EFFECTS OF WIND TUNNEL BLOCKAGE ON STREAMWISE SURFACE PRESSURES

P.J. Saathoff and W.H. Melbourne*

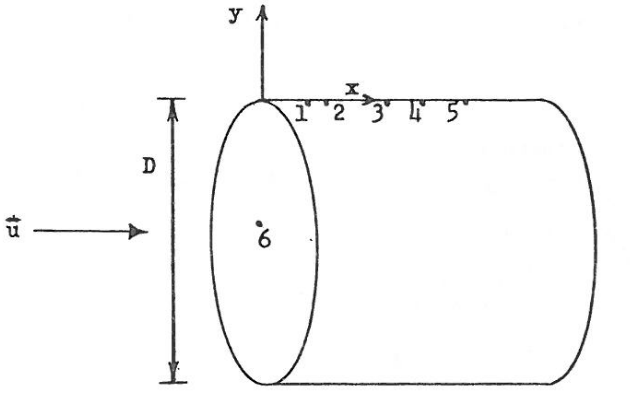
Introduction

Studies of wind tunnel blockage effects have generally concentrated on obtaining corrections to bluff body drag (i.e. front face and base pressure) measurements. Little work has been published concerning effects of wall constraint on streamwise pressure measurements. As a result, these effects are usually ignored even at relatively high blockage ratios. (Blockage ratio is the ratio of effective model area, S, to tunnel cross-sectional area, C.) Some researchers [1 and 2] have attempted to remove blockage effects by altering the tunnel test section in some way. However, the effectiveness of these measures is open to question.

Awbi [3], from a study using two-dimensional rectangular cylinders in smooth flow, has shown that increasing the blockage ratio can lead to early reattachment of separated shear layers depending on the streamwise depth of the model. Hunt's [2] measurements on cubical building models in boundary layer flows indicated that for a relatively high blockage (S/C = 8%) fluctuating pressure coefficients, $C\sigma_p$, may be as much as 10% too large.

Experimental Procedure

Mean, fluctuating and peak pressures were measured on the streamwise surfaces of five axisymmetric cylinders with aspect ratio (L/D) of 1.0, where L is the streamwise depth and D is the cylinder diameter. Cylinder diameters ranged from 36 to 255 mm. Locations of pressure tappings are shown in Figure 1.



Pressure Tapping	Distance from Leading Edge (x/D)
1	0.09
2	0.19
3	0.39
4	0.59
5	0.78

Figure 1. Locations of pressure tappings

Experiments were performed in the 2 m x 2 m section of the 450 kW wind tunnel and in the 0.9 x 1.2 m 35 kW tunnel in the Department of Mechanical Engineering, Monash University. Blockage ratios ranged from 0.025% to 1.3% and 0.9% to 4.6% in the large and small tunnels, respectively. Most experiments were performed in grid-generated turbulence at a value of turbulence intensity $(\sigma_u/\bar{u})$ of approximately 8%. Measurements were also obtained in smooth flow in the small tunnel. Turbulence parameters associated with each tunnel configuration are given in Table 1.

* Department of Mechanical Engineering, Monash University

Table 1. Wind Tunnel Configurations

Tunnel	Grid	Bar width (mm)	Downstream distance (m)	Turbulence Intensity $\sigma_u/\bar{u}$	Integral Scale L_x(m)	Range of L_x/D
450 kW 2 m x 2 m	A	35	2.0	8.0	0.08	0.3 - 2.1
	B	100	5.0	8.0	0.20	0.8 - 5.7
	C	303	11.7	8.3	0.55	2.2 - 15.3
30 kW 0.9mx1.2m	D	37	1.5	8.2	0.07	0.3 - 1.9
	E	70	3.0	8.2	0.13	0.5 - 3.7
	Smooth Flow			0.7		

A SETRA Model 237 pressure transducer was used to measure mean, fluctuating and peak pressures. The reference static pressure was obtained with a pitot-static tube upstream of the cylinder. Static pressure was measured at the cylinder location to determine the correction factor and this factor was slightly adjusted to give $C_{\bar{p}}$ of 1.0 at the stagnation point (Tapping 6). A restrictor was used in the plastic tube connecting the transducer to the pressure tappings, providing a flat frequency response (±15%) up to 70 Hz and 100 Hz for the largest and smallest cylinders, respectively.

The experimental setup is shown in Figure 2. An additional pressure tapping was placed on the bottom surface of each cylinder at x/D = 0.09. The orientation of the cylinder was adjusted so that the difference in $C_{\bar{p}}$ on the top and bottom surfaces was less than 2%, so that approximately axisymmetric flow was ensured.

