Investigation of Slot Cooling at High Subsonic Speeds

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Results of an experimental and numerical investigation of tangential slot injection for film cooling in subsonic boundary layers are presented. The experimental investigation has been performed at subsonic freestream Mach numbers of 0.4, 0.6, and 0.8. The data compare favorably with numerical predictions obtained from a finite difference boundary-layer solution developed for slot injection at supersonic speeds. The experimental results obtained indicate that the value of the adiabatic coolant effectiveness correlates with the parameters $(x/s)\lambda^{-0.8}$.

Nomenclature

Q = local heat transfer at the wall
T = temperature
t = time
ϵ = adiabatic effectiveness
ρ = density
d = thickness
c = heat capacity
λ = coefficient of mass injection defined by $(\rho_j u_j/\rho_e u_e)$
h = heat transfer
x = longitudinal distance
s = slot height
M = freestream Mach number
m = injected mass flow $\rho_j u_j s$

Subscripts

e = external conditions
oj = stagnation conditions of the jet
oe = external stagnation conditions
o = conditions without injection
j = cooling jet conditions
w = wall conditions
adj = adiabatic conditions with injection
ade = adiabatic wall conditions without injection

Introduction

THE possibility of increasing the turbine temperatures in turbojet engines is of extreme importance both for propulsion applications and for power generation applications, because higher turbine temperatures increase the thermodynamic efficiencies of the turbojet. An increase in turbine temperature, however, presents serious cooling problems both for the burner structure and for the stator and rotor turbine blades. Present turbine cooling methods use either internal cooling or localized mass injection (film cooling) through discrete orifices inclinded at an angle to the surface of the blade. Although this type of film cooling with discrete orifices has been successfully used to cool the surface of the blade downstream of its leading edge, it cannot be applied efficiently to the leading edge of the blade. In addition, localized cooling using discrete orifices generates large temperature gradients and tends to produce large thermal stresses (e.g. Ref. 1). Also, the efficiency of the film cooling system with discrete holes is not as high as that for film cooling with slot injection. For this reason, slot injection film cooling has recently been considered interesting, especially when large cooling is required.

An approach where by the air is injected tangentially through slots has been investigated at NYU under an Air Force contract. Such a scheme is, in principle, more efficient; however, it is more difficult to implement because it requires new methods of blade construction. In the present study, no attempt has been made to develop a practical design. The NYU slot injection investigation is divided into three parts. The first part includes an analysis of the cooling efficiency of the system. Some of the conclusions of such an analysis have been presented in Ref. 2. The second and third parts are related to the detailed investigation of tangential cooling at transonic speed, and to the analysis of upstream slot injection at the leading edge of the turbine blade. This report discusses the results of an experimental and numerical investigation of tangential slot injection film cooling with zero pressure gradients.

Description of Research

Slot injection into a turbulent boundary layer has been investigated at hypersonic speeds in Refs. 3-6. Only a few experiments are available at low subsonic speed, and large differences exist among the results presently available.[7-10] Such results, when compared with the results obtained at supersonic speed, tend to indicate important Mach number effects. The use of film cooling in turbine applications requires the ability to predict coolant effectiveness in the presence of pressure gradients for flow speeds in the range of $M \sim 0.4$ to 0.9. Basic information on cooling effectiveness in this speed range is not available. To obtain basic information useful for preliminary design, the present experimental investigation was conducted for the case of tangential slot injection with zero pressure gradient for several freestream Mach numbers. The basic goal of this phase of the investigation was to furnish the experimental data required to extrapolate the results obtained to many different set of boundary conditions, and to determine the Mach number effects. This has been achieved by correlating the coolant effectiveness derived from the ex-

