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Flow characteristics of one-side-mounted windows

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Abstract

Full-scale measurements of the flows through openings under one-side-mounted casement windows are reported. Together with previous studies on scale-model windows, the results provide a sound basis for a quantitative approach to describe the flow characteristics of this window-type. Since the design of windows considered is commonly applied in naturally ventilated buildings, the presented description of the flow through those window openings can be widely employed.

1. Introduction

For residences, schools, greenhouses, livestock buildings etc., natural ventilation is an important tool to control the indoor climate. It directly affects factors such as temperature, humidity and composition of the air. These items are of interest with respect to the comfort and well-being of the occupants and the energy consumption of the building. To design a building, or to improve the control strategy of the indoor climate, a good understanding of the ventilation features is essential. In view of their importance, ventilation characteristics of buildings and the mechanisms of ventilation have been subjects of extensive research; e.g. see refs. 1–3.

In general, when air infiltrates an enclosure through an opening, the pressure difference between the enclosure and the environment can be considered as the driving force for the flow. The volume flux of the air depends not only on the existing pressure difference and the area of the opening, but also on the flow resistance of the opening through which the air has to pass. Though this basic principle is well established, a universally applicable "law of ventilation" is not available. The pressure distributions and the corresponding types of flow near the windows are not only caused by uncorrelated physical aspects such as temperature differences, wind speed and wind direction, but they also depend on a variety of parameters like window-type, the location of the windows, shape and size of the building.

By separating the driving force and the flow characteristics of the ventilation opening, the effect of the various parameters can be better understood. When studying the origin of the generated pressure difference, one can distinguish two types of natural ventilation: (a) caused by wind effects, or (b) caused by a difference in air temperature between the inside and outside air. Both effects are mutually independent and can be described separately. The ventilation caused by wind effects through one-side-mounted windows is treated in another study [4].

The flow characteristic of an opening, relating the volume flux through the opening to the existing pressure difference, is given by the geometry and dimensions of the opening. To be able to calculate the natural ventilation rate of a building, accurate information concerning the flow characteristics of the windows is required. Research on the effect of the inlet configuration on the ventilation is usually directed towards model studies [5–10]. In all these studies, fixed opening structures were considered. For many windows however, the window opening areas can be varied by means of some opening component, characterized by the angle with the plane of the wall.

A type of window frequently used for natural ventilation, is the one-side-mounted casement window. Warren [11] investigated ventilation rates of enclosures fitted with this type of window in a wind tunnel and in a field experiment. The measurements

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were performed at different window angles, wind speeds and wind directions. Total effects were studied and no distinction between the driving force and the flow characteristics of the window opening was made. Baturin [12] published data (obtained from laboratory tests) of flow characteristics of a single, top-hung flap for some fixed opening angles and geometries. No general description of the flow characteristics was given.

An approach to describe the flow characteristics of one-side-mounted windows was outlined in the thesis of Bot [13], in which the ventilation of greenhouses was studied. In his approach, the flow generated by a specific pressure difference over the window was related to the dimensions of the window and the window opening angle. His numerical results on the flow characteristics are based on flow experiments in scale models only (1:30 and 1:10).

Full-scale measurements of the flow through the opening under one-side-mounted windows are an essential supplement of this research to definitely confirm the above-mentioned approach. The present paper resumes, in short, some relevant aspects of Bot's thesis and presents full-scale measurements of the flow characteristics of windows on a cover of a Venlo-type greenhouse. Just for this type of building, with its identical windows distributed evenly on the cover, a knowledge of the flow characteristics of the windows can be applied immediately. With the known flow characteristics of the windows, the effect of environmental conditions such as wind speed and temperature difference between the interior and exterior on the ventilation process can be studied.

2. Principal considerations

The flow characteristic of an opening relates the volume flux (ϕ_v) through the opening to the driving force for the flow, i.e., the existing pressure difference (ΔP).

In the case of air exchange through the opening under a one-side-mounted window, it is obvious that at a given pressure difference the volume flux will vary with the size of the window and with its opening angle. Consequently, this should be incorporated in the general expression for the flow through this type of window opening.

