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SINGLE-SIDED NATURAL VENTILATION DRIVEN BY A COMBINATION OF WIND PRESSURE AND TEMPERATURE DIFFERENCE

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ABSTRACT

Natural ventilation is a commonly used principle when ventilation systems for buildings are designed. The ventilation can either be obtained by automatically controlled openings in the building envelope, or it can just be the simple action of opening a door or a window to let the fresh air in. In both situations the aim is to obtain a good indoor environment but to control the amount of air, some basic knowledge of the flow through an opening is necessary.

The amount of air going through the window opening in single-sided ventilation will depend on the wind speed near the building, the temperatures inside and outside the room, the wind direction, the turbulence characteristics in the wind and the pressure variations caused by e.g. wind gusts. Finally it also depends on the size, type and location of the opening. Therefore, expressions for this prediction mainly depend on unsteady parameters, which make the prediction difficult.

From earlier work, a few design expressions for single-sided ventilation already exist, but none of these include the wind direction, which here is an important parameter. Therefore several wind tunnel experiments are made in this work to find a new design expression which includes all of the above parameters.

KEYWORDS

Single-sided natural ventilation, wind tunnel, measurements, air change rates

INTRODUCTION

The decision of using natural ventilation for building ventilation when buildings are being build or renovated, is often taken on the basis of a lot of discussions. One of the main arguments against natural ventilation is the fact, that it can be difficult to control the amount of air going through the openings. Thereby, it might also be difficult to control the indoor environment in the building, which is important for our well-being and health. On the other hand natural ventilation is a passive technology which helps us reduce the damaging outlets to the environment and makes the building independent of unstable energy sources as e.g. oil.

To be able to use natural ventilation some requirements for e.g. internal heat load in the building, depth of the rooms, room height and surroundings must be fulfilled since only limited natural driving forces and cooling capacity of outdoor air is present in this type of ventilation. It must also be accepted that it can be difficult to keep stable indoor conditions, since outside weather conditions often change. Even though it seems like a lot of obstacles, natural ventilation is becoming more and more common when solutions for ventilation of schools and offices are being designed. Furthermore the natural ventilation can also be used for passive cooling of the buildings during night, where the cold outdoor air can help cool down the building also with energy savings as a result.

Considering single-sided natural ventilation, the air flow rate through the opening is more difficult and inaccurate to predict than when cross ventilation is used. The reason for this difference is the airflow process in single-sided natural ventilation, which is not well-known and often unsteady as well. Besides

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being dependent on wind speed, wind direction and temperature differences between inside and outside the building, the airflow in single-sided ventilation is also influenced by the turbulence characteristics (turbulence intensity and length scales) in the wind and the variation in pressure differences induced by e.g. wind gusts. Since these parameters are unsteady the airflow in single-sided ventilation is much more difficult to calculate. Earlier work has been made considering some of these parameters which have led to different empirical expressions developed on the basis of wind tunnel experiments and/or full-scale outdoor experiments.

From analysis of a series of wind tunnel experiments it has been the aim of this work to make a new design expression for the airflow rate that includes wind direction, temperature difference and wind speed together with the effect on the airflow rate coming from the unsteady effects in the wind near the opening. A clear dependency between the wind direction and the amount of air going through the opening was found. This dependency is not included in earlier investigations. During the experiments it was also found that the flow might change from being dominated by wind speed to being dominated by temperature difference when the ratio between the two forces is changing. This change is also found in the shape of the velocity profiles measured in the opening.

EARLIER WORK MADE WITH SINGLE-SIDED NATURAL VENTILATION

Through the last decades different research has been made with the aim of developing expressions for calculation of airflows in single-sided natural ventilation. Here a small review is made for some existing expressions from literature for calculation of airflows in cases with airflow driven by thermal buoyancy, by wind and by both thermal buoyancy and wind.

Airflows driven by thermal buoyancy

The airflow driven only by thermal buoyancy in a single opening will be bidirectional with warm indoor air flowing out in the top of the opening and cold outdoor air flowing in at the bottom of the opening. This means that the direction of the velocity changes at the level of the neutral plane in the opening.

