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The effects of turbulence on the mean flow past square rods

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There are two main effects of turbulence on the mean flow past rods of square cross-section aligned with the approaching flow. Small-scale turbulence increases the growth rate of the shear layer, while large-scale turbulence enhances the roll-up of the shear layer. The consequences of these depend on the length of a square rod. The mean base pressure of a square rod varies considerably with turbulence intensity and scale as well as with its length.

1. Introduction

The flow in the Earth's boundary layer is highly turbulent, and this can significantly influence the wind loads experienced by buildings and structures. Apart from unsteady buffeting loads induced directly by the approaching turbulence, there is a complex interaction between the turbulence and the flow past such bluff structures which leads to changes in the mean and unsteady wind loads.

The classical examples of the effect of the freestream turbulence on bluff-body mean flow are those on drags of bluff bodies with smooth surface separation such as a circular cylinder and a sphere. It is shown (Fage & Warsap 1929) that the addition of turbulence causes the drag of a circular cylinder to decrease critically at a lower Reynolds number than in smooth flow through earlier transition of the boundary layer. According to Bearman (1968), the critical Reynolds number for a circular cylinder depends on the Taylor parameter $(u'/U)\ (D/L_y)^{\frac{1}{5}}$, where U is the mean speed of the approaching flow, u' the r.m.s. value of the longitudinal component of turbulence, L_y the lateral scale and D the cylinder diameter.

On the other hand, it is now well known that turbulence can also influence significantly the drags of bluff bodies with sharp-edged separation for which the shear layers are fully turbulent at moderate Reynolds numbers. For example, turbulence increases the drag of a square plate with its flat face normal to the flow while it decreases that of a square cylinder. It is generally argued (Bearman 1978) that the main effect of turbulence in these cases is to increase the growth rate of the shear layer. The consequences of this increased growth rate depend upon the shape of the afterbody, the part of a bluff body downstream of the separation point. That is, turbulence increases the drag of a bluff body with a short afterbody while it reduces that of a bluff body with a long afterbody, eventually leading to earlier reattachment of the shear layers.

Notwithstanding this broad understanding of the interaction between turbulence and the near wake of a bluff body, information we have on this problem is still far from complete and no clear picture has so far emerged of the sensitivities of turbulence intensity and scale. What is most puzzling is that previous work has indicated very little or no effect of turbulence scale on the drags of sharp-edged bluff bodies despite significant effect of turbulence intensity. This is true with two-dimensional bluff bodies such as rectangular cylinders (Bearman 1972; Laneville, Gartshore & Parkinson 1975; Nakamura & Tomonari 1976; Petty 1979; Laneville & Williams 1979) and also with a cube, one of the most typical three-dimensional bluff bodies (Roberson *et al.* 1972; Bearman 1980). The only exception where there is significant effect of turbulence scale is square and circular plates with their flat face normal to the flow. Bearman (1971) reported that the mean base pressure of square and circular plates decreased as $(u'/U)\ (L_x/h)^2$ increased, where L_x is the longitudinal scale of turbulence and h is the size of a plate. On the other hand, Humphries & Vincent (1976) claimed that it was not controlled by $(u'/U)\ (L_x/h)^2$ but by a different parameter $(u'/U)\ (L_x/h)$. A correct similarity parameter controlling the plate flow has not yet been established.

The present investigation is a first step towards finding a way to the solution of the puzzling problem just described. A wind-tunnel measurement was made on square rods with different lengths with their square face normal to the flow to investigate the effects of turbulence intensity and scale on the mean-flow characteristics. In the experiment square rods of various sizes were mounted at different locations downstream of a turbulence-producing grid. A wide range of L_x/h covering from about 0.08 to 14 along with turbulence intensity u'/U covering from 3.5 to 13 % was obtained, while the length-to-size ratio d/h of rods ranged from 0.1 to 2.0, where d is the length of a rod. The results in the present investigation suggest that considerable modifications need to be made to the traditional picture of the structure of the near wake of a three-dimensional sharp-edged bluff body. In particular, it is shown that the mean base pressure of a square rod can be varied considerably with turbulence intensity and scale as well as with the length of a rod.

2. Experimental arrangements

2.1. *Wind tunnel and turbulence-producing grid*

The experiments were conducted in a wind tunnel with a 4 m high by 2 m wide by 6 m long rectangular working section. The tunnel can provide a very uniform smooth flow with turbulence intensity of about 0.12 %. To create a nearly homogeneous isotropic turbulence field, two square-mesh biplanar grids of rectangular-section bars were used. They had $M = 60$ cm and $b = 15$ cm and $M = 13$ cm and $b = 2.5$ cm respectively, where M and b are the mesh and the bar size of a grid. These two grids are hereinafter referred to as the large and the small grid respectively. The working section of 6 m in length was too short for the experiment using the large grid to be made, so the diffuser was modified to extend the length of the working section by 6 m. The measurement of the three velocity components of turbulence was made with linearized constant-temperature hot-wire anemometers in combination with a data recorder and an A/D converter. The digitized data were analysed with an electronic computer to get the turbulence intensities and scale together with the power spectra.

