage. In most of the studies the opening area is referred with respect to area of the wall (porosity) and is calculated by the following equation:

$$\text{porosity} = \frac{A_{opening}}{A_{wall}} \tag{4}$$

Column 14 gives the proposed formula for C_D or outcome whenever applicable.

Examination of Table 1 reveals the following:

- No study has considered all the parameters involved.
- Although wind is the most important driving force for single-sided ventilation in low rise buildings or for small temperature difference, no experimental study has been carried out for the evaluation of discharge coefficient in that case, to the authors' best knowledge.
- The impact of the porosity of the building envelope has only been considered by Heiselberg et al. (2001; 2002a; 2002b). It was found that the absolute value of discharge coefficient is uncertain at small opening areas and measured values above 1 can be caused by incorrect estimation of the geometrical opening and infiltration/exfiltration. However, the relationship between discharge coefficient and porosity of the building envelope has not yet been examined and more research is required to clarify this issue.
- The case of more than one opening in the same façade has not been considered.

COMPARISON AMONG DIFFERENT STUDIES

In order to identify the possible discrepancies between the various proposed discharge coefficient values, a comparison among different studies was performed. However, the opening type and the conditions under which the experiments were carried out are different among the various studies making such comparisons problematic. The authors attempted to compare "similar" cases by using specific (partial) data from various literature sources. For more information the reader should refer to these literature sources where additional cases are discussed. Cross and single-sided ventilation are considered separately.

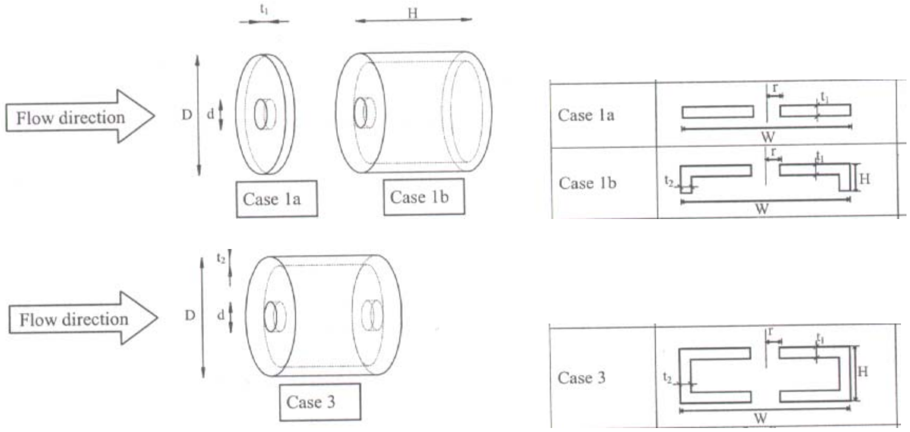
Cross ventilation. In this section a comparison among different studies for cross ventilation is carried out. Figure 1 illustrates the building models. For more information regarding the experimental set up, the building models, opening type and dimensions the reader should refer to the corresponding literature sources. Figures 2 and 3 present the discharge coefficient as a function of the porosity for circular and rectangular (windows) openings respectively. Cases with equal inlet and outlet opening area, thin opening walls, and normal wind incidence angle are considered.

Analysis of Figure 2 shows the following:

