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The Stepped Supersonic Intake

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Abstract

On supersonic aircraft engine intakes with external compression, the pre-entry pressure rise has an important influence on design. A novel technique to control the pre-entry shock is a stepped supersonic intake. The height of the step can be adjusted to match the shock system with the intake height. The step has to be retracted for subsonic operations of the intake. Apart from only experiments at a Mach number of 2 by Goldsmith and Osborne which did indicate that in principal the pressure recovery can be improved with this concept, this type of intake has not been investigated in any detail. In order to understand the performance of a stepped intake 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 1.46. The datum intake model was sharp lipped and similar in geometry to those of earlier studies by Seddon and Haverty at the Royal Aerospace Establishment, Farnborough. Tests were performed for the datum intake, stepped intake with and without a passive boundary-layer control. Typical results show that the intake performance can be improved at low mass flow ratios by a step at the inlet.

Notation

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

Subscripts

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

Introduction

The role of the aircraft intake is to supply air to the engine over a range of flight conditions. 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[1] (Fig. 1a). The large overall pressure rise in a supersonic intake and the presence of pre-entry shock waves presents the worst possible situation for a boundary layer. The result may be flow deterioration in one or more well known forms such as separation or boundary layer profile distortion.

The loss in total pressure of the air passing through an intake is the standard measure of intake efficiency. For a sidewall intake with an external boundary layer the loss in total pressure is made up of four components - the boundary layer frictional losses of the approaching airflow, the boundary layer frictional losses within the intake duct, the shock losses across the pre-entry shock wave and losses associated with the viscous interaction of the shock with the intake boundary layer[2] (Fig. 1b). For supersonic intakes this final interaction loss represents a major portion of the total losses. In general the losses arising from the shock wave boundary-layer interaction can be reduced by controlling the shock and/or associated boundary-layer separation. Due to the interactive nature of the two control of one always results in changes to 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 shock.

The boundary-layer control methods generally

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forward of the entry plane of an intake. The wedge angle for a turbulent boundary-layer is typically 10 degrees and would generate a two shock compression of air flow. The shock angle and shock position of the leading oblique shock are functions of freestream Mach number and step height respectively. Thus for a given flight Mach number the height of the step can be adjusted to match the shock system with the intake. The step is retracted at subsonic speeds. The separated flow downstream of the step can be removed by a boundary layer bleed. Experiments by Goldsmith and Osborne have shown that for an efficient bleed downstream of a step, the bleed height should be at least the step height. But such an arrangement would cause a restriction when the step is retracted for subsonic operations. Even with a bleed lip height less than the height of the step, the pressure recovery increase is still significant. However the bleed mass flow requirements for a significant improvement in pressure recovery is large. The effect of a step on the stable operating regime of an intake is similar to that of boundary-layer blowing in the sense that the buzz levels in the intake are reduced.

A stepped supersonic intake can be used in conjunction with a passive boundary-layer control device and the merits of such a concept are assessed in this paper.

Experimental Programme

Experiments were conducted in a 127 mm x 77 mm intermittent supersonic blowdown tunnel at a total pressure of one atmosphere. Tests were performed at a nominal test section Mach number of 1.46. The datum intake model was sharp lipped and similar in geometry to those of early studies by Seddon and Haverty(2,12) at the Royal Aerospace Establishment, Farnborough. The intake model had an exit flap operated by 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. 5. 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 boundary-layer trip was made of carborundum powder 3 mm wide. The Reynolds number at the intake entry based on the approach plate length and boundary layer thickness were 1.37×10^6 and 4.18×10^4 respectively. 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 at the intake traversing station t to measure the total pressure profiles within the intake duct.

The passive bleed device used in these experiments for boundary-layer control (Fig.5) had a blowing slot tangential to the surface to prevent over thickening of the boundary-layer and the consequent effect of softening the shock system. Downstream of the shock a wide slot was used to ensure that the bleed was full. This contrasts with transonic experiments where narrow slots were used for passive control(13).

The step intake device had a step height of 2.5 mm and length 2 mm position near the intake entry. The height of the step was slightly greater than the boundary-layer thickness at the intake entry $\delta_u = 2.31$ mm.

Intake mass flow was calculated from the total and static pressures recorded at the intake measuring station f which was downstream of the intake diffuser and passive control device. The procedure for calibration was similar to that given in Reference 1.

Tests were performed for the datum intake, intake with a step only (A), and an intake with a combination of passive control and step (B) and an intake with the passive control device only (C). A configuration (D) was also considered for comparison of the relative merits of the devices tested. This is a passive control device[7] similar to (C) except that in this device the bleed is vented to a position on the plate well upstream and away from the centre line of the intake and where the pressure was free stream pressure. The test conditions were tabulated in Table 1.