2.2. *Models and measurement procedures*

The models used in this investigation were square rods with different lengths ranging from $d/h = 0.1$ to 2.0 which were made of plywood or acrylic resin. The size of square rods was varied from $h = 2$ to 40 cm. As shown in figure 1, the model was connected at the centre of the rear face to a supporting metal tube of 40–90 cm in length with a diameter smaller than $0.1h$ approximately. The whole assembly of the model and the support was suspended on the centreline of the working section by using piano

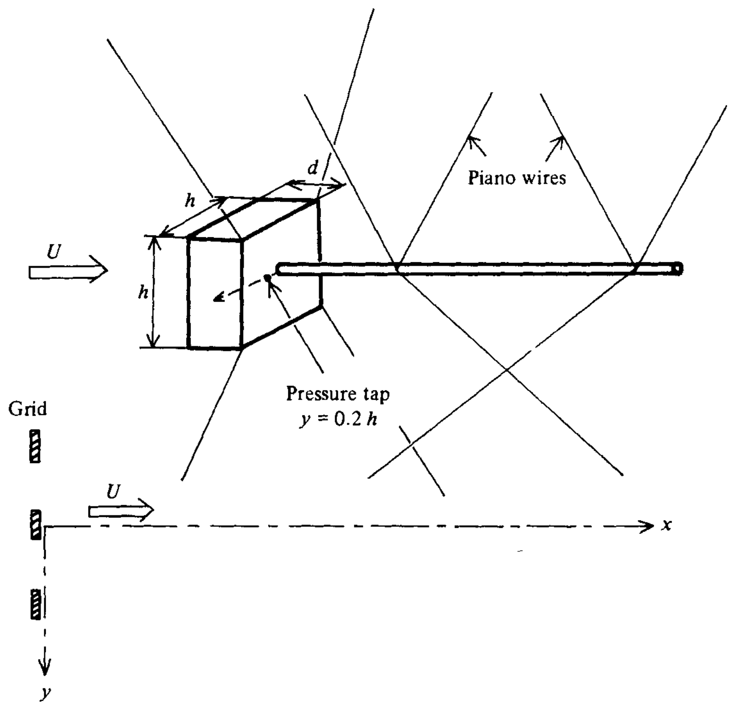


FIGURE 1. Square rod suspended by piano wires in grid-generated turbulent flow.

wires. In the experiment the pressure at a location $0.2h$ away from the centre of the rear face of a rod was chosen and measured as base pressure. For some of the models, measurements were added of the pressure distributions along the centreline of the side and rear faces and along the wake axis. The surface static pressures were measured by using pressure taps of 0.3 mm diameter. The wake static pressures were measured by using a long pressure tube of 2 mm diameter, set parallel with and $0.2h$ off the model centreline, which had four equally spaced holes of 0.3 mm diameter on its circumference. The pressure was determined with a calibrated inductance-type pressure transducer, and the mean pressure p is presented in the form of a pressure coefficient $C_p = (p-p_0)/(\frac{1}{2}\rho U^2)$, where ρ and p_0 are the air density and the mean static pressure of the freestream respectively. The values of p_0 and U were determined with a Pitot-static tube placed at the model position in the empty working section.

In the experiment the effect of turbulence intensity was examined by positioning the rod at various distances x downstream of the grid, and the effect of turbulence scale was mainly examined by working with different sizes of rod. All the measurements were made at a constant flow speed of 10 m s^{-1}, except for some supplementary ones. Correspondingly, the value of Reynolds number, based on h, ranged from 1.4×10^4 to 2.8×10^5, approximately.

3. Experimental results

3.1. *Grid turbulence*

The variations of the intensity and the longitudinal scale of the u-component of turbulence behind the grid, along the centreline of the working section, for the large and the small grids are shown in figure 2. The power spectrum of the u-component of turbulence for the large grid, measured at $x = 10M$, is shown in figure 3 together

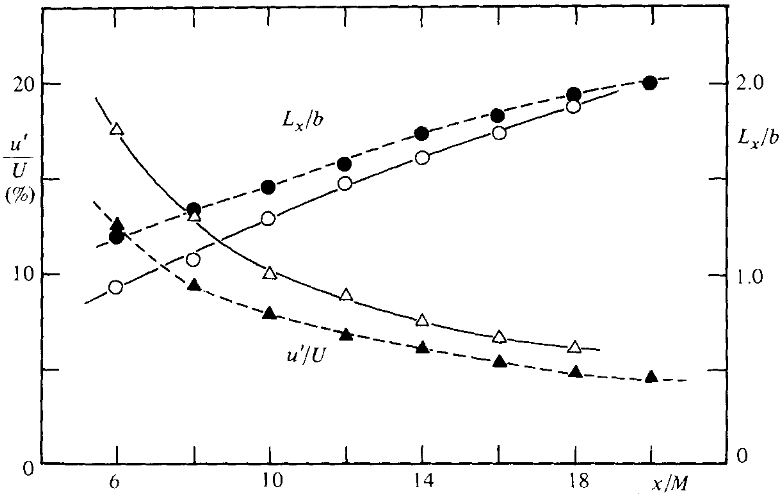


FIGURE 2. Variation of the intensity and longitudinal scale of the u-component of turbulence with distance from the grid: △, ○, large grid; ▲, ●, small grid.

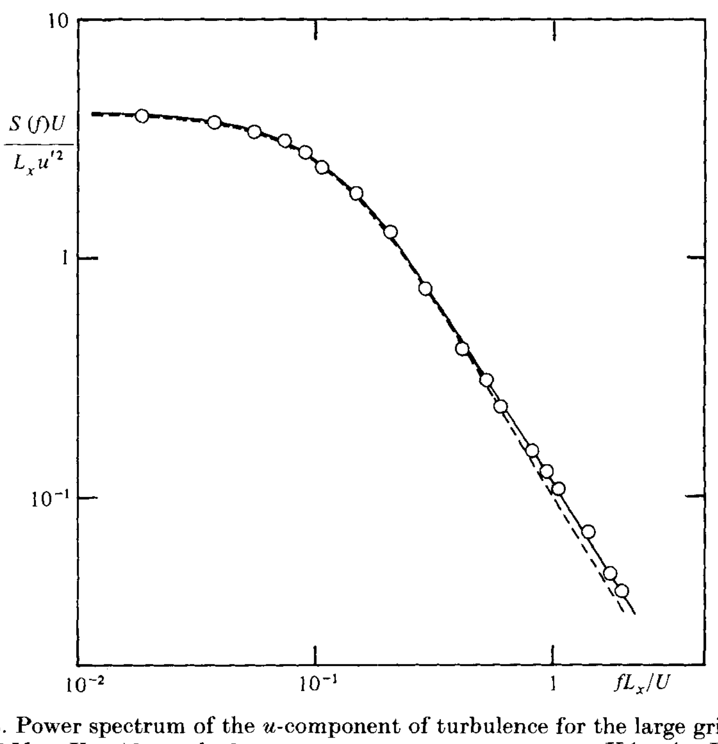


FIGURE 3. Power spectrum of the u-component of turbulence for the large grid, measured at $x = 10M$ at $U = 10$ m s^{-1}: ○, present measurement; ---, von Kármán (Hinze 1975).

