Interference effects on the pressure distribution on the ground plane around a low-rise and a tall body in tandem arrangement†

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In this paper, the pressure distribution and flow visualisation on the ground plane around a low-rise prismatic body with height to width ratio (h/b) of 1 and a tall body (h/b = 5) in tandem arrangement are presented. Two cases are considered: (i) when the shorter body is in front and the tall body at the rear, (ii) when the tall body is in front and the short one at the rear. In each case the gap between the two is systematically varied. The results indicate that in both cases it is the tall body which controls the pressure and the flow field and due to the resulting interference effects very severe flow conditions can be expected around the low-rise body.

Prismatic bodies with square cross-section and height-to-width ratio of 1 and 5 are typical shapes of low-rise and tall buildings. A clear understanding of the flow field around such three-dimensional bluff bodies would be helpful in estimating the forces and analysing the fluid motion around buildings. The dispersion of affluents released, the movement of waste material, and the pedestrian comfort are some of the other features which could be better understood and controlled by analysing the flow around these bluff bodies1-4. Another important aspect which decides the general wind environment is the interference effects of one body on another5. It would be both interesting and useful to study such effects on the flow field as buildings invariably occur in combination. The flow around buildings near the ground surface would be very much influenced by the pressure distribution on the ground plane. Such pressure distributions would reveal the regions of favourable and adverse pressure gradients which in turn decide the direction of ground surface flow-towards or away from the buildings. In the present study, the pressure distribution on the ground plane around prismatic bodies with square cross section and differing height to width (h/b) ratio is considered. A low-rise body with h/b = 1 and a tall body with h/b = 5 are considered in tandem arrangement. Two cases are investigated: (i) when the short body (h/b = 1) is in front and the tall body (h/b = 5) is at the rear, and (ii) when the tall body is in front and the short one at the rear. The gap (g) between the bodies is systematically varied in each case. Some flow visualization results are also described which give a qualitative physical picture of the interference effects on the flow field. The results presented are applicable to understand flow around buildings in practical situations. But there are some limitations in the applicability of the results which are pointed out at a later stage.

Experimental Procedure
The experiments are carried out using the wind tunnel facility shown in Fig. 1. Air from the blower passes through a set of screens and a settling chamber which terminates in a nozzle conforming to DIN 1952 standards. The dimensions of the nozzle exit are 295 mm × 365 mm (365 mm being the height). The velocity at exit is very uniform, the variation both in the horizontal and vertical planes (taken at the central section of the nozzle exit) being less than 0.5 per cent.

A stand designed and fabricated out of mild steel angles is used to support the surface plate on which the bodies are placed. A smooth hylam sheet 12 mm in thickness with a length of 1140 mm and a width of 655 mm is used as the surface plate. Pressure tappings (1 mm in diameter) are provided all along the length of the plate (on the central line) with a centre to centre distance of 6 mm. There is provision for levelling the surface plate and also varying its position in the vertical direction. The plate is positioned in front of the nozzle so that its leading edge abuts with the lower edge of the nozzle as shown in Fig. 1. The position of the pressure tappings coincide with the middle of the

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Fig. 1—Experimental set-up

nozzle exit. The pressure taps are connected through PVC tubing to the scanning boxes type FC091 (Make: Furness Controls, U.K.). The boxes are in turn connected to micromanometer Type FC012 (Make: Furness Controls, U.K.). The accuracy of the manometer is 0.01 mm water column and by the use of the scanning boxes the pressure at several stations could be monitored quickly and accurately.

Prismatic bodies with width $b$ equal to 30 mm made out of fine teak wood and finished to have smooth surface and sharp edges (to eliminate Reynolds number effect) are utilised. Measurements are carried out (along the centre line) with individual bodies and with bodies in tandem arrangement to study interference effects. Results are obtained when the single body is placed at the leading edge and at several distances from the leading edge of the plate in order to obtain a comparison between such results and the pressure distribution obtained when two bodies are simultaneously placed on the plate in tandem arrangement. Both when the bodies are kept at the leading edge and in the boundary layer, there is sufficient length of the surface plate behind the bodies. The uniform pressure distribution on the surface plates without the bodies confirmed the proper alignment of the surface plate.

All measurements are carried out at a exit velocity of 15.5 m/s which gives a Reynolds number (referred to the width of the body) of 30000. The results can be used for analysing practical situations as they are independent of Reynolds number since prismatic bodies with sharp edges are used. (The limitations are pointed out at a later stage). Regarding the Reynolds number effect, it may be relevant to point out that Castro and Robins\(^6\) have shown that for uniform approach flow conditions and sharp-edged bodies, for a Reynolds number of 30000 and above, the separating shear layer is turbulent right from the leading edge and the results can be expected to remain unaltered beyond $Re = 30000$. Further, the earlier results of Gowda and Sithee\(^5\) are also at a Reynolds number of 30000. The pressure distributions on the surface plate is obtained without the bodies and this is utilised as the reference pressure for the calculation of $C_{pw}$. The velocity in the free stream approaching the bodies is used for the calculation of the reference dynamic pressure. For the tunnel cross-section used, i.e., 295 mm × 365 mm, the blockage for the body with $h/b = 5$ is 3.8\% and is much less for the shorter body. Since an open test section is used and the blockage ratio is not high, the blockage effects will be very small and hence neglected.

