Experimental Studies On Impingement Pressure

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Abstract. This paper is concerned with low density jet interaction with a flat and curved surface at transitional Knudsen numbers where, at present, very little experimental results are available. Pressure distribution on the models impinged upon by a highly under expanded low density free jet is measured using thermistors. Experimental results indicate the influence of curvature effects of the model surface, background pressure, plate location and its geometry on the impingement pressure. Measurements show good agreement with available experimental results and DSMC predictions. The pressure profiles indicate the suitability of modified Newtonian impact theory in the transitional Knudsen number regime.

Keywords: low density jets, impingement, normal force, thermistor, modified Newtonian theory
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INTRODUCTION

The flow of exhaust gases from highly under expanded nozzles to near-vacuum results in a low density free jet. The impingement of such a jet plume on the adjacent surfaces can lead to various effects depending on the proximity of the jet source, its orientation in space and the ambient pressure levels. Forces and heating effects are considered to be the major effects in a typical plume impingement situation. The normal and shear stresses due to impingement contribute to the structural loads. In contrast to the fairly large number of investigations involving impingement of supersonic jets in continuum regime, there have been only a few relevant studies in low density jet impingement. In the present work, detailed experimental studies have been conducted on the effects of plume impingement covering a range of Reynolds and Knudsen numbers. The data generated provides values of forces measured under a range of experimental conditions and will be complimentary to the ongoing computational studies using DSMC. Another aim of the experimental program is implementation of a procedure using thermistors to measure the impingement pressure on planar or curved surfaces. A review of methods for the study of spacecraft control thrusters impinging on surfaces with typical results has been given in [1]. The successful use of a balance in the measurement of normal and tangential forces induced upon impingement on a flat plate has been described in [2]. The basic phenomenon of the undisturbed plume flow, in the context of analytical plume model, [3], has been studied [4]. The experimental determination of the pressure and tangential forces was made possible by the use of two balances [4]. The proposed the use of Newtonian impact theory in [5] to predict surface pressures due to plume impingement was later found to be inadequate and that the plume surface interaction flow field is also to be taken care of in achieving better results [4].

Self-impingement on space vehicles occurs at surfaces nearly parallel to the plume axis. Only very small angle of attack experiments are sufficient for simulating such cases. By varying the angle of attack, from 0 to 90 degree, the impingement pressure and shear stress on flat plates was determined in flow regime varying from continuum to free molecular [6], [7]. The extensive experimental study of the flows due to under expanded jets impinging on plates has been conducted in continuum flows [8]. Normal force due to impingement of low density free jets has been measured on a flat plate using thermistors [9] and in continuation to the above measurements, quantitative assessment of the impingement effects of low density jets in transitional Knudsen numbers has been reported [10]. The simulation of the plume impingement problem using DSMC [11] provided good comparison with the experimental results of [4], [6] in the overlapping region of the experimental parameters.

The present experimental investigation is aimed at more exhaustive measurements of the impingement pressure on a flat plate and a cylinder kept at different inclinations to the jet axis for relatively lower pressure ratios and for transitional Knudsen numbers. Experimental results at transitional Knudsen numbers are scanty in literature. The applicability of the modified Newtonian theory as presented by Legge [4] for the range of experimental parameters could also be verified from the present studies.

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. It is possible to maintain different ratios of upstream stagnation (Po) to downstream (Pc) pressure in the facility. More details of the facility have been described elsewhere ([9], [10]). Dry air is allowed to expand through a convergent – divergent nozzle of throat radius(r*) 0.5mm, area ratio 59.9 and nozzle divergence angle 15.32 degrees. 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 with the use of MKS BARATRON and Edwards Wide Range Gauge. Flat plate model having dimensions 200mm X 200mm X 12.5mm and cylindrical model with 56mm outer diameter and 200mm length were used. NTC thermistors (Betatherm Ireland, Model 2K3MBD1) of resistance 2000Ohms (at temperature 298K) and temperature coefficient of – 4.39% were found suitable for sensing the low pressure on the plate surface. These fast response types, miniaturised (diameter of 1.0 mm) and closely matched thermistors are flush mounted on the top surface of the models (equally spaced at 5mm for flat plate model andat 10mm for cylinder) facing the flow. The models could me moved in steps of 0.1mm by means of the traverse mechanism.

