PASSIVE BOUNDARY-LAYER BLEED FOR SUPERSONIC INTAKES

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ABSTRACT

Passive boundary layer control experiments were conducted on a small supersonic sidewall intake at a Mach number of 1.36 to study the possibility of improving the intake performance by such a control. The passive bleed configuration tested had a wide suction slot in the intake duct and a narrow tangential injection slot upstream of the intake entry. The slots were interconnected by a breather passage. The results of the experiments showed that for a supersonic intake passive control can reduce the shock interaction losses, improve the overall pressure recovery, and control the pre-entry shock position.

NOTATION

P	total pressure
ΔP	loss of total pressure
A	cross sectional area
δ_u	undisturbed boundary-layer thickness
h	height
C_p	pressure coefficient
C_{ps}	pressure rise to separation
y	vertical displacement from intake floor
x	horizontal displacement from intake entry
η_R	intake ram efficiency (Fig.1b)

SUBSCRIPTS

∞	conditions in freestream
en	conditions in intake entry
t	condition at intake traverse station
ex	conditions at intake exit
f	conditions at intake measuring station
a	relating to approach
d	relating to duct
sh	relating to shock system
i	relating to shock interaction

INTRODUCTION

On supersonic aircraft engine intakes with external compression, the pre-entry pressure rise has an important influence on design. The presence of pre-entry shock waves and overall pressure rise in the intake may lead to flow distortion and boundary-layer separation resulting in deterioration of the intake performance.

The intake efficiency can be increased by active boundary-layer control such as boundary-layer removal by suction through a large slot, known as boundary-layer trap (example Concorde) or by re-energizing the boundary-layer by injection of a jet of air at high velocity. The latter method has been widely used in subsonic flow to prevent separation (example: high lift flaps) but not adopted as an alternative to bleed in intake design.

Passive boundary-layer control where the static pressure difference across the shock wave is utilised to both blow the air upstream and suck the air downstream of shock has been studied for transonic flows. Such a technique to improve the performance of supersonic intakes has not been investigated.

An experimental study on the possibility of improving the performance of supersonic intake is presented in this paper.

PRE-ENTRY FLOW AND CONTROL

The performance characteristics of a supersonic intake are strongly influenced by the shock system set up near the intake entry. This shock system decelerates the freestream supersonic flow to a subsonic flow of Mach number $\approx$ 0.4, which is the required airspeed for efficient engine compressor performance (Fig. 1a). for a sidewall intake, with an external boundary-layer, the total pressure loss ΔP consists of the boundary-layer friction losses of the approaching airflow ΔP_a, the boundary-layer friction losses within the intake duct ΔP_d, shock losses across the pre-entry shock wave ΔP_{sh} and losses associated with the viscous interaction of the shock with the intake boundary-layer ΔP_i so that

$$\Delta P = \Delta P_a + \Delta P_d + \Delta P_{sh} + \Delta P_i$$

As shown in Fig. 1b taken from Ref. 1 ΔP_i represents a major proportion of the total losses. Since intake efficiency is directly proportional to intake pressure recovery it is therefore necessary to reduce ΔP_i

in order to improve intake performance. In general the losses arising from the shock wave boundary-layer interaction can be reduced by controlling the shock and/or the associated boundary-layer separation. Due to the interactive nature between the two, control of one always leads to the control of the other. In the case of supersonic intakes it is beneficial to reduce the losses associated with the shock induced separation without a penalty on the static pressure rise across the shockwave.

The boundary-layer control methods generally used in supersonic intakes are boundary-layer bleeds and boundary layer diverters. In the case of a bleed, which can be a ram bleed or flush bleed a separate duct is used to remove the boundary-layer. An example of this type of control is the bleed system developed for Concorde[2] (Fig. 2) with a wide flush bleed at the throat of the intake. In the case of diverters, which may be of the channel or step type, the intake stands off from the aircraft surface, the boundary-layer on the surface being diverted away from the intake (fig. 3). Typical results for a wedge intake incorporating a channel type diverter[3] show that the reduction in total pressure loss is a function of the ratio of diverter height to boundary-layer thickness.

Experiments have shown[4,5,6] that these control methods can reduce the total pressure losses other than shock losses by 50% to 75%.

Another method of boundary-layer control is by blowing. An example of the use of blowing in tests on a supersonic intake is illustrated in Fig. 4. In experiments performed by Wong and Hall[7] the gain in pressure recovery is substantial and in this case somewhat greater than that obtained with a distributed bleed. As an alternative to the boundary-layer bleed, however, blowing so far as is known has not been adopted in a practical supersonic intake design.

In all the above control methods the extent of overall performance is limited due to the drag associated with the control device. A method which is currently being studied to reduce drag and alleviate buffet in transonic flow is passive boundary-layer control[8] (see Fig. 5). The concept consists of a porous surface and cavity or plenum located in the region of the shock interaction. The static pressure rise across the shockwave results in a flow through the cavity from downstream to upstream of the shock. This has the effect of thickening the boundary layer approaching the shock which, in turn, produces a system of weaker oblique shocks which reduces shock losses. Suction downstream of the shock may also reduce boundary-layer losses resulting in significant drag reduction.

