Three-Dimensional Flow Effects in a Two-Dimensional Supersonic Air Intake

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The internal flow in a two-dimensional mixed compression intake having focussed internal compression was examined experimentally at its design Mach number of 3.05, using pressure instrumentation and flow visualization. A pair of streamwise vortices was identified, which apparently resulted from interaction of the sidewall boundary layers with the internal shock system and which, depending on detailed geometry, could dominate the flow in the subsonic diffuser. It is argued that similar flows could exist in a variety of intakes designed for supersonic flight, with implications for both turbine and ram compression engine applications.

Nomenclature

H_i = intake model capture height
P_s = static pressure
P_t = total pressure
P_{t0} = tunnel stagnation pressure
Q_r = ramp bleed mass flow/intake capture mass flow, %
t = ram scoop at ramp bleed slot
δ_2 = deflection at supersonic ramp hinge, deg
η_{cr} = diffuser exit area mean P_t/P_{t0} at critical

Introduction

IN engine air intakes designed for high Mach number operation, external drag considerations often dictate that some of the supersonic compression should occur internally. The drag benefits (relative to fully external compression designs) can be offset by penalties which include more demanding requirements for controlling interaction of internal wall boundary layers with the adverse pressure gradients in the supersonic and transonic regions. With two-dimensional configurations in particular, the sidewalls represent added internal surface area wetted by supersonic flow, providing for more boundary layer growth upstream of the throat and adding potential (relative to axisymmetric designs) for troublesome three-dimensional flow effects.

Experiments were undertaken to investigate the effects on these problems of using a highly concentrated internal compression field which minimised both the length of the supersonic diffuser and the supersonic wetted area, and which could be matched to a simple slot bleed system. This involved an internal shock configuration which, in broad terms, was a two-dimensional equivalent of previously tested axisymmetric arrangements.[1] In comparison with some high performance designs which employ long internal contractions to limit the adverse pressure gradients throughout the supersonic diffuser,[2,3] this approach offered the attractions of overall compactness and potential simplicity of boundary layer control. In axisymmetric form, it also yielded economy of bleed mass flow rate.[1] The vehicle for this study was a two-dimensional, variable ramp intake model which was tested at its design Mach number of 3.05.

Received Dec. 11, 1985; revision received May 7, 1986.

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Model Geometry

A photograph of the intake model, which had a capture area approximately 70 mm × 70 mm, is shown in Fig. 1. A sectioned elevation of the model appears in Fig. 2, which also defines the more important geometric variables and flow measurement stations. The internal profiles of the supersonic diffuser are shown in more detail in Fig. 3, along with the theoretical shock system and local values of Mach number for the "design" geometry, corrected for the displacement effect of the boundary layers on the ramp and cowl surfaces. Approximately 50% of the supersonic area contraction occurred internally.

The four internal oblique shock waves were designed to focus near the downstream edge of the ramp bleed slot, which was formed at the duct throat by the gap between the supersonic and subsonic diffuser ramps. A second (flush) bleed slot was positioned on the cowl side of the throat. There was no provision for direct control of the boundary layers on the sidewalls; a measure of indirect control was anticipated, through the agency of local secondary flows involving migration of the sidewall boundary layers towards the ramp bleed slot, under the influence of the pressure gradients associated with the internal supersonic compression field.[4] For some tests the bleed slot was increased in streamwise width next to the sidewalls, by forward notching of the trailing edge corners of the supersonic ramp, both to help accommodate this additional flow and to allow for anticipated local forward deflection of the cowl shocks where they intersected the sidewall boundary layers. A benefit of experimental convenience which accrued from the absence of boundary layer control devices on the sidewalls was the facility for uninterrupted schlieren observation of the flow in the intake throat, through the circular windows which are visible in Fig. 1.

The subsonic diffuser did not include full transition of the duct cross section from rectangular at the throat to the circular shape which would be required at the diffuser exit for mating to a turbine engine. For most of the tests described, however, generous corner fillets were included to reduce the influence of corner flows.