Thermistor self-heat mode sensing application is made use in the impingement pressure (Pi) measurement. In an environment where the vacuum levels can vary continuously, the heat dissipation is substantially reduced due to lesser number of molecules in contact with the themistor bead, thereby changing the voltage current characteristics. A Wheatstone bridge circuit has been developed in house with a single balancing thermistor kept outside the low density tunnel. The deflection of the bridge, which is due to the differences in thermal characteristics between the thermistor kept outside the tunnel and of that mounted on the test plate inside the tunnel is indicative of the impingement pressure on the test surface. The thermistors are calibrated for various levels of vacuum. In each run, when one thermistor acts as a pressure sensor the adjacent one is sealed off from the impinging jet, which acts as a temperature-compensating element. This technique reduces the error due to the heating up of the model when exposed to the stagnating flow for longer test time. Both the thermistors were connected in a bridge network and the switching with the reference thermistor is done using high-speed relays and a microprocessor. The current in both the arms of the bridge were set to 1mA and the current flow is also monitored. The thermistor measurement system is capable of scanning 64 locations on the plate simultaneously and the bridge unbalance is digitized using a 12bit A/D card housed inside the computer. A LabVIEW® based application program was developed to monitor and record all the measurements. This facilitated the availability of a large number of experimental data sets for different tunnel conditions in a short time. Experiments were conducted with varying plate locations and orientations.

The plate/model inclination angle (β) was kept at 0 degrees, 45 degrees and 90 degrees for parallel, oblique and normal impingement cases respectively. Perpendicular distance from the center of the nozzle exit to the model is denoted by zN. Distance x is measured along the model surface and the point at which the perpendicular from the center of the nozzle exit meets the model surface is taken as the origin (x = 0). The radial streamline of the plume originating from the center of the nozzle exit and directed towards any point of measurement (P) on the model makes an angle α, which is defined as the local angle of attack. An uncertainty of ± 4.5%, arising mainly from thermistor gauge error and digitization error, is estimated to be present in the measured values of the impingement pressure.

RESULTS AND CONCLUSIONS

Impingement pressure measurements were conducted on the flat plate for different plate inclination angles. The stagnation pressure Po varied from 0.01 bar to 0.16 bar. Downstream chamber pressure was in the range 2×10^{-7} bar to 2.6×10^{-5} bar. Corresponding pressure ratios were in the range 5×10^{4} to 6×10^{3} . Reynolds numbers were in the range 30 to 800 and Knudsen numbers were in the range 0.922 to 0.024. Temperature in the stagnation chamber (To) was 305K.The measured pressure distributions on the flat plate for parallel impingement is given in Fig 1.The present results agree well with the results of Legge in ref [4]. A comparison with the DSMC results from Hyakutake [11] shows that fair agreement exists when $x/z_N < 1.5$. Maximum impingement pressure on the flat plate is found at regions near $x/z_N = 0.75$. During experimentation the low-density jet expands against a finite non-zero background pressure. For DSMC studies the background pressure was set as absolute vacuum. The discrepancy of the present measurements with the predicted values using DSMC may be attributed to this. For oblique impingement, the present results agree fairly well with Legge's result for $x/z_N = 2.0$.This is clear from Fig 1. For the present study it is seen that maximum impingement pressure is only slightly influenced by the background pressure. But the measured values are considerably larger than DSMC calculations in the far field. This demonstrates the influence of the background pressure on the impingement pressure. Pressure distributions on the flat plate with the jet impinging normal to the surface are given in Fig.2.

In continuum flows, the modified Newtonian law of the following form gives the impingement pressure coefficient Cp.

$$c_{p,\mathrm{mod}\,Newtonian} = \frac{\gamma+3}{\gamma+1}\sin^2\alpha \qquad (1)$$

where γ is the adiabatic exponent and α is the local angle of attack (in radian). A locally applicable formula, based on a curve fit of experimental data, has been suggested which takes the form

$$c_p = c_{p,\mathrm{mod}\,Newtonian}.(0.6 + \frac{0.63}{\alpha}) \qquad (2)$$

Fig. 3 shows the comparison of experimental data with modified Newtonian approximation [Eq. (2)] for experimental conditions corresponding to transitional Knudsen numbers. It has been reported in previous investigations that the locally applicable laws usually underestimate the experimental results. It is observed that fair agreement exist between the experimental pressure profiles (covering transitional Knudsen numbers) and the approximation function.

Impingement pressure measurements were conducted on the cylindrical model for different inclination angles. All experimental parameters remained the same as that of flat plate model.The measured pressure distribution on the cylindrical model for parallel, oblique and perpendicular impingement has been compared with that of flat plate model. A typical result is shown in Fig.4. The effect of plume impingement on the model surface may depend on the radius of curvature of the surface. The pressure profiles on the curved surface indicate this trend, the fact that a decrease in the wall curvature leads to a weaker interaction shock with increased expansion of the flow in the vicinity of the model surface. Similar to the flat plate model, the peak pressure occurs at the point of impingement in all configurations. The flow rapidly expands from near continuum to highly rarefied flow resulting in different types of interaction with the surface. But the impinging shock is established in front of the impinged surface as is evident from the normal pressure profiles (Fig. 5) and another discontinuity where the lip shock may intersect with the model surface. The resulting pressure profiles in comparison to the flat plate profiles reveal the fact that the quality of the disturbed flow due to impingement depend on the geometry of the model surface. The striking characteristics of these profiles are lower values of the impingement pressures and greater influence of background pressure for cylindrical models.