	u'/U (%)	L_x (cm)	$u':v':w'$	$L_x:L_y:L_z$
Large grid	10.0	19.7	1.28:1.01:1.00	1.97:1.00:1.00
Small grid	8.0	3.6	1.30:1.13:1.00	1.80:1.00:1.05

TABLE 1. Turbulence characteristics for the large and the small grids, measured at $x = 10M$ at $U = 10$ m s^{-1}

with the theoretical one of von Kármán for isotropic turbulence (Hinze 1975). The power spectrum was calculated on the basis of the autoregressive model. Figure 3 indicates good agreement between the two spectra. The longitudinal scale of turbulence L_x was evaluated with the value of the power spectrum at zero frequency on the assumption of Taylor's frozen turbulence (Hinze 1975). The lateral scales of turbulence L_y and L_z were obtained by the velocity-correlation measurements. Table 1 shows the turbulence characteristics for the two grids, measured at $x = 10M$ at $U = 10$ m s^{-1}. The variation of the mean-flow speeds in the lateral direction for the large grid was within $\pm 2\%$ at $x = 10M$ over the central portion of 120 cm ($= 2M$), and for the small grid it was no worse. These results suggest that the turbulence field behind the grid in the present experiment was reasonably satisfactory over the tested range.

3.2. *Preliminary pressure measurement*

Preliminary pressure measurements indicated that a supporting tube with a large diameter gave no small disturbance to the near wake and yielded somewhat higher values for base pressure. After some trials, it was found that a supporting tube with a diameter smaller than $0.1h$ could ensure correct values for base pressure. The pressure distributions over the rear face for square rods with $d/h = 0.1$ (square plate), 0.5 and 1.0 (cube) in smooth flow, not shown in this paper, indicated that the pressure was sensibly uniform except for a cube, where it decreased gradually towards the downstream edge. The results suggested that the choice of the pressure at $y = 0.2h$ as base pressure was reasonably correct.

Because the experiment was made with models with different sizes, the effects of Reynolds number and the tunnel blockage had to be examined before any effect of turbulence was to be assessed. The measurement of the base pressures for a square plate of $h = 10$ cm in smooth flow, over a Reynolds-number range of interest, showed good collapse. This was the same with the three other square rods with $d/h = 0.5$, 1.0 (cube) and 2.0.

The results of measurement for the pressures for square rods with different sizes have been corrected for the effect of a tunnel blockage using the method of Maskell (1965). The drag coefficients of square rods required for the correction were estimated using the formula based on Bearman's measurements on square and circular plates (Bearman 1971): $C_{\mathrm{D}} = 0.803 - 0.908 C_{\mathrm{pb}}$. Figure 4 shows two base-pressure coefficients, uncorrected and corrected, for the four different square rods, measured in smooth flow for various values of the size h at a constant flow speed of 10 m s^{-1}. The corrected base pressure coefficients are seen to be sensibly constant over the tested range of h. Therefore it is suggested that the corrected base-pressure coefficients would be independent of both Reynolds number and the tunnel blockage, over the range to be investigated in turbulent flow.

3.3. *Effects of turbulence intensity and scale on base-pressure coefficient*

Figure 5 shows the variations of the base-pressure coefficient for a square rod with the length ratio, measured in smooth flow and in turbulent flows with $u'/U = 8\%$ and $L_x/h = 0.24$ and with $u'/U = 7.6\%$ and $L_x/h = 2.4$. The value of the base-pressure coefficient for a square plate in smooth flow, equal to -0.390, is comparable to the measurement of Bearman (1971), which gave a value of -0.363. The base pressure decreases slightly with increase in d/h up to about 0.5, and then increases rather rapidly. After $d/h = 1.6$ is exceeded, the base pressure remains nearly constant, indicating that the flow reattaches on the side of a rod (Nakaguchi 1978).

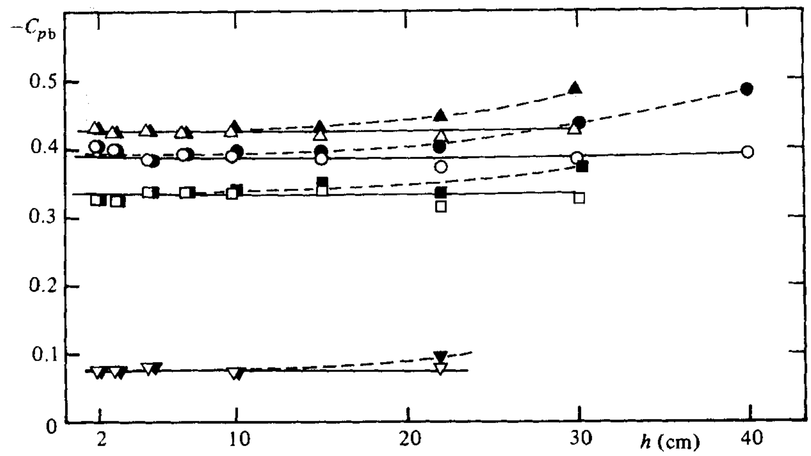


FIGURE 4. Uncorrected and corrected base-pressure coefficients for various values of the rod size. Smooth flow:

