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Experimental Evaluation of the Discharge Coefficient of a Centre-Pivot Roof Window

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Abstract

Windows are a component of naturally ventilated buildings. The scientific knowledge of how to estimate of airflow rates through windows is limited, especially in the case of centre-pivot roof windows. The flow through this type of windows is traditionally characterized by the orifice plate flow equation. This equation involves a discharge coefficient of the window. The value of the discharge coefficient is the major cause of erroneous estimation of airflow rates. This paper focuses on the experimental study of the discharge coefficient (C_D) of a centre-pivot roof window. The measurements were performed in the energy flex house of the Technological Institute - Denmark. The discharge coefficient is evaluated for both inflows and outflows. It is concluded that the use of single value of C_D for different flap opening angles is one of the cause of erroneous estimation. Likewise, the value of C_D for inflows and outflows are not the same for a given pressure difference. The discharge coefficient varies with sash¹ opening angle and flow direction.

Keywords – centre-pivot roof window; discharge coefficient; airflow rates

1. Introduction

The classical approach to compute the flow through pipes and ducts is the use of orifice plate flow equation. This equation equates the real flow to the ideal flow by a coefficient called the discharge coefficient (C_D). *There are numbers of assumptions in the derivation of this equation that limits its application. However, some of the assumptions (to some extent) fulfil the requirement of airflow rate through building openings and windows [1] . Therefore, it is common practice to use this equation to estimate the airflow rates through windows and other openings. Furthermore, the values of C_D*

¹ For convenience the opening component which opens at an angle to the plane is termed as sash.

for windows and other openings are derived from data traditionally used for fluid flow in pipes [2] .

Validation studies show that the discharge coefficient remains the major source of error in the modelling of natural ventilation [2, 3]. Often a constant value of C_D is used in practice. The constant value of the C_D (usually 0.6) can only be used for sharp edge openings. The C_D for operable windows is not constant but varies with the sash opening angles or the opening areas. In recent years, there have been few studies about the calculation method of C_D of windows with moveable sash. However, most of the studies are about the façade windows [2, 4, 5]. There are very few studies about roof windows, for instance Bot et al. [6] described the C_D of a roof window in terms of a mathematical expression that is a function of the friction factor of opening without sash, friction factor of opening with sash, aspect ratio, Reynolds number and the angle of open sash. But the formulation is only valid for top hung windows (both façade and roof). Z. Li et al. [7] experimentally investigated the behaviour of a centre-pivot roof window for single-sided buoyancy-driven ventilation. Iqbal et al. [4] predicted the C_D of a centre-pivot roof window using CFD techniques. However, present study focuses on the experimental evaluation of the C_D of a centre-pivot roof window.

2. Method

The orifice plate flow equation was used to estimate the flow through the centre-pivot roof window. The equation in its original form is as follows:

$$q = C_D A \sqrt{\frac{2\Delta P}{\rho}} \iff C_D = \frac{q}{A \sqrt{\frac{2\Delta P}{\rho}}} \quad (1)$$

Where, C_D is the discharge coefficient, q {m³/s} is the airflow rate through the centre-pivot roof window, A {m²} is the minimum opening area of the window, ΔP {Pa} is the pressure difference across the window and ρ {m³/kg} is the density of air passing through the window.

To achieve the goal of finding the C_D of a centre-pivot roof window, an experimental setup was built in the energy flex house (EFH) of the Technological Institute (TI) Denmark. There was a VELUX² centre-pivot roof window in the EFH. Use of (1), to

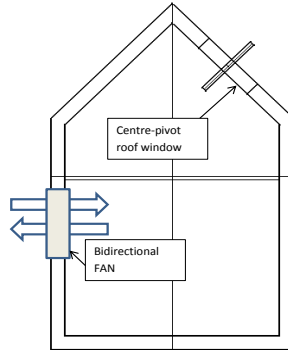


Figure 1. Schematic diagram of the experimental setup

² VELUX is a Danish window and skylights manufacturer

obtain the C_D of the window, requires the knowledge of the airflow rate (q) through the window and the pressure difference (ΔP) across the window. For measuring q through the centre-pivot roof window, a mechanical fan was installed on the exterior door of the EFH. All internal doors were kept open and all windows and other similar openings were kept closed. As a consequence, the airflow rate generated by the mechanical fan was equal to the sum of the airflow rates through the window and the leakage. The schematic diagram of the experimental setup is illustrated in Figure 1. The pressure difference (ΔP) across the window is the difference between the outside surface pressure and the inside pressure of the EFH. From known ΔP , q and the opening areas, the C_D was evaluated using (1).

