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HEAT TRANSFER ON A FLAT PLATE IN HELIUM AT MACH NUMBERS 67.3 AND 87.6 AND IN HYPERSONIC CORNER FLOW WITH AIR AT MACH NUMBER OF 19

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FOREWORD

This report was prepared under contract No. NASW-1785 for NASA Headquarters, Office of Advanced Research and Technology, Research Division, under the technical direction of Mr. I.R. Schwartz. The research was conducted at the Mechanical Engineering Laboratory, General Electric Research and Development Center in Schenectady, New York.

SUMMARY

Local surface heat transfer rates were measured on a sharp flat plate with helium at Mach numbers of 67.3 and 86.8 in a hypersonic shock tunnel. The strong interaction parameter, $M_1^3/\sqrt{Re_x}$, varied from 730 to 16,500 and leading edge Knudsen numbers were 8.39 and 17.1 respectively. Towards the leading edge region the heating rates were much less than the theoretical prediction of Li and Nagamatsu due to the rarefied flow effects but much greater than the diffuse free molecule limit.

Surface heat transfer rates in the corner flow region produced by the intersection of two perpendicular flat plates with sharp leading edges were determined with air at a Mach number of approximately 19. Tests were conducted at rarefied and continuum flow conditions with unit Reynolds numbers of approximately 900 and 29,000 with corresponding leading edge Knudsen numbers of 35 and 1.0. At low density conditions the local heating rates were increased approximately 35 percent in the vicinity of the corner region, but at continuum flow conditions the heat transfer rates were not increased as much as the rarefied hypersonic flow. By comparing the local heat transfer coefficient in the corner flow region with the strong interaction theory of Li and Nagamatsu, it was possible to determine the corner flow effects on the heating rates.

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LIST OF SYMBOLS

C_h	heat transfer coefficient (Stanton number)
C_p	specific heat at constant pressure
C_v	specific heat at constant volume
D	coefficient from Ref. 11
E	voltage
H	enthalpy
I	current
k	thermal conductivity
Kn	Knudsen number
M	Mach number
P	pressure
q	heat transfer rate
R	resistance or gas constant
Re/in	unit Reynolds number
Re_x	length Reynolds number
S'(0)	coefficient from Ref. 38
t	leading edge thickness or time
T	temperature
v	velocity
$\bar{v}$	average molecular velocity
$\bar{V}_\infty$	rarefaction parameter
α	gage resistivity
γ	ratio of specific heats
λ	mean free path
μ	viscosity

ν	kinematic viscosity
ξ	time for one molecular collision
ρ	density
τ	variable of integration
χ	strong interaction parameter

<u>Subscripts</u>

a	conditions after a normal shock
b	gage backing material or conditions before a normal shock
o	initial conditions
f	final conditions
w	wall conditions
w,i	insulated wall conditions
1	leading edge conditions
5	stagnation conditions

1.0 INTRODUCTION

For the development of future hypersonic manned vehicles such as the hypersonic cruise airplanes and space shuttle, the most critical problem is associated with the viscous-inviscid interactions on the lifting surfaces and hypersonic inlets at high altitudes. The flight Mach numbers for these hypersonic vehicles will be in the range of 5 to 26 and altitudes of 10 to 70 miles. Also, there is need for information regarding the shock wave and viscous interaction phenomena for flight Mach numbers of over 100 for space vehicles re-entering the atmosphere from distant planets. At these hypersonic Mach numbers the flow in the corner region between the intersection of the lifting surface with the body and with fin surfaces is not too well understood. The impingement of shock waves, generated by the fore bodies, on the aft sections and lifting surface can produce extremely high local heat transfer rates. These hypersonic viscous flow phenomena will occur over a range of flow conditions from free molecule at extremely high altitudes, rarefied flow with slip flow at the intermediate altitudes, and continuum flow at low altitudes. The local induced pressure, heat transfer rate, and skin friction depend upon the flight Mach number, altitude, and the shape of the vehicle exposed to the atmosphere. The available experimental and theoretical references on the hypersonic rarefied flow phenomena are still limited because of the complexity of the flow and the difficulty in obtaining experimental and analytical results.

Rarefied hypersonic flow past a flat plate with a sharp leading edge has been investigated in various experimental facilities to determine the formation of the shock wave and the boundary layer at the leading edge region. These experimental studies[1-8] have indicated that close to the leading edge of a sharp flat plate the flow can be described on the basis of kinetic theory. And downstream of this region the shock wave and boundary layer are merged with velocity slip and temperature jump for rarefied hypersonic flow conditions. The length of the non-continuum flow region is dependent upon the free stream Mach number and the mean free path in the free stream. Following the region of the slip flow at the surface the shock wave and the boundary layer are merged with no slip at the surface as initially discussed by Shen[9] and Li and Nagamatsu[10,11], as the strong interaction region. As the boundary layer develops on the plate the shock wave and the boundary layer become separated and farther downstream the shock wave becomes weak and is located far away from the boundary layer. This region is referred to as the weak interaction as postulated by Lees and Probstein[12]. Various investigators[13-16] have analyzed the strong interaction region at hypersonic Mach numbers with no slip flow at the plate surface and the results are similar, but when the slip flow effects are large both local induced pressure[2,4,6] and heat transfer rates[3,5,8] are drastically less than that predicted by strong interaction theories with no wall slip.

Besides the experimental investigations of the hypersonic leading edge phenomena numerous theoretical studies have been conducted to solve the problem by making certain assumptions regarding the flow in the vicinity of the leading edge. The existing theoretical results are still not adequate for the accurate prediction of the induced pressure, local heat transfer rate, skin friction, and shock wave and boundary layer shapes for two- and three-dimensional surfaces in rarefied hypersonic flow conditions. In the immediate vicinity of the leading edge of the sharp flat plate with the leading edge Knudsen number, which is the ratio of the mean free path in the free stream to the leading edge thickness, greater than 1, the flow may be considered as being in the near free molecule region where the kinetic theory may be applicable. Li and Nagamatsu[16] applied the kinetic theory concept to show that the slip flow region over a sharp plate is a function of the free stream Mach number and the mean free path. Charwat[17], Bird[18], and Huang[19] have analyzed the leading edge flow phenomena by considering the collision of the molecules with the surface for rarefied flow conditions. With the assumption that the shock wave and boundary layer are merged in the vicinity of the leading edge, Oguchi[20], Chow[21], Shorestein and Probstein[22], Rudman and Rubin[23], and Eiler[24] have obtained solutions with velocity slip and temperature jump at the surface. The analytical predictions of the rarefied hypersonic flow from these theories are still limited in applicability and require further refinements in the analysis and additional experimental data to define the rarefied hypersonic flow over a flat plate more explicitly.

The three-dimensional viscous flow occurring along the corner of two intersecting flat plates has been investigated experimentally and theoretically in recent years for supersonic and low hypersonic free stream Mach numbers, and a summary of the limited available publications on the subject is presented in Refs. 28 and 30. Charwat and Redekeopp[26] investigated the corner flow formed by two intersecting wedges over a Mach number range of 2 to 4. By careful probing of the corner flow they were able to determine the complex shock wave and boundary layer existing in the corner region. Nardo and Cresci[29] investigated the corner flow existing between the two intersecting flat plates in a hypersonic blowdown tunnel at a Mach number of 11.2. Both surface pressures and local heat transfer rates were determined in the corner region and impact pressure and total temperature surveys were conducted to determine the shock wave and boundary layer in the corner flow. The flow phenomena existing in the corner region was determined over a range of the strong interaction parameter $\chi = M_1^3/\sqrt{Re_x}$ with the maximum value of 5 for the survey. For this value of the strong interaction parameter the shock wave and boundary layer interaction at the leading edge region is not large so that the induced pressure on the surface is also quite low. Pal and Rubin[27] have investigated analytically the incompressible viscous flow along a right angle corner. No analysis has been conducted for the corner flow in rarefied hypersonic flow at high Mach numbers.

The present report presents the heat transfer results for the leading edge phenomena on a flat plate in rarefied helium flows at Mach numbers of 67.3 and 86.8. These extremely high Mach numbers were selected for the purpose of extending the slip flow region in the vicinity of the leading edge region and to investigate the local heat transfer rates at a very high strong interaction parameter of 10^4. Also, the effects of monotonic gas compared to the diatomic gases on the rarefied hypersonic flow phenomena were studied by the use of helium gas instead of air as presented in most published experimental data on the subject. Henderson[31] had investigated the induced pressure distribution for a sharp flat plate in helium at a Mach number of 40 for high enough density so that continuum flow conditions existed on the plate with a maximum strong interaction parameter of approximately 140. The local heat transfer rates for the plate at these high Mach numbers are correlated with the strong interaction theory of Li and Nagamatsu[11] and the free molecule flow values with the assumption of diffuse reflection at the surface.

Besides the study of the flow over a flat plate with helium, a preliminary investigation was conducted to study the viscous hypersonic flow in the corner region of two intersecting flat plates with sharp leading edges. These investigations were conducted with air at a Mach number of approximately 19 for continuum and rarefied flow conditions. The local heat transfer rates were determined in the corner flow region by locating the vertical plate at various distances from the center line of the horizontal plate containing the gages.

2.0 EXPERIMENTAL APPARATUS AND MODEL

2.1 The Tests with Helium and Air

The tests with helium and air as the test gas were conducted in the straight through test section of a multiple nozzle, combustion driven shock tunnel described in Ref. 32. The 103 foot long driven tube of 4 in. diameter was evacuated and filled with helium or dry air as the working gas. At the end of this driven tube a conical nozzle with a total angle of 30° and an exit diameter of 24 in. was attached. The nozzle is placed inside a 200 cubic foot dump tank which is normally evacuated to less than 3 microns of mercury to facilitate the flow establishment with weak starting shock waves. A scribed diaphragm is placed just upstream of the nozzle entrance which bursts with the arrival of the incident shock wave. The throat diameters for the present investigations to produce helium flow Mach numbers o 67.3 and 86.8 were 0.190 and 0.100 in. respectively. For the corner flow investigation with air, the larger throat diameter of 0.190 in. was used to produce a flow Mach number of 19 in the test section. The incident shock wave reflects from the end of the 4 in. driven tube and the compressed and heated gas produced by the reflected shock wave expands into the nozzle to produce rarefied hypersonic flows.

A Berkeley counter was used to measure incident shock wave velocity to determine the reflected stagnation temperature by assuming equilibrium flow after the shock waves. The reflected pressure at the entrance to the nozzle was measured with a Kistler piezoelectric pressure transducer. To minimize the vibrations due to the opening of the scribed diaphragms at the driver and nozzle ends of the driven tube, the flat plate was mounted on a hollow sting independently supported and isolated from the dump tank and the floor. The shielded electrical leads from the piezoelectric impact pressure and sputtered platinum heat gages were brought out through the sting to the amplifiers before going to the oscilloscopes. A detailed description of the shock tunnel, instrumentation and procedures for determining the flow condition in the test section is presented in Refs. 32 and 33.

2.2 Flat Plate Models

The flat plate heat transfer model used for the heat transfer investigation with helium and air is shown in Fig. 1a. With this model it is possible to vary the leading edge thickness from 0.001 to 0.500 in. by attaching thicker pieces at the bottom wedge surface of the plate. The wedge angle for the plate was 15°, and two thin side plates were attached to sides of the 10 in. by 16 in. long plate, Fig. 1a, to prevent the disturbances from the bottom surface affecting the heat transfer measurements. For the investigation of the heat transfer distribution in the hypersonic corner flows, another flat plate with dimensions of 6 in. and 16 in. with a leading edge thickness of 0.001 in. was mounted perpendicular to the horizontal plate with the heat gages as shown in Fig. 1b. It was possible to mount the vertical plate at various distances from the centerline of the horizontal plate, and for the present preliminary corner flow investigation the plate was placed at 0.50, 1.00, and 1.5 in. from the center line.

Twelve sputtered platinum heat gages were located along the center of the plate at distances of 0.19 to 12.94 in. from the plate leading edge. Platinum was sputtered on a backing of Pyrex to a thickness of approximately 350Å and electrically insulated by a thin film of silicon dioxide. Two different sets of sputtered platinum heat gages were used to determine the local heat transfer rate along the plate surface for helium at very high Mach numbers. For the corner flow study with air the second set of heat gages was used. The impact pressure in the plane of the leading edge, cf. Fig. 1a, was measured with a Kistler quartz piezoelectric pressure transducer. To obtain accurate calibrations, both the heat gages and the impact pressure gage were dynamically calibrated in the 8-inch diameter shock tube, before and after each series of tests as discussed in Ref. 34. Both flat plate models were mounted with the horizontal plate on the center of the conical nozzle just downstream of the exit.

