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A 6 m cube in an atmospheric boundary layer flow Part 1. Full-scale and wind-tunnel results

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Abstract. Results of measurements of surface pressure and of velocity field made on a full-scale 6 m cube in natural wind are reported. Comparisons are made with results from boundary-layer wind-tunnel studies reported in the literature. Two flow angles are reported; flow normal to a face of the cube (the 0° case) and flow at 45°. In most comparisons, the spread of wind-tunnel results of pressure measurements spans the full-scale measurements. The exception to this is for the 0° case where the roof and side-wall pressures at full-scale are more negative, and as a result of this the leeward wall pressures are also lower. The cause of this difference is postulated to be a Reynolds Number scale effect that affects flow reattachment. Measurements of velocity in the vicinity of the cube have been used to define the mean reattachment point on the roof centre line for the 0° case, and the ground level reattachment point behind the cube for both 0° and 45° flow. Comparisons are reported with another full-scale experiment and also with wind-tunnel experiments that indicate a possible dependency on turbulence levels in the approach flow.

Key words: full-scale; wind; pressure; velocity; cube; wind-tunnel.

1. Introduction

At the initial stage of organising CWE2000, there was discussion on the standing of computational methods applied to problems in wind engineering. To assess progress, a test case was proposed with boundary conditions closely defined. Solutions were sought from the computational wind engineering community by creating an element of competition and offering anonymity, if requested. It was also the intention to use standard packages and published results to assist in the assessment.

The test case selected was a cube: Silsoe Research Institute had constructed a 6 m cube as part of an experimental programme on ventilation and dispersion which included surface pressure and velocity measurements. The example of the cube is also widely used in wind-tunnel studies with results available in the literature.

Part 1 of this two-part paper presents the results from full-scale and wind-tunnel measurements, whilst Part 2 presents comparisons with the computed solutions.

The objective was an attempt to answer two questions : -

What confidence can be placed on computational solutions?

Is a computational solution as reliable as a wind-tunnel experiment?

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2. The test case

The test case was the full-scale 6 m cube constructed in a relatively open field site at Silsoe. The approach fetch was cut grass extending some 600 m upstream over flat ground. The mean velocity profile was found to follow a log-law with a derived roughness length of 6 to 10 mm. Further upstream there was a village of predominately two storey buildings that may be responsible for increasing the turbulence levels at the experimental site. There are a number of buildings on the site that may create interference although these effects have been minimised by selecting appropriate wind directions for data collection.

3. Full-scale measurements

The cube is shown in Fig. 1. It is mounted on an internal turntable enabling it to be rotated through 360^{o} to suit the prevailing wind direction. The site plan, Fig. 2, shows the presence of other buildings on the site and their plan dimensions. The Silsoe Structures Building has a ridge height of 5.3 m whilst the slurry tanks are 2.4 m high. To minimise interference effects from surrounding buildings and also to reject flow of higher turbulence caused by rougher fetch, the acceptance angle for wind direction was limited to $-15^{o} < \theta < 5^{o}$.

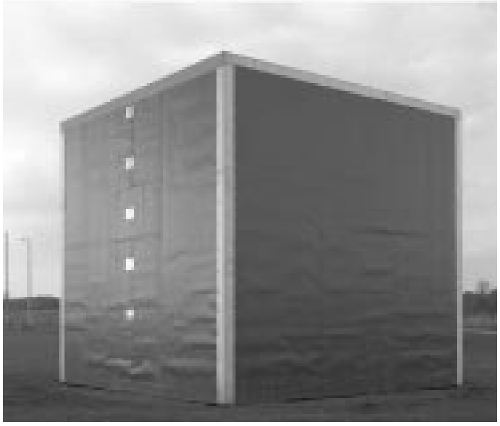


Fig. 1 The 6 m cube at Silsoe 1

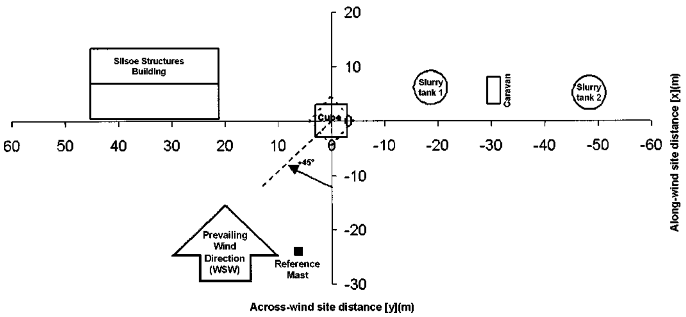


Fig. 2 Site plan

3.1. Wind structure

For a limited period only, simultaneous measurements were made using four 3-component sonic anemometers to define the approach flow at heights of 1, 3, 6 and 10 m. A summary of the results is presented in Table 1; full details will be published elsewhere. The representative Jensen Number (h / z_0) was 750.