3. Experimental Setup



Figure 2. Reference pressure box



Figure 3. Fan and venturi setup



Figure 4. Pressure taps location on site (17.1° open)



Figure 5. Pressure transducers

Leakage Test

Before the measurements of the discharge coefficient, the leakage tests were performed in the energy flex house. Blower door techniques were used to measure the leakage. The tests were performed according to the Danish/European norm EN 13829. The uncertainty in the leakage airflow is ± 0.0224 l/s at 50 Pa of pressure difference. Moreover, the tests were performed for both pressurization and depressurization. The leakage rate of depressurization was used to correct inflow rates through the window. Likewise, the leakage rate from pressurization was used to correct the outflow rates through the window.

Reference Pressure Box

The reference pressure (Figure 2) box was used to avoid the fluctuating reference pressure. The reference pressure box was placed about 50 m away from the measurement setup in a store room of another house. The pressure in the reference box was the absolute atmospheric pressure. The pressure difference across the window could also be measured by taking a pressure difference inside and outside of the window. However, the reference pressure box was used because the measurement setup was designed to measure the wind pressure coefficient (not discussed in this article) along with the discharge coefficient (C_D).

Fan and Venturi Setup

The airflow rate through the window was controlled by means of a mechanical fan. The flow rate through the mechanical fan was measured with an elliptical venturi nozzle according to ISO-5801 with an uncertainty of $\pm 2\%$. The venturi was installed at the intake of the fan. The airflow rate through the venturi was calibrated according to the pressure difference between atmospheric pressure and the static pressure at the bell mouth. Therefore several pressure taps were installed around the circumference of the bell mouth of the venturi. All pressure taps were connected to a pressure transducer via a tube. The other terminal of the transducer was connected to the reference box. Figure 3 shows the onsite installation of the fan and venturi setup during the measurements of C_D .

Pressure Taps and Tubing

In practice, it is common to make holes in the roof to measure accurate outside surface pressure. This was not possible in the EFH due to the thickness of the roof. Therefore, pressure taps were placed across the centre-pivot roof window. The pressure taps are shown Figure 4. It should also be noted that the maximum possible opening angle of the sash is 17.1° .

There were six sides of the window and an average static pressure of each side of the window was measured by connecting several taps (along each side of the window) to a single pressure tube. Therefore, six tubes were connecting six outside pressure taps to the positive terminals of six pressure transducers. All negative terminals of these pressure transducers were connected to the reference pressure box through a common tube. Hence, each pressure transducer showed the pressure difference between the reference box and the outside surface. The overall outside surface pressure was the length weighted average pressure (of each side of the window). Likewise, one pressure transducer was measuring the pressure difference between the reference pressure box and the inside of EFH. The inside pressure was measured by a vertical tube inside the room with 5 taps at different heights (the difference between taps was 75cm). One pressure

transducer was measuring the pressure difference between the reference box and the fan setup. Figure 6 illustrates the schematic layout of the pressure measurement setup.

4. Pressure Transducer

A total of eight pressure transducers (Figure 5) were used in this measurement. Six were measuring pressure across the window, one was measuring the inside pressure and one was measuring the fan and venturi setup pressure difference. All eight transducers were programmable differential pressure and flow transmitter for low pressure and flow measurements. According to the manufacturer there was $\pm 0.5\%$ uncertainty in the measurements of pressure difference. However, random errors were reduced by logging the data every 30 s.

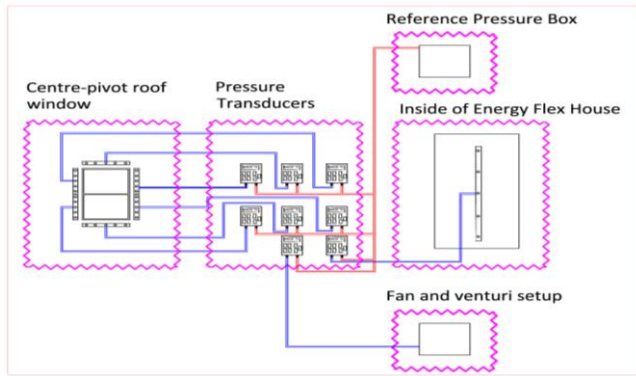


Figure 6. Schematic layout of pressure measurement setup

5. Findings

The window was located at a height of almost 5m from the floor; therefore, it was not possible to measure (manually) the opening area of the window. The centre-pivot roof window in the EFH can only be operated by remote control. Remote control displays the opening position of sash in terms of percentage. Only four opening areas were known according to the percentage opening shown in remote control. Therefore, the measurements were performed only for known opening areas. The details of opening areas are tabulated in Table 1.