Test Conditions

The model was fixed at zero incidence, and tested at its design Mach number of 3.05. With a tunnel stagnation pressure of 650 kPa, the test Reynolds number was 2.64×10^6 based on intake capture height.

Pressure Recovery Performance

The area mean critical pressure recovery measured with a 20-point pitot tube array at station C (see Fig. 2) is shown plot-

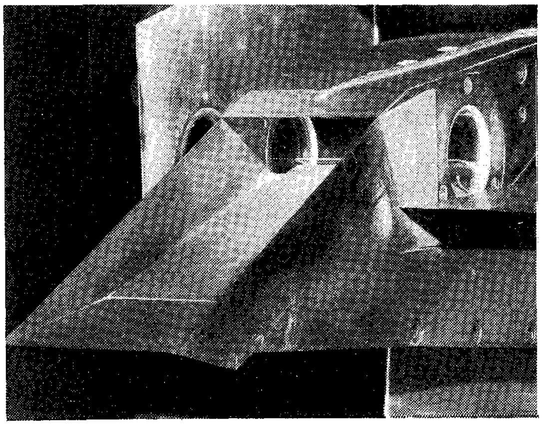


Fig. 1 Photograph of model.

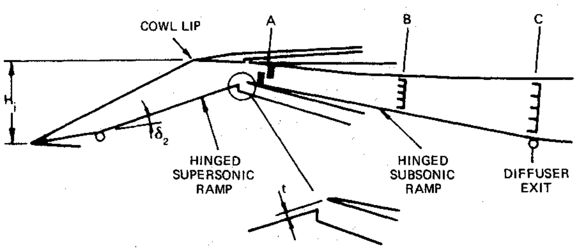


Fig. 2 Intake geometry.

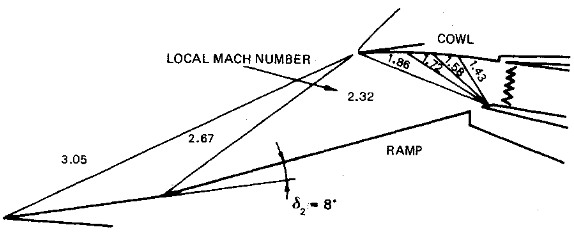


Fig. 3 Supersonic diffuser.

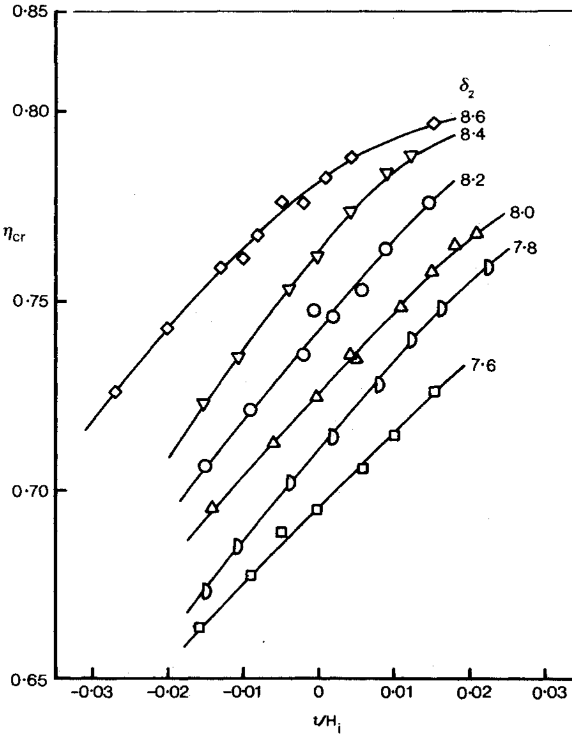


Fig. 4 Pressure recovery vs bleed slot geometry.