Such a method has not been studied for reducing total pressure losses in supersonic intakes. In this research work passive boundary-layer control has been adapted to produce a reduction in total pressure losses in a supersonic intake without significantly affecting intake static pressure recovery.

Experimental Programme

Experiments were conducted in a 127 mm x 77 mm intermittent supersonic blow down tunnel at a total pressure of one atmosphere. The nominal Mach number in the test section was 1.4. The datum intake model was sharp lipped and similar in geometry to those of early studies by Seddon and Haverty[1,9] at the Royal Aerospace Establishment, Farnborough. The intake model had an exit flap operated by a micrometer to control the exit area A_{ex} and therefore the mass flow A_{∞}/A_{en} through the intake. The details of the intake model are given in Fig. 6. The intake model was mounted on a tilting plate as a mechanism to vary the Mach number at the inlet of the intake (Fig. 7). The plate was tripped 5 mm from the leading edge to produce a turbulent boundary-layer. The plate and floor of the intake had pressure orifices along the streamwise centreline for static pressure measurements.

The intake also had a pitot traversing gear to measure the total pressure profiles within the intake duct.

A passive bleed device used in these experiments for boundary-layer control is shown in Fig. 8. This configuration evolved after discussions with E.L. Goldsmith[10]. In this device the upstream blowing is tangential to the surface rather than at an angle as investigated in some of the transonic flow experiments. This was to prevent over thickening of the boundary-layer and the consequent effect of softening the shock system. At downstream of the shock a wide slot was used to ensure that the bleed was full. This contrasts with transonic experiments with narrow slots.

Intake mass flow was calculated from the total and static pressures recorded at the intake measuring station as outlined in the Appendix.

Tests were performed for the datum intake and passive controlled intakes at a fixed freestream Mach number of 1.36 and for values several of mass flow ratio. For the passive control experiments, four configurations were chosen. Passive control configurations A, B, C correspond to a fixed suction slot and three different injection slot locations. Configuration D corresponds to a relatively wider suction slot. The test conditions are tabulated in Table 1.

The measurements included mean pressure distribution on the centreline of the floor of the intake and pitot traverses downstream of the intake entry, total pressure measurements at locations in the intake measuring station and optical flow visualisation using the shadowgraph technique.

Results and Discussion

The Mach number profile at the intake entry plane (83 mm from the plate leading edge) without the presence of the intake (i.e. undisturbed boundary-layer) is shown in Fig. 9. As can be observed in this figure the Mach number profile is similar to that measured by Seddon and Harvey in their experiments. The non-dimensional boundary-layer thickness of the undisturbed boundary-layer in this plane was δ_u/h_{en} = 0.22. This compares well with the values of δ_u/h_{en} = 0.23
in the experiments of Seddon and Haverty.

Fig. 10 shows for the datum intake the variation of static pressure coefficient C_p on the intake floor for a freestream Mach number of M_∞ = 1.36 and for several values of mass flow ratios A_∞/A_{en}. It is seen from this figure that the pressure coefficient at the entry C_{pen} reaches a value of 0.37 and is invariant with A_∞/A_{en}. This indicates separated flow at the foot of the shock. According to Gadds theory extended in Ref. 1 to include energy entrainment in the boundary layer the value of pressure coefficient for separation to occur at this Mach number is C_{ps} = 0.38 which agrees closely with the present results. It is also observed from this figure that a reduction in A_∞/A_{en} moves the shock and therefore separation point upstream of the entry plane. This should increase the height of the separated flow region at the entry, which is the mechanism for reducing the mass flow through the intake when A_{ex}/A_{en} is reduced.

Fig. 11 shows the corresponding pressure distribution for the intake with a passive control configuration B. Several features of passive control can be observed from this figure. The static pressure at the intake entry plane C_{pen} increases when
A_∞/A_{en} is reduced. In the case of datum intake C_{pen} was virtually constant within the range of mass flow ratios tested. The pre-entry shock stands upstream of the injection slot. The maximum pressure rise, due to pre-entry shock occurs at this slot position, over a range of A_∞/A_{en}. This would suggest that the height of the dead air region does not increase with the decrease in A_∞/A_{en}. The upstream interaction region increases with the decrease in A_∞/A_{en}.

The pressure distribution on the intake floor for the datum model is compared with passive control configurations B and C in Fig. 12. The results shown here are for A_∞/A_{en} = 0.63.

