THE DISCHARGE COEFFICIENT OF A CENTRE-PIVOT ROOF WINDOW

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ABSTRACT

Accuracy in estimation of airflow through windows is the key parameter for modelling and designing of naturally ventilated buildings. The flow through windows is usually described by the orifice flow plate equation. This equation involves the discharge coefficient. In practice, often a constant value of discharge coefficient is used. The constant value of discharge coefficient leads to deceptive airflow estimation in the cases of centre-pivot roof windows. The object of this paper is to study and evaluate the discharge coefficient of the centre pivot roof window. Focus is given on unidirectional flows i.e. inflow and outflow. CFD techniques are used to predict the airflow through the modelled window. Analytical orifice flow equation is used to calculate the discharge coefficient. Results are compared with experimental results. It is concluded that the single value of the discharge coefficient leads to ambiguous estimation of airflow rates. The discharge coefficient decreases with increase in flap opening area. The discharge coefficient also depends upon the flow direction

KEYWORDS

Centre-pivot roof window, discharge coefficient, CFD

INTRODUCTION

The amount of air entering through natural ventilation (or in hybrid systems) is extremely difficult to predict accurately as airflow depends on unknown wind and buoyant effects. In practice, the orifice flow equation is used to compute the airflow through the intentional openings and windows. The discharge coefficient (C_D) in this equation is usually taken as constant. The constant value of the discharge coefficient is valid only for constant opening areas [8], [4]. Hence, the use of constant value of C_D for operable windows leads to deceptive results. The exactness of the C_D can have a significant impact on the ability of a mathematical model to predict the airflow rates [4], [6].

There is a need of evaluation of C_D of operable (i.e. with flap) windows. Operable windows are broadly used in residential buildings for ventilation. Scientific literature on façade windows is somehow available. However, the literature on roof windows (especially center-pivot roof window) is not much discussed. This paper focuses on the discharge coefficient of a center-pivot roof window.

Airflow rate through the opening is the integral of velocity over the opening area i.e. $q = \int v dA$ [10]. In practice it is difficult to do this integration. Therefore an alternate way has to be adopted. The airflow passet through the opening acquires the shape of a jet [3]. Therefore the volume flowrate at the vena contracta of the jet is the actual volume flow rate through the opening. Velocity (v_c) in the vena contracta is defined in terms of a theoratical (frictionless flow) velocity (v_{th}) and the velocity coefficient (C_v). The area (A_c) of vena contracta is defined in term of the opening area (A) and the contraction coefficient (C_c). The velocity in the vena contracta is constant therefore the flow rate (q_c) in vena contracta is:

$$q_c = A_c v_c = C_c C_v A v_{th}$$

The theoratical velocity (v_{th}) is mainly due to pressure difference (ΔP) and the product of C_c and C_v is called the discharge coefficient (C_D).

$$v_{th} = \sqrt{\frac{2\Delta P}{\rho}} \quad \text{and} \quad C_D = C_c C_v$$

The C_c and C_v are mostly discussed in literature but in practice, especially with operable windows, they are exteremly difficult to estimate. Therefore, the discharge coefficient is usually used to define the flow. From above mentioned corelations, the airflow through an opening is defined as:

$$Q \equiv C_D A \sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

This is generally referred as orifice flow plate equation. A colossal literature is available for estimation of C_D. However, a constant values of C_D is predominantly used in practice. These constant values are derived from the data used to estimate the flowrate in pipes [8].

Bot et. al. performed [7] a full scale measurements of flowrate through one side mounted casement windows (façade window). The authours defines the resistance coefficient/friction factor in terms of aspect ratio of the window and opening angle. *The resistance coefficient(ζ) is a coefficient that defines the pressure drop due to friction in the opening and flow. Theoratically, it is* $\Delta P_{fr} = \frac{1}{2}\zeta\rho v_c^2$[i]. The authours use the cross sectional opening area, and from the results of their research it can be concluded that the overall discharge coefficient of the top hinged window increases with the increase in opening angle.

