Low Density Heat Transfer to Blunt Cylinders

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Abstract. Experimental studies of heat transfer to blunt bodies were performed in the transition regime. The studies were at Mach numbers of 6.38 and 7.6 at stagnation temperatures of 500, 600 and 700 K. The heat flux was measured using slug gauges inserted in Macor models. The data is presented in terms of non dimensional parameters such as Stanton number, Knudsen number and Cheng's rarefaction parameter.

INTRODUCTION

When an aerospace vehicle flies through the atmosphere at very high speeds, it is subjected to aerodynamic heating. The extent of heating depends, among other factors, on the density of air through which the vehicle is travelling. Aerospace missions involve design and deployment of vehicles that encounter all density flow regimes during their flight path. The physics of flight in the free-molecular and in the continuum regimes has been reasonably well understood, whereas that in the transitional regime is still subjected to considerable study and research. In continuum flow, the mean free path length is extremely small in comparison to the boundary layer thickness and analysis at the macroscopic level with the energy and Navier-Stokes equations yield valid solutions. With increasing gas rarefaction, the intermolecular collisions become lesser and the macroscopic analysis is not feasible. In the free molecule regime, the frequency of intermolecular collisions becomes much less and analysis is possible in a microscopic level with the use of kinetic theory. Thus the basic formulation of the flow phenomena and heat transfer in the continuum and free molecule regimes is much more refined compared to the other regimes of rarefied flows. One of the aspects of flight in the transitional zone that remains to be understood is the heat transfer to the bodies flying at high speeds. The present work attempts to shed light on this aspect.

There is already a large amount of data available for stagnation point heat transfer to hemispherical bodies in the continuum and near continuum flow regimes. Potter [1] has shown that at high Reynolds numbers there is good agreement between experimental data and widely used theories such as that by Fay and Riddell [2]. At lower Reynolds numbers, continuum theories initially under-estimate and progressively over-estimate the heat transfer when compared to experimentally determined data. There is much less heat transfer data available [3] on bluff bodies with flat leading surfaces in the transition flow regime. Such a geometry is particularly of interest and currently available data show that large changes, relative to the hemisphere, occur in the heat transfer distribution across the face of the body. In continuum flow, the stagnation point heat transfer rate to the flat face is only half of that to a hemisphere but it rises to higher values towards the edge. In free-molecule flow conditions, the heat transfer rate at the stagnation point on these two shapes is equal. Furthermore, the heat transfer distribution across the flat face is constant in free molecular flow whereas for the hemisphere it is very similar to that found in continuum flow. Metcalf et al. [4] generated experimental data for the heat transfer to hemispheres and bluff cylinders in the transition regime. They presented the measured stagnation point heat transfer rates in terms of Stanton numbers. From the plot of Stanton number versus Knudsen number they show the influence of stagnation temperature. This effect is very noticeable in the Monte-Carlo computation made by Bird [5] for a hemisphere at a speed ratio of 10. They made a comparison between the variation of Stanton number with Cheng's rarefaction parameter K_r^2 [6] for flat faced and hemispherical cylinders. It is shown that the variation in the data for a bluff cylinder between the continuum and free molecule limits is quite similar to that found on a hemisphere. It appears that the rapid rise in Stanton number with decreasing Cheng's parameter and that the ratio of heat transfer rates at stagnation point on the bluff face and hemisphere is maintained at a value of 0.5 down to Cheng's parameter of the order of 4. Both shapes appeared to produce a free molecule Stanton number at Cheng's parameter~0.1.

The heat transfer rates can be predicted with sufficient accuracy both in the continuum and free molecular regimes. The difficulty lies in calculations in the transition regime. The heat transfer in the transition regime is usually calculated using approximate bridging relations in terms of the heat transfer rates in continuum and free

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14. ABSTRACT
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molecular regimes and a weighing function based upon the Nusselt number. These approximate bridging relations can be obtained from the literature [7]. Recent studies using DSMC simulations have shown that the weighing function that should be used is also a function of the geometry involved [8]. However, not much experimental data is available to undertake such studies. The availability of an accurate bridging relation that can be used with confidence will be of much value, since it simplifies the calculations for the designer. From the data generated in this study, attempt can be made to obtain suitable bridging relations. Hence the objective of the present work is to make measurements of heat transfer to (i) flat headed cylinder (ii) hemi-spherical headed cylinders under low density conditions. The low density conditions covering Knudsen number range corresponding to that from continuum to free molecular are included in the experiments.