$d/h = 0.1$ (square plate)	0.1	0.5	1.0 (cube)	2.0
uncorrected	●	▲	■	▼
corrected	○	△	□	▽

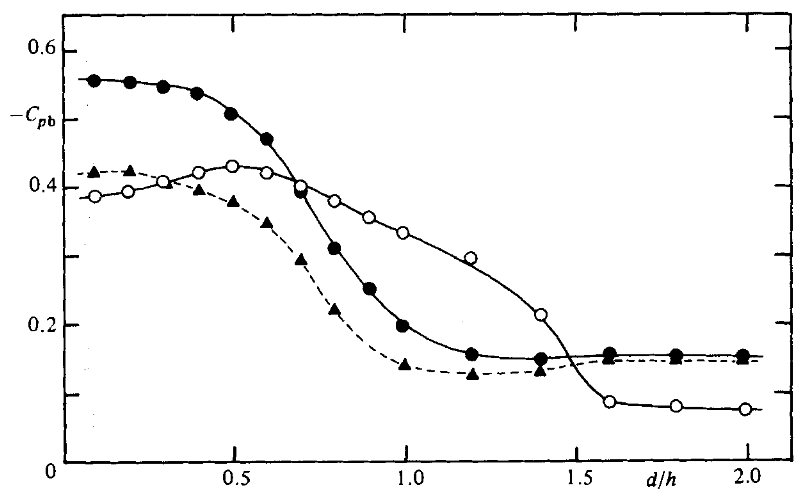


FIGURE 5. Base-pressure coefficient *vs.* length ratio: ○, smooth flow; ▲, turbulent flow, $u'/U = 8\%$, $L_x/h = 0.24$; ●, turbulent flow, $u'/U = 7.6\%$, $L_x/h = 2.4$.

The flow reattachment for long rods was verified in the present investigation by the measurement of pressure distributions, which will be shown later (figure 8*d*), together with the wool-tuft observations. Figure 5 also shows that turbulence reduces the base pressure of a short rod, raises that of a long rod and reduces again that of a very long rod with the flow reattachment.

In figure 6(*a*) the base-pressure coefficients of a square plate and a cube in turbulent flow are shown plotted against L_x/h, the turbulence scale relative to the rod size, for various values of turbulence intensity, while those for square rods with $d/h = 0.5$ and 2.0 are shown in figure 6(*b*). The corresponding smooth-flow values obtained in the present measurements are also shown in these figures. The results of Bearman for a square plate for $u'/U = 8.3\%$ and for a cube for $u'/U = 7.7\%$ (Bearman 1971, 1980)

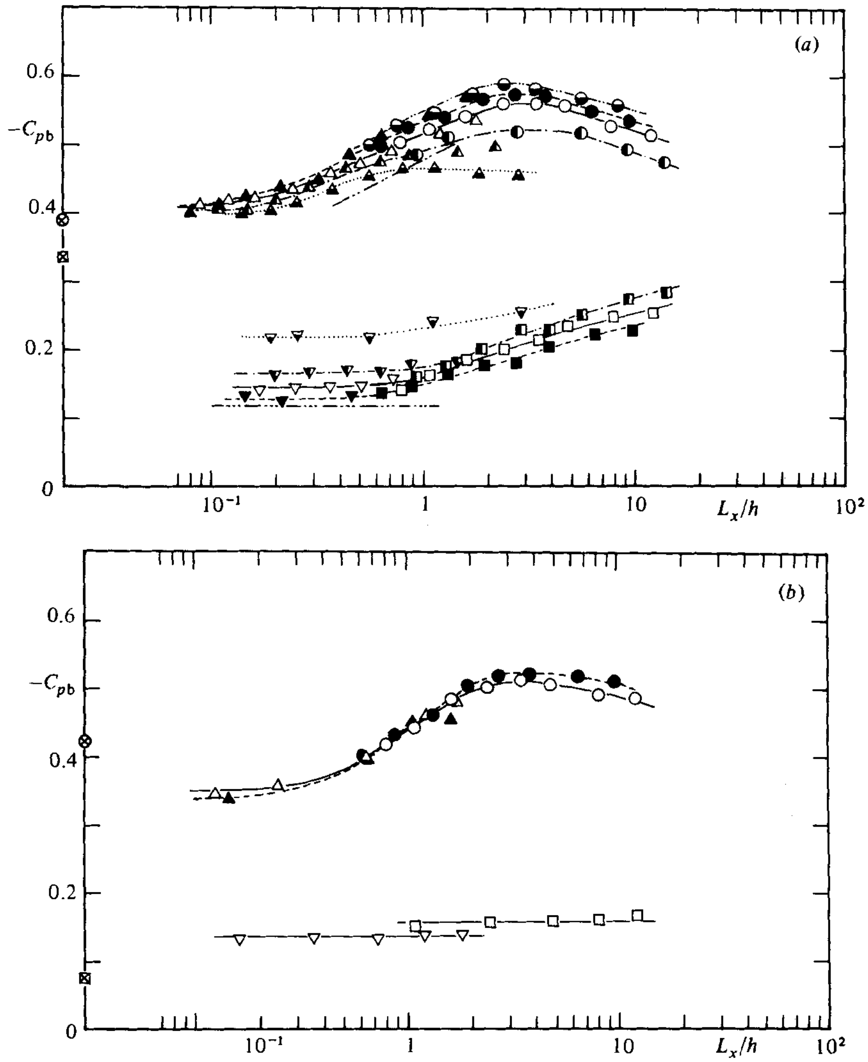


FIGURE 6. Base-pressure coefficient *vs.* turbulence scale relative to the rod size. (*a*) Square plate and cube. Smooth flow: ⊗, square plate; ⊠, cube. Turbulent flow:

	large grid				small grid			
u'/U (%) =	6.1	7.6	10.0	13.0	3.5	6.1	8.0	10.8
d/h								
0.1 (square plate)	◐	○	●	⊖	◮	◭	△	▲
1.0 (cube)	◧	□	■		⧩	⧨	▽	▼

—·—, square plate (Bearman 1971), $u'/U = 8.3\%$;

—···—, cube (Bearman 1980), $u'/U = 7.7\%$.

