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Technical Notes

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Effect of Total Temperature on Boundary-Layer Stability at Mach 6

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Nomenclature

A = disturbance amplitude, nondimensional
C_H = nondimensional heat transfer coefficient, $\dot{q}/\rho_e u_e c_p(T_r - T_w)$
c_p = constant pressure specific heat, J/(kg · K)
k = thermal conductivity, W/(m · K)
N = integrated amplification rate, $\ln(A/A_0)$
Pr = Prandtl number, $\mu c_p/k$
$\dot{q}$ = heat flux, W/m^2
R = $\sqrt{Re}$
Re = Reynolds number based on boundary-layer edge conditions, $\rho_e u_e s/\mu_e$
s = running length along cone surface, m
T = temperature, K
u = velocity component parallel to model surface, m/s
γ = adiabatic exponent, nondimensional
μ = viscosity, kg/m/s
ρ = density, kg/m^3

Subscripts

e = boundary-layer edge conditions
r = recovery temperature
w = wall conditions
0 = stagnation conditions, lower neutral bound location

Introduction

DYNAMIC similarity, the condition that the dependent variables of two flowfields collapse in non-dimensional coordinates, is often assumed in analyses of boundary-layer stability. To achieve similarity, all of the parameters in the equations of motion, such as local Reynolds number and local Prandtl number, must be the same at corresponding points in the two flows. A mathematical analysis of the equations of motion for a compressible, ideal gas flow shows that, in general, exact dynamic similarity can only exist if γ and the Prandtl number are constant, and all of the transport properties are proportional to a power of the absolute temperature.[1] Because of the deviation of the transport properties of air from a power-law temperature dependence, exact dynamic similarity will not exist for significant changes in total temperature even if freestream Mach number, Reynolds number, and T_w/T_0 are fixed. Linear stability calculations[2,3] for a cone at Mach 8 showed that, with other parameters held fixed, boundary-layer stability increased with increasing total temperature.

Little experimental verification of these effects exists. The one extant experimental[4] study is difficult to interpret because the unit Reynolds number was not held fixed as the total temperature was varied. The present project addressed this lack of data by examining the stability of the hypersonic boundary-layer flow over a cone as total temperature was varied and Mach number, Re, and T_w/T_0 were held constant.

Experiment and Computations

Tests were carried out in the Arnold Engineering Development Center von Kármán Gas Dynamics Facility Tunnel B (AEDC VKF-B) in 1991. The AEDC VKF-B facility and its freestream disturbance levels have been described elsewhere.[5,6] Tests were carried out at a freestream Mach number of 5.96 and total temperatures of 472 K (low T_0 case) and 583 K (high T_0 case). The tunnel stagnation pressure was fixed at 3.69×10^5 Pa for the low T_0 case and 5.07×10^5 Pa for the high T_0 case to maintain a constant freestream (upstream of the model shock) unit Reynolds number of 3.3×10^6 m^{-1}. The model, shown in Fig. 1 and described previously,[7–9] was a sharp-nosed (50-μm-radius), 1.016-m-long cone with half-angle of 7 deg. Model instrumentation consisted of four static pressure orifices and eight Schmidt–Boelter[10] heat transfer gauges. Previous Schmidt–Boelter gauge measurements under comparable conditions showed ±10% accuracy in heat transfer.[11] A heat exchanger in the model cooling circuit maintained the model wall temperature at $T_w/T_0 = 0.63$. The boundary-layer edge unit Reynolds number derived from measured pitot pressure and total temperature was 4.13×10^6 m^{-1}.

The constant-current hot-wire instrumentation was described in a previous publication.[12] Measurements were taken at 25.4-mm intervals in the streamwise direction. At each axial station, the hot-wire broadband rms voltage was recorded while the hot wire was traversed through the boundary layer. Hot-wire measurements were made at the wall-normal station where the broadband rms voltage fluctuations peaked. The hot wires used in this test were not calibrated. The amplitude ratios of fluctuating voltages are believed to approximate those of fluctuating flowfield variables.[7,8,12,13]

The e$^{\text{Malik}}$ linear stability code[14] was used to calculate N factors for the two total temperature cases. The boundary-layer basic state was computed using the built-in similarity solver in the e$^{\text{Malik}}$ code,

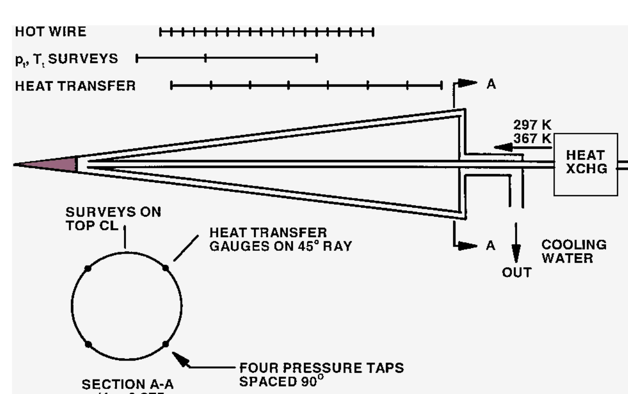

Fig. 1 Schematic of model and instrumentation.