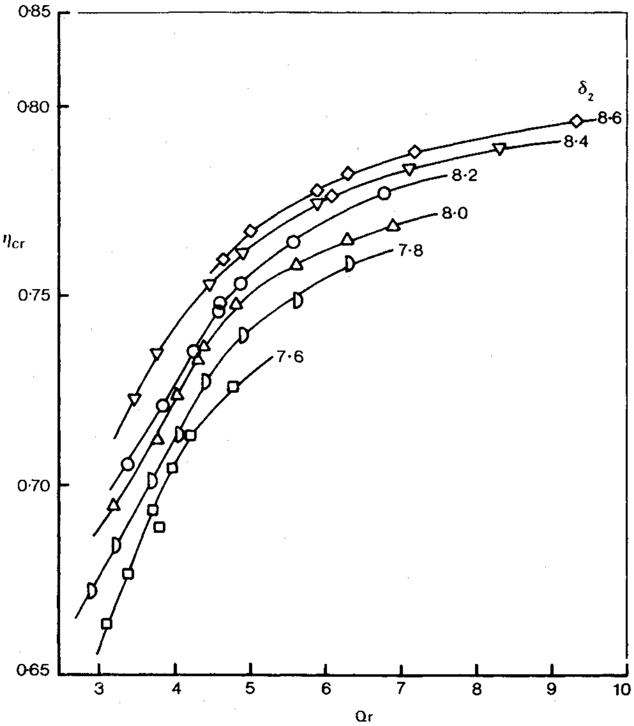


Fig. 5 Pressure recovery vs ramp bleed.

ted against ramp bleed slot geometry in Fig. 4 for a number of different supersonic ramp angle settings. The corresponding variation of ramp bleed mass flow rate appears in Fig. 5. The flow rate through the cowl bleed slot was found not to be an important variable; the optimum setting in fact was zero. This result was consistent with previous findings with axisymmetric test geometries having minimum length cowl surfaces.[1,5]

Pressure recovery performance is summarized by the cross plot in Fig. 6. For comparison the figure includes a curve of theoretical shock recovery vs ramp angle calculated from surface geometry alone, i.e., totally ignoring boundary layer effects. The difference between the theoretical and experimental curves, i.e., the "extra-to-shock" loss, correlates closely with ramp bleed flow. The minimum recorded difference was about 10% of the free stream total pressure with 8% ramp bleed. This is somewhat higher than might be hoped for in a high performance intake.

Internal Flow Behavior

Figure 7a shows a schlieren photograph of the flow in the throat of the model with the ramps close to their design positions and the flow near critical. While there is some evidence of interaction between shock waves and the sidewall boundary layers, the flow appears to be basically two-dimensional with the oblique shock system closely resembling its design configuration, as depicted in the interpretation shown in Fig. 7b. The measured wall static pressure distribution, which is compared with the theoretical inviscid distribution over the full length of the intake duct in Fig. 8, confirms that the design compression field was realized in the supersonic diffuser, but reveals a somewhat difficient static pressure rise through the terminal shock system in the intake throat.

Figure 9 shows profiles of total pressure measured at three pitot rakes mounted near the duct centerline on the upper (cowl), lower (ramp), and sidewall surfaces at station A in Fig. 2, i.e., immediately downstream of the throat. Values of total pressure in the bulk of the flow were marginally higher than