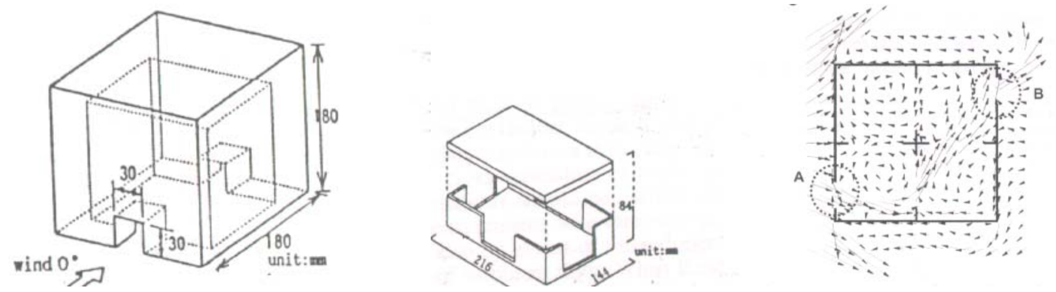
- Discharge coefficient values vary from 0.6 to 1.
- The experimental results by Sandberg (2002) and Jensen et al. (2002a) give similar C_D values only for porosities between 10 and 20%, hence there is lees dependence on the opening configuration for larger porosity.
- For small porosities (less than 10%), large differences are observed and discharge coefficient values even more than 1, which does not have any physical meaning, have been reported. This is may be due to the fact that the orifice equation was used for very small openings, and the assumption of fully developed turbulent flow is not valid. Note that small porosities are more important for natural ventilation.

Analysis of Figure 3 reveals the following:

- Large discrepancies between the empirical discharge coefficient values proposed by Aynsley et al. (1977) and the experimental studies. In fact, Aynsley et al. (1977) results show an increase of the discharge coefficient with porosity, which could be expected based on the traditional resistance approach, while Heiselberg et al. (1999 and 2002b) found that the discharge coefficient decreases with increase of the porosity (side hung window and the configuration W2 - inner window. For configuration W1 (corner window) C_D is almost constant. However, for the configuration W1-4 an increase of the discharge coefficient with the porosity was observed. Similar observations were reported by He et al. (1995); In this study, wind tunnel experiments with a cubical building model with and without a partition wall having an opening of the same dimension as each pair of openings on the exterior wall showed that the airflow rate became larger with a partition wall, although the total airflow resistance was increased. This is probably due to the fact that the resistance approach does not consider the Reynolds number dependence of the discharge coefficient. However, experimentally deduced discharge coefficient values could be overestimated at low porosities due to the fully developed turbulent flow assumption (orifice equation) or inaccurate opening area estimation.

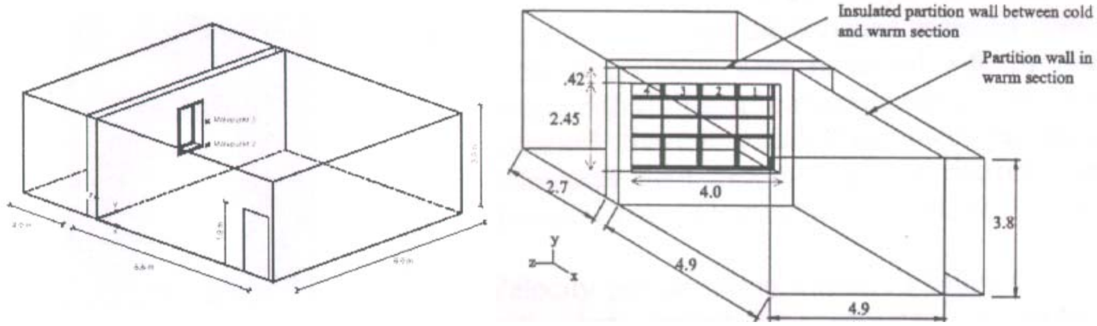


a. Sandberg (2002) and Jensen et al. (2002a).



b. Murakami et al. (1991) model 1 and 2 respectively.

c. Sawachi (2002).



d. Heiselberg et al. (1999) side hung window.

e. Heiselberg et al. (2002b), bottom hung window.

Figure 1. Illustration of the models used by (a): Sandberg (2002) and Jensen et al. (2002a); (b): Murakami et al. (1991); (c): Sawachi (2002); (d): Heiselberg et al. (1999); (e): Heiselberg et al. (2002b).

