The use of BLC in conjunction with a boat-tailed afterbody has been suggested here as a possibility, but, at present, there is little reason to think that this possibility is likely to be promising. Boat-tailed afterbodies have been shown to give large reductions of drag without BLC, and only detailed investigations can show whether there might be additional advantages in using BLC to give low drag with even shorter afterbodies.

CONCLUSIONS AND DISCUSSION

Consideration of known methods of reducing the drag of a blunt-based body of revolution has shown that a boat-tailed afterbody is much more effective than any other device that has been tried. Moreover, the boat-tailed afterbody can still give a good reduction of axial force at yaw angles up to about 15°.

A road vehicle must operate near the ground and cannot usually be axi-symmetric, although cylindrical road tankers for carrying liquids are of some interest. Much more experimental work will be needed before it is possible to design with confidence a practicable vehicle with a rear end shaped to take advantage of the boat-tail principle. The "Kamm back" that is already being used may be thought of as a shape with a roof-line as in Fig. 5, but with nearly straight boundaries at the sides and bottom. Such a shape may sometimes give a useful reduction of drag at zero yaw, but in a side-wind there is likely to be separation at the edges of the sloping afterbody and some of the beneficial boat-tail effect may then be lost. More experimental work is needed to develop practicable shapes based on the boat-tail principle, which give a low axial force, even when yawed.

The further complications of shear flow and turbulence in the atmospheric wind must also be considered.

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DISCUSSION

Prepared Discussion

T. Morel *(General Motors Research Laboratories)*

This discussion will concern itself with the effect of base cavities on the drag of an axisymmetric body. As Professor Mair mentioned in his paper, the subject was studied about 10 years ago by Goodyer who concluded that the effect of ventilated cavities is to increase drag. The purpose of this discussion is to point out that, while the conclusion arrived at by Goodyer is indeed correct for deep cavities, the opposite is true for cavities of smaller depth.

Our experimental setup consisted of a long circular cylinder, suspended on six wires and aligned with the flow, at the end of which were attached interchangeable afterbodies (Fig. 11). These afterbodies had cavities of three different types, and of six different depths. Altogether, 18 different configurations were tested. The three types of cavities were: solid-walled; slotted, with twelve longitudinal slots; and slitted, with 12 slots which ran out the end of the cavity. All the slots started right at the body base. The depths studied were 0.1, 0.2, 0.35, 0.5, 0.7 and 0.9 times the body diameter. I should point out that the single cavity tested by Goodyer, and which was mentioned by Professor Mair, had a depth of 0.96 times the cylinder diameter.

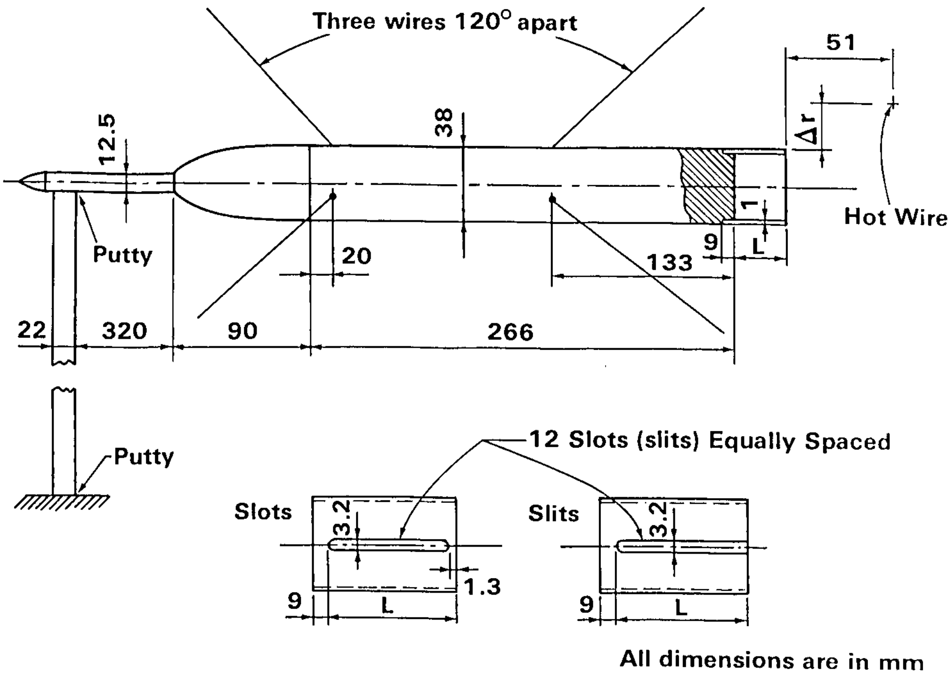

Fig. 11. Sketch of the experimental arrangement showing the test body and the dimensions of the interchangeable add-on cavities. All dimensions are in mm.

