

Towards a better understanding of pressure equalization

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ABSTRACT: A series of wind tunnels tests are presented on a cube, equipped with a permeable outer layer. The influences of cavity depth and opening width have been investigated. This research shows that a wind direction of 75 degrees with respect to the considered panel gives the highest differential pressures relevant for cladding. For smooth flow conditions uniform cavity flows are found, with local effects at the openings in the reattachment zones. Large gaps and small cavity depths have a positive effect on pressure equalization. However, the varied gap width and cavity depth in the current study show minimal effects. It is possible that measures leading to significant effects are outside the range of current practice.

KEYWORDS: Local wind loads, pressure equalization, building facades

1 INTRODUCTION

Rain screen facades are being applied frequently. The façade consists of an air tight inner layer, a cavity (usually partially filled with thermal insulation) and a permeable outer layer. This outer layer can be made of a variety of materials, e.g. natural stone, wood or metal. The permeability allows the pressures over the cladding to equalize. This minimizes the pressure difference over the cladding, thus preventing rain ingress, and reducing the local wind loads. As a result, relative lightweight solutions for the façade and its fixings can be applied. The extent of pressure equalization is sensitive to the detailing of the façade. A number of parameters, such as cavity depth, opening ratios, the extent to which compartments are realized in the cavity, and the complexity of the flow nearby the building influence the pressure distributions over the façade. The relation between these parameters and the pressure distributions are not explicitly known, which makes it difficult to accurately predict the differential pressure over individual façade elements.

The majority of research on pressure equalization has been carried out with respect to rain penetration. The relevant pressures in those studies is the pressure at the windward side of a building, which is the driving force for wind-driven rain. Brown et al. (1991) conclude that the cavity volume should be minimized to improve the speed of pressure equalization, since it reduces the amount of airflow required. Studies of Inculet & Davenport (1994) and Van Schijndel & Schols (1998) show that the higher frequency pressures (>0.1 - 1.0 Hz) are more damped than the lower frequency pressures.

For wind loads on permeable façades the pressure in the separation zones at the side faces of the building is of relevance. From wind tunnel tests, carried out by Gerhardt & Kramer (1983) and Gerhardt & Janser (1994), it was concluded that the detailing of the extremities, open or closed, has a major effect on the pressure equalization and the differential pressures near corners. The largest mean differential pressures are found at the reattachment point, where the mean external pressure has its minimum. For peak pressures, the largest differential pressure occurs near the

leading edge, where the flow is fully separated. Both for the means and peaks, smooth flow leads to the highest values. A good correlation between cavity flow and external flow is found for small gap widths where the gap flow resistance is high.

Cheung and Melbourne (1988) have performed an extensive wind tunnel study on permeable roofs where they varied the porosity of the roof and the cavity volume. The effect of the internal volume depends upon the distance from the leading edge and of the porosity. Except for regions very close to the leading edge ($x/L < 0.02$), a combination of high porosity and small internal volume leads to the highest reduction in mean differential pressures. The effect of the internal volume on the peak differential pressures is small.

A simple test has been set up to separately investigate these parameters. This paper focusses on the effect of the cavity volume and opening width on the wind loading of façade elements.

2 EXPERIMENTAL SET-UP

A research project has been set up in the Netherlands, to understand the local wind loads of rain screen facades. A full scale, in-situ, test has been started on a 150 m high building in Rotterdam, and both CFD and wind tunnel work has been planned. This paper deals with a wind tunnel test in which parametric studies are carried out. The wind tunnel experiments were carried out in the open circuit atmospheric boundary layer (ABL) wind tunnel of TNO in the Netherlands. Pressure measurement have been performed on a floating cube with dimensions 60x60x60 cm positioned at half tunnel height (h_{ref}). Measurements were done with a smooth up-stream fetch and no roughness elements. The oncoming flow was measured above the center of the turntable with a one-component Dantec Dynamics hot wire anemometer. Ten measurements were performed with a 500 Hz sampling frequency for a total period of approximately 41 s. At a velocity of 15.16 m/s (± 0.04 m/s) the turbulence intensity was 0.38% ($\pm 0.05\%$). The main flow properties are given Figure 1.