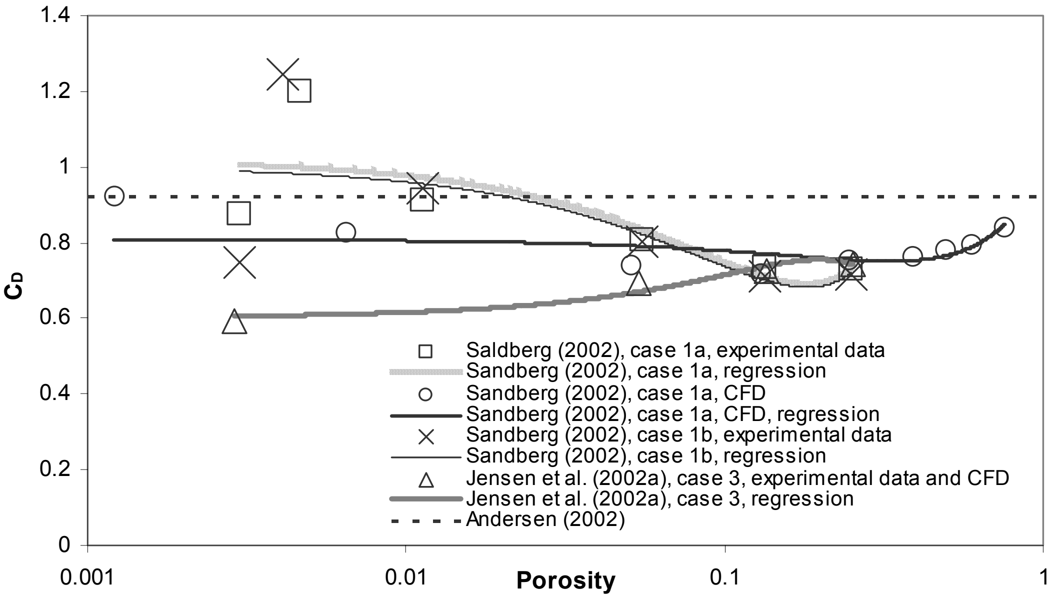


Figure 2. Discharge coefficient as a function of the porosity of the opening (circular openings).

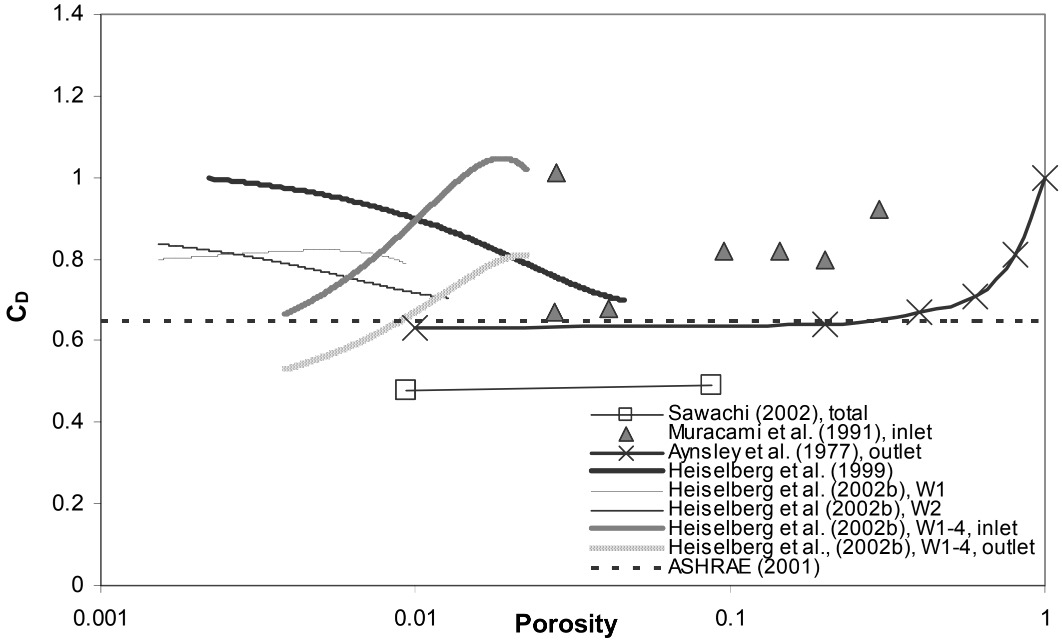


Figure 3. Discharge coefficient as a function of the porosity of the opening (rectangular openings, windows).

