Low Density Jet Impingement - Measurement of Heat Transfer

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Abstract. This paper presents the results of the experimental studies carried out to measure the heat transfer due to impingement of low-density free jets on flat plate and curved surface. Experiments were conducted using a low density wind tunnel simulating flow fields covering transitional Knudsen numbers. Dry air at low pressure is heated to the required stagnation temperature and is allowed to expand through a convergent–divergent nozzle. The nozzle is a scaled up version of a typical ERNO 0.5 N thruster nozzle with exit Mach number is 6.0. The pressure ratios varied from 16000 to 200 and stagnation temperature varied from 450K to 1000K Reynolds number varied from 5 to 500 and Knudsen numbers were in the range 0.02 to 3.36. 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 location of the positions where the maximum heating is observed is also found to move downstream of the nozzle exit as the stagnation pressure is increased. For lower stagnation pressure (Po), the maximum heating occurs upstream of the intersection of the plume boundary and the plate surface. Plume model interaction is found to be more for flat plates and the heating rates are higher when compared to the cylindrical model. The effect of model surface curvature on the impingement flow field and associated shock heating is also evident from the results.

Keywords: Low density jets, impingement heat transfer, transitional Knudsen number, plume flow, shock heating.
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INTRODUCTION

The situation of heat and momentum transfer due to the impingement of a low density free jet on adjacent surfaces arises in a wide variety of aerospace applications [1]. Several experimental studies have been conducted to measure and analyze the shear and normal forces due to impingement [2-6]. The analysis of the thermal flux to the surface which is a major effect of plume impingement becomes non trivial in certain regimes of plume rarefaction particularly in transitional Knudsen numbers. Only a few experimental and semi empirical results are available in the literature on this problem [7-9].

EXPERIMENTAL PROCEDURE.

The experiments were conducted using the Rarefied Gas Dynamics Facility of the Indian Institute of Technology Madras. It is a continuously run low density wind tunnel capable of maintaining vacuum down to 10^{-5} Torr. 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 details of the facility have been described elsewhere[4,5]. 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. A flat plate model was fabricated out of aluminium with a water cooling jacket on its rear part. The model with overall dimensions 185mm X 185mm X 25.4mm was mounted on a X-Y-Z traverse powered by stepper motors. Aluminium cylindrical model of diameter and length was used for measurement of heat transfer on curved surfaces. Suitable slot was made on the cylindrical model to keep the Macor strip containing platinum thin film gauges flush mounted. Chilled water is made to circulate through the jacket before each run to keep the model at lower temperature. Dry air at low pressure is heated to the required stagnation temperature and is allowed to expand through a convergent–divergent nozzle. The nozzle is a scaled up version of a typical ERNO 0.5 N thruster 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. For the present experiments the flat plate model was kept at positions so as to have parallel, oblique and perpendicular impingement. A schematic of the experimental setup is given in Fig.1

Platinum thin film gauges, with Macor® as the backing substrate, is used for monitoring the surface temperature of the plate during impingement by the hot jet. Thin film resistance gauges (a total of 21 numbers) were made on a Macor® strip of dimensions 140mm X 10mm using platinum organo-metallic ink. The Macor® strip, containing gauges, was flush mounted with the plate surface. The sensing length and width of each platinum sensor is around 3.0 mm and 0.2 mm respectively. This facilitated the measurement of temperature on the impingement flow field along a two dimensional strip centered over the projection of the plume axis of symmetry on the flat plate. The spacing between two sensors for the first 16 sensors was around 5.0 mm and for the remaining sensors it was 10.0 mm. The resistance of the sensors varied from 50 Ohms to 70 Ohms. Sensors were powered using a 10mA constant current supply .The small current keeps the self Ohmic heating of the sensor very small. Each sensor is connected to a data acquisition card (sampling speed 200 kHz) housed inside a PC. Resistance of a platinum thin film sensor is very sensitive to temperature changes and would increase with temperature during the impingement of the jet. This would result in a change in voltage with respect to time, which in turn gives the temporal variations in temperature at the sensor location on the model surface.

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 [10, 11]. The platinum film is on the Macor® substrate which is a good thermal insulator. Due to the extremely small thickness (~1μm) of the platinum thin film when compared to the thickness of the backing material, the lateral heat transfer would be negligibly small in comparison with the longitudinal heat flow. The heat transfer process is thus reduced to a problem of one dimensional transient heat conduction on a semi-infinite body. The expression for heat flux (q) in to the body [10] is as follows.

$$q = \frac{\beta}{\sqrt{\pi}}[\frac{T(t)}{\sqrt{t}} + \frac{1}{2}\int_0^t \frac{T(t)-T(\tau)}{(t-\tau)^{3/2}} d\tau] \tag{1}$$