Results and Discussion

The results are obtained for both the cases for $g/b = 1, 2, 3, 4, 5, 6, 7$ and 8. In all the figures where the pressure distribution is presented the results obtained for the relevant single body cases without interference are also included for comparison purposes.

Pressure distribution for case (i)—The front body is always located at the leading edge and the rear body is located at various positions to obtain the different $g/b$ ratios. The results are presented in Figs 2-7 for $g/b = 1, 2, 3, 4, 6$ and 8. (The results for $g/b = 5$ and 7 have not been given as they are typically similar to those in other figures).

Considering first the pressure distribution behind the rear body, it is seen that in all the Figs 2-7 the $C_{pw}$ distribution behind the tall body is considerably altered due to the interference effects of the front body. The point of $(C_{pw})_{\text{max}}$ at the rear would indicate the point of flow reattachment. When there is no well defined peak in the $C_{pw}$ distribution, a tangent can be
drawn from the point of inflexion and the intercept of this tangent on the horizontal axis would then approximately indicate the location of the reattachment point. Such tangents have been drawn in Fig. 2 and it is seen that the reattachment point decreases from about $x/b = 4$ for the no-interference case to about $x/b = 2.5$ with interference. Such a decrease is evident at other values of $g/b$ also (Figs 3-7). This decrease is most probably due to the turbulence generated by the front body. Further the $(C_{pw})_{\text{min}}$ with interference occurs close to the body in all cases (Figs 2-7) indicating that the saddle point moves closer to the body with interference. The interference effects behind the rear body appear to be maximum for $g/b = 2$; but even at the large gap ratio of $g/b = 8$ (Fig. 7) the effects persist. There is in general an increase in the base pressure due to interference.

Focussing the attention now on the pressure distribution in the gap between the bodies it is quite interesting to observe the strong influence of the tall body on the gap flow, specially at low values of $g/b$ (Figs 2 and 3). Positive pressures occur in the gap though attenuated compared to the values for the no-interference case (represented by triangles). The pressure distributions indicate a flow from the front of the rear body towards the front body (which is in fact revealed by the flow visualisation results.

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**Fig. 2** — Interference effects on pressure distribution: $g/b = 1$

**Fig. 3** — Interference effects on pressure distribution: $g/b = 2$

**Fig. 4** — Interference effects on pressure distribution: $g/b = 3$

**Fig. 5** — Interference effects on pressure distribution: $g/b = 4$
The pressure distributions just behind the front body with and without interference, become nearly the same only at \( g/b = 6 \) (Fig. 6). This is also the case in the \( C_{pw} \) variation in front of the rear tall body. Beyond \( g/b = 6 \), the interference effects as far as the gap flow is concerned can be expected to be only marginal in the near vicinity of the bodies.

**Pressure distribution for case (ii)**—The results for this case when the tall body is at front are shown in Figs 8-13 for \( g/b = 1, 2, 3, 4, 6 \) and 8 (here also the results for \( g/b = 5 \) and 7 are not shown). Focussing the attention on the wake of the rear body and considering Fig. 8 (\( g/b = 1 \)) it is seen that the \( C_{pw} \) distributions with and without interference are nearly the same for \( x/b < 2 \). But it is to be noted that at this position the short rear body is completely submerged in the wake of the tall front body. Hence, the \( C_{pw} \) values observed with interference are in effect due to the wake of the front body rather than that due to the rear body. At other values of \( g/b \), i.e., \( \geq 2 \) (Figs 9-13) the near wake length along the flow direction of the rear body is considerably reduced. Also the base pressure increases due to interference similar to case (i).

Considering next the \( C_{pw} \) variation in the gap between the bodies, the strong influence of the tall body in this case also is clearly seen. For example, at \( g/b = 1 \), the \( C_{pw} \) values with interference nearly coincide with those for the tall body without interference indicating that the downstream body has very little influence on the pressure distribution. Whereas, it was the reverse when the tall body was at rear (Fig. 2). Some noticeable influence of the rear body on the \( C_{pw} \) distribution in the gap is observed at \( g/b = 2 \) and 3 (Figs 9 and 10). At higher \( g/b \) values (Figs 11-13) again there is very little influence of the short body on the pressure distribution in the gap. Further, the steep adverse pressure gradient that occurs in
front of the rear body without interference (due to the formation of the horse-shoe vortex\(^4\)) is absent for \(g/b \leq 5\). Only at \(g/b = 6\), a small adverse pressure gradient region is seen but very close to the front of the rear body. This region increases further at \(g/b = 8\) but is much smaller than that for the no-interference condition. This indicates that the formation of a well defined horse-shoe vortex can be expected in front of the rear body only for \(g/b \geq 6\) (which in fact is revealed by the flow visualisation results presented later).

