Experimental investigation on the supersonic jet impingement

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In order to understand the effects of supersonic jet impingement, static tests are conducted in a small-scale rocket motor loaded with a typical nitramine propellant to produce a nozzle exit Mach number of 3. This jet is made to impinge on a plate aligned vertically to the nozzle axis. The distance between the nozzle exit and the plate is varied from 2 to 6 times the nozzle exit diameter. The pressure rise due to jet impingement on the plate has been measured using pressure transducers located at ten different radial locations. The pressure-time data are analyzed to get an insight into the flow field upstream of the plate. The maximum pressure exerted on the plate is about 20-30% of the maximum pressure generated in the combustion chamber. Ten static tests are carried out to obtain the effects of nozzle divergence angle, axial distance between the nozzle exit and the plate and the chamber stagnation pressure on the flow field.

Vertically launched containerized missiles have become popular in the area of medium range air defence system. The flame deflector is one of the important components of the vertical hot launch system. It is most frequently a large curved duct or plate, which performs the disposal of the exhaust gas away from the launch installations. It is required to withstand the high velocity and high temperature of the exhaust for a large number of rocket launches.

Nakatogawa and co-workers carried out investigations on under-expanded jet impinging normally on a flat plate using heated air as a medium and obtained a relation between disintegration of a supersonic jet and jet noise. Donaldson and co-workers conducted experiments on subsonic and sonic air jets impinging on plates at various angles and obtained surface pressure profiles of mean and turbulent flow properties. Hunt made surface pressure and shadowgraph measurements of four different supersonic air jets (Mach numbers varying between 1.64 to 2.77), impinging normally on a large flat plate. Lamont and Hunt carried out experiments on the impingement of under expanded plates and wedges. Shadowgraph pictures and pressure measurements were used for the flow field analysis. Iwamoto reported experimental study of under-expanded dry air sonic jets impinging on a flat plate. The flow field was visualized using shadow photography and Mach-zehnder interferometry. Prasad and co-workers carried out experiments of supersonic dry air jet (Mach number=2.2) impinging on an axisymmetric deflector model to obtain the pressure distribution. Flow visualisation was carried out by schlieren pictures of the free and impinging jets. Bouslog and co-workers carried out simulated tests of under expanded exhaust plumes (accelerated unheated high pressure air) impinging on the face of a multi-tube launcher assembly to arrive at certain conclusions on the relationship between the configuration parameters and flow field parameters. Cold gas and double base solid propellant static rocket tests were conducted inside the launcher tubes by Batson and Bertin to obtain the wall pressure distribution. Venugopal and co-workers carried out experimental investigations on the supersonic jet interactions in open and closed plenum chambers simulating the conditions of the rocket moving inside a canister launcher. Based on extensive pressure measurements, it was concluded that the maximum pressure exerted on the plenum chamber back plate was about 25-35% of the maximum stagnation pressure developed in the rocket motor. Chandrashekar and co-workers carried out heat flux measurements in the supersonic rocket plume impingement regions of closed plenum chamber. Elango and co-workers carried out heat flux measurements in the supersonic rocket plume impingement regions of open plenum chamber simulating the conditions of a hot launch system. The maximum heat flux obtained was about 40 MW/m² due to the supersonic plume impingement on the plenum chamber wall.
It is clear from the literature survey that the supersonic jet impingement studies are receiving attention due to their importance in rocket technology. The present investigations are aimed at obtaining radial pressure distributions at various axial distances due to the impingement of high velocity (Mach number=3) and high temperature rocket exhaust gases generated by burning nitramine propellant. A valuable database has been developed. This can be used both by the numerical fluid flow modelers and structural designers of launchers.

**Experimental**

Several static rocket motor firings have been carried out to obtain the pressure distribution as a result of supersonic rocket exhaust jet impingement. The hardware set up for the experiments consists of: (i) scaled solid rocket motor mounted on a thrust stand, and (ii) a channel mount for vertical placement of impingement plate with a provision to vary the axial distance between nozzle exit and the plate. The solid rocket motor is a standard ballistic evaluation motor of inner diameter 90 mm; length 120 mm and thickness 20 mm made up of stainless steel to withstand a maximum chamber pressure of 150 bar. The rocket motor nozzle is designed to produce an exit Mach number of 3. The exit and throat diameters of the nozzle are 24.3 mm and 9.6 mm respectively to arrive at the exit to throat area ratio of 6.4. The propellant used in this study is a nitramine grain consisting of nitrocellulose 54%, nitroglycerine 39%, RDX 5% and carbamite 2%. The ignition was provided by burning a pyrotechnic mixture through an electrically initiated squib.