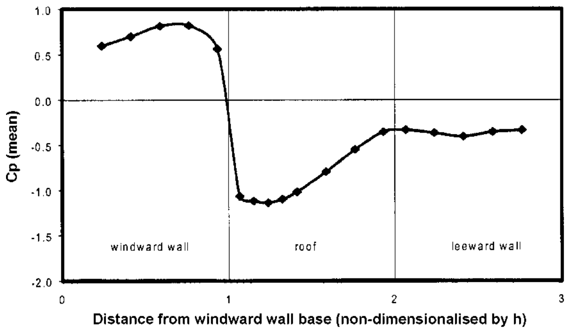
Throughout the experiment, wind velocity was measured upstream of the cube at a height of 6 m, and this was used for non-dimensionalising the results. Also at this upstream position, a static pressure probe (Moran and Hoxey 1979) was mounted to provide the backing pressure for all pressure measurements.

3.2. Surface pressure

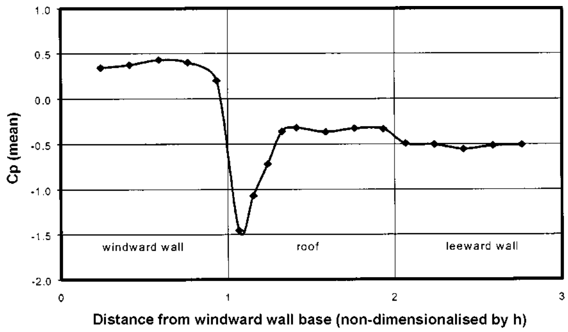
Tapping points of 9 mm internal diameter were installed in the cube on a vertical centreline cross-section (16 tappings), on a horizontal mid-height cross-section (16 tappings) and at additional points on one quadrant of the roof (27 tappings). Simultaneous measurements were made from 32 tapping points at a time. Pressures were recorded for periods of 30 minutes at a data collection frequency of 4 samples/s. Subsequent analysis included mean and rms coefficients calculated for 10 min periods. Mean pressure coefficients for the vertical centreline are shown in Fig. 3, and for the horizontal section in Fig. 4. Figs. 3a and 4a are for the 0° case, while Figs. 3b and 4b are for the 45° case. The pressure distributions on the roof are illustrated in the contour plots in Fig. 5.

Table 1 Properties of the approach flow

z (m)	U (m/s)	Iu	Iv	Iw	uw (m/s)^2
1	6.97	0.243	0.196	0.077	-0.281
3	8.65	0.208	0.166	0.072	-0.270
6	9.52	0.193	0.150	0.078	-0.251
10	10.13	0.186	0.151	0.083	-0.343

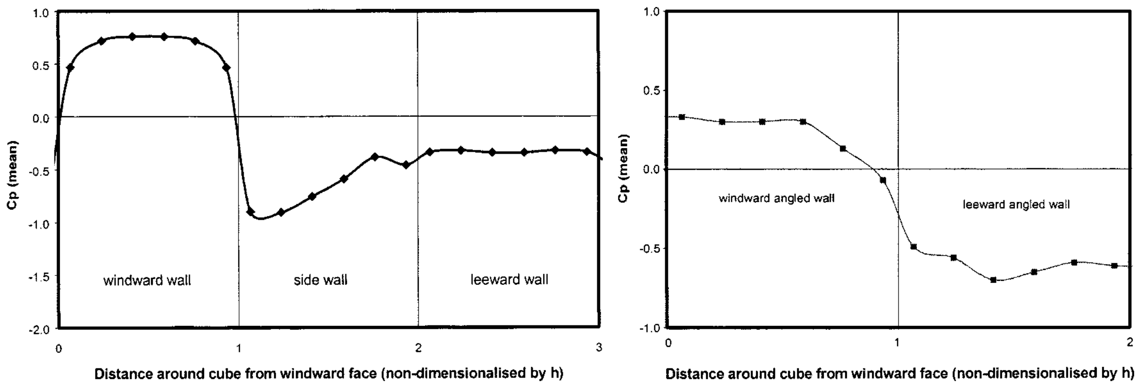


(a)



