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Swept-Slot Film-Cooling Effectiveness in Hypersonic Turbulent Flow

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Nomenclature

M = Mach number
s = slot height
T = temperature
u = velocity
x = coordinate in freestream direction
y = coordinate normal to plate surface
ε = effectiveness parameter $(T_{t,\infty} - T_{eq})/(T_{t,\infty} - T_{t,j})$
λ = mass flow parameter, $\rho_j u_j/\rho_\infty u_\infty$
ρ = density
Λ = slot sweep angle in plane of the flat plate
θ = surface streamline direction relative to x-axis

Subscripts
eq = equilibrium
j = slot
t = total or stagnation
∞ = freestream

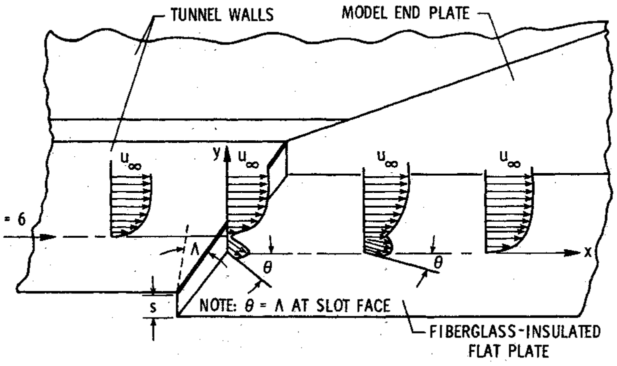

Fig. 1 Swept-slot film-cooling model.

Introduction

FILM cooling provides a means of reducing the operational surface temperature of a high-speed vehicle below the radiation equilibrium temperature. Experimental studies of tangential slot injection at Mach 6[1,2] have shown that the film-cooling effectiveness in a two-dimensional, high-speed turbulent flow is significantly greater than indicated by extrapolations of previous low-speed results. However, practical applications of slot injection film cooling (particularly on wings) will generally require the slots to be swept relative to the inviscid streamline direction. The effect of sweeping the slot on the film-cooling effectiveness downstream of the slot has not been previously investigated. The present Note presents measurements of surface equilibrium temperature downstream of swept slots with sonic tangential air injection into a thick hypersonic turbulent boundary layer and compares these results with unswept slot results.[3]

Experimental Approach

The experimental investigation was conducted in the Langley 20-in. Mach 6 wind tunnel[4] at a freestream total temperature and unit Reynolds number per centimeter of 492°K and 0.287×10^6, respectively. The model (see Fig. 1) was a fiberglass flat plate (35.5 cm wide and 91.4 cm long) mounted parallel with and recessed below the flat tunnel wall. The slot flow was ejected tangentially over the surface of the flat plate from a two-dimensional sonic slot swept at either 22.5° or 45° relative to the freestream flow. The slot flow was ejected normal to the slot and was swept at either 22.5° or 45° relative to the freestream direction. The slot configuration could be adjusted to provide slot heights of 0.159, 0.476, and 1.111 cm with the outer slot wall thickness (wall between slot flow and freestream) held constant at 0.159 cm. The slot flow temperature was varied from 136°K to 311°K. The slot mass flow rate was uniform over a midspan of at least 21 cm and could be metered to insure sonic slot injection. Surface temperatures were measured by flush-mounted thermocouples located along the centerline of the insulated flat plate surface. The surface temperatures were considered to be in equilibrium when for a period of at least 100 sec they changed less than 0.1%.

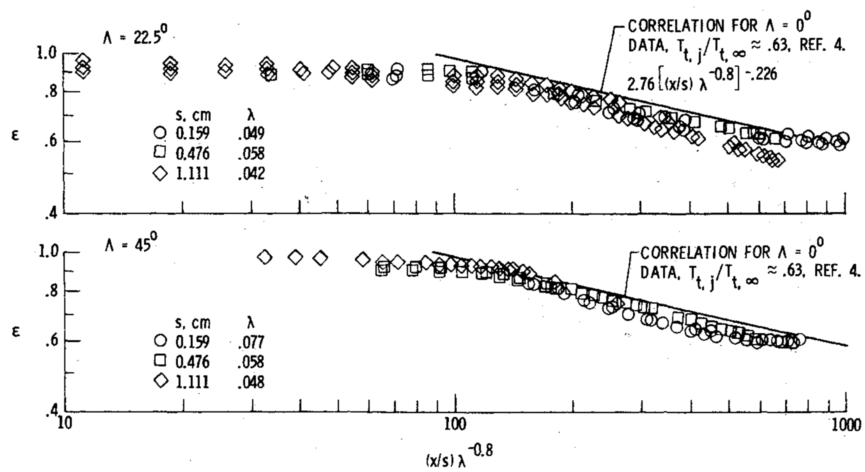

Fig. 2 Film-cooling effectiveness for $T_{t,j}/T_{t,\infty} \simeq 0.60$.