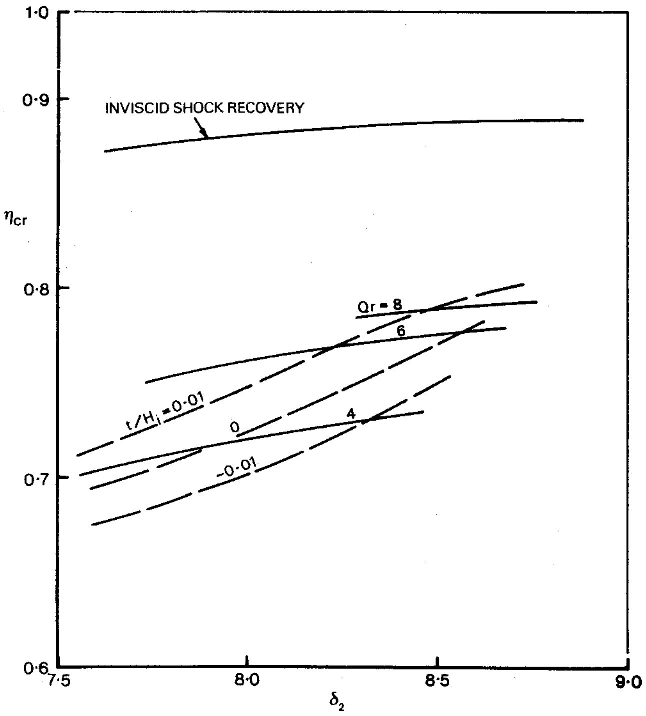
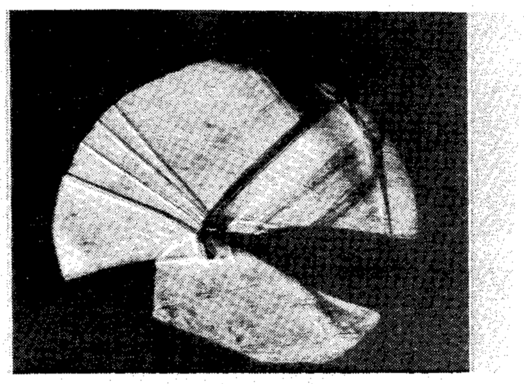
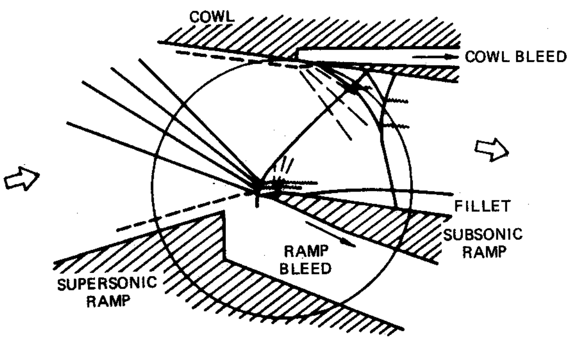


Fig. 6 Pressure recovery vs ramp angle.



a) Schlieren photograph.



b) Two-dimensional interpretation.

Fig. 7 Flow in model throat.

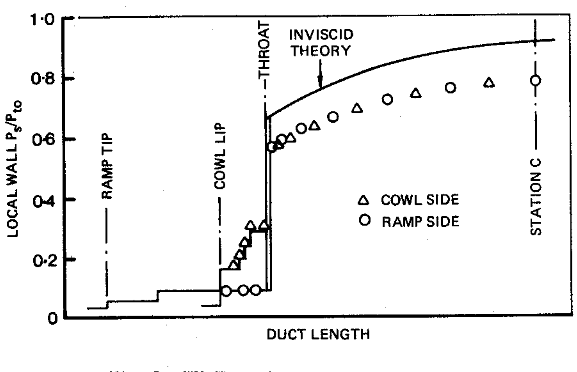


Fig. 8 Wall static pressure distribution.

the theoretical inviscid value, and the vertical flow profile was generally quite healthy and apparently well equipped to negotiate the pressure rise in the subsonic diffuser.†

However, the profile measured at the sidewall rake, which generally featured a trough in total pressure about rake midspan, indicated the presence of substantial three-dimensional flow effects in that region. The same effects were evident in the cross-sectional distribution of total pressure measured by a pitot array at station B, an example of which appears in the upper diagram of Fig. 10. There the shapes of the total pressure isobars suggested the existence of a pair of streamwise vortices, located as indicated by the broken lines.