3.0 TEST CONDITIONS AND DATA ANALYSIS

3.1 Flow Conditions in the Test Section

The reflected stagnation temperatures at the end of the driven tube for both helium and air were calculated by the shock wave equations. For these calculations the temperature and the pressure in the driven tube were determined before each shot and the shock velocity was measured at the end of tube. With helium the reflected temperature was approximately 2280°R so that the ratio of the specific heats was taken to be 1.67. But with air the reflected temperature was approximately 2100°R, which was calculated by assuming the air to be in equilibrium after the incident and reflected shock waves as discussed in Refs. 32 and 33 with the equilibrium thermodynamic properties for air[35-37]. With air the reflected pressures were high enough for the temperature to have nearly equilibrium conditions in the reservoir and in the nozzle expansion region[33].

With helium the reflected pressure and temperature were approximately 1350 psia and 2280°R respectively for both flow Mach numbers in the test section of 67.3 and 86.8. A combustion driver technique was utilized to produce the desired shock Mach number in the driven tube to produce the reflected stagnation condition at the entrance to the nozzle. With air the experiments were conducted over a range of reflected stagnation pressure, P_5, from 75 to 2220 psia and stagnation temperature, T_5, of approximately 2100°R at a test section Mach number of approximately 19 to study the heat transfer in the corner flow region of two intersecting flat plates. For both helium and air the impact pressure at the plate leading edge plane was used to determine the leading edge Mach number using the real gas properties through the normal shock wave for air. With helium the stagnation temperature and pressure were low enough so that perfect gas relationships were used to determine flow Mach number from the measured impact pressure.

3.2 Heat Transfer Gage Data Analysis

To obtain the heat gage calibration, the gages were mounted in a flat plate and placed in the center of the 8 in. diameter calibration shock tube[34]. A piece of plexiglas, which extended 8 in. forward from the leading edge and along the side of the flat plate, was used to produce surface conditions that simulated a wall mounting of the flat plate.

As a weak shock wave passes over the heat gage, there is a step rise in the temperature of the gage which produces a voltage change across the gage. For a step temperature increase, the heat transfer rate q(t) for the assumed semi-infinite backing material is

$$q(t) = \left(\frac{(\rho C_p k)_b}{\pi}\right)^{1/2} \frac{\Delta T}{\sqrt{t}} = \left(\frac{(\rho C_p k)_b}{\pi}\right)^{1/2} \frac{\Delta E}{\alpha I R_o \sqrt{t}} \qquad (1)$$

where $(\rho C_p k)_b$ are the density, specific heat, and thermal conductivity, respectively, of the backing material for the thin film gages, and ΔT is the temperature rise of the gage, which is observed as the voltage change ΔE on the oscilloscope. The change in the gage resistance, ΔR, due to a surface temperature change, $\Delta T = T_f - T_o$, is

$$\Delta R = R_f - R_o = R_o \alpha \Delta T \tag{2}$$

where R_o and R_f are the gage resistances at temperatures T_o and T_f, and α is the resistivity. The gage is operated at a constant current I and thus, the voltage change ΔE across the gage for a temperature change ΔT is

$$\Delta E = I \Delta R = I\ R_o \alpha \Delta T \tag{3}$$

For a constant wall temperature, T_w, the local heat transfer rate at the wall from the passage of a normal shock wave over a plate is given by[38]

$$q(t) = -k_w \sqrt{u_a / 2u_b\ t\ \nu_w}(T_w - T_{w,i})S'(0) \tag{4}$$

where k_w and ν_w are the gas conductivity and kinematic viscosity at the wall temperature, $T_{w,i}$ is the insulated wall temperature, u_b and u_a are the free stream velocities before and after the normal shock, and $S'(0)$ is a coefficient tabulated in Ref. 38. By equating Eqs. (1) and (2) the value of the gage coefficient $\sqrt{(\rho C_p k)_b}/\alpha$ can be determined by

$$\frac{\alpha}{\sqrt{(\rho C_p k)_b}} = \frac{\Delta E}{I\ R_o\ k_w(T_w - T_{w,i})\sqrt{\frac{\pi\ u_a}{2\ u_b\ \nu_w}}\ S'(0)} \tag{5}$$

The heat gages were calibrated over a shock Mach number range of 1.5 to 3, and the calibrating shots were adjusted to produce pressure rises on the plate surface corresponding to the pressure increases encountered in the test section flows. By this method the gage calibration contained any strain gage effects that the thin platinum film might exhibit under the pressure loading. Also, all of the electronic circuits related to each gage, including the oscilloscope used in the calibration were also used in the actual tests in the shock tunnel.

The reduction of the temperature-time oscilloscope traces requires the relationship between the heat transfer rate q(t) and temperature T(t), and such a relationship is given in Ref. 39 as

$$q(T) = \frac{\sqrt{\pi}(\rho C_p k)_b}{2\ \alpha\ I_o\ R_o}\left[\frac{\Delta E(t)}{\sqrt{t}} + \frac{1}{\pi}\int_0^t \frac{\sqrt{\tau/t}\ \Delta E(t) - \Delta E(\tau)}{(t - \tau)^{3/2}}\, d\tau\right] \tag{6}$$

The local heat transfer rates were calculated from this equation using the voltage-time traces of the gages and the gage coefficients determined from the calibration shock tube. To solve this equation for each heat gage trace, a GE 605 computer was utilized.

3.3 Viscosity and Knudsen Number for Helium and Air

The helium viscosity relationship from Ref. 40 in terms of slugs per foot-sec. is given by

$$\mu = 7.173 \times 10^{-9}\ T^{0.647} \tag{7}$$

where T is the absolute temperature in °R. Helium was treated as a perfect gas for the pressures and temperatures encountered in the experiments so that the ratio of specific heats was taken to be $\gamma = 5/3$, and the values of C_p, C_v, and R were taken to be constant in the reduction of the data.

With air as the test gas the local static temperature in the vicinity of the plate was approximately 30°R at a Mach number of 19. And for this low temperature, the equation for the viscosity in slugs per foot-sec. was taken to be

$$\mu = 8.04 \times 10^{-10}\ T, \quad 0 \leq T \leq 180°R \tag{8}$$

Since the reflected stagnation temperature was in the range 2100°R, the gas was assumed to be in equilibrium[32,33] in the reservoir as well as during the expansion process in the nozzle. Below a static temperature of 400°R in the nozzle, the air was assumed to be a perfect gas with a constant ratio of specific heats of 1.40.

The mean free path at the plate leading edge λ_1 was determined for both helium and air by[41]

$$\lambda_1 = \frac{\mu_1}{0.499\ \rho_1\ \bar{v}_1} \tag{9}$$

where $\bar{v}_1$ is the average molecular velocity given by

$$\bar{v}_1 = \left(\frac{8RT_1}{\pi}\right)^{1/2} \tag{10}$$

For both gases the leading edge Knudsen number is defined as the ratio of the mean free path ahead of the plate to the leading edge thickness t,

$$Kn_1 = \frac{\lambda_1}{t} \tag{11}$$

It was shown in Ref. 16 from the kinetic theory standpoint that the distance traveled along the plate for a time of one intermolecular collision in the free stream is given by

$$\xi_1 = M \lambda_1 \tag{12}$$

which indicates that at high Mach numbers the leading edge slip flow region can become appreciable.

4.0 HEAT TRANSFER FOR A FLAT PLATE IN RAREFIED HYPERSONIC HELIUM FLOWS

The heat transfer on a sharp flat plate, Fig. 1a, was investigated at flow Mach numbers of 67.3 and 86.8 with helium as the test gas. For these studies of rarefied hypersonic flow effects at extremely high Mach numbers, the reflected stagnation pressure and temperature were approximately 1340 psia and 2280°R respectively, as indicated in Table I. These reflected flow conditions were achieved with the use of a combustion driver and the driven tube filled with helium. Local heat transfer rates were calculated by numerically integrating the voltage-time trace for each gage using Eq. (6). These results are presented in Fig. 2 as a function of the distance from the leading edge for flow Mach numbers of 67.3 and 86.8. Two different sets of heat gages were used to determine the local heat transfer rates at these Mach numbers. For these tests the ratio of the wall temperature to free stream stagnation temperature was 0.237. At a Mach number of 67.3 the unit Reynolds number was 13,240 and leading edge Knudsen number of 8.39 so that the local heat transfer rate increased monotonically towards the leading edge of the flat plate. In the previous investigation with air at Mach numbers of 19.2 and 25.4, Ref. 5, the local heat transfer rates increased rapidly towards the leading edge for unit Reynolds numbers larger than 6,000 and leading edge Knudsen numbers less than 6 at a free stream Mach number of 25.4. Thus, with helium at a Mach number of 67.3 the unit Reynolds number is high enough so that the rarefied flow effects on the local heat transfer rate in the vicinity of the leading edge are not too large.

As the flow Mach number in the test section was increased to 86.8 with approximately the same reflected stagnation condition, the unit Reynolds number decreased to 8,270 and the leading edge Knudsen number increased to 17.1 as presented in Table I. For these lower density conditions in the test section, the local heat transfer rates did not increase rapidly towards the leading edge in Fig. 2 compared to the Mach 67.3 case with higher density in the test section. The shape of the local heat transfer distribution is similar to that observed with air in Ref. 5 for a flow Mach number of 25.4 with unit Reynolds number of 2241 and leading edge Knudsen number of 16.9. It was observed in Refs. 3, 5, and 8 that at very low density hypersonic flow conditions the local heat transfer rate is nearly constant over the initial portion of a sharp flat plate. These results would indicate that the rarefied flow effects were present for the helium at a Mach number of 86.8, but to achieve nearly constant heat transfer rates at the plate leading edge region, it is necessary to operate at lower free stream density conditions with unit Reynolds number less than 2,000 and leading edge Knudsen number greater than 60.

The comparison of these preliminary heat transfer results with helium at very high Mach numbers with the air data[5] at Mach numbers of 19.2 and 25.4 indicates that for a given unit Reynolds number greater rarefied flow effects are observed at the higher Mach numbers with helium than air at lower Mach numbers. Thus, these results for the local heat transfer rates indicate that flow Mach number, unit Reynolds number, and leading edge Knudsen number are variables which influence the degree of rarefied flow phenomena. Additional investigations will be conducted with helium at higher and lower densities than that existing at Mach numbers of 67.3 and 86.8 for the present tests, and also helium at lower Mach numbers and higher density will be conducted to minimize the rarefied flow phenomena and to correlate with the strong interaction theory of Li and Nagamatsu[11], based upon the assumption of no slip flow at the surface.

To obtain some indication regarding the level of the local heat transfer rate relative to the free stream kinetic energy and the distance along the plate in terms of the mean free path λ_1 in the free stream, the local heat transfer rates normalized by the free stream kinetic energy are presented in Fig. 3a and 3b as a function of the mean free path along the plate for the two Mach numbers of 67.3 and 86.8. For these figures the free stream kinetic energy was taken to be the value existing at the leading edge of the plate. For a free molecule flow with diffuse reflection at the surface, the heat transfer would be constant along the plate as discussed in Ref. 42. And the normalized heat transfer rate is given by

$$\frac{q}{\frac{1}{2}\rho_1 u_1^3} = \frac{1}{\sqrt{2\pi\gamma}}\frac{1}{M_1}\left[1 + \frac{4}{\gamma M} - \frac{4RT_w}{u_1^2}\right] \tag{13}$$

where γ is the ratio of specific heats, 5/3 for helium. The values of this quantity for flow Mach numbers of 67.3 and 86.8 are presented in these figures.

For a flow Mach number of 67.3, Fig. 3a, the first heat gage is located at approximately 23 mean free paths from the plate leading edge. But the distance traversed along the plate for the time of one collision in the stream, given by Eq. (12), is 0.565 in., which corresponds to 67.3 mean free paths from the leading edge. This distance corresponds to a location between the second and third heat gage on the plate. The scatter in the heat transfer rates between the two sets of heat gages are small as indicated in this figure. The experimental heat transfer rates at the plate leading edge region are much higher than the value for a free molecule flow with diffuse reflection. Similar results were observed with air at Mach numbers of 19.2 and 25.4 for various density conditions in Ref. 5. Towards the back end of the flat plate the local heat transfer rates were less than the free molecule value because of the viscous effects producing thick boundary layers at hypersonic Mach numbers.

In Fig. 3b the normalized heat transfer rates are presented as a function of the mean free path for a flow Mach number of 86.8. Because of the low free stream density in the test section, there was slightly greater scatter in the heat transfer rates towards the leading edge compared to the previous lower Mach number of 67.3 in Fig. 3a. At this higher Mach number the first heat gage is located 10.5 mean free paths from the leading edge, and the distance traversed along the plate in the time of one collision in the free stream is approximately 1.5 in. This distance corresponds to a location slightly downstream of the sixth heat gage. The heat transfer rates over this distance are much higher than the value based upon the free molecule flow with diffuse reflection and also are not constant as postulated for a free molecule flow. Again the local heat transfer rates towards the aft portion of the plate are slightly less than the free molecule value for a Mach number of 86.8 and wall temperature ratio of 0.237.

