Experimental Studies On Heat Transfer To Bodies In Hypersonic Rarefied Gas Flows

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Abstract. This paper presents the results of experimental measurements on heat transfer to simple aerodynamic shapes while encountering hypersonic rarefied gas flows. The study cover a wide range of aero-thermal simulation parameters including a wide range of Knudsen numbers from near continuum to transitional regimes of rarefied flows. Flat headed cylinder and hemispherical headed cylinder were the two models selected for aerodynamic heating studies. Platinum thin film heat transfer gauges were employed to measure the surface transient temperature and heating rates are determined employing a numerical procedure. The sensor locations on the models covered flat faces as well as hemispherical end curved faces. Contrary to the usual procedure of heat flux determination, curvature effects were also considered in solving the one dimensional heat conduction equation for temperature signals from the curved locations. Aerodynamic heating studies indicate the influence of Knudsen number, model shape and stagnation conditions on the heating pattern. Flat headed cylinder experience large changes in heat transfer over its face when compared to hemispherical model. Significant difference in heat transfer is observed when curvature effects are considered. Stanton number value steadily decreases with increase in Cheng's rarefaction parameter but reaches a limiting value at the same rarefaction parameter only for higher stagnation temperatures.

Keywords: Heat transfer, Hypersonic, Rarefied, Transition regime, Curvature effects, Cheng's rarefaction parameter.
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INTRODUCTION

Any effort to improve the knowledge on aerodynamic heating of aerospace vehicles at various levels of atmospheric rarefaction attracts considerable attention even today. It is well known that the flow field around a body in a rarefied atmosphere may be controlled to a significant degree by viscous and other transport effects. The density of the surrounding medium influences the extent of heating in a considerable way. Theoretical predictions of heating rates are often restricted to continuum and free molecular regimes whereas detailed experiments are necessary to generate the required design data for the transitional regime. In general there is good agreement between experimental data and widely used theories such as Fay and Riddell when the Reynolds number (based on free stream conditions) is high. As the flow become rarefied, continuum theories initially under estimate and then progressively over estimate the experimentally determined data [1]. Bridging functions are often developed to predict heat transfer characteristics in the transition regime and Direct Simulation Monte Carlo (DSMC) is found to be successful in this regime of rarefaction [2]. A proper validation of these models is highly essential before they are put to use with complete confidence. Experimental measurements are thus important. Experimentally measured heat transfer data on bluff faced bodies at transition regime is reported in [3, 4]. Cheng's rarefaction parameter has been introduced and modified form of Cheng's theory is applied. The hypersonic shock layer theory of the stagnation region at low Reynolds number proposed by Cheng [5] takes in to account the salient features of the transport processes within the shock layer. The main objective of the present study is to investigate on the effect of stagnation temperature on the Stanton number primarily at transitional Knudsen numbers. The variation of Stanton number with Knudsen number at near continuum flows at much higher enthalpies has been studied using Hypersonic Shock tunnel. The variation of Stanton number with Cheng's rarefaction parameter for flat faced and hemispherical headed cylinder has also been studied. Platinum thin film heat transfer gauges are employed for recording temperature variations at various spatial locations over the model surface [6]. Curvature effects are also considered in heat flux determination i.e for solving the one dimensional heat conduction equation using the measured temperature history from the curved locations of the hemispherical headed model [7].

EXPERIMENTAL PROCEDURE.