(*b*) Square rods with $d/h = 0.5$ and 2.0. Smooth flow: ⊗, $d/h = 0.5$; ⊠, $d/h = 2.0$. Turbulent flow:

	large grid		small grid	
u'/U (%) =	7.6	10.0	8.0	10.8
d/h				
0.5	○	●	△	▲
2.0	□		▽	

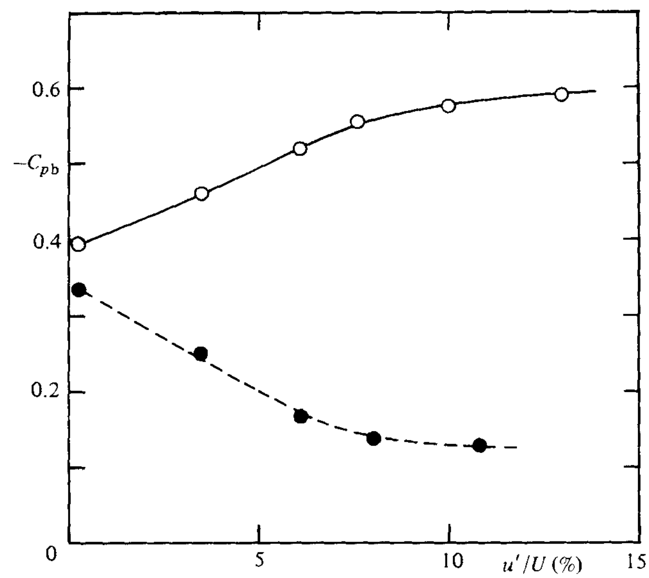


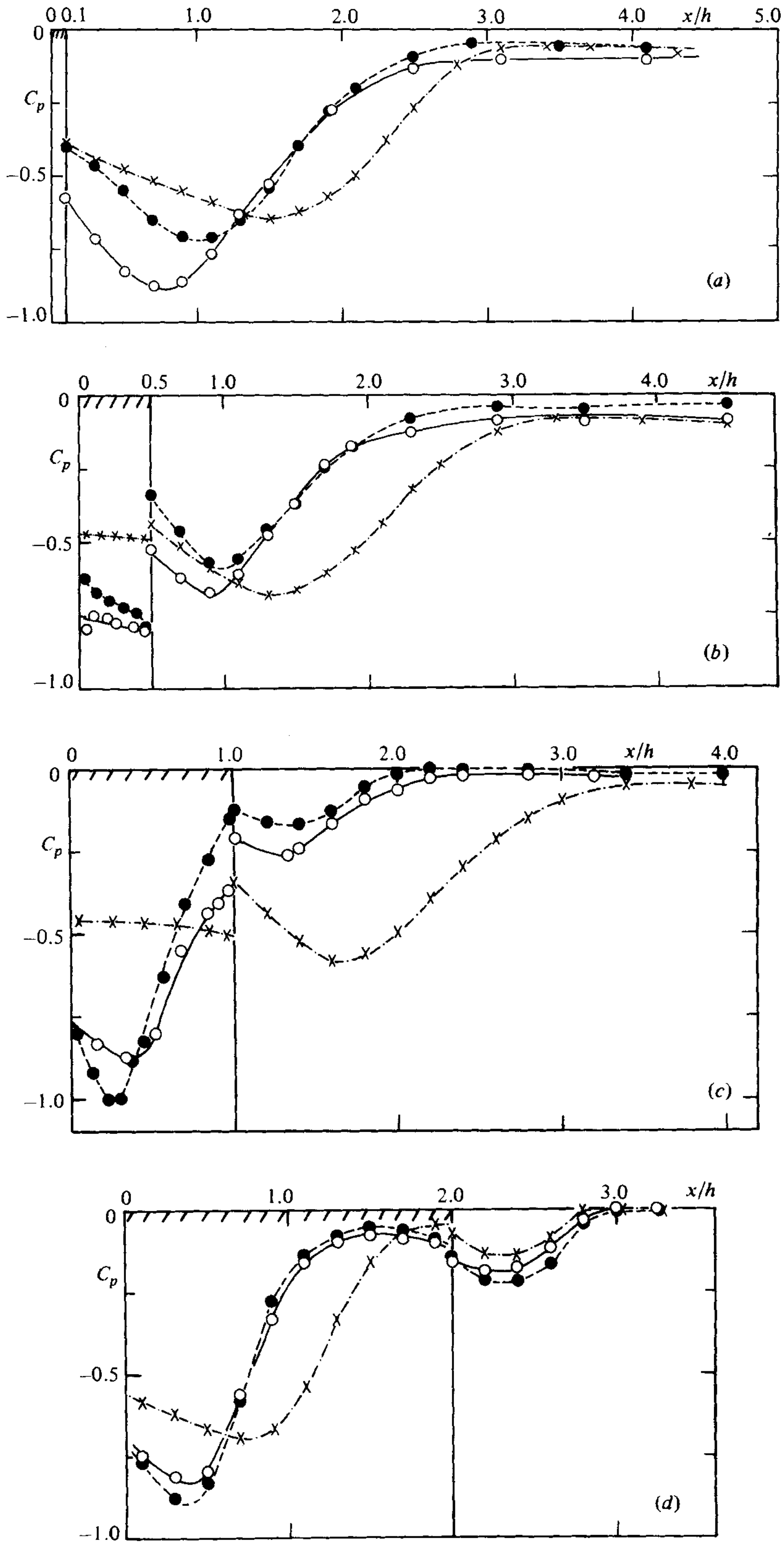
FIGURE 7. Base-pressure coefficient *vs.* turbulence intensity: ○, square plate, $L_x/h = 2.4$; ●, cube, $L_x/h = 0.24$.

are shown in figure 6(*a*) for comparison. Figure 7 shows the variations of the base-pressure coefficients of a square plate and a cube with turbulence intensity for turbulence scale equal to $L_x/h = 2.4$ and 0.24 respectively.