There are a number of theories on the hypersonic leading edge flow phenomena in the free molecule to continuum flow region[16-25]. Most of the available theories consider the flow to be in continuum flow with slip at the plate surface and some of the references treat the problem from the kinetic theory concept[17-19,25]. But the existing theories do not consider all of the important physical parameters, free stream Mach number, unit Reynolds number, wall temperature ratio and leading edge Knudsen number. It was observed in Ref. 5 that by keeping the leading edge Knudsen number constant for leading edge thicknesses of 0.001 and 0.010 in. at a flow Mach number of 19.2, the local heat transfer coefficient was not the same, and by keeping the unit Reynolds number constant and leading edge Knudsen differed by a factor of 10, the local heat transfer variation with the strong interaction parameter was not the same because of the leading edge bluntness effects. The existing theories do not contain the leading edge Knudsen number explicitly in the analysis. In Ref. 8 some of the existing theories have been compared with the experimental flat plate pressure and heat transfer measurements.

To determine the effects of wall temperature ratio on the surface induced pressure and local heat transfer rate on a flat plate at hypersonic Mach numbers, Li and Nagamatsu[44] applied the method of similar solution concept. For the application of the similar solutions to a noninsulated hypersonic flow, the free stream Mach number was considered to be much greater than sonic, and the velocity at the edge of the boundary layer was nearly constant and equal to the free stream velocity. The induced pressure near the plate leading edge was assumed to vary as $x^{-1/2}$ as originally shown in Ref. 10 and observed experimentally by a number of investigators[1,2,4,7,8] in the no slip flow region, or continuum flow at high density conditions. Besides these conditions, it was assumed that the Prandtl number of the fluid was unity and the viscosity was a linear function of the temperature. With these assumptions the hypersonic boundary layer equations were transformed into a system of ordinary differential equations. In Ref. 11 and 44 these were solved for the ratio of specific heats of 1.4 and 1.67 and for ratios of wall to stagnation temperature of 0 to 2.0.

Within the framework of the above approximations for the similar solutions, the strong interaction between the leading edge shock wave and the viscous boundary layer on a flat plate in hypersonic flow is characterized by the following general law[11]. The heat transfer coefficient is given by

$$C_{h_1}\sqrt{Re_x} = D(M_1^3/\sqrt{Re_x})^{1/2} \tag{14}$$

where

$$C_h = \frac{q}{\rho u(H_5 - H_w)} \tag{15}$$

H_5 = stagnation enthalpy

H_w = wall enthalpy

and $Re_x = \rho_1 u_1 x/\mu_1$ is the Reynolds number based on the free stream density ρ_1, viscosity μ_1, and velocity u_1 and M_1 is the free stream Mach number. The expression for D and its values are presented in Ref. 11 as functions of the ratio of the specific heats and wall temperature ratio.

Eq. (14) can also be written as

$$C_{h_1}M_1^3 = D(M_1^3/\sqrt{Re_x})^{3/2} \tag{14a}$$

and this relationship was used to correlate the experimental heat transfer data with the theoretical predictions in Figs. 4a - c, for helium flow Mach numbers of 67.3 and 86.8. The local heat transfer data was used to calculate the heat transfer coefficient and the conditions existing at the flat plate leading edge were used for the correlation. For the Mach 67.3 test the strong interaction parameter, $\chi = M_1^3/\sqrt{Re_x}$, varied from 740 to 6000 for the heat gage locations as shown in Fig. 4a. And the leading edge Knudsen number was 8.39 with unit Reynolds number of 13,240. Over the strong interaction parameter range of 740 to approximately 2500 the parameter $M_1^3 C_{h_1}$ varied nearly linearly with χ with the slope close to that predicted by the Li-Nagamatsu[11] theory for the cooled wall condition. But the experimental curve was shifted to the right, which could be due to the slip flow phenomena near the leading edge because of the reasonably large leading edge Knudsen number and the high free stream Mach number. For the strong interaction parameter range of 2500 to 6000 the $M_1^3 C_{h_1}$ values depart from a straight line because of the slip flow effects as observed in Ref. 5 with air at Mach numbers of 19.2 and 25.4. The departure from the linear variation is not very large in the vicinity of the leading edge, which indicates that the slip flow effects are not large because of the reasonably high unit Reynolds number. In this figure the diffuse free molecule flow value is also plotted, and the comparison with the experimental local heat transfer rates indicate that even in the vicinity of the leading edge the heating rates are much greater than the free molecule value. Much lower unit Reynolds number or low free stream densities and large Knudsen number are necessary at a flow Mach number of 67.3 to achieve heat transfer rates predicted by the diffuse free molecule flow theory.

In Fig. 4b the local heat transfer results at a free stream Mach number of 86.8 are presented as a function of the strong interaction parameter χ. For this test condition the strong interaction parameter varied from 2000 to 16,500 and the leading edge Knudsen number was 17.1 for a unit Reynolds number of 8,270. Over a χ range of 2000 to approximately 4500 the local heat transfer coefficient varied nearly as $\chi^{-3/4}$, which is the predicted theoretical variation of Li and Nagamatsu[11]. Again the experimental heat transfer coefficient has a slope close to the theoretical value for the cooled wall condition but the curve is displaced to the right. This displacement as a function of χ could be due to the slip flow effects near the leading edge because of the large Knudsen number of 17.1 and very high flow Mach number of 86.8. Over a χ range of 4500 to 16,500, the heat transfer coefficient departs from the linear variation, predicted theoretical for no slip flow at the surface, and towards the leading edge with high χ values the heat transfer coefficient is approaching a constant value. Similar results were observed at low density conditions with air at Mach numbers of 19.2 and 25.4 in Ref. 5.

The departure from the linear variation is greater for this Mach number and unit Reynolds condition than for the lower Mach number of 67.3 in Fig. 4a. These results indicate that greater slip flow effects are present for the Mach 86.8 test conditions than for the Mach 67.3. Even with the heat transfer coefficient approaching a constant value near the leading edge, the heat transfer rates are still much greater than the diffuse free molecule value as is indicated in Fig. 4b. Thus, the free stream conditions must be very low for a flat plate at a Mach number of 86.8 to achieve the diffuse free molecule value.

The comparison of the variation of the local heat transfer coefficient with the strong interaction parameter for a flow Mach number of 67.3 and 86.8 is presented in Fig. 4c with the theoretical prediction of Li and Nagamatsu for a cooled wall condition. In this figure the range of χ is from 740 to 16,500 and in most of the available experimental references the strong interaction parameter and the flow Mach number are much less than the values obtained in the present investigation with helium. The slopes of the experimental heat transfer coefficients for both Mach numbers are very close and agree with the theoretical prediction. But towards the leading edge region for both Mach numbers the slope departs from the linear variation for no slip flow at the surface. By increasing the flow Mach number from 67.3 to 86.8 with corresponding decrease in unit Reynolds number from 13,240 to 8,270, the region of linear variation of the heat transfer coefficient was increased from 2500 to approximately 4500 as shown in this figure. The diffuse free molecule heat transfer coefficient increased with the free stream Mach number. These local heat transfer results for helium at very high Mach number indicate that the variation of the heat transfer coefficient with the strong interaction parameter is proportional to $x^{-3/4}$ as predicted in Ref. 11 for the region away from the leading edge where there is no slip flow at the surface. Further experimental and analytical investigations must be conducted to determine the slip flow effects on the local heat transfer rates and induced pressures at very high flow Mach numbers in air and helium flows.

The normalized local heat transfer parameter $M_1^3 C_h / \bar{\chi}^{3/2}$ is presented in Fig. 5a as a function of the rarefaction parameter $\bar{V}_{\infty_1} = M_1/\sqrt{Re_x}$ for a free stream Mach number of 67.3. Over a range for the rarefaction parameter of 0.16 to 0.45, the parameter $M_1^3 C_h / \bar{\chi}^{3/2}$ is nearly constant indicating that the slip flow effects are small over the aft portion of the flat plate. But for the range of $\bar{V}_{\infty_1}$ from 0.45 to 1.35 the local heat transfer coefficient is approaching the slope of the diffuse free molecule heat transfer rate. For this Mach number the strong interaction parameter varied from 740 to 6000 while the corresponding rarefaction parameter varied from 0.16 to 1.35, for the heat gage locations on the plate. The decrease in the $M_1^3 C_{h_1} / \bar{\chi}^{3/2}$ with the rarefaction parameter from the constant value for the no slip condition is not large. Thus, the slip flow effects are not large over the flat plate near the leading edge region. Lower density conditions are necessary at this Mach number of 67.3 to achieve greater rarefaction effects. Similar results for the local heat transfer rates from continuum to rarefied flow conditions were observed in Ref. 5 for air at Mach numbers of 19.2 and 25.4. The rarefaction parameter varied from 0.04 to 2.0 in these experiments and the slip flow effects became noticeable for a rarefaction parameter of approximately 0.3.

At a flow Mach number of 86.8 the normalized heat transfer coefficient parameter was nearly constant for the rarefaction parameter range of 0.26 to approximately 0.58, Fig. 5b. While for a Mach number of 67.3, the slip flow effects became evident for rarefaction parameter of approximately 0.40, and for air at a Mach number of 25.4 in Ref. 5 the slip flow effects became noticeable for a rarefaction parameter value of approximately 0.3. Thus, these experimental results for the local heat transfer results for a sharp flat plate in air at Mach numbers of 19.2 and 25.4 and in helium at Mach numbers of 67.3 and 86.8 indicate that the value for the rarefaction parameter at which the slip flow effects begin to decrease the local heat transfer rate increases with the flow Mach number. Over a range of rarefaction parameter of 0.6 to 2.2 for the Mach number of 86.8, the normalized heat transfer coefficient parameter is approaching the slope for the diffuse free molecule heat transfer value as shown in Fig. 5b. But the value of the local heat transfer rate even at the large rarefaction parameter of 2.0 is higher than the free molecule value. Similar results with air at Mach numbers of 19.2 and 25.4 were obtained in Ref. 5 at low density flow conditions. Additional experimental and analytical investigations must be conducted at hypersonic Mach numbers in air and helium flows to resolve the phenomenon of the leading edge shock wave and boundary layer formation on a flat plate.

5.0 HEAT TRANSFER IN HYPERSONIC CORNER FLOW WITH AIR AT A MACH NUMBER OF 19

The two flat plates with sharp leading edges used to investigate the hypersonic corner flow phenomenon are shown in Fig. 1b. The vertical plate was mounted perpendicular to the horizontal plate with the intersection parallel to the free stream and the leading edge of both plates in the same plane. Heat gages on the horizontal plate were located along the center line from 0.19 to 12.95 in. from the leading edge. Since the width of the sputtered platinum heat gages was approximately 0.5 in., the increase in the local heat transfer rate due to the shock wave from the vertical plate is not as large as for shorter width gages. For the present investigation the vertical plate was located at 0.5, 1.0, and 1.5 in. from the centerline of the horizontal plate.

The complete model was mounted on a sting in the shock tunnel with the leading edge of the plate located slightly downstream of the 24 in. diameter conical nozzle[32,34]. The combustion driver technique was used to produce the heated and compressed air at the end of the 103 foot long driven tube. To minimize the real gas effects the air was heated to a reflected stagnation temperature of approximately 2100°R at the entrance to the conical nozzle. The hypersonic corner flow phenomenon was investigated at reflected stagnation pressures of approximately 75 and 2200 psia with corresponding unit Reynolds numbers of approximately 900 and 29,600 respectively as presented in Table II. These reflected stagnation pressures were selected to study the corner flow phenomenon for rarefied and continuum flow conditions. Before these heat transfer investigations were conducted, the heat gages were calibrated in the 8 in. shock tube, and the calibration was checked after the tests in the shock tunnel. An impact pressure probe located in the plane of the flat plate leading edge, cf. Fig. 1a, was used to determine the flow Mach number for an assumption of equilibrium expansion in the conical nozzle[33]. The model wall to reflected stagnation temperature ratio for these tests was approximately 0.27 as presented in Table II.

The local heat transfer rates are presented in Figs. 6a and b as a function of the distance from leading edge of the horizontal plate for vertical plate distance from the centerline of 0.5, 1.0 and 1.5 in. In Fig. 6a the surface heating rates are presented for the reflected stagnation pressure of approximately 75 psia, stagnation temperature of 2100°R, and flow Mach number of 19. For these test conditions the leading edge Knudsen number was approximately 35 with a unit Reynolds number of about 900 as presented in Table II. Previous investigations[5] of the heat transfer rates on the horizontal plate by itself in the shock tunnel at Mach numbers of 19.2 and 25.4 with air indicated that the rarefied effects were quite large at these low unit Reynolds numbers. Since with a combustion driven shock tube technique, it is extremely difficult to produce exactly the same reflected stagnation conditions for all shots, there is a slight variation in the reflected stagnation conditions, as shown in Table II and Fig. 6a.