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perimental data as a function of a nondimensional parameter, which has been used successfully for hypersonic flow. The experimental data has also been compared with the numerical results obtained from a numerical solution technique capable of analyzing turbulent boundary layers and slot injection with variable pressure gradients. Such a comparison indicates satisfactory engineering agreement between theoretical and experimental results. The nondimensional correlation and the numerical program provide the flexibility of extrapolating the experimental data to different boundary conditions. Presently, boundary-layer analyses are available for classical two-dimensional boundary-layer phenomena which give satisfactory engineering results. In addition, mixing-type analyses have been developed where by using empirical information on transport properties, mixing characteristics can be predicted. However, the flowfield where the two phenomena interact (e.g., slot injection) has been analyzed and compared with experiments only for a few boundary conditions and only at supersonic and hypersonic speeds. The existing numerical program,[11] developed by NASA, has been validated for slot injection into supersonic and hypersonic turbulent boundary layers, but has not been validated for subsonic speeds. Therefore, the present investigation has generated experimental data to validate the method of Ref. 11 so that it can be applied to flow conditions representative of current turbine applications. It is known that the transport properties are dependent on the Mach number, and are affected by density gradients; therefore, it is not clear, *a priori*, that the method of Ref. 11 could be used without substantial modification in the transonic range. The method assumes that the pressure gradient normal to the surface is small, and that the static pressure of the injected flow and outside flow is matched. The method uses, for the definition of the transport properties in the mixing region, empirical expressions found valid for free mixing, while at the wall it uses empirical expressions found valid in boundary-layer analyses. The variation of the transport property coefficients with respect to normal direction is obtained by matching the two expressions.

The present experimental investigation is limited to the case of zero pressure gradients. Therefore, the comparison presented here between experimental and numerical results can only be useful in determining the validity of the numerical method used for this type of boundary condition. However, the main unknown in analyzing problems of this type is the selection of the satisfactory definition of the turbulent transport properties coefficients, in terms of local turbulent phenomena, and in terms of the local flow conditions. It can be expected that gradual and favorable pressure gradients, as encountered in turbine blades downstream of the leading edge, will not affect such a definition. Therefore, the comparison presented here is the first important step required to generate confidence in the practical design use of the selected numerical method. The investigation has been carried out at NYU; however, the numerical results have been generated by J.N. Hefner of NASA Langley Research Center.

Description of the Experimental Program

The investigation was conducted at the NYU Aerospace facility in Westbury, New York. An axially symmetric center body, having a sufficiently large diameter, was tested in the axially symmetric subsonic tunnel. The stagnation temperature for all the tests was normally 900°R, and the model wall temperature was 520°R. The resulting temperature ratio approximates that used in turbine applications. Each test was performed by accurately measuring the flow stagnation conditions, the model wall temperature, and by controlling the axial symmetry of the flow. The injection flow conditions were determined at the injection station, and the coolant mass flow was measured by means of flow meter. Two series of tests were conducted: one series having injection velocities lower than freestream, and the second having velocities higher than freestream. Schematics of the apparatus used are presented in Fig. 1.

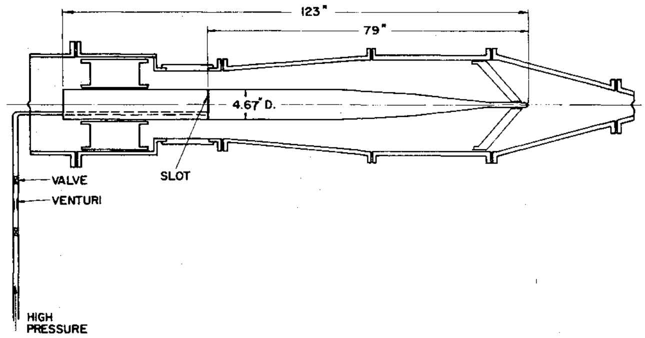

Fig. 1 Schematic design of model and wind tunnel.

