Effect of Geometry Modifications on Effectiveness of Slot Injection in Hypersonic Flow

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Nomenclature

b	= distance slot elevated above plate surface
C_f	= local skin friction coefficient, $\tau/(\frac{1}{2}\rho_\infty u_\infty^2)$
C_p	= pressure coefficient
h	= backward-facing step height
M	= Mach number
p	= static pressure
s	= slot height
t	= lip thickness
T	= temperature
u	= velocity in streamwise direction
x	= coordinate in streamwise direction
y	= coordinate normal to plate surface
ϵ	= cooling effectiveness, $(T_{t,\infty} - T_{eq})/(T_{t,\infty} - T_{t,j})$
λ	= mass flow parameter, $\rho_j u_j/\rho_\infty u_\infty$
ρ	= density
τ	= shear stress

Subscripts

eq	= equilibrium
j	= slot
t	= total or stagnation
∞	= freestream
o	= no slot or step

Introduction

EXPERIMENTAL studies[1-3] of tangential slot injection into a Mach 6 turbulent boundary layer have shown that the film cooling in two-dimensional high-speed flow is significantly more effective than that predicted by extrapolating previous low-speed results. Furthermore, it was shown that tangential slot injection significantly reduces the local skin friction downstream of the slot. Although the results are promising, the effects of systems penalties for collecting, ducting, and injecting the slot air must be included for an overall evaluation. Recent unpublished work by Lockheed Aircraft Company and a NASA funded contract to Advanced Technology Laboratories[4] have shown, at least for subsonic speeds, that the systems penalties can be significant. Therefore, because of the probability of rather large systems penalties, the effectiveness of slot injection for film cooling and skin friction reduction must be optimized. This Note presents measurements of surface static pressures, equilibrium temperatures, and skin friction downstream of tangential slot injection into a thick turbulent hypersonic boundary layer from two modified slot configurations. The data are compared with results obtained for "baseline" configurations reported in Refs. 2 and 3 to determine whether simple modifications to the slot configuration can produce improved cooling effectiveness and skin friction reduction.

Experimental Approach

The experimental investigation was conducted in the Langley 20-in. Mach 6 Wind Tunnel[5] at a freestream total temperature and unit Reynolds number of 492 K and 0.287 × 10^6/cm, respectively. The model was the fiberglass flat plate (35.5 cm wide and 91.4 cm long) used in the work of Refs. 2 and 3 mounted parallel with and recessed below the flat tunnel wall. The slot flow was ejected tangentially over the surface of the flat plate from the two-dimensional slot configurations. Configurations I and III are the "baseline" configurations, and are similar except that the slot height of configuration III is three times larger than for configuration I. Dimensions for the configurations are given in Table 1.

Table 1 Slot configuration dimensions

Configuration	t, cm	s, cm	b, cm	h, cm
I	0.157	0.160	0.000	0.317
II	1.110	0.160	0.000	1.270
III	0.157	0.478	0.000	0.635
IV	0.157	0.478	0.635	1.270

The "baseline" slot configurations were simply modified by thickening the slot lip (configuration II), and by elevating the location of the slot exit above the flat plate (configuration IV). Both modifications created an increase in the height of the backward-facing step. The slot mass flow rate was uniform over a midspan of at least 21 cm, and was regulated so that the ratio of the measured sonic slot mass flow to the calculated freestream mass flow (λ) varied from 0.016-0.174. The turbulent wall boundary layer over the slot was approximately 6.2 cm thick.

Data obtained in this investigation include surface pressures, equilibrium temperatures, and skin friction. The surface static pressures were measured by multirange capacitance-type pressure transducers calibrated to better than 1% full scale accuracy. 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 the temperature change for a period of at least 100 sec was less than 0.2%. Skin friction was measured using multitype, multiple-sensitivity skin friction balances with a floating element having a diameter of 0.94 cm, and a surrounding air gap width of 0.01 cm. Details of these balances and their calibration procedure are discussed in Ref. 3.

Results

Surface static pressures measured downstream of the modified slot configurations II and IV are shown in Fig. 1, for various slot mass flow rates. Fairings of the "baseline" data are also shown. The concept of nearly "matched" pressure[2, 6] refers to the case where the slot and freestream static pressure are nearly equal, and the downstream static pressure along the wall is approximately constant. "Matched" pressures were not obtained for the modified configurations; instead, a rather severe adverse pressure gradient extends between 100 and 300 slot heights downstream of the slot. This is probably caused by the significantly larger step heights and resulting base flow regions associated with the modified slot configurations. Measured pressures downstream of the modified slots for the various injection rates are only slightly higher than typical base pressure measurements obtained in the 20-in. Mach 6 Tunnel ($p/p_\infty = 0.27$-0.40), and calculated base pressure ratios ($p/p_\infty = 0.3$) based on $C_p = 1/M^2$ at comparable flow conditions.