The minimum distance between the nozzle exit and the flame deflector plate in a typical hot launch system is about three nozzle exit diameters. In the present study, ten static tests were carried out using two different nozzle configurations having the divergence angles of 2° and 13°. The impingement plate was kept vertically in front of the rocket jet exhaust at different distances in terms of nozzle exit diameters such as 2 to 6. Fig. 1 shows the schematic of the impingement plate and the rocket motor. Pressure measuring locations are also indicated. The details of the pressure taps are shown in Fig. 2.

**Results and Discussion**

The pressure - time plots obtained during a typical static test (13° nozzle configuration and \(x/D=3\)) are shown in Fig. 3. These data are utilised for the understanding of the flow field. The data in channel 2 could not be obtained due to clogging of the tapping. As the present investigation is confined to the plume impingement phenomena, the chamber stagnation pressure - time data is not analysed from the viewpoint of the internal ballistics of the grain.

It is reported [14] that the impinging free jet has complicated flow elements consisting of barrel shock, exhaust gas jet boundary, Mach disk, contact surface, reflected shock, plate shock, sub-tail shock and stagnation bubble as depicted in Fig. 4.

**Effect of nozzle divergence angle**

The pressure distribution on the vertical plate along the radial direction is shown in Fig. 5 for two different divergence angles of the nozzle (2° and 13°) keeping the rocket motor chamber pressure (50 bar), axial distance (\(x/D=3\)) and nozzle exit mass flux (381 kg/m²s) constant.

As the jet spread in 2° nozzle is less compared to the 13° nozzle, higher pressures are felt on the plate.
Fig. 4 — Typical flow field of an impinging free supersonic jet

centre and nearby regions. The centre line pressures are 11 bar and 6 bar for 2° and 13° divergence angles respectively. However, the flow shock patterns on the plate are varying with the nozzle configuration. In the 13° nozzle configuration, the maximum pressure of 9.5 bar does not occur at the centre, but away from the centre at about \( r/D = 0.3 \). A similar observation has been reported by Kim and Chang\(^\text{14} \). This indicates that there is a likelihood of ring-shaped stagnation line at the boundary of the stagnation bubble on the plate. The flow field pattern is not very different for 2° nozzle configuration. In this case the maximum pressure is obtained on the centre line of the plate and a significant drop in pressure is noticed before a jump in the pressure, most likely due to a recompression shock wave around \( r/D = 0.5 \). Had the pressure taps
been closer to the plate centre, the flow field close to the jet axis would have been clearly indicated.

**Effect of axial distance**

In order to obtain the effect of axial distance on the flow field, the pressure data collected during the static tests are plotted along the radial distance of the impingement plate for 2° and 13° nozzle configurations. Fig. 6 shows the plate pressure distribution along the radial distance for two different axial locations such as \( x/D = 2 \) and 6.

The stagnation pressure in the rocket motor and the nozzle exit mass flux are kept constant at 50 bar and 408 kg/m²s respectively for 2° nozzle divergence angle. The pressure distributions are similar in both the cases; closer the distance from the plate to the nozzle exit, larger the pressure obtained, indicating stronger shocks. It is clearly seen that the maximum pressures are exerted away from the centre line indicating the interaction of plate shock, the reflected shock and stagnation bubble at the locus formed off-axis. Fig. 7 shows the radial plate pressure distribution at two different axial distances \( x/D = 5 \) and 6 for the 13° nozzle configuration at a chamber pressure of 45 bar and the nozzle exit mass flux of 348 kg/m²s.

The distributions are similar for both the axial distances. The maximum pressures are felt off-axis in this case too with larger pressures for shorter axial distances. This also indicates that the impingement plate lies in the second shock cell beneath the Mach disk. The flow fields become influenced by the mixing of the jet as the distance between the plate and the nozzle exit increases.\(^{15}\)

**Effect of combustor stagnation pressure**

The combustor stagnation pressure plays a vital role in the flow field of the impingement plate. From the pressure-time traces of the static test, plate pressure data are extracted for different stagnation pressures of the combustor and replotted. Fig. 8 shows the radial distribution of pressure on the plate for two different combustor stagnation pressures such as 50 bar and 30 bar keeping the plate at an axial distance of \( x/D = 3 \) and at a mass flux of 381 kg/m²s for 13° nozzle configuration.

