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DRAG REDUCTION BY THE PRODUCTION OF A SEPARATION BUBBLE ON THE FRONT OF A BLUFF BODY

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Summary

The aerodynamic drag of a rectangular block having a length-to-width ratio of 5 with square cross section was measured in a wind tunnel at low Mach number and zero yaw condition. It has been found that substantial drag reduction can be achieved by devices fastened on the face of the body producing a separation bubble over the front surface. The simple add-on devices examined were a backward facing step and a fence attached to the front end, which can be utilized to reduce the aerodynamic force acting on vehicles, structures and buildings.

Notation

c_D	drag coefficient
c_{Db}	base drag coefficient
$c_p = \dfrac{p - p_\infty}{(\rho/2)\, v_\infty^2}$	pressure coefficient
h	width of body (m)
l	length of body (m)
m, b	dimensions of add-on devices (m)
p	local pressure (Pa)
p_∞	pressure in undisturbed flow (Pa)
$Re = \dfrac{v_\infty\, \rho\, h}{\mu}$	Reynolds number
v_∞	undisturbed velocity (m s^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Introduction

The greatest part of drag acting on bluff bodies (e.g. on buses, trucks, buildings) is the fore-body drag which is the integral of the pressure differ-

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ence $p - p_\infty$ over the projection of the front end. That is why reduction of the fore-body drag offers great potential in the reduction of fuel consumption of commercial vehicles. The value of pressure integral over the front face can be reduced by decreasing the local pressure, i.e. by accelerating the flow over the front face. The conventional method of flow acceleration is "streamlining" the fore-body, rounding up or bevelling the leading edges, application of chambered add-on devices, such as lips, fairings as well as turning vanes exerting their effect through similar mechanisms as the rounding of edges. These conventional methods of fore-body drag reduction have been reviewed by Hoerner [1], Koenig-Fachsenfeld [2] and Hucho [3].

Significant drag reduction can be realised by using two bodies in tandem [4, 5]. The boundary layer separation on the edges of a plate positioned in front of the bluff body creates a shear layer on the edge of which the flow velocity exceeds the undisturbed velocity. Thus, the pressure in the separation bubble decreases causing a significantly smaller net drag than that without a plate. This method is widely used for drag reduction of trucks where the wind deflector on the roof of the tractor suspends the second stagnation point developed on the face of the trailer. The wider practical application of this method is constrained by functional, aesthetical and legal aspects. That is why an extension of the method proposed by Roshko and Koenig [4] has been investigated, utilizing the pressure decrease in the separation bubble produced over the front face of bluff bodies by add-on devices. The practical applications of this method seem to be suitable for reduction of drag of buses, trucks, buildings, etc.

Experimental arrangement

The aerodynamic drag of a 1 m long rectangular block with 0.2 m square cross section has been measured in a recirculating type vertical wind tunnel of open test section with a diameter of 1.4 m. The Reynolds number based on the body width varied in the range 1.3—3 $\times$ 10^5, the turbulence intensity

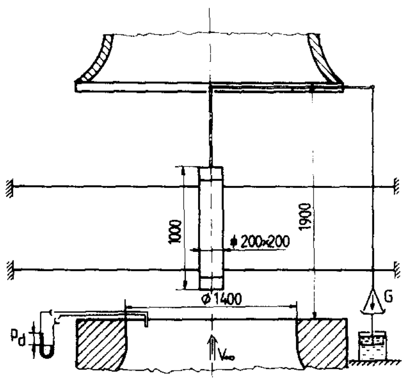


Fig. 1. The bluff body in a wind tunnel.

in the empty test section was 0.6%. Wind tunnel tests were carried out at zero yaw condition, when the area blockage ratio was 2.6%.

The bluff body was suspended on a balance (Fig. 1), the beam of which was covered to avoid flow interaction. The drag force was measured by determining the decrease in weight of the model. The transverse and torsional motions were impeded by wires of diameter 0.6 mm, and the streamwise vibrations were damped by a liquid-filled damper. The flow velocity was measured by a Pitot-static tube and a Betz type micromanometer. The static pressure distribution was measured with 252 pressure taps and a Betz type micromanometer.