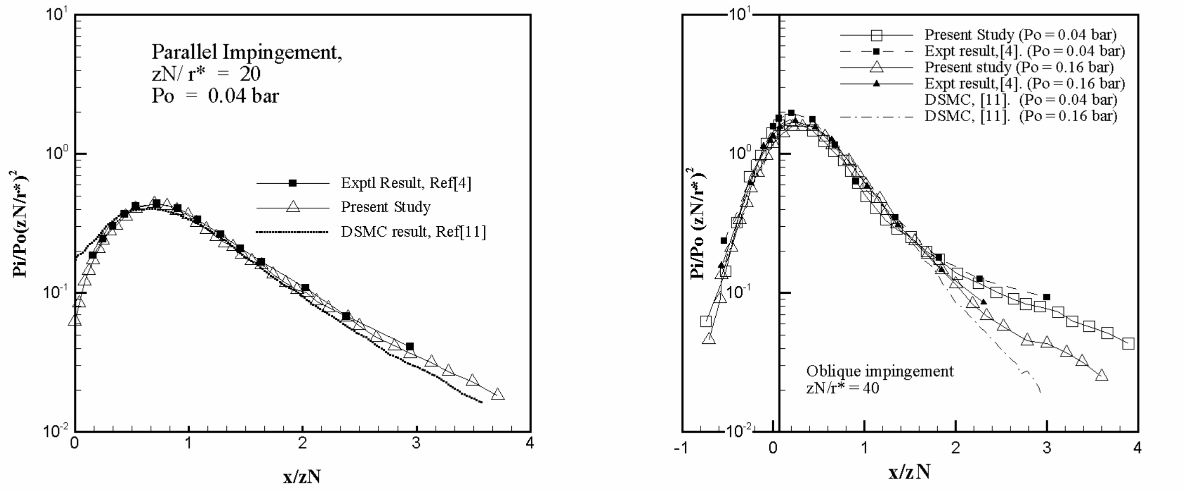

FIGURE 1. Pressure distributions on a flat plate (Parallel and Oblique impingement)

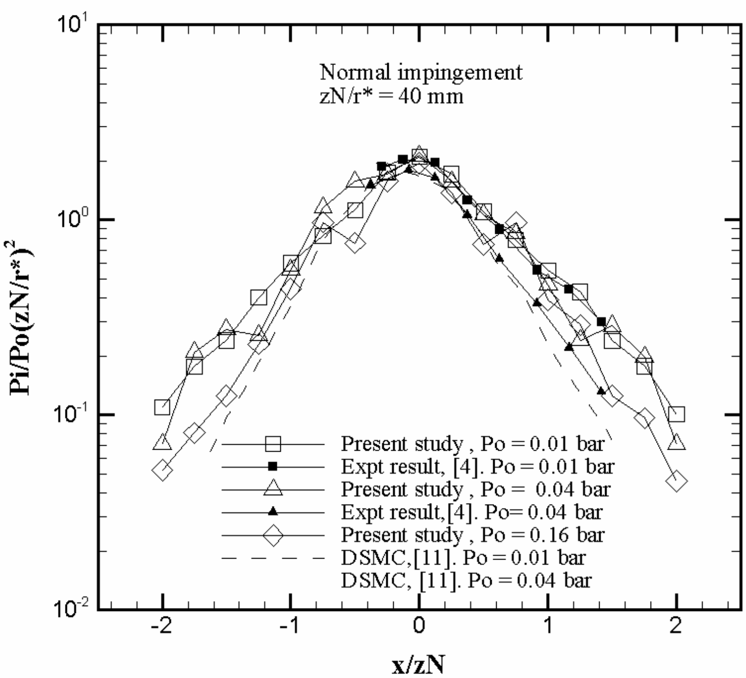

FIGURE 2. Pressure Distributions on a Flat Plate (Normal Impingement, β = 90 degrees)