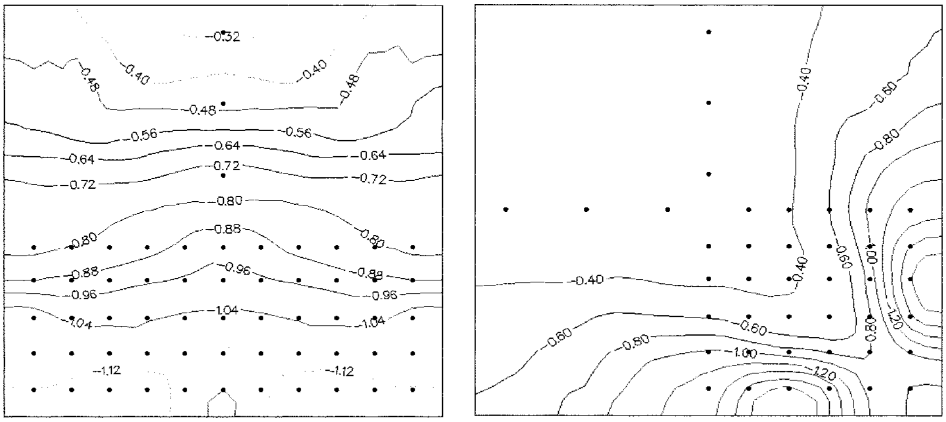
(b)

Fig. 3 (a) Pressure distribution around a vertical centreline for 0° wind angle (b) Pressure distribution around a vertical centreline for 45° wind angle



(a) (b)

Fig. 4 (a) Pressure distribution at mid height for 0° wind angle (b) Pressure distribution at mid height for 45° wind angle



(a) (b)

Fig. 5 (a) Pressure distribution on the roof for, 0° wind angle (b) Pressure distribution on the roof for, 45° wind angle

3.3. Velocity field

Velocity measurements were made at specified points around and over the cube using four sonic anemometers. Measurements from the four sonic anemometers were recorded at 10 samples/s and these were synchronised with measurements from the reference sonic anemometer which were used for non-dimensionalising. Some preliminary results are presented in Fig. 6 for the 0° case in a plane through the centre of the cube.

3.4. Flow characteristics

In one study, the four sonic anemometers were positioned on the roof centreline, sensing velocities at 60 mm (0.01 *h*) above the surface, in order to define the mean reattachment point. The mean

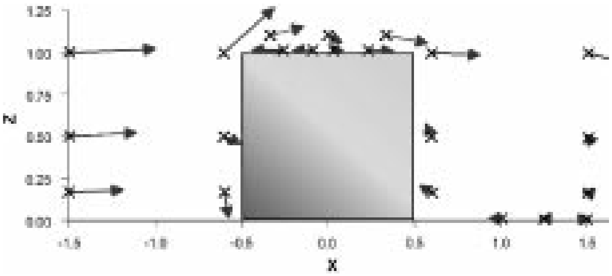


Fig. 6 Flow vectors measured on the cube centre plane $y = 0$ (co-ordinates non-dimensionalised by h)