This diagnosis was supported by evidence from flow visualization using pigmented oil to reveal streamlines on the internal surfaces of the model. Photographs of the streamline patterns appear in Figs. 11 and 12, each with an inset sketch showing a qualitative interpretation of the corresponding surface flow. These visualization experiments were performed without corner fillets in the subsonic diffuser, a factor thought not to be significant as far as the basic structure of the flow is concerned. Figure 11 shows the streamline pattern on the surface of one sidewall in the throat region. There was a line of three-dimensional separation coincident with the first cowl shock, which was to be expected since the static pressure ratio across the shock (2.0) was some 30% higher than that required for separation of turbulent boundary layers at swept plane shock waves in this Mach number range.[6] This line of separation, together with the subsequent secondary flow encouraged by the following cowl shocks and the presence of the ramp bleed, served effectively to divert the sidewall boundary layer flow toward the bleed slot as was intended. However, the residual skewness in the sidewall flow immediately downstream of the bleed slot, probably combined with vorticity associated with the three-dimensional separation at the leading cowl shock, evidently created a strong vortex in each of the two corners between the sidewalls and the subsonic ramp surface. The resulting streamline pattern left on that surface appears in Fig. 12. Lines of three-dimensional separation emanated from the two ends of the ramp bleed slot, converging downstream as the vortex pair developed. Interaction between the two vortices in the adverse pressure gradient eventually resulted in an area of flow separation from the diffuser floor upstream of station C. The distortion of the flow at the diffuser exit which appears in the lower diagram of Fig. 10 (here with corner fillets fitted) is a result of this flow structure.

†Integration of the vertical profile assuming two-dimensional throat flow (arguably reasonable in view of the locally high aspect ratio of the rectangular duct) yielded local area mean total pressure recoveries as high as 87%. Compared with the maximum measured pressure recovery at station C of about 79%, this would have indicated a highly inefficient subsonic diffuser.

Flow Control

Devices investigated for controlling the two vortices and their effect on pressure recovery and flow quality at the diffuser exit included vortex generators, and vanes attached to the sidewall surfaces, and distributed sidewall bleed. The most effective measure, however, was found to be addition of slot bleed in the corners between the sidewalls and the subsonic ramp near the origin of the vortices, as shown in the plan view

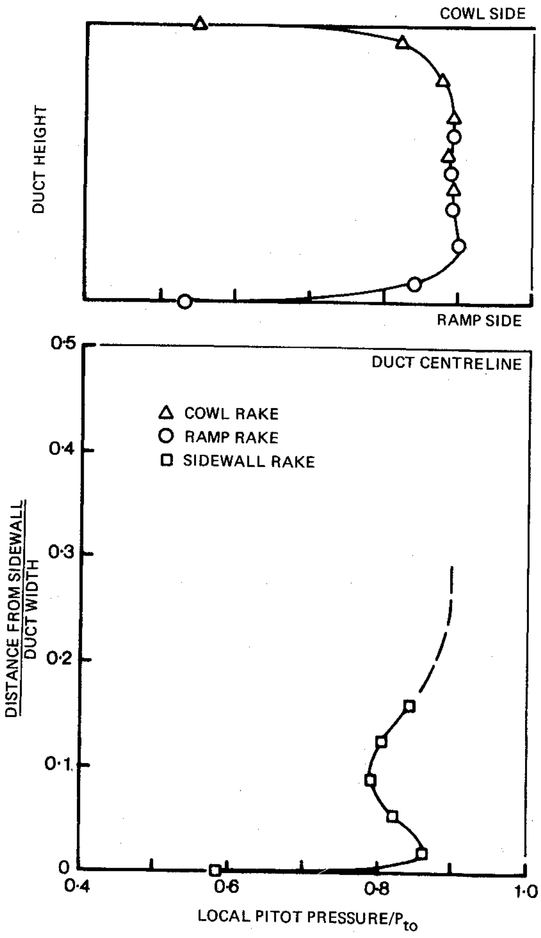


Fig. 9 Throat flow profiles.