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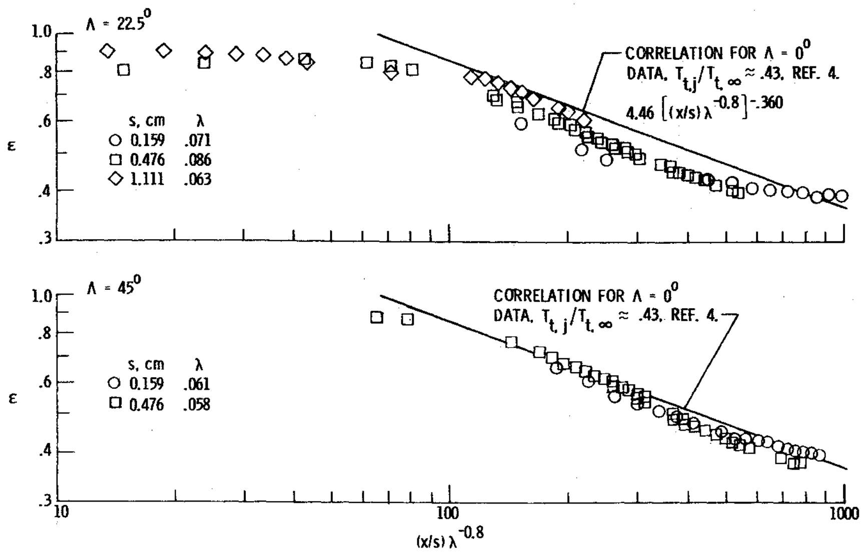

Fig. 3 Film-cooling effectiveness for $T_{t,j}/T_{t,\infty} \simeq 0.32$.

Table 1 Cooling effectiveness correlations for swept slot injection, $\varepsilon = a[(x/s)\lambda^{-0.8}]^{-b}$

Λ	$T_{t,j}/T_{t,\infty}$	a	b
0°	0.63	2.76	0.226
22.5°	0.60	3.12	0.263
45°	0.60	3.33	0.269
0°	0.43	4.46	0.360
22.5°	0.32	4.51	0.390
45°	0.32	5.19	0.393

Results

A summary of the equilibrium temperatures measured downstream of the swept slots ($\Lambda = 22.5°$ and $\Lambda = 45°$) for $T_{t,j}/T_{t,\infty} \simeq 0.6°$, and 0.32 is presented in Figs. 2 and 3 in a form which correlated the data in Refs. 1–3. The distance parameter $(x/s)\lambda^{-0.8}$, which is based on the chordwise distance downstream of the slot, correlates the effectiveness data for both slot flow temperatures in a relatively narrow band for the slot mass flow rates and slot heights of the present investigation. Table 1 presents straight line correlations for the swept slot data as well as that for the unswept slot data of Ref. 3 for similar total temperature ratios and mass flow rates.

The effect of slot sweep on the film-cooling effectiveness is clearly seen in Figs. 2 and 3. Although the cooling effectiveness is lower and decreases more rapidly for the cooler slot flow temperature ($T_{t,j}/T_{t,\infty} \simeq 0.32$), the film-cooling effectiveness for the swept slots decreases only slightly below that for the comparable unswept slots for both sweep angles and both slot flow temperatures. The total cooled area downstream of the swept slot is therefore approximately equivalent to that for the unswept slot since the slot width for both the swept and the unswept slots is identical; also oil flow studies, not shown herein, show that the streamlines downstream of the swept slot remain nearly parallel as the slot flow mixes with the freestream boundary layer and turns toward the freestream direction. These results indicate that three-dimensional slot injection film cooling is nearly as effective as two-dimensional slot injection and therefore film cooling becomes even more attractive as a viable active cooling concept for high-speed flight vehicles.

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