First of all, the flow through a rectangular opening without a flap (Fig. 1) can be considered. If a pressure difference is maintained over this opening, a stationary volume flux ϕ_v will be generated. A relationship between ΔP and the corresponding flux was established by Bot [13] in experiments with

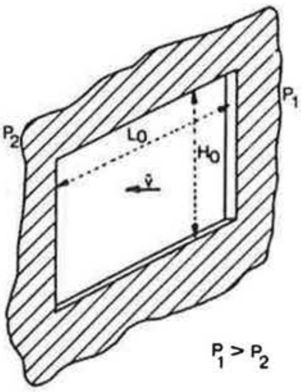

Fig. 1. Rectangular opening.

scale models. In these experiments, scale-model windows (i.e., rectangular openings with different dimensions of length and height) were mounted on a model greenhouse with the same scale factor. Through the windows, an airflow could be generated, from the inside of the greenhouse to the outside, or the reverse. For various flow velocities through the window opening, the corresponding air volume flux and pressure drop across the opening were recorded. The Reynolds numbers in the opening were chosen within the same range as those occurring in full-scale ventilation ($200 < Re < 21000$). From the experiment, it appeared that for the flow region chosen, the viscosity is of minor importance. Consequently, the flow is mainly affected by the density ρ_o of the air and the shape of the opening. This can be expressed in an Euler-like relation:

$$\frac{\Delta P}{\frac{1}{2}\rho_o \bar{v}^2} = F_o(L_o/H_o) \qquad (1)$$

where

ρ_o = density of the air in the opening
$\bar{v}$ = average velocity of the air in the opening
L_o, H_o = length and height of the opening respectively.

The aspect ratio L_o/H_o of the opening is defined as the geometric ratio of length over height. The function $F_o(L_o/H_o)$ is called the friction factor of the opening. In the model experiment, this factor indeed turned out to be dependent on the dimensions of the opening only and the fitting curve through the measuring points could be described by:

$$F_o = 1.75 + 0.7 \exp[-(L_o/H_o)/32.5] \quad \text{for } L_o/H_o > 1 \qquad (2a)$$

or

$$F_o = 1.75 + 0.7 \exp[-(H_o/L_o)/32.5] \quad \text{for } L_o/H_o < 1 \qquad (2b)$$

In both cases Re must satisfy $200 < Re < 21000$.

When the same opening is considered, but now with a flap mounted on one side of the frame of the opening (Fig. 2, one-side-mounted window), the friction factor F_w of the opening under the window and the effective opening area A_w depend on the opening angle. Bot now supposed that this dependency can be represented by two new functions $f_1(\alpha)$ and $f_2(\alpha)$, which relate F_w to F_o and A_w to $A_o = L_o H_o$:

$$F_w = F_o f_1(\alpha) \tag{3a}$$

$$A_w = A_o f_2(\alpha) \tag{3b}$$

Calling $\bar{v} = \phi_v / A_w$, we can now reformulate eqn. (1) as:

$$\Delta P = F_w \times \tfrac{1}{2}\rho_o \left(\frac{\phi_v}{A_w}\right)^2 \tag{4a}$$

or

$$\Delta P = [F_o / f_w(\alpha)] \times \tfrac{1}{2}\rho_o \left(\frac{\phi_v}{A_o}\right)^2 \tag{4b}$$

or (the flow equation in terms of the square law):

$$\phi_v = \frac{1}{\sqrt{F_o / f_w(\alpha)}} \times A_o \left(\frac{2\Delta P}{\rho}\right)^{1/2} \tag{4c}$$

where the term $[F_o / f_w(\alpha)]^{-1/2}$ is referred to as the discharge coefficient and where

$$f_w(\alpha) = \frac{[f_2(\alpha)]^2}{f_1(\alpha)} \tag{5}$$

The definition of the window function $f_w(\alpha)$ in this way is preferable to its reciprocal form, since it now approximates zero for $\alpha = 0$ (closed windows).

The function $f_1(\alpha)$, defining the ratio F_w/F_o, can be found when we can establish a value for the friction factor F_w of the opening under the window. For this purpose, for the time being, it is stated that the effective opening area of the opened window equals the smallest area under the flap, i.e., area AEFB in Fig. 2. We notice that in this effective opening area, the length and height are $L = L_o$ and $H = H_o \sin\alpha$.