The time dependent relative temperature *T(t)* in the above equation can be expressed in terms of voltage *E(t)* and is related to *T(t)* when the temperature coefficient of resistance(α) and the initial resistance(R_0)of the thin film are known. The heat transfer rate can be expressed as

$$q = \frac{\beta}{\sqrt{\pi}\alpha E_f}[\frac{E(t)}{\sqrt{t}} + \frac{1}{2}\int_0^t \frac{E(t)-E(\tau)}{(t-\tau)^{3/2}} d\tau] \tag{2}$$

β in the Equation 2 is the gauge backing material property[10] whose value is taken as 1882 $J.m^{-2}.K^{-1}.s^{-1/2}$ and α is taken as $0.00215K^{-1}$, obtained from calibration of the sensor at different known temperatures. $E_f = R_0 I$ is the initial voltage drop before the flow impinges on the surface. A numerical integration procedure is adopted [11] 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.

RESULTS AND CONCLUSIONS

An analytical method for the approximate prediction for the convective heat transfer to a flat surface impinged upon by an under expanded jet under continuum flow conditions have been proposed earlier. It was concluded that introduction of non dimensional variables can greatly reduce the number of parameters in a meaningful correlation of the experimentally measured heat transfer rate (q_{exp}) with theoretical prediction (q_{ref}). Here, q_{ref} can be expressed in the following form.

$$q_{ref} = \rho_0 U_L \mathrm{Re}^{*-0.5} (\frac{r^*}{zN})^{1.5} c_p (T_0 - T_w) C^{-0.5} \qquad (3)$$

where ρ_0 is the stagnation density, U_L is the limiting velocity based on a particular stagnation conditions, Re^* is the Reynolds number based on throat diameter, $r^*$is the throat radius, c_p is the specific heat at constant pressure, T_0, the stagnation temperature, T_w is the model temperature and C is the Chapman-Rubesin constant. It was also shown that

$$\frac{q_{exp}}{q_{ref}} = f(x/zN, y/zN, \theta, \gamma, \nu) \qquad (4)$$

where x and y are the local surface coordinates, θ is the surface angle with respect to the nozzle centerline axis, γ is the specific heat ratio and ν the nozzle half angle. Z_N is the normal distance between the nozzle centreline axis and the model surface plane (x-y plane). Experiments were performed by allowing low density jets to impinge on the test model surface. The pressure ratios varied from 16000 to 200 and stagnation temperature varied from 450K to 750K. The vertical distance from the nozzle centreline axis to the plate surface (zN) varied in the different sets of experiments from 10mm to 30mm. Reynolds number and Knudsen number were based on nozzle throat diameter. Reynolds number varied from 5 to 500 and Knudsen numbers were in the range 0.02 to 3.36. For parallel impingement, the effect of stagnation conditions and plate locations on the heat flux distribution was studied. Experiments were conducted for oblique and normal impingement cases also. In all cases, the measured heat flux values are non-dimensionlised with calculated reference value, q_{ref}, based on stagnation conditions.

Variation of heat flux with change in plate position i.e., zN/r*, for Knudsen numbers covering two distinct regimes of rarefaction is shown in Fig.2. For impinging flow fields covering transitional Knudsen numbers a power law variation is observed such that the measured heat flux varies with $(zN/r^*)^{-1.6}$. As the Knudsen number decreases to continuum regime, the measured heat flux is found to vary with $(zN/r^*)^{-1.43}$. The theoretical model from Equation 3 predicts variation in heat flux with $(zN/r^*)^{-1.5}$ for continuum flow field. From the kinetic theory of gases, the variation in the free molecular limit is proportional to $(zN/r^*)^{-2}$. The power law index value of -1.6 along with the existence of experimental conditions correspond to transitional flows confirms the fact intermediate rarefaction regime exist over the model surface. This necessitates the analysis of transitional free jets and its interaction with the model surface for providing physical explanation to the experimental observations.

The normalized heat flux profiles are found to vary with stagnation pressure. It is seen from Fig. 3 that for a constant stagnation temperature and plate position, the heating rate reaches a peak value before it decreases downstream along the impingement area. The location of the positions where the maximum heating is observed is also found to move downstream of the nozzle exit as the stagnation pressure is increased. Peak heating is observed at large impingement angle and the maximum heat transfer rate is also sensitive to the density levels of the impinging flow field.

The influence of stagnation temperature on the heat flux distribution was also studied. Keeping the stagnation pressure to a lower value (Po=10 Torr, pressure ratio Po/Pc =16000 and Knudsen number in the transitional range) and the plate position fixed, T_0 was varied from 750K to 450K resulting in a change in the mass flow rate and hence jets with different total enthalpy. Resulting profiles are given in Fig. 4. It shows the same trend for the distribution of heat flux but for the fact that the position of the peak heating location is quite insensitive to jet stagnation temperature in rarefied jets when the Kn number is in the range 3 to 0.66 at least for the sensor locations in the present experiments. Similar investigations with higher stagnation pressure (Po =160Torr, Po/Pc =2000, Kn = 0.04) in the same temperature range showed a shift in peak heating location with change in T_0 (see Fig. 4). DSMC simulations conducted with the same experimental parameters resulted in similar trends.

