Stagnation-Point Nonequilibrium Heat Transfer

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Nomenclature

St	=	Stanton number $q/\rho_\infty U h_t(1 - h_w/h_t)$
C_w	=	atom mass fraction at wall
$(C_w)_{max}$	=	Eq. (3)
h_w	=	enthalpy at wall
h^0	=	average dissociation enthalpy for air
L	=	nose radius
Re_s	=	Reynolds number $\rho_\infty UL/\mu_s$
T_w	=	temperature of wall
U	=	freestream velocity
ρ_∞	=	freestream density
$(\rho_\infty)_{max}$	=	Eq. (4)
μ_s	=	viscosity evaluated at stagnation conditions

Introduction

In the past few years, an extensive amount of literature has been published on the effects of surface catalycity on nonequilibrium stagnation-point heat transfer. Solutions are usually presented in a form that is not very suitable for engineering calculations. In addition, where solutions or correlations are available for engineering calculations, they are restricted to chemically frozen boundary layers with equilibrium edge conditions. It is the purpose of this paper to present a correlation of a set of solutions obtained from a viscous shock-layer analysis. This correlation permits a rapid means of calculating the heat-transfer rate to a noncatalytic or fully catalytic wall accounting for the effects of nonequilibrium chemistry and vorticity interaction. This correlation spans an altitude range between 150,000–280,000 ft and a velocity range between 15,000–26,000 fps. For altitudes below 150,000 ft, a nonequilibrium boundary-layer analysis would be more appropriate, and for altitudes above 280,000 ft, the assumption of a thin shock wave (use of the Rankine-Hugoniot relations) is no longer valid. The results presented in this paper represent an extension of the work presented in Refs. 1 and 2.

Results and Discussions

Figure 1 is a plot of the Stanton number as a function of the Reynolds number, which is evaluated immediately behind the shock wave assuming that the shock wave is chemically frozen. We note that if in the Stanton number

$$St = \frac{q}{\rho_\infty U h_t(1 - h_w/h_t)} \tag{1}$$

the wall enthalpy is defined as

$$h_w = h^0 C_w + (h_w)_{C=0} \tag{2}$$

then the Stanton numbers for catalytic and noncatalytic conditions, at a constant velocity, lie on the same curve. The spread between the curves for different velocities is sufficiently small so that interpolation for intermediate velocities is sufficiently accurate for engineering purposes. In the limit of high Reynolds numbers the viscous shock-layer solutions join smoothly with the boundary-layer correlations of Ref. 3.

In order to calculate the heat-transfer rate from the Stanton number, the enthalpy of the gas at the wall must be known. Assuming that the wall temperature is known, the enthalpy for the catalytic wall can be determined directly since the atom concentration is zero or near zero. For the

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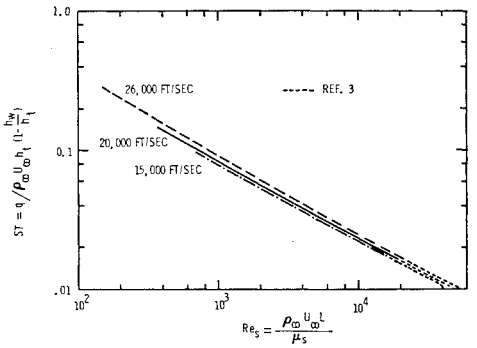

Fig. 1 Stanton number correlation as a function of Reynolds number for catalytic and noncatalytic surfaces.

noncatalytic wall case, the atom concentrations at the wall, for a 1-ft nose radius, are shown in Fig. 2 as a function of the freestream density. We note that the curves, for different velocities, have the same general shape. Thus, if the ordinate is normalized with respect to the maximum value of C_w and the abscissa with respect to the density at which C_w is a maximum, the universal curve shown in Fig. 3 is obtained. In this figure the normalizing functions are given by

$$(C_w)_{max} = \left[0.608\left(\frac{U}{10^4}\right)^2 - 1.03\right]\left(\frac{10^3}{T_w}\right)^{1.65} \tag{3}$$

$$(\rho_\infty)_{max} = \left[1.22 \times 10^{-5} + 3.76 \times 10^{-3}\left(\frac{10^4}{U}\right)^7\right]\frac{1}{L} \tag{4}$$

These functions represent the point on the curve of C_w vs ρ_∞ at which the wall atom concentration attains its maximum value.

