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Towards validation of a numerical model of a test cell laboratory

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ABSTRACT

This work represents the determination of the discharge coefficient c_d of a window in the Research Centre on Zero Emission Buildings' (ZEB) Test Cell Laboratory (TCL), located at the campus of the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, for the later use in building energy performance simulation (BEPS) software. For example, the BEPS program IDA Indoor Climate and Energy (IDA ICE) considers window openings to always be of rectangular shape and the user can only enter the percentage of window area to be opened together with a discharge coefficient c_d . By adjusting the c_d which depends on the actual shape of the window and whether the opening is used for single-sided natural ventilation or cross ventilation among others, it is possible to approximate other window opening forms such as tilted, pivoted etc.

While several studies found the discharge coefficient for large, sharp-edged openings such as windows or doors to be between 0.60 and 0.65 (Cruz & Viegas, 2016; Flourentzou, van der Maas, & Roulet, 1998; Heiselberg, Svidt, & Nielsen, 2001), it is still questionable which value to use for tilted windows.

For a subsequent calibration process of a simulation model of the TCL it was necessary to perform measurements for the discharge coefficient which describes flow losses in natural ventilation, based on the research of Heiselberg et al. (2001) in order to quantify airflows through the opened window. Measurements were carried out using Blowerdoor test equipment to determine c_d for the TCL's window. This was done for a tilted window with different opening angles and different pressure differences across the window. By experiment, the mean c_d was found to be 0.75. It can be seen that Heiselberg et al. results are slightly higher than the ones obtained in the present work. This is most likely a result of different window shapes (vertical vs. horizontal shape, but both bottom hung) and measurement inaccuracies. The results of these measurements can be used as input to BEPS programs.

KEYWORDS

Building energy performance simulation model, calibration, discharge coefficient, measurements

INTRODUCTION

Natural ventilation is often used to supply indoor environments with fresh air from the outside and it is considered to be able to reduce cooling energy demands of office buildings significantly, since people are found to be satisfied with a wider temperature range and their office indoor environment in general when given control over it (Brager, Paliaga, & de Dear, 2004; de Dear & Brager, 1998; Leaman & Bordass, 1999). The use of natural ventilation instead of mechanical cooling systems therefore can enhance working conditions while saving energy costs.

The quantification of air flowing through a window thus plays a critical role in determining the cooling potential and the indoor thermal comfort. While several studies confirmed the discharge coefficient c_d , which is often used in BEPS programs to account for turbulence and friction losses, for sharp-edged openings to be between 0.60 and 0.65 (e.g. Cruz & Viegas, 2016; Flourentzou et al., 1998; Heiselberg et al., 2001), it is still questionable which c_d to use in case of tilted windows since it is very much dependent on the specific case of application, as the following literature review will show.

Wang et al. (2017) investigated a row of windows typically used in buildings, both analytical and with Computational Fluid Dynamics (CFD) simulations. The model used for the analytical approach originally goes back to Awbi (1996) and describes the volume flow rate through a single opening due to temperature difference. Wang et al. found good coherence between their detailed CFD calculations and the analytical approach for the tilted window with a maximum deviation under 20 %. But they also suggested dismissing a constant c_d of 0.6 for all kinds of window openings when using the analytical model. The coefficient increases with increasing buoyancy and decreases with an increasing flow area.

The module for air flow networks in the simulation program TRNSYS (Transient System Simulation Tool) integrates a COMIS (Conjunction of Multizone Infiltration Specialists) type network into the program suite, that offers the possibility to calculate bidirectional air flows through opened (including tilted) windows and their c_d factor (TRNSYS, 2009). At standard opening angles from $\alpha = 3^\circ$ to 7° the equation gives discharge coefficients lower than 0.65 (mostly between 0.3 and 0.5).

Maas (1995) conducted CFD calculations and measurements for different opening angles ($\alpha = 1.02^\circ$ to 7.17°) of a tilted window (width $w \times$ height $h = 0.82 \text{ m} \times 1.12 \text{ m}$) with and without a window reveal of 20 cm under realistic boundary conditions (measurements in an actual building). Similar to Hall (2004) Maas found that a radiator right below a window leads to a lower air exchange through the window. Furthermore, he quantified the impact of a window reveal with a decrease of air flows through the window with 50 % (Maas, 1995).