P. Heiselberg et. al. [8] uses the minimum opening area to estimate the discharge coefficient of a façade window with movable flap. Experimental results showed that the discharge coefficient is not constant for different flap opening angles. The authours conclude that the value of discharge coefficient is approaching to 1 with the decrease in flap opening angle (corresponding to minimum opening area). Only for large opening angles the value of 0.6 can be used as a discharge coefficient of a window with movable flap.

Andersen [2],[3] discussed theoretically, friction and contraction coefficients of openings with movable flaps. The authour use artificial as well as pure resistance coefficients along with artificial and real opening angle to calculate the contraction coefficient. The authour conclude that (for centrally hinged flap) the contraction coefficient decreases with increase in the flap opening angle. Furthermore, the resistance coefficient (both artificial and theoratical) increases with the increase in flap opening angle. The real opening angle is dependent on aspect ratio of the window. Therefore, the contraction coefficient, and consequently the discharge coefficient, is also dependent on the aspect ratio of the window. For sharp edged openings, the discharge coefficient is about 0.61 [2], [3].

Hult et. al. [4] determines the discharge coefficient of the façade window using CFD. The authours conclude that the discharge coefficent of a façade window is reliant upon aspect ratio and window opening angle. However, for larger opening angle it approaches to the commonly used value of 0.6. According to their research, the CFD results suggest that the actual flow through a top-pivoted window may be as much as twice the flow predicted by EnergyPlus software.

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[i] *The definition is from theoratical books and from (ANDERSEN 1996)*

METHODS

CFD techniques was used to test the dependence of discharge coefficient (C_D) on the flap opening angle(α). The CFD domain was defined in such a way that on right side of the domain the outflow through the window could be examined, and the inflow through the window could be examined from the left side of the domain. For reducing the processing time, only half part of the window was examined by using symmetric boundary condition. Height and width of the domain was selected in such a way that the size of the domain had no influence on the local velocities and the pressure distribution around the window. The model room was defined as shown in Figure 2. InVent was the opening in the model room with the window and OutVent was the opening without any window. Both InVent and OutVent were on the roof with slope/pitch of 45^o. The window and flap geometry were kept simple because the details of window (minor bends on flap) has insubstantial affect on overall discharge coefficient [1].

The polyhedral meshing scheme was used with 8 prism layers mesher at the boundaries. The base size was 1 m. The prism layers were 8% of the base cell size. The surface growth rate was 1.3. Allowable skewness for cells was 85^o. Several parts of the domain had customised surface mesh size to ensure proper mesh quality. The Inlet was the velocity-inlet, the Outlet was the pressure-outlet. The domain top, left and the right boundaries were symmetric boundaries and all other boundaries were walls with no slip conditions.

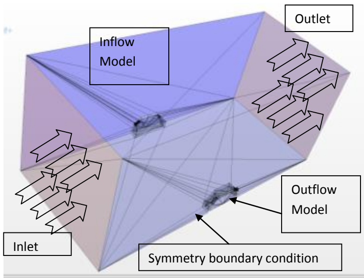

Figure 1 CFD Domain

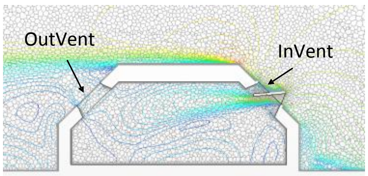

Figure 2 Model room with InVent and OutVent

Physics:

A body interacts with the surrounding fluid through pressure and shear stress, and the resultant force in the direction of stream is the drag force. The drag coefficient D_f is used to define the drag force when the detailed information about pressure and shear stress is not known i.e. it is a ratio between the drag force and the wind pressure force [10]. The minimum number of cells was selected in such a way that by increase in the number of cells, there is no effect on the D_f of the model room. This means that the further decrease in cell sizes had no effect on the local velocity and the pressure distribution around the building.