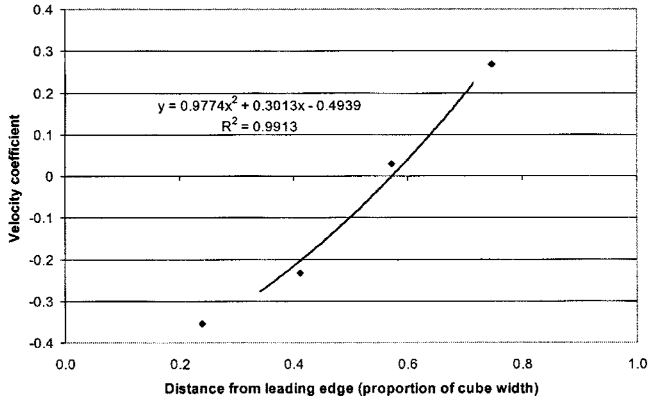
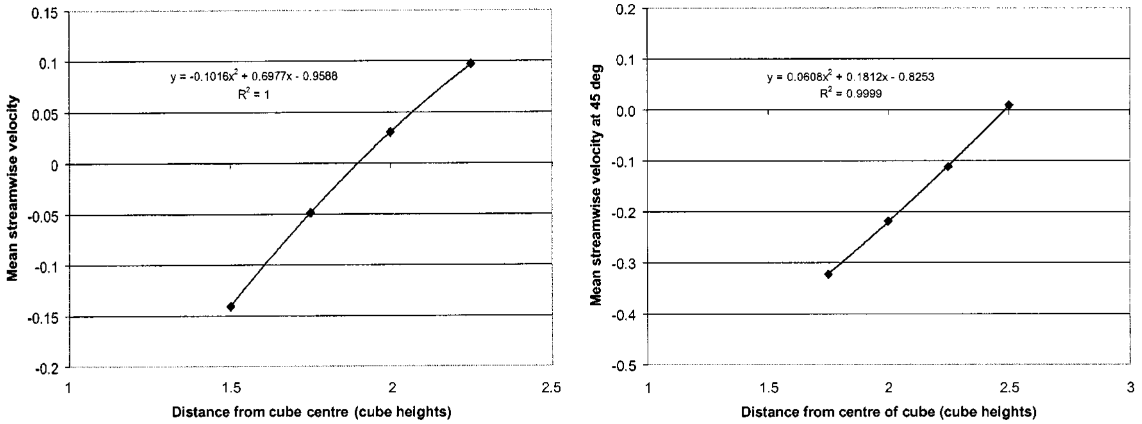


Fig. 7 Streamwise mean velocity close to the roof surface for 0° wind angle



(a) (b)

Fig. 8 (a) Streamwise mean velocity close to the ground behind the cube for 0° wind angle. (b) Streamwise mean velocity close to the ground behind the cube for 45° wind angle

streamwise velocity ratios from these anemometers are shown in Fig. 7 for the 0° case, from where it can be deduced that the condition $\bar{u} = 0$ at 0.01 h above the surface (i.e., reattachment) occurs at 0.57 h from the leading edge (wind normal to cube face).

A similar method was used to deduce the wake reattachment point at near-ground level (z = 0.01 h) behind the cube. The mean velocity ratios are shown in Fig. 8a and the condition where $\overline{u}$ = 0 is 1.9 h behind the cube centre for wind normal to the cube face (1.4 h behind the cube). This study was repeated for the 45° wind direction case, producing the results shown in Fig. 8b. In this case the mean reattachment was 2.5 h behind the cube centre.

4. Wind-tunnel results

A survey of the literature has identified a number of wind-tunnel studies that have been included in this comparison; the details of these studies are summarised in Table 2. The information presented here has been derived from the publications only, and in some cases important details are not given; also many of the data points are reproduced from information presented in figures in the original publication and so are not the source numerical data. In this respect, some interpretations of the original data have had to be made, which may not result in a true representation of the original measurements. It should also be noted that the results of Stathopoulos and Dumitrescu-Brulotte (1989) are for a building with a square base and height 0.90 of base dimension i.e., not a cube.

Results of this comparison are presented in Figs. 9 and 10 for wind normal to the cube face, and in Figs. 11 and 12 for the smaller data set relating to flow at 45°.

5. Discussion

5.1. Windward wall, 0° wind

The wind-tunnel results for the pressure distribution on the windward wall (Fig. 9a) all show the same pattern and the differences are within 0.15 in Cp. The differences tend to be systematic and possibly relate to differences in the boundary-layer simulation, although the sensitivity to simulation