The measurements included mean pressure distribution on the centre line of the floor of the intake, pivotal traverses downstream of the intake entry, total pressures at the intake measuring station and optical flow visualisation using shadowgraph.

Results and Discussion

Although the results presented here are essentially for M = 1.46 the boundary-layer Mach number profile at the intake entry shown in Fig. 8 is for M = 1.36 as this Mach number is close to the intake test conditions for Ref. 2. The profile shown is at the intake entry plane (83 mm from the plate leading edge) without the presence of the intake (i.e. undistributed boundary-layer). As can be observed in this figure the Mach number profile is similar to that measured by Seddon and Haverty(2) in their experiments and is a turbulent profile. The non-dimensional boundary-layer thickness of the undisturbed boundary-layer in this plane was $\delta_u/h_{en} = 0.22$. This compares well with the values of $\delta_u/h_{en} = 0.23$ in the experiments of Seddon and Haverty(2).

Fig. 9 shows for the datum intake the variation of static pressure coefficient C_p on the intake floor for a freestream Mach number of $M_\infty = 1.46$ and for several values of mass flow ratios A_∞/A_{en}. The sharp rise in C_p upstream of the intake entry indicates the presence of the pre-entry shock system. The pressure coefficient at the entry C_{pen} reaches a value of 0.370 and is invariant with A_∞/A_{en}. This indicates separated flow at the foot of the shock. According to Gadd's theory extended to include energy entrainment in the boundary-layer(1), the value of forward of the entry plane of an intake. The wedge angle for a turbulent boundary-layer is typically 10 degrees and would generate a two shock compression of air flow. The shock angle and shock position of the leading oblique shock are functions of freestream Mach number and step height respectively. Thus for a given flight Mach number the height of the step can be adjusted to match the shock system with the intake. The step is retracted at subsonic speeds. The separated flow downstream of the step can be removed by a boundary layer bleed. Experiments by Goldsmith and Osborne have shown that for an efficient bleed downstream of a step, the bleed height should be at least the step height. But such an arrangement would cause a restriction when the step is retracted for subsonic operations. Even with a bleed lip height less than the height of the step, the pressure recovery increase is still significant. However the bleed mass flow requirements for a significant improvement in pressure recovery is large. The effect of a step on the stable operating regime of an intake is similar to that of boundary-layer blowing in the sense that the buzz levels in the intake are reduced.

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An intake which can operate efficiently over a wide range of flow regimes is a variable geometry intake, the design of which is rather complex. A novel variable geometry intake[5,6]is a stepped supersonic intake with an active bleed downstream of the step.

Passive boundary-layer control[7] is an other method which is currently being studied to enhance the performance of a supersonic intake. Results of small scale experiments on a supersonic intake with a step and with and without passive control are presented in this paper.

Control of Pre-Entry Flow

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. 2, 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 strength and/or the associated boundary-layer separation. Owing 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(3) (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(4) show that the reduction in total pressure loss is a function of the ratio of diverter height to boundary-layer thickness.

Experiments have shown(8-10) that these control methods can reduce the total pressure losses other than shock losses by 50% to 75%.

Blowing (Fig.4) is an alternative way of controlling the boundary-layer in an intake but has not been adopted in a practical intake design presumably due to the fact that in a typical intake design, the air is at a pressure about ambient and boundary-layer bleed is a logical method for controlling the boundary-layer separation. However there have been some experimental studies[11] on boundary-layer blowing to control the intake performance. These experiments indicate that about 10% increase in pressure recovery can be obtained for a 2% blowing mass flow. The gain in pressure recovery with a distributed blowing is relatively smaller. Blowing also can enlarge the buzz free operation of an intake.

Another concept for controlling pre-entry shock is passive boundary-layer control. The concept applied to transonic flow over an aerofoil consists of a porous surface and a cavity or plenum located in the region of the shock interaction. The static pressure rise across the shock wave is to create an airflow through the cavity from downstream to upstream of the shock wave. This flow has the effect of thickening the boundary-layer upstream of the shock leading to a system of relatively weaker shocks with reduced wave drag. The passive action also produces suction which controls boundary-layer separation downstream of the shock. Significant drag reduction and alleviation of buffet levels on aerofoils in transonic flow have been achieved with passive control.

The passive control has potential applications in supersonic intakes for controlling the pre-entry shock and buzz levels. Experiments conducted by the authors[7] in a small supersonic intake at Mach numbers of 1.36 and 1.46 and with a passive control device (Fig. 5) have shown that passive control can reduce the shock interaction losses appreciably, and the injection slot located at a distance equal to the height of the intake produces maximum reduction in pressure recovery. Improvement in pressure recovery of the order of 5% can be achieved with passive control.