For these low density conditions at a Mach number of 19, the local heat transfer rates over the initial portion of the sharp flat plate are about the same with some differences due to the slight differences in the stagnation temperature. With the vertical plate located 0.5 in. from the centerline the local heating rates started to increase from the second gage located at 0.310 in. from the leading edge with the peak increase occurring at approximately the 1.1 in. location as shown in Fig. 6a. In the previous investigation of the surface pressure distributions and schlieren photographs of the shock wave and boundary layer formation for a sharp flat plate in Ref. 4, the shock wave and boundary layer thickness of 0.25 in. occurred at a distance of approximately 0.9 in. from the plate leading edge. Thus, for these flow conditions, there seems to be an upstream effect of the shock wave from the vertical plate on the heating rates on the horizontal plate. At this vertical plate location, the maximum heat transfer rate was increased approximately 25 percent with the 0.5 in. wide heat gages. At a Mach number of 11.2 and strong interaction parameter χ of 2.5 in Ref. 29, the peak increase in the local heating rates was much greater than that observed in the present investigation at a Mach number 19.0. In Ref. 43, for flow over a wedge in a helium tunnel at a Mach number 28.9 with a sharp flat plate mounted perpendicular to the wedge surface, there was only about a 30 percent increase in the surface pressure due to hypersonic corner flow phenomenon.

Downstream of the region of the intersection of the leading edge shock wave from the vertical plate, for distances greater than 2 in., the local heat transfer rates are less than values for the vertical plate located farther away from the plate centerline as indicated in Fig. 6a. This is due to the thicker boundary layer existing on the horizontal plate because of the merging of the boundary layers for the two plates in the corner region for a lateral location of 0.5 in. for the vertical plate. The lower heating rates existed for this vertical plate location up to the last heat gage location of 12.9 in. With the vertical plate located 1.0 in. from the centerline, the leading edge shock from the vertical plate leading edge would intersect the heat gages on the horizontal plate at a distance of approximately 2.5 in. from the leading edge, based upon the schlieren photographs of the flow over a flat plate at a Mach number of 19 in Ref. 4. At this location the local heat transfer rates on the horizontal plate were not affected as much as for the vertical plate at the 0.5 in. location as shown in Fig. 6a. Evidently the leading edge shock wave from the vertical plate is weak and the boundary layer on the horizontal plate is thick at the 2.5 in. location so that the leading edge shock wave effects on the heating rates are attenuated. Similar results with the vertical plate mounted at a distance of 1.5 in. from the centerline, where the leading edge shock wave from the vertical plate intersects the heat gages at approximately 5 in. from the leading edge of the horizontal plate. For this condition the vertical plate shock wave effects on the heat transfer rates were not apparent for heat gages located upstream and downstream of the 5 in. location. Thus, these results for the low density hypersonic corner flow phenomenon indicate that the effects of the leading edge shock wave and boundary layer from the vertical plate on the local heat transfer rates are only important towards the plate leading edge region.

The corner flow heat transfer rates at the higher reservoir pressure of approximately 2200 psia for nearly continuum flow conditions are presented in Fig. 6b at a Mach number of 19.9 and total temperature of approximately 2000°R, Table II. For these test conditions the unit Reynolds number was approximately 29,000 and leading edge Knudsen number of about unity. At these high reservoir pressures the leading edge shock wave from the vertical plate placed 0.5 in. from the centerline would intersect the heat gages at approximately 1.1 in. downstream of the horizontal plate leading edge. As observed at lower density in Fig. 6a, the local heating rates are increased both upstream and downstream of 1.1 in. location in Fig. 6b. But downstream of this shock intersection region the local heat transfer rates are higher than the values observed with the vertical plate placed at 1.0 and 1.5 in. from the centerline. At the lower density condition the heating rates downstream of the shock wave intersection were lower than that for the plate placed farther away from the centerline as shown in Fig. 6a. Boundary layer surveys should be made at these two reservoir pressure conditions to determine the reason for the different type of heating rates downstream of the shock wave intersection region. For the vertical plate located at 1.0 and 1.5 in. from the centerline the local heat transfer rates did not indicate the increase in the heating rates due to the shock wave intersecting with the horizontal plate. From Ref. 4 the leading edge shock wave intersections with the horizontal plate are at 4.3 and 7.0 in. for the vertical plate located at 1.0 and 1.5 in. respectively. Thus, at these high density conditions the corner flow effects on the local heat transfer rate are limited to very close to the corner region.

In Figs. 7a and 7b the local heat transfer coefficient is plotted as a function of the strong interaction parameter with the vertical plate at distances of 0.5, 1.0, and 1.5 in. from the centerline for two reflected reservoir pressures of approximately 75 and 2200 psia. For these two reservoir pressures the strong interaction parameter varied from 13.3 to 530 over the heat gages on the horizontal flat plate. For the lower pressure of 75 psia the strong interaction parameter ranged from 62 to 530 and the heat transfer rates in the corner flow region are presented in Fig. 7a. In this figure the heat transfer coefficient for the strong interaction theory[11] is also presented for the wall temperature ratio of 0.247 as a reference. In Ref. 5 it was observed that the local heat transfer rates departed from the theoretical values for unit Reynolds number of 900 per inch, which is close to the value for the present tests. For the vertical plate located 0.50 in. from the centerline, the local heat transfer coefficients over the initial two heat gages from the leading edge were nearly constant for χ values of 530 and 375 respectively as shown in Fig. 7a. And the heat transfer coefficients were nearly an order of magnitude less than that predicted by the strong interaction theory with no slip flow at the surface. Close to the region of the intersection of the leading edge shock wave from the vertical plate, the local heat transfer coefficient increased and approached the theoretical curve. Downstream of the shock wave intersection region, the local heat transfer rates were close to the theoretical values, with the slope of the $M_1^3 C_{h_1}$ curve being slightly greater than the theoretical slope in Fig. 7a.

The effects of the corner flow upon the local heat transfer rates on the horizontal plate were rather small for the vertical plate locations of 1.0 and 1.5 in. from the centerline as indicated in Fig. 7a. For both of these vertical plate locations the variations of $M_1^3 C_{h_1}$ with the strong interaction parameter χ were quite similar with large departures from the theoretical value near the leading edge. At the 1.0 in. location for the vertical plate the local heat transfer coefficients were about the same as for the 0.5 and 1.5 in. plate locations over the initial two heat gages, but at a χ value of 250 the local heat transfer rates were about 35 percent less than the 0.5 in. plate location. For χ values less than 150 the local heat transfer coefficients were greater than for the 0.5 in. plate location as indicated in Fig. 7a, and the slope of $M_1^3 C_{h_1}$ as a function of χ approached the theoretical value. For the vertical plate at the 1.5 in. location, the local heat transfer coefficients were very close to the values for the 1.0 in. plate location. Again for χ values less than 150 the local heat transfer coefficients were appreciably greater than for the plate location of 0.5 in. The variation of the heat transfer coefficient with χ for this plate location was similar to that observed in Ref. 5 for the flat plate at the low density conditions. By plotting the corner flow heat transfer coefficient, $M_1^3 C_{h_1}$, as a function of the strong interaction parameter χ and comparing the experimental data with the strong interaction theory of Li and Nagamatsu[11], it is possible to determine the increase in the heating rates due to the hypersonic corner flow phenomenon.

The variations of the local heat transfer coefficient as a function of the strong interaction parameter for nearly continuum flow conditions in the vicinity of the leading edge region for reflected pressures of approximately 2200 psia are presented in Fig. 7b for a free stream Mach number of 19.9 and vertical plate locations of 0.5, 1.0, and 1.5 in. from the centerline. For this high density flow condition in Ref. 5 for the local heat transfer rates it was observed that the rarefied flow effects were negligible. Over the heat gage locations the value of the strong interaction parameter varied from 13.3 to 120. Over the first two heat gages from the leading edge the local heat transfer coefficient was close to the strong interaction theory of Li and Nagamatsu for a wall temperature ratio of 0.267. With the vertical plate located at 0.5 in. the local heat transfer rates increased from the fourth heat gage location downstream from the theoretical values due to the shock wave intersection with the horizontal plate.

For the vertical locations of 1.0 and 1.5 in. from the centerline, the shock wave from the vertical plate increased the heating rate slightly above the theoretical values as indicated in Fig. 7b, and the increase was not as large as for the 0.5 in. plate location. The departure in the heat transfer coefficient from the theoretical value was the least for the 1.5 in. plate location, and the departure increased as the vertical plate approached the centerline. Because of the high density flow conditions in the test section, unit Reynolds number of approximately 29,000 per inch, Table II, the boundary layers on the plates are much thinner than for the lower density conditions so that the hypersonic viscous corner flow effects are smaller than for the rarefied flow conditions as indicated in Figs. 6 and 7. These hypersonic corner flow effects on the local heat transfer rates were determined for the horizontal and vertical plates with a sharp leading edge. Much larger effects would probably be observed with a blunter leading edge that would have a stronger shock wave at the leading edge, and experiments will be conducted to determine the bluntness and angle of attack effects on the hypersonic corner flow phenomenon.

6.0 CONCLUSIONS

Local surface heat transfer rates were measured on a sharp flat plate at zero angle of attack with helium at Mach numbers of 67.3 and 86.8 in a hypersonic shock tunnel. For these Mach numbers the strong interaction parameter, $\chi = M_1^3/\sqrt{Re_x}$, varied from 730 to 16,500. The leading edge Knudsen numbers were 8.39 and 17.1, and the unit Reynolds numbers were 13,240 and 8,270 at Mach numbers of 67.3 and 86.8 respectively.

For both Mach numbers the slopes of the local heat transfer coefficient with the strong interaction parameter downstream of the leading edge region agreed with the strong interaction prediction of Li and Nagamatsu. But for both Mach numbers the experimental data was shifted to the right of the theoretical curve.

Towards the leading edge region the local heat transfer rates became much less than the theoretical prediction and approached a constant value due to the rarefied flow effects. But the local heat transfer rates at both Mach numbers were much greater than the free molecule limit with diffuse reflection at the plate surface.

The experimental heat transfer data indicated the beginning of the rarefied flow phenomena for values of rarefaction parameter, $\overline{V}_{\infty_1} = M_1/\sqrt{Re_x}$, of approximately 0.4 and 0.6 for Mach numbers of 67.3 and 86.8 respectively. These values are much higher than those observed with air at Mach numbers of 19.2 and 25.4.

The local heat transfer rates in the corner flow region produced by the intersection of two perpendicular flat plates with sharp leading edges were determined with air at a Mach number of approximately 19. Two reflected stagnation pressures of approximately 75 and 2000 psia were used at a reflected temperature of approximately 2000°R. For these test conditions the unit Reynolds numbers were approximately 900 and 29,000 and the leading edge Knudsen numbers were approximately 35 and 1.0. The strong interaction parameter varied from 13 to 530. For these investigations the vertical plate was placed at 0.5, 1.0, and 1.5 in. from the centerline of the horizontal plate.

At the low density flow conditions, the local heat transfer rates were increased approximately 35 percent in the corner region due to the interaction of the shock wave and boundary layer from the two sharp flat plates. For the high density continuum flow conditions, the local heat transfer rates in the corner flow region were increased but not as much as for the rarefied hypersonic flow.

By comparing the local heat transfer coefficient in the corner flow region with the strong interaction theory of Li and Nagamatsu, it is possible to determine the corner flow effects on the heating rates. Further experimental and analytical investigations must be conducted to understand the hypersonic corner flow phenomena with lifting surfaces.

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TABLE I

CONDITIONS FOR HELIUM TESTS

Run	P_5 (psia)	T_5 (°R)	T_w/T_5	M_1	(Re/in)	λ_1 (In. x 10^3)	Kn_1
1	1336	2280	0.237	67.3	13,240	8.39	8.39
2	1346	2280	0.237	86.8	8,270	17.1	17.1

TABLE II

CONDITIONS FOR CORNER AIR FLOW TESTS

Run	P_5 (psia)	T_5 (°R)	T_w/T_5	Y (in.)	M_1	Re/in	λ_1 (In. x 10^3)	Kn_1
1	75	2160	0.250	0.5	19.0	790	37.0	37.0
2	80.5	2160	0.250	1.0	19.0	891	32.8	32.8
3	75.5	2000	0.270	1.5	19.0	936	31.4	31.4
4	1988	2000	0.270	0.5	19.9	26,600	1.12	1.12
5	2220	2000	0.270	1.0	19.9	29,600	1.02	1.02
6	2220	2000	0.270	1.5	19.9	29,600	1.02	1.02

FIGURE 1A. FLAT PLATE HEAT TRANSFER MODEL.