The "Two layer realizable k-ε turbulent" model was used to compute the airflow and its physical behaviour [6]. The working fluid was incompressible ideal gas. The flow was 3D steady state. Flow and energy were both modelled using the segregated approach. The second-order upwind discretisation scheme was used for both flow and energy. Under relaxation factors for velocity, pressure and energy were 0.7, 0.3 and 0.9 respectively. Inlet condition (Inlet -Figure 1) for the turbulent kinetic energy ($k_o = 1.5(T_i U_o)^2$) and the dissipation rate ($\varepsilon_o = k_o 1.5/l_o$) were according to Nielsen [9] recommendations. Where, T_i is the turbulence intensity and was taken as 4% with inlet temperature of 293K. U_o is inlet velocity in $\{m/s\}$. $l_o\{m\}$ is length scale and was taken as one-tenth of the height of the inlet. The inlet velocity was selected in such a way that for each simulation the airflow through the window was fully developed turbulent flow. The C_D value for fully developed turbulent flow does not vary with Reynolds number [6]. The equation (1) was used to find out the C_D for the window (Figure 4).

The flowrate at InVent (Figure 2) was estimated by the flowrate at the OutVent (Figure 2). The flow $Q\{m^3/s\}$ at OutVent was calculated by integration of velocity over the area of OutVent i.e. the face area of the cells at the interface (OutVent and external region) times the perpendicular component of the velocity i.e.

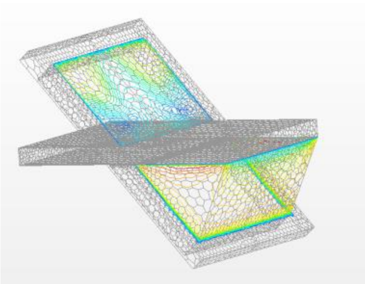

Figure 3 Outside pressure (average)

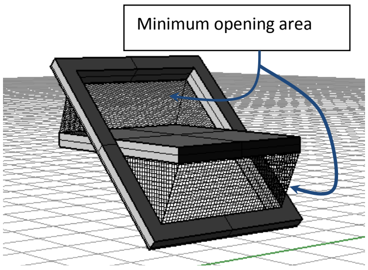

Figure 4 Centre-pivot roof window and minimum opening areas

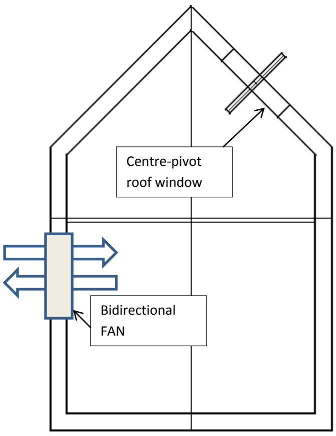

Figure 5 Schematic of on-site measurements

$$Q \equiv \sum_{i=1}^{n} A_i v_i = \frac{1}{\rho} \sum m_i \quad (2)$$

Where, $A_i\{m^2\}$ is the face area of cell at the interface and $v_i\{m/s\}$ is the perpendicular (to A_i) component of the velocity. The airflow rate can also be calculated by the mass flow rate divided by the density as shown in Equation (2). The density ρ is constant i.e. 1.2 kg/m^3, m_i is mass flow rate in kg/s.

Pressure difference:

To measure the pressure difference (ΔP) across the InVent one probe was measuring the pressure inside the room (in the centre of the room). The outside pressure was an area weighted average of outside pressure at the InVent opening as shown in Figure 3.

Opening area:

The C_D was also dependent on the opening area. Therefore it was evaluated for two different opening areas. One was the minimum opening area (A_{min}). The minimum opening area is shown in Figure 5. The sum of two minimum opening areas is the total minimum opening area (see Figure 5). For flap opening angles of 50^o and greater, the minimum opening area is the sum of two face cross sections of the window.

Another way to define the opening area is the gross face area (A_{face}) of the opening i.e. 1.14 x 1.4.