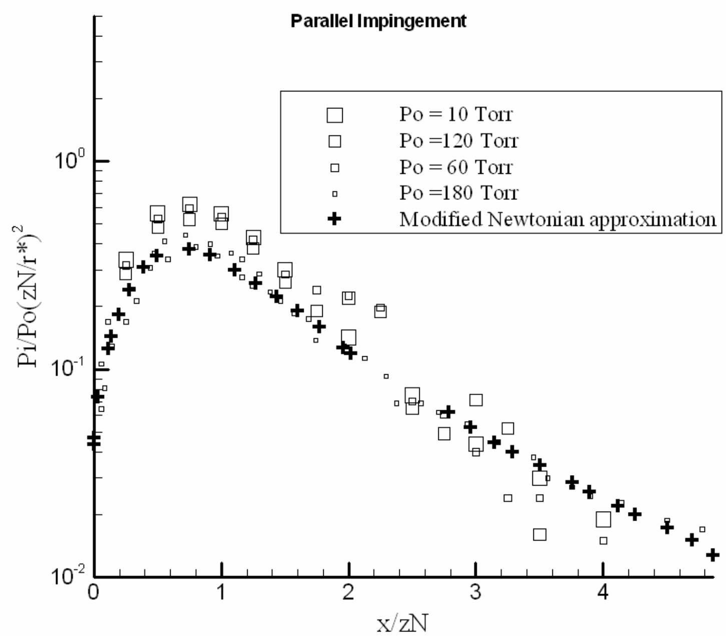

FIGURE 3. Comparison of experimental data with modified Newtonian approximation.

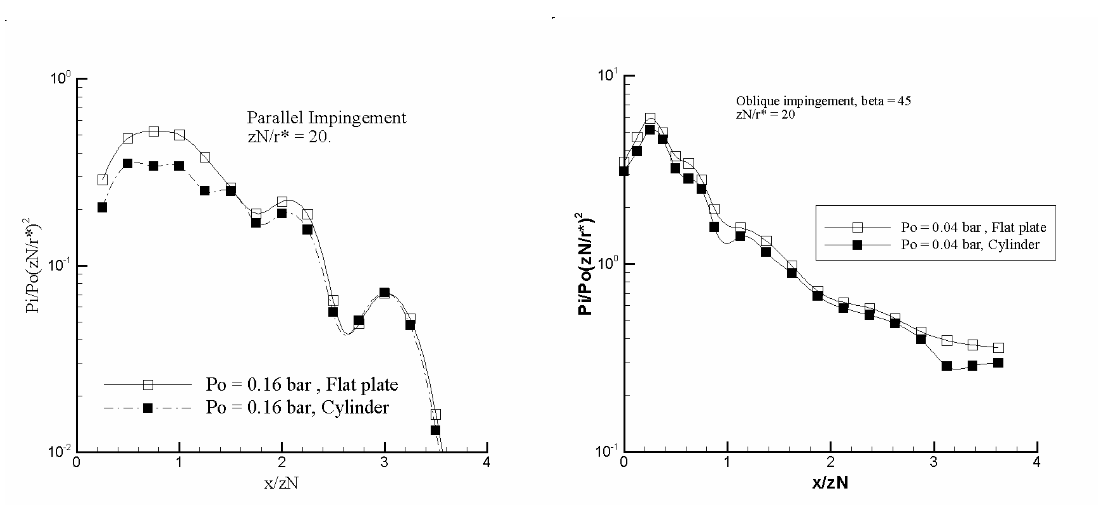

FIGURE 4. Parallel and oblique impingement pressure profiles for flat plate and cylinder

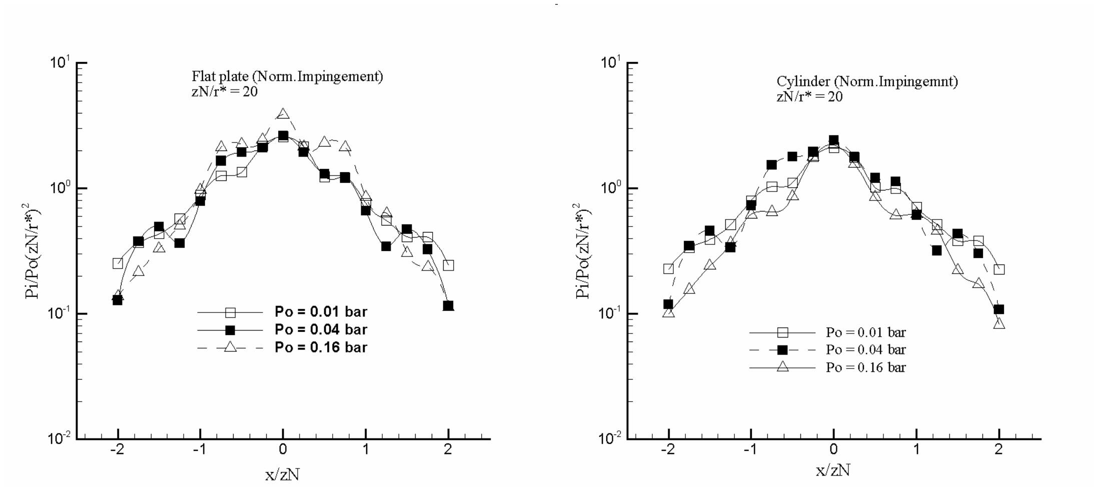

FIGURE 5. Normal impingement profiles for flat plate and cylinder

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