The passive control configurations B and C have virtually no effect on the overall static pressure recovery but have significant effects on the pre-entry flow. When the results of passive control configurations are compared with the datum model it is observed that whereas configuration C reduced the value of pressure coefficient to separation, configuration B has increased this pressure value to 0.4. The configuration B also produces a post shock expansion indicating a change in the geometry of the separation bubble. It could be hypothesised that these changes are brought about by the recirculating airflow in the passive control region. It can also be inferred from Fig. 12 that the leading edge of the λ shock system is just upstream of the injection slot location. This is confirmed by the shadowgraphs taken for the same test conditions (Fig. 13). Further as mentioned earlier (Fig. 11) the leading leg of λ is virtually anchored close to the injection slot for a range of mass flow ratios. These findings suggest passive control is an effective technique for controlling pre-entry flow in supersonic intakes.

The effect of increased suction slot width for a given injection slot location can be observed by comparing the pressure distributions for the configurations B and D (Fig. 14). The increase in suction slot width increases the pre-entry pressure rise but has resulted in a reduced overall pressure recovery probably due to reduced pressure recovery in the diffuser. The wider slot occupies a significant part of the diffuser and therefore reduces the effective area of diffusion. As will be seen later this configuration actually produces more losses. Fig. 14 also indicates that the width of the suction slot has only a weak influence on the pre-entry shock location and the height of the separated flow.

The total pressure profiles P/P_∞ measured on the centreline of the datum intake at a location x/h_{en} = 1.8 and downstream of the pre-entry shock is shown in Fig. 15. Results shown here are for mass flow ratios 0.92, 0.83, 0.73 and 0.65. The total pressure profiles clearly show the boundary-layer separation over the range of mass flow ratios A_∞/A_{en} consistent with the pressure distributions shown in Fig. 11. The height of the separated flow increases with the decrease in A_∞/A_{en} from about 0.2 h_{en} for A_∞/A_{en} = 0.92 to 0.4 h_{en} for
A_∞/A_{en} = 0.65 due to forward movement of the pre-entry shock as observed also by Seddon and Haverty.

The total pressure profiles for the datum model is compared with those for passive control configurations B and D in Fig. 16. Results shown here are for an area ratio A_{ex}/A_{en} = 0.81. The figure shows that the configuration B is very effective in reducing the total pressure losses over the entire height of the intake. The configuration D shows a reduction on total pressure losses only close to the surface but an increase in total pressure losses over most of the intake which also results in a reduced static pressure rise in the intake as observed in Fig. 14.

In Fig. 17 the total pressure losses are compared, which includes the shock losses and shock interaction losses (ΔP_{sh} + ΔP_i), for all the configurations tested and for a range of mass flow ratios. The total pressure loss integral ΔP was obtained by the summation

$$\Delta P = \frac{1}{h_t} \sum_{y=0}^{y=h_t} \left(1 - \frac{P}{P_\infty}\right) dy$$

where h_t is the height of the intake at the traversing station. The approach loss ΔP_a has been calculated from the undisturbed boundary-layer profile.

The results shown in this figure indicate that the position of the blowing slot is crucial to achieve the beneficial effects of passive control. Positioning the injection slot too close to the suction slot (Configuration A) could have resulted in both slots within the separated region in which case the passive control is ineffective. positioning the injection slot too far upstream (configuration C) might have resulted in the excessively separated boundary-layer entering the intake with a detrimental effect on shock boundary-layer interaction. Configuration B, where the injection slot is positioned at a distance from the entry approximately equal to the height of the intake appears to produce a considerable reduction in ΔP. The width of the suction slot is also an important parameter. The suction bleed width of configuration B corresponds approximately to the height of the separated boundary-layer downstream of shock ($\sim$ 0.5 h_{en}) which produces a greater reduction in ΔP when compared to the wider bleed slot (configuration B) whose width is about twice the height of the separated boundary-layer.

The height of the injection slot in all the configurations tested was approximately equal to twice the displacement thickness of the attached boundary-layer approaching the intake. It is likely that a larger slot would have thickened the boundary-layer excessively and weakened the shock wave to produce increased losses and reduced pressure recovery.

Fig. 18 shows a plot of the overall pressure recovery P_f/P_∞ vs mass flow ratio for control configurations A, B, C and the datum intake. The value of P_f is an average value of total pressure at the intake measuring station based on only a 12 point pitot array which although is standard procedure for evaluating P_f may be inaccurate on a small intake with a thick boundary-layer and large flow distortion, therefore results should be viewed with caution. Nevertheless, the results shown in the figure reinforce the earlier discussion that passive boundary-layer control (configurations B and C in this plot) can improve overall pressure recovery of a supersonic intake.

Compared to the datum intake the maximum value of mass flow ratio has been reduced with the application of the passive control configurations tested. A possible reason could be that not all the air from the injection slot re-enters the intake duct due to spanwise spillage. Further the injection slot is not precisely parallel to the intake floor and therefore velocity components normal to the freestream flow may be introduced here, reducing mass flow at the intake entry.

Conclusions

Passive shock boundary-layer control experiments were conducted on an intake in a small supersonic tunnel at a Mach number of 1.36. The results of the experiments showed that.

(i) The pre-entry shock position can be controlled by positioning the injection slot.