- Disagreement between wind tunnel results by Sawachi (2002) and the other studies. This study showed no variation of the discharge coefficient with porosity. Moreover, the proposed C_D value of 0.48 for porosities of 1% and 9% is much lower than the values found from the other experimental studies with the same porosity.
- The experimentally deduced discharge coefficient values given by Murakami et al. (1991) and Heiselberg et al. (1999 and 2002b) show larger variability with porosity especially at low porosity values compared to Aynsley et al. (1977).

- Higher inlet discharge coefficients values compared to outlets (Heiselberg et al. 2002b). However, larger outlet C_D values have been reported by Vickery and Karakatsanis (1987), Murakami et al. (1991) and Jensen et al. (2002a). In fact, discharge coefficient values higher than 1 for the outlet reported by Vickery and Karakatsanis (1987) and Jensen et al. (2002). Unrealistic results for outlet discharge coefficients (pressure loss coefficient) also reported by Murakami et al. 1991 which was explained by the fact that the approximation of the airflow through small openings is no longer valid in the case of cross ventilation. The application of power balance model (energy conservation law) instead showed very reasonable results.

Figure 4 indicates the discharge coefficient variation with the wind incidence angle. The discharge coefficient decreases with the increase of the wind angle as it was expected. More specifically, the discharge coefficient varies between 0.58 and 0.1 for wind incidence between 0 and 90°. This is a considerable variation, which should be considered in natural ventilation design. Unfortunately, discharge coefficient values for wind incidence other than 0° are not available in textbooks and more research is required to clarify this issue. It appears also that CFD predictions (Jensen et al, 2002b) show good agreement with the experimental data. Only for small angle of incidence a slight overestimation of the CFD values is observed. However, the proposed C_D values for $\theta = 0°$ are much lower compared to those proposed by Murakami et al. (1991) and Heiselberg et al. (1999 and 2002b) for the same porosity (see Figure 3).

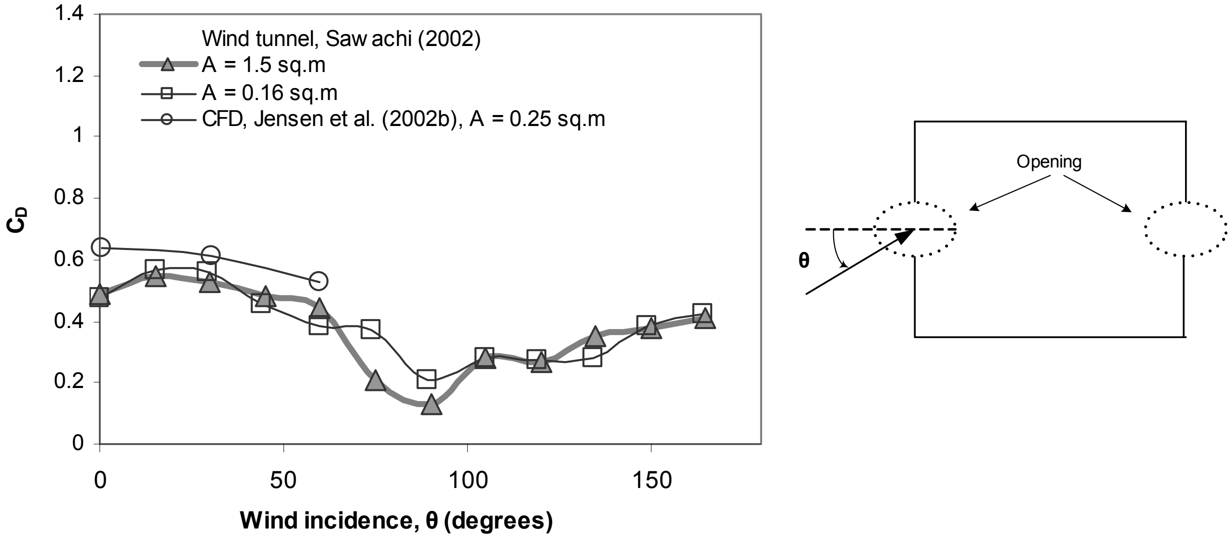


Figure 4. Discharge coefficient as a function of wind incidence angle.