The volume flow rate in this case can be found from expression (1) derived in (Warren et al. 1985).

$$Q_v = \frac{1}{3} \cdot C_D \cdot A \cdot \sqrt{\frac{(T_i - T_e) \cdot g \cdot (H_t - H_b)}{\bar{T}}} \quad (1)$$

Airflows driven by wind

When only wind drives the airflow through the opening the mean wind speed needs to be considered together with the effect from the turbulence in the wind and the fluctuations in pressure at the opening. In the work from 1985 made by P.R. Warren and L.M. Parkins some expressions are found, which include theoretical considerations of both wind tunnel and full-scale experiments. In the paper it is noted that higher rates may be achieved for other combinations of windows, certain wind directions and tall buildings. The expressions are seen in (2) and (3), (Warren et al. 1985).

$$Q_v = 0.1 \cdot A \cdot U_L \quad (2)$$

$$Q_v = 0.025 \cdot A \cdot U_R \quad (3)$$

The subscripts L and R refer to the point of the measured velocity. L stands for local (in front of the window), and R stands for reference velocity, which, in exp (3), is measured at the height of 10m. Both expressions are based on the same basic expression ($Q/(AU)=\text{constant}$). This expression is defined by Warren as the flow number F , which often is denoted F_L , F_T or F_R . (T stands for top of building).

$$F = \frac{Q_v}{A \cdot U} \quad (4)$$

Airflows driven by wind and temperature difference

When the airflow is driven by a combination of wind and temperature difference the shape of the

velocity profile in the opening will change depending on which of the two forces that dominate. An example of this is shown in Figure 1.

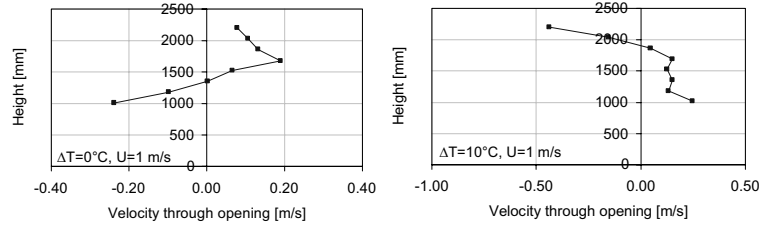


Figure 1. Change in velocity profiles with increase in temperature difference (ΔT). The opening is positioned between $h=910$ mm and $h=2310$ mm. Positive values indicate an ingoing flow. (Larsen 2006)

In the work made by W. De Gids and H. Phaff in 1982, an expression for calculation of the mean velocity in the opening is derived for the case with airflows driven by both wind and thermal buoyancy. Their expression is based on full-scale outdoor experiments. The experiments were carried out at three different locations on buildings in urban environment with surrounding buildings up to four floors high. All measurements were made on the first floor of the building. The experiments consisted of measurements of wind speeds, window and room air velocities, air change rates and temperature. The total number of measurement cases was 33. The expression is shown in (5). (De Gids et al. 1982)

$$U_m = \sqrt{C_1 \cdot U_{10}^2 + C_2 \cdot h \cdot \Delta T + C_3} \quad (5)$$

From a best fit to the 33 measurements the constants were found as shown in (6). (De Gids et al. 1982)

$$U_m = \sqrt{(0.001 \cdot U_{10}^2 + 0.0035h\Delta T + 0.01)} \quad (6)$$

The volume flow rate is then found as a product of the mean velocity and the opening area. This is seen in (7), which disregards the use of a C_D -value. The C_D -value is instead included in U_m . This decision makes the accuracy of the calculation dependent on window type since it is not possible to change the characteristics of the window in the expression simply by changing the C_D -value. The value $\frac{1}{2}$ is added to find the volume flow rate, which comes from the fact, that only half of the window area is used as inlet.

$$Q_v = A_{eff} \cdot U_m = \frac{1}{2} \cdot A \cdot U_m \quad (7)$$

WIND TUNNEL EXPERIMENTS WITH SINGLE-SIDED NATURAL VENTILATION

To achieve detailed information about the airflow rate in a building under different ratios of temperature difference and wind speed a number of wind tunnel experiments were carried out in a full-scale wind tunnel at the Japanese Building Research Institute (BRI), (see Sawachi et al. 1999 & Sawachi 2002). The aim was to find a new design expression for single sided natural ventilation where the wind speed, the turbulence intensity, the wind direction, the pressure difference measured across the opening and the temperature difference between inside and outside of the building are all included. The BRI wind tunnel is shown in Figure 2.