DETAILS OF EXPERIMENTS

The experiments for the measurements of low density heat transfer were held on the Low Density Wind Tunnel, Shock Wave Laboratory (SWL), Aachen. The tunnel consists of two crossed cylinders made of stainless steel with diameters of 1.8m and 2.4 m and lengths 6m and 4m respectively as the vacuum tank. The vacuum tank has a total volume of 28m^3. An x-y-z traverse is located inside the tank. In free jet experiments the stagnation chamber and nozzle assembly is mounted on the traverse unit. Minimum pressure achieved during experimental runs was 0.0004 mbar. The stagnation chamber which has an effective volume of 0.32 m^3 is mounted on the traverse located inside the vacuum tank. A heating unit is fitted in the rear part of the stagnation chamber by which temperatures up to 700^0C are possible to be achieved. Empty space between the two heaters as well as that between the stagnation chamber and the heaters is filled with ceramic balls of 5mm diameter to enhance the heat transfer to the test gas. Two thermocouples of K type (chromel – alumel) were connected spaced annularly close to the stagnation chamber into the heater region. The ceramic meshes at the ends of the heater chamber prevents the loss of pebbles due to the flow.

Two models of 10mm diameter were used in these experiments. The models were made of Macor. The flat headed cylindrical model had two slugs of copper located on the front surface of the model One of them was at the center and the other close to the outside edge of the front surface. The hemispherical model has cylindrical afterbody of the same dimension as the flat headed cylinder and has one slug on the forward stagnation point. . The calibrated thermocouples fused to the slugs are of K-type.

The investigated free jet was produced by letting the gas expand from the high pressure stagnation chamber to the low pressure vacuum tank through a sharp edge orifice of 10mm diameter. The Mach number distribution along the centerline of the free jet can be calculated empirically from the equation given below [9]:

$$M = 3.26(X/D - 0.40)^{\gamma-1} - \frac{0.5(\gamma+1)(\gamma-1)}{3.26(X/D-0.13)^{\gamma-1}} + 0.2(X/D-0.40)^{-3(\gamma-1)}$$

for $X/D \geq 1.0$

Here, M is the Mach number and X/D the axial distance normalized by the orifice diameter.

The heat flux on the model was measured using slug gauges. A slug of a metal is buried in the surface across which the heat transfer rate is to be measured. Neglecting losses through the insulation and through the wires used for temperature sensing,

Heat transferred in = energy stored

$$A\dot{q}dt = McdT$$

where A = surface area of slug, m^2, $\dot{q}$ = local heat transfer rate, W/m^2, M = mass of slug, kg, c = sp. heat of slug J / kg.K, T = slug temperature, K

Then,

$$\dot{q} = \frac{Mc}{A}\frac{dT}{dt}$$

Thus $\dot{q}$ may be determined by measuring dT/dt if Mc/A is known. Since the thermocouple reads T rather than dT/dt, a graphical or numerical differentiation is done to get $\dot{q}$. The equation for $\dot{q}$ written above can be employed ignoring the heat losses to the casing. The equation predicts that for a constant $\dot{q}$, T increases linearly with time and without limit. Actually the unavoidable heat losses eventually make dT/dt approach zero.

The measurement of heat flux using the slug gauges involves recording the time rate of rise of the slug temperature when subjected to the impingement of the low density hot jet under the various operating conditions. To enable the operating conditions to be set before the jet is let on to the model fitted with the slugs, a magnetically operated shield was hung between the exit of the orifice and the model. The complete rising of the shield requires about 20 seconds. The temperature rise of the slug on the model was recorded with zero time corresponding with the switching on of the movement of the shield. The rise in temperature of the slug was recorded up to about 150 seconds at intervals of about 1.0 sec. The experimental values of temperature showed an almost steady increase with time.