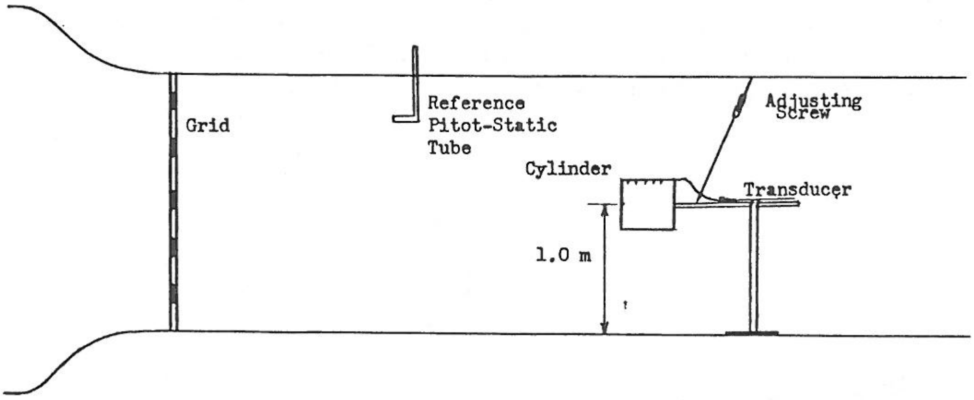


Figure 2. Experimental Configuration (not to scale)

Results

Space limitations permit only a small portion of the results to be discussed here. Figure 3 shows mean pressure coefficient at Tapping No.1 (x/D = 0.09) as a function of S/C for five flows having approximately the same turbulence intensity. For comparison, results obtained in smooth flow are also presented. The five flows at $\sigma_u/\bar{u}$ = 8% encompass a wide range of turbulence scales. However, as noted previously [4], little effect of scale is evident.

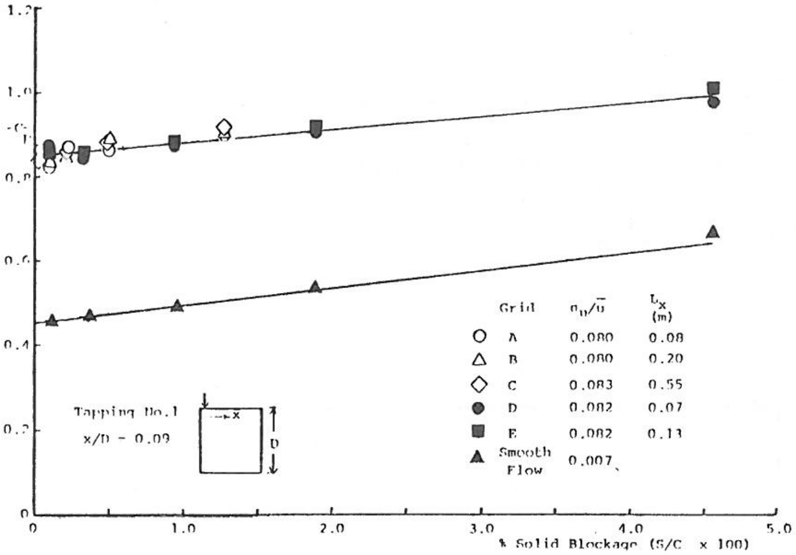


Figure 3. Mean pressure coefficient at Tapping No.1 as a function of wind tunnel blockage

The slopes of the blockage curves are approximately 3.0 and 4.0 for the turbulent and smooth flow cases, respectively. Flow reattachment did not occur in smooth flow, therefore blockage corrections are larger in this case. In the turbulent flow an increase in S/C from 0 to 4.6% increases $|C_{\bar{p}}|$ by approximately 15%. In coefficient form:

$$C_{\bar{p}_c} = C_{\bar{p}_m} + 3.0\,(S/C) \qquad (1)$$

where subscript c indicates the corrected value and subscript m indicates the measured value. Although Equ.(1) is applicable only at Tapping No.1, it is expected that at different $\sigma_u/\bar{u}$ the slope of the blockage curve would be the same, providing reattachment occurs.

Blockage corrections to fluctuataing pressures are complicated by the fact that C_{σ_p} is dependent on relative scale, L_x/D where L_x is the longitudinal integral scale of the turbulence. Figure 4 shows C_{σ_p} measured at Tapping No.1 as a function of S/C for five different flows with $\sigma_u/\bar{u} \approx 8\%$. Corresponding values of L_x/D are shown next to each data point.