With this length and height, the aspect ratio of the effective opening adopted is known and can be substituted in eqn. (2). So the function $f_1(\alpha)$ can be written according to eqn. (3) as:

$$f_1(\alpha) = \frac{F_w}{F_o} = \frac{1.75 + 0.7\exp[-(L_o/H_o \sin\alpha)/32.5]}{1.75 + 0.7\exp[-(L_o/H_o)/32.5]} \tag{6}$$

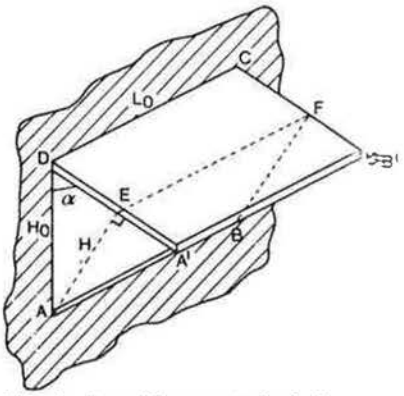

Fig. 2. One-side-mounted window.

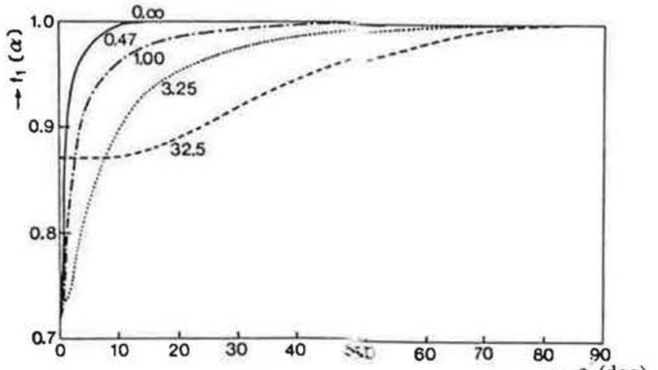

Fig. 3. The function $f_1(\alpha)$ as a function of the window opening for various aspect ratios.

Equation (6) holds for $L_o/H_o > 1$ or $L_o/H_o \sin\alpha > 1$. For $L_o/H_o < 1$ or $L_o/H_o \sin\alpha < 1$, the corresponding relation can be found in a completely analogous way.

In Fig. 3 a graph of $f_1(\alpha)$ is given for some aspect ratios according to eqn. (6). The Figure shows that for small aspect ratios the increase of the function $f_1(\alpha)$ to the value 1 is faster than for larger aspect ratios. For aspect ratios approximating zero and infinity, $f_1(\alpha)$ equals 1 for all opening angles. For a very small split the influence of a flap is clearly negligible, even for very small opening angles!

We want to stress that in general the friction factor is not strongly dependent on the aspect ratio. So an eventual error in the value of the friction factor F_w resulting from our *ad hoc* supposition about the effective opening area under the window flap (area AEFB in Fig. 2, i.e., $L_o H_o \sin\alpha$), will not give rise to serious miscalculations in $f_1(\alpha)$ following eqn. (6).

To establish the function $f_2(\alpha)$, defining the ratio A_w/A_o, the effective exchange area A_w of the opening under the window has to be known or estimated. Again, we can suppose that the effective opening area is represented by the smallest area under the window, i.e., area AEFB in Fig. 2. In this way the simple function $f_2(\alpha) = \sin\alpha$ could be estimated, relating the exchange area under the window (Fig. 2) to that without a window (Fig. 1). It is obvious however, that some contraction will appear in the opening and that the side areas DAE and CBF of the opening (Fig. 2) will also contribute to the effective exchange opening under the window flap. It seems likely that the side area effect will increase for decreasing aspect ratios. However, a summation of the three areas as the representation of the effective opening area is too simple since it can be expected that $f_2(\alpha)$ will not exceed the value 1. To determine $f_2(\alpha)$ as a function of the aspect ratio, eqns. (5) and (4b) can be combined to:

$$f_2(\alpha) = \left[\tfrac{1}{2}\,\rho_o\left(\frac{F_o}{A_o^{\,2}}\right)\times f_1(\alpha)\right]^{1/2} \times \frac{\phi_v}{(\Delta P)^{1/2}} \qquad (7)$$

This formula implies that, when air volume fluxes and pressure differences are measured for a range of opening angles of windows with different aspect ratios and therefore different friction factors, values of $f_2(\alpha)$ can be determined experimentally for each specific combination of window and window angle as the quotient of ϕ_v over $(\Delta P)^{1/2}$ with the 'correction' factor $[\frac{1}{2}\,\rho_o(F_o/A_o^2)\times f_1(\alpha)]^{1/2}$. In this factor, the above-mentioned function $f_1(\alpha)$ given by eqn. (6) can be incorporated.

