Cross ventilation analyzed by recording pressure distribution on the floor of wind tunnel models

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ABSTRACT

Cross-ventilation is difficult to predict and control because wind exhibits a large degree of variation in both speed and direction. Consequently, the design of a well functioning cross-ventilation system presently demands thorough and often expensive wind tunnel and CFD investigations. If one can lower the cost needed for these investigations much will be gained. This paper considers the possibility to classify types of flows based on straightforward static pressure measurements. The wind tunnel at the University of Gävle was provided with a pressure plate with 400 pressure taps organized in a square grid. Models of a house with two openings located opposite to each other were placed on the pressure plate and subjected to steady wind flow conditions. Three distinct types of flows were identified by systematically changing the opening size and recording the related static pressure distribution. The occurrence of the different regimes can be explained by jet flow theory. The most important parameter was the internal length of the house divided by a characteristic length of the opening which is the parameter associated with the development of jet flow.

1. INTRODUCTION

Cross ventilation is a particularly useful ventilation strategy in countries with a hot and humid climate. However in countries with colder climates, as in the Scandinavian countries, this is for obvious reasons not the case. However, global climate change may alter attitudes towards cross-ventilation even in these northern countries. Europe in the summer 2003 may reflect the impact of these global changes; the 2003 European temperatures were several standard deviations away from the mean of the past centaury. France alone reported 15000 deaths due to the 2003 heat wave. Therefore it is of interest to study cross-ventilation in the type of houses existing in countries with normally a colder climate. This is one impetus for this work.

A model house built of Plexiglas, Fig. 1, was oriented with the gable walls perpendicular to the wind direction in the wind tunnel. The blockage caused by the model amounted to 0.77 %, which is less than the upper limit accepted for wind tunnel tests (ASCE No.67 (1999)). To achieve sufficiently high levels of pressures, which allowed high accuracy pressure readings, the wind tunnel was run without roughness elements. This gives to a more uniform velocity profile than the correct boundary layer velocity profile. However this deviation from a more realistic profile will not be important in this context given the relatively small vertical dimensions of the openings.

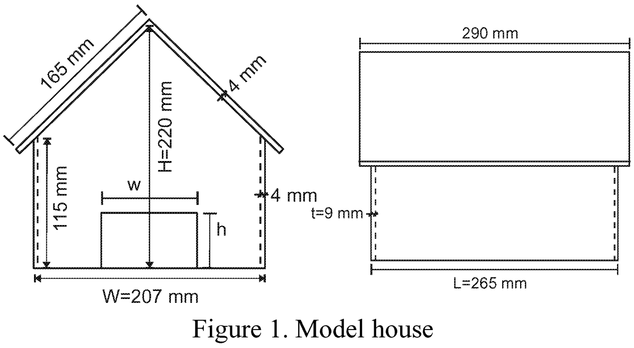

Figure 1. Model house

The basic configuration was taken as a house without any openings. The basic configuration was then amended by introducing two openings of the same size located opposite to each other and placed on the centre line through the buildings. The size of the openings was systematically changed and the pertinent parameters for these changes are shown in Table 1, where A_0 is the opening area and A is the façade area.

Table 1. Experimental parameters.

Opening h	w	$\frac{A_o}{A}$ [%]	$\frac{h}{H}$ [-]	$\frac{w}{W}$ [-]	$\frac{t}{\sqrt{A_0}}$ [-]	$\frac{L}{\sqrt{A_0}}$ [-]
0	0	0	-	-	-	-
4	4	0,05	0,02	0,02	2,25	66,3
7	7	0,14	0,03	0,03	1,29	37,9
17	17	0,83	0,08	0,08	0,53	15,6
20	80	4,61	0,09	0,39	0,23	6,6
40	80	9,23	0,18	0,39	0,16	4,7
50	80	11,54	0,23	0,39	0,14	4,2
55	80	12,69	0,25	0,39	0,14	4,0
60	80	13,84	0,27	0,39	0,13	3,8
65	80	15,00	0,30	0,39	0,12	3,7
70	80	16,15	0,32	0,39	0,12	3,5
80	80	18,46	0,36	0,39	0,11	3,3