Equation (4) contains the term $1/L$, which arises from the scaling law $\rho_\infty L$ = const. Since this scaling is valid only when the dominant chemical reaction is dissociation, the correlation curve of Fig. 3 should not be extrapolated to higher values of the abscissa. The curve as shown in Fig. 3 is exact for a nose radius of 1 ft. For other nose radii the curve is valid only in the region where recombination is insignificant. In particular, for a nose radius of 0.5 ft, Fig. 3 is exact up to $\rho_\infty/(\rho_\infty)_{max} \sim 0.5$ and at $\rho_\infty/(\rho_\infty)_{max} = 1$, the maximum error in predicting C_w is approximately 5% (i.e., underestimates C_w). Likewise for a nose radius of 0.1 ft, Fig. 3 is exact up to $\rho_\infty/(\rho_\infty)_{max} \sim 0.3$. Since the wall atom concentration is dependent on the wall temperature, the function $(C_w)_{max}$ contains a wall temperature correction factor that is valid for wall temperatures between 500° to 3000°R.

Conclusions

A simple and rapid procedure is presented for the calculation of stagnation point heat transfer to fully catalytic or

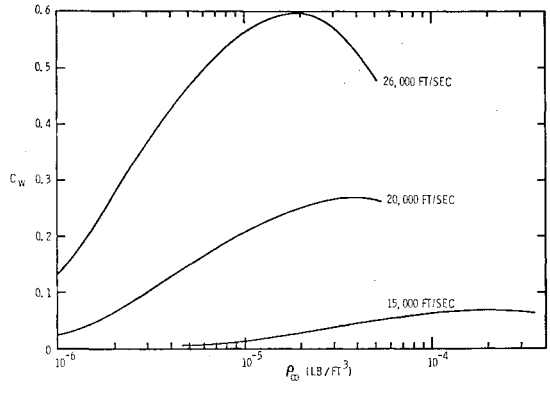

Fig. 2 Variation of wall atom concentration with freestream density.

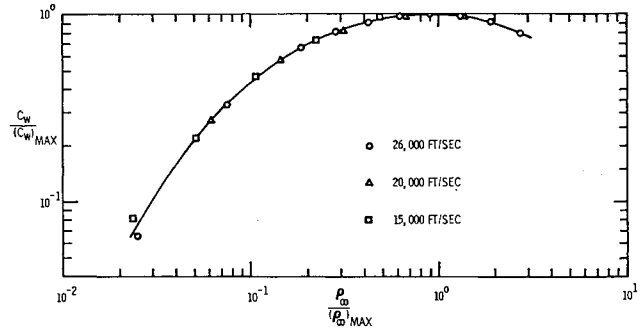

Fig. 3 Correlation of wall atom concentration.

noncatalytic surfaces in the viscous shock-layer regime through the use of correlation equations and curves. The heating rates calculated from these correlations include the simultaneous effects of chemical nonequilibrium and vorticity interaction for a stagnation region with an arbitrary surface temperature and body radius. By the use of the procedure presented, it is possible to predict the maximum and minimum heating rates for the major portion of a glide re-entry trajectory.

References

[1] Tong, H. and Suzuki, B. H., "Stagnation point heat transfer to surfaces of arbitrary catalycity," AIAA J. 2, 2051–2052 (1964).

[2] Tong, H. and Suzuki, B. H., "Stagnation point heat transfer to surfaces of arbitrary catalycity in non-equilibrium shock layer flows," The Boeing Co., Rept. D2-22853 (January 1964).

[3] Detra, R. W. and Hidalgo, H., "Generalized heat transfer formulae and graphs," Avco Research Rept. 72 (March 1960).

Heat-Transfer Measurements of Entry Cones with Maneuvering Surfaces

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TESTS were recently conducted in the Boeing 12-Inch Hypersonic Wind Tunnel with conical ceramic models and heat-sensitive paint. The models were simulated entry cones with maneuvering surfaces as shown in Fig. 1. The test conditions were a stagnation pressure of 1250 psia and a stagnation temperature of 770°F; at Mach 6.08 this results in a freestream Reynolds number of 13.75×10^6/ft. The purpose of the test was to compare the straight cone heating-rate values with the protruding control devices.

