Effectiveness of Passive Devices for Axisymmetric Base Drag Reduction at Mach 2

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Experiments have been made to assess the effectiveness of passive devices for reducing base and total afterbody drag at Mach 2. The devices examined include primarily base cavities and ventilated cavities. Results show that ventilated cavities offer significant base-drag reduction and net-drag reduction of engineering value. A correlation of base- and net-drag reduction for ventilated cavities has been suggested. Typical effects of these devices on boat-tailed and flared bases have also been assessed.

Nomenclature

A = forebody (max) cross-sectional area, 490.625 mm^2
A_v = total area of ventilation
C_{DA} = total afterbody drag coefficient, net-drag force/$(q_\infty A)$
C_{DB} = base-drag coefficient
C_{pb} = base-pressure coefficient
D = forebody (max) diam, 25 mm
h = cavity depth
L = afterbody length
M_∞ = freestream Mach number
q_∞ = freestream dynamic pressure
t = cavity lip thickness

Introduction

BASE drag arising from flow separation behind blunt bases can form a significant fraction of total drag in connection with missiles and projectiles at low supersonic Mach numbers.[1] Of the methods for axisymmetric base-drag reduction, the applications of base bleed and afterbody boattailing are well known.[2] At subsonic and transonic speeds, although vortex shedding is less pronounced in the axisymmetric case in comparison with the two-dimensional case, it was demonstrated[3] that certain passive devices/base modifications offer appreciable base-drag reduction and net-drag reduction of practical value. These devices included base cavities, ventilated cavities, and vortex suppression devices (involving highly three-dimensional, separation edges).

At supersonic speeds, however, wake behind a blunt base is practically steady with no significant periodicity[4] except for turbulence in the free shear layers, and it seems unlikely that devices which are meant to interfere with the vortex shedding may lead to any beneficial effect in terms of drag. It therefore appears appropriate to examine the effectiveness of devices that may influence the mean flow in the near wake for altering the base pressure.

In this paper, we present a detailed assessment of the effectiveness of base cavities, ventilated cavities, and other bleed configurations at a typical supersonic Mach number; such an assessment does not seem to have been reported in the published literature (to the authors' knowledge). Accurate afterbody total drag measurements have been made to quantitatively assess the net-drag reduction that is typical of these devices.

Experiments

Experiments have been performed in a 30×30 cm, supersonic blow-down tunnel at a nominal freestream Mach number of 2.0 and at a Reynolds number (based on model length of 30.5 cm, see Fig.1) of 10×10^6.

A sketch of the model support system along with the afterbody model and the drag balance is shown in Fig. 1. The metric part consists of a fixed cylindrical section 30 mm long and a removable afterbody typically 100 mm long (Fig. 1). The balance measures the total axial force (drag) experienced by the metric part of the model. Total-drag measurement facilitates direct assessment of net-drag reduction and includes automatically the effects of three-dimensional flow variations, if any, resulting from the base modifications. Base pressure is measured at a single location on the model centerline. All tests were carried out at zero incidence. The model boundary layer was tripped in the nose region at a distance of 25 mm from the apex.

Figure 2 shows geometric details of various afterbody models with base modifications. These may be classified under base cavities (configurations CH1–CH5, CT1–CT5, BC1, FC1), and ventilated cavities (configurations VC1–VC7, BV1, FV1). Configuration BD1 is a bleed device without a cavity; several variants of this were also examined. A cylindrical afterbody 100 mm long (see Fig.1) is used as a baseline configuration for assessing base- and net-drag reductions. Similarly, for the assessment of BC1, BV1, FC1, and FV1, corresponding unmodified boat-tailed and flared bases BBO and FBO (not shown in Fig. 2) are used.

Tunnel stagnation pressure was measured accurately with a 150-psia transducer. Two 5-psid transducers were employed to measure the diffferences, namely, of the freestream static to the base pressure and freestream static to the split pressure. Uncertainty in measured total-drag coefficient is estimated to be within ±0.004; the results (to be presented) indicate that the typical uncertainty in the drag coefficient is probably much better than the preceding value.

Results and Discussion

Results of base-pressure coefficient C_{pb} and total afterbody drag coefficient C_{DA} for various configurations shown in Fig. 2 are presented in Figs. 3–5 and in Table 1. The forebody sectional area (A) is used for defining C_{DA}.

Received Feb. 6, 1989; revision received Aug. 1989.