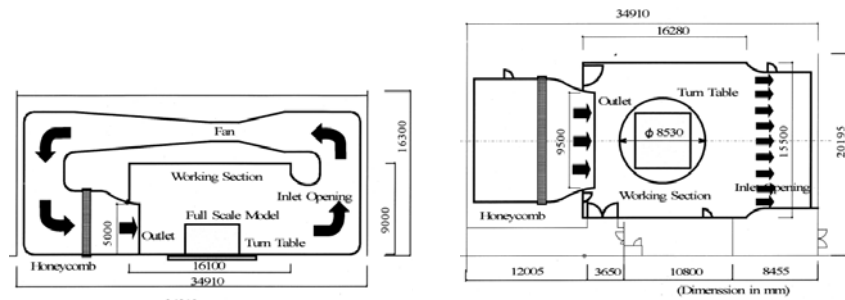


Figure 2. The dimensions and principle in the BRI wind tunnel. (BRI)

The building was sized 5.56 x 5.56 x 3 m, which means that scale effects were avoided, see Figure 3. The opening was 0.86 x 1.4 m. The internal room height was 2.4 m and the thickness of the walls was 0.1 m. The room volume was 68.95 m³. The wind speed in the tunnel could be varied between 1-5 m/s with a turbulence intensity less than 5%.

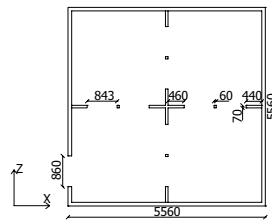


Figure 3. The building in the wind tunnel at BRI (left) and the dimensions (in mm) of the building (right).

During the experiments the model was rotated between 0° and 345° with either a 15° or a 30° increase to get measurements for different directions of the wind, see description of incidence angle in Figure 4. The wind speed varied between 0 m/s, 3 m/s and 5 m/s and the temperature difference between 0°C, 5°C and 10°C. In total 159 different cases were measured. The air change rate was measured with the tracer gas decay method. Table 1 shows the amount of different measurements.

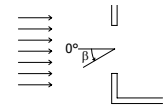


Figure 4. Definition of the incidence angle of

Table 1. Description of parameters measured during the wind tunnel experiments.

Parameter	Description
Tracer gas	Tracer gas was extracted from eight tubes distributed equally in the room and connected to a small container, which was connected by a single tube to the gas analyzer. Before the experiments started full mixing was accomplished by use of four fans in the room.
Velocity	The velocity profiles in the opening were measured in 24 points with 3D ultrasonic anemometers at a frequency of 10 Hz. To avoid blocking of the opening area the velocity was measured in one column at a time. As a constant wind speed was used it was assumed that steady state conditions were obtained in the opening, and similar results therefore could be found even if the velocity profiles were not measured simultaneously.
Temperature	The temperature difference driving the air through the openings was measured both outside the building (2 points), in the opening (24 points) and at 16 positions inside the building. The measurements were made with a frequency of 1/15 Hz.
Pressure	The pressure difference was measured between 2 points in the floor inside the building and 7 points on the outside surface of the building.

The wind speed profile in this type of wind tunnel is almost uniform, which results in a wind profile that differs from outdoor conditions. To study the effect of this, the pressure distribution found on the wind tunnel building was compared with the pressure distribution on a similar outdoor building. Here it was found that the pressure distribution close to the opening had similar characteristics even though the level was different and it was therefore assumed that the measurements made in the wind tunnel could represent outdoor conditions. The blocking ratio in the wind tunnel working section was 12% and compared to the outlet the blocking ratio was 34%. It is due to this rather large blocking ratio that the levels of surface pressures on the building were affected.

EXPERIMENTAL RESULTS

To find the effect of different ratio between temperature difference and wind speed, at first the air change rate is plotted as a function of increasing temperature differences and fixed wind speed, see Figure 5. Afterwards the temperature difference is fixed to find the effect from increasing wind speed, see Figure 6. In Figure 5 it is seen, that increasing the temperature difference will have the largest effect at low wind speeds. Especially in the cases where the wind flows parallel to the opening or the opening is at leeward side (90° to 270°) the effect from the temperature difference is large. This indicates that the airflow through the opening in these cases is mainly driven by the temperature difference. When the speed increases, the effect of the temperature difference is reduced. At 3 m/s the effect of the temperature difference is largest at the angles between 105° and 210° . At 5 m/s the effect of the temperature difference becomes hard to see and is close to non-existing. All measurements show that incidence angles between 0° and 60° (wind directly towards the opening) results in a slightly higher air-change rate than the rest of the measured positions.

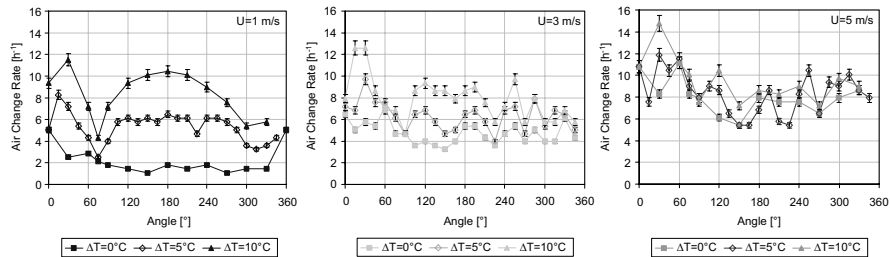


Figure 5. Effect on the air-change rate from changing the temperature difference at different incidence angles and wind speeds.