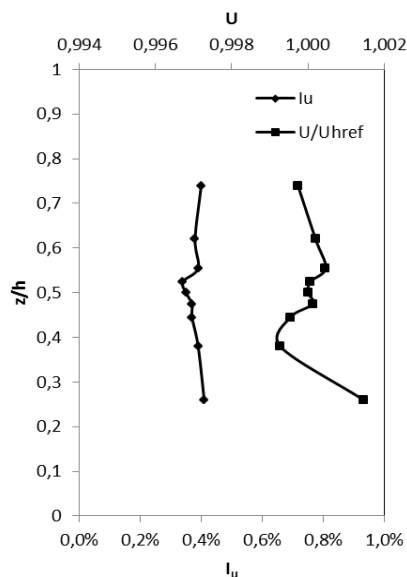


Figure 1. Main flow properties

The cube consists of an airtight inner cube and an outside layer. This layer consists of flat plates with open joints of 8 mm width. Figure 2 gives the outline of the cube. External pressures

and cavity pressures, and flow speeds in the cavity have been measured at different angles of attack. The reference dynamic pressure and oncoming flow velocity ($U_{ref}=14.9$ m/s) have been measured using a pitot static probe at half the height of the model. The pressures were simultaneously sampled at 20Hz. For every wind direction, 32 time series of 60 s each have been obtained.

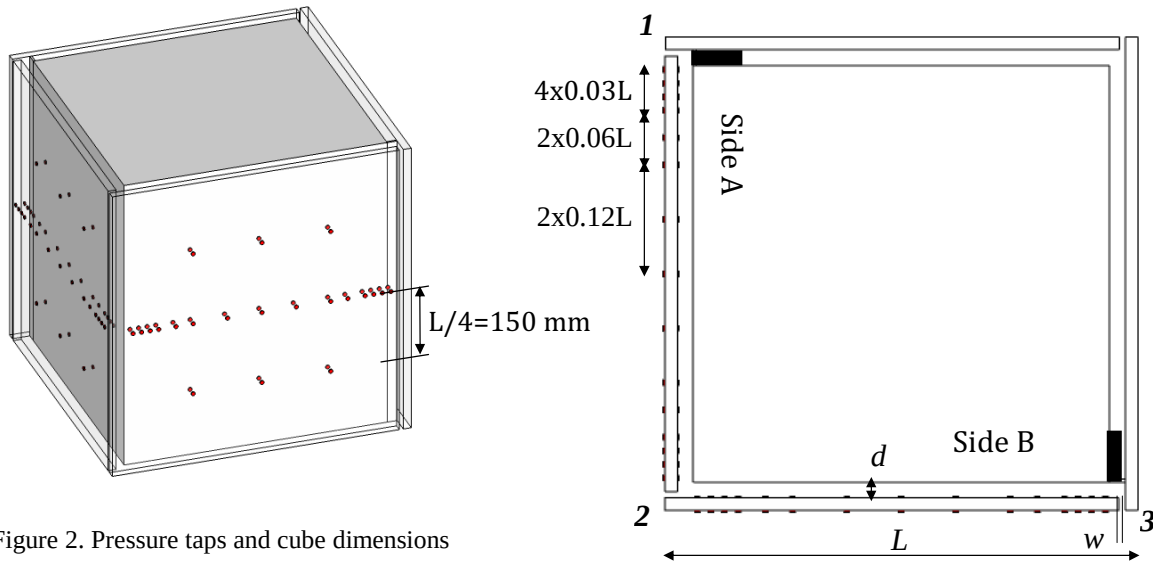


Figure 2. Pressure taps and cube dimensions

Mean, standard deviation and peak pressure coefficients are derived for each of these series according to:

$$C_p(\theta, t) = \frac{p(\theta, t) - p_a(\theta, t)}{\frac{1}{2} \rho U_{ref}^2} \quad (1)$$

Of which both mean values $\bar{C}_p$ and peak-values $\hat{C}_p$ are presented. Using the time signals of external p_e and cavity pressures p_c , time series of the differential pressure were derived. The resulting differential pressure coefficients C_{pdiff} are given by:

$$C_{pdiff}(\theta, t) = \frac{p_e(\theta, t) - p_c(\theta, t)}{\frac{1}{2} \rho U_{ref}^2} \quad (2)$$

Negative values correspond to a direction pointing outwards of the cube and positive values towards the cube.