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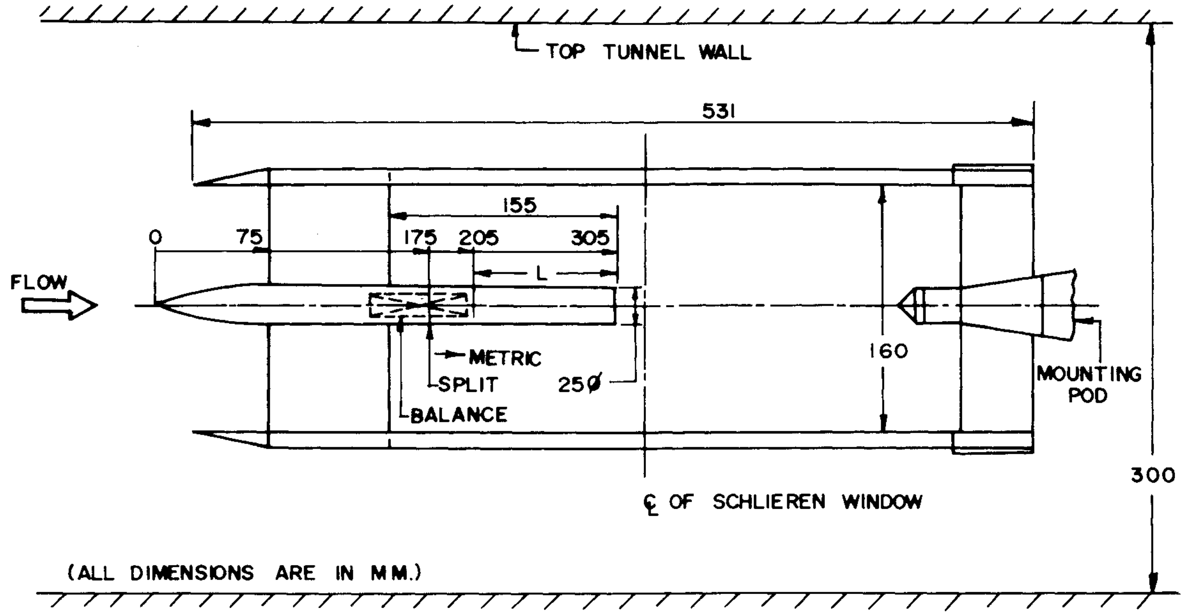
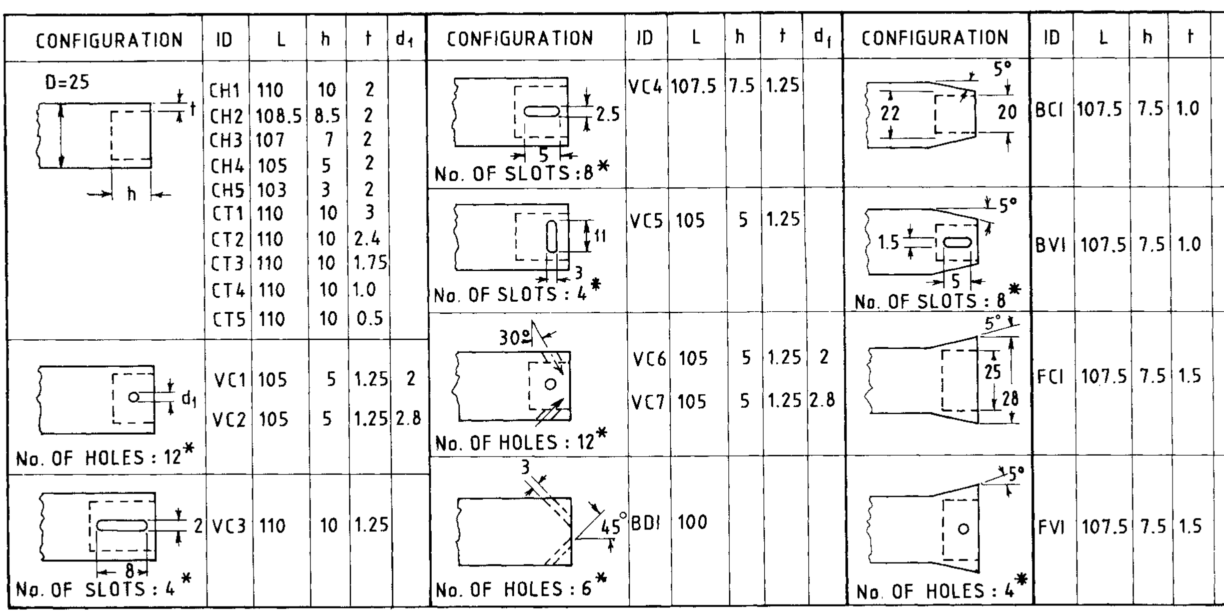


Fig. 1 Sketch of model and support system.