When the air change rate is seen as a function of increasing wind speed the results in Figure 6 is found. In the isothermal cases the curves are close to parallel which simply shows that higher wind speed results in higher air-change rates. When the increase in wind speed is combined with a temperature difference this effect fades, especially at angles where the wind has no direct influence on the opening. In the cases where the temperature difference is 5°C these angles span from 135° to 270° , but when the temperature difference is increased to 10°C the spectre of angles with small or no influence from increased wind speed is from 90° to 270° , which indicates a stronger influence from thermal forces.

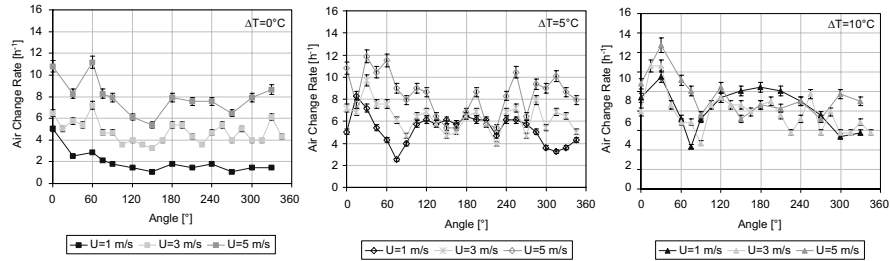


Figure 6. Effect on the air-change rate from changing the wind speed at different incidence angles and temperature differences.

During the experiments the velocity profiles in the opening was also measured. Here it was found that the shape of the profiles change depending on the dominant driving force. This was illustrated in Figure 1 for a temperature dominated case. In these measurements it was also seen that the velocity profiles in the wind dominated cases did not change shape.

ANALYSIS – NEW DESIGN EXPRESSION FOR SINGLE-SIDED VENTILATION

The results from the wind tunnel experiments show that the volume flow through an opening in single-sided ventilation depends wind direction, which haven't been included in earlier expressions for calculation of single-sided natural ventilation. This parameter will be included in the new design expression. Further more, it is seen that an increase in temperature difference or wind speed also in some cases will increase the flow. This increase is dependent on the ratio between the wind speed and temperature difference, which also needs to be considered in the new design expression.

As a basis for a new design expression an expanded version of the orifice equation (Etheridge et al. 1996) is used, see (8), which is the same basic expression as used by De Gids and Phaff. In the present work the driving pressure is divided into three different contributions coming from wind (P_{wind}), thermal forces ($\Delta P_{thermal}$) and fluctuations in the opening (ΔP_{fluct}). ΔP_{fluct} is an empirical expression found from a combination of turbulence in the wind, the temperature difference, the wind speed and the pressure difference in the opening.

$$Q_v = \pm C_D \cdot \frac{1}{2} A \cdot \sqrt{\frac{2 \cdot |P_{wind} + \Delta P_{thermal} + \Delta P_{fluct}|}{\rho}} \quad (8)$$

After a combination of theoretical analysis and analysis of the measurements, expressions for the pressures P_{wind} , $\Delta P_{thermal}$ and ΔP_{fluct} are found and a new expression for calculation of single-sided natural ventilation takes form in (9).

$$Q_v = \pm C_D \cdot \frac{1}{2} A \cdot \sqrt{f(\beta)^2 \cdot |C_p| \cdot U_{ref}^2 + \frac{(T_i - T_e) \cdot g \cdot (H_t - H_b)}{T} + \frac{\Delta C_{p,opening} \cdot (T_i - T_e)}{U_{ref}^2}} \quad (9)$$

Since one of the aims with the new design expression was that it should be easy to use, two additional help-functions are necessary. These are $f(\beta)$, which include the variations in pressure as a function of wind direction, and $\Delta C_{p,opening}$, which is the largest measured deviation between C_p -values in the opening. The functions are shown in Figure 7.

