Interaction between an Upstream Facing Wall Jet and a Supersonic Stream

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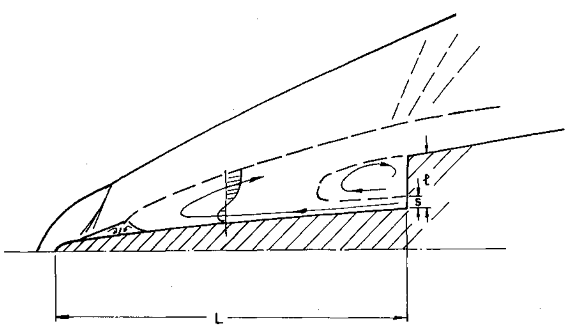
Theme

THE interaction of an upstream facing wall jet with a supersonic counterflowing stream gives rise to a complex flowfield. The description of this flowfield is interesting for the general understanding of complex interaction problems and for possible engineering applications. The injected gas penetrates upstream and then reverses interacting with the main-stream flow. A high mixing rate between the two counterflowing streams is characteristic of this flowfield. Depending on the issuing jet conditions, different degrees of penetration and interaction can take place with correspondingly greatly diverse flowfield structures.

The purpose of the present study has been to obtain a qualitative and quantitative description of the flowfield generated by the two interacting streams; in particular to determine the main parameters governing the flowfield and their influence on the penetration and the interaction phenomena.

a) shadowgraph picture



b) flow model

Fig. 1 Flowfield produced by upstream subsonic injection along the wall.

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Index category: Jets, Wakes, and Viscid-Inviscid Flow Interactions.

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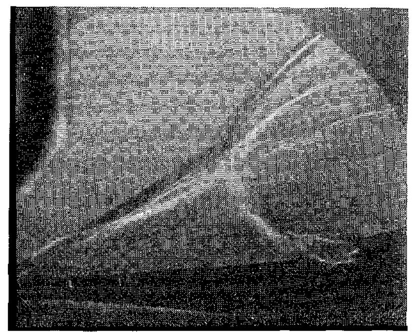
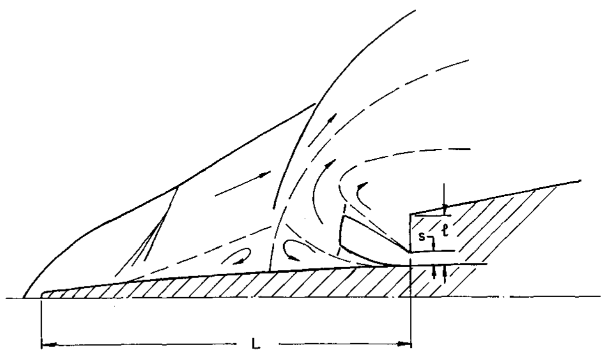


a) shadowgraph picture



b) flow model

Fig. 2 Flowfield produced by upstream supersonic injection along the wall.

Content

A) *Description of the Physical Phenomena.* The flowfield resulting from the upstream injection along a wedge wall into a supersonic (Mach 6) main stream is illustrated with shadowgraph pictures and explanatory sketches of the flowfield in Fig. 1 for a subsonic jet and in Fig. 2 for a supersonic jet.

The boundary layer separates, since the main stream has to overcome a large adverse pressure gradient generated by the injected flow and by the step which, together act as an obstruction to the main stream. The injected flow is separated from the main stream, by a dividing streamline whose position is determined by the condition of equal pressures on both sides at the stagnation point. The jet total pressure is decreased to the value on the dividing streamline by the dissipative effect of viscosity. The viscous dissipation occurs through the mixing, the shock (if the jet is supersonic) and the effect of the boundary layer on the wall. In the subsonic case (Fig. 1) the jet flow mixes initially with the coflowing stream of the recirculation region generated by the step in the injection system, and then with the primary flow. The jet flow reverses because of the difference in momentum and mass flow in the direction of the main stream.

If the jet is supersonic (Fig. 2) a shock system forms to permit the jet stream to flow in the opposite direction. The jet's kinetic energy dissipation and the shock boundary layer interaction induce a turning of the streamlines, impeding the injected gas from penetrating relatively large distances along the wall. These qualitative observations suggest that the important parameters governing the structures of the flowfield are: the kinetic conditions of the two streams and their reference Reynolds number, the mass flow ratio or mixing parameter $\lambda = \rho_j u_j/\rho_e u_e$ and the geometrical parameters s/l and l/L.

B) *Experimental Investigation.* A series of experiments varying the previous parameters was conducted in a Mach 6 wind tunnel. The stagnation pressure was maintained between 1000 and 1200 psia and the stagnation temperature was maintained in the range of 600–900°R, with a resulting Reynolds number of the order of 10^8. The injectant was air, cooled by liquid nitrogen. The model was a two-dimensional wedge instrumented with thermocouples and pressure taps on both surfaces. The jet penetration distance and the degree of interaction between the two streams are the most relevant physical quantities in the determination of the flowfield structure. They were determined from a combined observation of the following experimental output: a) pressure distribution b) adiabatic wall temperature distribution c) shadowgraph pictures. The results show: a) large penetration distances in the case of high subsonic or low supersonic jet and b) large interaction forces for higher supersonic injections.