On-site measurements:

On-site measurements were performed in the Energy Flex House (EFH) of the Technological Institute of Denmark (Copenhagen). The house was equiped with the VELUX centre-pivot roof window. Blower door test, for infiltration/exfiltration, were perform before the measurements. Only outflow measurements were compared in this study, because this study is mainly focused on CFD, and measurements were performed only for validation purpose. The flow through the window was the sum of fan flow and infiltration/exfiltration. Figure 5 shows the schematic diagram of the measurements setup. The discharge coefficient was calculated by using equation (1) and minimum opening area. The outside pressure was the area weighted average pressure around the window. Inside pressure was the average inside pressure of the house. The centre-pivot roof window in the EFH was fully automatic and it was not possible to open the window more than 17^o. Therefore, discharge coefficient only for very small (α<17^o) opening angles was measured.

RESULTS

Figure 7 illustrate the discharge coefficients ($C_{D,min}$) of a centre-pivot roof window when minimum opening area is used in equation (1). The CFD results for $C_{D,min}$ of inflow through the window (flow from outside to inside) is represented by the blue line. The CFD results for $C_{D,min}$ of outflow (flow from inside to the outside) is represented by the red line. The green line is $C_{D,min}$ that is obtained by the on-site measurements. As mentioned earlier, it was not possible to measure (onsite) the discharge coefficient for angles greater than 17°. Therefore, measurement data is available only for 17°, 14°, 9.3° and 4.6°. It should be noted that the minimum opening area is taken from the manufacturer catalogue. On the contrary, with available computing power for CFD calculations, it was very time consuming to go below 15° of opening angle. That's why the CFD simulation was performed only for 15°, 25°, 35°, 45°, 50° and 90°. It should be noted that the minimum opening areas were calculated through the CAD drawings.

Figure 6 illustrate the discharge coefficients ($C_{D,face}$) when the gross face opening area is used in equation (1). The blue line shows the $C_{D,face}$, obtained from CFD calculations, when flow is directed inward. Whereas, the redline is the $C_{D,face}$ (CFD result) when flow is directed outward.

DISCUSSION

From Figure 7, apperantly there is a difference between the $C_{D,min}$ values evaluated by the measurements and by the CFD. One of the reason is ideal versus real condition. However, the trend of decrease in $C_{D,min}$ is almost the same.

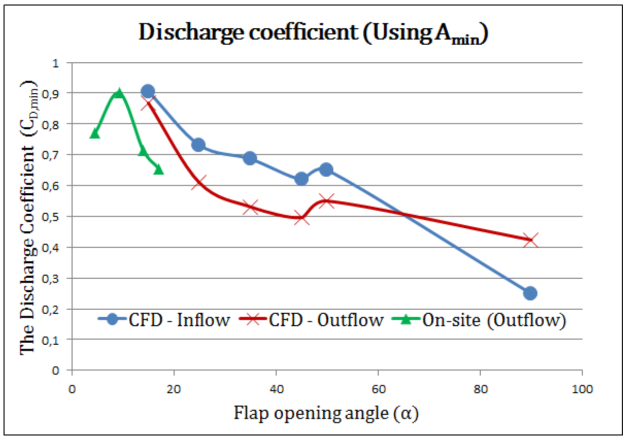

Figure 7 Discharge coefficient of the centre-pivot roof window using minimum opening area