Measurement results from the 17.1° opening angle and the 9.3° opening angle are discussed in the main text of this paper. The behavior of the 14° and the 4.6° opening angle are similar to the 17.1° and the 9.3° opening angle respectively. Therefore, the results from the 14° opening angle and the 4.6° opening angle are presented in Annex I.

Table 1. Opening angles and opening areas

S. No.	Remote control opening percentage	Opening angle	Opening Area (m ²)
1	100%	17.1°	0.340442
2	82%	14°	0.253775
3	54%	9.3°	0.141647
4	27%	4.6°	0.060614

The fan performance was based on the fan inlet and fan outlet ambient conditions. Therefore, with available fan setup it was not possible to create very high pressure differences during the 17.1° opening angles. Likewise, for the 9.3° opening angles, it was not possible to create a low pressure differences. One of the main reasons was the huge volume of the EFH (~800 m³) and comparatively the fan system was smaller. Moreover, there was a pressure loss in more than 6 m flexible duct and other connection between the fan and the venturi setup.

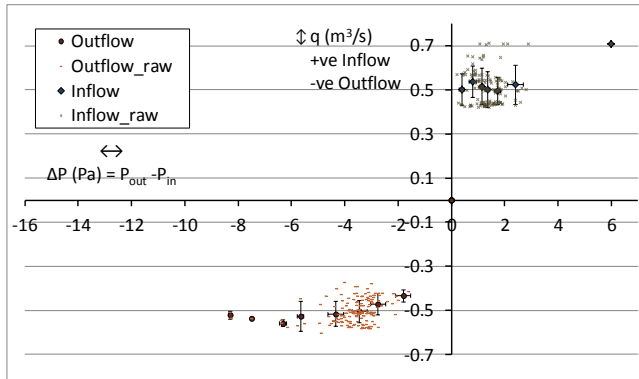


Figure 7. Airflow rates through the centre-pivot roof window (17.1° open)

In order to obtain a discharge coefficient, using orifice plate equation, there is a need to check the dependence of the airflow rate through the window on the pressure difference across the window. The dependence can be seen by plotting the raw data of airflow rates and the pressure difference from the measurements. Therefore, graphs are plotted between the airflow rates versus the pressure difference and the discharge coefficient versus the pressure difference. These plots may show that either the airflow rates through the window follow the orifice plate flow equation or not. The horizontal axis in each plot is the pressure difference (ΔP) across the window. The ΔP is taken as the outer surface pressure (P_{out}) minus the inside pressure (P_{in}). Therefore, the ΔP is negative for outflows and it is positive for inflows. The vertical axis in Figure 7 and Figure 9 shows the airflow rates

(q) through the window. Inflow rates are positive and outflow rates are negative. The vertical axis in Figure 8 and Figure 10 are the C_D values calculated by using q , ΔP and (1). In each figure, both raw data and the averaged data are plotted. The raw data are the data that are directly extracted from the data logger. Data was logged for every 30s. It means that the raw data are the instantaneous values of q , ΔP . The raw values of C_D are calculated from the instantaneous values of q and ΔP . The raw data in figures are named as Inflow_raw and Outflow_raw for inflows and outflows respectively. For averaging, the data is split into bins of 1 Pa ΔP . The points with error bars in each figure are the arithmetic mean of each bin data. The error bars are the standard deviation of the averaged data.

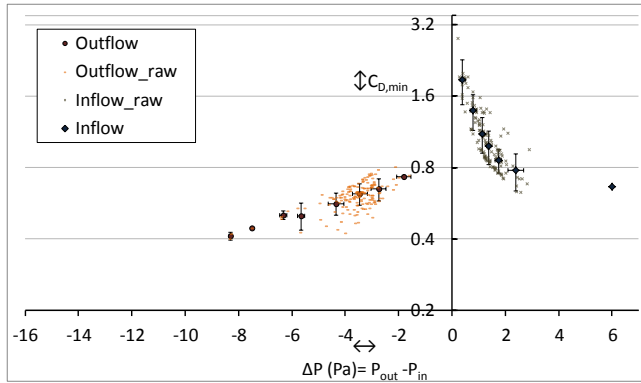


Figure 8. Discharge coefficient of the centre-pivot roof window (17.1° open)