The tests were conducted by injecting the models and calibration spheres painted with Detectotemp† into the wind tunnel and recording the resultant color changes with a motion picture camera. This motion picture data was transformed into heat-transfer coefficients by a method developed at the Boeing Company.[1,2] This transformation results in a series of h vs time curves, one for each color change, and is shown in Fig. 2.

These curves are used by ascertaining the color-change time for an area of interest and by referring to the curves. If the area goes through three color changes, three coefficients will be obtained that will or should be essentially the same.

The experimental results are compared with theory in Fig. 3. It can be seen that these results agree well with laminar

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† Distributed by the H. V. Hardman Company, Belleville, N. J.

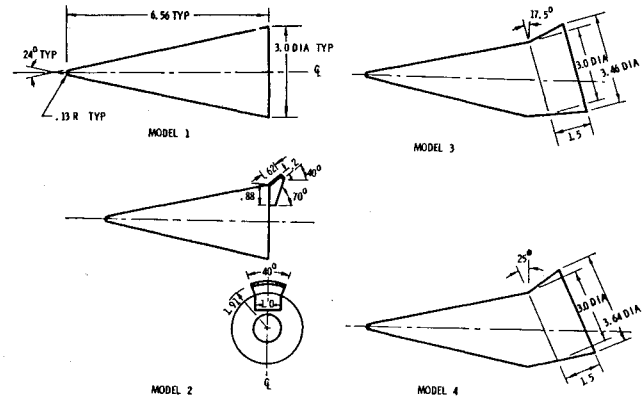

Fig. 1 Model configuration.

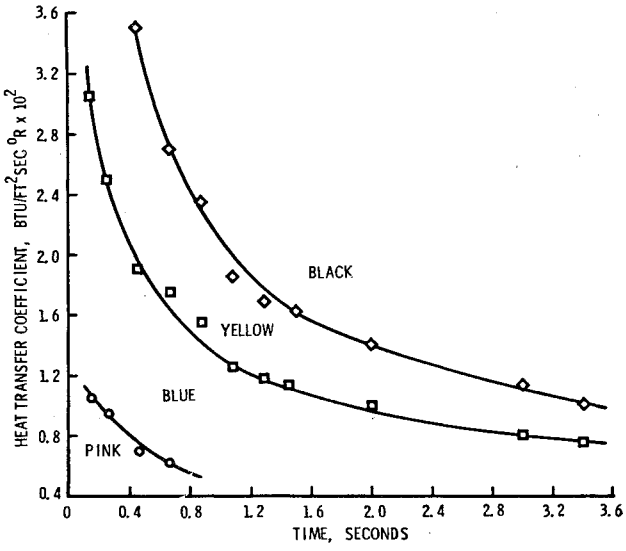

Fig. 2 Calibration curves.

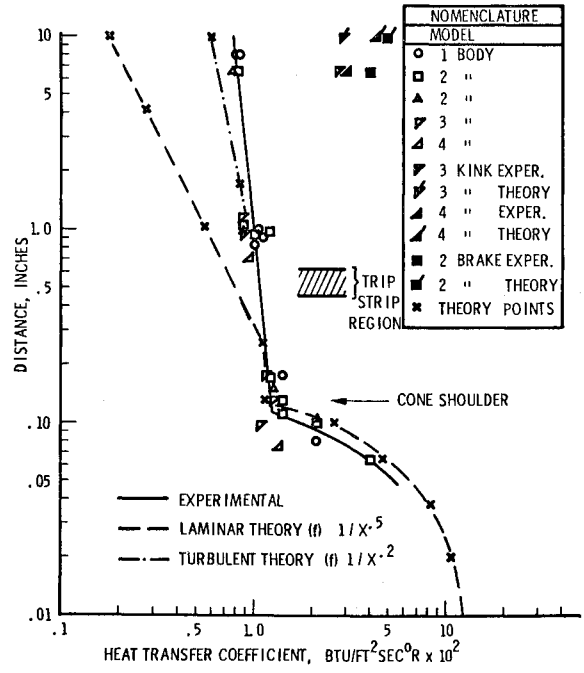

Fig. 3 Comparison of test results with theory.