An intake which can operate efficiently over a wide range of aircraft operations is a variable geometry intake. But such an intake involves complexity in design and increased weight of aircraft. A stepped supersonic intake[5,6] (Fig. 6) is a novel variable geometry technique that can be used to control the pre-entry shock and intake geometry. The concept consists of a forward facing step which produces wedge shaped boundary-layer separation ahead of the step. The step could be placed on or well the pressure coefficient for separation to occur at this Mach number is $C_{ps} = 0.375$ which agrees closely with the present results. The value of C_p at the intake entry remains almost constant with respect to mass flow, however the pressure rise then continues in the intake duct, increasing in magnitude as the mass flow is reduced. The pressure recovery in the duct is smaller than that which would take place in a one dimensional diffuser flow. 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.

The total pressures at the duct traversing station situated at the mid point of the intake diffuser ($x/h_{en} = 1.8$) and for three mass flow ratios are given in Fig.10. As A_{ex}/A_{en}, and therefore A_∞/A_{en}, is reduced the height of the separated flow grows and the increase in P/P_∞ with y/h_{en} is spread over a greater proportion of the duct height. The maximum value of P/P_∞ is reduced as mass flow decreases. There is also an increase in the value of P/P_∞ at the wall as mass flow decreased due to the corresponding rise in the static pressure at the traversing station.

In the present series of tests it is suggested that the flow reattachment occurs at a point upstream of the intake measuring station ($x/h_{en} = 5.20$) for all values of intake mass flow, as total pressure is always greater than the static pressure at this station.

Static pressure distribution along the intake centre line for the intake configurations A, B, C and datum and for mass flow ratios of 0.74 and 0.88 are shown in Figs.11. Some typical shadowgraph pictures for some of the configurations are shown in Fig.12. The pressure distributions (Fig.11) share some of the flow features discussed for the datum intake. Compression in two stages is apparent in the pre-entry flow indicating shock bifurcation in this region (Fig.12). Considering that the leading edge of a 10 degree wedge would be located at $x/h_e = -1.95$ and the injection slot is located at $x/h_e = -1.14$, the leading edge of the λ shock system is always at or ahead of the leading edge wedge for configurations with the step (A and B) and ahead of the injection slot for configuration C.

At a mass flow ratio of 0.74 (Fig.11a) the step configuration (A) produces a stronger shock system and increased pressure recovery. The effect of bleed with a step (B) or bleed only (C) weakens the shock system. Bleed only configuration produces smearing of the shock system.

As the mass flow is increased (Fig.11b) the static pressure rise through the pre-entry oblique shock decreases for the configurations tested (A, B and C). There is also a decrease in the strength of the normal shock particularly for configuration A.

These changes in shock strength with the changes in mass flow may be induced by a small change in the equivalent wedge angle for the step and the flow induced by the passive bleed for the configurations with the bleed.

It has been shown that for the configurations with passive bleed (A), the total pressure in the breather passage was approximately 50% of the free stream pressure and increased as the mass flow is increased. This suggests that the total pressure in the breather passage is linked to the static pressure at the intake entry i.e. the static pressure close to the bleed slot.

The total pressure profiles at the traversing station for the datum is compared with configurations A, B and C in Fig.13. The traversing station is situated at $x/h_e = 1.81$ downstream of the intake entry. At a mass flow ratio of 0.74 (Fig.13a) and compared to the datum the step configuration (A) has increased the total pressure in the lower point of the boundary-layer. The viscous losses have reduced. It appears from the pressure distribution that the flow has reattached itself just downstream of the step. Changes in the total pressure by configuration B is small. The bleed appears to offset any gain produced by the step by increasing the approach losses. Configuration C produces increased total pressures on the upper part of the boundary-layer due to reduced shock losses.

However at a higher mass flow ratio of 0.88 (Fig.13b), configuration A has resulted in a significant decrease in the total pressures across the entire traversing station indicating an extended area of boundary-layer separation of the pre-entry flow. The effect of configuration B is somewhat similar to that at the lower mass flow rate. Significant increases in total pressures are produced by configuration C due to the combined effect of both suction downstream and blowing upstream and weakening of the shock system.

The total pressure loss integral calculated from the total pressure profiles are plotted against the corresponding mass flow values in Fig.14. The results shown here are for the four configurations A,B,C and D. It is clear from this figure that the total pressure losses for configurations A, B are smaller for lower mass flow ratios and the passive control bleed devices C and D produce lower pressure losses for all the mass flow rates considered. For the configurations tested an improvement in total pressure through the traversing station occurs only when the total pressure at the intake flow is greater than that of the datum i.e. reduced viscous losses.