The base pressure of a square plate (figure 6*a*) decreases with both L_x/h and u'/U from about $L_x/h = 0.15$. The results using two different grids show satisfactory collapse. The agreement between the present measurements and those of Bearman is fairly good. It is shown that base pressure does not become infinitely low with turbulence scale. For u'/U equal to and greater than 7.6 % approximately, it reaches a minimum at about $L_x/h = 2.5$, and then increases slowly towards the smooth-flow value. On the other hand, as L_x/h is lowered beyond about 0.15, the base pressure remains nearly constant and very close to the smooth-flow value. The effect of turbulence intensity for its large values is found to be relatively small (see also figure 7). Previous measurements (Nakamura & Ohya 1982) indicated relatively strong influence of turbulence intensity on the base pressure of a square plate. However, repeated measurements presented in figures 6(*a*) and 7 have shown that this is not the case; the erroneous results could have been due to the poor precision of the pressure measurement for model locations closer to the grid.

The variation of the base pressure of a cube with L_x/h is also very characteristic. In agreement with Bearman (1980), the base pressure remains nearly constant over a range of L_x/h from about 0.2 to 0.7. However, as L_x/h is increased from about 0.7, the base pressure begins to decrease gradually towards the smooth-flow value. The base-pressure characteristics of a square rod with $d/h = 0.5$ (figure 6*b*) have much

FIGURE 8. Pressure distributions on the centreline of the side face of a square rod and along the wake axis. (*a*) Square plate: ×, smooth flow; ●, turbulent flow, $u'/U = 10.8\,\%$, $L_x/h = 0.145$; ○, turbulent flow, $u'/U = 10.0\,\%$, $L_x/h = 1.95$. (*b*) Square rod with $d/h = 0.5$: ×, smooth flow; ●, turbulent flow, $u'/U = 10.8\,\%$, $L_x/h = 0.145$; ○, turbulent flow, $u'/U = 10.0\,\%$, $L_x/h = 3.8$. (*c*) Cube: ×, smooth flow; ●, turbulent flow, $u'/U = 10.8\,\%$, $L_x/h = 0.145$; ○, turbulent flow, $u'/U = 10.0\,\%$, $L_x/h = 6.5$. (*d*) Square rod with $d/h = 2.0$: ×, smooth flow; ●, turbulent flow, $u'/U = 8.0\,\%$, $L_x/h = 0.36$; ○, turbulent flow, $u'/U = 7.6\,\%$, $L_x/h = 4.8$.



0 0.1
1.0
2.0
3.0
4.0
x/h
5.0
0
C_p
−0.5
−1.0
(a)
0
0.5
1.0
2.0
3.0
4.0
x/h
0
C_p
−0.5
−1.0
(b)
0
1.0
2.0
3.0
x/h
4.0
0
C_p
−0.5
−1.0
(c)
0
1.0
2.0
3.0
x/h
0
C_p
−0.5
−1.0
(d)

in common with those of a square plate and a cube. Namely, as L_x/h is increased, the base pressure is higher than the smooth-flow value initially and then decreases rather rapidly beyond it to increase again gradually after reaching a minimum. The effect of turbulence intensity is also small over a tested range. The base pressure of a square rod with $d/h = 2.0$ is shown to remain nearly constant over a range of L_x/h tested, although it is detectably lower than the smooth-flow value.

3.4. *Longitudinal pressure distributions*

In figures 8(*a–d*) pressure distributions along the centreline of the side face of the four different square rods together with those along the wake axis are presented for representative flow conditions. These results supplement the base-pressure measurement in obtaining the overall picture of the turbulence effect on the mean-flow field.

The results for a square plate are presented in figure 8(*a*). The pressure along the wake axis for smooth flow reaches a minimum value some way downstream of the base. In general, the effect of turbulence is to produce a lower minimum pressure at a location closer to the base, that is, to reduce the size of the base cavity. As was shown in figure 6(*a*), small-scale turbulence does not influence the base pressure significantly. However, this does not necessarily mean the absence of the turbulence effect on the whole mean-flow field. In fact, small-scale turbulence for $L_x/h = 0.145$ does reduce the size of the base cavity significantly. Also, the effect is much stronger for large-scale turbulence ($L_x/h = 1.95$) than for small-scale turbulence ($L_x/h = 0.145$). This is in accordance with the base-pressure variation for a square plate shown in figure 6(*a*).

Figure 8(*b*) shows the results for a square rod with $d/h = 0.5$. The pressures on the side face for smooth flow are reasonably uniform; the flow visualization (Nakaguchi 1978) indicates that the flow is separated throughout. Turbulence reduces the pressures on the side face considerably. In small-scale turbulence ($L_x/h = 0.145$), the side-face pressure decreases towards the downstream edge, and there is a large pressure recovery from the side face to the base. The fairly uniform pressure distribution on the rear face, not shown in this paper, indicated that the pressure recovery largely occurred near the sharp downstream edge. In contrast, the results for large-scale turbulence ($L_x/h = 3.8$) show that the pressure distribution on the side is fairly uniform with a relatively small recovery from the side to the rear face. The reduction in the base cavity size is also observed, but to a lesser extent, in comparison with the case of a square plate. According to the wool-tuft observation, there was no flow reattachment at the downstream edge in turbulent flows.