The stagnation pressure of 50 bar corresponds to near adapted nozzle situation and 30 bar corresponds to the over expanded condition of the nozzle (ratio of nozzle exit pressure to ambient pressure is about 0.7). It is evident that the lesser chamber pressure gives rise to lesser plate pressure. However, the pressure variation shown in Fig. 8 for the higher chamber pressure (50 bar) is different from the lower chamber pressure (30 bar). The case corresponding to higher chamber pressure indicates a maximum plate pressure away from the centre line. This gives a possibility of reflected and plate shock interactions at a ring shaped stagnation line in the boundary of the stagnation bubble. The same pattern is not seen when the chamber pressure is reduced to 30 bar, which corresponds to the over expanded nozzle condition. Ideally, no change in the shock pattern is expected on the plate so long as the nozzle exit flow is supersonic, immaterial of the nozzle exit being under expanded or over expanded. However, in the present case, there may not be a stagnation bubble region ahead of the plate or may be that the bubble is unstable as the whole process is transient. The pressure distribution resembles the characteristics of a subsonic jet. It is indicative of the effect of mixing of the jet being predominant over the shock wave interactions. Fig. 9 shows the effect of stagnation pressure for the 2° nozzle configuration maintaining the axial distance,
and mass flux at 3 and 381 kg/m²s respectively. The radial pressure distributions are similar to the ones obtained in the previous case. In the 2° nozzle case, the magnitude of pressure are higher compared to the 13° nozzle case due to the lesser jet spread for the same momentum of the jet. It is evident from the radial pressure distributions that the nozzle exit conditions give rise to variations in the flow pattern on the impingement plate, in spite of the same supersonic jet Mach number.

**Maximum radial pressure distribution**

In order to consolidate the plate pressure data and to find the maximum possible pressure loads exerted on the plate, the maximum pressure values are

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**Fig. 9 — Radial pressure distribution**

**Fig. 10 — Maximum radial pressure distribution (2° nozzle configuration)**

**Fig. 11 — Maximum radial pressure distribution (13° nozzle configuration)**
extracted from the pressure - time traces and replotted in Figs 10 and 11 for the two different nozzle configurations. The consolidated data are shown in Tables 1 and 2. The maximum pressure as a percentage of the maximum combustor pressure is between 20-30% for a variation of axial distance \((x/D)\) between 2 to 6. The nozzle exit mass flux variation is between 350-415 kg/m\(^2\)s. This is a very useful input to the structural designer of the impingement plate. In all the radial pressure plots, the pressures are nearly uniform over 0.3 \(D\) radial distance from the centre. It is basically due to the presence of plate shock ahead of the plate with varying shock strength at different axial distances. The variations of pressure at radial locations greater than 0.3 \(D\) are due to the interactions of plate shock, reflected shock and the jet boundary.

**Conclusions**

Ten static tests have been conducted by keeping the distance between the nozzle exit and the plate varying from 2 to 6 nozzle exit diameters for two different nozzle divergence angles of 2° and 13° to investigate the flow field. The maximum pressures are exerted on the plate away from the axis for 13° nozzle configuration, whereas, the maximum pressures are exerted on the axis in 2° nozzle configuration indicating different shock flow interactions.

Closer the axial distance from the nozzle exit to the plate, larger has been the pressure exerted on the plate, indicating strong shocks in the flow field.

The radial pressure variations on the plate are different for different stagnation pressures produced in the rocket combustor. In the event of having the same nozzle exit Mach number, the chamber pressures alter the strength of the shocks in the flow field.

The maximum pressure exerted on the plate is about 20-30% of the maximum rocket combustor stagnation pressure. Appreciable variations of pressure are noted over a radial distance of about 0.75 times the nozzle exit diameter.

**Nomenclature**

- \(D\) = nozzle exit diameter
- \(L\) = length of the grain
- \(M\) = mass of the grain
- \(P\) = pressure
- \(P_a\) = ambient pressure
- \(P_c\) = combustion chamber pressure
- \(P_{max}\) = maximum pressure
- \(P_{cmax}\) = maximum combustion chamber pressure
- \(r\) = radial distance
- \(x\) = axial distance
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