The purpose of this paper is to show the effects of opening size and cavity width on the peak differential pressures. To study these effects, the configurations described in table 1 have been used. C0 consists of measurements of external pressures only on a closed cube. The basic configuration is C1A, with a gap width of 8 mm and a cavity depth of 20 mm. These sizes correspond on a 1:1 scale to measures found in current practice. The effects of the gap width and cavity depth are investigated by applying the other configurations of table 1.

Table 1. Configurations

Configuration	Gap width w (mm)	Cavity depth d (mm)	Outer dimensions $L \times L$ (mm)	Opening 1 x/L (-)	Opening 2 x/L (-)	Opening 3 x/L (-)
C0 (closed)	0	0	600x600	-	-	-
C1A (reference)	8	20	600x600	-0.97	-0.03	0.97
C1D	4	20	600x600	-0.97	-0.03	0.97
C1E	16	20	600x600	-0.96	-0.04	0.96
C1F	8	10	580x580	-0.97	-0.03	0.97
C1G	8	40	640x640	-0.97	-0.03	0.97

3 RESULTS

Results are presented for two sides of the cube (referred to as side A and side B, see figure 2), for approach flow directions towards those sides. This section starts with the external pressure distribution over C0, the closed cube. Subsequently, the pressure distributions over the outer layer and cavity are given for reference case C1A, followed by data obtained after varying the opening width and cavity depth.

3.1 Cube without openings (C0)

The mean external pressure coefficients of the closed cube are given in figure 3 for 4 angles of attack, zero being the direction perpendicular to side B. For the purpose of this study, the negative external peak pressure coefficients are of main interest. The mean peak external pressure coefficients are given in figure 4. The approach flow direction of 15 degrees give the largest external loads on side A. Note that these values correspond to approach flow direction of 75 degrees for side B, because of symmetry over the diagonal.

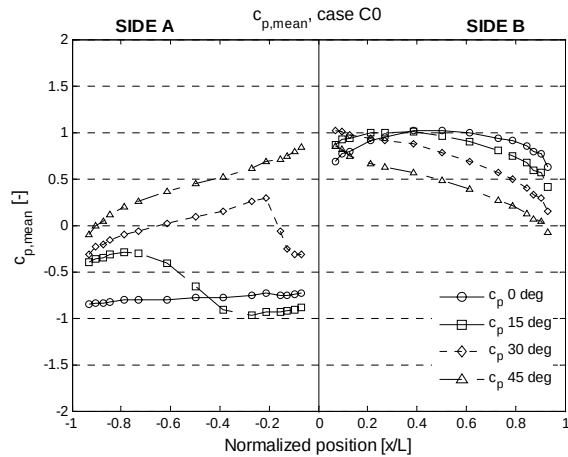


Figure 3: Mean pressure coefficient

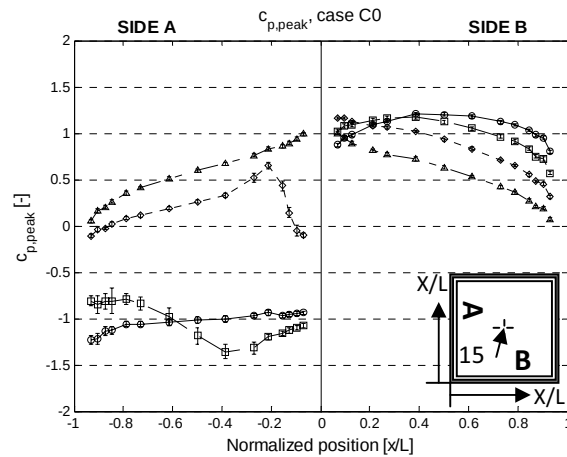
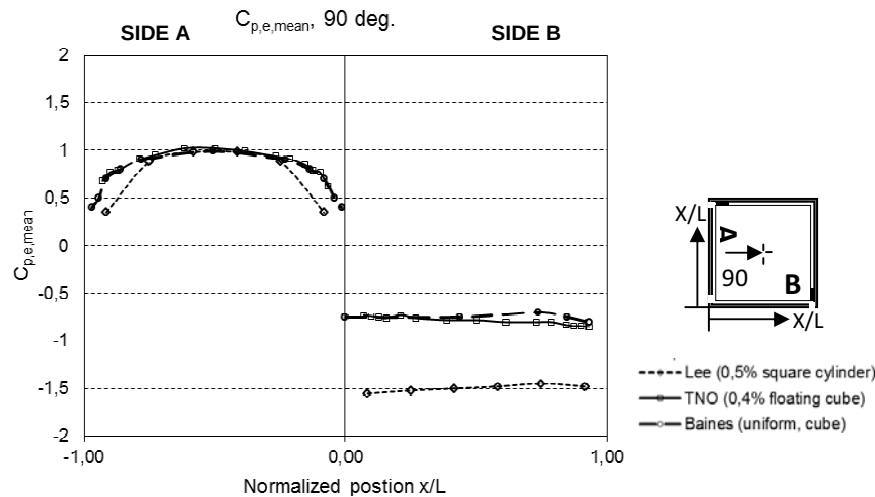