(ii) Passive control devices can reduce the shock interaction loss appreciably with an improvement in the overall pressure recovery.

(iii) The location of the upstream injection slot and width of the suction slot are critical to achieve significant improvements in the intake performance.

and

(iv) Large scale tests may be needed to support some of the findings of the present investigations.

APPENDIX

A 4 x 3 pitot probe array is situated at the intake measuring station enabling total pressure and, hence, mean pressure recovery to be calculated. Four static pressure probes are also located in the measuring station and the intake mass flow is determined form the total pressure recovery and static pressures applying the equation

$$\frac{A_\infty}{A_{en}} = \frac{P_f}{P_\infty}\left(\frac{A*}{A}\right)_f \times \frac{A_f}{A_{en}}\left(\frac{A}{A*}\right)_\infty$$

For each pitot the local Mach number is found and hence the local value A^*/A. The individual products of p/p_∞, A/A^* and the elemental area ΔA associated with the pitot position are summed as below

$$\frac{A_\infty}{A_{en}} = \left[\sum_{n=1}^{12} \frac{P_n}{P_\infty} \left(\frac{A*}{A} \right)_n \frac{\Delta A_n}{A_{en}} \right] \times$$

$$\left(\frac{A}{A*} \right)_\infty k_t$$

The calibration factor k_t is determined from a known mass flow in this case a pitot intake operating at supercritical/critical flow conditions (i.e. A_∞/A_{en} = 1.0).

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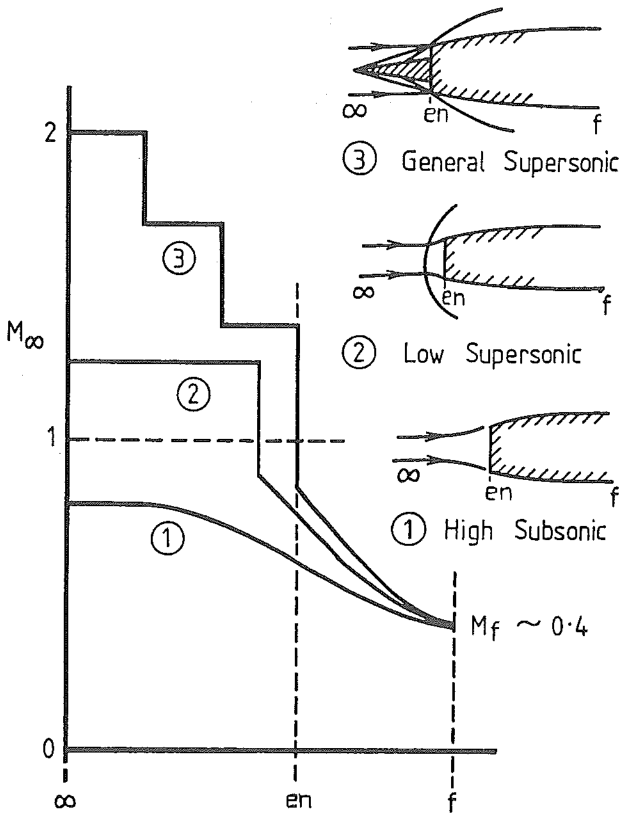


Fig. 1(a). Flow deceleration in an engine.

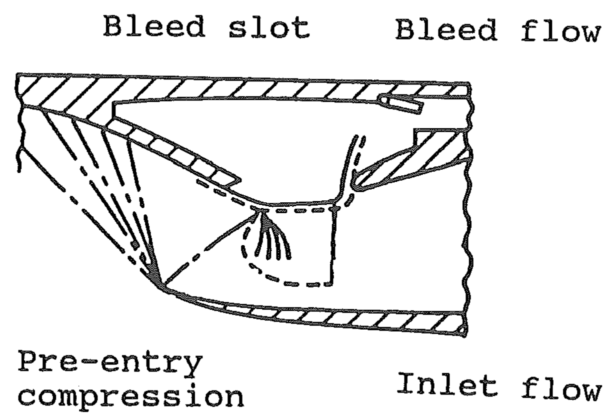


Fig. 2. Ram bleed for a supersonic intake.

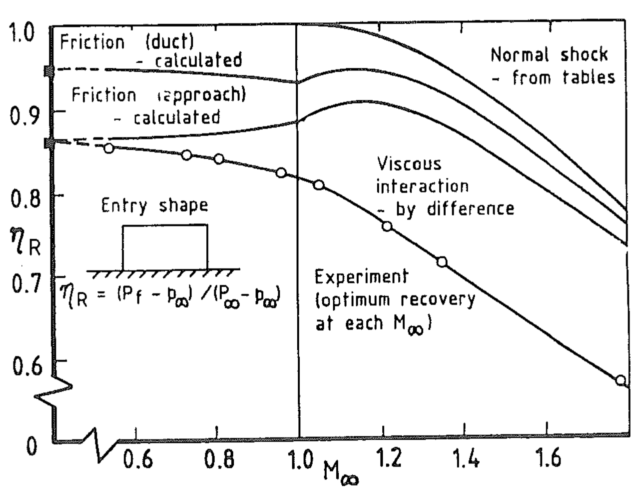


Fig. 1(b). Total pressure losses in an intake.