3. Experimental set-up

A compartment (floor area $= 6.50\times 6.70$ m^2, Fig. 4) was built in the centre of a Venlo-type greenhouse with dimensions 26.6×22.2 m^2. The side walls of that compartment were made of blisterpadding mounted on a wooden frame. The compartment was built as airtight as possible. Each of the four windows in the cover of the compartment was constructed in such a way that two different window types, with aspect ratio 1.00 ($L_o = H_o = 0.71$ m) and 0.47 ($L_o = 0.73$ m and $H_o = 1.55$ m) were available (Fig. 5).

In this experiment, the airflow through the window was generated by a high capacity airblower (Nordisk ventilator, type CNA 400) mounted in an opening in one side wall of the compartment. The direction of the airflow could be altered.

To measure the air volume flux, a large tube, with a propeller inside serving as volume flux meter, was mounted at the outlet of the blower. The diameter of the propeller almost equalled the internal diameter of the outlet tube. The volume flux meter, in combination with the blower, was calibrated first in a wind tunnel at the Institute of Agricultural Engineering (IMAG-DLO) in Wageningen, The Netherlands. According to Berckmans [14], measured values with this device are dependent on the pressure head over the propeller. Therefore series of ϕ_v (air volume flux generated by the blower) and n (rotation velocity of the propeller) were measured at static pressures across the inlet and the outlet of the blower (P_{i-o}) varying from 0 to 40 Pa (Fig. 6). It is to be noticed that, especially in the case of small airflows, the rotation number of the propeller is influenced by the pressure head P_{i-o}. In our work,

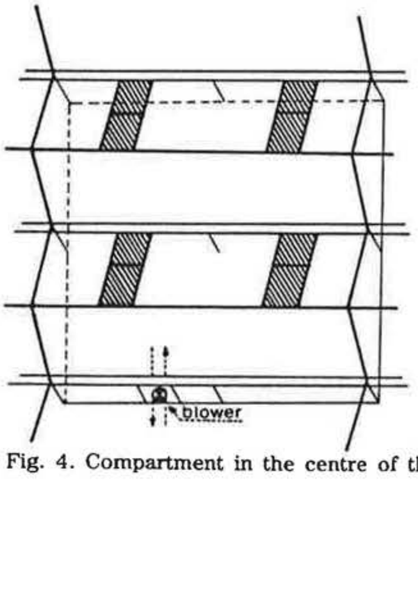

Fig. 4. Compartment in the centre of the greenhouse.

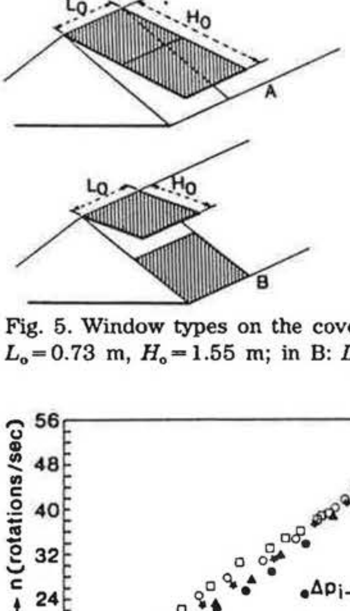

Fig. 5. Window types on the cover of the compartment. In A: $L_o = 0.73$ m, $H_o = 1.55$ m; in B: $L_o = 0.71$ m, $H_o = 0.71$ m.

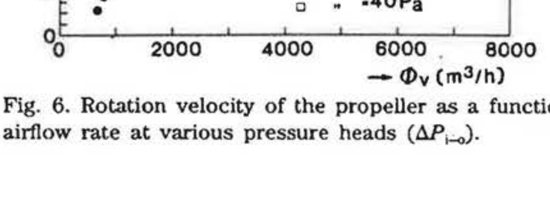

Fig. 6. Rotation velocity of the propeller as a function of the airflow rate at various pressure heads (ΔP_{i-o}).

as a rule, ϕ_v and n were large enough to neglect the influence of this effect.

During the experiments only one window was opened in the compartment. In this way, it is exactly known how much air is blown or sucked through this window. Moreover, larger pressure differences could be established.