The building porosity is a parameter of importance for the wake. In (Sandberg, Heiselberg, Kobayashi and Linden (2008)) it is shown that the ratio between of the momentum flux of the effluent (jet force) and the drag force (drag coefficient C_D) of objects provided with small openings is $2(A_O/A)/C_D$. We can expect the magnitude of the drag coefficient to be somewhat larger than 1 and not to vary so much. Therfore we can expect the ratio between the momentum flux of the effluent and the drag force to be proportional to twice the porosity, $2(A_O/A)$. For large values of the porosity (A_O/A) the efflux from the leeward opening may collide with the backflow in the near wake. If the porosity exceeds a certain value the momentum flux from the discharge through the opening can blow away the near wake. A similar behavior has been observed with models of compact cities with narrow streets (Jian, Sandberg, Li (2008)). In this case the backflow from the wake penetrates into the street and generates a flow opposite to the wind direction.

The relative height h/H of an opening can also be expected to be of importance for the evolution of the vortex present on the windward side of a house with no openings.

The length, t, (i.e. wall thickness) of the opening divided by a characteristic linear dimension of the opening, $\sqrt{A_0}$, is a measure of how "sharp" (sharp-edged or crack) the opening is.

The length, L, of the house divided by a characteristic linear dimension of the opening is of importance for the development of the internal flow. For a turbulent jet to be developed a certain distance is required. This distance is dependent on the Reynolds number (Todde, Spazzini and Sandberg (2008)). The distance decreases with increasing Reynolds number to attain an asymptotic value of about 6 times the linear dimension of the inlet. Based on this we can conclude from Table 1 that only for the three first cases can we expect a jet to be developed. A jet is a boundary layer type of flow with the pressure inside the jet close to the ambient pressure adjacent to the jet.

The pressure on the centerline of the leeward and windward side of the basic configuration is shown in Fig. 2. For this case the stagnation point is located at 72 % of the building height on the windward face.

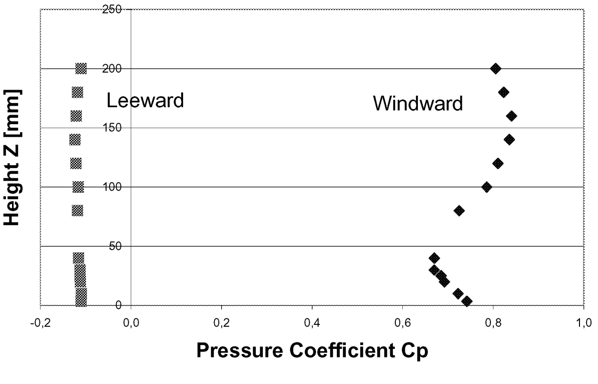

Figure 2 Pressure on the centerline of the windward and leeward side.

Figure 3 displays the pressure recorded with the pressure plate when the model house was provided with an opening porosity of 0.05 %. Each crossing of the reference mesh represents a measuring point. The distance between the measuring points is 37 mm. The pressure landscape shows a pressure peak on the windward side and on the sides of the buildings there are is a pressure minimum. Within the building the pressure is in this case uniform.

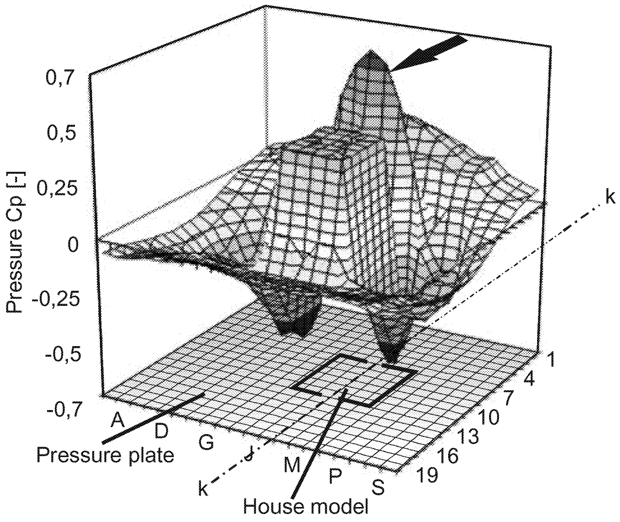

Figure 3 Pressure on ground recorded by the pressure plate. K-K is the centerline. The arrow indicates the wind direction.