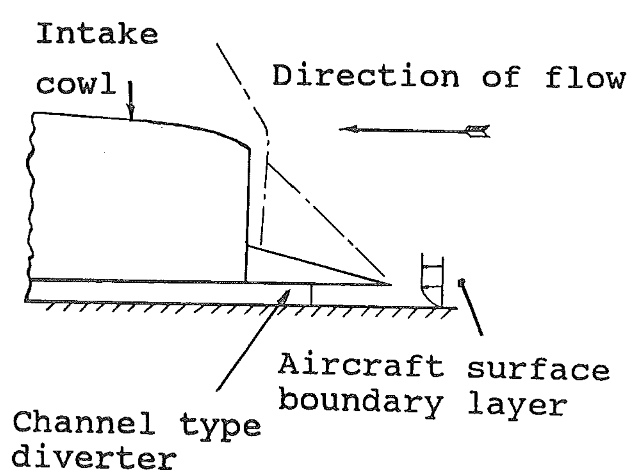


Fig. 3. Boundary-layer diverters for a supersonic intake.

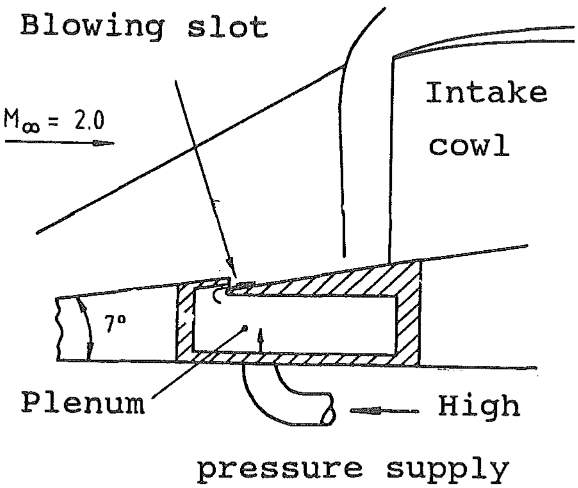


Fig. 4. Blowing in a supersonic intake.

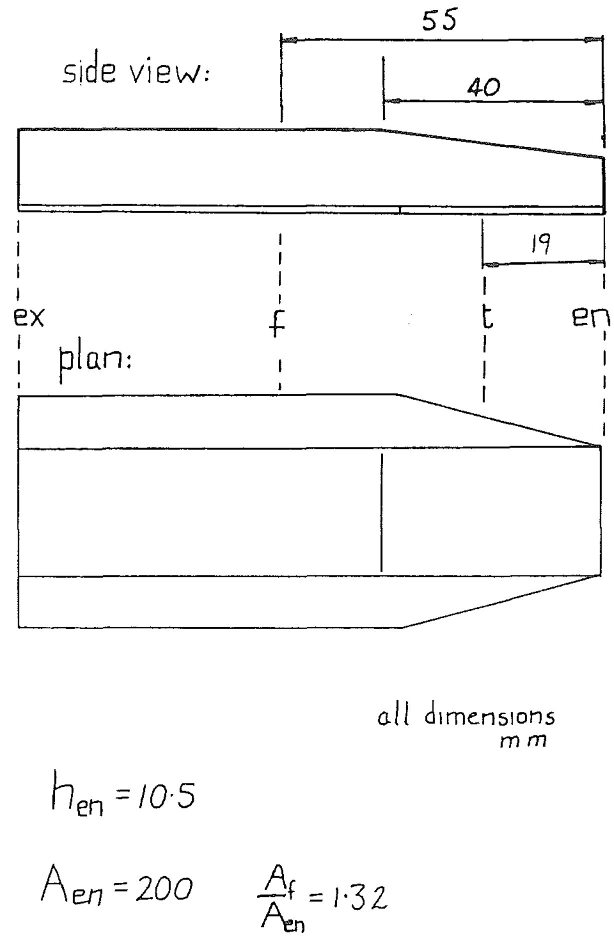


Fig. 6. Details of intake model.

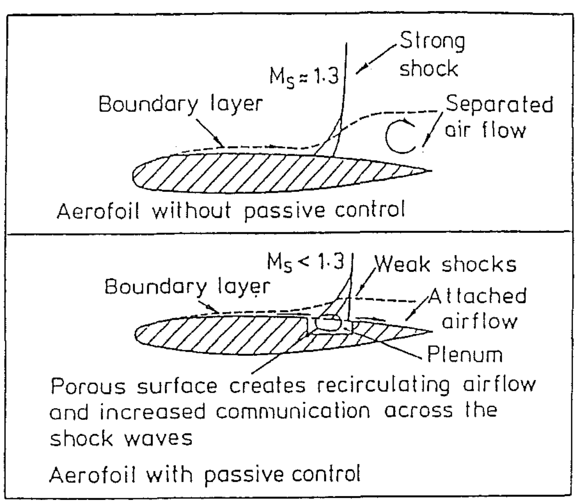


Fig. 5. Passive shock wave boundary-layer control in transonic flow.