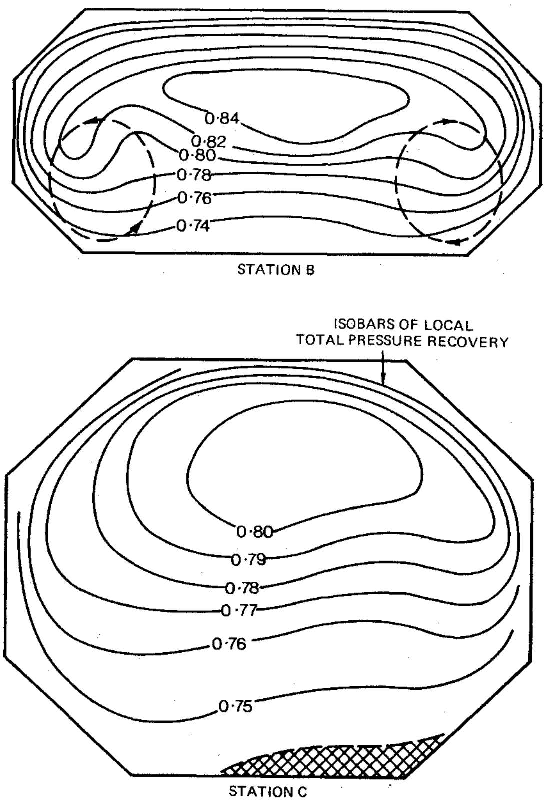


Fig. 10 Flow distributions in subsonic diffuser.

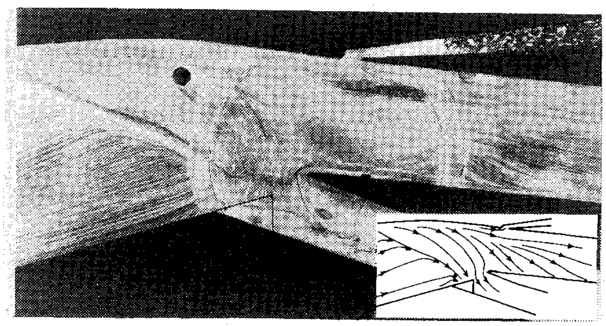


Fig. 11 Surface streamlines on sidewall.

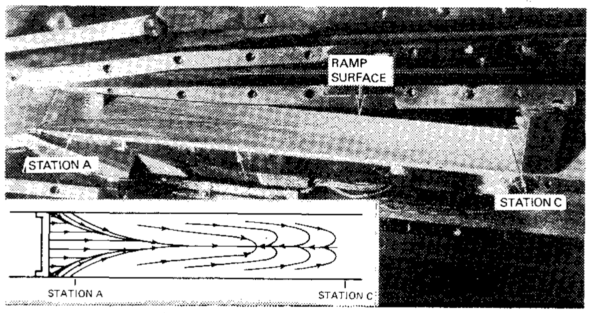


Fig. 12 Surface streamlines on subsonic ramp.

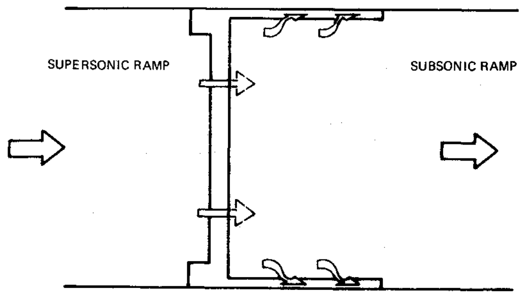


Fig. 13 Corner bleed arrangement.

of the ramp bleed region in Fig. 13. At the cost of substantially increased bleed mass flow rate, the "extra-to-shock" loss was significantly reduced (Fig. 14) and the flow quality in the subsonic diffuser greatly improved (Fig. 15). However, the effective exchange rate between bleed flow penalty and improved performance would be unlikely to be favorable in a typical installation. This is illustrated in Fig. 16, where pressure recovery is plotted against total ramp bleed, which here includes the flow passing through the corner slots as well as the flow through the original ramp bleed slot. Because of interaction (mainly via back-pressure) between the two speed regions, the addition of corner bleed necessitated some 5-6% increase in total bleed flow before any improvement in pressure recovery became evident.