2. DOES THE PRESSURE ON GROUND REFLECT THE FLOW ABOVE?

The static pressure recorded on the ground is assumed to show the characteristics of airflow inside a building. It is believed that if the openings are small, pressure becomes uniform within a building and can be replaced by the pressure recorded on the floor. Even in cases of large openings where static pressure does not seem to be uniform, the pressure on the floor could reflect the spatial pressure above the floor.

Kobayashi et al. (2007) have analyzed the same model by using CFD. Figure 4 shows the distribution of static pressure for both on the ground and above floor at different heights for the cases w=17, h=17 mm (Porosity 0.83 %), and w=80, h=80 mm (Porosity 18.5 %). The vertical axis is normalized by the dynamic pressure, and for the horizontal axis, the length of the model. In the results for the smaller opening, static pressure at the height of 10mm is lower than others because of the contraction of the flow into the model. In general, however, static pressure is almost uniform inside the model because flow is well developed inside the model like a jet. Therefore, it seems possible to replace the spatial distributions of static pressure outside of the jet by that on the ground. In the case of the larger opening, on the other hand, the static pressure on the ground is different from that above the ground, which is lower than that on the ground. This is because the jet flow exits the leeward opening before it is fully developed. In such a case, pressure inside a building is not uniform in the horizontal direction and there also seems to be a particular distribution in vertical axis. However, the variation of the pressure above the ground is quite similar to that on the ground, and this can be obviously distinguished from that in the case of small opening. From these results, we can conclude that the pressure recorded on the ground can reflect the variation of the pressure above the ground, and pressure measurement on the ground could provide a useful method for classifying the characteristics of the flow through a building.

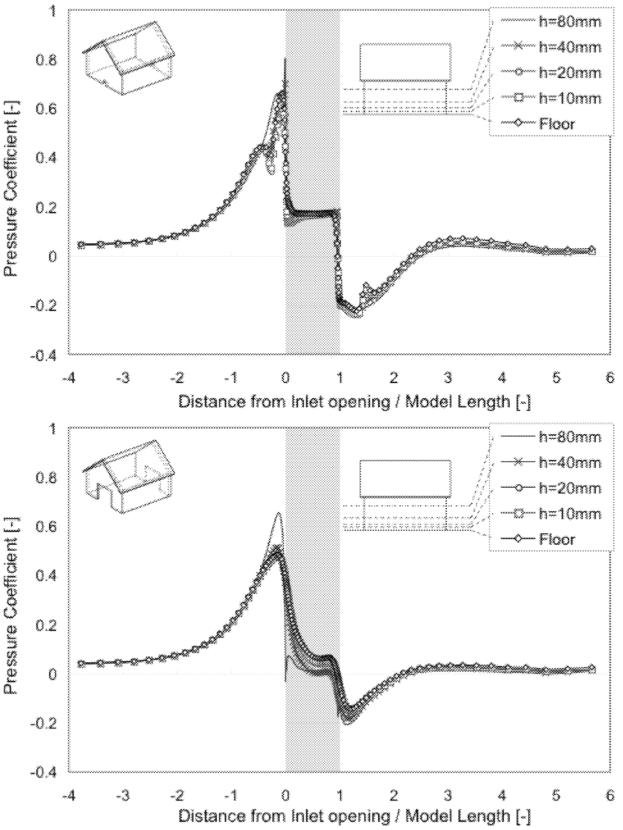

Figure 4. Static pressure along the center-line on and above the ground obtained from CFD; top w=17, h=17mm. below: w=80, h=80mm. Wind direction is from left to right.