Considering both the pressure distributions for cases (i) and (ii) presented in Figs 2-13, it is seen that in both cases it is the tall body which controls the pressure distribution and hence the flow pattern particularly in the gap between the bodies. Another interesting feature noticed is that in case (ii) (i.e., when the tall body is in front), upto \(g/b = 3\), the pressure in front of the rear body is lower than that at its base indicating a possible flow from the base towards the front and to the possibility that there could result a thrust force rather than a drag force on the rear body. (The confirmation of the later requires measurement of pressure distribution on the bodies).

**Flow visualisation results**—To obtain a better insight into the interference effects flow visualisation studies are carried out and for this purpose an aluminium surface plate is utilised. A homogeneous mixture of lamp black and kerosene is applied uniformly on the surface plate supporting the bluff

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Fig. 8 — Interference effects on pressure distribution : \(g/b = 1\)

Fig. 9 — Interference effects on pressure distribution : \(g/b = 2\)

Fig. 10 — Interference effects on pressure distribution : \(g/b = 3\)

Fig. 11 — Interference effects on pressure distribution : \(g/b = 4\)
bodies. Runs are made at the same Reynolds number as earlier (i.e., $Re = 3 \times 10^4$) and the flow patterns obtained. They are shown in Figs 14-16.

Fig. 14 (a-d) shows the results for the single bodies (i.e. without interference) when at the leading edge and in the boundary layer. These are shown to bring out the differences in the patterns with and without interference. Figs 14 a and b show the flow patterns when the body is placed at the leading edge of the plate. Fig. 14 a for $h/b = 1$ at the leading edge shows that the reattachment occurs around $2b$ behind the body. The two vortical patterns which are the foot prints of the arch vortices are seen clearly with a small region of outward flow close to the body. In fact, the vortical patterns showed considerable unsteadiness while the flow was taking place; the fluid collected within the vortices executed a sort of ovalling motion within the boundary of the vortical trace seen in the photograph. Fig. 14 b, for $h/b = 5$ at the leading edge shows that the reattachment occurs around $4.5b$ behind the body in this case. Also the flow pattern close to the body and in the far wake are distinctly different compared to that for the short body (Fig. 14 a). These are very well reflected in the pressure distribution behind the corresponding bodies without interference (e.g. squares in Figs 7 and 13). The location of $(C_{pw})_{max}$ gives the position of the reattachment points and the $(C_{pw})_{min}$ points the position of the saddle points behind. Figs 14c and d, where the bodies are placed in the boundary layer, show the horse-shoe vortex (HSV) in front of the bodies. These photographs are taken with the bodies placed at a distance of $s/b = 4$ from the leading edge of the plate. The displacement thickness ($\delta^*$) and the momentum thickness ($\theta$) at this location are $0.931$ mm and $0.670$ mm respectively. The shape parameter $H = \delta^*/\theta$ is 1.39. Hence, the flow pattern shown are for turbulent horse-shoe vortices. The shape and the structure of the HSV changes with the height of the body as can be seen in Figs 14 c and d. These aspects are discussed in detail in Ref. 4.
The interference effects are shown in Figs 15 and 16 for cases (i) and (ii) mentioned earlier. In each case the front body is located at the leading edge of the support plate. Though the results have been obtained for $g/b = 1, 2, 3, 4, 5, 6, 7$ and $8$ for each case, only typical results at chosen $g/b$ values are shown in Figs 15 and 16. Fig. 15a shows the resulting flow pattern due to the presence of a tall body ($h/b = 5$) at a small distance behind the short body, i.e., $g/b = 1$. It is seen that the interference effects are indeed severe with the flow pattern around the shorter body being completely altered compared to Fig. 14a. There is a strong flow from the front of the tall body towards the base of the shorter body completely displacing the vortical pattern. With the result, two vortices are seen on either side of the short body. The strong flow towards the
shorter body is due to the adverse pressure gradient created by the tall body which is evident in the $C_{pw}$ distribution for the corresponding position (Fig. 2). When the spacing between the two bodies increases to $g/b = 2$ (Fig. 15b), the flow in the gap between the bodies continues to occur towards the base of the shorter body with two vortical patterns occurring just near the two corners of the rear face. The pressure gradient still seen in Fig. 3 for this configuration is responsible for this flow pattern. At $g/b = 3$ (Fig. 15c), two vortices are formed behind the front body. It is quite interesting to observe the flow around the rear body at this $g/b$ value. At the front there is an outward flow which then turns and moves around the body.
which is due to the formation of a HSV. Also the interaction between this flow and the flow from the vortices formed behind the front body can be seen. The formation of two vortices behind the front body very similar to those observed without interference (i.e. Fig. 14a) are seen only at $g/b = 6$ (Fig. 15d). This is also reflected well in the $C_{pw}$ distribution for the corresponding position in Fig. 6. Further, in Fig. 15d, a distinctive trace of fluid emanating from the vortices at the rear of the front body and going around the rear body is seen. The flow behind the front body was observed to be strongly unsteady. The fluid collected in the vortices at the base is 'pumped' out alternatively giving rise to the trace mentioned above. Sometimes there is no pumping but the vortex core appears to ‘dance’ within a prescribed boundary. The HSV in front of the rear body is very clearly seen in Fig. 15d. (The $C_{pw}$ distribution in Fig. 6 corresponds with this observation). Another interesting feature seen in Fig. 15d is that, due to the strong adverse pressure gradient created by the tall body, the flow behind the low-rise body is seen to be deflected outwards. Because of this process, even at larger distances on either side of the tall body sufficiently strong flows (or currents) can be found near the ground level. This is not the case when the tall body is in front, the results of which are described in what follows.