Figure 8(*c*) suggests that, although the flow around a cube is separated throughout for the smooth approaching flow, the separated shear layer in turbulent flow reattaches somewhere on the side face. The wool-tuft observations confirmed this. The side-face pressure distribution for $L_x/h = 6.5$ clearly indicates the weakened effect of turbulence. Also, with increasing turbulence scale the wake pressure distribution tends to approach that of the smooth flow, though gradually. For a square rod with $d/h = 2.0$ (figure 8*d*), the pressure distribution for smooth flow shows that the shear layer reattaches somewhere on the long side face. Turbulence reduces the reattachment length and also the value of the base pressure. However, no significant effect of turbulence scale is indicated over a range tested. This is in agreement with the observations of Hillier & Cherry (1981) on a blunt-faced circular-section cylinder.

4. The structure of the near wake of a square rod

4.1. *The near wake of a square plate*

It has been shown from the present experiment that the near wake of square rods can be influenced by turbulence of two different scales, namely by small- and large-scale turbulence. Here small-scale turbulence specifically refers to the case in which the size of the energy-containing eddies is comparable to the thickness of the separated shear layer, while large-scale turbulence refers to the case in which the size of the energy-containing eddies is comparable to that of the whole near wake. It is generally agreed that the main effect of small-scale turbulence is to increase the growth rate of the shear layer, while that of large-scale turbulence is to enhance the roll-up of the shear layer, both resulting in an increased entrainment of fluids from the base region to sustain low base pressure.

The near wake of a square plate is found to be influenced more significantly by large-scale rather than small-scale turbulence. In particular, the reduction in base pressure is significant for large-scale turbulence, while it is negligibly small for small-scale turbulence. Therefore it should be appreciated that the model of a closed wake cavity for the mean flow past three-dimensional sharp-edged bluff bodies (Bearman 1980; MacLennan & Vincent 1982) might be misleading in this context if only the extra entrainment of fluids due to small-scale turbulence were taken into account.

4.2. *The shear-layer–edge direct interaction*

The work by Nakaguchi, Hashimoto & Muto (1968) on two-dimensional rectangular cylinders showed that, as the cylinder depth increases from zero, the base pressure decreases rapidly to a critical minimum at a depth just beyond 0.6 times the height, as depicted in figure 9. The decrease in base pressure for the depths below the critical is associated with increased curvature of the shear layer in roll-up (Nakaguchi *et al.* 1968). The increase in base pressure for the depths above the critical is associated with the direct interference of the downstream edge with the shear layer by which vortex formation is delayed further downstream (Bearman & Trueman 1972). It should be added that the shear-layer–edge direct interaction also yields a side-face pressure distribution of reattachment type, that is, low pressure followed by high pressure of some level, which is similar to that of a reattached flow (Nakamura & Tomonari 1981).

According to the work of Nakamura & Tomonari (1976) on rectangular cylinders in turbulent flow, the main effect of turbulence is to lower the value of the critical depth by promoting the shear-layer–edge direct interaction. Gartshore (Laneville *et al.* 1975) made an interesting observation that it was small-scale turbulence approaching the mean stagnation line that significantly affected the flow around a bluff body. The significance of small-scale turbulence, as suggested by Gartshore, may be understandable if we remember that it is the shear-layer–edge direct interaction that controls the critical change in base pressure.

In figure 5 one can see that the variation of the base pressure of a square rod with the length ratio for smooth flow is similar to that for a two-dimensional rectangular cylinder, although much less pronounced in comparison with the two-dimensional counterpart. As suggested by Bearman (1978), the shear-layer–edge direct interaction also controls the base pressure of a three-dimensional sharp-edged bluff body when the length exceeds the critical.

In the case where the approaching flow is turbulent, combined effects of turbulence

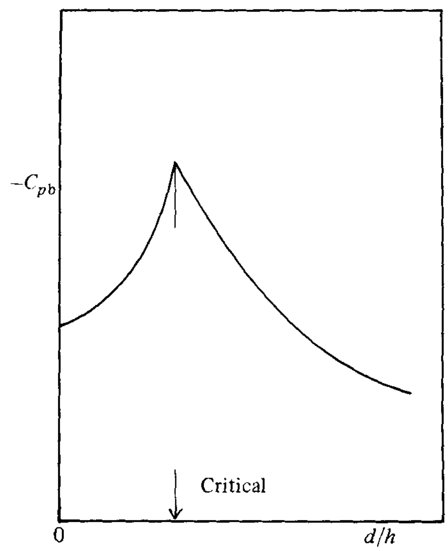


FIGURE 9. Base-pressure coefficient *vs.* depth ratio for a two-dimensional rectangular cylinder.

and length ratio should appear. For example, a square rod with $d/h = 0.5$ would behave as a postcritical rod in turbulent flow because it is nearly critical in smooth flow. Therefore small-scale turbulence would promote the shear-layer–edge direct interaction thus inducing a considerable pressure recovery near the downstream edge and raising the base pressure. As the scale of turbulence increases, the effect of large-scale turbulence would manifest itself on the one hand, and the shear-layer–edge interaction would be weakened on the other; accordingly, the base pressure is expected to decrease. The experimental results shown in figures 6(*b*) and 8(*b*) on a square rod with $d/h = 0.5$ seem to support this idea.

The same argument is also applicable to the case of a cube. In fact, the increase in base pressure due to the direct interaction (reattachment) appears to be centred around small-scale turbulence. Also, the weakening of this direct interaction for large-scale turbulence is clearly seen in the side-face pressure distribution (figure 8*c*). However, in contrast with a square rod with $d/h = 0.5$, no significant effect of large-scale turbulence on a cube is observed.