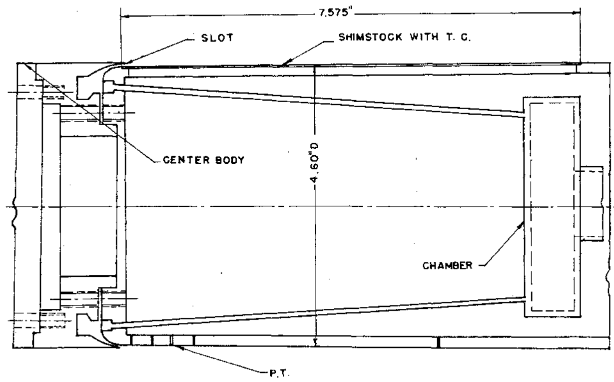

Fig. 2 Detail of the slot configuration.

The upstream portion of the model was supported in a region of very low velocity. The downstream portion of the model was supported 2 ft downstream of the slot. A conical skirt mounted on the aft portion of the model was used for throttling the flow in order to vary and control the stagnation pressure and Mach number in the region of the measurements. All the tests were performed at a static pressure equal to 15 psi. The turbulent energy of the freestream was measured to be approximately 3% in the region of the measurements. The tunnel calibration along the central body without a slot showed uniform static pressure in the region of the measurements.

Model Design and Instrumentation

The design of the model used in the tests shown schematically in Fig. 1 is an axially symmetric body. The body has a gradual longitudinal variation of radius that corresponds to the growth of the displacement thickness of the boundary layer, so that the pressure gradient on the forebody is minimized. The pressure in the region downstream of the injection is constant. The slot is located 66.5 in. downstream of the nozzle entrance. The portion of the model immediately upstream and downstream of the slot is instrumented by means of pressure taps and heat transfer gages mounted on the inside surface of the model. The heat transfer is determined by using the transient technique which keeps the model initially at uniform temperature; the test is initiated in a few milliseconds. The variation of surface temperature is measured and related to the local heat transfer at constant wall temperature. For this measurement thermocouples mounted on a thin skin section ($d = 0.015$ in.) of the model are used. The thermocouples are installed on the back surface of the thin skin so that no disturbances are introduced at the surface of the model. The measurements are performed before the wall temperature changes. Figure 2 presents a schematic of the model configuration in the vicinity of the slot. The instrumented portion of the model extends about 20 in. downstream of the slot and 7.5 in. upstream of the slot. The height of the injection slot tested is 0.035 in. The model diameter just downstream of the slot is 4.60 in., the diameter upstream of the slot is 4.67 in.

All experimental pressures and temperatures were recorded on a multichannel recording galvanometer. The response time of the galvanometer is less than 0.01 sec, and therefore it was possible to employ a scani-valve to record the pressure distribution on the model at the rate of 20 points per sec. The procedure used for the test keeps the model initially at uniform temperature. The tunnel is evacuated before the tests and then started in a few milliseconds by opening a quick operating valve placed at the throat of the divergent section shown in Fig. 1. The thermocouple records the value of dT/dt. The value of dT/dt at conditions where the temperature of the model was uniform has been used for the analysis. Knowing the value of dT/dt together with the physical properties of the model, the heat transfer is derived by the relation

$$Q=\rho_{w,m}c_{w,m}d_{w,m}(dT_w/dt) \tag{1}$$

where the subscript w,m denotes wall material. Several runs are obtained for each condition in order to reduce experimental errors. In all of the tests performed, the wall temperature of the model has been kept equal to the coolant air temperature in order to facilitate the analysis of the data.

This method used in the tests permits us to determine effectiveness for isothermal conditions. Often in tests of this type, the local adiabatic wall temperature is measured in order to obtain adiabatic effectiveness $\epsilon=(T_{adj}-T_{oe})/(T_{oj}-T_{oe})$ in place of isothermal effectiveness. This procedure requires a running time of the order of minutes, and a complex model design to eliminate the effect of longitudinal temperature gradients. In practical applications a combination of external and internal cooling takes place; therefore, analytical relations between the two quantities are required in order to analyze the coolant requirements. As discussed later, by maintaining in the tests a coolant temperature equal to the initial surface temperature, a relationship between the two quantities can be obtained analytically. Therefore in all the tests the initial model wall temperature T_w has been maintained equal to coolant temperature T_{oj} by circulating coolant air over the model prior to the tests.