The variation of drag coefficient with cavity depth is shown in Fig. 12. At small cavity depths, there is a small but measurable drag decrease with all three types of cavities. At larger depths, the solid-walled cavity still shows some drag reduction even at the last point tested. However, the two ventilated cavities, the slotted and the slitted, both show a dramatic drag increase. The Goodyer data points for the zero depth case and for his deep ventilated (slitted) cavity are included for comparision. The base pressure, measured at a centerline tap inside the cavities (Fig. 13), had trends similar to those for the drag coefficient. However, the magnitude of the variation in C_{pb} was more pronounced than for the drag coefficient; we don't know quite why, but presumably the smaller effect on drag is accounted for by skin friction along the cavity walls.

One of the objectives of this study was to inquire into the mechanisms of drag generation. It has been proposed by Nash *et al* (1963)* that the reason why cavities reduce the drag of 2-dimensional bodies is the inhibition of vortex shedding. This is also what Peter Bearman, David Maull and Professor Mair mentioned briefly in their presentations. One may ask, is this the same mechanism which makes a cavity work in the axisymmetric case? To test this possibility we measured the periodic component in the near wake. A hot wire was placed at the shear layer edge about one diameter

**Nash, J. F., Quincey, V. G. & Callinan, J. (1963), Experiments on Two-Dimensional Base Flow at Subsonic and Transonic Speeds, Aeronautical Research Council, R&M 3427.*

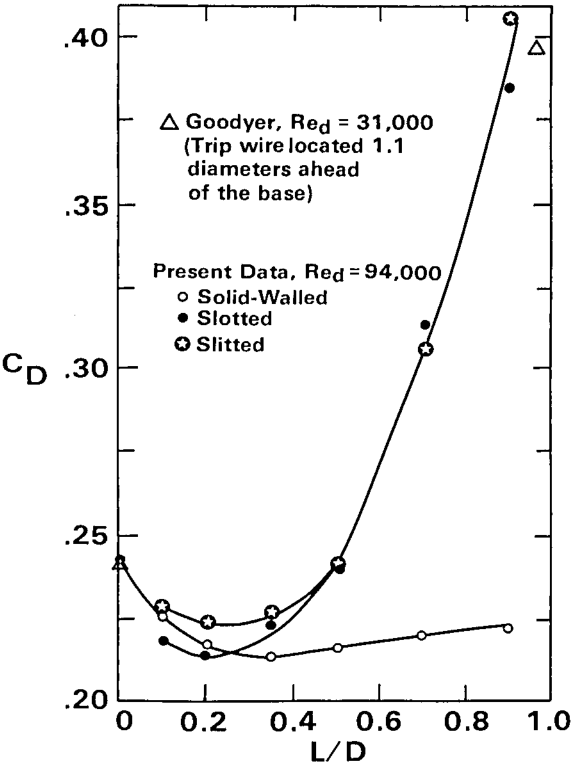

Fig. 12. Drag coefficient vs. cavity depth for the three cavity geometries.

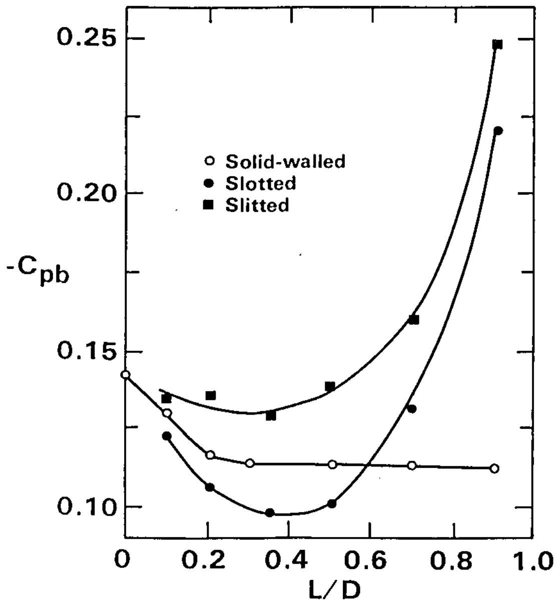

Fig. 13. Centerline base pressure coefficient vs. cavity depth.