The recorded values of temperature against time obtained from the experiments were deduced to obtain the rate of rise of the slug temperature. The slopes of the temperature – time plots were determined graphically. The graphs were plotted neglecting the first 20 seconds of the experimental values because the jet flow field over the model was fully established only after the complete lifting of the shield. For the experiments reported in this paper the slugs used were of copper. The size of the slugs were 2.0 mm and1.5mm long. The mass of the slugs varied between 0.0415 gm and 0.0505 gm.

RESULTS AND DISCUSSION

Experiments were performed for Mach numbers (M) of 6.38 and 7.6 for stagnation temperatures of 500K, 600K and 700K.The measured values of heat flux are plotted against Knudsen number for the case of the flat headed cylinder in Figure 1, corresponding to a stagnation temperature of 700 K. In Figure 2, plots are made for the three stagnation temperatures at a Mach number of 7.6. The values of heat flux measured by the slugs at the center and at the edge are given in the plots. As expected, the heat flux decreases with increasing value of Knudsen number. It is also seen that the heat flux measured at the edge of the flat headed cylinder is consistently more than that at the center. One plausible explanation for this behavior is the proximity of the bow shock formed to the body surface at the edges. The dependence of heat flux on the stagnation temperature irrespective of the degree of rarefaction is evident from Figure 2.

The plot of heat flux against Cheng's parameter (Kr^2) against heat flux for M=7.6 and stagnation temperature of 700 K is given in Figure 3. The measured values are well correlated with the Cheng's parameter which is defined as

$$Kr^2 = \varepsilon\left(T_*/T_0\right)^{0.25} \mathrm{Re}_2$$

where $\varepsilon = (\gamma - 1)/2\gamma$, $T_* = (T_2 + T_W)/2$ and Re_2 and T_2 represent post shock Reynolds number and temperature respectively and T_w the adiabatic wall temperature.

In Figure 4, the plot of Stanton number against Knudsen number is given. The plot corresponds to the experiments on flat headed cylinder and to the three stagnation temperatures employed in the experiments. The experimental points fall in between the calculations made using the closed form equations given by Fay and Riddell [2]for continuum flows and by Schaaf and Talbot[10] for free molecular flows. In Figure 5, the calculated values of Stanton number for all experiments on the flat headed cylinder are plotted against the Cheng's parameter. Because of limitations of the facility, experimental points are not available in the continuum range corresponding to $Kr^2 > 3.0$. In the transition regime (beyond $Kr^2 = 0.4$, which is generally considered as the free molecular limit) the plots give a very linear behavior.

Figure 6 depicts the effect of Mach number on heat flux which is plotted as a function of Knudsen number. The plot corresponds to experiments done on hemispherical headed cylinder at Mach numbers of 7.6 and 6.38. As seen in the figure, for the constant stagnation temperature of 600 K, higher heat flux is measured in the case of M=6.38. This possibly is due to the lower stream temperature of the higher Mach number stream which causes lesser heat transfer to the model. The corresponding plot of Stanton number as a function of the Cheng's parameter is in Figure 7.

The values of heat flux under identical operating conditions on the flat headed and hemispherical headed cylinders are plotted in Figure 8. As is evident from the Figure there is not much quantitative difference between the heat flux values at the edge of the flat headed cylinder and that on the forward stagnation point of the hemispherical headed model. At higher density regions represented by the higher values of Kr^2, the heat flux on hemispherical model is marginally higher.