Experiments were conducted using the two hypersonic testing facilities available at Indian Institute of Technology Madras. Heat transfer studies conducted using the Rarefied Gas Dynamics facility covered transitional Knudsen numbers with stagnation temperature up to 1000K. An electric pebble bed heater capable of heating the low density air to a temperature of about 1000K is attached to the stagnation chamber of the tunnel. A shielded thermocouple of K type is employed to monitor the stagnation temperature of the heated air. It is possible to maintain different ratios of upstream stagnation (Po) to downstream (Pc) pressure in the facility. The upstream stagnation pressure was measured using a capacitance type MKS BARATRON pressure gauge and a Wallace and Tiernan analog pressure manometer. The downstream pressure was monitored using MKS BARATRON and Edwards Wide Range Gauge. Dry air at low pressure is heated to the required stagnation temperature and is allowed to expand through a convergent–divergent nozzle. The throat radius of the nozzle(r*) is 0.5 mm, nozzle half angle (ν) is 14.5 degrees and the exit Mach number is 6.0. Between the nozzle exit and the test model is a shutter that can be removed suddenly (in less than 0.2 sec) using a remotely controlled gear motor. This facilitates the sudden impingement of the hot jet on the model surface. Flat headed cylinder and hemispherical headed cylinder were the two models selected for aerodynamic heating studies. These models, with 10mm diameter and 40mm length, were machined out of Macor and platinum thin films were made on different locations over the model surface including the stagnation point. The theory for heat conduction in a non-homogeneous body can be used to relate the measured surface temperature history to the rate of heat transfer to the model. The heat transfer process is thus reduced to a problem of one dimensional transient heat conduction on a semi-infinite body. If the heat transfer data is obtained on the premise that flat plate conditions apply, then errors will be introduced if the surface is actually curved. The amount of such errors will depend on how far the heat penetrates into the substrate relative to the radius of curvature of the surface. The expression for heat flux (q) in to the body is as follows.

$$q = \frac{\sqrt{\rho c k}}{\sqrt{\pi}} \int_0^t \frac{dTs}{d\tau} \frac{1}{\sqrt{t-\tau}} d\tau - \frac{k\sigma}{2R}(Ts - Ti) \qquad (1)$$

Ts and Ti refer to the temperature of the surface and the initial temperature respectively. σ , the solution index, which has got a value of 0 for flat plate and 2 for spherical solution. The time dependent relative temperature in the above equation can be expressed in terms of voltage *E(t)* and is related to *T(t)* when the gauge backing material property, the temperature coefficient of resistance(α) and the initial resistance(R_0)of the thin film are known. The gauge backing material property value is taken as 1882 $J.m^{-2}.K^{-1}.s^{-1/2}$ and α is taken as $0.00215K^{-1}$, which is obtained from calibration of the sensor at different known temperatures. A numerical integration procedure is adopted to evaluate the heat transfer rate. The resulting equation for heat transfer rate is free from integration approximations and the accuracy of the procedure is limited only by the degree to which the true function $E(\tau)$ is approximated by a piecewise linear approximation. The complete procedure is implemented in a computer program to calculate the heat transfer rate.

Heat transfer studies conducted using the Hypersonic Shock Tunnel Facility covered stagnation temperature up to 5000K at near continuum levels of rarefaction. The shock tube for the shock tunnel is combustion driven. Rupturing the diaphragm is accomplished by the pressure developed due to combustion of a mixture of H_2 and O_2 diluted with He. Helically spaced spark plugs are connected to a high voltage ignition unit, which generate sparks for the

Instantaneous combustion of the gas mixture. The driven section of the shock tube is rectangular in cross section (40 x 80mm). The circular driver and the rectangular driven section are connected by means of a transition segment at the diaphragm station. The diaphragms used are 0.9mm thick aluminium sheet and are properly scribed.

The shock tunnel can be operated with the divergent nozzle (Straight through mode) or with a convergent divergent nozzle (Reflected mode). The test gas undergoes double shocking in the reflected mode thereby generate higher stagnation enthalpies. The nozzle used for straight through type is a conical nozzle for Mach number 5. By the use of replaceable throat for the C-D nozzle, it is possible to generate Mach numbers 10 and 12. Both the nozzles are made out of FRP except for the brass throats in the CD nozzle. The test section is a rectangular box made out of mild steel (M.S) and is of an enclosed free jet type. The dump chamber is attached to the downstream end of the test section. The circular windows on both sides of the test section are used as instrumentation ports. Mechanical type vacuum pumps are used to evacuate the driver and driven sides of the shock tube whereas a diffstak and another oil diffusion pump backed by mechanical type pumps are used for evacuating the dump chamber.