downstream from the end of the cavity, and the velocity signal was processed to obtain its spectrum. The results for the solid-walled cavity are shown in Fig. 14, plotted against the Strouhal number S_D based on the cylinder diameter. The spectra displayed definite peaks, and so there is no question whether or not there is periodicity behind axisymmetric cylinders in high Reynolds number flow. I should point out that the separated boundary layer was fully turbulent and was relatively thick, with $\delta/D = 0.16$. For clarity, all spectra in Fig. 14 are displaced vertically from each other. If you would inspect them closely you would notice that the magnitude

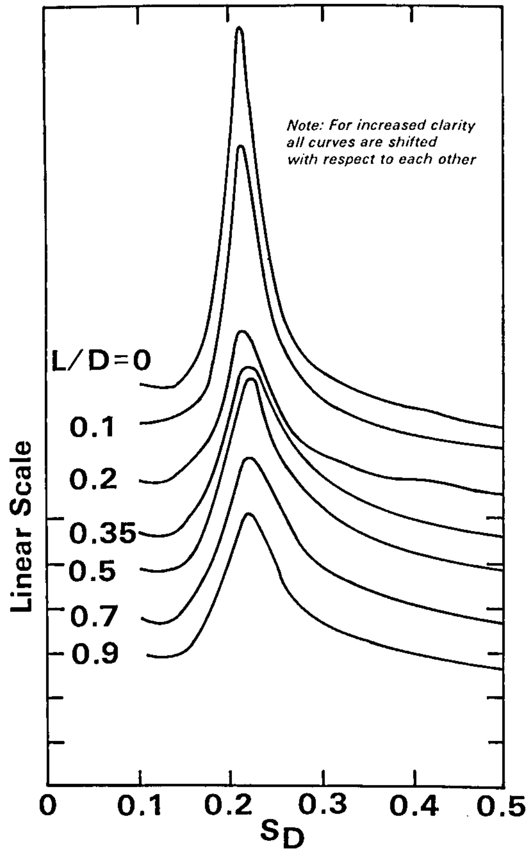

Fig. 14. Axial-velocity spectra for solid-walled cavities. Measured with a hot wire placed at the edge of the wake at x/D = 1.33 downstream from the cavity end.

of the spectrum peak follows roughly the same trend as the drag coefficient for the solid-walled cavity; that is, it decreases when the C_D decreases and vice versa. This seems to support Nash's idea about the mechanism involved in cavity drag reduction; however, Fig. 15 showing the spectra for the slotted cavity seems to dispute it. In this case the trend of the spectrum peak magnitude is monotonic, and the cavities succeed in wiping out the periodicity at L/D between 0.5 and 0.7. However, as we have seen in Fig. 12, the drag did not follow such a trend, but increased sharply beyond L/D = 0.35.