Grabe (2013) found that the assumption of equal in and outflow cross sections might not be right. Smoke visualizations showed the outflow area (in case of warmer indoor temperatures located at the window top) being constantly larger than the inflow area by the factor 2.5 (Grabe, 2013). In a precedent study Grabe, Svoboda, and Bäumler (2014) found that the incoming mass flow through a tilted window can be expressed through a logarithmic relation (Grabe et al., 2014).

Heiselberg et al. (2001) investigated the characteristics of air flow in rooms for a bottom hung ($w \times h = 1.6 \text{ m} \times 0.4 \text{ m}$) and a side hung window ($w \times h = 0.81 \text{ m} \times 1.38 \text{ m}$) in a series of laboratory measurements. The windows were mounted in a wall separating two rooms, one of which simulating outdoor conditions. A ventilation system was used to generate pressure differences and to measure the air flow rates through the openings. For the case of the bottom hung window with single sided ventilation three opening areas have been investigated: 0.019 m^2 , 0.026 m^2 and 0.045 m^2 . For this window, the measured discharge coefficients showed a significant dependency on the opening area, the window type and the pressure difference between the two rooms used for the experiment, but only a small dependency on the temperature difference. For the largest opening area the c_d was roughly between 0.78 and 0.85, for the intermediate between 0.87 and 0.92 and for the smallest between 0.96 and 1.02 (Heiselberg et al., 2001).

A comparison of the named studies is not trivial, as all the named authors pointed out that their findings would be valid for similar boundary conditions and window shapes only. The big difference from Heiselberg's findings to those from TRNFLOW for example, is mainly a result of different area calculations and different governing equations.

ZEB Test Cell Laboratory

The measurements for this study were conducted at the ZEB Test Cell Laboratory (Goia et al. 2017), a facility used for testing building envelope systems in calorimetric and comparative tests. It is located on the campus of the NTNU in Trondheim, Norway. The building consists of two 10.9 m² test cells, each surrounded by a guard volume. Both cells have one façade to the outside, facing exactly South, which can be replaced according to the research needs. This way it is possible to investigate different window types, window opening strategies, façade types, insulations, heating, ventilation and lighting strategies etc. with real weather conditions and, if required, with real occupants. Each cell and each guard volume can be conditioned independently from each other. This part also has an own, independent HVAC system. Fig. 1 shows a 3D perspective from inside the Test Cell Laboratory with highlighted investigated window (red).

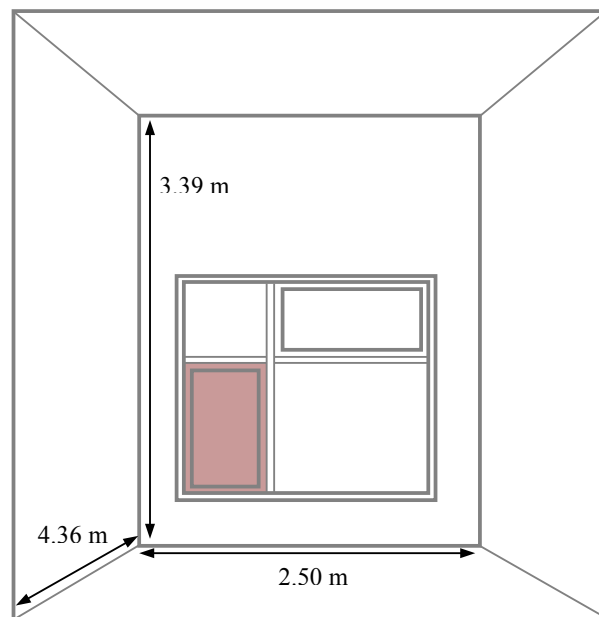


Fig. 1. 3D perspective from inside the Test Cell Laboratory. Highlighted, the investigated window.