Figure 4: Peak pressure coefficient

The mean pressure distributions show that the positive pressure coefficients decrease with increasing angle of attack, while simultaneously there is a shift of the maximum value towards the leading edge. At side A, the flow direction of 15 degrees show a clear separation zone, as well as reattachment. The mean peak pressure coefficients (0.1s peaks) are slightly higher, and have their maximum of -1.4 at $x/L = -0.39$ by 15 degrees angle of attack. At the reattachment zone high standard deviations are found, which affect the mean peak pressure coefficients of this flow direction.

The values for this cube have been compared with earlier reported values in literature. Unfortunately, no values for a non-surface mounted "floating" cube could be found by the authors. Data considered are surface mounted cubes and 2-dimensional cylinders with square cross-section. Measurements of the pressure distribution around square cylinders in turbulent flow have been presented by Lee (1975). A cube in uniform flow has been reported by Baines (1965).



The floating cube is best comparable with a surface-mounted cube in uniform flow field and end effects dominate the flow.

3.1 Differential pressures over a permeable layer: the reference case

The reference case has 3 openings (see figure 2): one at the leading edge of side A (2), one at the trailing edge of A (1) and one at the trailing edge of side B (3). Figure 5 shows the mean values of the external pressure coefficients and the cavity pressure coefficients for 4 angles of attack. The flow directions contain the highest pressures for side A (15 degrees) and B (75 degrees). The external pressure is not affected by the openings, resulting in the same external pressure coefficients as for the closed cube. At side A, the cavity pressures are dominated by opening 1, whereas at side B, the cavity pressures are determined by both openings (2 and 3). As expected the pressure in the cavity is uniform, except from local effects near the openings.

Figure 6 presents the mean peak pressure coefficients. Due to higher external pressures at the openings, the mean peak pressure coefficients of the cavities are higher than the mean pressure coefficients. Since the turbulence is low, the effect is rather small. As already concluded by Geurts (2000, 2005) pressure equalization is a very fast process and all external fluctuations are immediately followed by the cavity. The mean peak pressure coefficients of the separated flow near the leading edge (flow directions 15 degrees for side A and 75 degrees for side B) increase a bit more. The largest difference occurs where the flow is reattached and high standard deviations (not shown here) are found.