Pressure recoveries recorded at the intake measuring station using a 12 point pitot array are presented in Fig.15. The measuring station is situated 5.2 h_{en} downstream of the intake entry. Results for the four configurations are compared to the datum intake. All the configurations tested gave improved pressure recoveries for low mass flow ratios whereas configuration C and D gave improved pressure recoveries for the entire range of mass flow ratios tested. The control configurations produced a decrease in maximum mass flow and this is likely due to span wise spillage.

Conclusions

The results of small scale experimental investigations on the control of pre-entry shock by using (A) a step at the intake entry, (B) a step in conjunction with a passive boundary-layer control, (C) passive boundary-layer control and (D) bleed only are presented in this paper. The conclusions which can be drawn from these investigations are that the control devices A and B are effective in terms of controlling the pre-entry shock position and improving pressure recovery at small mass flow ratios whereas passive boundary layer control (C) and bleed only configurations (D) are effective for producing improved pressure recovery over both small and large mass flow ratios.

A solution for improving the performance of a supersonic intake over a wide range of mass flow ratios is to have a step only configuration (A) for low mass flow ratios. At high mass flow ratios the step is retracted and the intake is operated with a bleed only configuration (D).

References

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Intake	Configuration
Datum	Datum intake
A	Step
B	Passive control + Step
C	Passive control
D	Bleed (suction) only

Table 1

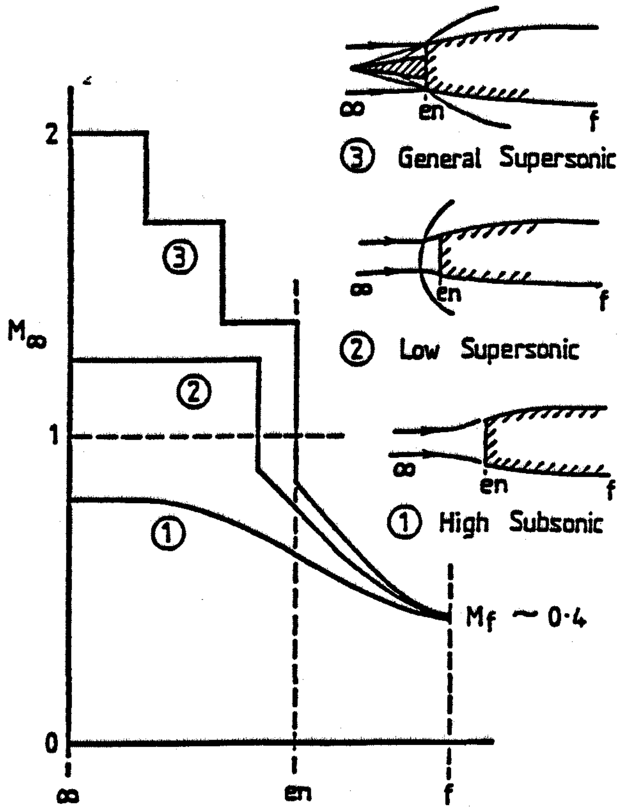

Fig. 1(a) Flow deceleration in an engine (from Refs.1 and 2).

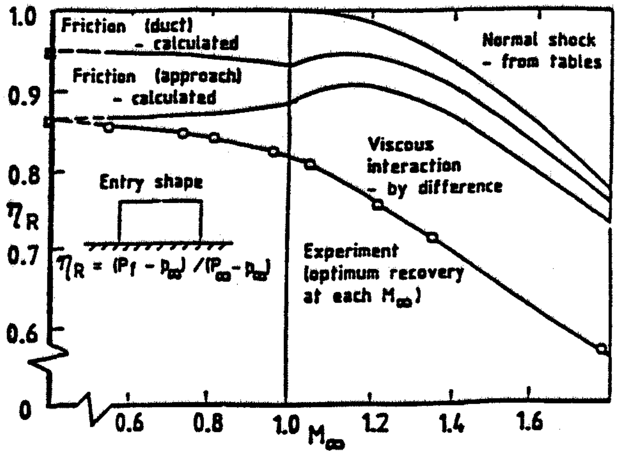

Fig. 1(b) Total pressure losses in an intake (from Refs. 1 and 2).