Experimental Results

The tests have been conducted at three Mach numbers (i.e. 0.4, 0.6, 0.8) and at several rates of injection defined by the coefficient λ defined as

$$\lambda=\frac{\rho_j u_j}{\rho_e u_e} \tag{2}$$

where j represents the slot flow quantities of and the freestream quantities. The value of λ defines the non-

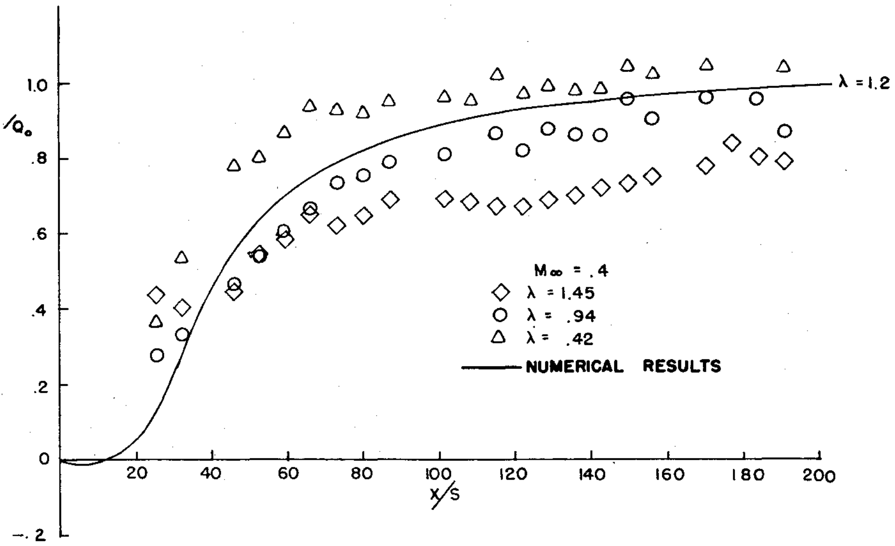

Fig. 3 Variation of the ratio Q_j/Q_o as a function of x/s at $M=0.4$.

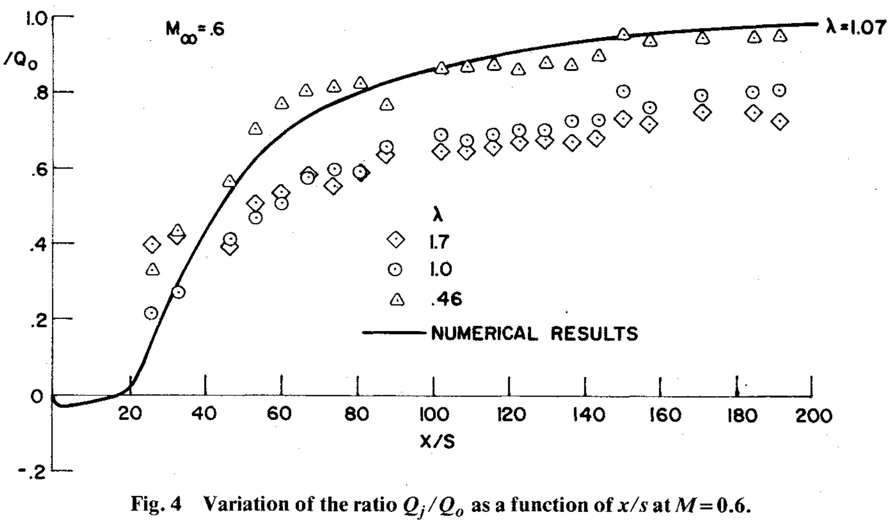

Fig. 4 Variation of the ratio Q_j/Q_o as a function of x/s at $M=0.6$.