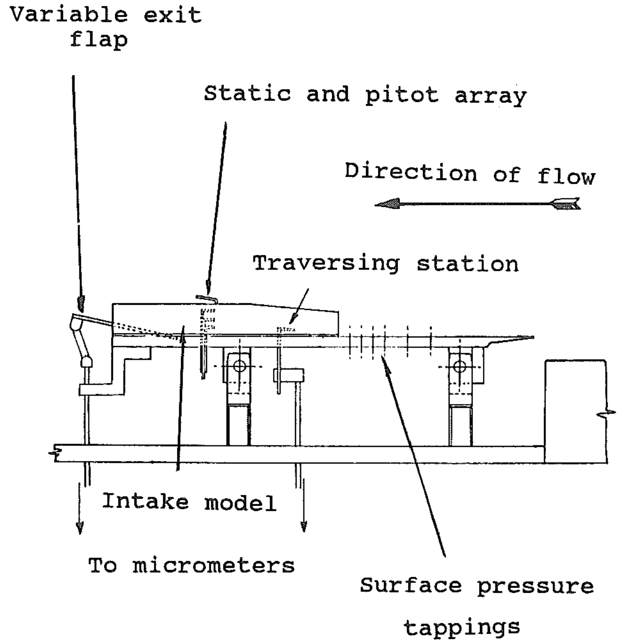


Fig. 7. Model arrangement in the tunnel.

Passive control	Injection slot position $-\frac{x_{inj}}{h_{en}}$	Injection slot area $\frac{A_{inj}}{A_{en}}$	Bleed slot area $\frac{A_{bld}}{A_{en}}$
A	0.57	0.095	0.47
B	1.14	0.095	0.47
C	2.19	0.095	0.47
D	1.14	0.095	0.95

Table 1. Test configurations

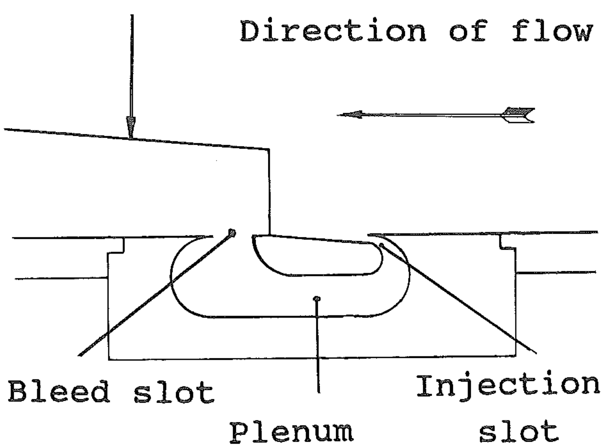


Fig. 8. Details of passive bleed device.

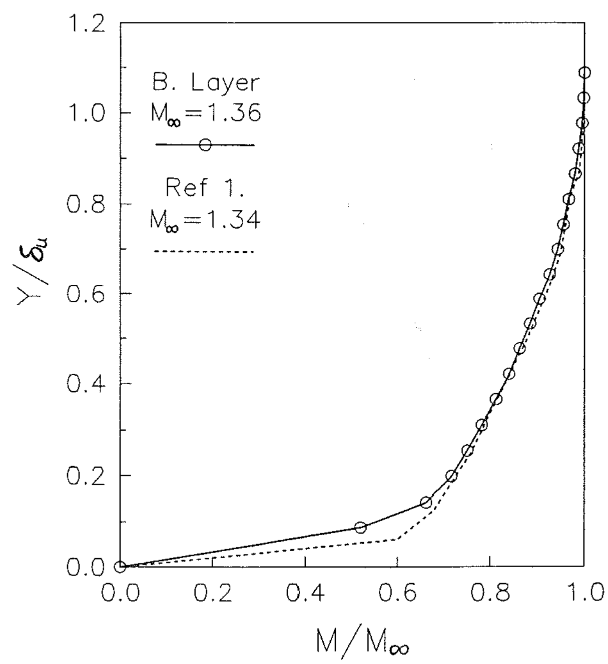


Fig 9. Mach number profile in entry plane: intake removed.