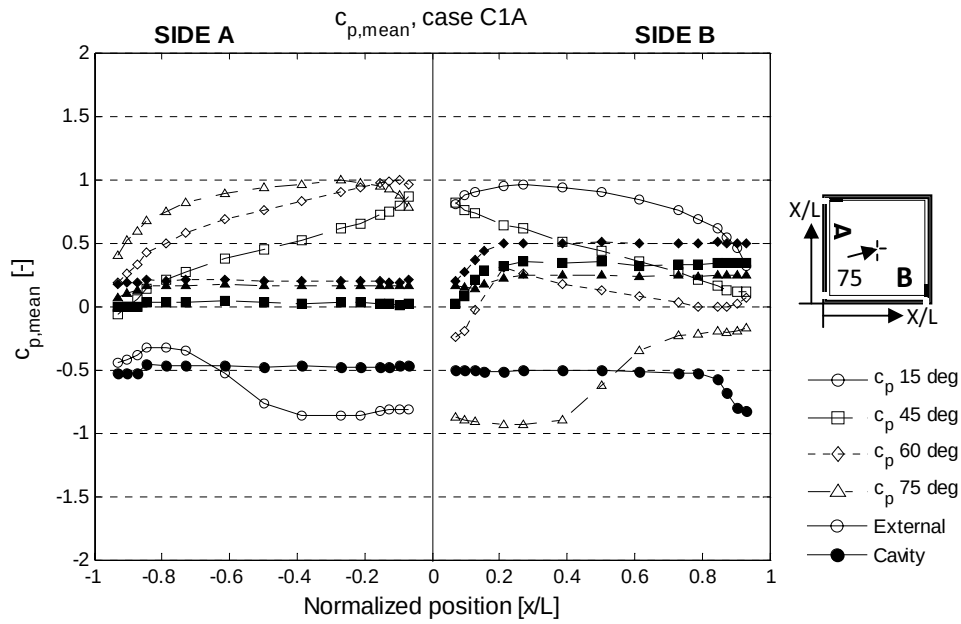


Figure 5: Mean pressure coefficients of reference case

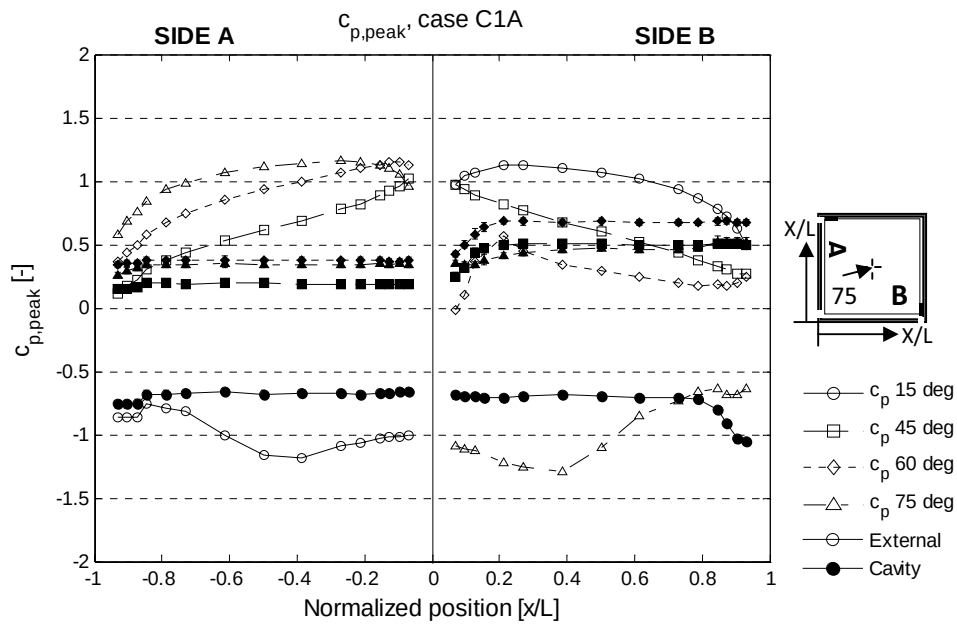


Figure 6: Mean peak pressure coefficients of reference case

For cladding the differential pressure is the most interesting one. The mean peak differential pressure coefficients are shown in figure 7. Negative values correspond to a direction pointing outwards of the cube and positive values towards the cube. On side A the cavity pressures have the same sign as the external pressures and lower differential pressures are found. On side B the opposite is true and the differential pressures are higher than the external pressures.