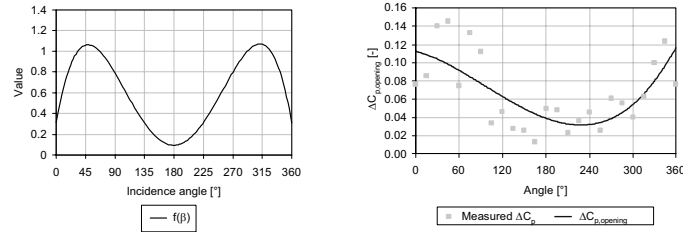


Figure 7. The help-functions $f(\beta)$ and $\Delta C_{p,opening}$.

The design expression is further simplified in (10) by use of three constant weight factors depending on the wind direction. These weight factors include the constant or nearly constant parts of P_{wind} , $\Delta P_{thermal}$ and ΔP_{fluct} . Since the C_D -value for the opening used in the experiments is unknown, it is chosen to include the C_D -value directly as a part of the weight factors. This simplification will make the expression valid only for openings with a C_D -value close to the one valid for this type of opening. The design expression for single-sided ventilation can now be set up.

$$Q_v = A \cdot \sqrt{C_1 \cdot f(\beta)^2 \cdot |C_p| \cdot U_{ref}^2 + C_2 \cdot \Delta T \cdot H + C_3 \cdot \frac{\Delta C_{p,opening} \cdot \Delta T}{U_{ref}^2}} \quad (10)$$

The three constants C_1 , C_2 and C_3 (shown in Table 2) are found by use of the least squares method on expression (10) fitting it to the 159 measurements divided into directions. The average deviations found when the expression was compared to the wind tunnel measurements are also seen in Table 2.

Table 2. Values for C_1 , C_2 and C_3 as a function of wind direction

Direction	Incidence angle, β	C_1	C_2	C_3	Average deviation
Windward	$\beta=285^\circ\text{-}360^\circ$, $\beta=0^\circ\text{-}75^\circ$	0.0015	0.0009	-0.0005	28%
Leeward	$\beta=105^\circ\text{-}255^\circ$	0.0050	0.0009	0.0160	19%
Parallel flow	$\beta=90^\circ$, $\beta=270^\circ$	0.0010	0.0005	0.0111	18%

To test the correctness of this new design expression outdoor, 48 experiments were made on a full-scale office building with a window opening close to the one used in the wind tunnel experiments. Unfortunately, it was not possible to have a large variety of incidence angles during the outdoor experiments. The opening was mainly at windward side and the results showed good agreement with an average deviation of 14%.

CONCLUSIONS

Even though natural ventilation is more and more often used for building ventilation, the design of openings for this type of ventilation still includes some uncertainties. One of the aims in this work was to gain more knowledge of the airflow through openings in single-sided natural ventilation. From earlier work it is known that the wind speed and temperature difference influences the air change rate. The studies of earlier work also show some uncertainties regarding the effect on the air change rate from the direction of the wind.

To obtain detailed information about the airflow through the opening in single-sided natural ventilation, 159 full-scale wind tunnel experiments were carried out. During the experiments the wind direction, wind speed and temperature difference were changed. From the experiments it was concluded that the air change rate does depend on the wind direction. Besides this the temperature difference and wind

speed needs to be included in the new design expression together with the effect on the airflow rate coming from the unsteady effects in the wind near the opening. In the experiments it was also found that the dominating force (wind pressure or temperature difference) changes as a function of wind direction and also as a function of the ratio between them. This effect was also found by studying the shape of the velocity profiles in the opening.

From analysis of the wind tunnel experiments a new design expression was set up. The expression makes it possible to predict the airflow in single-sided natural ventilation including the effect from different wind directions. The design expression is divided into three cases (windward, leeward or parallel flow) because of different flow patterns near the opening. The expression was compared to outdoor measurements and here the uncertainty in the predictions was found to 14%.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A_{eff}	Effective area used for inlet	[m ²]	Q_v	Volume flow rate	[m ³ /s]
A	Total area of the opening	[m ²]	$\bar{T}$	Average temperature	[K]
C_D	Discharge coefficient	[-]	ΔT	Temperature difference	[K]
C_1	Dimensionless coefficient depending on the wind effect		T_e	External temperature	[K]
C_2	Buoyancy constant		T_i	Internal temperature	[K]
C_3	Turbulence constant		U_L	Local speed in front of window	[m/s]
g	Gravitational acceleration	[m/s ²]	U_m	Mean air velocity in opening	[m/s]
h	Height of the opening	[m]	U_R	Reference wind speed	[m/s]
H_b	Height, bottom of the opening	[m]	U_{10}	Mean wind speed in H=10 m	[m/s]
H_t	Height, top of the opening	[m]	ρ	Density of the air	[kg/m ³]
ΔP	Pressure difference across the opening	[Pa]			

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