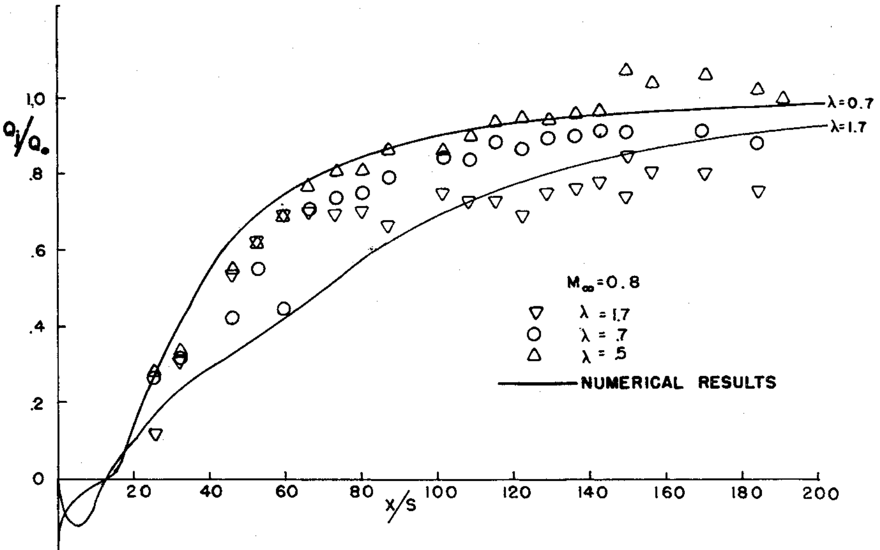

Fig. 5 Variation of the ratio Q_j/Q_o as a function of x/s at $M = 0.8$.

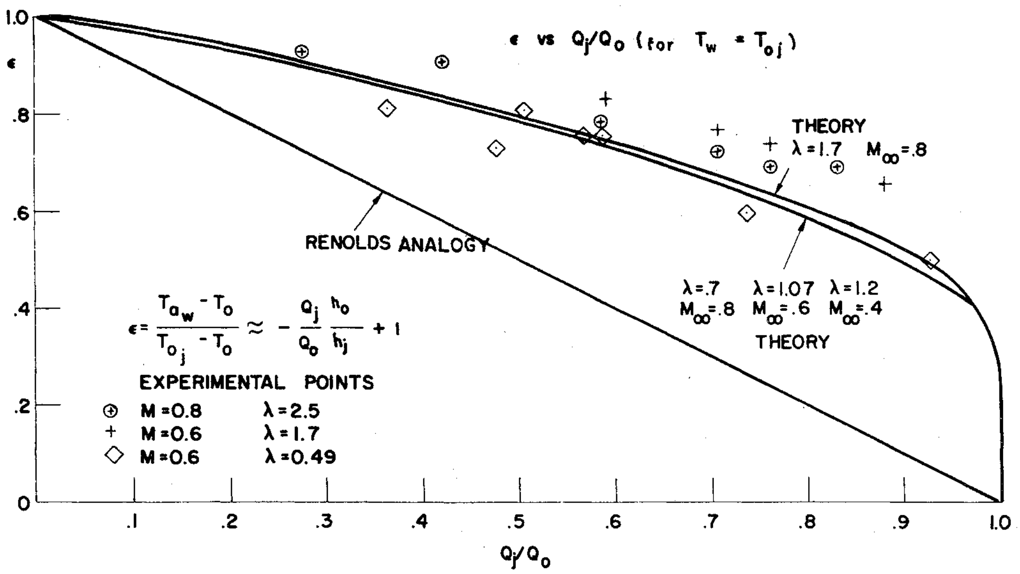

Fig. 6 Relation between Q_j/Q_o and ϵ for the condition of $T_w = T_{oj}$ given by the numerical results.

dimensional mass flow because the slot height is constant. Some of the results are presented in Figs. 3, 4, and 5 for the three Mach numbers and for three values of λ. The figures show the data in terms of the ratio Q_j/Q_o as a function of x/s where x is the distance from the slot, and s the slot height. Q_j is the value of the local heat transfer with slot injection and Q_o is the value of the measured local heat transfer with no slot; therefore, the value Q_o should be interpreted as the local heat transfer when $T_{oj} = T_{oe}$, $\lambda = 1$ and the interaction between the jet and the external flow is zero.