The pressure in the compartment and outside the compartment near the window was sampled by a pressure sensor following Elliott [15]. It consists of a thin circular disk with a diameter of 40 mm and mean thickness of 2 mm, positioned on a long thin stem (Fig. 7). The sampling ports are located at the upper and lower centre of the disk, sampling static and dynamical pressures local to the disk.

Special attention has been paid to the dimensions of the instrument to eliminate dynamical pressure changes (i.e., dynamic pressure noise generated by the interference between the flow field and the sensor body) at the sampling points. A detailed description is given in ref. 15.

During the experiments, two parallel linked sensors were positioned outside the window out of the main flow generated by the blower. Another pair of parallel linked sensors, the reference sensors, were positioned in the compartment. The sensed pressures were led to a differential microbarometer (Datametrics type 590D) with an operation range of -100 Pa to $+100$ Pa and an accuracy of 0.05% of the reading. To eliminate high frequency noise in the pressure signal during the measurements, a pneumatic low-pass filter with a first-order time constant of 70 seconds was placed between all sensors and the barometer. Calibration of the pressure probes and testing of the sensors in combination with the filters and the microbarometer was performed according to Jacobs [16, 17].

Moreover, to minimize the low frequency pressure noise due to the blast of the wind outside, measurements were performed during periods with low wind speeds, not exceeding 1 m/s.

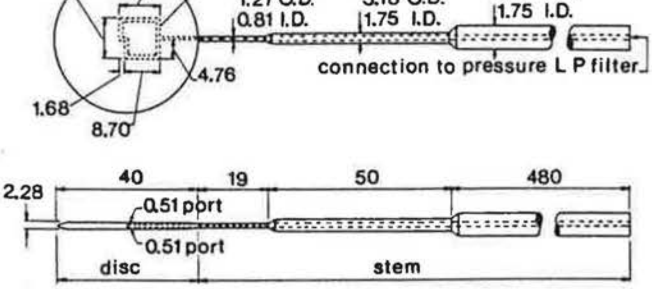

Fig. 7. Pressure sensor (dimensions are in mm).

4. Results and discussion

For the window with aspect ratio 0.47, measurements were performed at window openings ranging from 0 to 14°. For the window with aspect ratio 1.00, the measurements were carried out at opening angles varying from 0° to 77°. For both window types, the function $f_2(\alpha)$ was determined experimentally from the measured ϕ_v and ΔP, according to eqn. (7). The results are presented in Fig. 8, together with some theoretical results (the dotted curves) which will be discussed later.

We notice that for windows with a lower aspect ratio, at small opening angles, the increase of $f_2(\alpha)$ with increasing opening angle is stronger than for windows with larger aspect ratio. This tendency suggests that somehow the effect of the side areas under the window has to be taken into consideration. The side areas will be relatively more important for windows with lower aspect ratio than for windows with larger aspect ratio.

To interpret these results, we start with our first simple statement, neglecting any side area effect, that $f_2(\alpha) = \sin\alpha$. To determine the additional effect of the side area to the total ventilation, we adopt the considerations of Bot [13]. Looking at the model of Fig. 9, Bot estimated the part of the side area which remains free to contribute to the total ex-

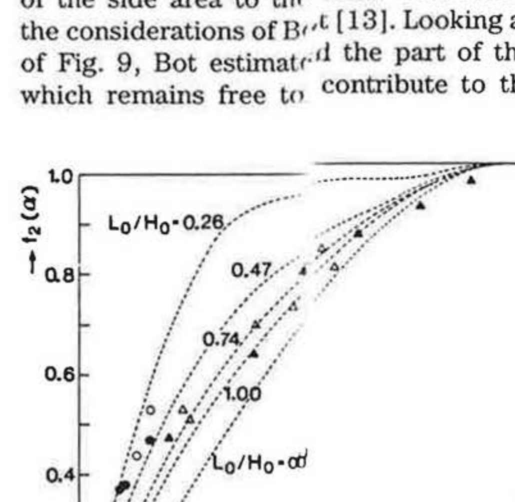

Fig. 8. Full-scale measured values of the function $f_2(\alpha)$ together with a theoretical model (dotted curves) related to the opening angle.