The distance needed to dissipate through mixing the jet kinetic energy (i.e., the penetration of the jet) increases with the jet total pressure. For low supersonic jet this conclusion holds if the height of the jet is such that the supersonic injectant flow becomes subsonic by viscous mixing dissipation without shock. If the jet is supersonic and a jet shock is present, the penetration decreases, as discussed before, while the interaction increases. The ensuing expansion gives rise to a reverse flow that has a radius of curvature proportonal to the jet Mach number. A large radius of curvature produces a bow shock in front of the reverse flow which increases the slope of the main shock (i.e. the interaction between the two streams).

The dependence of the penetration distance on the geometric parameters s/l and l/L and on the mixing parameter λ, maintaining $M_j \simeq 1$, is best correlated by the cooling effectiveness γ, defined as a function of the adiabatic wall temperature, $\gamma = (T_{aw} - T_{0\infty})/(T_{oj} - T_{0\infty})$.

A straight line correlation is obtained plotting γ as a function of a new parameter χ, defined as a product of powers of the main parameters (Fig. 3). The above correlation indicates the possibility of using the upstream injection scheme for cooling purposes. A study of the application of this scheme to the leading edge cooling of a body in a supersonic stream, when the total pressure losses through the bow shock must be maintained relatively small, is presented in detail in Ref. 1.

C) *Theoretical Analysis.* Following the described flowfield model the mixing between the two counterflowing streams essentially governs the structure of the flowfield in the case of high jet penetration. The mixing region is amenable to theoretical analysis if the usual boundary layer approximations are assumed to be valid, and the pressure is assumed constant in the region of interest, as inferred by the experimental observations. The flowfield in the mixing region is essentially nonsimilar because of the jet velocity decay in the upstream direction. A locally similar analysis was conducted by combining; 1) A station by station similar solution dependent on the local external stream conditions, and 2) a nonsimilar solution essentially valid near the wall in the jet region which takes into account the influence of the initial profile and the decay of u_j with the upstream distance

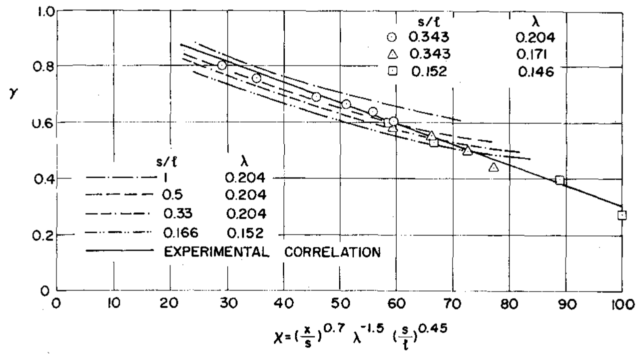


Fig. 3 Comparison of theoretical and experimental cooling effectiveness.

from the jet. Under the similarity assumption, the unknown function $u = u/u_1$ and $g = T/T_1$ are determined from the following system of equations,[2] $gu'' - g'u' + g^2 fu' = 0$, $u = gf'$, $g = 1 + B(u-1) - C(u^2 - 1)$, B and C are functions of the external stream properties.

The wall boundary layer can be neglected in the mixing region calculation, if the height of the injection system is large with respect to the boundary-layer thickness in the immediate vicinity of the jet. The dividing streamline can be considered, without loss of generality, the axis $\eta = 0$, and its position determined later on, imposing the condition that the wall corresponds to $\eta = \eta_0$, a value that bounds the lower momentum stream. Therefore the three boundary conditions are expressed by

$$u = u_1 \text{ for } \eta \to \infty \quad f = 0 \text{ for } \eta = 0 \quad u = u_2 \text{ for } \eta = \eta_0$$

where η_0 is determined by the integral condition

$$f = \int_0^{\eta_0} \frac{u}{g} d\eta = 0$$

The ordinary differential equation system was solved numerically with a quasilinearization technique. For the nonsimilar solution the improved Oseen linearization[3] was used and the momentum and energy equations, reduced to the heat transfer equation form, were analytically solved. This linearized solution is not valid far away from the jet region, therefore it was used only as a guide in selecting the similar profile valid at each particular axial station, by matching the u_2 of the similar solution with the velocity $u(x, o)$ of the nonsimilar solution. The agreement with the experimental results is fairly good for the shape of the dividing streamline while the penetration length is not predicted as well. The theoretically predicted cooling effectiveness, and therefore the adiabatic wall temperature, is shown in Fig. 3 as a function of the parameter χ. The predictions compared with the experimental measured values are in good agreement in the range $30 \leq \chi \leq 70$.

The discrepancies between the experimental results, and the theoretical model are due to the approximations adopted. However, the model provides a very simple means of predicting the flowfield's major features in a satisfactory way.

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