Results

Figure 2 [6] shows the variation of the drag coefficient with edge radius at Reynolds number 2.6×10^5, with and without a transition wire. In the former case the transition fixing wire (of diameter 0.6 mm) was fixed around the periphery of the front face. (The trailing edges of the bluff body were sharp in all the experiments reported here.) The results of measurements show that the rounding up of the leading edges is a very effective method for reducing the drag of a bluff body. Figure 3 [7] shows the pressure distribution in the medium plane of bluff bodies with sharp and rounded leading edges. As a consequence of flow acceleration, the pressure decreases on the front face and over a relatively large area of the periphery of the front end the pressure is smaller than that of undisturbed flow. This suction on the periphery compensates for the overpressure on the inner part of front face so that the fore-body drag coefficient calculated with measured base drag and estimated side wall skin friction is nearly zero ($c_{Df} \simeq 0.01$) cor-

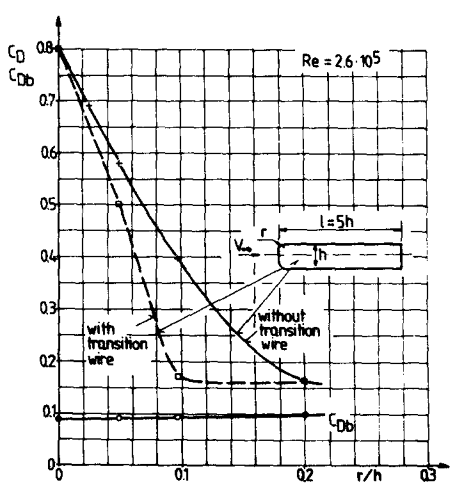


Fig. 2. Aerodynamic drag vs. radius of leading edges.

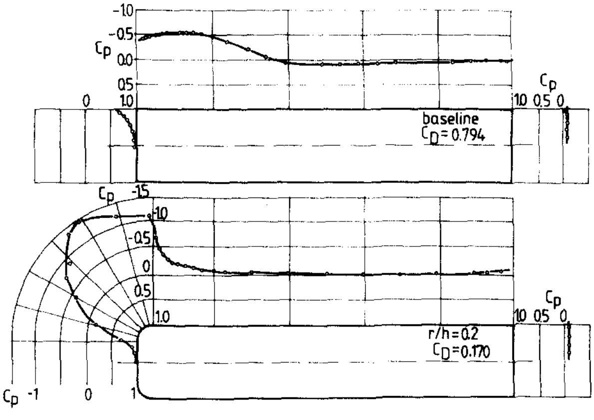


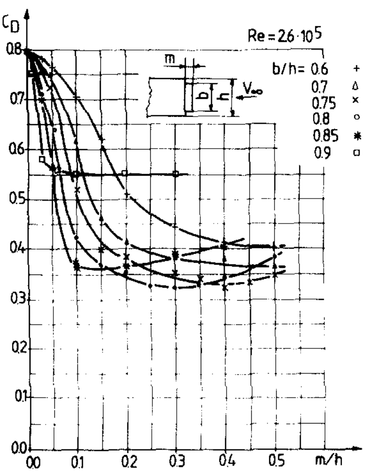
Fig. 3. Pressure distributions on bluff bodies.

responding to the lowest fore-body drag coefficients reported by Hoerner [1] and Roshko and Koenig [4].

The boundary layer separation can produce a separation bubble with low pressure, e.g. behind a two-dimensional backward facing step or fence.

It has been supposed that the region of relatively low pressure near the periphery of the front face can also be produced by separation of the boundary layer.

The drag reducing effects of various add-on devices attached near the periphery of the front face of the block have been investigated: the backward facing step, various protuberances separating the boundary layer, and fences proposed by Litvai [8].