Configuration	ID	L	h	t	d_1
D=25	CH1	110	10	2	
	CH2	108.5	8.5	2	
	CH3	107	7	2	
	CH4	105	5	2	
	CH5	103	3	2	
	CT1	110	10	3	
	CT2	110	10	2.4	
	CT3	110	10	1.75	
	CT4	110	10	1.0	
	CT5	110	10	0.5	
No. OF HOLES : 12*	VC1	105	5	1.25	2
	VC2	105	5	1.25	2.8
No. OF SLOTS : 4*	VC3	110	10	1.25	
No. OF SLOTS : 8*	VC4	107.5	7.5	1.25	
No. OF SLOTS : 4*	VC5	105	5	1.25	
No. OF HOLES : 12*	VC6	105	5	1.25	2
	VC7	105	5	1.25	2.8
No. OF HOLES : 6*	BDI	100			
	BCI	107.5	7.5	1.0	
No. OF SLOTS : 8*	BVI	107.5	7.5	1.0	
	FCI	107.5	7.5	1.5	
No. OF HOLES : 4*	FVI	107.5	7.5	1.5	3

ALL DIMENSIONS ARE IN mm. * SPACED UNIFORMLY AROUND CIRCUMFERENCE

Fig. 2 Details of afterbody models.

Cylindrical Bases

Results for base cavities (configurations CH1–CH5, CT1–CT5) are shown in Figs. 3 and 4 bringing out the effects of cavity depth h and lip thickness t. Both base and total drag show an initial decrease up to a value of $h/D = 0.20$ and then remain constant for larger values of h/D. A similar qualitative behavior is seen with increase in lip thickness. Interestingly, the base-drag reduction, although small, is practically realized as net-drag reduction, suggesting negligible losses associated with base cavities. Optimum values of h/D and t/D, for maximum net-drag reduction, have values of about 0.20 and 0.04, respectively.

Effects of ventilated cavities with holes normal to the surface (configurations VC1–VC5) are displayed in Fig. 5; C_{pb} and C_{DA} are plotted against normalized total area associated with ventilation (A_v/A) for each device. The flagged symbols in Fig. 5 refer to models VC1 and VC2 wherein some holes were plugged (but symmetry retained) to provide data at lower values of A_v. Ventilation provides a natural bleed of air into the base region, augmenting the base pressure. A significant increase in base pressure, of as much as 50% for VC5, may be seen. Schlieren photographs of the near-wake flow (Fig. 6) for the baseline and configurations VC4 and VC5 clearly show that the free shear layers move outward to accommodate the higher base pressure resulting from the bleed effect; the higher base pressure leads to weakening of the shoulder expansion fan and of the recompression waves. The total drag reduction, however, is relatively smaller for these cases, indicating appreciable device losses, which result from the destruction of the streamwise momentum of air in passing through the holes and possible shock losses.

A correlation for the reduction in base and net drag (already evident in Fig. 5) is shown explicitly in Fig. 7; the lines drawn through the data are meant only to enhance visual clarity.

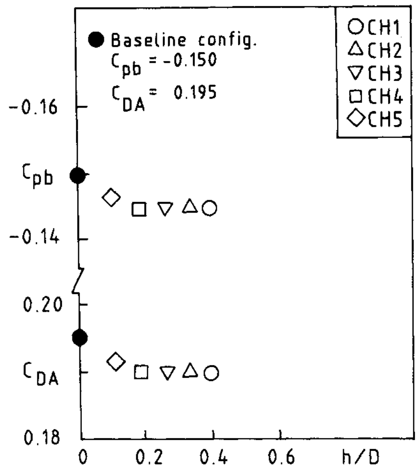


Fig. 3 Effects of cavity depth.

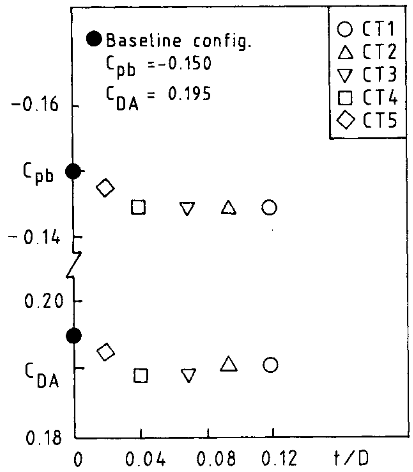


Fig. 4 Effects of cavity lip thickness.