Discussion

For use in a turbine engine installation, where there usually are demanding requirements in terms of compressor inlet flow distortion (both mean and dynamic) as well as pressure recovery, the intake design as tested seems unlikely to provide an optimum solution. It would probably be necessary to compromise to some extent on the compactness of the internal contraction, in order to spread the initial cowl compression and avoid the use of cowl shocks having sufficient strength to cause three-dimensional separation of the sidewall boundary layers. The initial source of vorticity in the throat region would thereby be weakened.

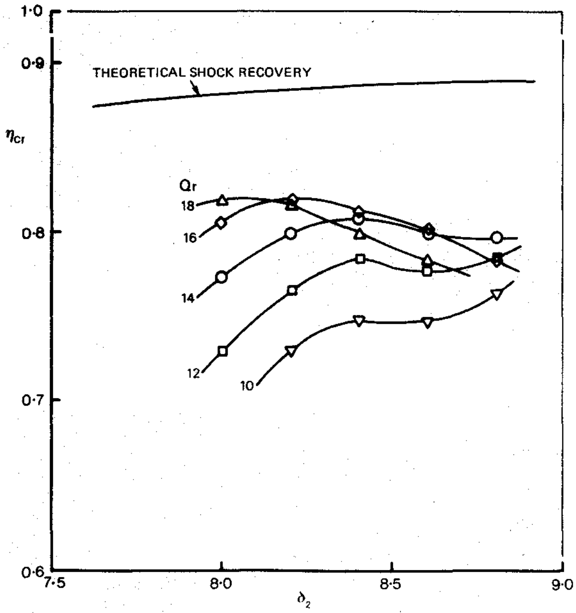


Fig. 14 Performance with corner bleed.

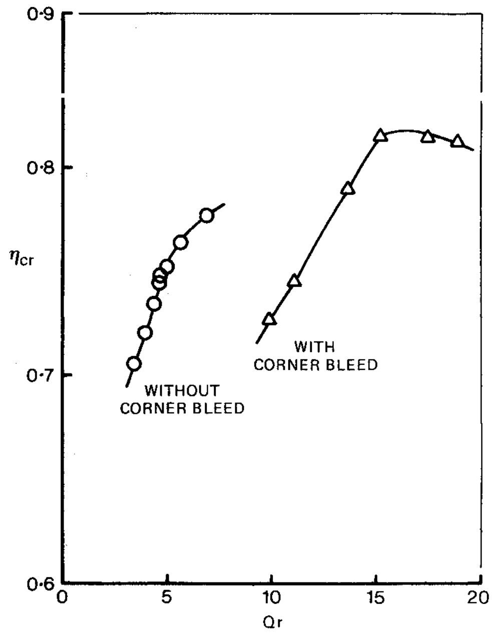


Fig. 16 Comparative performance, $\delta_2 = 8.2$ deg.

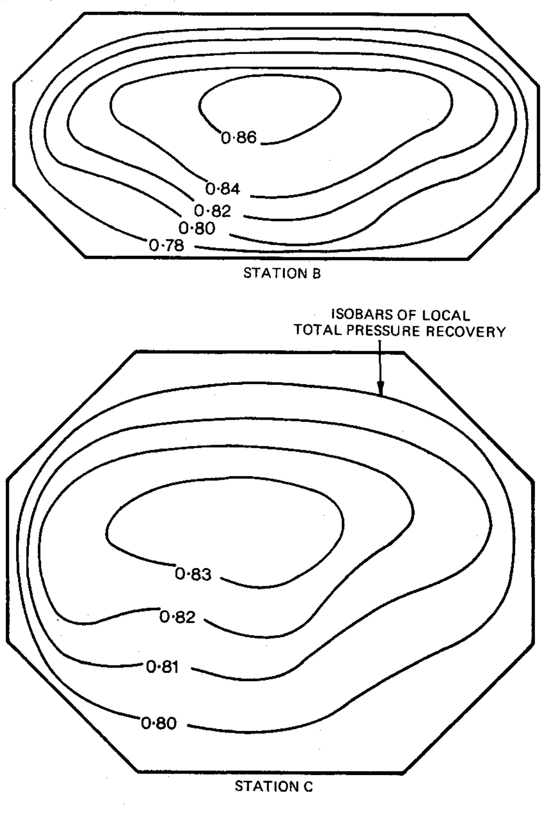


Fig. 15 Diffuser flow distributions with corner bleed.