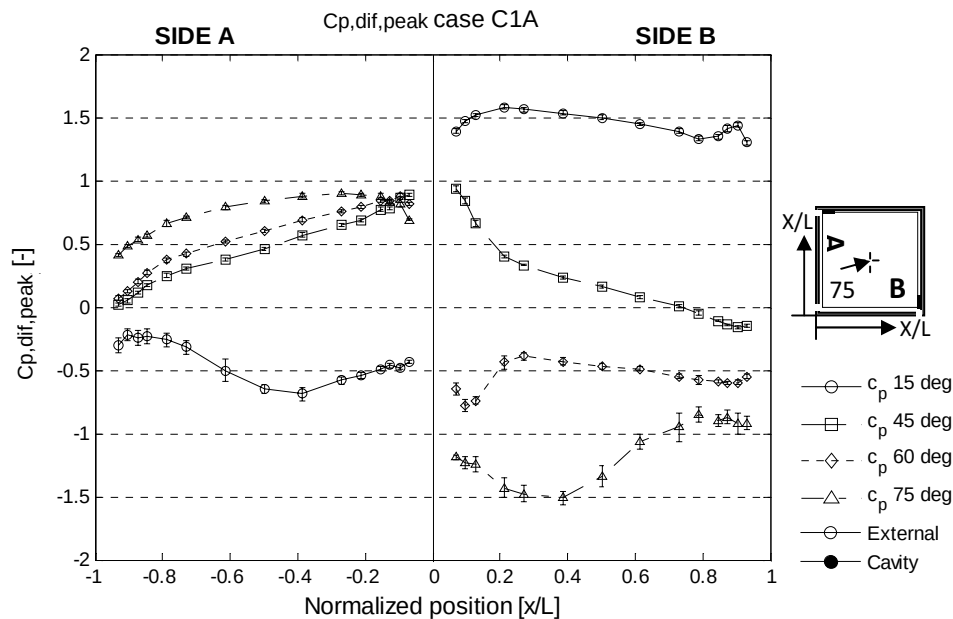


Figure 7: Mean peak differential pressure coefficients of reference case

Of the 4 considered wind directions, the highest outward pointing differential pressures are found for 75 degrees approach flow. On the leading edge the external pressure contributes for 2/3 in this pressure, on the trailing edge the cavity pressure and external pressure contribute equally.

3.2 Effect of gap width (C1D, C1A, C1E)

Three series of measurements have been conducted to investigate the effect of the gap width between the panels on the pressure distributions in the cavity. The gap width was varied between 4, 8 and 16 mm. Results are presented here for the approach flow direction of 75 degrees (figures 8 and 9). At this approach direction, the largest differential pressures have been measured in the reference case (with the 8 mm gap width).

Due to a higher flow resistance, the lowest pressures in the cavity and accordingly the highest differential pressures are expected with the smallest gap widths. Figure 8 does not show this effect: the smaller gap of 4 mm width gives similar values as the 8 mm gap at side A. However, it does show the opposite effect for the 16 mm gap where lower differential pressures are found. Side B results in higher mean differential pressure coefficients with increasing gap width. Since a wider gap leads to better pressure equalization at opening 2, a higher cavity pressure is present. The external underpressure combined with the cavity overpressure results in higher differential pressures over the outer layer.

The mean peak coefficients (figure 9) are even harder to compare for the different gap widths. Higher gap widths result in higher standard deviations in the cavity near opening 3 and near opening 2 to lesser extent. These local effects disturb the mean peak differential pressure coefficients and a trend is no longer visible. Figures 8 and 9 show that a more distinguished gap width difference is necessary to determine the gap width effect.