The variation of the discharge coefficient with the pressure difference and the opening area for a side and a bottom hung window was studied by Heiselberg et al. (2001). The study found that especially in the case of the side hung window the discharge coefficient varies at small pressure differences across the opening, while it becomes constant at large pressure differences. This indicates a Re dependency that might be important to consider since natural ventilation systems most of the time operate at small pressure differences. Kurabuchi et al. (2002) and Ohba et al. (2002) investigate the ratio of ventilation driving pressure of crossflow at the opening. A new model was proposed to estimate cross ventilation flow rate and inflow angle at an opening. This model named as local similarity model of cross ventilation is based on the fact that dynamic similarity of airflow can be approximately determined under the condition where the ratio of ventilation driving pressure to the interfering crossflow dynamic pressure in the vicinity of the opening is consistent. The interfering flow is defined as the airflow tangential to the opening, which might disturb the approach flow entering the building through the opening. However, the proposed discharge coefficient values for a window opening are much lower (between 0.2 and 0.4) compared to those found by Heiselberg et al. (2001) (between 0.65 and 1).

Single-sided ventilation. Several studies have been carried out to investigate the heat and mass transfer through doorways but there are limited studies that provide discharge coefficient values for natural ventilation configurations such as windows in the case of single-sided ventilation; this might be due to additional complexities caused by the bi-directional character of the flow for stack-driven ventilation or the uncertainties due to the wind turbulence for wind-driven ventilation.

A simulation study for the prediction of air flow through natural ventilation configurations using large-eddy simulation (Chen, 2003) found that it appears more difficult to predict the performance of single ventilation openings compared to cross ventilation. In a study carried out by Dascalaki et al. (1995), totally 52 single-sided ventilation configurations were tested and the measured flow rates were compared with those predicted by using several airflow network tools. Similar values were predicted by all tools for each experiment, since all tools use the same technique and equations to predict the air flow, but the predicted flow rates were far from the mean measured values due to the use of the same discharge coefficient for any opening configuration (C_D = 1). Haghighat et al. (1991) studied the mechanism of single-sided ventilation due to wind induced pressure. The study found that the turbulent wind pressure has a direct impact on the ventilation performance in buildings. This effect is more significant when the mean pressure difference across openings is low and its turbulent component is high, which usually occurs in single-sided ventilation situations. A review of the existing information on heat and mass transfer through large openings was presented by Santamouris et al. (1995). A sensitivity analysis performed to identify the discrepancies between the various proposed formulas showed differences up to 40% in the case of buoyancy dominated flow.

Figure 5 shows the variation of the discharge coefficient with the temperature difference for different single-sided ventilation configurations. In this figure the results of full-scale experiments in four different test buildings regarding the discharge coefficient of internal doorways published by Pelletret et al. (1991) are compared with empirical formulas proposed by Riffat (1989). The empirical formula proposed by Riffat (1989) is the outcome of an experimental study carried out in a real house aiming to determine the heat and mass transfer through an internal doorway separating the lower and upper floors of the house. The empirical formula proposed by Kiel and Wilson (1989) gives the discharge coefficient of an exterior doorway and is the outcome of an experimental study carried out in a full-scale test house.