A summary of the equilibrium temperatures measured downstream of the modified slot configurations is presented in Fig. 2 in a form which correlated the "baseline" data in Refs. 2 and 3. The straight-line fairings represent the "baseline" data for configurations I and III. The present data, which correlate in a relatively narrow band for the mass flow rates of the present study, show that the slot modifications (i.e., thick slot lip or elevated slot) only slightly influenced the film cooling effectiveness compared to that

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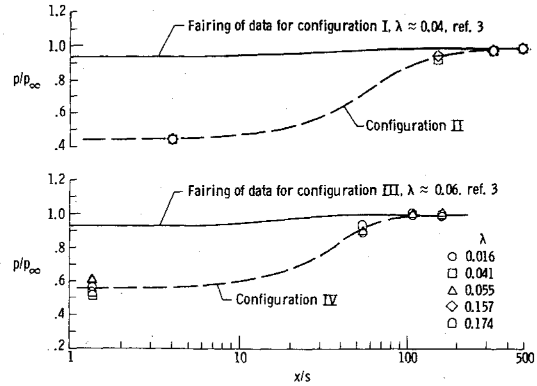

Fig. 1 Surface static pressures downstream of slot configurations.

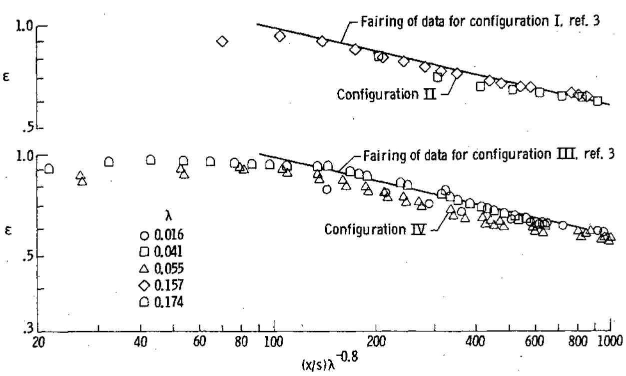

Fig. 2 Film cooling effectiveness for thick slot lip (configuration II) and elevated injection slot (configuration IV).

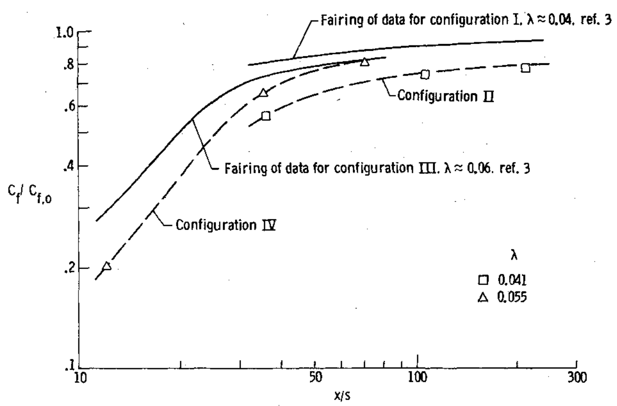

Fig. 3 Skin friction reduction for slot injection configurations.

found previously for the "baseline" slot configurations. Although it was intended to simply show the influence of the thick slot lip or the elevated slot, these data also include the influence of an overall increase in step height.

The effect of the slot modifications on the downstream skin friction is shown in Fig. 3 for slot mass flow ratios comparable to the nearly "matched" pressure conditions found for the "baseline" configurations. Configurations II and IV produced significantly larger local and integrated skin friction reductions in comparison to the "baseline" configurations. In fact, configuration II reduced the integrated skin friction over a distance of x/s between 36 and 210 by 15% below that obtained for configuration I; configuration IV produced an additional 5% skin friction reduction over that obtained for configuration III between x/s of 12 and 70. The reduced skin friction may be attributed to the larger step heights and rather severe adverse pressure gradients created by the modified slot configurations.

Although the present results show that simple modifications to the "baseline" slot configurations can enhance the skin friction reductions obtained with tangential slot injection, slot base drag estimates indicate that neither of the modifications will lessen the impact of the systems penalties for collecting, ducting, and injecting the slot air. The base drag for configuration II with the thick slot lip is over eight times greater than the incremental skin friction reduction obtained with that configuration; the base drag for configuration IV with the elevated slot is approximately fifteen times greater than the incremental skin friction reduction obtained with that configuration. Therefore, both of the present modified slot configurations significantly increase the overall slot-injection systems penalties.

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On Thermally Induced Non-Fourier Stress Waves in a Semi-Infinite Medium

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Nomenclature

c = velocity of thermal wave
c_v = specific heat
c_e = stress wave velocity
k = thermal conductivity
I_0 = Bessel function of order zero
I_1 = Bessel function of order one
t = time
T = temperature
$\bar{T}$ = Laplace transform of T with respect to time variable
T_0 = reference temperature
p = Laplace transform variable
q = heat flux
u = elastic displacement
x = space variable
α = thermal diffusivity
$\bar{\alpha}$ = thermal expansion coefficient
ρ = density
λ,μ = Lame's constants
σ_{xx} = stress in x-direction
$\bar{\sigma}$ = Laplace transform of σ

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