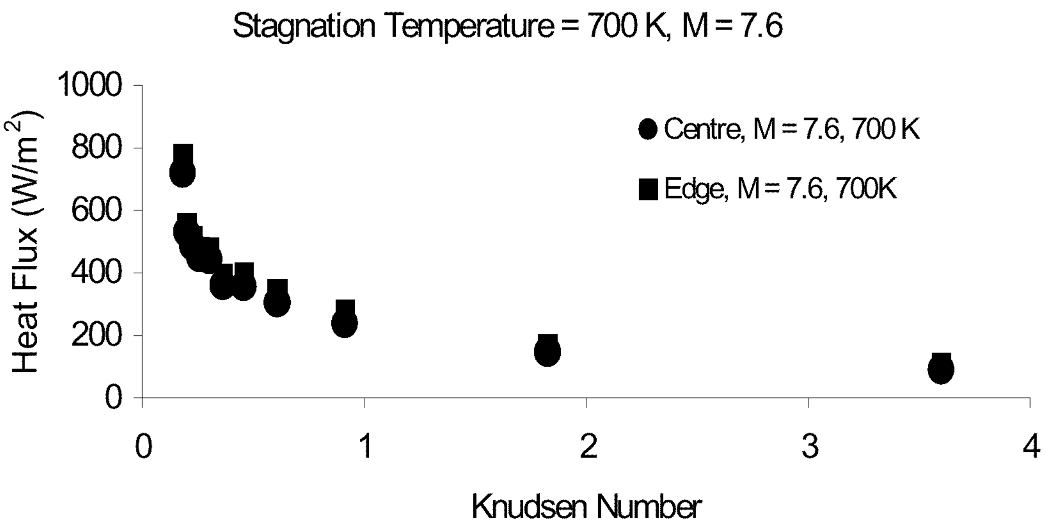

FIGURE 1. Variation of heat flux with Knudsen number for a flat headed cylinder.

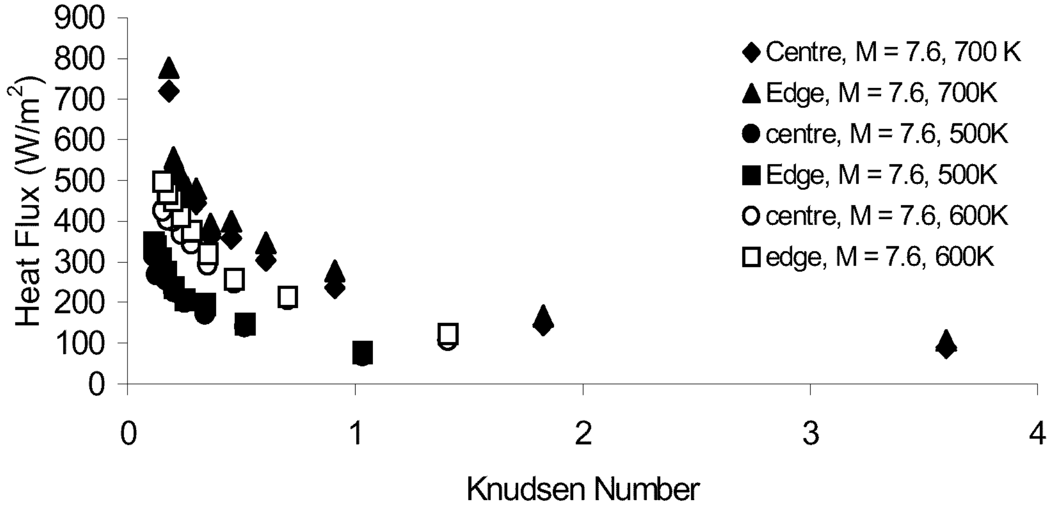

FIGURE 2. Effect of Stagnation temperature on heat flux for a flat headed cylinder.