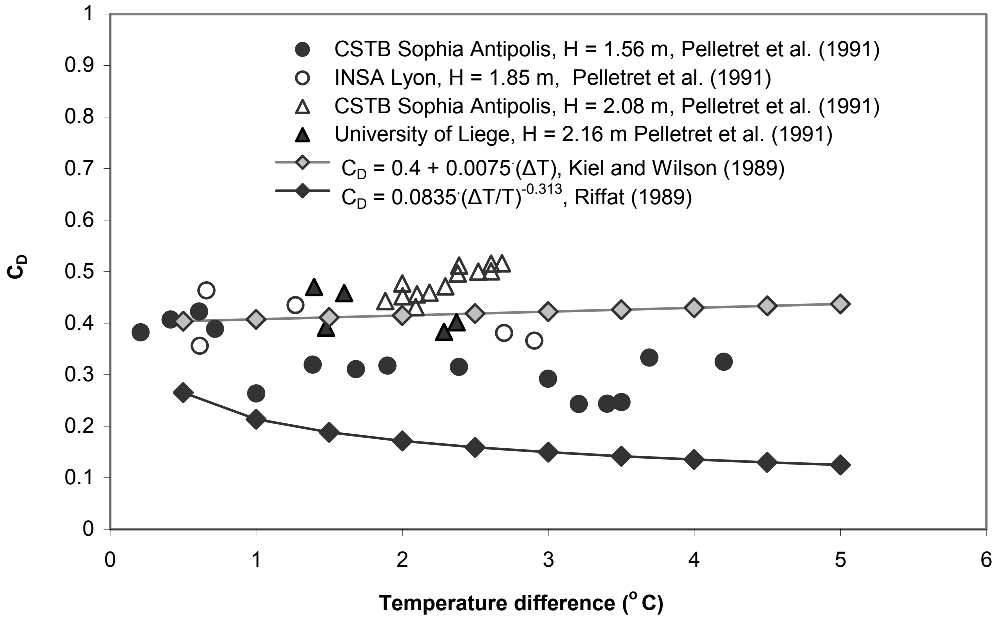


Figure 5. Discharge coefficient as a function of the temperature difference.

Analysis of Figure 5 shows the following:

- The experimental results show slight decrease of the discharge coefficient with the temperature difference (except for the case of CSTB Sophia Antipolis, H = 2.08 m). The proposed formula by Riffat (1989) shows the same trend. This may be due to the increase in interfacial mixing as a result of the direct transfer of some cold air. In addition, the increase in density difference can cause an increase in turbulence which will affect the coefficient of discharge (Riffat 1989). However, the formula for steady buoyancy-driven flow proposed by Kiel and Wilson (1989) shows a slight increase of the C_D with ΔT.
- There is significant impact of the opening height on discharge coefficient. The proposed formula by Pelletret et al. (1991) is:

$$C_D = 0.21 \cdot H, \quad 1.5 \text{ m} \le H \le 2 \text{ m} \tag{6}$$

The difference in C_D values (for the same ΔT and H) derived from the different experiments confirms that the discharge coefficient is dependent also on a number of parameters such as Re, zone geometries and experimental conditions.

- Relatively good agreement between the experimental data (Pelletret et al. 1991) and the discharge coefficient values calculated using the formula proposed by Kiel and Wilson 1989, for temperature difference up to 3 °C. On the contrary, the C_D values calculated using the proposed formula by Riffat (1989) do not seem to agree with the experimental results. This is most probably due to the fact that the proposed formula by Riffat (1989) is for vertical and not horizontal airflow.
- Lower discharge coefficient values compared to those for cross ventilation (Figure 3). This is probably because the airflow through an open window into a room still preserves a large part of its mean kinetic energy when it remains inside the room. A major part of its preserved energy is directed outside the room through the leeward opening without interior dissipation; this is reflected in the decreasing values of ζ (or increasing values of C_D - see Equation 3) in the case of cross ventilation (Murakami et al. 1991).

CONCLUSION

The review of current literature has shown that the discharge coefficient is the result of a multivariable impact and the use by designers of a constant value such as that given in textbooks or works of reference is an invalid simplification. More specifically, considerable variation of the discharge coefficient with porosity, opening configuration, Re, wind incidence angle, local geometrical and airflow conditions, opening height, and temperature difference has been found even in simple cases such as low-rise buildings with one opening in the façade. Comparison of different studies showed large differences in cross ventilation. The differences are larger (up to 50%) at small porosities (less than 15%). Several problems with the application of the orifice equation to the calculation of wind-driven cross ventilation rate have been pointed out. Generally, lower discharge coefficient values are observed for buoyancy-driven single-sided ventilation compared to cross ventilation.

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