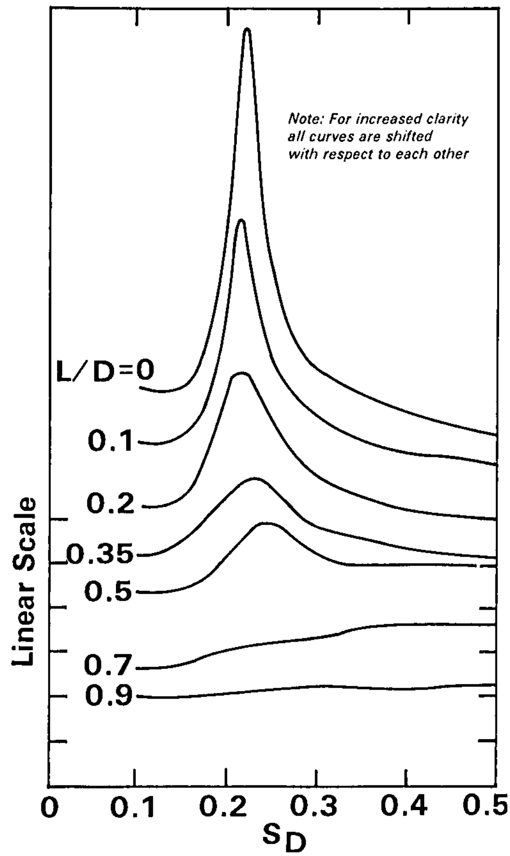

Fig. 15. Axial-velocity spectra for slotted cavities. Measured at the same location as for the solid cavities.

In summary, ventilated cavities can provide advantages over those with solid walls, but one has to pay attention to optimization of their geometry.

K. R. Cooper *(National Research Council, Canada)*

In some data I've seen, trapped vortices were used at the base of an axisymmetric body to reduce base drag. I wonder if you could comment on the effectiveness of this technique, using a disk displaced from the end of the body, or a circumferential groove machined in the boat-tailed surface near the base to lock the vortex in place, or some other similar technique.

W. A. Mair

I did some experiments with disks at the back of a body, either one disk or two disks; one could go on and have an entire grooved afterbody. I think the general conclusion was that this does work fairly well but not as well as a smooth boat-tail. That is why I didn't include it in my catalogue of drag reducing devices. It's interesting, perhaps, that it works nearly as well.

G. Heskestad *(Factory Mutual Research Corporation)*

Ten years ago I did some work on a drag reducing system for actual road vehicles that employed suction. Many people like to refer to it as boundary layer suction, but I don't think it should be called boundary layer suction. It is a principle which has been described in connection with other flow geometries, like the flow through a step expansion in a pipe going from a small diameter to a large one.* If you apply suction at the convex corner of the junction between the two diameters you get a great increase in the pressure recovery through the step. We wondered whether such a suction slot placed around the trailing perimeter of a constant area road vehicle would reduce its drag. We equipped a Volkswagen panel truck with a suction slot around its entire trailing perimeter and with some suction hardware. We ran deceleration experiments on the truck as a means of evaluating any drag reduction. Unfortunately, I never wrote up the work for publication, although an internal report can be made available. The drag coefficient, as measured through differences in deceleration, went from 0.54 down to 0.38. This is quite a large reduction even though there wasn't much reduction potential available, considering that the estimated base-pressure drag coefficient was on the order of 0.23. However, there is always the problem that power has to be provided for the suction flow. This made it less impressive, and instead of an actual reduction in drag coefficient of 0.16, we got 0.09. To get this

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number we had to make certain assumptions about the pumping power. The overall concept does seem worth keeping in mind as another item in the library of drag reducing techniques.

W. A. Mair

I think that is very interesting. I'm very glad to hear that you did get a net overall drag decrease, because that's always the worry – the power you save in relation to the power you use. I think it's very encouraging.

R. Sedney *(U.S. Army Ballistic Research Laboratories)*

It was very interesting to listen to your list of disappointments because it sounded like what I've been hearing in ballistics for 15 years or so. In fact the other thing that fascinated me was that just about every drag reducing technique that you mentioned has been considered in ballistics. Many of them are apt to reduce drag, but of course it is a matter of making them into a practical system. The best one in ballistics is the boat-tail. Base bleed has also been known for many years to reduce drag but it hasn't been made practical yet. In both cases, base bleed and the boat-tail, a great deal of cut-and-try is necessary. It is very easy to end up increasing the drag in some of the other cases you mentioned.

From what you said about base bleed, I wouldn't be convinced yet that it isn't a practical way to reduce drag. In the case of supersonic flow almost anything you do, as long as you don't inject too much momentum, will reduce drag. The largest gains, however, are obtained by injecting the mass in certain ways. For example, injection around the periphery of the base would be better than near the center. It isn't just the area over which the mass is introduced, but where it is introduced.

W. A. Mair

Yes, I'm sure that's true. I probably did dismiss base bleed a bit too hastily; there are various ways you can do it, certainly. The two investigations I referred to in my paper actually did leave out the case of injection around the edge of the base rather than further in. They both started with most of the base area being used for bleed, and then effectively blanked it in from the outside to change the bleed area. It is possible, of course, that some other arrangement might be more fruitful.