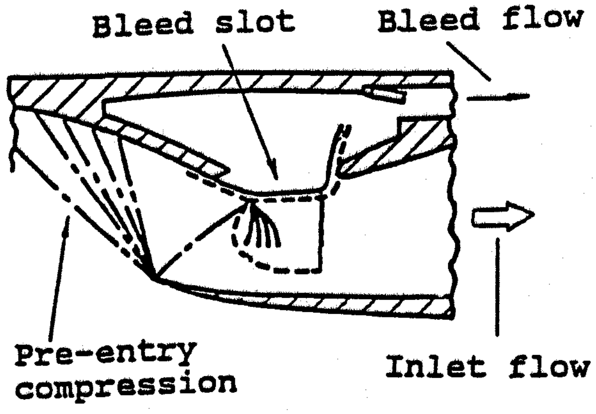

Fig. 2. Ram bleed

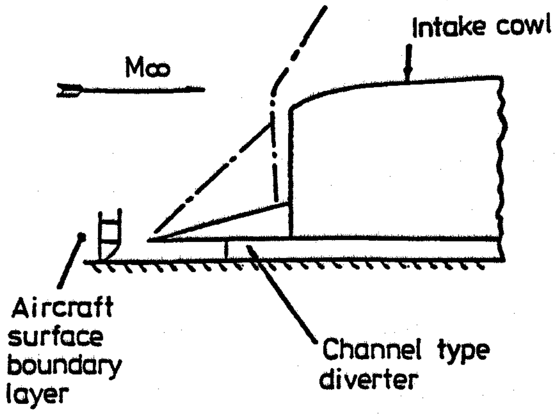

Fig. 3. Diverters

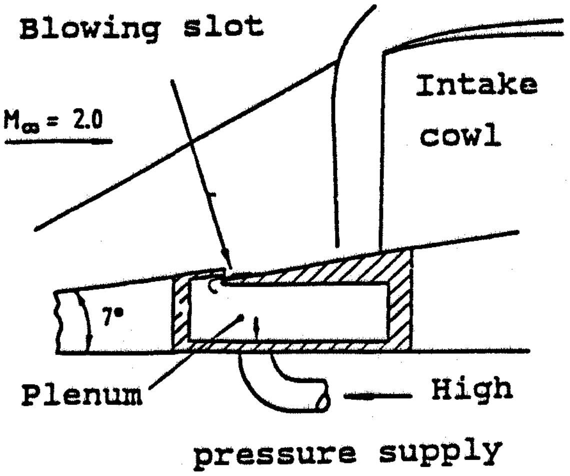

Fig. 4. Blowing in a supersonic intake.

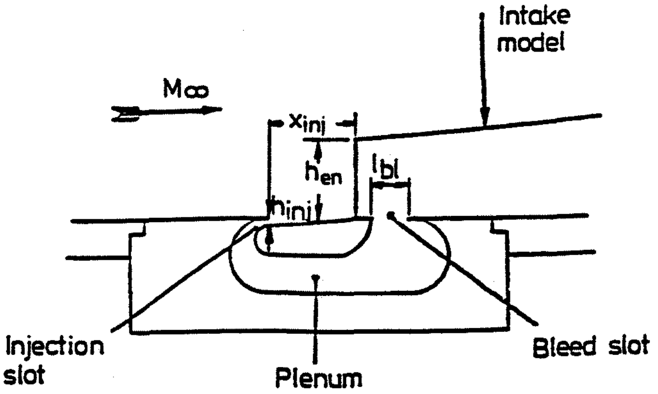

Fig. 5. Passive boundary layer control.

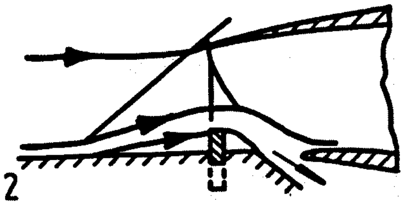

Fig. 6. The step intake.

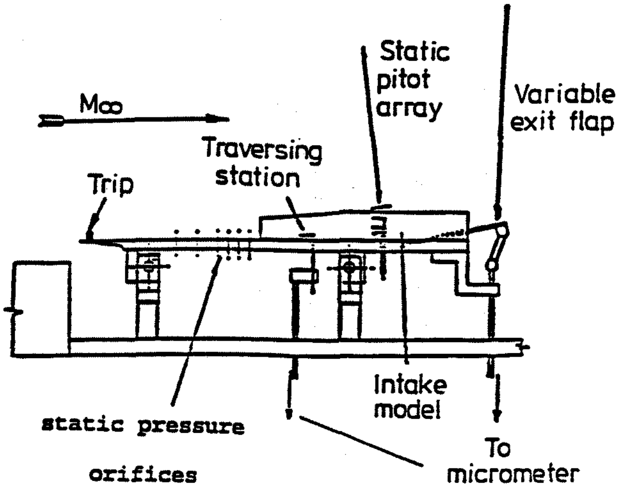

Fig. 7. Model arrangement

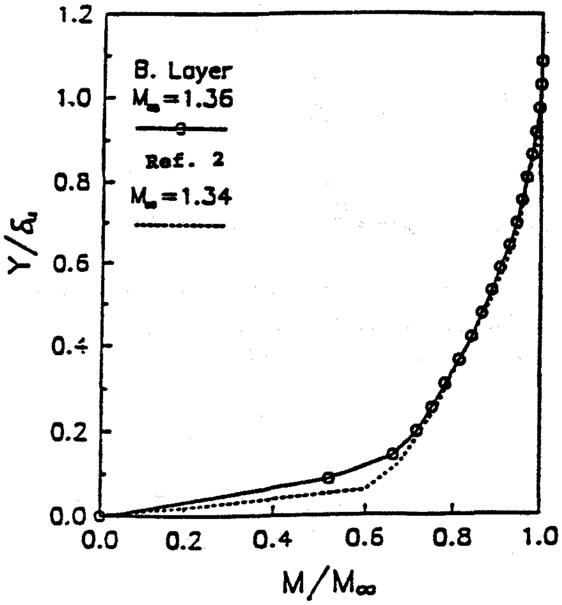

Fig. 8. Inlet velocity profile.