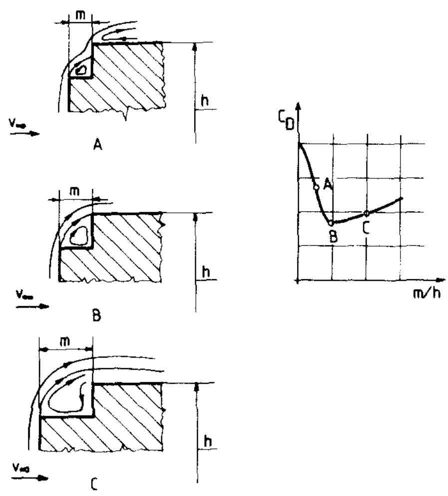


Fig. 4. Drag reduction by using a "step" on the front face.

Fig. 5. Flow pattern in separation bubble at different step heights.

Figure 4 shows the drag coefficient as a function of relative step height at constant step widths. The drag reduction effect of a backward facing step is considerable; the drag of the block decreases by nearly 60%, and the decrease of fore-body drag is estimated to be about 75%. At small step width, where the separation bubble follows the outer edges of the front face, the drag decreases rapidly with the increasing step height then it remains constant or increases slightly.

The characteristic change of drag with step height can be explained by regarding Fig. 5, which is a sketch of streamlines in the medium plane of the body, corresponding to three different step heights. In the case of a small step the flow separating on the front edge impinges on the periphery of the face of the body (Fig. 5A). Therefore two different areas of the periphery can be distinguished: the area beneath the separation bubble characterised by low pressure and the area of impingement where the pressure is higher. Increasing the step height increases the area of low pressure and that of higher pressure decreases. Thus the drag coefficient decreases rapidly. With wider steps (i.e. smaller b/h values) the decrease in drag with step height is not as large because the increased separation bubble width, caused by a given increase in step height, changes the pressure over a smaller area than at greater b/h values. Figure 5B shows the streamlines belonging to a higher step where, except for the corner regions, the shear layer bounding the separation bubble joins smoothly on the side walls of the bluff body.

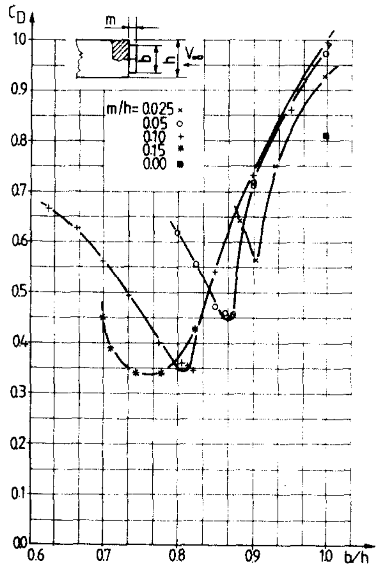
Near the corners impingement of the flow can be observed to increase the drag [4]. On further increase of the step height the width of the separation bubble increases and the reattachment line reaches the side walls (Fig. 5C). This is accompanied by opposing effects, especially at larger step widths. The drag decreases by increasing the face area near the corners covered by the separation bubble. At the same time, extension of the separation bubble over the side walls causes a pressure increase on them, therefore the drag increases.

Drag reduction is due to pressure reduction in the cavity around the front face, filled by the separation bubble. The pressure coefficient, c_p, beneath the separation bubble belonging to the maximum drag reduction at various step widths decreased from about 0 at b/h = 0.6 to about -1 at b/h = 0.85.

Figure 6 shows the drag reduction using a fence fastened near the periphery of the front face of a bluff body. The fence was manufactured from metal sheet of thickness 1 mm. A sketch of the streamlines can be seen in Fig. 7. The boundary layer separation on the edge causes a separation bubble in the cavity around the fence. The drag reduction effect of the fence is a little smaller (58%) than that of the step.

Figure 8 shows the pressure distribution on the block with a backward facing step and a fence on the front face. It can be seen that the pressure in the separation bubble behind the fence is lower than that behind a step, which is the consequence of the greater angle between the tangent of shear layer at the separation point and the undisturbed flow [9]. In spite of the lower pressure in the separation bubble, the fence does not reduce the drag more than the step because it increases the pressure over the inner part of the front end. Comparison of the pressure distributions along the sides of the block (Figs. 3 and 8) shows that the shape of the pressure distribution with a step or fence is closer to that with rounded than with sharp edges, but the nearly constant pressure in the vicinity of the leading edge indicates the presence of a small separation bubble over the sides. Velocity measurements in the boundary layer supported this assumption.