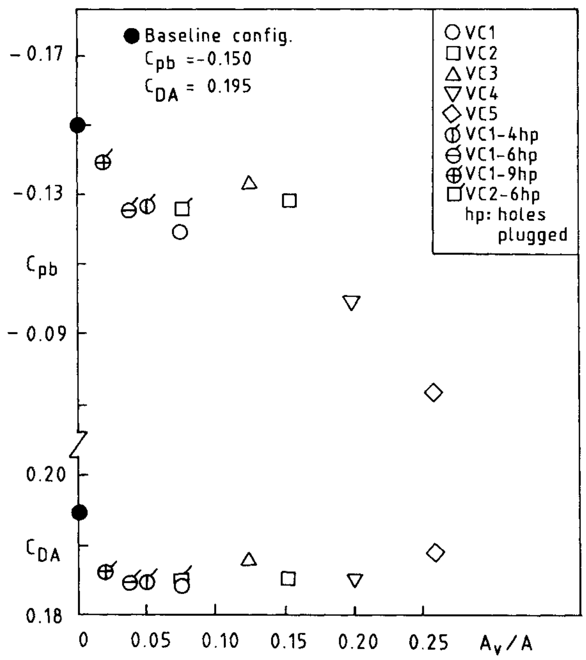


Fig. 5 Effects of cavity ventilation.

There is no ambiguity about the magnitude of net afterbody reduction (in view of direct measurement), but some assumptions are necessary to estimate the reductions in base drag since base-pressure information is known only on the model centerline. For axisymmetric bases in subsonic flow, base pressure variations of 5–10% across the radius have been observed[5]; one can expect at least similar variations for bases with cavities or with ventilation. However, in the absence of such information in literature, particularly at supersonic speeds, the measured base pressure on the centerline has been assumed uniform across the base in estimating the base drag. It is likely that the estimates of base-drag reductions shown in Fig. 7 are probably optimistic, but certainly significant. The total area of ventilation, A_v is proportional to the total bleed mass into the base region in an approximate sense. Although ΔC_{DB} exhibits a highly nonlinear variation with A_v, the net-drag reduction shows a gradual variation, with an optimum ventilation area of about 5% for maximum net-drag reduction. A similar correlation in terms of A_v/A was observed for the base-drag reduction at transonic speeds,[3] but the net drag

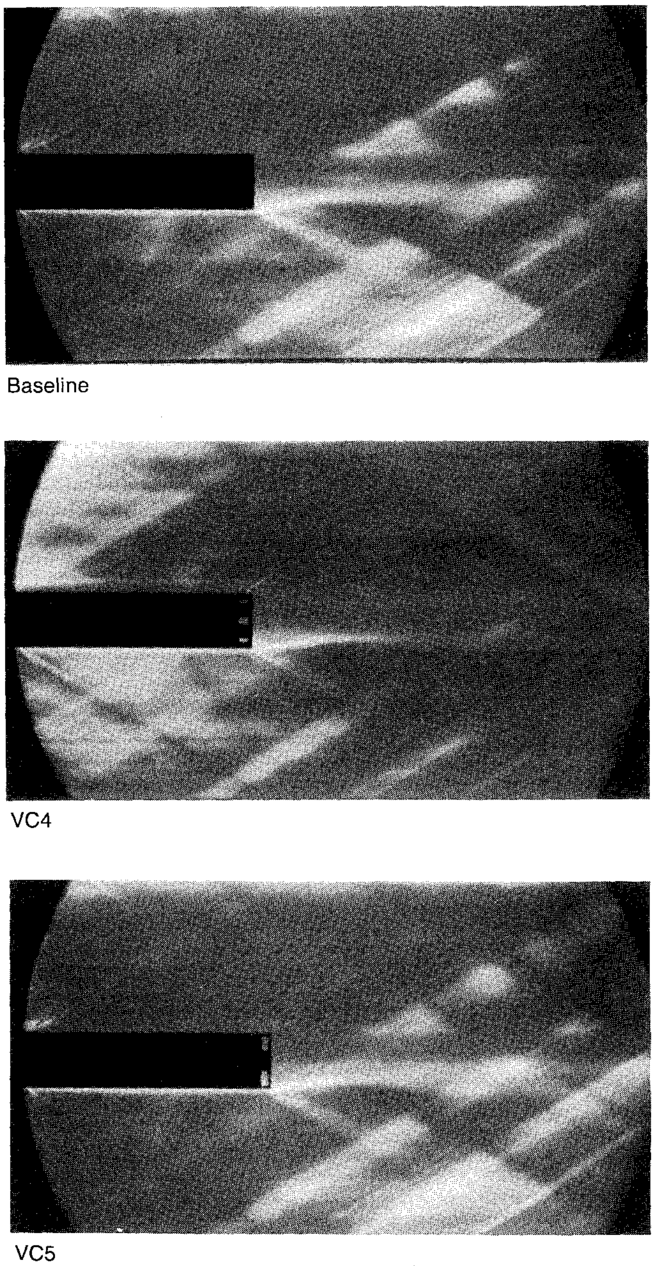


Fig. 6 Schlieren photographs.