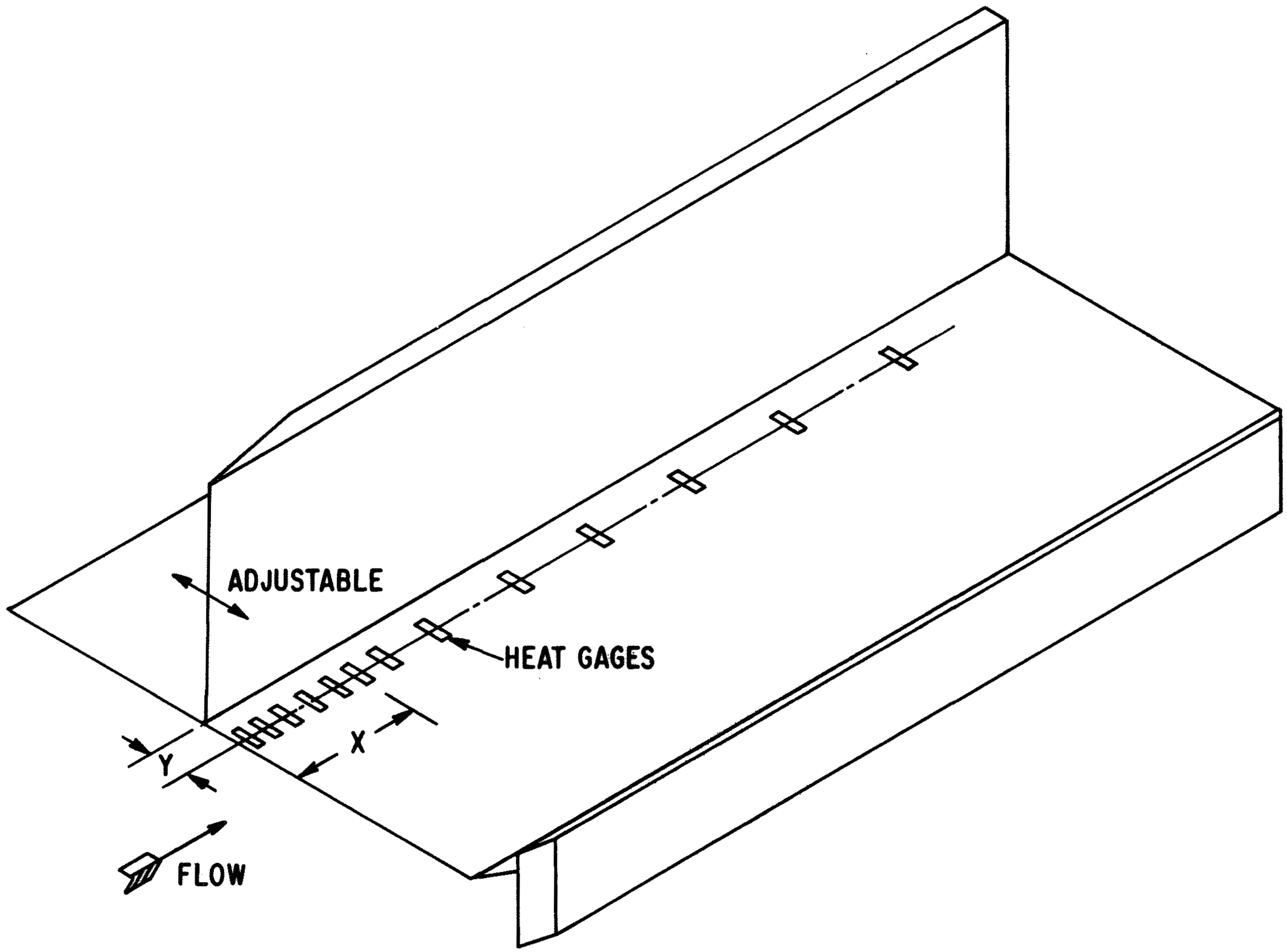


FIG. 1b SCHEMATIC OF FLAT PLATE HEAT TRANSFER MODEL FOR CORNER FLOW ARRANGEMENT

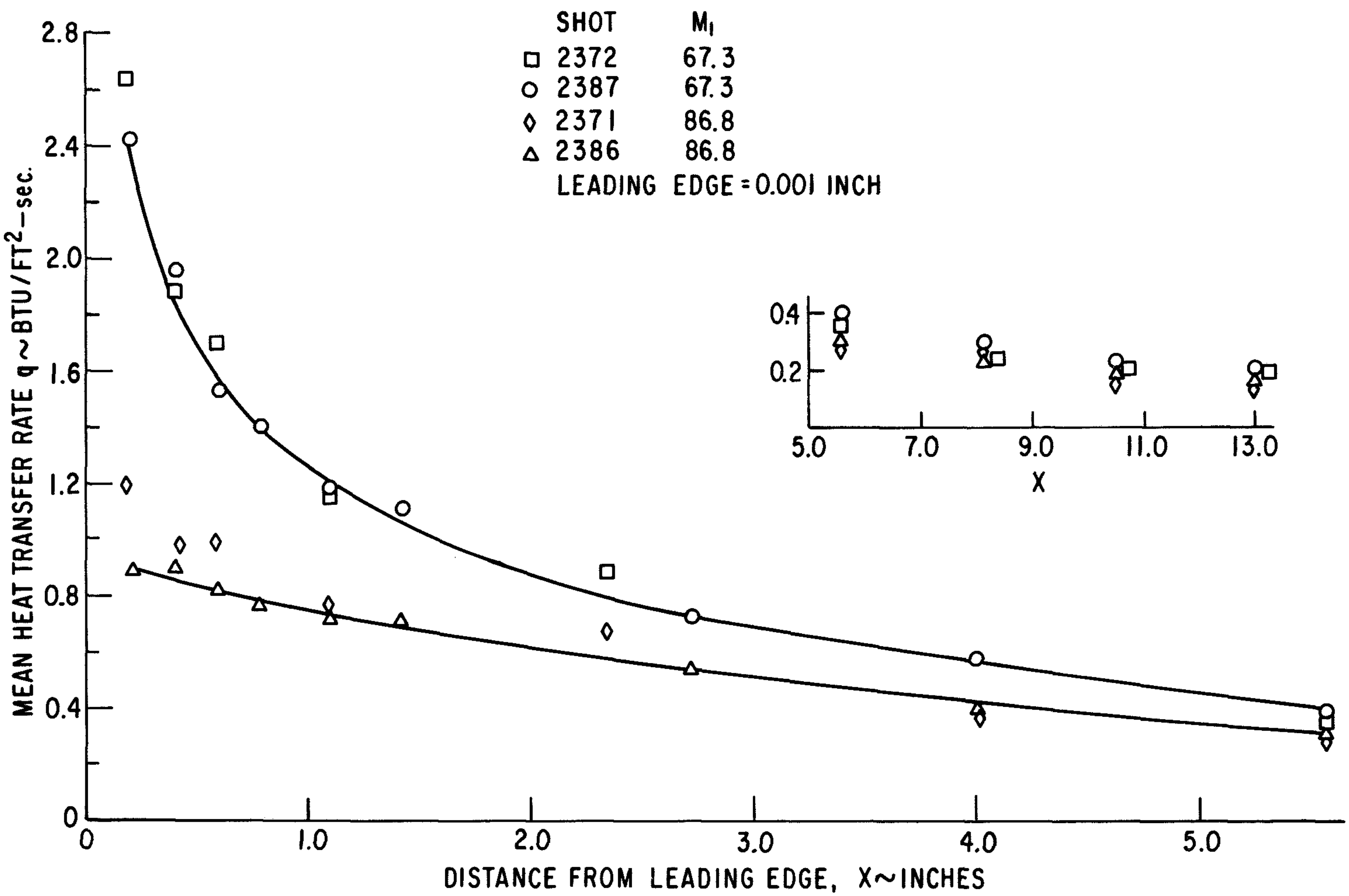


FIG.2 HEAT TRANSFER RATE DISTRIBUTION ALONG THE PLATE, M_1 = 67.3 AND 86.8

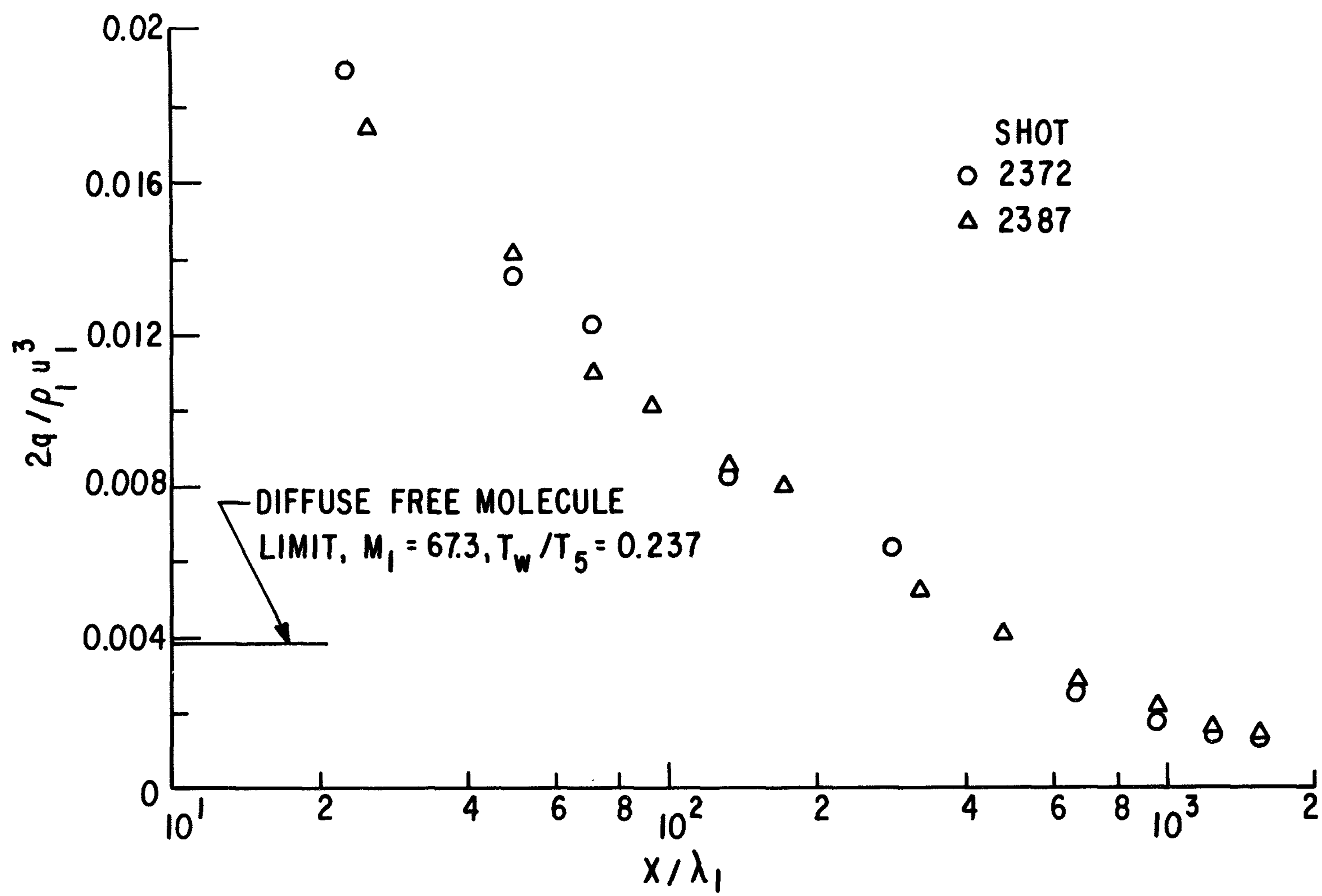


FIG.3a NORMALIZED HEAT TRANSFER RATE VS. DISTANCE ALONG PLATE IN MEAN FREE PATHS, M_1 = 67.3

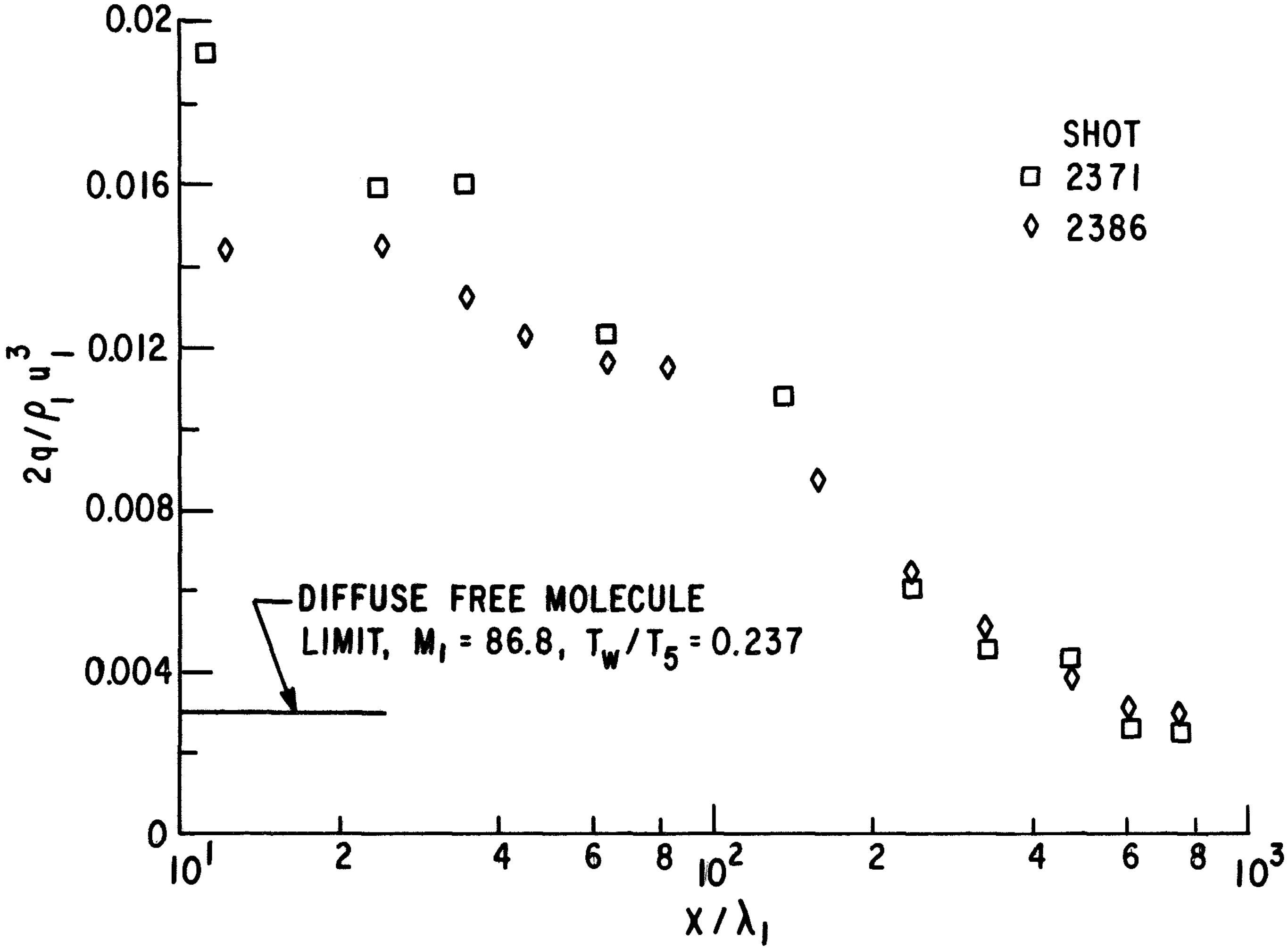


FIG.3b NORMALIZED HEAT TRANSFER RATE VS. DISTANCE ALONG PLATE IN MEAN FREE PATHS, $M_1 = 86.8$