3. RESULTS

Figure 5 displays the recorded pressure along the centerline of the pressure plate (line K-K in Fig. 3) when the house is provided without openings. The shadowed area denotes the position of the house.

At the front of the windward façade there is a vortex. The rotation of the vortex is reflected in the pressure distribution. The location of the minimum pressure can be interpreted to be the location of the point of maximum velocity.

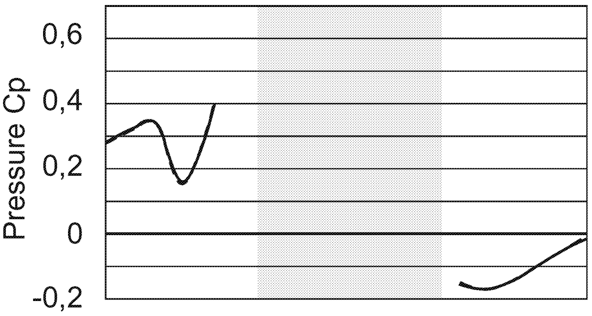

Figure 5 No openings. Pressure along the centerline of the pressure plate. Wind direction from left to right.

Figure 6 shows measured results for models with openings. On the windward side there is at first an increasing pressure due to the deceleration of the flow caused by the blockage of the house. These results are plotted for openings with $L/\sqrt{A_O} =$ 66, 3, 37, 9 and 15, 6. These lengths allow the inlet jet flow to be developed.

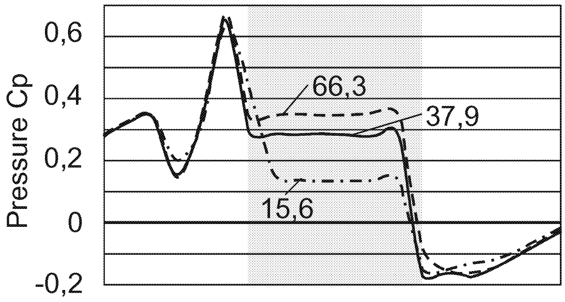

Figure 6 Pressure distribution along the centerline of the pressure plate for $L/\sqrt{A_O} =$ 66.3, 37. 9 and 15. 6.

The maximum pressure is now followed by a decreasing pressure due to an acceleration of the flow through the opening. Outside the region of the inlet jet development, pressure within the model building is uniform. On the leeward side there is a decrease in pressure caused by an accelerating flow through the opening on the leeward side of the building.

The uniform pressure within the building can be explained with the aid of jet theory. Due to entrainment of ambient air the jet expands and its cross section increases with distance from the opening. In an undisturbed ambient environment a jet grows linearly with distance from the inlet. Therefore the jet cross section at the end of the room is proportional to $L/\sqrt{A_O}$ and when arriving at the opposite opening the jet cross section is larger than the size of the opening. As a consequence there is a large pressure drop across the opening on the leeward side. With increasing opening size the distance $L/\sqrt{A_O}$ decreases and subsequently the relative increase in size of the cross section of the jet is less. Therefore the pressure drops on the lee--ward side is less. Exactly the same behavior occurs when the opening size is less on the leeward side than on the windward side; see Figure 18 in True et al (2003).

The next group of pressure distributions results, Fig. 7, exhibits a different behavior. Now almost all the pressure drop occurs across the windward opening. The pressure is now negative within the model building but still it is relatively uniform.

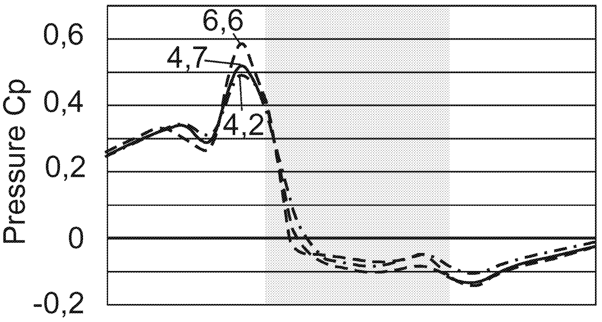

Figure 7 Pressure distribution along the centerline of the pressure plate for $L/\sqrt{A_O} = 6.6$, 4.7 and 4.2.   .