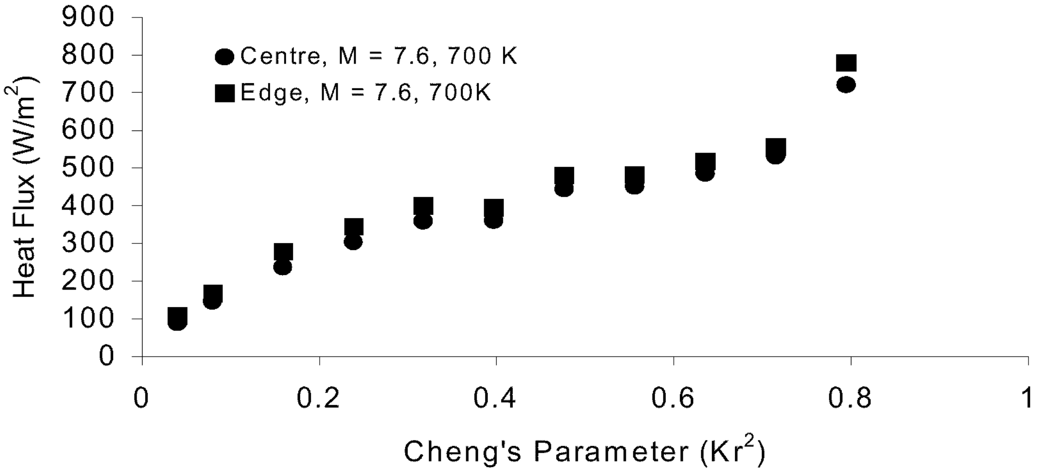

FIGURE 3. Heat flux on Flat headed cylinder Vs Cheng's Parameter.

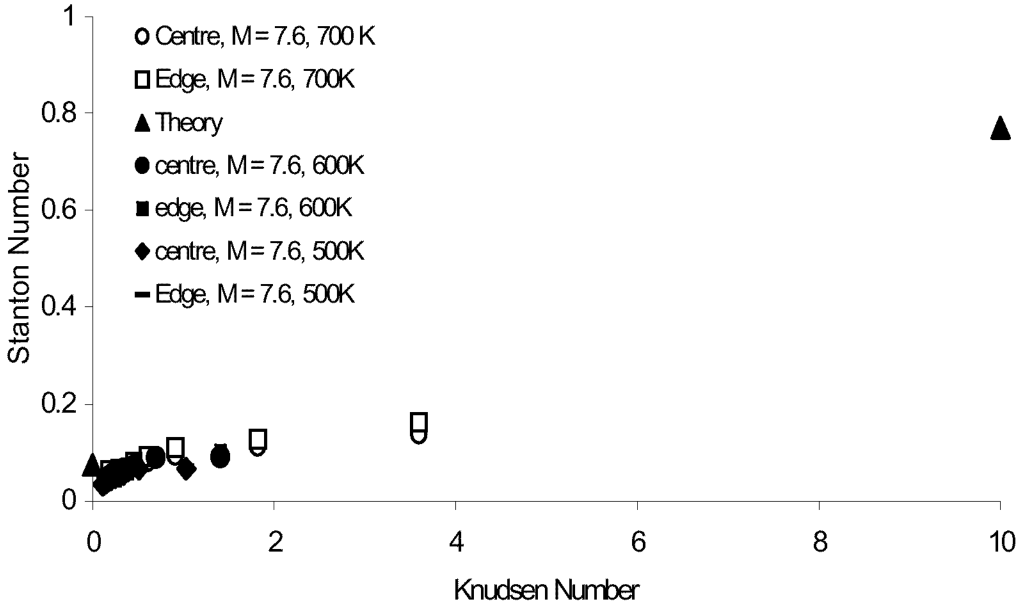

FIGURE 4. Stanton numbers from experiments and theory (flat headed model)