A comparison between some of the calculated and measured values of Q_j/Q_o is shown in Figs. 3, 4, and 5. The agreement obtained in all comparisons appears to be satisfactory from an engineering point of view. Improvement in the predictions could be obtained by changing the constants in the expression that defines the transport properties in the boundary layer program.

Derivation of Adiabatic Efficiency

Since the experimental and numerical results compare satisfactorily, a relationship between isothermal and adiabatic effectiveness can be derived by combining analytical and experimental results. The adiabatic efficiency ϵ is defined as

$$\epsilon = \frac{T_{adj} - T_{oe}}{T_{oj} - T_{oe}} \tag{3}$$

where the T_{adj} is the adiabatic wall temperature with injection

$$\frac{Q_j}{Q_o} = \frac{h_j(T_{adj} - T_w)}{h_o(T_{ade} - T_w)} = \sim \frac{h_j}{h_o}\left(\frac{T_{adj} - T_w}{T_{oe} - T_w}\right) \tag{4}$$

when $T_w \equiv T_{oj}$

$$\frac{Q_j}{Q_o}\frac{h_o}{h_j} = \frac{T_{adj} - T_w}{T_{oe} - T_w} = \frac{T_{ajd} - T_{oe}}{T_{oe} - T_{oj}} - \frac{T_{oj} - T_{ie}}{T_{oe} - T_{oj}}$$

$$= -1 + \frac{T_{adj} - T_{oe}}{T_{oe} - T_{oj}} \tag{5}$$

and

$$\epsilon = \frac{T_{adj} - T_{oe}}{T_{oj} - T_{oe}} = 1 - \left(\frac{h_o}{h_j}\right)\frac{Q_j}{Q_o} \tag{6}$$

In order to use this relation all the tests have been performed for the condition $T_w = T_{oj}$. Then if $h_j/h_o = 1$, ϵ as a function of Q_j/Q_o is given by a straight line although (Reynolds analogy). In general, the Reynolds analogy does not apply, although a unique relation can be postulated to exist because a single expression is used to represent all transport property

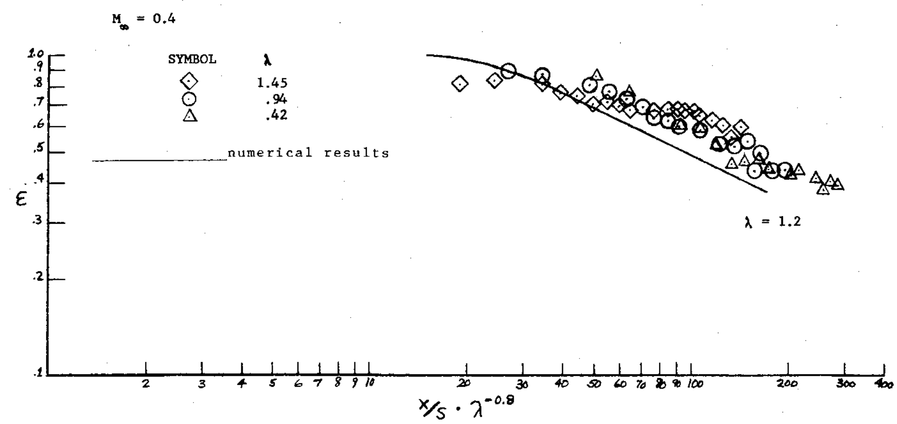

Fig. 7 Variation of ϵ as a function of $(x/s)\lambda^{-0.8}$ for different values of λ at $M=0.4$.