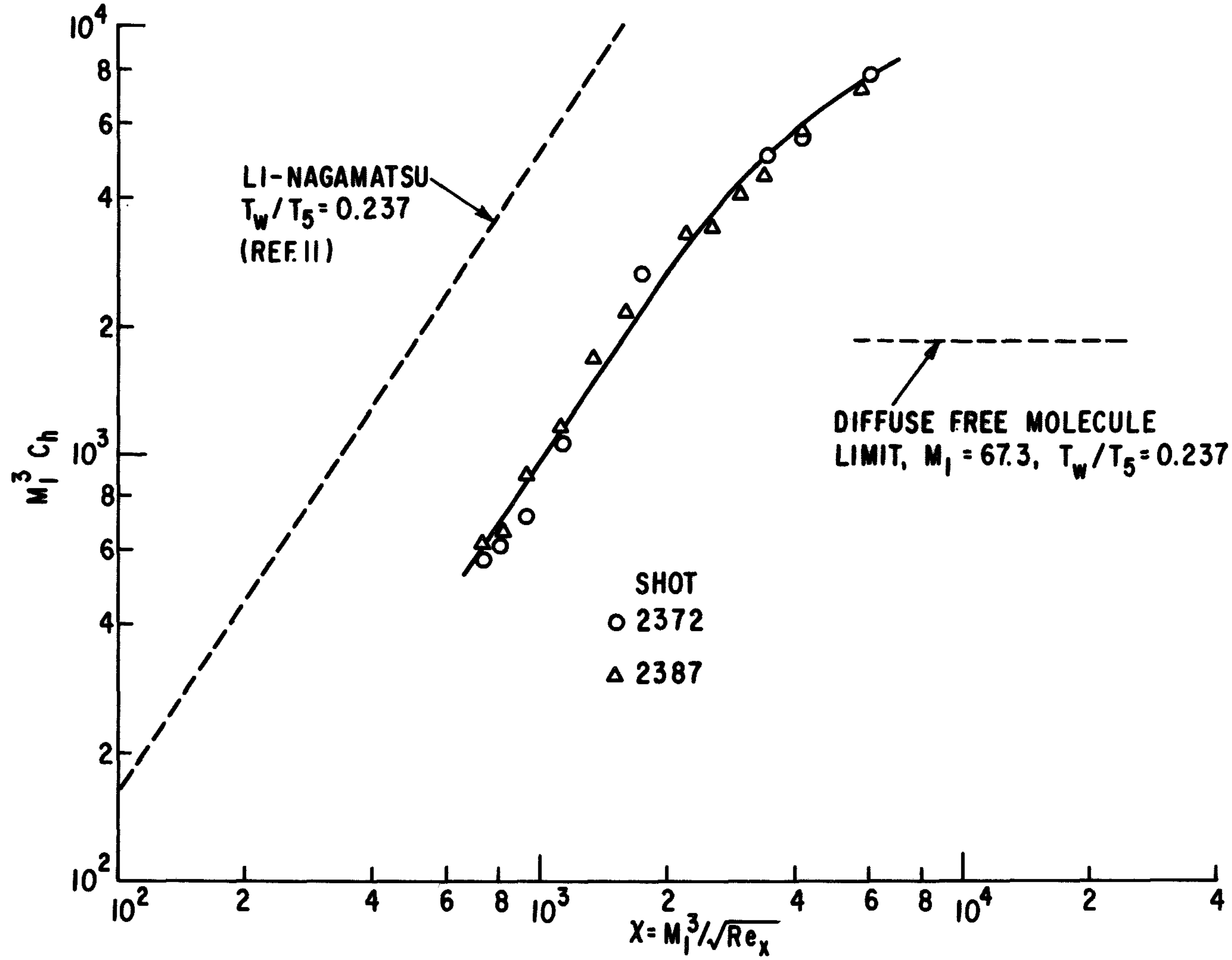


FIG.4a HEAT TRANSFER COEFFICIENT AS FUNCTION OF STRONG INTERACTION PARAMETER, $M_1 = 67.3$

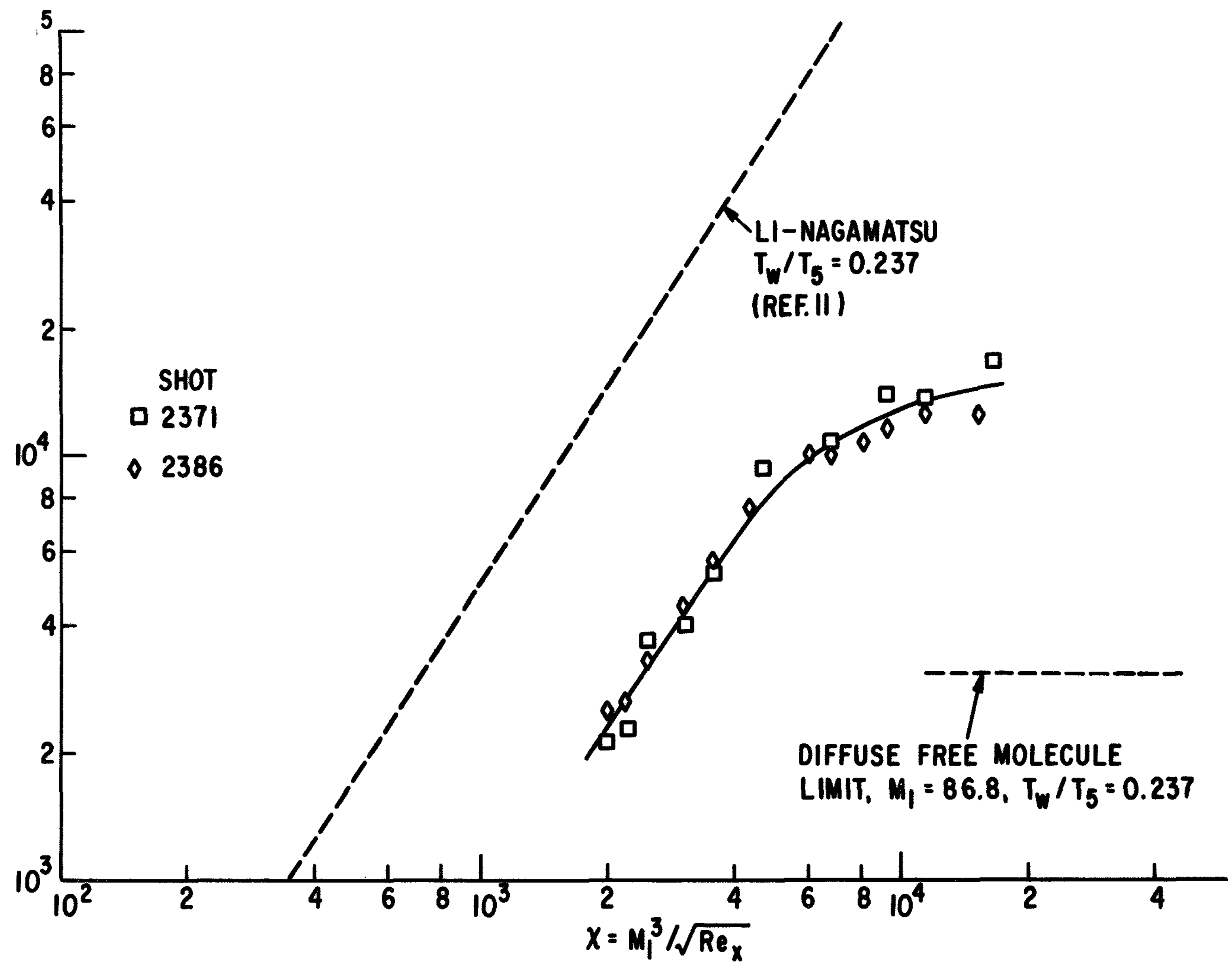


FIG.4b HEAT TRANSFER COEFFICIENT AS FUNCTION OF STRONG INTERACTION PARAMETER, $M_1 = 86.8$

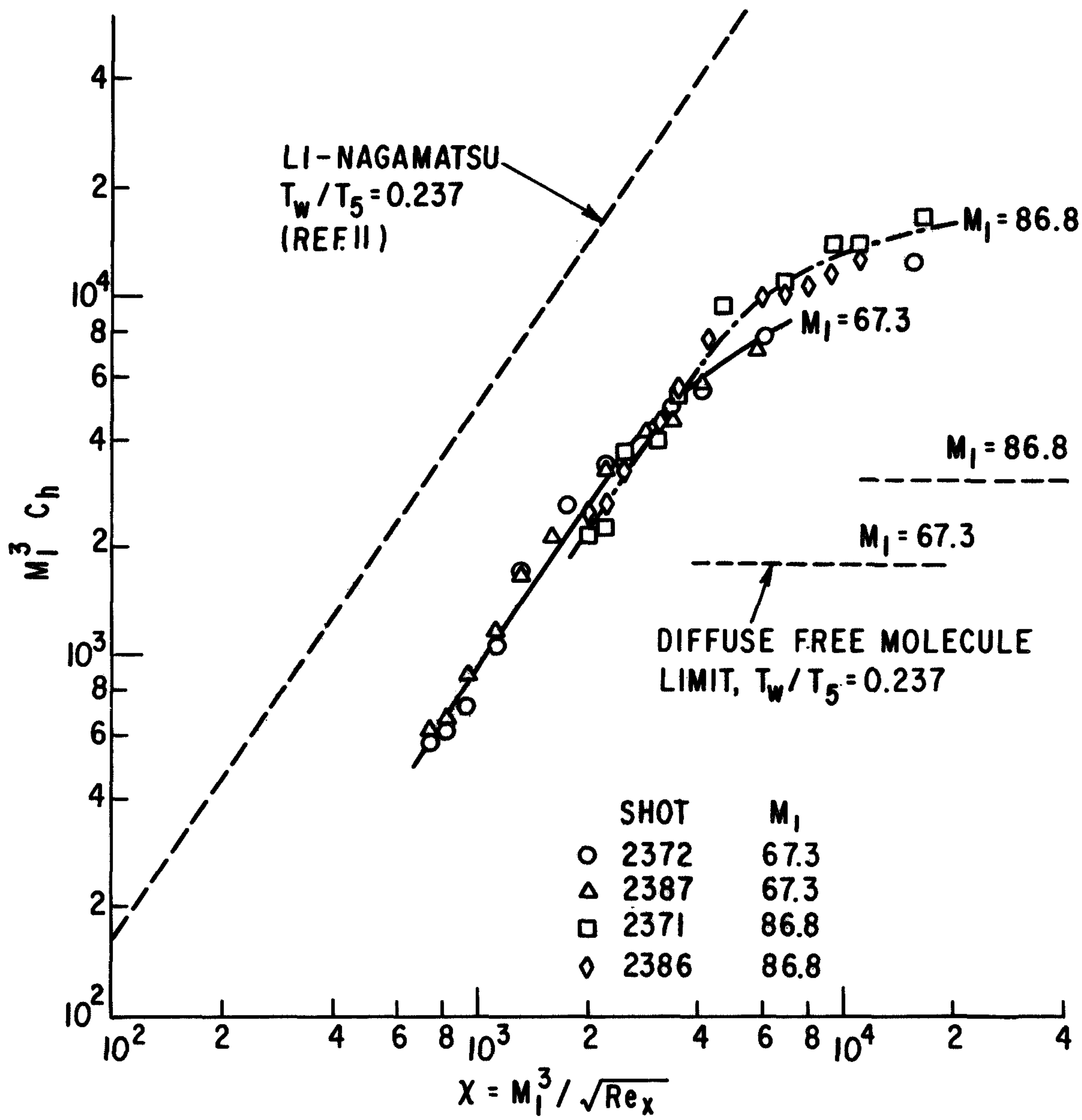


FIG.4c HEAT TRANSFER COEFFICIENT AS FUNCTION OF STRONG INTERACTION PARAMETER, M_1=67.3 AND 86.8

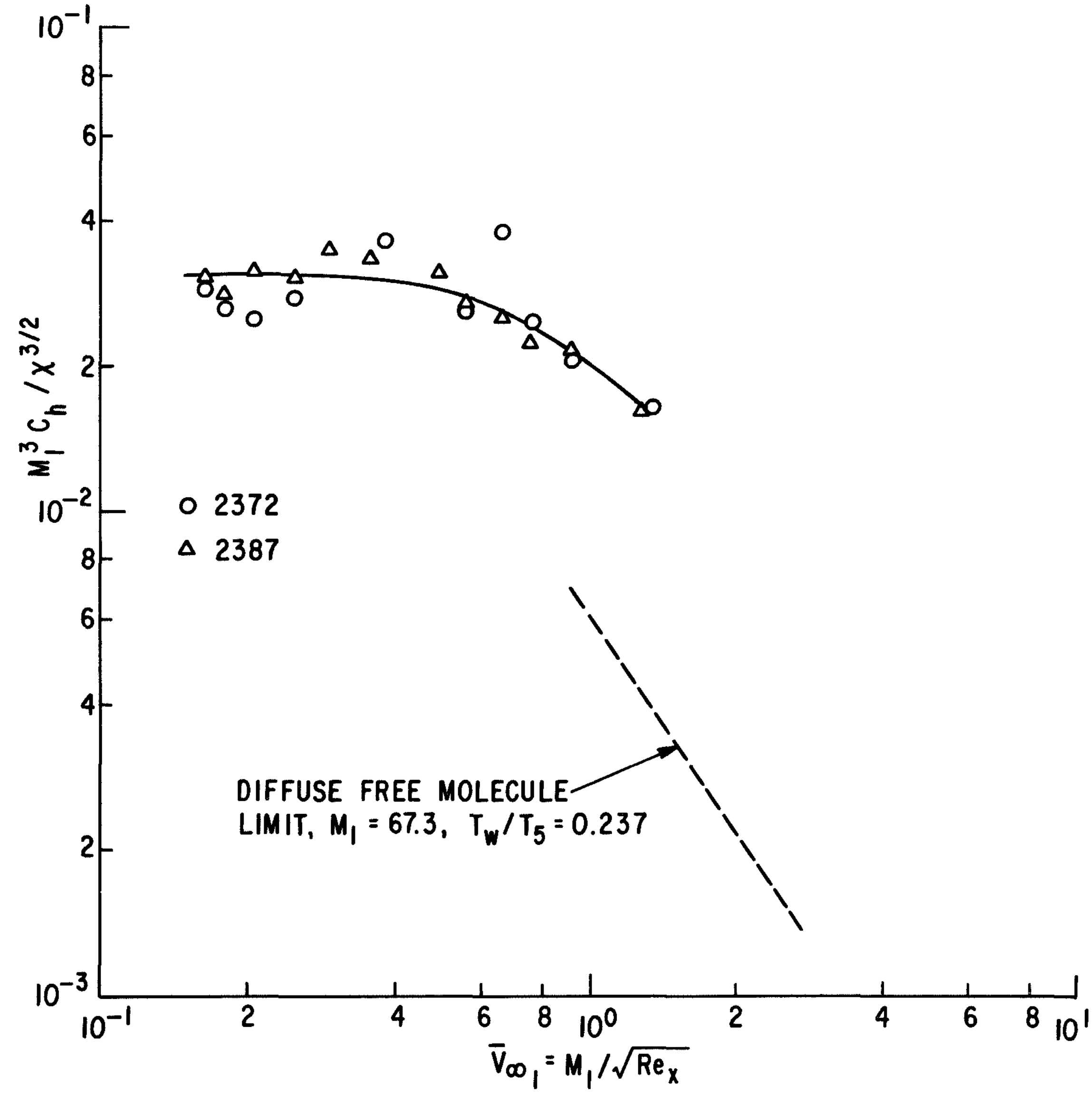


