Engineering Notes

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Heat-Transfer Measurements in a Separated Laminar Base Flow

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Nomenclature

h = static enthalpy
H = total enthalpy
L = axial length of cone
M = Mach number
$\dot{q}_b$ = base heat flux
R = base radial coordinate
R_B, R_N = base and nose radius, respectively
R_N/R_B = bluntness ratio
Re = Reynolds number
St = Stanton number
T = temperature
u = velocity
θ_c = cone half-angle
μ = viscosity
ρ = static density

Subscripts

c = base recirculation condition
s = stagnation condition
w = wall condition
∞ = freestream condition

NUMEROUS experimental and theoretical investigations have focused on the convective heat-transfer characteristics associated with separated flows.[1] In particular, several experimental studies have been conducted to examine aerodynamic heating to the blunt base of axisymmetric bodies, both slender cone[2-7] and blunt entry probe[8] configurations, in laminar hypersonic flow conditions.

This paper presents new experimental base heat-transfer data for a slender re-entry vehicle in hypersonic flight ($M_\infty = 16$). The measurements were obtained on the flat base of a slightly blunted, 9° half-angle cone. Instrumentation consisted of asymptotic thermocouple circular-foil calorimeters; data were telemetered at a commutated sample rate of 15/sec.

Base heat-transfer data for two radial locations are presented in Fig. 1. Measured Stanton numbers exhibit an inverse dependence on Reynolds number for laminar boundary-layer flow. Heating levels vary significantly with radial position, and this radial variation (gradient) remains essentially constant for the Reynolds number range considered. Similar radial gradients have been observed previously,[2-6,9] with the maximum heat-transfer occurring at or near the center of the base.

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The present measurements ($R/R_B = 0.08$) are compared in Fig. 2 with ground-test data for sharp- and blunt-nose slender cones at zero incidence. All data were measured at or near the base centerline, and most were obtained using interference-free support techniques. While the ground-test compilation displays an overall Reynolds number effect that is consistent

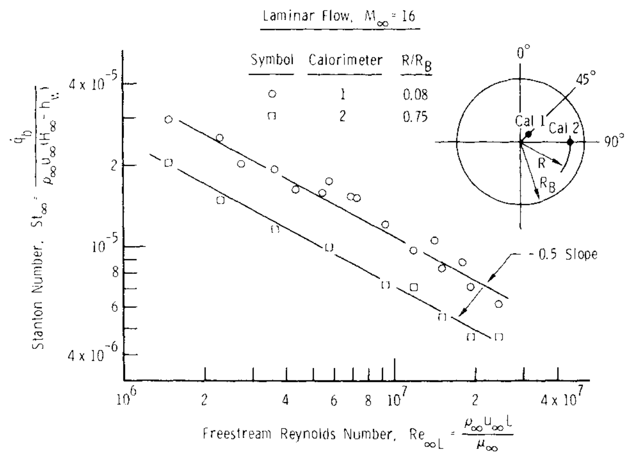

Fig. 1 Flight-test base heat-transfer measurements.

Sym	θ_c	R_N/R_B	Base Geometry	Support	M_∞	$T_w/T_{s\infty}$	Ref
○	9°	0.05	Flat	Reentry/Telemetry	16	0.02	Present
◇	10°	0.05	Flat	Wires/Free Flight	12.6	0.18	5
◆	9°	0.3	Flat	Wires/Free Flight	12.6	0.18	5
⊙	10°	0.05	Flat	Wires/Free Flight	12.6	0.13	5
◇	10°	0.05	Flat	Wires/Free Flight	12.8	0.25	5
◆	9°	0.3	Flat	Wires/Free Flight	12.8	0.25	5
▽	10°	0.05	Flat	Wires/Free Flight	17.9	0.17	5
▼	9°	0.3	Flat	Wires/Free Flight	17.9	0.17	5
⊖	9°	0.0	Hemisphere	Side Sting	8.63	0.27	2
□	9°	0.0	Hemisphere	Side Sting	9.15	0.27	2
■	6.3°	0.3	Hemisphere	Side Sting	9.10	0.27	2
△	5°	0.0	Flat	Wires	8	0.32	3
◇	10°	0.0	Rounded Shoulder	Free Flight/Telemetry	10	0.28	4
⊖	15°	0.0	Flat	Free Flight/Telemetry	14	0.03	7
⊗	15°	0.1	Flat	Free Flight/Telemetry	14	0.03	7
▲	15°	0.2	Flat	Free Flight/Telemetry	14	0.03	7
●	15°	0.3	Flat	Free Flight/Telemetry	14	0.03	7
⬢	15°	0.4	Flat	Free Flight/Telemetry	14	0.03	7

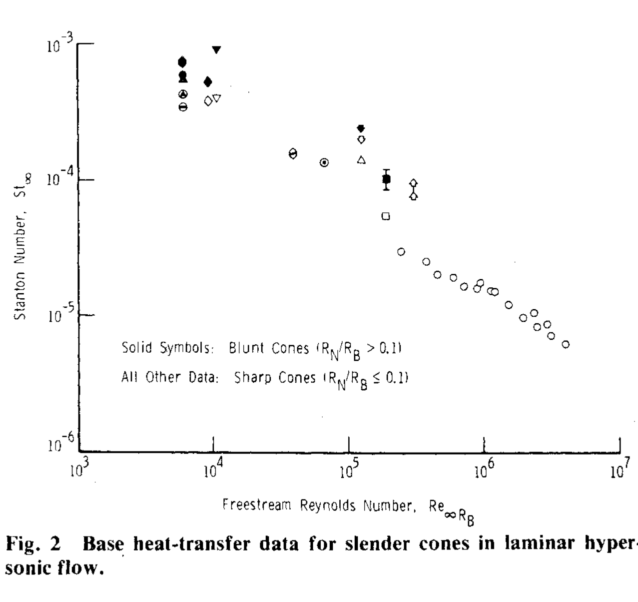

Fig. 2 Base heat-transfer data for slender cones in laminar hypersonic flow.