RESULTS AND CONCLUSIONS

Experiments were performed using flat headed and cylindrical models for Mach 6 rarefied flows in the stagnation temperature range 600K to 1000K. The Knudsen numbers based on model radius were in the range 0.04 to 2.5. In all experiments the wall temperature was approximately 310K. The heat flux values at the stagnation point as well as on the edge of the face of the flat headed cylinder are calculated at different stagnation conditions. The results are presented in Fig.1. Two major observations from these results are the dependence of heat transfer process on Knudsen number and stagnation temperature. The sensor located on the edge of the face shows higher heating rates compared to stagnation point and such behaviour has been reported in earlier studies [4]. But the difference in heating rates at these locations is influenced by the stagnation conditions as uniform heating rates are observed as the flow becomes more rarefied. The measured stagnation point heat transfer rates are then used along with the stagnation and tunnel conditions to get the Stanton number distribution for the entire range of Knudsen numbers. The flat faced cylindrical model was also tested using the hypersonic shock tunnel at Mach 5.5 for stagnation temperature up to 5000K. The Knudsen numbers for these simulations were in the range 0.001 to 0.01. Heat flux was calculated using the same procedure. The Stanton number distributions for the entire range of Knudsen numbers are given in Fig.2. The results are in good agreement with the results of [2].

Heat flux has been calculated on the hemispherical model using the usual procedure applied for flat surfaces and also using the modified method considering the curvature effect. The results for two different stagnation temperatures are presented in Fig.3. The result show considerable difference in heat flux at lower levels of rarefaction. The stagnation point recorded lower values of heat flux compared to the flat headed model. The results indicate the fact that radial conduction effects can have a significant influence in transient heat flux experiments if the model surface is curved. The plot of heat flux against Cheng's rarefaction parameter (Kr^2) for both models for different stagnation temperature is given in Fig. 4. It can be seen that the measured values are well correlated with the rarefaction parameter described for the post shock properties at the nozzle exit Mach number and the selected value of the adiabatic wall temperature. These measurements were conducted at similar operating conditions.

At lower density regions represented by lower values of rarefaction parameter, both the models record almost equal values of heat flux. But considerable difference is observed as the density levels are increased. At higher values of rarefaction parameter, the heat flux on hemispherical model is higher. It is known that Cheng's theory is strictly valid for $Kr^2 \geq O(1)$ this parameter can provide meaningful correlation of the flow filed conditions at various stagnation temperature. Exploiting this fact, the variation of Stanton number with rarefaction parameter at different Tw/T0 values is plotted in Fig.5. It can be seen that Stanton number value steadily decreases with increase in Cheng's rarefaction parameter but reaches a limiting value at the same rarefaction parameter for higher stagnation temperatures. For lower values of To, such a trend is not observed from the present study.

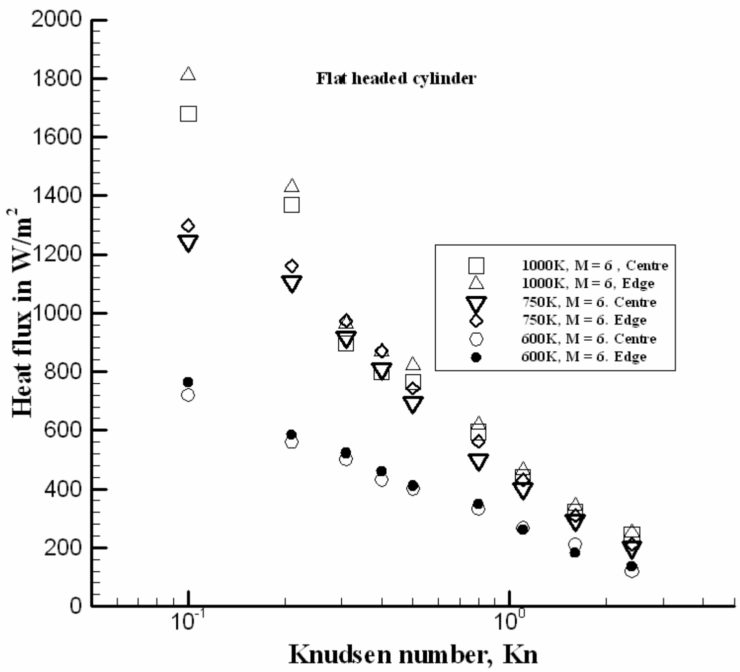

FIGURE 1. Variation of heat flux for a flat headed cylinder at transitional Knudsen numbers.