Figure 7 shows the behaviour of the airflow rate through the window when sash is 17.1° opens. There is no clear pattern shown in Figure 7. Apparently the airflow rate does not obey the orifice plate flow equation. In spite that the q does not seem to be dependent on ΔP as it should be according to (1), the C_D by using (1) is evaluated. The C_D for 17.1° sash opening is presented in Figure 8. The Figure 8 shows that the C_D decreases with increase in ΔP i.e. C_D depends on Re . Moreover, the C_D is different for inflows and outflows. In Figure 9, where the sash opening is 9.3° open, the q clearly shows its dependence on ΔP across the window. Consequently the average C_D is constant. Figure 10 shows the dependence of C_D (for the 9.3° sash opening) on ΔP across the opening. The raw data of C_D is not very much constant but at least for higher ΔP the arithmetic mean can be used to represent the average value of the data. The average value of C_D for inflow is 0.98 and for outflow is 0.74. By using the arithmetic means of C_D and (1) two curves are plotted in Figure 9. One curve is for inflow and other for outflow. These curves (estimated flow behaviour) are in good agreement with the raw data for airflow rates versus pressure difference.

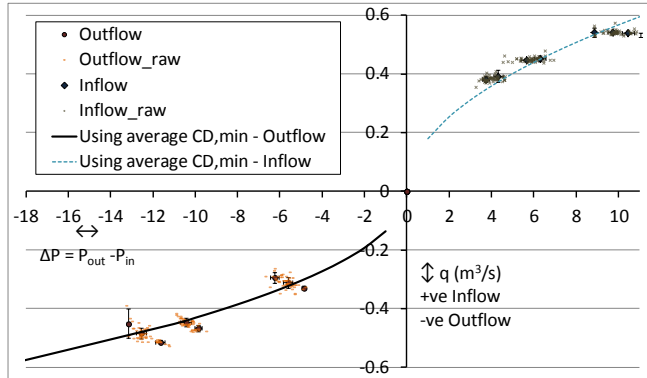


Figure 9. Airflow rates through the centre-pivot roof window (9.3° open)

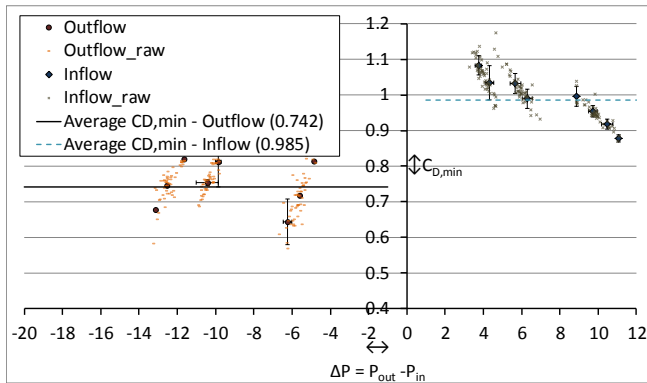


Figure 10. Discharge coefficient of the centre-pivot roof window (9.3° open)

6. Discussion

For large opening angles i.e. 17.1° and 14° sash opening angles (see Annex I), apparently the airflow rates are not only dependent on pressure difference. Here it is not advisable to conclude that the flow is independent of pressure difference without analysing the data in more detail. Foremost, the error in measurements cannot be ignored. Moreover, there is a need to analyse the data according to the outdoor conditions. Atmospheric conditions are very important for evaluation of the discharge coefficient for larger openings in the building. The flow through the window is influenced by the external wind velocity. For large openings, the flow is not solely pressure driven but it is also influenced by the kinetic energy in the air jet [1]. This is in contrast with one of the assumptions for the derivation of the orifice plate

flow equation. The data has to be split into bins of particular wind directions and wind velocities to analyse the measurements and results in more detail.

For smaller openings i.e. 9.3° and 4.6° sash opening angle, the airflow rates are proportional to the square root of the pressure difference. Hence, it can be seen that for smaller opening angles flow is solely driven by the pressure difference. According to Mukarami et al. [8] when the thickness of opening is large compared to the opening area then the flow is only driven by the pressure difference. In such cases, the airflow rate through the opening is independent of wind direction and kinetic energy in the air jet is dissipated. Therefore, the use of the orifice plate flow equation in its original form is applicable in smaller opening angles, provided that the C_D value is correct. For larger opening angles the original form of orifice plate flow equation may leads to erroneous estimation of the airflow rate through the window.