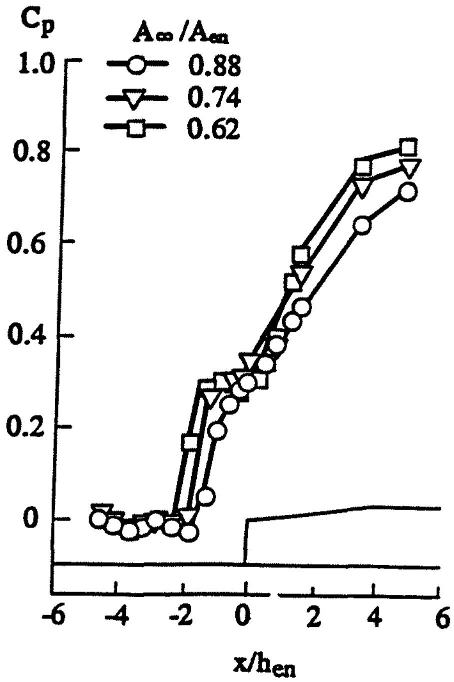

Fig. 9. Pressure distribution - datum.

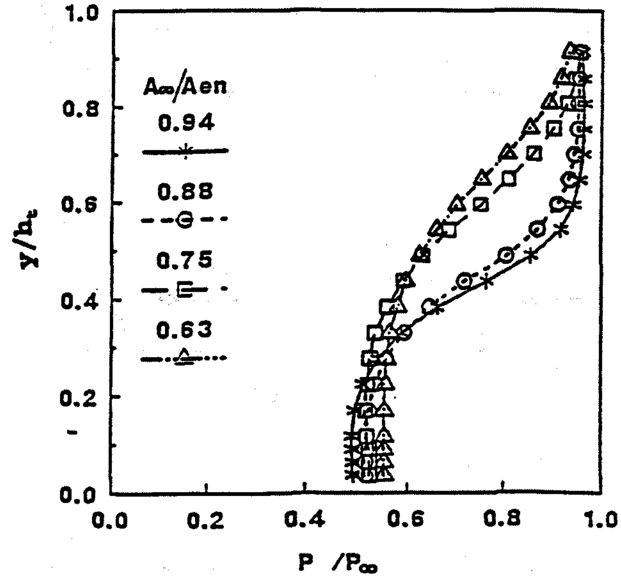

Fig. 10. Total pressure profiles - datum.

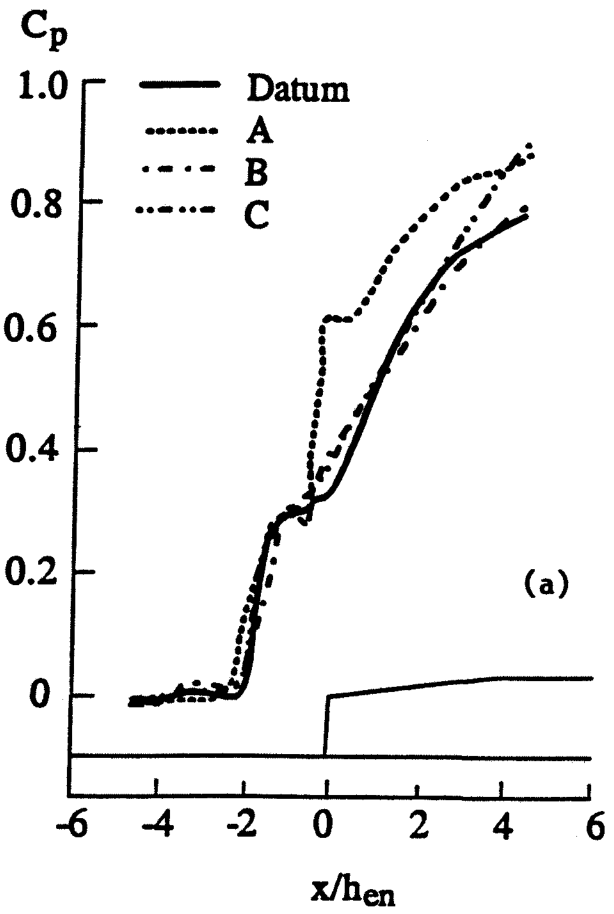

Fig. 11. A comparison of pressure distribution.