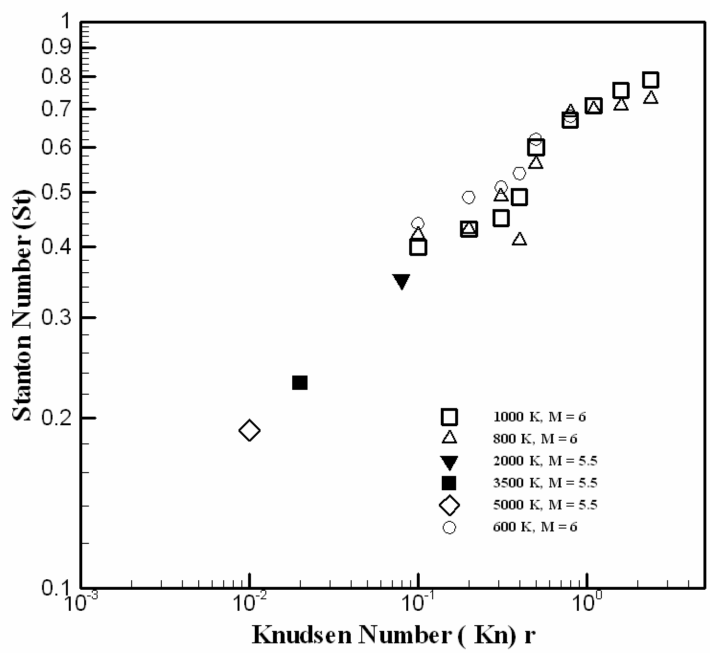

FIGURE 2. Variation of Stanton number as function of Kn and To (Flat headed cylinder)

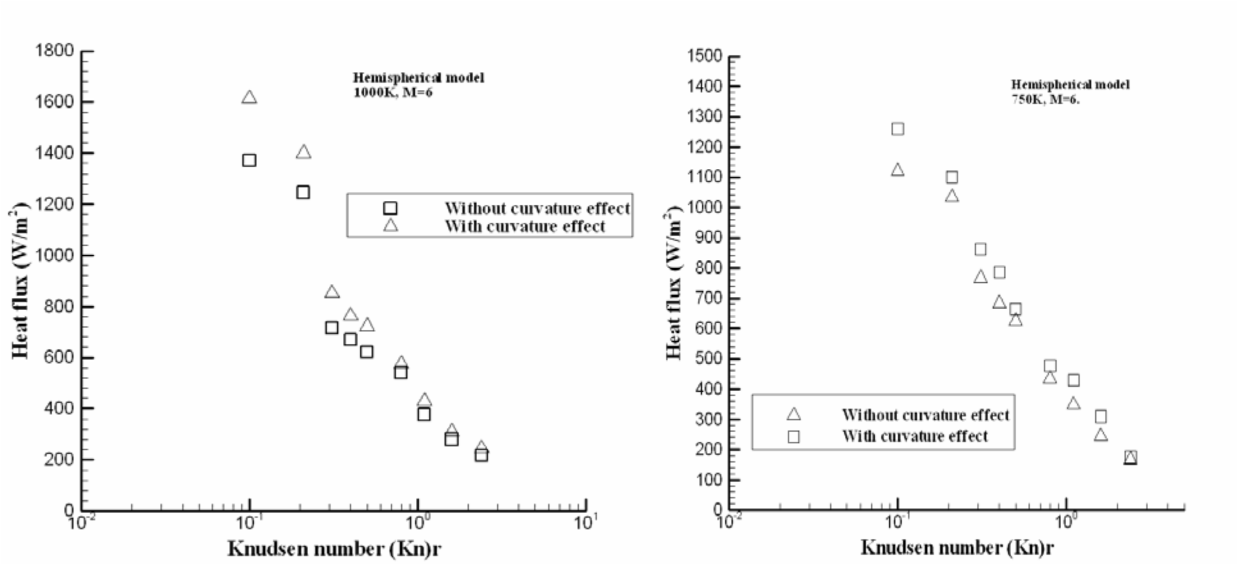

FIGURE 3. Variation of heat flux for a hemispherical headed cylinder at transitional Knudsen numbers.