Table 2 Characteristics of the full-scale and wind-tunnel tests

	Re No.	Comment	Size m	Scale	Power	h / z_0	$Iu(h)$
Silsoe	4.1×10^6		6	1:1		750	0.21
Baines	3×10^4				0.25		
Castro & Robins	10^5		60	1:300		50	0.27
Sakamoto & Arie	8×10^4	thin BL $h / \delta = 0.99$				$\sim 10^5$	
Stathopoulos & Dumitrescu-Brulotte	10^5	Not a cube $61\times 61\times 55$	55	1:400	0.15	1830	0.08
Hunt 100, 360	2×10^5		36	1:180		60	0.23
Murakami & Mochida	7×10^4				0.25	170	0.165
Ogawa, Oikawa & Uehara	3.5×10^5	Full-scale	1.8	1:1		480	0.22
Ogawa, Oikawa & Uehara (R0)	3.5×10^4	Wind tunnel no roughness	1.8	1:22.5		10500	0.067
Ogawa, Oikawa & Uehara (R6)	1.9×10^4	Wind tunnel 6 cm roughness	1.8	1:22.5		106	0.265
Minson, Wood & Belcher	6.3×10^4	LDA measurements	15	1:7.5		60	0.3
Anwer & Logan	5×10^3						0.11
Steggel & Castro						100	
Hölscher & Niemann	2×10^4 3×10^5	Average of 15 laboratories	50	1:1000 -1:167	0.22	250	0.1-0.3

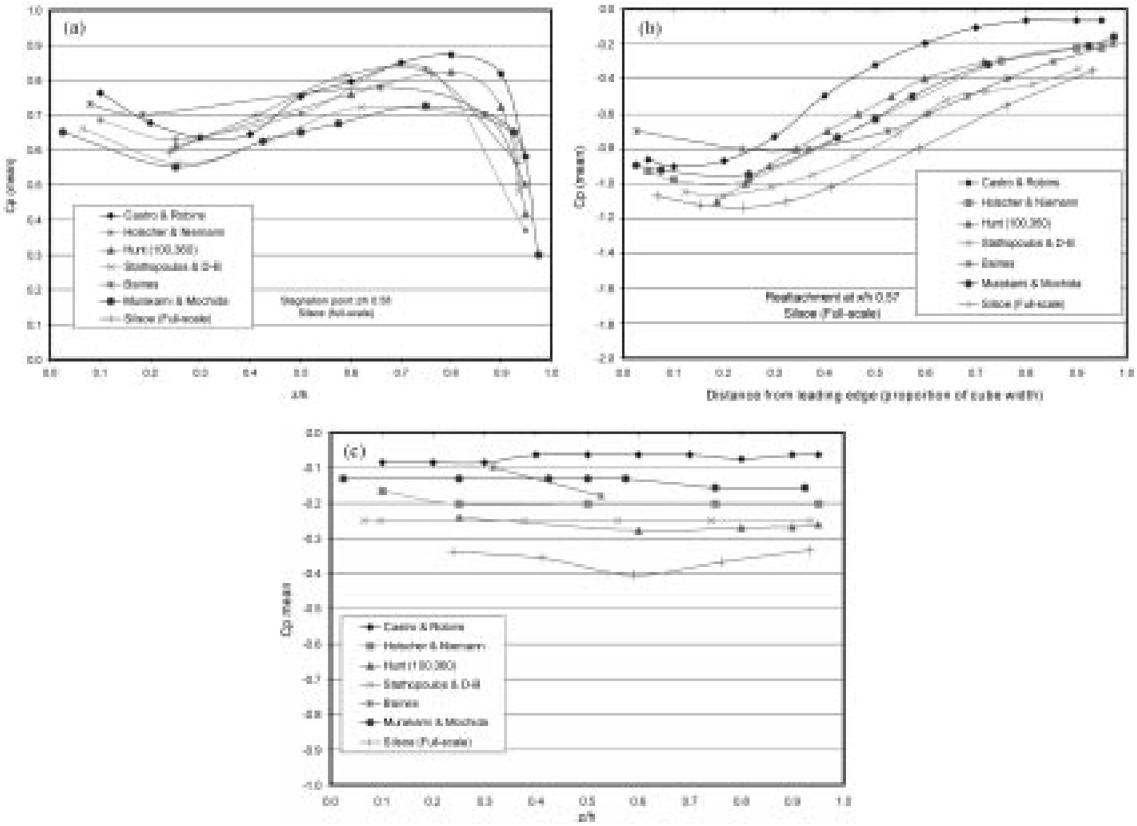


Fig. 9 (a) Pressure distribution on the windward face for 0^{o} wind angle (b) Pressure distribution on the roof for 0^{o} wind angle (c) Pressure distribution on the leeward wall for 0^{o} wind angle