4.3. *Turbulence parameter correlating the base pressures of a square plate*

As mentioned in §1, Bearman (1971) obtained a turbulence parameter $(u'/U)(L_x/h)^2$ for correlating the base pressures of a square plate based on the argument of the extra entrainment of the shear layer due to turbulence, while Humphries & Vincent (1976) proposed a different parameter $(u'/U)(L_x/h)$, both resting on their own experimental results. It is now clear that any similarity parameter of this kind would only be applicable to a certain limited range where the base pressure is decreasing with turbulence scale (figure 6*a*). In figures 10(*a*, *b*) the present experimental results for a square plate are shown plotted against these two different parameters. From comparison between the two figures, it is difficult to see which parameter is better in degree of correlation.

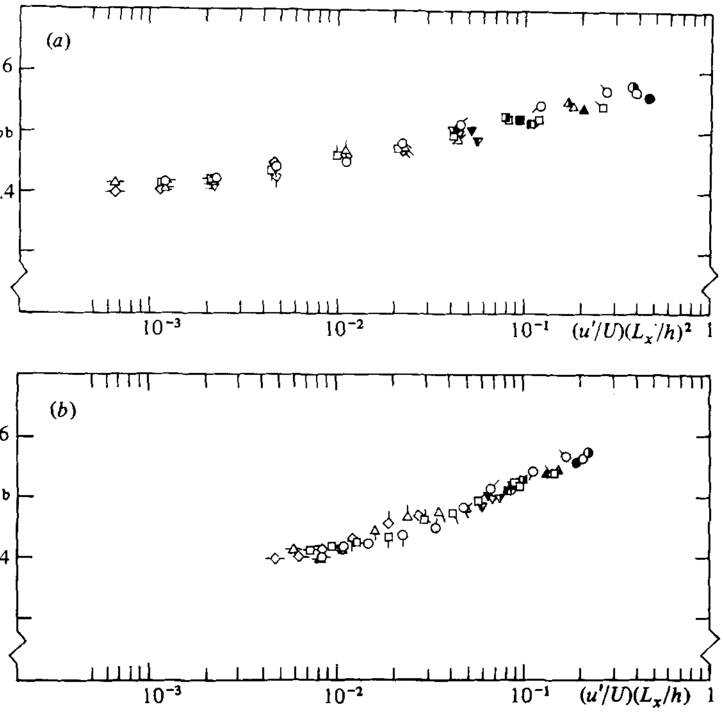


FIGURE 10. Correlation of the base-pressure coefficients of a square plate based on two different turbulence parameters. All the data are taken from figure 6(*a*); $u'/U = 3.5$–$13.0\,\%$, $L_x/h = 0.08$–2.4. (*a*) Bearman parameter. (*b*) Humphries & Vincent parameter.

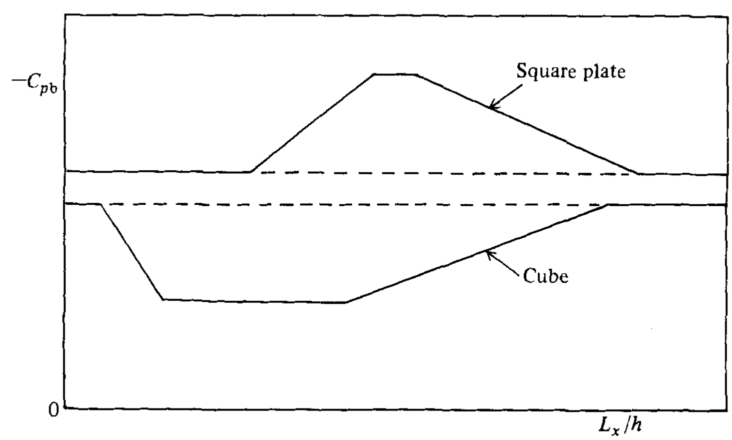


FIGURE 11. Hypothetical variation of the base-pressure coefficients of a square plate and a cube over a wide range of turbulence scale.

4.4. *The base-pressure variation over a wide range of turbulence scale*

It would be very difficult to extend the range of turbulence scale much further beyond the one tested. However, it may be inferred on physical grounds that turbulence of very large scale can only negligibly influence the mean flow past a bluff body. Namely, as L_x/h is very large, the size of the energy-containing eddies becomes much larger than the size of the body, so that their main behaviour will no longer be to mix with the wake flow but to cause an effect similar to that of a slowly varying mean-flow speed (Bearman 1971). Conversely, it may also be inferred that turbulence of very small scale should decay by itself through viscous action without strong interaction with the near wake of a bluff body.

To sum up, it is suggested that the dominant effect of turbulence on the mean flow past a three-dimensional sharp-edged bluff body may be restricted to a certain finite range of turbulence scale. The range of turbulence scale where its effect is strongest is dependent on the shape of a bluff body. The variations of the mean base pressures of a square plate and a cube over a wide range of turbulence scale are schematically illustrated in figure 11 in the light of the present experimental findings.

5. Conclusions

There are two main effects of turbulence on the mean flow past a three-dimensional sharp-edged bluff body. Small-scale turbulence increases the growth rate of the shear layer, while large-scale turbulence enhances the roll up of the shear layer. The consequences of these depend on the shape of a bluff body. For a square plate, both small- and large-scale turbulence can reduce the size of the base cavity. The effect of large-scale turbulence is much more significant, and this leads to a considerable reduction in base pressure.

As the length of a square rod is increased beyond the critical, the shear-layer–edge direct interaction controls the near wake, eventually leading to flow reattachment. One of the important results is to produce a pressure distribution of reattachment type on the side face of a rod. The effect of small-scale turbulence is to promote the shear-layer–edge direct interaction.

For a square rod with $d/h = 0.5$, the effects of both small- and large-scale turbulence are present. For a cube, small-scale turbulence induces the flow reattachment, while the effect of large-scale turbulence is weak. For a square rod with $d/h = 2.0$ where the flow reattaches on the side face in smooth flow, no significant scale effect is observed over the tested range, although the mean flow is considerably distorted by turbulence.

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