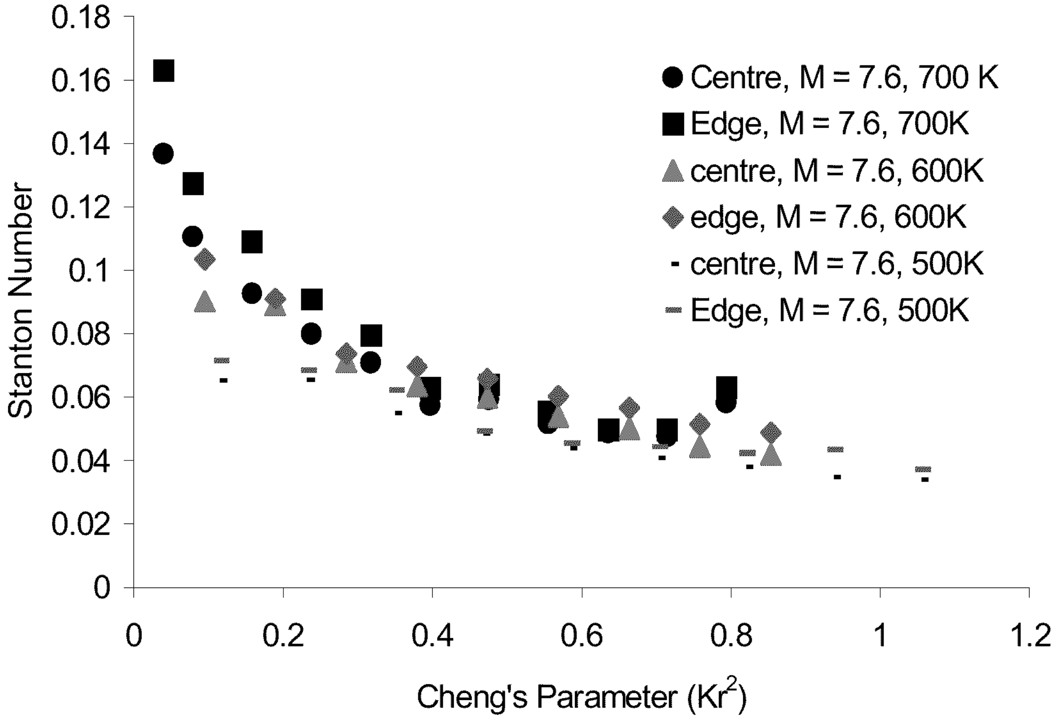

FIGURE 5. Stanton number on flat headed cylinder Vs. Cheng's parameter.

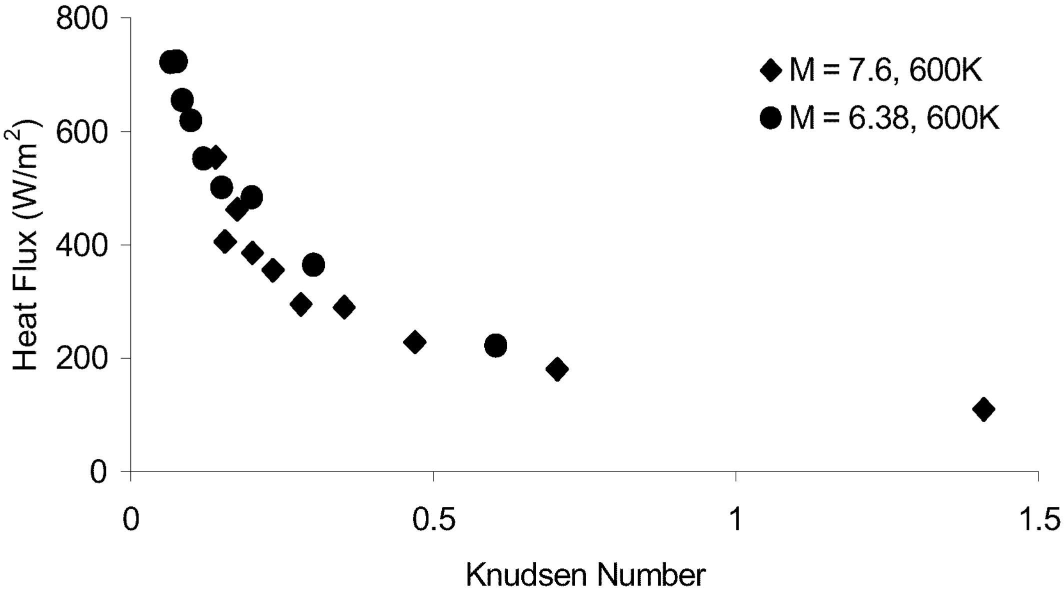

FIGURE 6. Effect of Mach number on heat flux on hemispherical model.