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with constant $Pr = 0.72$, and $c_p = 1004.5$ J/(kg K). Because Pr and c_p were constant, total temperature effects entered the basic state and stability calculations through the viscosity variation. N factors were calculated using the program option that maximizes growth rate at each x station, allowing wave angle to vary. Because wall cooling stabilized the first mode at the frequencies and Reynolds numbers computed, growth was confined to the second mode, and maximum growth always occurred at zero wave angle.

Results

Mean heat transfer measurements are compared to the heat transfer predicted by isothermal-wall laminar boundary-layer similarity solutions in Fig. 2. The discrepancy between the similarity solutions and the measured heat transfer at lower Reynolds number is believed to be due to the uncooled model nose tip, which is not accounted for in the similarity solution.[15] The transition location is defined in this Note as the location where heat transfer first rises above laminar values. Because of the paucity of data points and their scatter, transition was determined by fairing a straight line through the two most downstream data points where heat transfer has begun to rise definitively above laminar values and by determining where this line intersected the similarity solutions. By this criterion, transition occurs at approximately $Re = 3.6 \times 10^6$ for the high T_0 case, and $Re = 3.3 \times 10^6$ for the low T_0 case, which indicated the stabilizing effect of increased total temperature. An isolated rise in heat transfer occurs near $Re = 3.2 \times 10^6$, but this point is believed to be erroneous because the first consistent rise in heat transfer occurs downstream of this location.

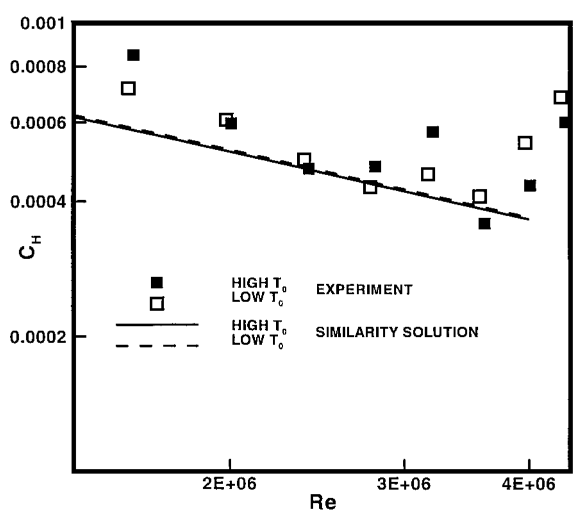

Fig. 2 Heat transfer for high and low total temperature cases.

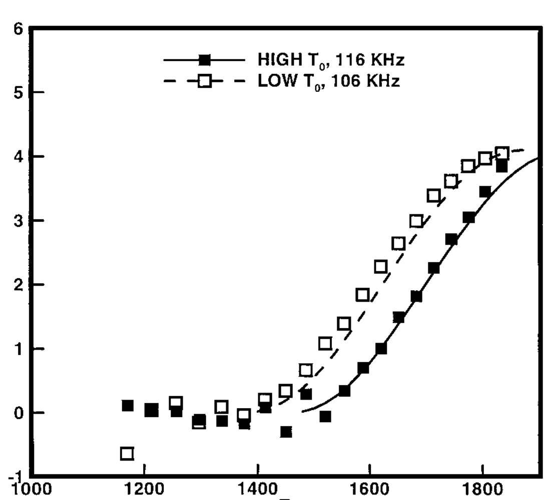

Fig. 3 Measured (symbols) and computed (lines) N factors for most dangerous frequencies for the high and low total temperature cases.

Computed N factors for the most dangerous frequency are compared to N factors derived from hot-wire measurements in Fig. 3. The most dangerous frequency is defined here as the first frequency component to attain an N factor of four. Detailed comparison of computed N factor envelopes to mean transition locations identified four as the correlating N factor.[15] Measured disturbance amplitudes were interpolated to the computed lower neutral bound location by the use of sixth-order polynomials, and this amplitude was used as the experimental A_0. An N factor of four occurs at a higher Reynolds number for the high T_0 case.

Conclusions

With nondimensional parameters held constant, both experiment and theory show an increase in boundary-layer stability with increased total temperature. This absence of dynamic similarity indicates the importance of considering total temperature effects even in nonreacting gas flows.

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