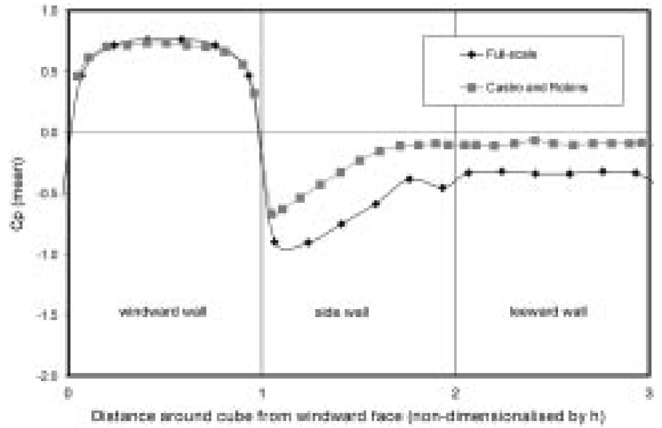


Fig. 10 Pressure distribution at mid height for 0^{o} wind angle

appears to be small. All the wind-tunnel results relate to cubes that are significantly larger in equivalent full-scale dimension (typically 50 m) than the full-scale comparison made here. The full-

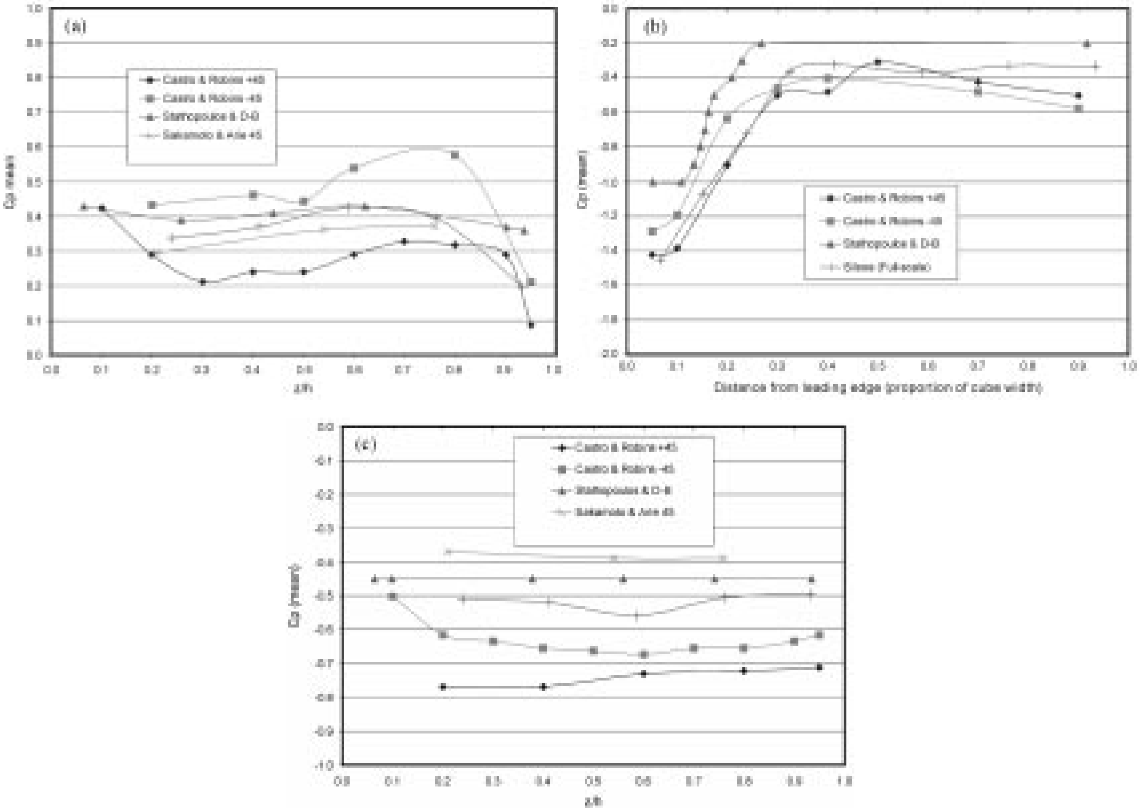


Fig. 11 (a) Pressure distribution on the windward wall for 45° wind angle (b) Pressure distribution on the roof for 45° wind angle (c) Pressure distribution on the leeward wall for 45° wind angle