FIG.5a NORMALIZED HEAT TRANSFER COEFFICIENT AS FUNCTION OF RAREFACTION PARAMETER, $M_1 = 67.3$

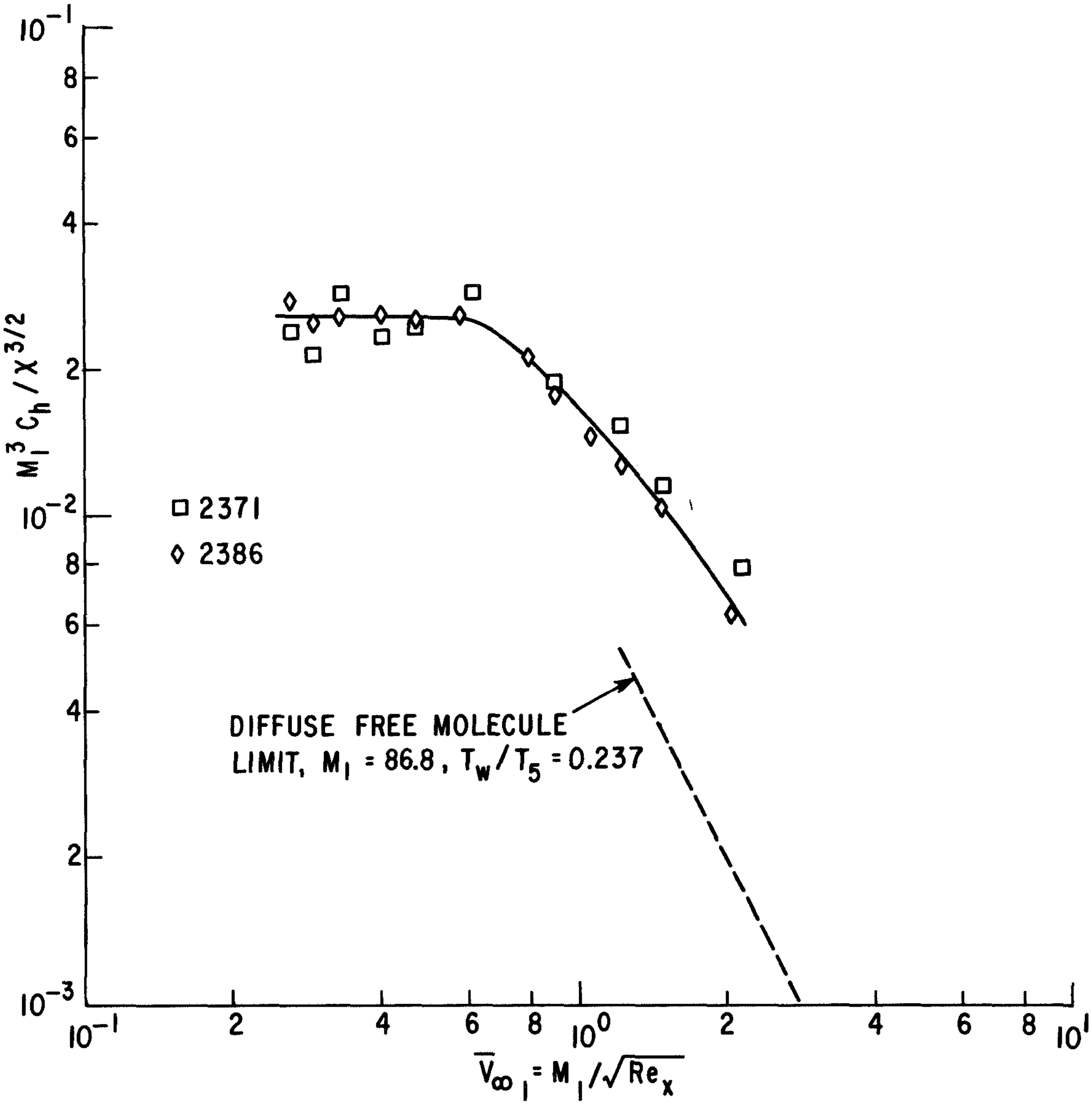


FIG.5b NORMALIZED HEAT TRANSFER COEFFICIENT AS FUNCTION OF RAREFACTION PARAMETER, $M_1 = 86.8$

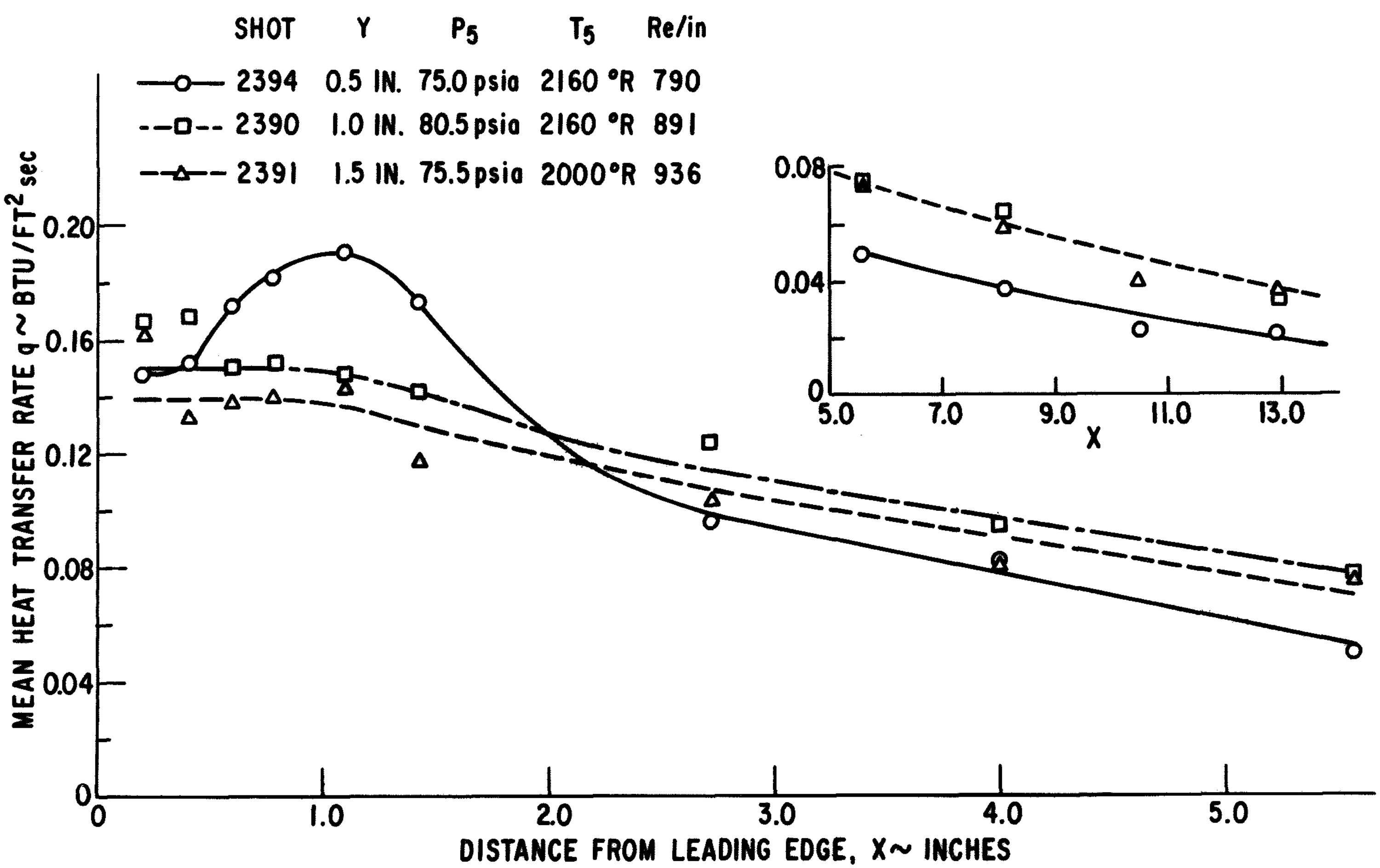
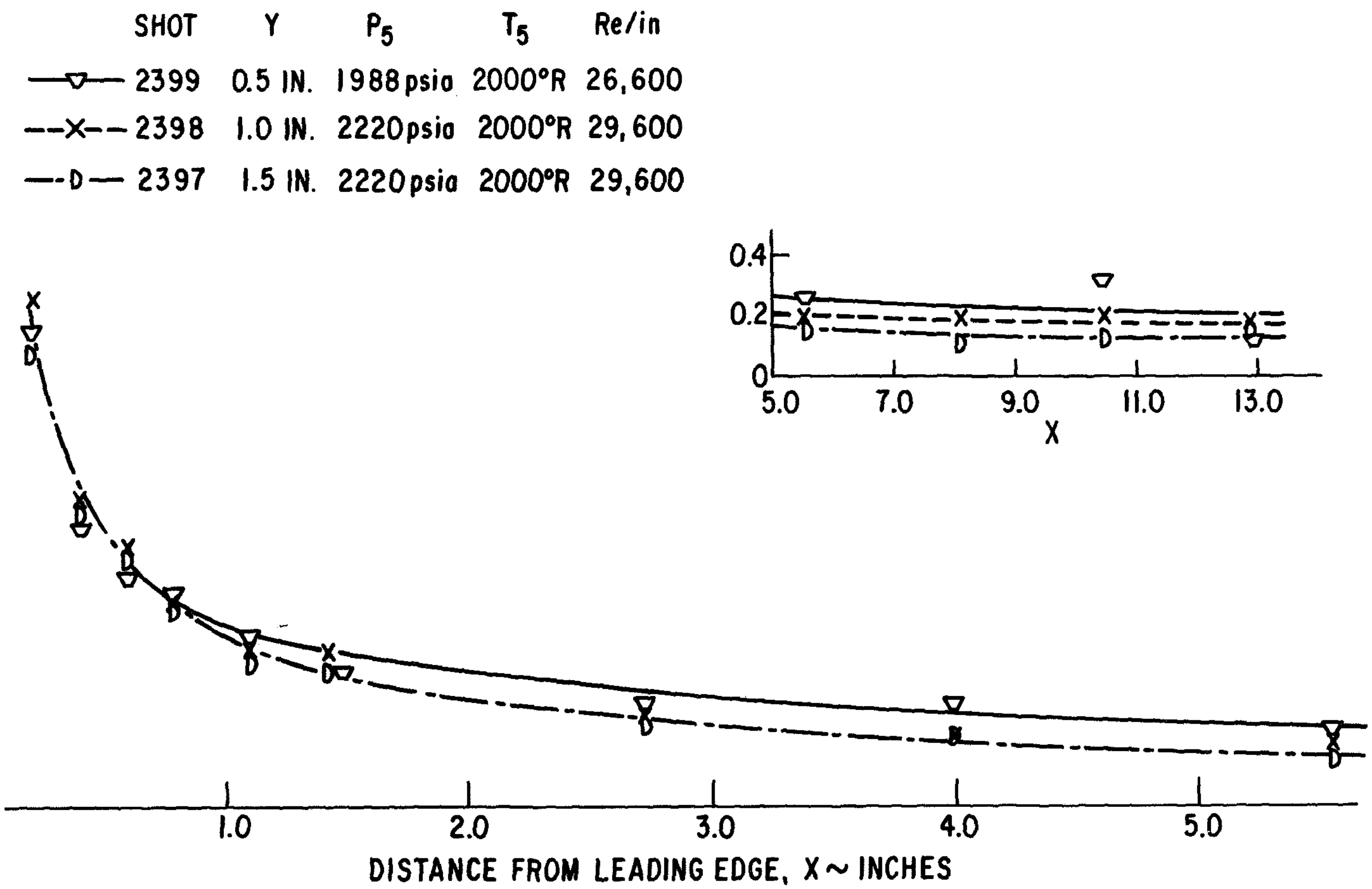


FIG.6a HEAT TRANSFER RATE DISTRIBUTION ALONG THE PLATE FOR REFLECTED STAGNATION PRESSURE, $P_5 \sim 75$ psia, $M_1 = 19.0$