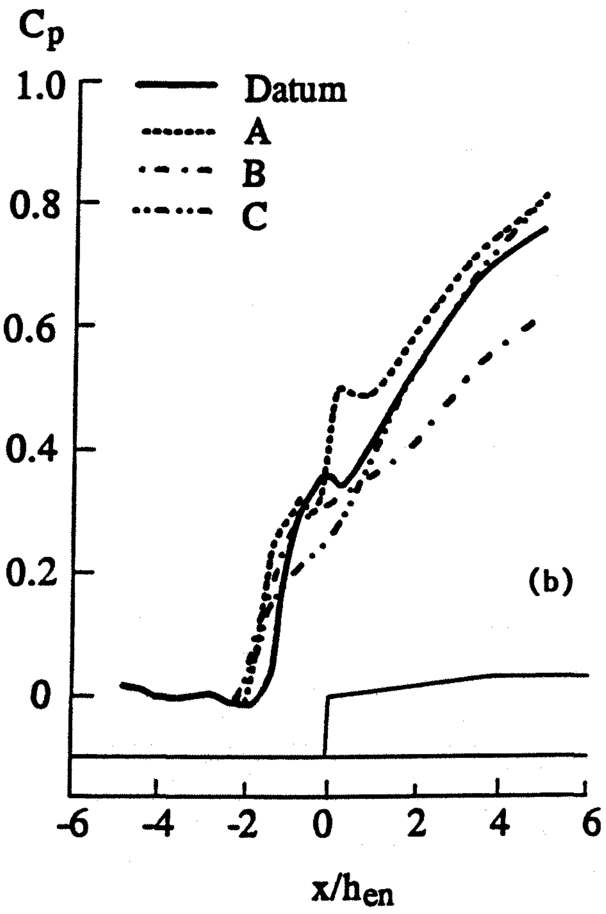

Fig. 11. Continued

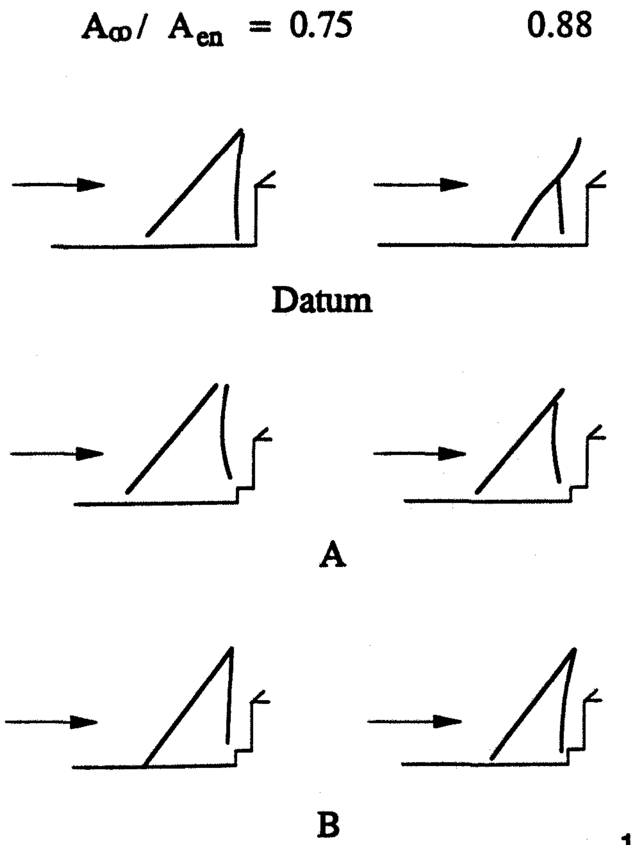

Fig. 12. Shadowgraph pictures.

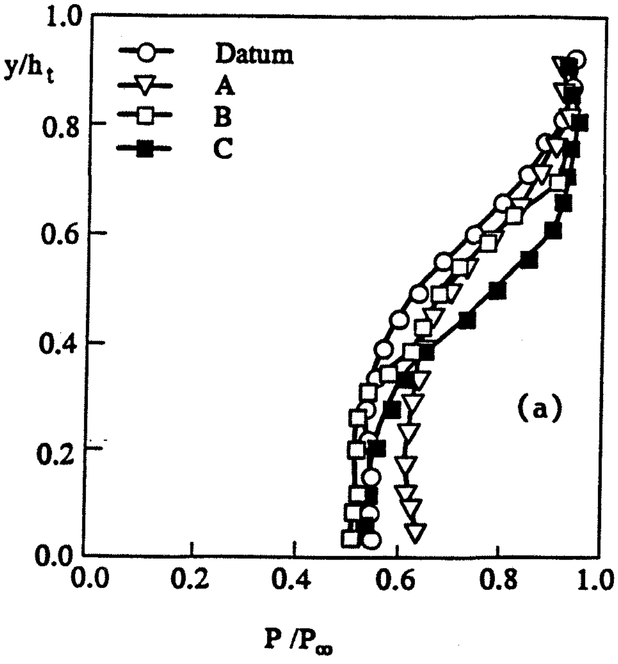

Fig. 13. A comparison of total pressure profiles.