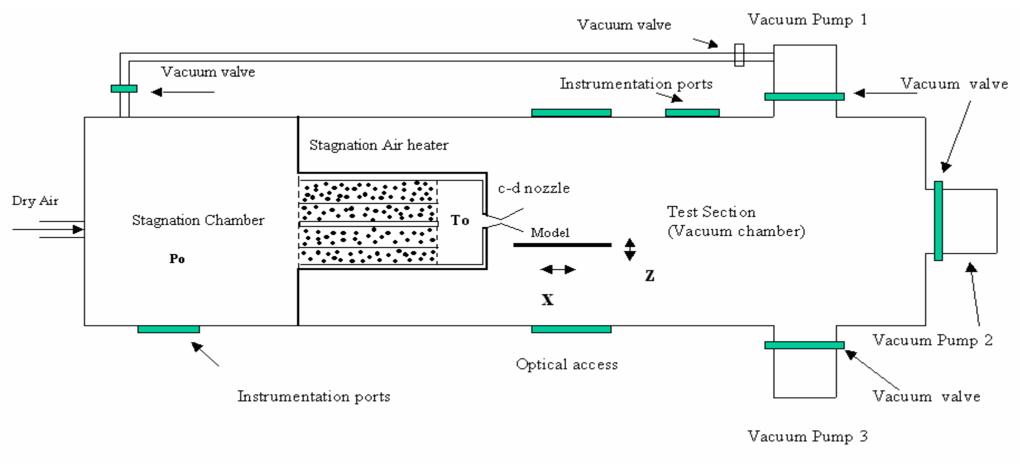

FIGURE 1. Schematic of the experimental setup with model- nozzle positions

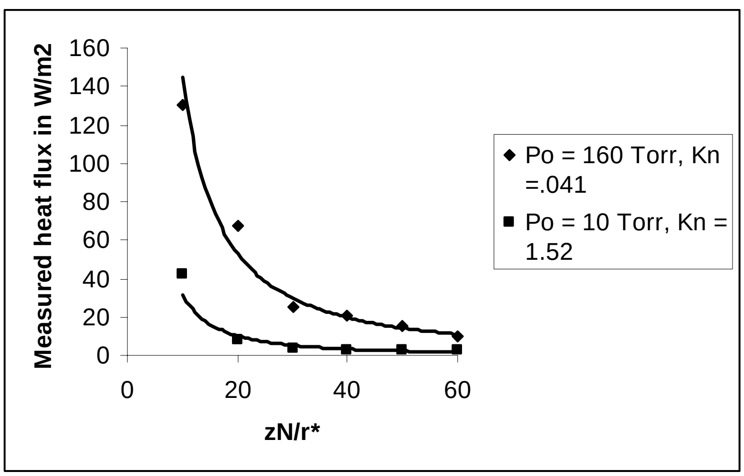

FIGURE 2. Typical variation of heat transfer with zN/r* (x/zN = 5, To = 600K)

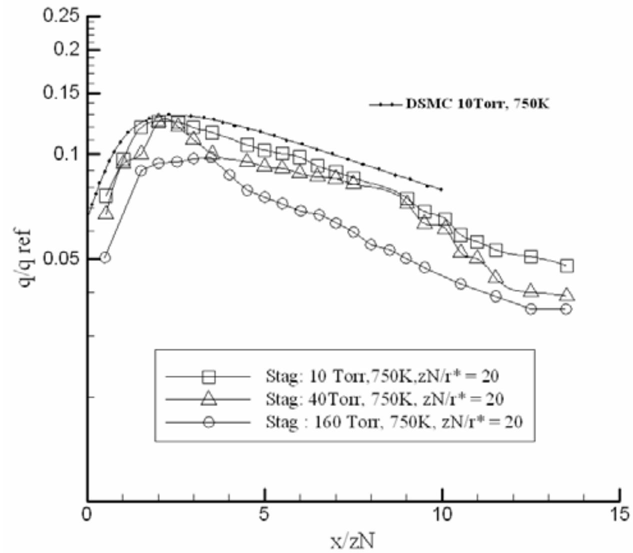

FIGURE 3. Effect of stagnation pressure on heat transfer (zN/r* =20)