6b HEAT TRANSFER RATE DISTRIBUTION ALONG THE PLATE FOR REFLECTED STAGNATION PRESSURE, $P_5 \sim 2200$ psia, $M_1 = 19.9$

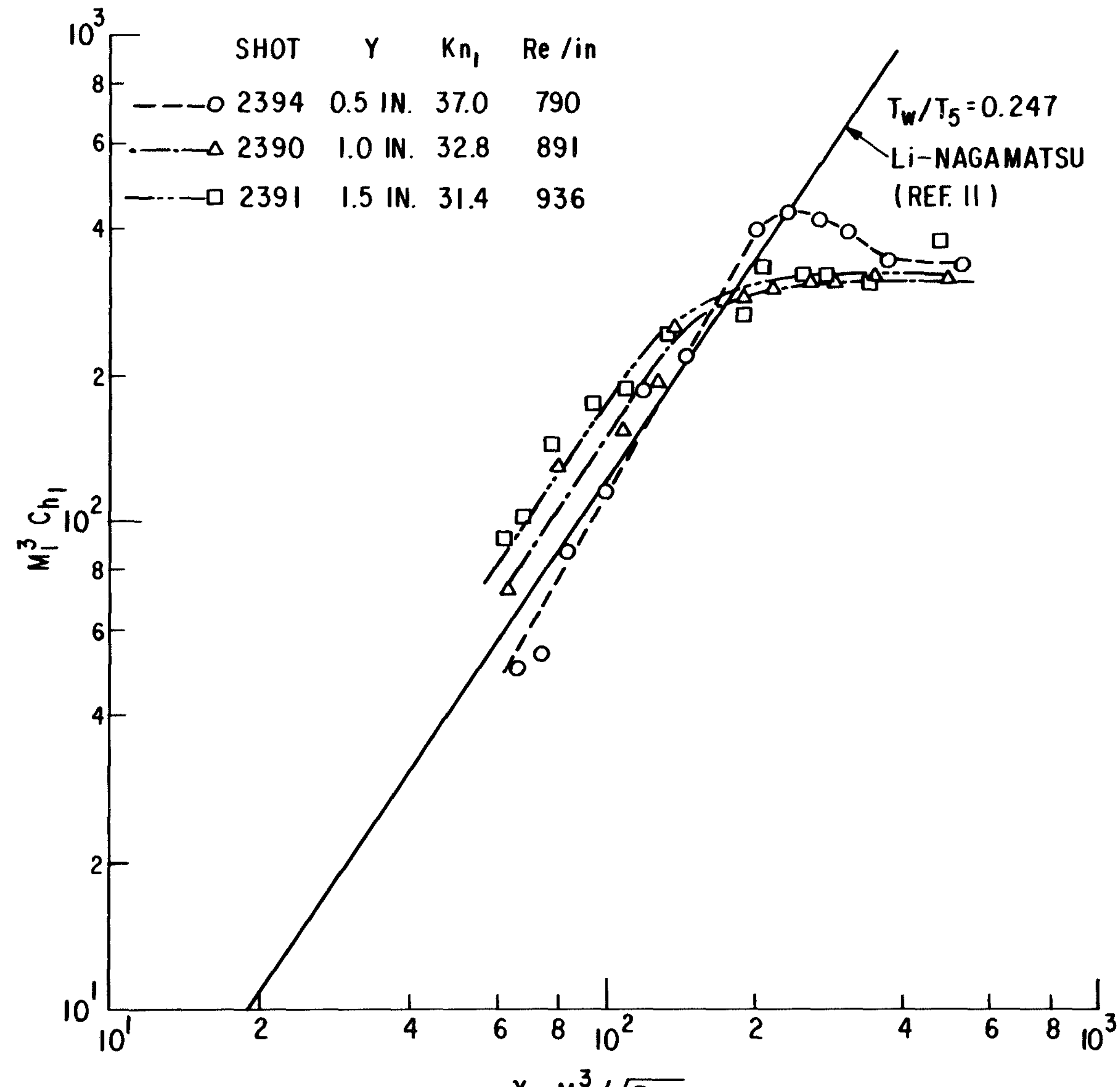


FIG.7a HEAT TRANSFER COEFFICIENT AS A FUNCTION OF STRONG INTERACTION PARAMETER FOR REFLECTED STAGNATION PRESSURE, $P_5 \sim 75$ psia, $M_1 = 19.0$

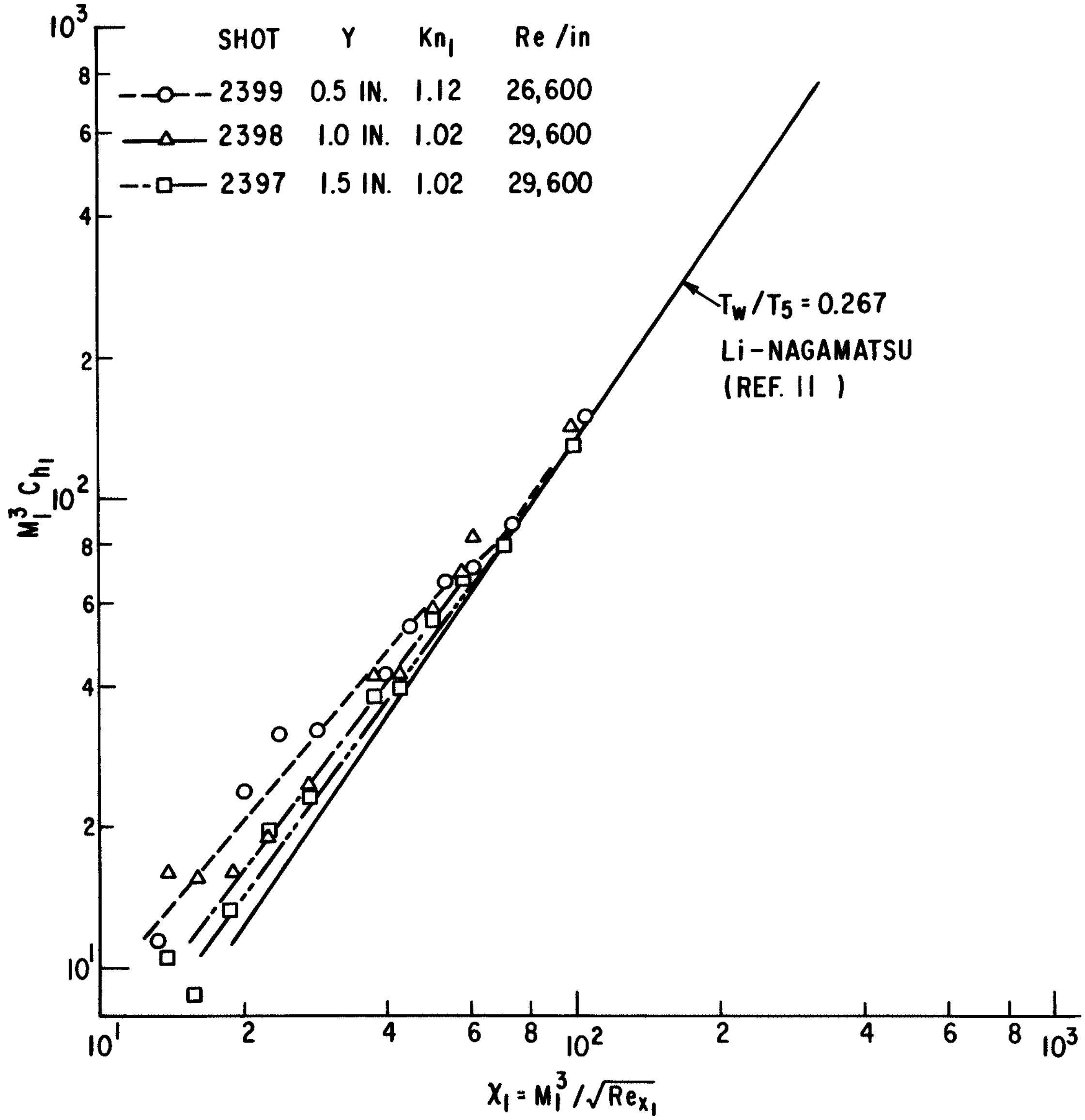


FIG.7b HEAT TRANSFER COEFFICIENT AS A FUNCTION OF STRONG INTERACTION PARAMETER FOR REFLECTED STAGNATION PRESSURE $P_5 \sim 2200$ psia, $M_1 = 19.9$