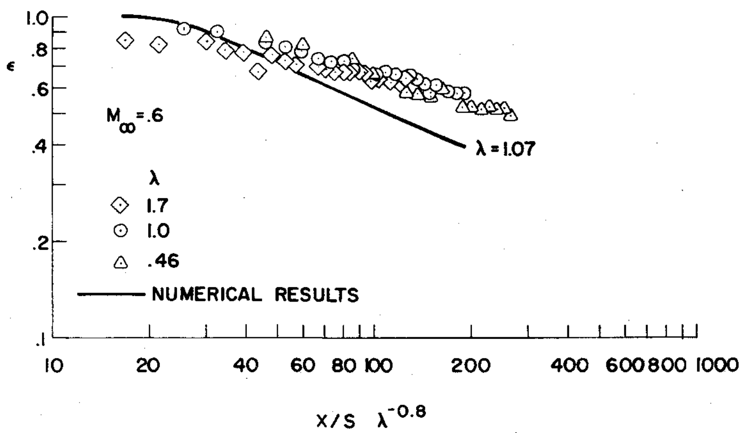

Fig. 8 Variation of ϵ as a function of $(x/s)\lambda^{-0.8}$ for different values of λ at $M=0.6$.

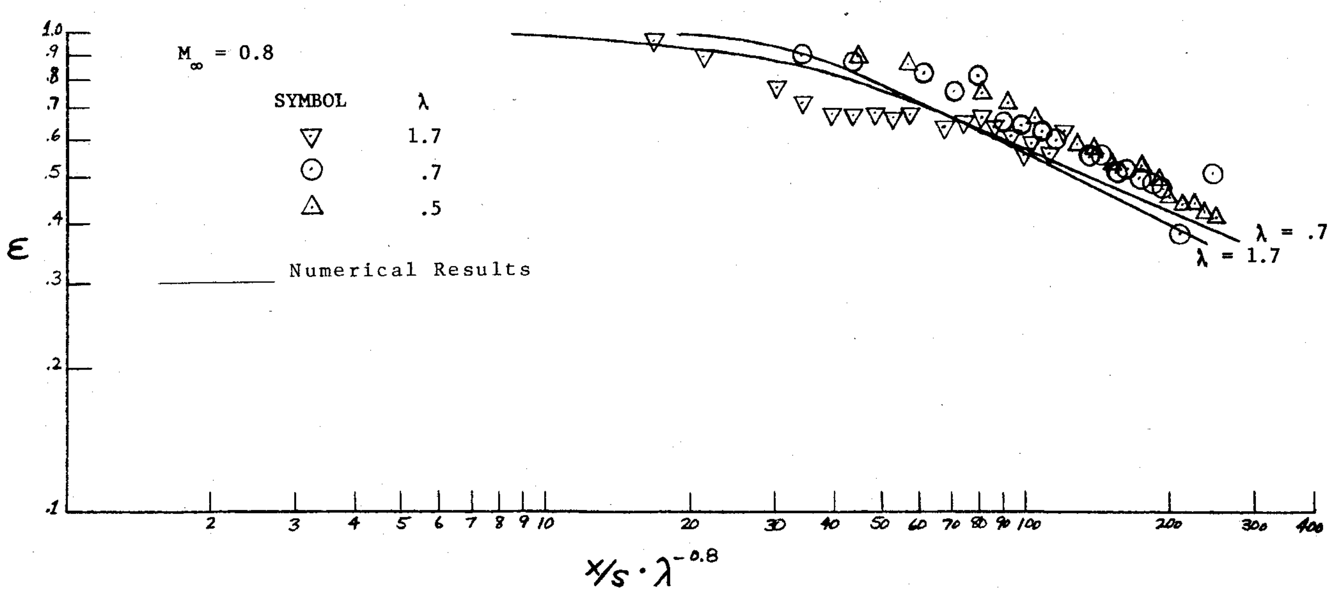

Fig. 9 Variation of ϵ as a function of $(x/s)\lambda^{-0.8}$ for different values of λ at $M=0.8$.