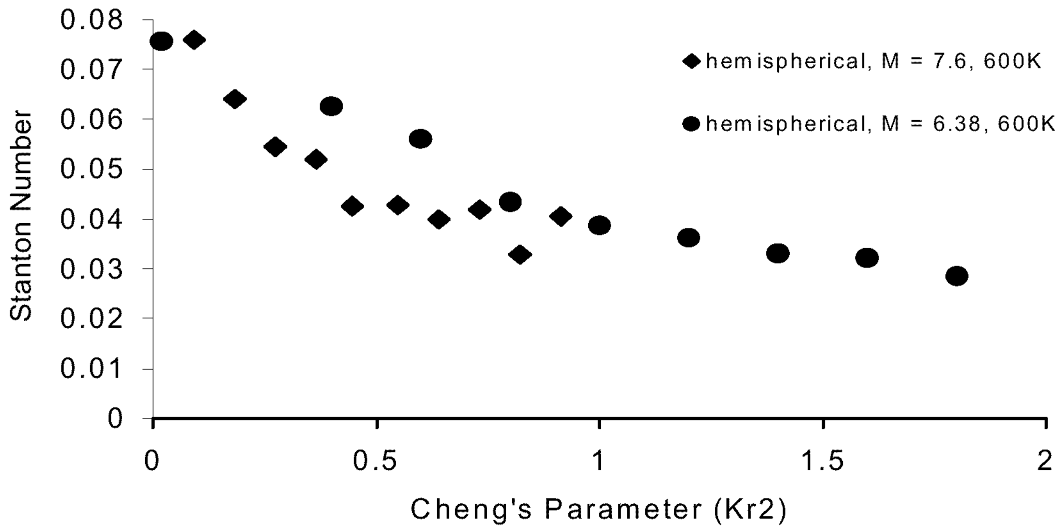

FIGURE 7. Stanton number as a function of Cheng's parameter for a hemispherical model.

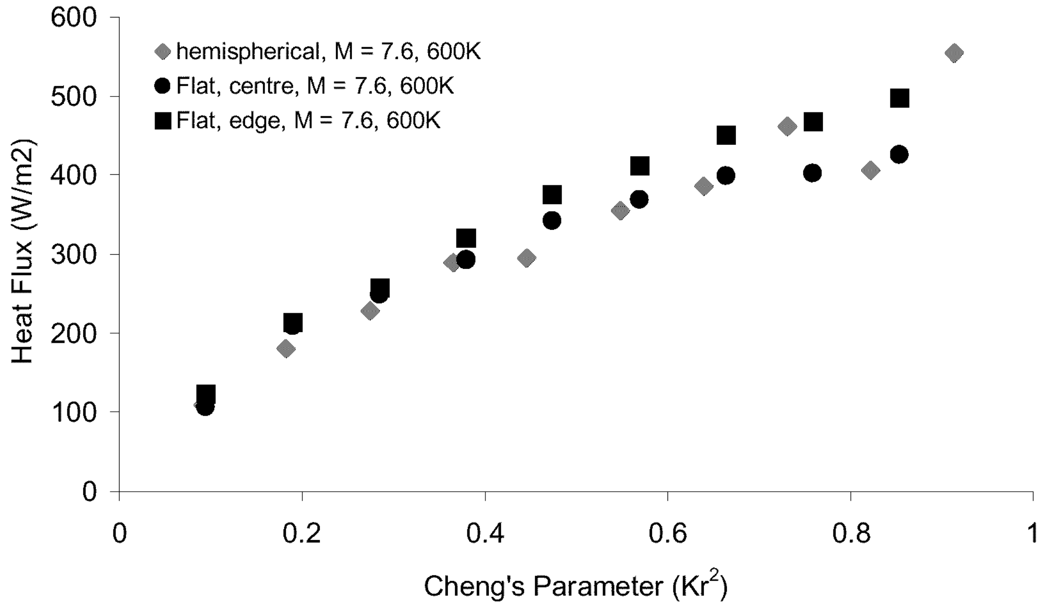

FIGURE 8. Comparison between heat flux to flat and hemispherical headed cylinders.

CONCLUSIONS

The low density heat transfer to blunt cylinders has been experimentally studied under predominantly transition flow conditions. The influence of model shape, stagnation temperature and Mach number on low density heat transfer has been investigated. The dependence of Stanton number on Knudsen number and on Cheng's parameter is seen to be following the same trends as the earlier [4] experimental results. The free molecular limit identified by the rapid rise in Stanton number is occurring at a value of $Kr^2 \sim 0.5$.The values of stagnation point Stanton number determined from the experimental values in the transition regime fall in between the calculated limits for continuum and free molecular regimes.

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