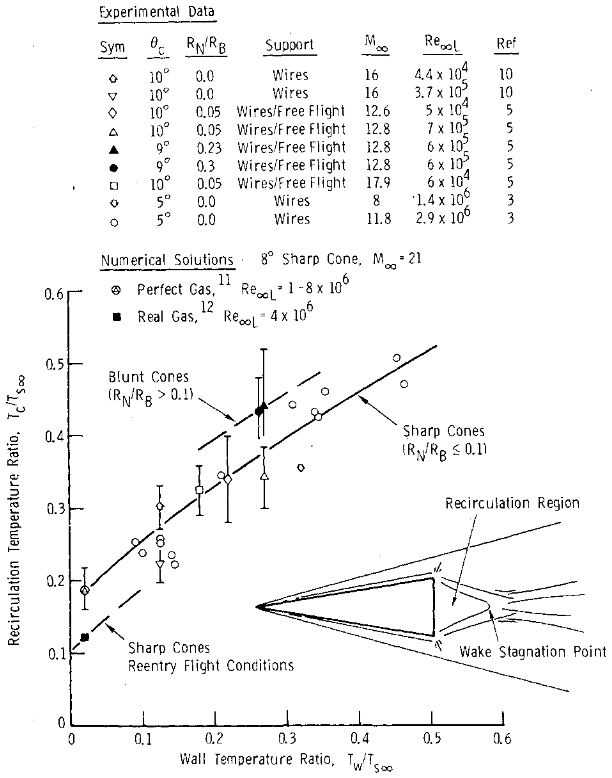

Fig. 3 Temperature in base recirculation region.

with the present re-entry flight measurements, the flight base heating levels are clearly differentiated (displaced) from the ground-test results, with the flight data indicating generally lower heating rates. In addition, a pronounced effect of nose bluntness is evident in the ground-test experiments in which increasing bluntness produces higher base heating rates.

Observed variations in heating levels between the flight and ground-test measurements, and between the sharp and blunt models, are attributed to differences in wake flow conditions (particularly temperature) in the base recirculation region.[5-7] Measurements for sharp cones[3,5,10] indicate that the temperature in the recirculating flow between the base of the body (outside the base-wall thermal boundary layer) and the wake stagnation point is very sensitive to wall temperature (Fig. 3); perfect-gas calculations[11] at cold-wall conditions ($T_w/T_{s\infty}=0.02$) confirm this trend. Additional cold-wall solutions[12] for a real-gas flow (indicative of re-entry flight) reveal substantial reductions in the recirculation temperature, whereas limited measurements for blunt cones[5] show a steadily increasing temperature as nose bluntness increases. These differences are manifested in the base heat-transfer data presented in Fig. 2. Compared to the ground-test data level for sharp cones, reduced heating in re-entry flight reflects decreased recirculation temperatures due to real-gas effects, while higher blunt cone heating rates are indicative of the higher recirculation temperatures resulting from increased energy deposited in the entropy layer. The conclusion is drawn that the trends in measured base heat-transfer rates are consistent with temperatures in the base recirculation region.

The dependence of base heat-transfer on wake flow conditions suggests a correlation of the measurements summarized in Fig. 2 with appropriate base recirculation parameters (Fig. 4). In evaluating the base flow characteristics, differences between ground-test (perfect-gas) and re-entry flight (real-gas) conditions, and between sharp and blunt cone flows, were considered. Recirculation temperatures were evaluated from Fig. 3 for the respective $T_w/T_{s\infty}$ to determine the recirculation region viscosity and the recirculation enthalpy used as the driving potential in the Stanton number. Average density and velocity in the recirculating flow were estimated,[13] where $\rho_c u_c/\rho_\infty u_\infty \approx 0.03$ for

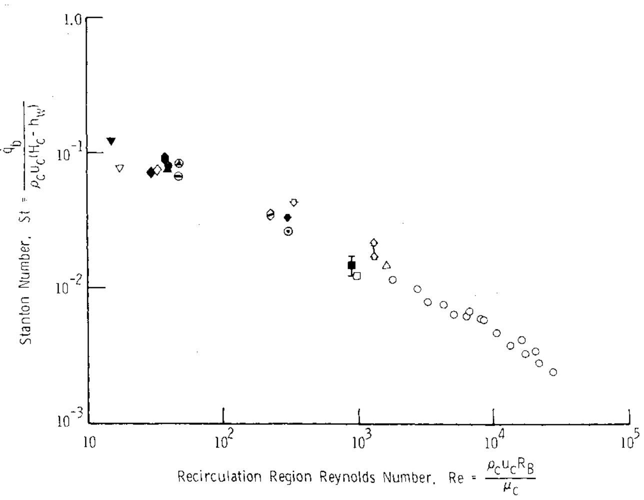

Fig. 4 Heat-transfer correlation based on recirculation parameters (symbols as in Fig. 2).

typical perfect-gas flows. For the flight data, this ratio was reduced to 0.025, reflecting real-gas effects in the base pressure and recirculation temperature.[12]

The results in Fig. 4 emphasize the importance of using realistic recirculation conditions in base heat-transfer studies. In particular, the present re-entry flight data support the conclusion that considerable attention should be given to real-gas effects in analyses of base heat-transfer data and in predictions of base heating in flight.

Acknowledgment

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