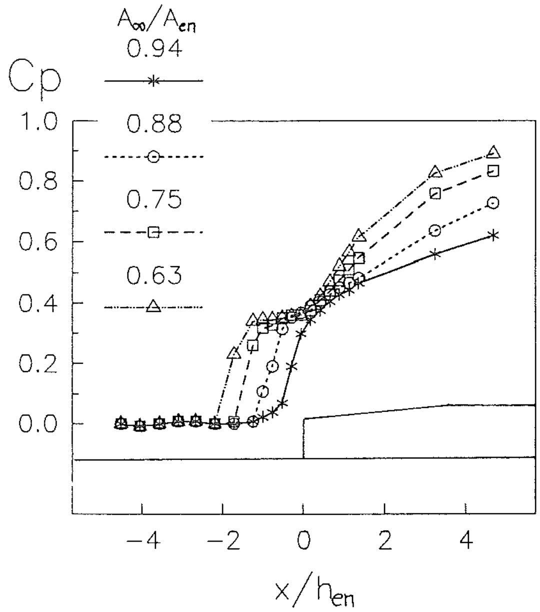


Fig 10. Cp Distribution datum intake. M =1.36 (for various A_∞/A_{en})

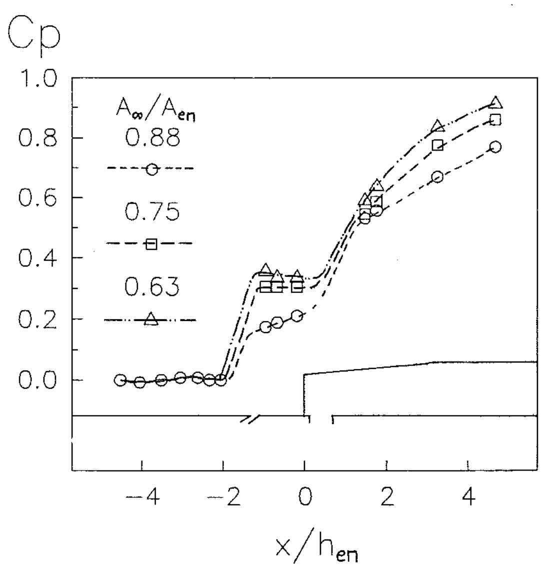


Fig 11. Cp Distribution passive control B. M =1.36 (various A_∞/A_{en})

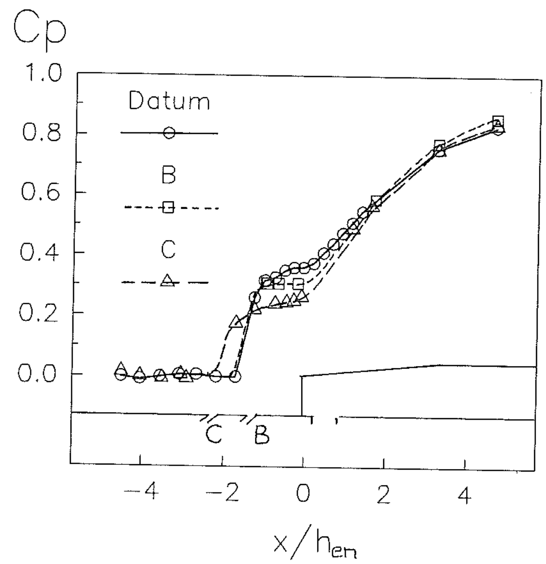
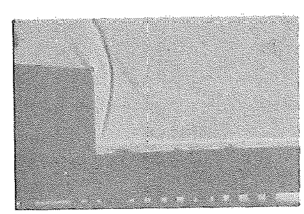
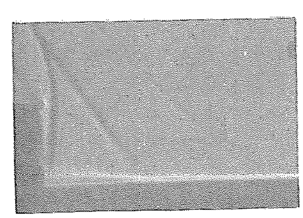