L_o/H_o	1.00	0.47
Flow direction inward	▲	●
Flow direction outward	△	○

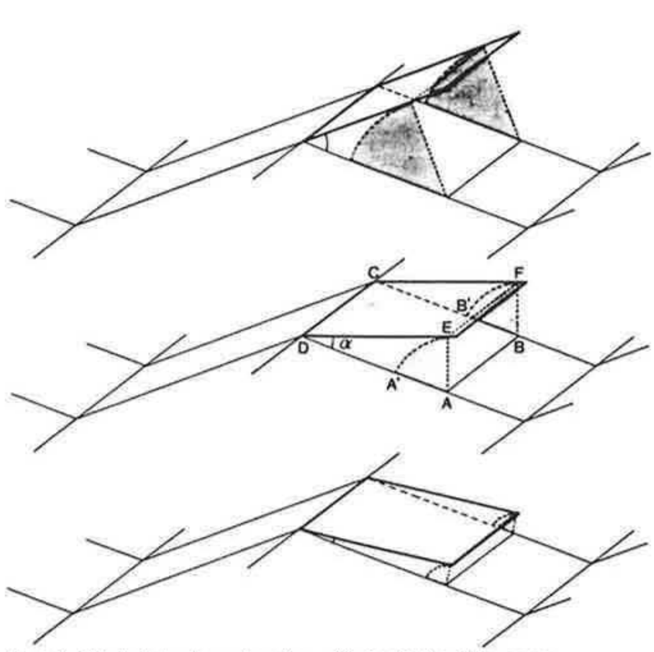

Fig. 9. Model to describe the effect of the side area.

change area. Some elementary geometrics then reveal that the effective opening of one side are amounts to:

$$\tfrac{1}{2} H_o^{\,2} \sin\alpha \cos\alpha - \left[\pi (H_o \sin\alpha)^2 \left(\frac{90-\alpha}{360} \right) \right]$$

In order to amount to some possible deviation from this model, Bot still introduced two arbitrary constants a and b, so that his final results for $f_2(\alpha)$ reads:

$$f_2(\alpha) = \sin\alpha \left[1 + a \frac{H_o}{L_o} \left(\cos\alpha - b \times 2\pi \left(\frac{90-\alpha}{360} \right) \times \sin\alpha \right) \right] \qquad (8)$$

Scale-model measurements reported by Bot gave fair agreement with eqn. (8) when $a=0.6$ and $b=1.00$. The a and b values indicate that the complete circular sections shield off the side areas ($b=1$) and that the front areas are more effective for the exchange of air than the shielded side areas ($a=0.6$).

Figure 8 shows that our experimental results are in full agreement with the geometrical model (represented by the dotted curves) describing the effective exchange area under the window. In the study on the scale models, the flow direction was from the inside to the outside of the model greenhouse. The full-scale measurements show that no clear effect on the measured values of $f_2(\alpha)$ can be observed from the flow direction through the window. This implies that the developed expression for $f_2(\alpha)$ holds for both flow directions.

In addition to the obtained values of $f_2(\alpha)$ from the full-size experiment, another measured quantity in this experiment supports the similarity of the flow properties in both full-size and model windows. In the case of the window with aspect ratio 1.00, which could be opened almost up to 90°, recorded pressure differences over the kinetic energy per unit volume in the opening (according to eqn. (1)), give relevant information concerning the friction factor F_o of the rectangular opening only.

Since both functions $f_1(\alpha)$ and $f_2(\alpha)$ approach 1.00 at full opening, the window function $f_w(\alpha)$ will do the same according to eqn. (5). Measured values of $\Delta P/(\frac{1}{2}\rho_o\bar{v}^2)$ at increasing opening angle will, according to eqn. (4b), approximate the F_o value for the rectangular opening with aspect ratio 1.00 at full scale. From Fig. 10, it appears that the F_o value, based on eqn. (2) and derived from the experiments with scale models, matches well with the full-size measurements.