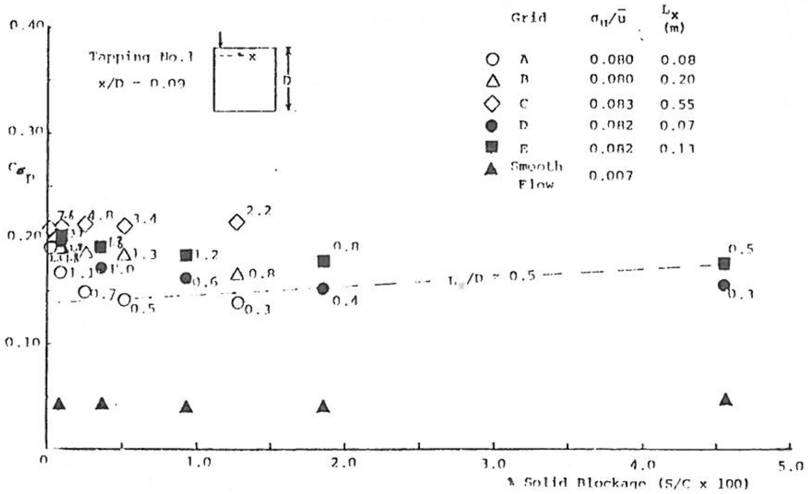


Figure 4. Fluctuating pressure coefficient at Tapping No.1 as a function of wind tunnel blockage and relative scale (L_x/D)

Although it is not possible to accurately determine the effect of S/C on $C\sigma_p$ especially at large L_x/D, it is clear that an increase in blockage produces an increase in $C\sigma_p$. For $L_x/D \approx 0.5$, an increase in S/C from 0 - 4.6% increases $C\sigma_p$ by approximately 20%. For this case:

$$C_{\sigma_{p_c}} = C_{\sigma_{p_m}} - 0.7\ (S/C) \qquad (2)$$

Considerable scatter is associated with peak pressure measurements. Therefore, blockage corrections cannot be directly obtained from the data. However, the significance of blockage effects on the peak pressure coefficient, $C_{\check{p}}$, can be inferred from the mean and fluctuating pressure data. The peak pressure coefficient can be obtained from the following:

$$C_{\check{p}} = C_{\bar{p}} - g\,C_{\sigma_p} \qquad (3)$$

where g is the peak factor.

For a normal distribution, the peak factor associated with a probability level of 10^{-4} is approximately 4.3. At high turbulence intensities, fluctuating pressures near separation are negatively skewed and peak factors of 10 are not uncommon.

The effect of wind tunnel blockage on $C_{\check{p}}$ can be estimated using Equ.(3). Assuming a peak factor of 6.0, S/C = 4.6% and $L_x/D = 0.5$, the uncorrected peak pressure coefficeint is:

$$C_{\check{p}} = -0.98 - 6.0(0.170) \approx -2.0$$

Substituting $C_{\bar{p}_c}$ and $C_{\sigma_{p_c}}$ into (3) the blockage corrected peak pressure coefficient is:

$$C_{\check{p}_c} = -0.85 - 6.0(0.140) \approx -1.7$$

Thus, a value of S/C of approximately 5% increases $|C_{\check{p}}|$ by approximately 15%.

Conclusions

Data obtained using axisymmetric cylinders suggest that a blockage ratio of 5% increases $|C_{\bar{p}}|$, C_{σ_p}, $|C_{\check{p}}|$ by approximately 15%. Although only data near separation was presented, corrections to other streamwise pressures will likely be of the same order of magnitude.

References

1. M. Kiya and K. Sasaki, 'Free-stream Turbulence Effects on a Separation Bubble", Jnl. Wind Eng. and Industrial Aerodynamics, 14, 375-386, 1983.

2. A. Hunt, 'Wind-Tunnel Measurements of Surface Pressures on Cubic Building Models at Several Scales', Jnl. Wind Eng. and Industrial Aerodynamics, 10, 137-163, 1982.

3. H.B. Awbi, 'Wind Tunnel Wall Constraint on Two-Dimensional Rectangular Section Prisms', Jnl. Wind Eng. and Industrial Aerodynamics, 3, 285-306, 1978.

4. R. Hillier and N.J. Cherry, 'The Effects of Stream Turbulence on Separation Bubbles', Jnl. Wind Eng. and Industrial Aerodynamics, 8, 49-58, 1981.