Fig 12. Effect of injection slot position on Cp distribution. A_∞/A_{en}=0.75



Datum



Configuration A

Fig. 13. **Shadowgraphs - datum and passive bleed.**

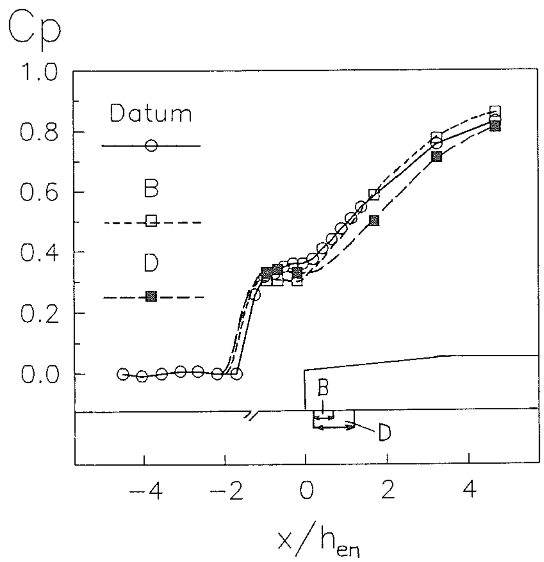


Fig 14. Effect of bleed slot width on Cp distribution. $A_\infty/A_{en}=0.75$

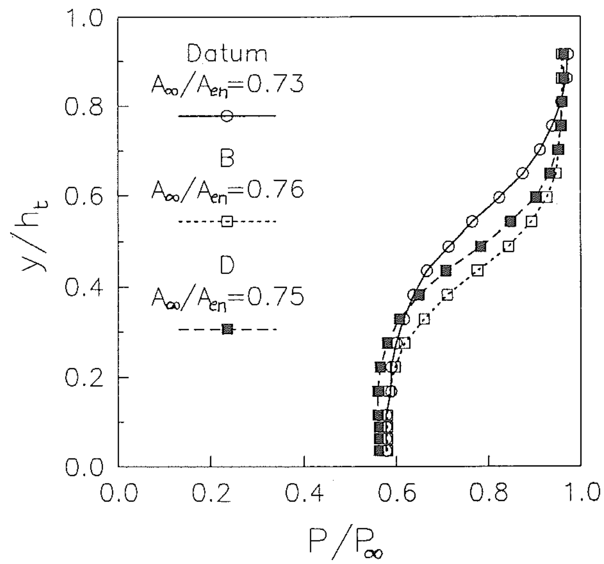


Fig 16. Total pressure profiles for passive control B and D. $A_{ex}/A_{en}=0.81$.

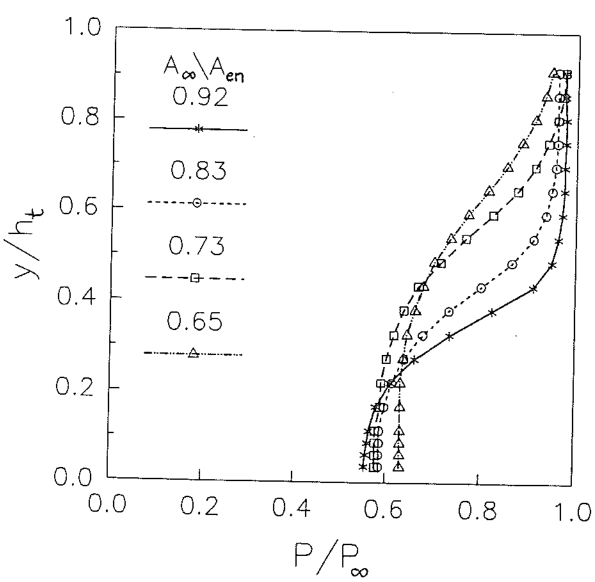


Fig 15. Total pressure profiles at traversing station: datum intake.

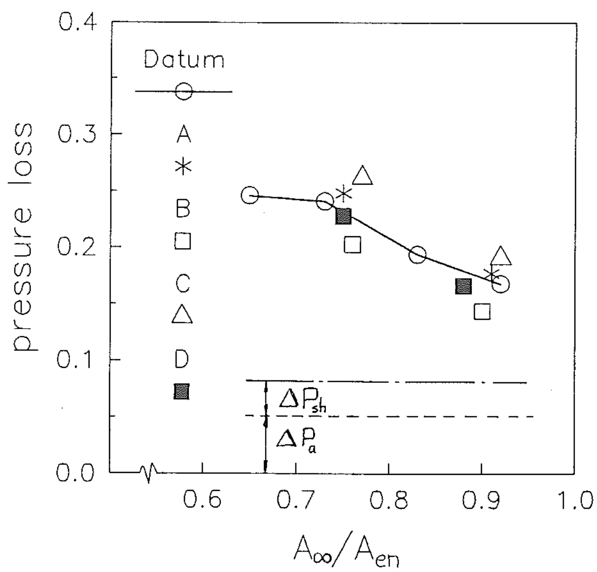


Fig 17. Pressure losses in duct boundary layer.

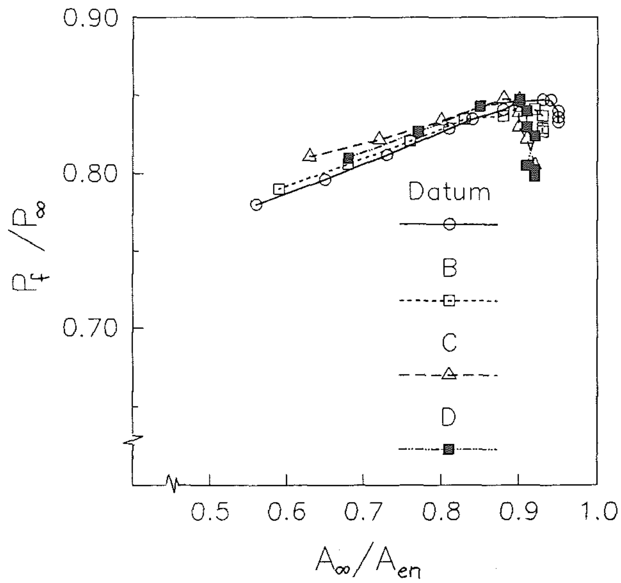


Fig 18. Pressure recovery for passive control B, C and D.