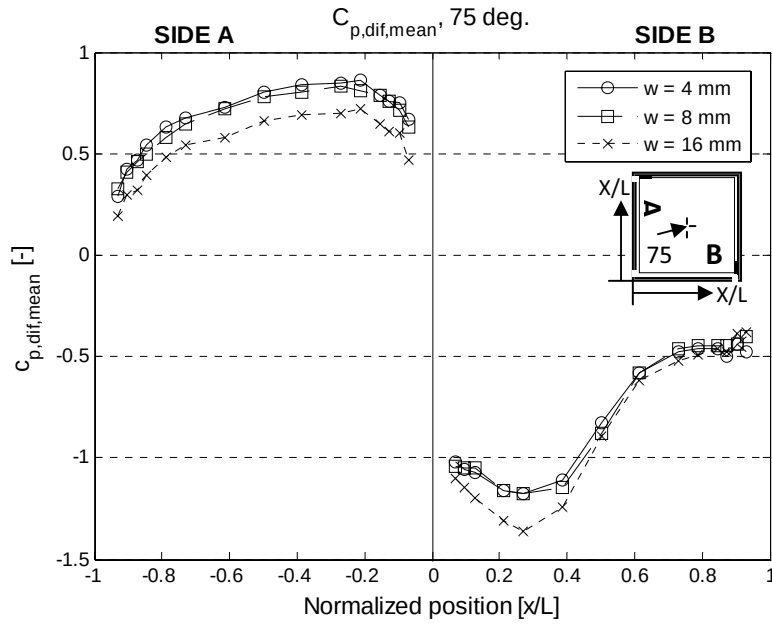


Figure 8: Mean pressure coefficient with varying gap width

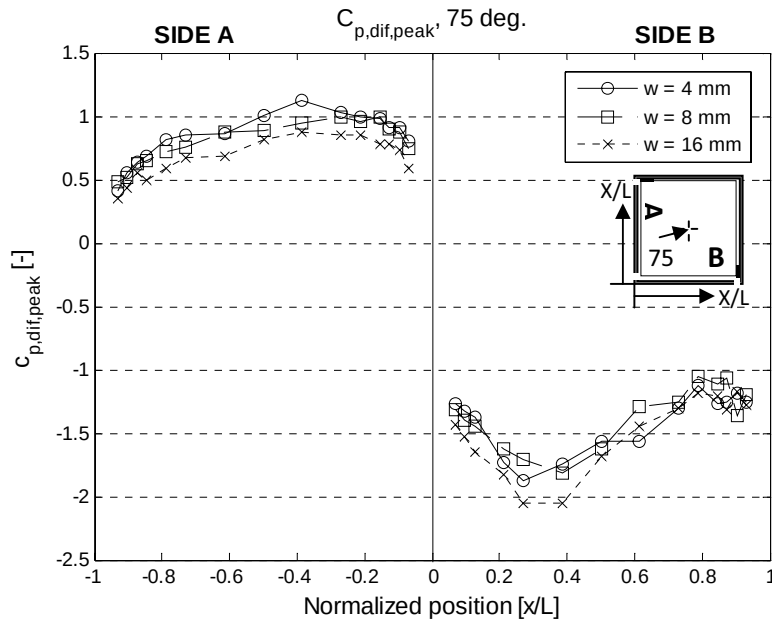


Figure 9: Mean peak pressure coefficient with varying gap width

3.1 Effect of cavity depth (C1F, C1A, C1G)

Again, three series of measurements have been conducted to investigate the effect of the cavity depth on the pressure distributions in the cavity. The cavity depth was varied between 10, 20 and 40 mm. Results are presented for the 75 degrees flow direction, that gave the highest differential

pressures for the reference case (with the 20 mm cavity depth). Unfortunately, also in this study the differences in cavity depth seem not distinguished enough to show clear effects. Brown et.al (1991) conclude that smaller cavity volumes, and thus smaller cavity depths, enhance pressure equalization and will lead to the smallest differential pressures. The mean pressure coefficients on the windward side show this trend, but very little (see figure 10). Side B shows the opposite effect due to the opposite sign of the pressures (externally and in the cavity).