In reality the C_D depends on the vena contracta of the air jet and the velocity distribution within the opening. However, in practice (for windows) it is expected to depend on geometrical parameters and the condition of airflow through the opening [1]. For practical purposes, C_D has to be estimated for inflows and outflows and for different opening angles. It is very important to define the area and the pressure measurement location when defining a C_D value. The area used in this study (corresponding to the sash opening angle) is the minimum opening area. Inside pressure is an average inside pressure and the outside pressure is the local surface pressure at the opening. The local outside surface pressure is estimated by installing the pressure taps very close around window. Therefore these values of discharge coefficient cannot be used, in (1), with the surface pressure estimated by the average wind pressure coefficients. Moreover, estimated values of C_D from these measurements cannot be used, in (1), with face cross sectional area of the window.

7. Conclusion

It is concluded that the discharge coefficient of the centre-pivot roof window changes with the sash opening angle. Furthermore, for larger opening angles the flow is not solely pressure driven. Therefore, the use of the orifice plate flow equation in its original form may leads to erroneous results. For smaller opening angles the orifice plate flow equation can be used along with corrected C_D values. The C_D values are different for different sash opening angles. Likewise, the C_D values are different for inflows and outflows.

8. Acknowledgment

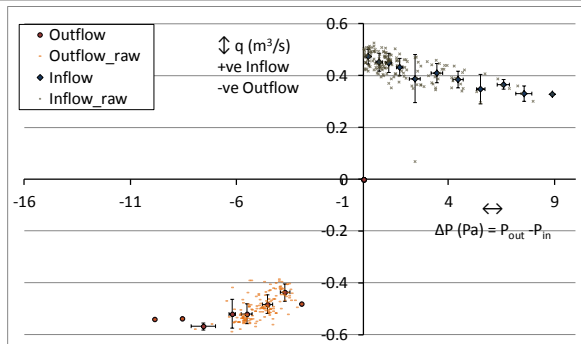
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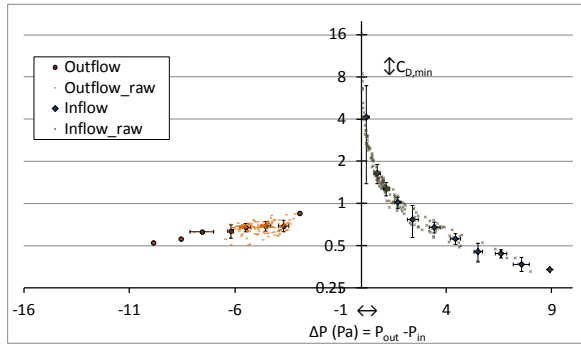
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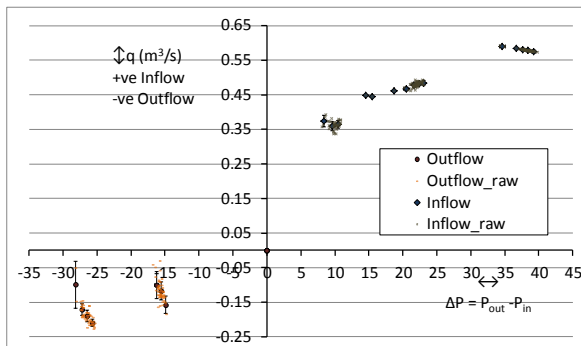
Annex I



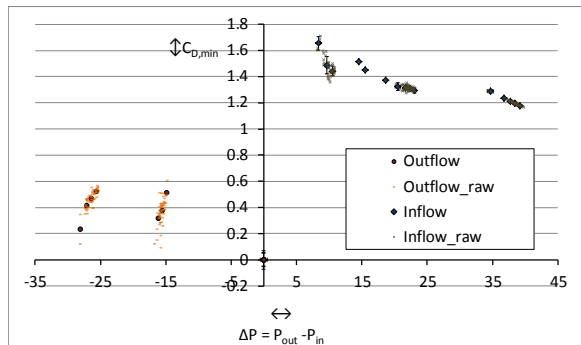
Annex I - Fig. 1 Airflow rates through the centre-pivot roof window (14° Open)



Annex I - Fig. 2 Discharge coefficient of the centre-pivot roof window (14° Open)



Annex I - Fig. 3 Airflow rates through the centre-pivot roof window (4.6° Open)



Annex I - Fig. 4 Discharge coefficient of the centre-pivot roof window (4.6° Open)