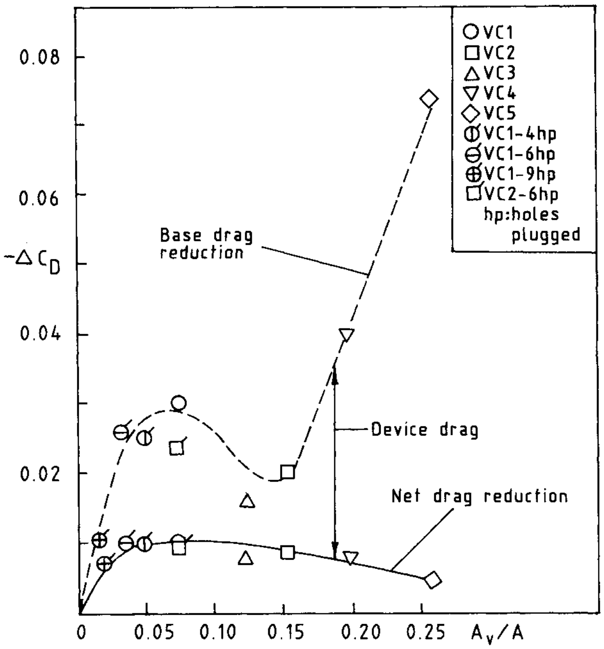


Fig. 7 Correlation of base and total drag reduction.

Table 1 Results of base pressure and afterbody drag

Config.	$-C_{pb}$	C_{DA}
VC6	0.130	0.190
VC7	0.110	0.189
BD1	0.107	0.190
BBO	0.129	0.160
BC1	0.127	0.158
BV1	0.110	0.157
FBO	0.166	0.266
FC1	0.164	0.265
FV1	0.123	0.250

reduction was found to be dependent on the cavity as well as ventilation geometry.

Table 1 shows results of base-pressure and afterbody drag for the configurations VC6, VC7, and BD1 with inclined bleed holds. Although the base pressure increase is comparable to configurations VC1–VC5, the drag values are relatively higher because of the increased losses due to increased bleed velocities (through the inclined bleed holes); shock losses may be a factor contributing to the higher device losses. Tests on variants of configuration BD1, having different bleed hole diameters or numbers of holes, yielded results similar to that of BD1, and therefore the data for these are not included in Table 1.

Boat-Tailed and Flared Bases

Results for the boat-tailed and flared (unmodified) baseline configurations BBO and FBO and with base modifications (configurations BC1, BV1, FC1, FV1) are included in Table 1. For the boat-tailed base, both cavity and ventilation have only a small favorable effect, a feature similar to the observation made at transonic Mach numbers.[3] For the flared base, on the other hand, ventilation is quite effective and the base- and net-drag reductions are comparable to those on cylindrical bases with ventilation (see Fig. 7).

Conclusions

Results are presented assessing the effectiveness of base and ventilated cavities for the reduction of base and net afterbody drag at Mach 2. Ventilated cavities (with holes normal to the surface) are promising as useful drag reduction devices at supersonic speeds. An increase in base pressure, of as much as 50% has been observed, which is significantly higher than the effects seen at transonic Mach numbers. However, the net afterbody drag reductions that can be realized are relatively lower and still comparable to those observed at transonic speeds; the net-drag reduction seen could mean as much as 3–5% of the total drag for a body of revolution at supersonic Mach numbers.

Both base cavity and ventilation have only a small effect with boat-tailing, which is perhaps the most effective passive technique of a reducing base drag. With a flared base, favorable effects of ventilation are as good as on cylindrical bases. It is likely that the drag reductions observed in this study are typical of what can be obtained from these devices at supersonic speeds.

With ventilation, the mechanism responsible for the increase in base pressure is primarily the well-known base-bleed effect affecting the mean flow in the base region. The mechanisms associated with base cavities are not clear; the dependence of base pressure on the cavity depth and lip thickness (although weak) suggests that the separation phenomenon may be similar to that causing lip shock formation[6] on wedge bases in supersonic flow.

Acknowledgement

This work was carried out with assistance from a grant received from the Aeronautical Development Agency, Bangalore. The assistance of the 0.3-m tunnel staff in carrying out the experiments and the staff of the Model Shop in the model fabrication are gratefully acknowledged.

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Associate Editor