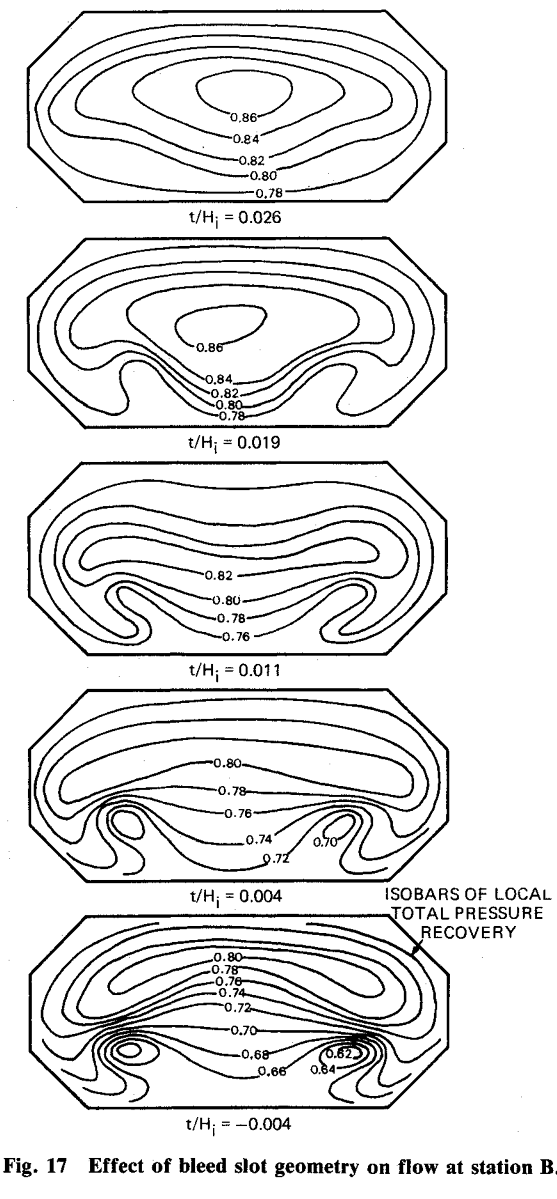


Fig. 17 Effect of bleed slot geometry on flow at station B.

The basic flow mechanism described should by no means be confined to the flight speed or detailed geometry of the present investigation. The essential ingredient for generation of the vortices is the interaction of sidewall boundary layers with a concentrated oblique shock system; potential for such interaction exists in many ramp intake designs, including some "external compression" arrangements.

In ram compression engines, conventional criteria relating to diffuser exit flow quality do not necessarily apply, and it is possible that the flows described could be turned to advantage. The potential contribution of swirling flows to achievement of efficient, compact ramburner design is well known,[7] and trading intake-induced vorticity for a modest reduction in mean pressure recovery might be beneficial in these circumstances. Returning to the results of the present investigation, the possibility of optimizing a design in this way is illustrated by Fig. 17, which displays a pronounced sensitivity of the vortex strength at station B to small variations in throat geometry.

Conclusion

Investigation of the flow in a two-dimensional supersonic intake has revealed the existence of streamwise vortices which apparently result from interaction of the sidewall boundary layers with the internal supersonic compression field and which, depending on detailed geometry, can dominate the flow in the subsonic diffuser. The resulting diffuser exit flow would be unlikely to be acceptable in a turbine engine installation, and redesign of the internal shock system would probably be required. However, it is possible that the flows described could be exploited for improvement of combustion efficiency in ram compression engines.

References

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