coefficients. In the case of slot injection, the value of Q_j/Q_o as a function of x/s has been calculated for several values of λ for the condition of T_w = constant and equal to T_{oj}. In addition, the value of T_{adj} has been determined so that a relation between isothermal and adiabatic efficiency has been derived. The numerical results, as expected, show that the relation between ϵ and Q_j/Q_o for all values of λ and M is given by a single curve independent of total enthalpy and velocity profiles, and that the quantities h_j/h_o and Q_j/Q_o are uniquely related (this relation has been determined by Professor Zakkay). This result permits us to infer ϵ from the measured value of Q_j/Q_o, and also permits us to obtain the value of Q_j for a given selected wall temperature. The relation obtained between ϵ and Q_j/Q_o is given in Fig. 6, and has been used to determine ϵ from the experimental data. Few experiments have been performed when T_{adj} has been measured to check the relation between Q_j/Q_o and ϵ. The experimental results are also shown in Fig. 6.

Adiabatic Efficiency

The values of the adiabatic efficiency ϵ have been plotted as a function of the parameter $(x/s)\lambda^{-0.8}$ in Figs. 7, 8, and 9.

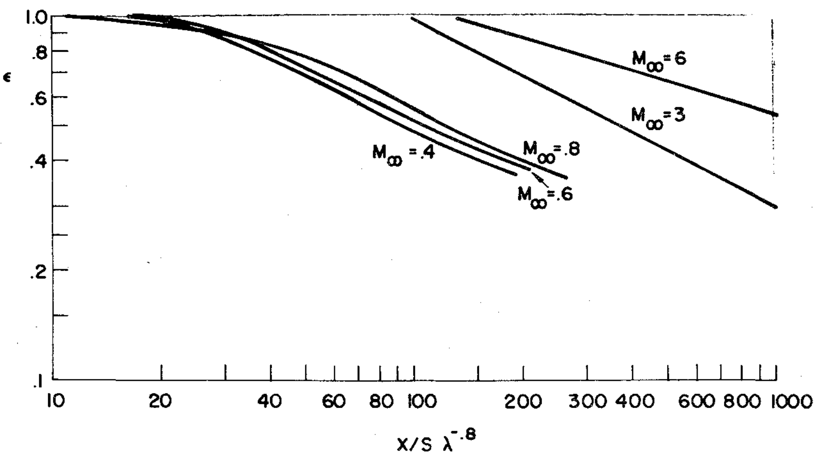

Fig. 10 Variation of ϵ as a function of $(x/s)\lambda^{-8}$ for different freestream Mach number.

For comparison, the numerical values of ϵ are shown as the solid line in the figures. All the results, numerical and experimental, correlate with the parameter $(x/s)\lambda^{-0.8}$ used before for hypersonic flow. The experimental data indicate a more gradual decay in ϵ with $(x/s)\lambda^{-0.8}$ than do the numerical values. Also, the experimental data show some small influence of the Mach number, whereas the numerical predictions indicate no influence of Mach number between $M=0.4$ and $M=0.8$. The trends given by the subsonic experimental data are compared with supersonic data in Fig. 10 to show the effect of Mach number on the cooling effectiveness. The fact that the value of ϵ obtained from the experimental results correspond well for all conditions with the parameter $(x/s)\lambda^{-0.8}$, as predicted by the numerical analysis, is an additional indication that the relation between ϵ and Q_j/Q_o obtained from the analysis, and used for determining ϵ, is valid generally. This result, if confirmed by other experiments, is important.

Conclusions

Slot injection into a subsonic turbulent boundary layer has been investigated experimentally at freestream Mach numbers of 0.4, 0.6, and 0.8. The results have been compared with the predictions obtained from a finite difference boundary-layer program developed by NASA for slot injection into turbulent supersonic boundary layers. The two sets of results compare favorably. Both the numerical and experimental cooling effectiveness results correlate with $(x/s)\lambda^{-0.8}$. The numerical results indicate that a unique relation exists between the isothermal effectiveness and adiabatic effectiveness; this indicates, therefore, the existence of similarity conditions for temperature and velocity profiles.

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