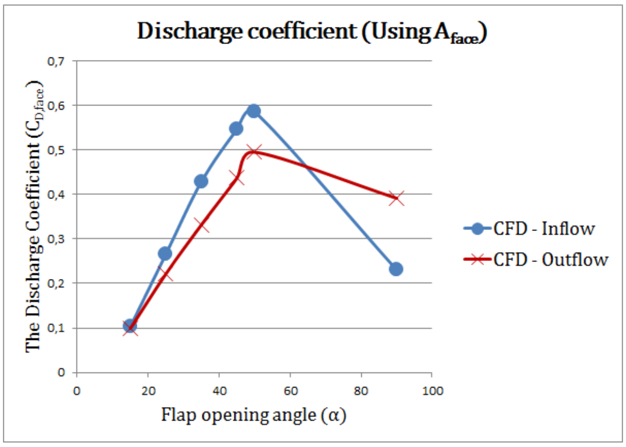

Figure 6 Discharge coefficient of the window using face area

Ergo, the problem might also be in calculation of the minimum opening area. Therefore, another quantity, C_D x A (so called effective area) of both, measurements and the CFD are compared. This comparision is shown in Figure 8. The difference in measurements and the CFD results are now minimum. The CFD results are in sound accordancewith the measurements at the angle of 15° and around. The concurrence, of CFD and the measurements, at low opening angles are taken as benchmark for higher opening angles. Hence, the realizable k-ε turbulent model predicts the flow (across the window) in a good agreement with the measurements.

The $C_{D,min}$ curve represents the change in the discharge coefficient due to (mainly) flow effect. Whereas, the $C_{D,face}$ curve represents the change in the discharge coefficient due to both flow and area effects.

The $C_{D,min}$ (as shown in Figure 7) decreases with the certain pattern until it reaches to 50° of the flap opening. At this point the A_{min} shifted from the position shown in Figure 4 to the face cross sectional area. Then the pattern of

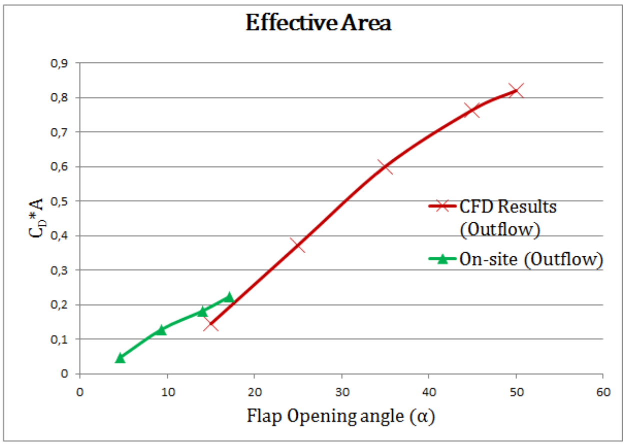

Figure 8 Comparison of CFD results with On-site experimental results

decrease in $C_{D,min}$ also changes. This change in $C_{D,min}$ is due to the change in A_{min} and due to the fact that pressure field on the roof surface (closed to the window) is disturbed.

In the caseof inflow through the window, the flow in each section of the window is not evenly distributed, except for very small opening angles. Flow in the lower section is much higher then in the upper section. At the angle of 90º there is no flow in the upper section of the window. In the case of outflow through the window, the flow in each section of the window is somewhat evenly distributed. Therefore, the $C_{D,min}$ inflow is higher than the $C_{D,min}$ values of outflow. This phenomenon negates the assumption of stagination condition at the inlet in determination of C_D. However, the slope/trend of the outflow curve is same as of inflow curve. After 50º of flap opening, the slope of outflow become lower than the inflow. Therefore, the $C_{D,min}$ at 90º of flap opening of outflow direction was higher value than that of inflow direction. The reason for difference in $C_{D,face}$ curves (for inflow and outflow direction) is also the same.

For more concrete conclusion, the results have to be evaluated for several openings with different aspect ratios. However, these results are only subjected to the particular window type and for natural ventilation caused by wind effect.

CONCLUSION

It is concluded that the k-ε turbulent model predicts the flow in sound agreement with the measurements. It is also concluded that in the orifice flow plate equation, the discharge coefficient is not a constant quantity. The $C_{D,min}$ decreases with flap opening angles. The trend of decrease in $C_{D,min}$ changes after 50º of flap opening angle. Likewise, the discharge coefficient also depends upon the flow direction. The $C_{D,min}$ is higher for inflow and the $C_{D,min}$ is lower for outflow. For higher opening angles (e.g. higher than 65º) the criteria is swapped.

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