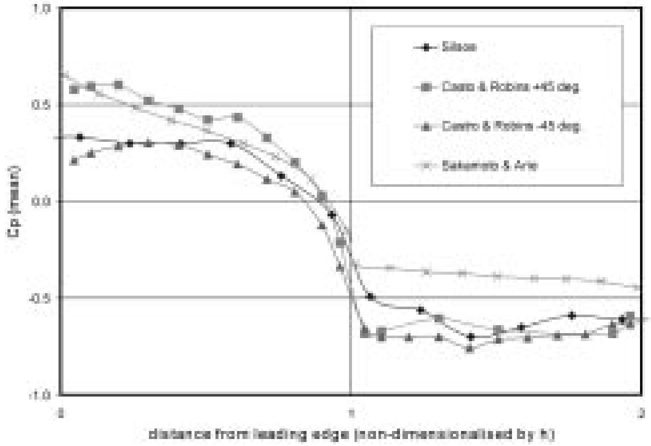


Fig. 12 Pressure distribution at mid height for 45° wind angel

scale results generally fall within the span of wind-tunnel measurements, with only a small excursion near the stagnation point. This may indicate a lower stagnation point at full-scale which may be scale related. Overall, the mean of the wind-tunnel results are in close agreement with the full-scale measurements over the windward wall.

5.2. Roof, 0^o wind

Within the region $0 < x/h < 0.1$, the wind-tunnel results agree to within 0.1 in *Cp*, with the exception of those from Baines (1963) (Fig. 9b). However, beyond $x/h = 0.1$, systematic differences occur yielding differences between wind tunnels of up to 0.5 in *Cp*. The full-scale coefficients are more negative than any of the wind-tunnel results, and a possible explanation is offered later in this paper relating to scale effects. The wind-tunnel studies, which provide pressure data, do not quantify the reattachment point on the roof. Castro and Robins (1977) do recognise there is evidence of reattachment, but Stathopoulos and Dumitrescu-Brulotte (1989) state 'there is no sign of flow reattachment'. The evidence from velocity measurements made 0.06 m above the surface of the 6 m cube show a mean reattachment point at 0.57 *h* from the leading edge. This point (defined as the point where local streamwise mean velocity = 0) varies with time, and can reach the extremes of the leading and trailing edges.

5.3. Leeward wall, 0^o wind

All the measurements show a near constant pressure on the leeward wall with the wind tunnels showing a spread of 0.2 in *Cp* and a mean value of -0.17 (Fig. 9c). The full-scale results give a mean of -0.37, a difference of 0.2 which may be a follow-on effect of the lower pressures on the roof.

5.4. Side wall, 0^o wind

The only set of wind-tunnel results for a horizontal section at mid height in the cited references are those measured by Castro and Robins (1977). These are compared with the full-scale results in Fig. 10. The pressure distribution comparison may be described similarly to that over the cube: good agreement on the windward face, but thereafter the full-scale results show a more negative pressure field, again possibly related to a scale effect associated with flow separation and reattachment. At the present time it is not clear whether flow reattaches on the side of the cube at mid height, although there are some indications that it does not reattach at the mid height of the cube.

5.5. 45^o wind direction

The 45^o wind direction produces more spread in the wind-tunnel results, although there are fewer measurements for comparison (Fig. 11 for the vertical centreline and Fig. 12 for the horizontal centreline). Castro and Robins (1977) commented on this in relation to their own experiments stating that 'the actual stagnation point was switching intermittently from one side to the other and on average the flow clearly preferred one of two states'. They present two cases for a $+45^o$ and a -45^o flow which are shown in Figs. 11 and 12, and as can be seen, these span nearly all the other measurements on the windward wall (Fig. 11a and 12). This intermittence does not appear to influence the pressures on the roof (Fig. 11b), or the leeward wall (Figs. 11c and 12).

The full-scale pressures for the 45^o flow direction fit comfortably within the span of wind-tunnel measurements and are close to the mean of the wind-tunnel results. There is no significant difference in the region of the roof edge vortex (Fig. 10b), and the comments below on scale effects appear not to apply in this region.