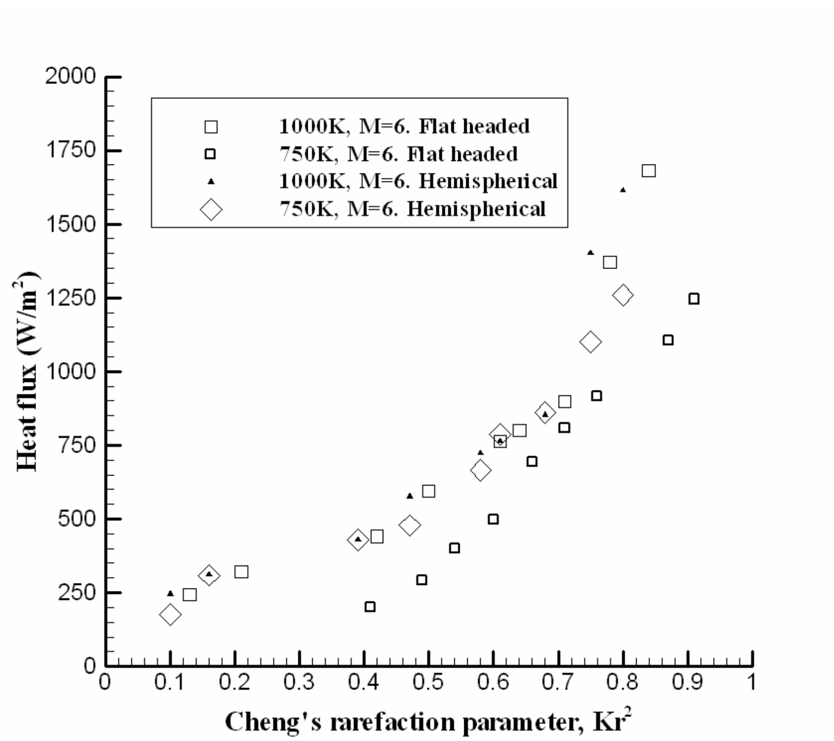

FIGURE 4. Stagnation point Stanton number on flat headed cylinder and hemisphere as function of Cheng's rarefaction parameter.

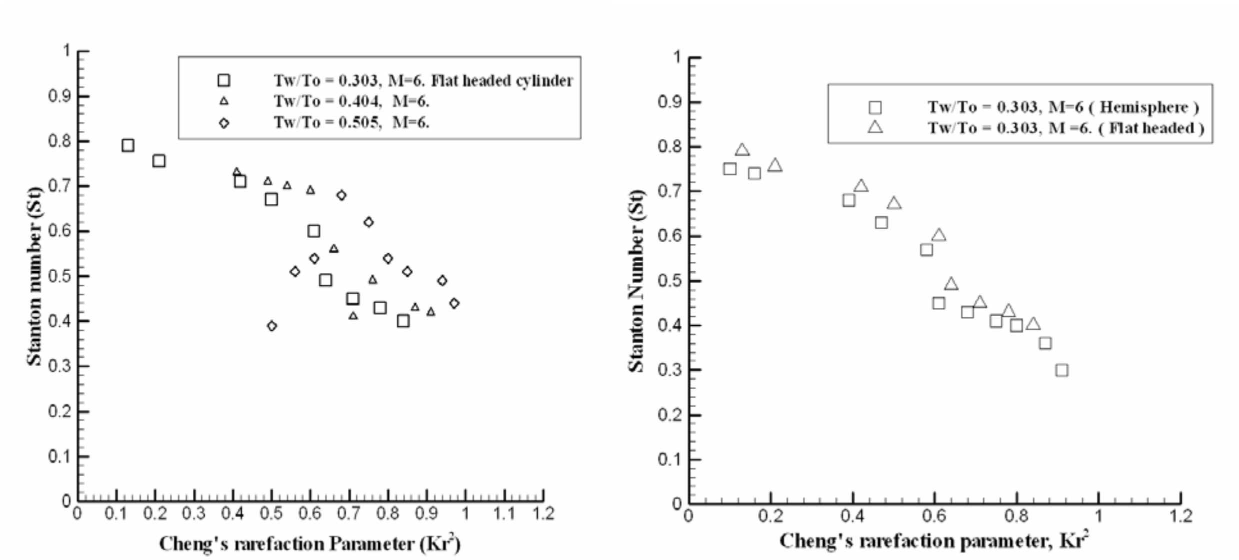

FIGURE 5. Stagnation point Stanton number on flat headed cylinder and hemisphere as function of Cheng's rarefaction parameter.

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