For practical reasons the application of a step or fence around the whole periphery of the front end can be inconvenient. Therefore experiments have been carried out with add-on devices applied only to part of the periphery.



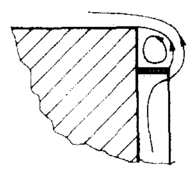


Fig. 6. Drag reduction by using a "fence" on the front face.

Fig. 7. Flow pattern in the separation bubble.

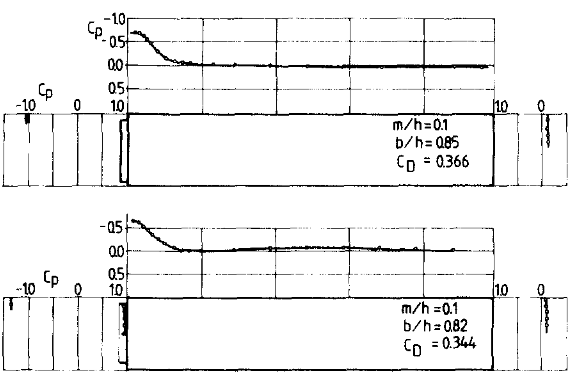


Fig. 8. Pressure distribution using a "step" and a "fence".

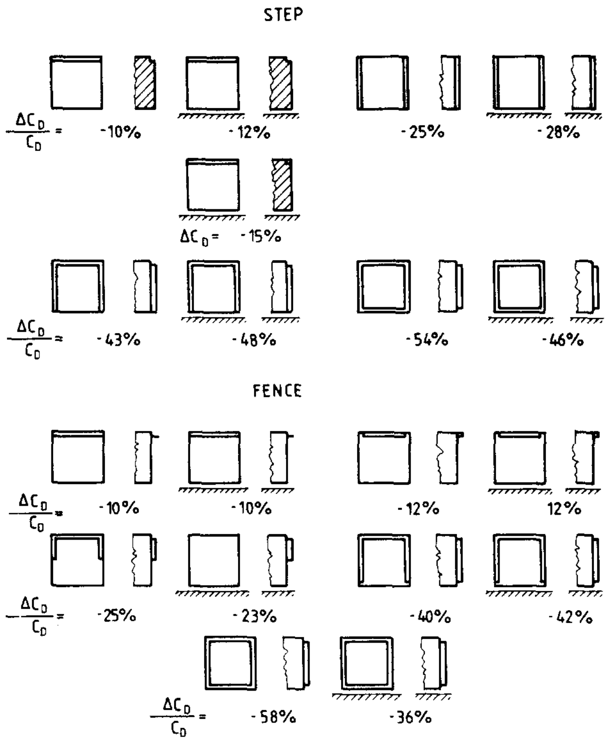


Fig. 9. Drag reduction by producing a separation bubble.

Figure 9 shows the drag reduction of several step and fence variations. It can be seen that the drag reduction effect of a relatively small change in fore-body shape can be considerable. Closing the cavity from the sides decreases the pressure by cutting off feed to the separation bubble. As a consequence of the proximity of the ground, simulated by a flat plate provided with a circulation control flap at the trailing edge, the drag reduction effect of add-on devices increases, disregarding cases where the step or fence was placed on the lower horizontal edge of the front face.

Conclusions

By producing a separation bubble over the periphery of the front end of a bluff body the aerodynamic drag can be reduced considerably. Drag reduction can exceed 50%. Add-on devices can also be used partially and effectively in proximity to the ground. This method can be utilized in optimising the body details of ground vehicles [3] by a suitable arrangement of miscellaneous body details, e.g. gutters, bumpers and frames, which results in a lower drag coefficient. The novel devices studied in this paper are subject to a patent application.

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