Figure 8 shows the two largest openings. Now the internal pressure is positive and there is a nearly continuous decay in pressure. The level of the pressure has increased because the pressure on the leeward side has increased.

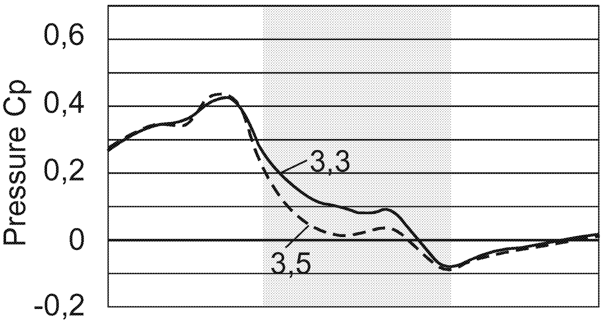

Figure 8 Pressure distribution along the centerline. $L/\sqrt{A_O} = 3.3$ and 3.5

In these cases there is probably little expansion of the inlet jet flow so presumably the velocity within the building is relatively constant. The decay of the static pressure must then be due to a loss in kinetic energy density. In these cases the porosity is relatively high, about 16 and 18.5 % respectively. A common characteristic of the flows in this case is a relatively high momentum flux.

Considering the pressure distribution on the windward side outside the building we now observe that now there is no dip in the pressure outside the building. This is a strong indicator of that the windward vortex has disappeared.

4. CONCLUSIONS

Based on the shape of the static pressure distribution within the house along the centerline and the relative magnitude of the pressure level one can distinguish three categories:

Type 1) Uniform and positive pressure

Type2) Negative and relatively uniform pressure

Type 3) Positive and decreasing pressure in the direction of the flow.

The first type appears for the cases with $L/\sqrt{A_0} \geq 15$. The internal length allows a jet to be developed and the pressure drop across the openings is controlled by the expansion of the jet. With increasing $L/\sqrt{A_0}$ the jet cross sections increases and impose a higher pressure drop across the leeward opening.

For the other cases the relative cross flow path, $L/\sqrt{A_0}$, is too short to allow a jet to be developed.

The second group exhibiting negative pressures inside has a large pressure drop across the opening on the windward side since there is no expansion of the flow after it has passed through the opening on the windward side due to the contraction of the flow caused by the opening. Therefore the flow contained within a dominant stream tube passes through the leeward opening with little resistance and thus little pressure drop.

The common characteristic of the third group is a large porosity. The large porosity makes the flow force of the efflux from the leeward opening so large that it affects the near wake. As a consequence the pressure on the leeward side increases which in turn imposes a higher-pressure level inside the building. The relatively high momentum of the flow also gives rise to an interaction with the air inside the building leading to an energy loss shown up as a decrease in static pressure (potential energy).

In terms of parameters we can now make the following classification into two main cases:

$L/\sqrt{A_0} >> 6$ Expansion of the internal flow due to fact that is the inlet jet has sufficient length to develop, compare Fig. 6.

$L/\sqrt{A_0} \leq 6$ Expansion of the inlet jet cross section is less than the size of the outlet opening cross section, compare Fig. 8.

The first class has a Type 1 pressure distribution and the second one has a Type 3 pressure distribution. In between there is an intermediate case with a Type 2 pressure distribution, compare Fig. 7. The conditions for the two main cases to appear can be expressed in terms of the porosity as $\sqrt{(A_0/A)} << L/\sqrt{A} \cdot 1/6$ and $\sqrt{(A_0/A)} \geq L/\sqrt{A} \cdot 1/6$.

The ground level pressures reveal the evolution of the vortex on the windward facade. With increasing opening height the vortex becomes weaker and finally it disappears.

Future work will be carried out with the aim of detailed mapping of the velocity vector field on the windward and leeward side with particle image velocimetry (PIV).

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