Technical Notes

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Effect of Adverse Pressure Gradient on Film Cooling Effectiveness

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Nomenclature

M_e = local Mach number
Re_c = coolant Reynolds number, $\rho_c u_c s/\mu_c$
u_e = local mainstream velocity
x = distance from the nozzle throat, or from the slot
λ_l = injection mass flow rate, $\rho_c u_c/\rho_e u_e$
μ_c = coolant absolute viscosity
μ_e = mainstream absolute viscosity
ρ_e = local mainstream density

1. Introduction

ADVANCES in high speed aircraft require a new technology to maintain a surface structure capable of withstanding the large heating load. One of the techniques is surface film cooling. Recent investigations indicate that better film cooling can be obtained in a high-speed flow than in a low-speed flow. However, previous results are for tangential slot injection without the effect of pressure gradient. In the present work, the effect of a streamwise adverse pressure gradient on the slot film cooling effectiveness has been investigated experimentally. Correlation of the experimental film cooling effectiveness was found. Results indicate that better film cooling effectiveness can be obtained when an adverse pressure gradient is present.

2. Experiment

Tests were conducted in a Mach 6 axisymmetric wind tunnel with a streamlined centerbody, followed by the cylindrical model with a tangential injection slot (slot height $s = 0.015$ in.). A shroud was used to generate an adverse pressure gradient in the test section. Thermocouples and pressure taps were used to measure the distributions of the heat transfer rates and surface pressures. The stagnation temperature $T_{o\infty}$ and pressure $p_{o\infty}$ of the present tests were approximately 830°R and 1900 psia, respectively. The corresponding freestream Reynolds number Re_∞ was 3.78×10^7/ft. Air, having stagnation temperature, $T_{oc} = 530$°R, was injected tangentially at sonic velocity in the downstream direction. The injection mass flow rate λ_∞ was between 0 and 0.61. Local adiabatic wall temperature T_{aw} was inferred from the heat-transfer measurement. Experimental film cooling effectiveness, $\varepsilon = (T_{aw} - T_{o\infty})/(T_{oc} - T_{o\infty})$, was found.

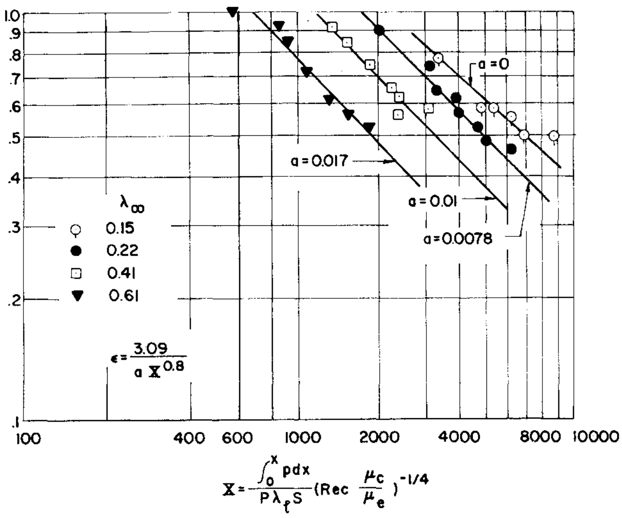

Fig. 2 Correlation of film cooling effectiveness.

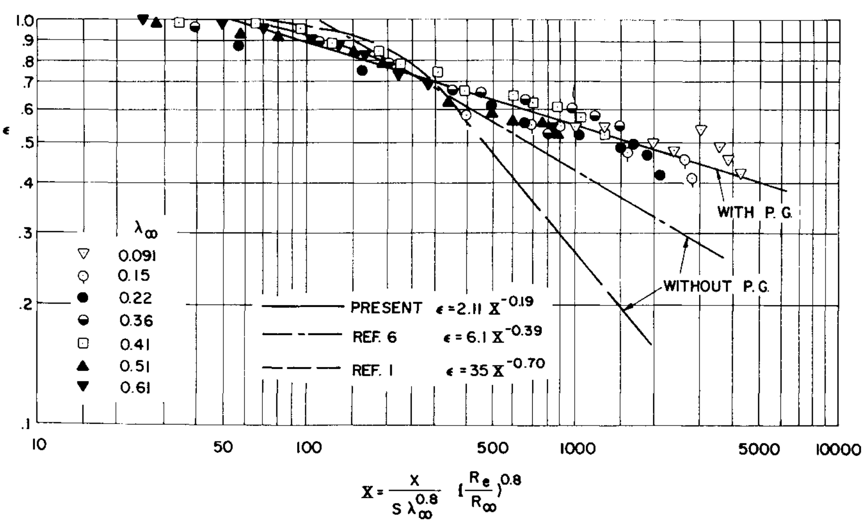

Fig. 1 Correlation of film cooling effectiveness.

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Index category: Boundary Layers and Convective Heat Transfer—Turbulent.