5.6. Flow separation, stagnation and reattachment

A summary of estimated and measured positions of upstream separation, windward wall stagnation, roof reattachment and downstream wake reattachment are listed in Table 3 for the 0^{o} flow direction. Wind-tunnel measurements by Ogawa *et al*. (1983) identify the significance of approach flow turbulence on roof reattachment. In a flow with low turbulence (Iu of 6%) they found no reattachment, whereas in a highly turbulent flow (Iu of 27%) there was no separation. The possibility of the 6 m cube full-scale measurements being affected by changes in turbulence level was investigated. This showed there to be no significant change in turbulence intensity with respect to wind speed for flow from a given direction and hence is unlikely to influence roof reattachment.

The down-stream wake reattachment for the 45^{o} flow direction is listed in Table 4. This shows an increased reattachment length of the order of 0.5 h. compared with that for the 0^{o} wind direction.

5.7. Reference static pressure

The reference static pressure used in the definition of pressure coefficient can be a key source of uncertainty. Each wind tunnel has its preferred source for the reference pressure, such as a pitot-

Table 3 Mean separation and reattachment lengths in units of height h for the 0^{o} case

	Upstream separation	Windward wall stagnation	Roof reattachment	Down-stream reattachment (from cube centre)
Silsoe (Full-scale)	0.75(est)	0.58	0.57	1.9
Ogawa *et al.* (Full scale)			0.55	2.4
Ogawa *et al.* (R0)			No reattachment	2.0
Ogawa *et al.* (R6)			No separation	1.7
Minson *et al.*		0.57	≈ 0.4	
Anwer & Logan				1.8
Murakami & Mochida			≈ 0.7	1.7

Table 4 Down-stream reattachment length in units of height h for the 45^{o} case

	Comment	Down-stream reattachment (from cube centre)
Silsoe (Fullscale)		2.5
Ogawa *et al.* (Full scale)		2.75
Ogawa *et al.* (R0)		2.7
Ogawa *et al.* (R6)		1.9
Steggel & Castro	Measured at $z / h = 0.5$	1.75

static probe or tunnel wall tap. The full-scale work used a static probe mounted upstream at $z = h$. Before use, the probe was calibrated against a tapping set flush in level ground. The results presented here appear to confirm that reference static pressure is comparable between full scale and the wind tunnels: no systematic differences have been observed.

5.8. Scale effects

There is an observable difference in pressure coefficients between the average of a number of wind-tunnel results and the full-scale results on the roof of the cube for the 0^o case (Fig. 9b), and on the side wall (Fig. 10). More detailed analysis of the full-scale data for the roof has shown a statistically significant variation of *Cp* with wind speed, and also a variation of mean reattachment point on the roof with wind speed. The trend was for the *Cp* to decrease (become more negative) and the reattachment point to move into wind with increasing wind speed. The wind tunnel *Cp* results being less negative is indicative of a Reynolds number effect, although: there is only scant evidence of delayed flow reattachment from the wind-tunnel studies. More detailed evidence is needed to substantiate this observation. A similar analysis of the pressures on the side wall does not show a trend with wind speed, which suggests that the flow does not reattach at cube mid height.

Since the effect of wind speed on *Cp* was significant on the roof of the cube in full scale measurements, the coefficients presented here have been derived for a wind speed of 10 m/s which equates to a Reynolds number of 4.1×10^6.

5.9. Vortex shedding

The spectra of surface pressure on the leeward wall, and of the transverse velocity in the wake showed small amplitude vortex shedding for the 0^0 case. The measurements were made with a mean reference velocity of 6.8 m/s and the vortex shedding frequency was 0.154 Hz, giving a Strouhal number (nh/U) of 0.14. It is emphasised that this was only relatively weak vortex shedding but it was sufficient to be readily detectable in wake flow velocity measurements.

6. Conclusions

Pressure distributions for a full-scale 6 m cube in an atmospheric boundary layer have been presented. These show generally good agreement with several wind-tunnel measurements reported in the literature. The exception to this is for the case where the wind is normal to a face when the full-scale measurements show larger suctions over the roof, leeward wall and side walls.

Full-scale velocity measurements have been made around the cube to describe the flow pattern, from which it has been possible to interpolate the mean reattachment points on the roof and on the ground in the wake flow.

There is some statistically significant evidence of a Reynolds number effect from the full-scale measurements in relation to both roof pressures and mean reattachment points. Most of the wind-tunnel pressure measurements provide further supporting evidence of a Reynolds number effect consistent with the pattern suggested from the full-scale but this is far from being conclusive.

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