The cell envelopes to the guard volume are made of prefabricated sandwich panels with two 0.6 mm stainless steel sheets and 10 cm injected polyurethane foam in between, resulting in a U-value of 0.23 W/m²K. Between the slab of the building and the test cell floor is a gap of ca. 0.5 m, which is also conditioned by the guard volume HVAC system. Its air exhausts are located along the test cell's surfaces to guarantee an even distributed air flow and temperature around it. A weather station on the roof is continuously collecting wind speed and direction, temperature, relative humidity, solar radiation and other weather data. These, along with the measurement values from the cells are stored on a server in the control room.

The facility is used for testing different building parts and conditioning strategies under real weather conditions, primarily for the purpose of indoor comfort analysis. A calibrated virtual model in a thermal simulation program therefore can help to reduce duration and costs of measurements by preselecting only the most promising set-ups for real life tests.

Research question

Many of the common BEPS tools, such as IDA ICE, require the input of a suitable discharge coefficient to consider special window opening forms (e.g. tilted window) for the

determination of natural ventilation air flows. As the literature review has shown, the discharge coefficient is not constant and it very much depends on the case of application.

Due to simplifications IDA ICE cannot determine the air flow through a tilted window correctly, as only rectangular windows are supported (Bring et al., 1999). A possible solution for the problem can be to change the window geometry in the simulation model. The program's distributor EQUA therefore gives modelling guidelines which can be seen in Fig. 2. With this approach, the window is split into several smaller ones, which correspond to the same area as the original one, so that solar gains and losses through heat transmission etc. stay the same. Only the grey parts are (fully) openable (Moosberger, 2017). However, it is still questionable which discharge coefficient should be inserted when this method is used. Therefore it was decided to perform measurements for the discharge coefficient based on the research of Heiselberg et al. (2001).

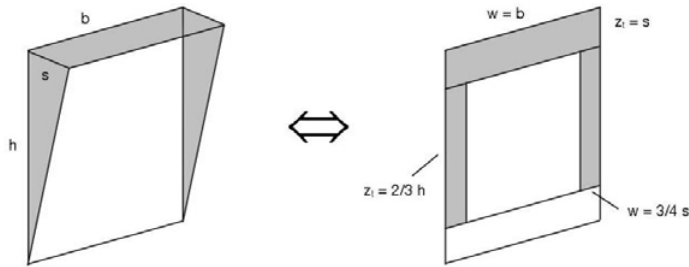


Fig. 2. EQUA's modelling guidelines for tilted windows (Brozovsky, 2018)

METHODS

Since the investigated window form significantly differs from the ones used in the previously listed studies, own measurements were taken. They were conducted at different pressure differences and opening degrees with Blowerdoor test equipment (Brozovsky, 2018). The pressure difference is measured by the Blowerdoor test equipment and the window's opening area was determined by measurements. Thereby the narrowest passage of the flow had to be found for the complex frame geometries. Following equations 1 - 3 were used for the calculations.

$$c_d = \frac{\dot{V}_{BD}}{\dot{V}_{theo}} \quad \text{eq. 1}$$

$$\dot{V}_{theo} = A_{op} \cdot u_{theo} = A_{op} \cdot \sqrt{2 \frac{\Delta p}{\rho_0}} \quad \text{eq. 2}$$

$$A_{op} = s \cdot (h + w) - A_c \quad \text{eq. 3}$$

with

\dot{V}_{BD}	Air volume flow measured by blower door [m ³ /h]
\dot{V}_{theo}	Theoretically achievable volume flow without friction [m ³ /h]
A_{op}	Opening area of window [m ²]
u_{theo}	Theoretically achievable mean air speed through opening without friction [m/s]
Δp	Pressure difference across opening [Pa]
ρ	Density of incoming air [kg/m ³]

The measures of the investigated window are $w \times h = 0.70 \text{ m} \times 1.21 \text{ m}$. The theoretically possible volume flow without friction then was obtained from the pressure difference and the density. The Blowerdoor equipment estimates the actually occurring air flow through the

rotational speed of the fan. Under realistic conditions, the actual air flow must always be lower than the theoretically possible flow. A high potential for error must be considered especially for small openings, when the clearance between the window frames is minimum. All measurements were taken under isothermal conditions. A_{op} was determined with equation 3 with tilt width s and window height h (according to Figure 2), window width w and constriction area A_c due to the window fitting etc.