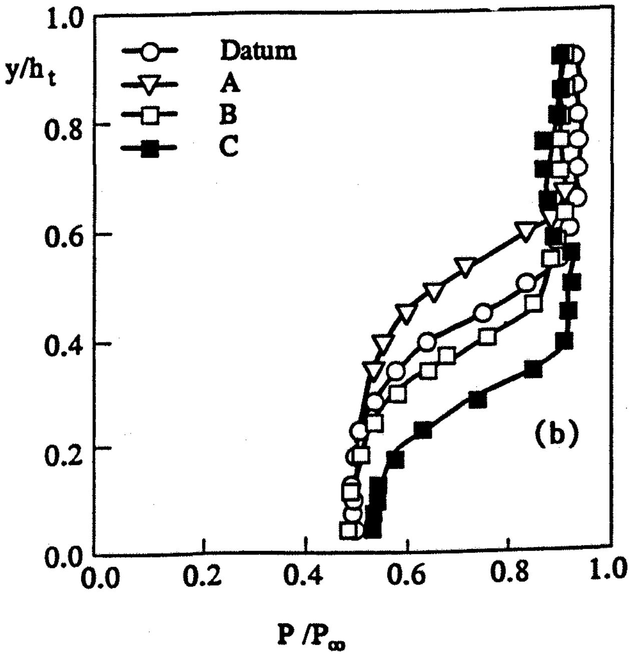

Fig. 13. Continued

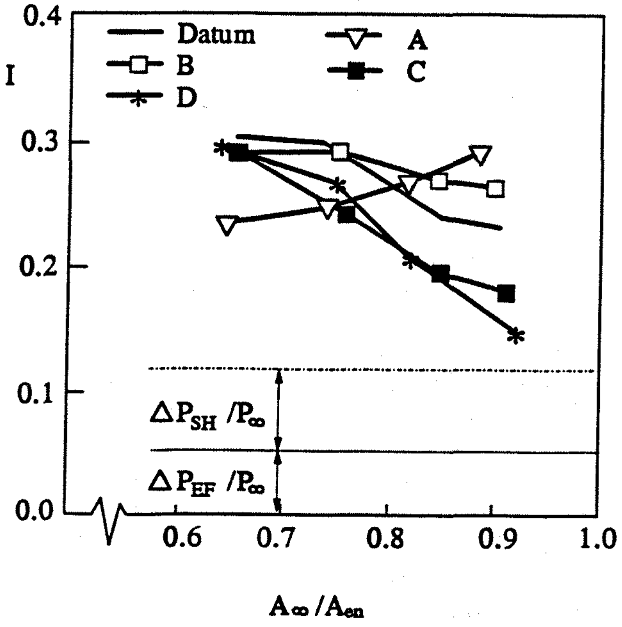

Fig. 14. Total pressure losses.

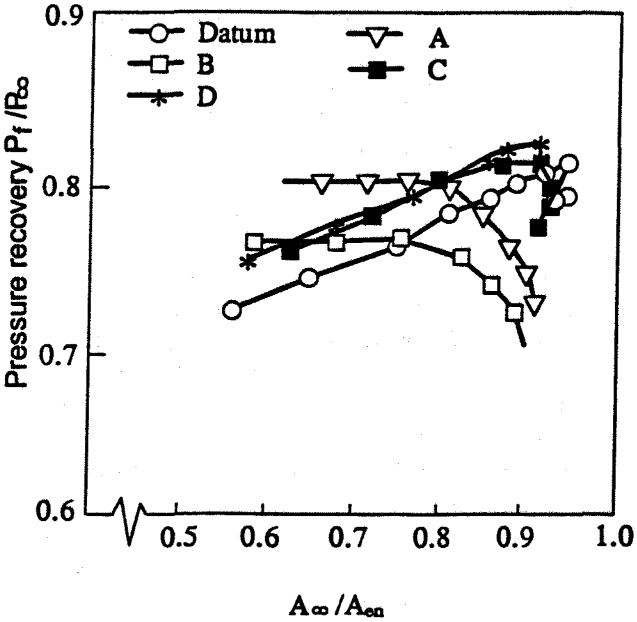

Fig. 15. Pressure recoveries.