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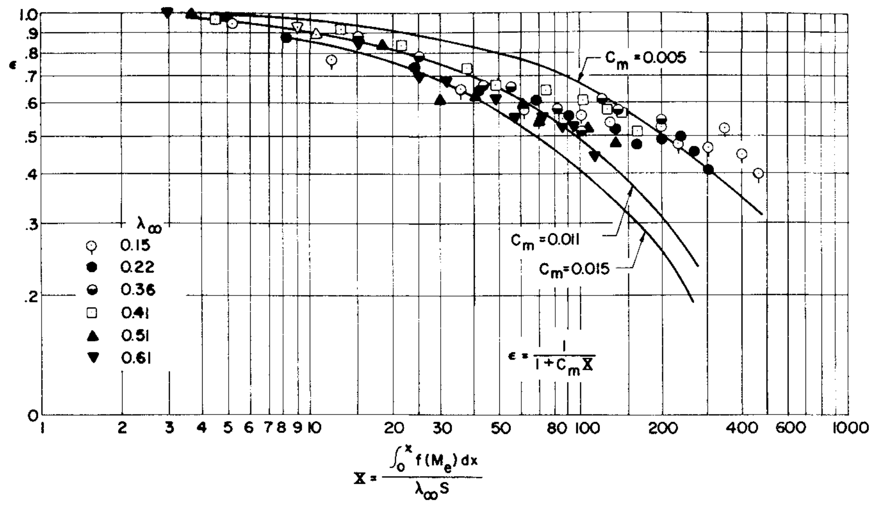

Fig. 3 Correlation of film cooling effectiveness.

The static pressures, both upstream and downstream of the injection slot, were measured, and agreed well with predictions by the inviscid Method of Characteristics. Static pressure measurements for various injection mass flow rates have shown that the coolant injection rate has little influence on the pressure. The transient-thin-wall technique was used to evaluate the heat-transfer rates. The heat-transfer rate increases longitudinally due to the presence of the adverse pressure gradient. The local heat-transfer rates decrease as the injection mass flow rates increase.

3. Film Cooling Effectiveness

In previous film cooling experiments at Mach 6 with zero pressure gradient,[1] the local adiabatic wall temperature was calculated from the measured heat-transfer rate, using the Flat Plate Reference Enthalpy Method. In the present work, the local adiabatic wall temperature was also calculated from the heat-transfer measurements, using the heat-transfer equation of Reshotko and Tucker[2] for a turbulent compressible boundary layer with pressure gradient. These local adiabatic wall temperatures were used to determine the present film cooling effectiveness. In the analyses of the correlations of film cooling effectiveness, boundary-layer models were reviewed.[3] Correlation was suggested for the case with pressure gradient effect. Jubasz[4] also developed a turbulent mixing model. Correlation of the turbulent mixing model correlates data from widely different flow regimes if a turbulent mixing level can be estimated. These two models are modified to predict the present experimental film cooling effectiveness.

For the boundary-layer model, the following additional assumptions are made: 1) the total mass of the film cooling layer, m_f, is proportional to the mass flow rate m_{bl} of the boundary layer, $m_f = aw_{bl}$; 2) under the effect of an external pressure gradient, the boundary-layer thickness δ can be estimated by

$$\delta = 0.37X\,Re_x^{-0.2}$$

with

$$X = \left(\frac{1}{P}\right)\int_o^x P\,dx, \quad Re_x = \frac{\rho_e u_e X}{\mu_e}, \quad P = \left[\frac{M_e}{1+\left(\frac{\gamma-1}{2}\right)M_e^2}\right]^4$$

According to the conservation of energy and mass, correlation of the film cooling effectiveness is found to be

$$\varepsilon = (3.09/a)X^{-0.8}$$
$$= (3.09/a)\left[\left(\int_o^x P\,dx\right)\Big/(P\lambda_l s)\right]^{-0.8}(Re_c\,\mu_c/\mu_e)^{0.2} \qquad (1)$$

For the turbulent mixing model, the following assumptions are made: 1) the external mainstream is isentropic; 2) entrainment mass flow rate m_e is proportional to the mainstream mass flow rate, $m_e = C_m \rho_e u_e$, with constant mixing coefficient C_m. By the equation of state of an ideal gas and conservations of energy and mass, correlation of the film cooling effectiveness is found to be

$$\varepsilon = 1/(1+C_m X)$$

with

$$X = \left(\frac{1}{\lambda_\infty s}\right)\left[\frac{\left(1+\frac{\gamma-1}{2}M_\infty^2\right)^3}{M_\infty}\int_o^x \frac{M_e\,dx}{\left(1+\frac{\gamma-1}{2}M_e^2\right)^3}\right] \qquad (2)$$

Carlson[5] developed an analytical model allowing for the variation of the mainstream Mach number and turbulence level. The film cooling effectiveness was found to be a strong function of the local Reynolds number, i.e., $\varepsilon \propto Re_x^{-0.8}$. For Mach 6 turbulent slot injection with zero pressure gradient,[6] it has been found that the experimental film cooling effectiveness was correlated by $\varepsilon = 6.1\ (x/s\lambda_\infty^{0.8})^{-0.39}$. It is expected that the present experimental data could be correlated in terms of the parameter $(x/s\lambda_\infty^{0.8})(Re_x/Re_\infty)^{0.8}$. In Fig. 1, present experimental film cooling effectiveness with the effect of an adverse pressure gradient can be correlated by

$$\varepsilon = 2.11[(x/s\lambda_\infty^{0.8})(Re_x/Re_\infty)^{0.8}]^{-0.19} \qquad (3)$$

Present experimental film cooling effectiveness is compared with theory given by Eqs. (1) and (2). The experiments can be correlated for different injection mass flow rates with a different mixing coefficient a, in Fig. 2. Present experimental film cooling effectiveness can be predicted satisfactorily by the theory with $C_m = 0.0101$ for $0 < X < 100$, in Fig. 3. The slot film cooling effectiveness for zero pressure gradient obtained at Mach 6 was compared with present test results in Fig. 1. Improved cooling effectiveness was obtained for the same injection mass flow rate when adverse pressure gradient was present.

References

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