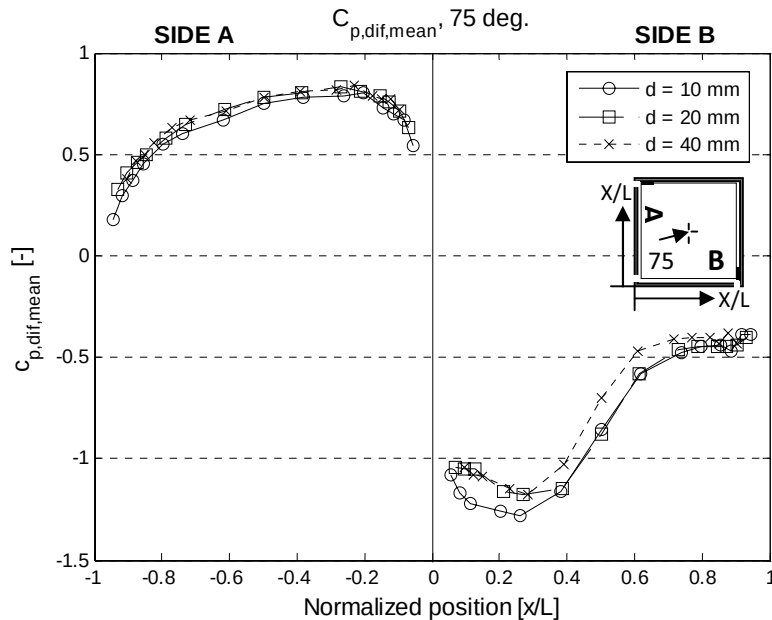


Figure 10: Peak pressure coefficient with varying cavity depth

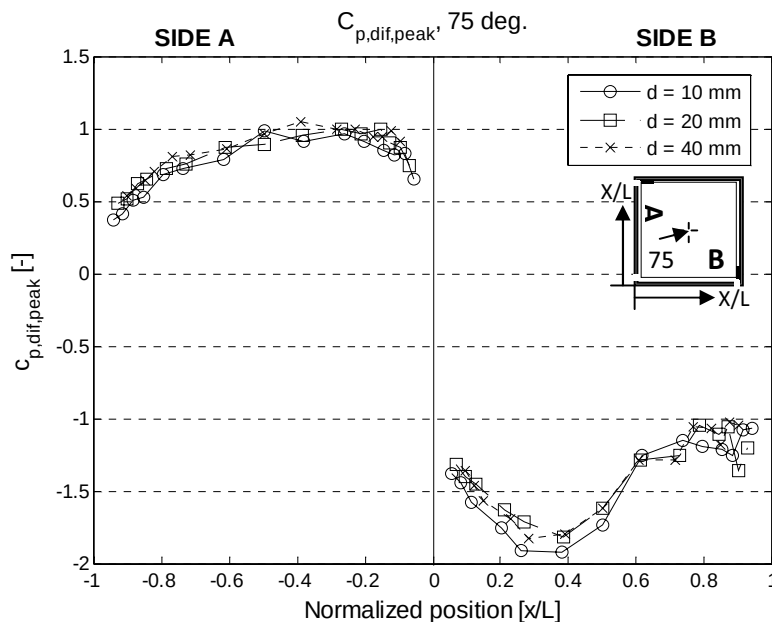


Figure 11: Peak pressure coefficient with varying cavity depth

The mean peak pressure coefficients show hardly any difference between the 3 cavity depths (figure 11). Like a large gap width a small cavity depth results in high standard deviations in the cavity near opening 3 and local effects disturb the flow pattern.

4 CONCLUSIONS

Measurements are performed on a cube with an airtight inner cube and an outside layer with open joints of 8 mm width and a cavity depth of 20 mm. These sizes correspond on a 1:1 scale to measures found in current practice. In smooth flow conditions a wind direction of 75 degrees with respect to the considered panel gives the highest differential pressures relevant for cladding. In general uniform cavity flows are found, with local effects at the openings in the reattachment zones. For unfavorable flow configurations, with overpressure in the cavity, the contribution of the cavity pressure to the total pressure difference is large. For the considered configurations between 1/3 and 1/2.

Large gaps and small cavity depths have a positive effect on pressure equalization. However the varied gap width and cavity depth in the current study are not distinguished enough to come up with final conclusions. It is possible that the measures for which the effects are clearly visible are outside the range of current practice. The tests in the next phase of this research should give an answer to that question.

Further research is ongoing, in which more configurations are being tested in turbulent flow conditions. Also upscaling to building level and validation with full scale measurements are part of the research program.

5 ACKNOWLEDGEMENTS

This research project is a collaboration of DHV, which took the initiative for the full scale measurements, Blitta, Centrum Natuursteen, Kenniscentrum Gevelbouw and TNO.

6 REFERENCES

- 1 Brown, W.C., M.Z. Rousseau, W.A. Dalgliesh, 1991. Field testing of pressure equalized rainscreen walls. Exterior Wall Symposium, Precast Concrete, Masonry and Stucco, 59-69.
- 2 Cheung, J.C.K., W.H. Melbourne, 1988. Wind loading on a porous roof, *Journal of Wind Engineering and Industrial Aerodynamics* 29, 19 – 28.
- 3 Gerhardt, H.J., F. Janser, 1994. Wind loads on permeable façades. *Journal of Wind Engineering and Industrial Aerodynamics* 53, 37 – 48.
- 4 Incullet, D.R., A.G. Davenport, 1994. Pressure equalized rainscreen: A study in the frequency domain. *Journal of Wind Engineering and Industrial Aerodynamics* 53, 63 – 87.
- 5 Schijndel, A.W.M. van, S.F.C Schols, 1998. Modeling pressure equalization in cavities. *Journal of Wind Engineering and Industrial Aerodynamics* 74-76, 641 – 649
- 6 Lee B.E., 1974, The effect of turbulence on the surface pressure field of a square prism, *J. Fluid Mech*, vol 69, part 2, 263-282
- 7 Baines, W.D, 1965. Effects of velocity distribution on wind loads and flow patterns on buildings. *Proceedings of Symp. 16, Wind effects on buildings and structures*, National Physical Laboratory England
- 8 Geurts, C.P.W., P.W. Bouma, A. Aghaei, 2005. Pressure equalization of brick masonry walls, in: *Proceedings of the 4th European-African Conference on Wind Engineering*, published on CD rom, Prague.
- 9 Geurts, C.P.W., 2000. Wind loads on permeable roof covering products, in: *Book of abstracts of the Fourth colloquium on bluff body aerodynamics and applications*, Ruhr Universität Bochum, 511-514.