The results for the case (ii) when the taller body is at front and the shorter one at the rear are shown in Figs 16a-d. In Fig. 16a ($g/b = 1$) it is clear to see that the rear
body is within the wake of the front body and as remarked in previous section the $C_{pw}$ distribution seen in Fig. 9 is due to the resulting flow field. Figs 16a-d at other $g/b$ values reveal the dominating influence of the taller body in deciding the gap flow which corresponds closely with the $C_{pw}$ distributions (Figs 9-13). Even at sufficiently large gap widths ($g/b = 6$; Fig. 16d) the wedge like far wake of the tall body is clearly seen, with the shorter body located within it and hardly deflecting the flow. Whereas, this is not the case in Fig. 15d at the same $g/b$ where the taller body is at the rear (which was pointed out earlier).

In all the cases presented in Figs 15 and 16, the wake behind the rear body is seen to be shorter than that of the corresponding no-interference case (Figs 14c and d) which is reflected in the $C_{pw}$ distributions presented in Figs 2-13. As remarked earlier, this is due to the turbulence generated by the upstream body.

**Limitations of the results presented**—Though the results presented are applicable to understand flow around buildings, it is pointed out here that in actual practice the buildings are exposed to a boundary layer type of velocity profile. As the present results are obtained with an uniform approach velocity profile there is some limitation on the applicability of the results to actual situation; for example, there could be quantitative differences in the $C_{pw}$ values. Also there will be some influence of the Reynolds number for buildings in atmospheric boundary layers. But even when the approach velocity profile is boundary layer type, the flow behind the front body would be highly disturbed and the pressure field on the ground plane within the gap between the bodies and that behind the rear body might not be very much different from the present results. Further, the present study provides the necessary basic results which can be used for obtaining the comparative influence when other approach flow conditions are used.

**Conclusions**

From the pressure distribution and the flow visualisation results, the following conclusions are drawn. (1) When a tall body is at the rear and close to a low-rise prismatic body, the resulting pressure gradient causes a flow towards the short body and strong vortical flows can occur around instead of at the base of the later. The HSV around the rear tall body is formed only for $g/b > 4$. Even at large $g/b$ values, sufficiently strong ground currents can be expected at large distances on either side of the tall structure located behind the short body.

(2) A low-rise body behind a tall body would distort the base flow behind the tall body only marginally. The short body would be completely enveloped by the wake of the tall body at low values of $g/b$. Some distortion of the pressure field in the wake of the tall body can be expected at $g/b = 2$ and 3.

(3) In all cases, the wake behind the rear body gets shortened probably due to the turbulence generated by the upstream body.

It is to be remarked here that the pressure measurements presented have been confined to the plane of symmetry only. Results at other planes away from the plane of symmetry are desirable.

**Nomenclature**

- $b$ = width of the body
- $C_{pw}$ = $(p_p-p)/1/2pU^2$, pressure coefficient on the ground
- $g$ = gap between the bodies in tandem arrangement
- $h = height of the body$
- $l = length of the body along the flow direction$
- $p = pressure at any point on the surface plate with the body$
- $p_r = pressure at the same point on the surface plate without the body$
- $s = distance from the leading edge of the surface plate to the front face of the body$
- $U_r = free stream reference velocity$
- $x = coordinate along the flow direction$
- $x' = coordinate along the centre line measured from the front face of the rear body$
- $\rho = density of air$

**References**