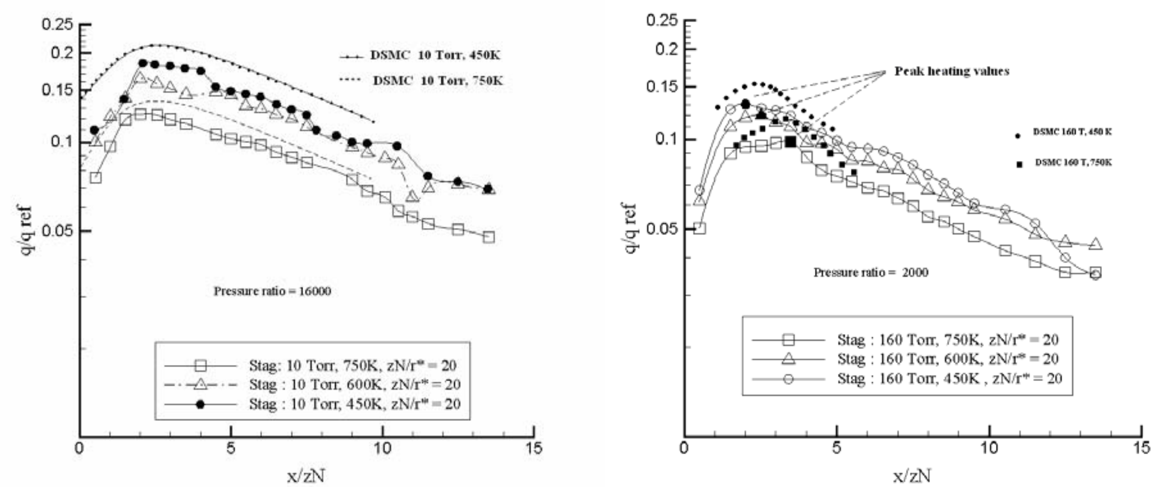

FIGURE 4. Effect of stagnation temperature on impingement heat transfer

The effect of pressure ratio (Po/Pc) on the measured maximum heat flux was also analyzed in transitional Knudsen numbers. Simulating an artificial leak of air into the vacuum chamber, the chamber pressure was varied keeping the stagnation pressure constant. The heat flux measured was found to be increasing steadily till it reaches a maximum at a particular pressure ratio (Fig.5). For the same Po and To, the trends are quite similar for sensor locations x/zN = 2, 3 and 5. Beyond a critical pressure ratio where the maximum heating is observed, the values are found to decrease and later become steady as pressure ratio goes up(flow field become more rarefied). At higher altitudes or higher plume total to ambient pressure ratios the peak heat transfer is insensitive to the ambient pressure. As the altitude or higher plume total to ambient pressure ratio is reduced the peak heating increases and has a maximum just before a pressure ratio is reached where the heating level breaks downward.

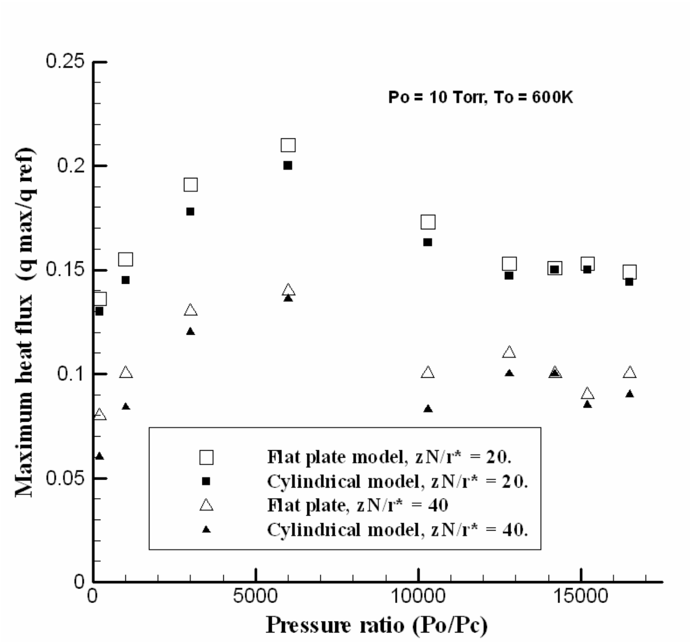

FIGURE 5. Effect of pressure ratio on normalised peak heating

The plume is greatly expanded at the higher altitudes and affects a large portion of the plate surface. As a result of this large expansion in the outer regions of the plume, the peak heating occurs considerably downstream of the intersection of the plume boundary and the body surface. As the ambient pressure increases with reduced altitude the mass flow that was included in the greatly expanded plume must be squeezed in to the smaller plume. The change in condition is felt predominantly in the outer regions of the new plume which included the peak heating location. The effect rapidly diminishes toward the inner portion of the plume. It may be concluded that higher the plume total to ambient pressure ratio, the maximum heat flux is quite insensitive to the ambient pressure. Such a variation is not clearly observed for jets with higher pressures where the flow field is more towards continuum.

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