RESULTS

Fig. 3 and Table 1 show the results of the analysed measurement data. As a comparison, also Heiselberg et al.'s findings (2001) with the largest window opening area are plotted on the figure. By experiment, the mean discharge coefficient was found to be $c_d = 0.75$ for the tilted window being used in the laboratory which is good accordance with the research by Heiselberg et al. (2001).

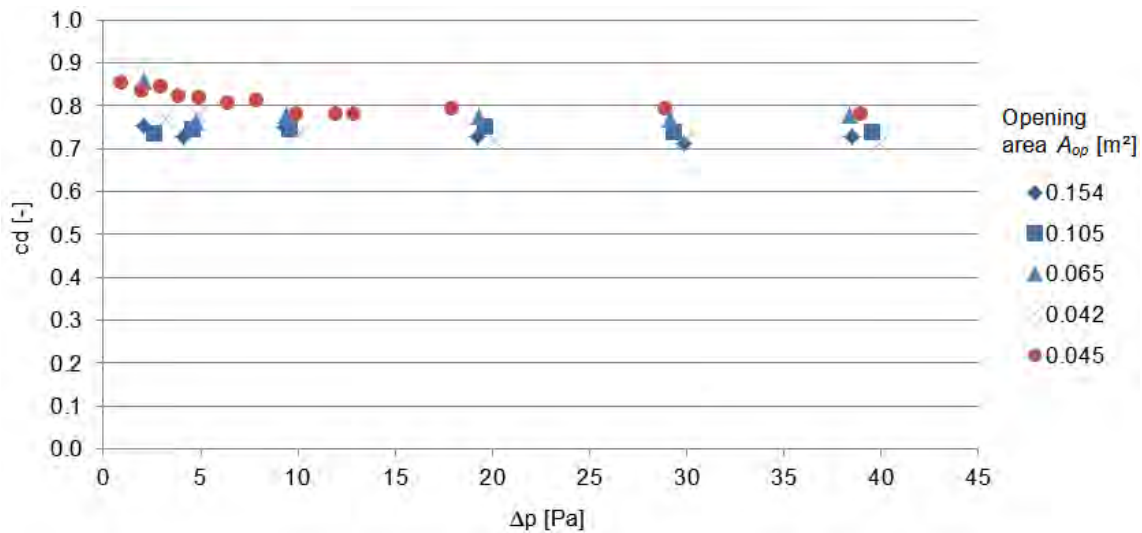


Fig. 3. Measured discharge coefficients for different opening areas and pressure differences (blue) and measurement results by Heiselberg et al. (2001) (red)

Table 1. Measured c_d values for different opening areas

Opening area A_{op} [m ²]	Tilt width s [m]	Tilt angle α [°]	Mean c_d [-]
0.042	0.024	4.1	0.74
0.065	0.037	5.4	0.79
0.105	0.060	7.1	0.74
0.154	0.088	8.5	0.73

DISCUSSIONS

It can be seen that Heiselberg et al. results are slightly higher than the ones obtained in the present work. This is caused by different window shapes (vertical vs. horizontal shape, but both bottom hung) and measurement inaccuracies. Still, the findings are in accordance with Heiselberg et al. as they assume that “[...] for large opening areas the discharge coefficient approaches the commonly used value of 0.6, while it will have a larger value for small opening areas” (Heiselberg et al., 2001) which was also found by Wang et al. (2017). The overall mean discharge coefficient for all opening sizes and pressure differences of the investigated and tilted window is $c_d = 0.75$.

CONCLUSIONS

The results of these measurements can be used as input to BEPS programs. It gives confidence in the use of discharge coefficients determined by Heiselberg et al. (2001). The obtained discharge coefficients were consequently used in a calibration process of an IDA ICE simulation model of the TCL (Brozovsky, 2018).

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