J. L. Stollery *(Cranfield Institute of Technology, England)*

Hearing Ray Sedney speak prompts me to ask him to confirm that it was tracer shells which showed base bleed to be so powerful in ballistics. Tracer shells are known to go far further than regular shells.

R. Sedney

Yes, at both subsonic and supersonic speeds the drag is lower with the tracer than without it.*

J. L. Stollery

To be more practical, we did some aerodynamic tests on a small delivery van; it was rather a blunt van, and we found a large difference in drag between road tests with the front windows open and shut. The window position changes the pressure distribution over the whole rear of the vehicle (Fig. 16). With the windows open a lot of air came into the van, and with leaky rear doors there was some base bleed at the rear, not intentional but unintentional. The figure shows the pressure distributions with windows open and closed. Notice that when the windows were closed the pressures were *negative,* but with open windows they were *positive.* Now, of course, there can be other explanations for this. For example, changes in the whole external flow field of the van may also have influenced the base pressure.

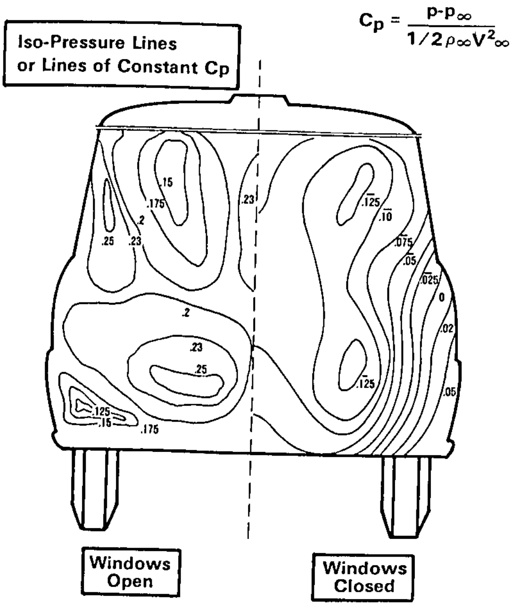

Fig. 16. Pressure distribution on the rear surface of a van, showing profound changes in pressure caused by opening of the van side windows.

Sedney, R. (1966), Review of Base Drag, Proceedings of AGARD Conference, AGARD-CP-10. Sedney, R. (1976), Aerodynamics of Base Combustion, Progress in Astronautics and Aeronautics, Vol. 40, AIAA and MIT Press.

H. H. Korst *(University of Illinois)*

You used C_q as a measure of "base bleed." One should interpret such a coefficient as representing the combined effects of both actual mass addition into the wake and that of the approaching boundary layer, the latter in the form of the equivalent bleed concept advanced by Sirieix, *et al.**

Some of the observed differences in the effectiveness of mass bleed are indeed due to variations in the relative importance of the boundary layer development upstream of the separation. In the case of high speed projectiles, the approaching boundary layer is not only thin, but it also expands sharply at the base so that its equivalent bleed contribution is small. Since such a boundary layer does not provide any effective "bleed" effect, mass bleed into the wake can provide some very significant benefits.

On the other hand, the momentum defect of the thick boundary layers found on road vehicles provides a strong initial bias level of the "bleed" effect. Now, in view of the diminishing returns of decreasing base drag by increasing bleed rate, one may expect that this bias level will reduce the effectiveness of any mass injection into the wake region.

W. A. Mair

I think this one needs some thought. It doesn't seem obvious that the boundary layer thickness would make a great deal of difference to the effectiveness, or otherwise, of base bleed. Perhaps it does, but I don't really see why it should. It does make some difference to the base pressure on a body of revolution, but not a very large one. You can double the boundary layer thickness and make only a comparatively small change in the base pressure coefficient. I don't really see why it should make much difference to the effect of base bleed, but perhaps we have to consider it. It's an involved subject.

W. A. Mair

Sirieix, M., Mirande, J. & Delery, J. (1966) "Experiences Fondamentales sur le Recollement Turbulent d'un Jet Supersonique," AGARD Conference, May 1966, Proceedings No. 4, Separated Flows, Part I, pp. 353-392.