In Table 1, a comparison is made between the flow characteristics given by Baturin [12] (expressed as values of $\Delta P/[\frac{1}{2}\rho_o\bar{v}^2]$ and based on a model study) and the calculated values of $F_o/f_w(\alpha)$ ($=\Delta P/[\frac{1}{2}\rho_o\bar{v}^2]$, see eqn. (4b)) based on the proposed approach. The figures in Table 1 indicate that agreement between our results and the values given by Baturin is good. This confirms the data given by Baturin and demonstrates that the above-mentioned approach allows the calculation of the flow charac-

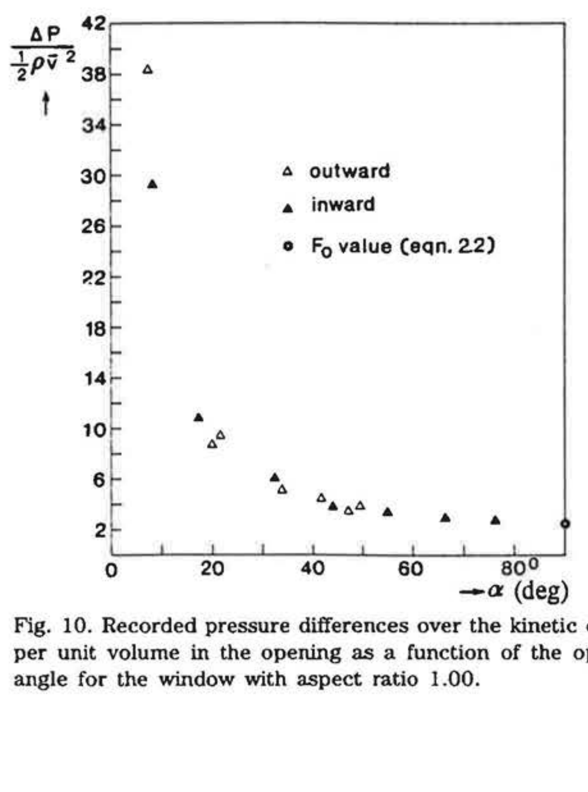

Fig. 10. Recorded pressure differences over the kinetic energy per unit volume in the opening as a function of the opening angle for the window with aspect ratio 1.00.

TABLE 1. Flow characteristics (expressed as values of $\Delta P[\frac{1}{2}\rho_o\bar{v}^2]$) given by Baturin ($\zeta$) and calculated on the basis of the presented approach ($F_o/f_w(\alpha)$)

α	$L_o/H_o=1$			$L_o/H_o=2$			$L_o/H_o=\infty$		
	ζ inflow	ζ outflow	$F_o/f_w(\alpha)$	ζ inflow	ζ outflow	$F_o/f_w(\alpha)$	ζ inflow	ζ outflow	$F_o/f_w(\alpha)$
15	16.0	11.1	18.69	20.6	17.3	24.1	30.8	30.8	25.00
30	5.65	4.90	6.75	5.90	6.9	7.77	9.15	8.60	7.00
45	3.68	3.18	4.12	4.00	4.0	4.38	5.15	4.70	3.50
60	3.07	2.51	3.08	3.18	3.07	3.13	3.54	3.30	2.30
90	2.59	2.22	2.43	2.59	2.51	2.41	2.59	2.51	1.75

teristics of one-side-mounted windows for various opening angles α and ratios of length L_o to height H_o.

5. Conclusions

The full-size measurements of window parameters of the flow through openings under one-side-mounted windows correspond with previous measurements carried out on similar scale-model windows. The results imply the validity of the developed approach to describe the flow characteristics of these types of window openings for both inflow and outflow. In this approach, the ratio between the length and height of the opening, i.e., the aspect ratio, plays an important role. A simple model of the exchange area under the window shows the effect of the side areas for various aspect ratios. The presented description of the flow characteristics can be a useful instrument for predicting the ventilation rate of buildings containing this type of window.

Nomenclature

A_o	opening area of rectangular opening (m^2)
A_w	effective opening area of one-side-mounted window (m^2)
$f_1(\alpha)$	function defined by eqn. 3a (−)
$f_2(\alpha)$	function defined by eqn. 3b (−)
$f_w(\alpha)$	window function defined by eqn. 5 (−)
F_o	friction factor of rectangular opening (−)
F_w	friction factor of window opening (−)
H	height (m)
H_o	height of rectangular opening (m)
L	length (m)
L_o	length of rectangular opening (m)
n	rotation velocity of propeller (rad s^{-1})
ΔP	pressure difference across the opening (N m^{-2})
ΔP_{i-o}	pressure difference across inlet and outlet blower (N m^{-2})
Re	Reynolds number (−)
$\bar{v}$	average air velocity in opening (m s^{-1})
α	window opening angle (deg)
ρ_o	density of air in the opening (kg m^{-3})
ϕ_v	air volume flux (m^3 s^{-1})

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