Characteristics of Supersonic Jet Impingement on a Flat Plate

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Abstract

Viscous solutions of supersonic jet impinging on a flat plate normal to the flow are simulated using three-dimensional Navier-Stokes solver. The jet impinging flow structure exhibits such complex nature as shock shell, plate shock and Mach disk depending on the flow parameters. Among others, the dominant parameters are the ratio of the nozzle exit pressure to the ambient pressure and the distance between the nozzle exit plane and the impinging plane. In the present study, the nozzle contour and the pressure ratio are held fixed, while the jet impinging distance is varied to illuminate the characteristics of the jet plume with the distance.

As the plate is placed close to the nozzle at 3D high, the computed wall pressure at or near the jet center oscillates with large amplitude with respect to the mean value. Here D is the nozzle exit diameter. The amplitude of wall pressure fluctuations subsides as the distance increases, but the maximum pressure level at the plate is achieved when the distance is about 4D high. The frequency of the wall pressure is estimated at 6.0 kHz, 9.3 kHz, and 10.0 kHz as the impinging distance varies from 3D, 4D, to 6D, respectively.

1. Introduction

Supersonic jet occurs in the exhaust from rocket motors and from V/STOL aircraft engines and in various other situations such as multistage rocket separation, deep-space docking, space-module attitude-control thruster operation, lunar and planetary landing and take-off, gun-muzzle blast impingement, shock-impingement heating, among others. When these jets impinge on solid objects, such as part of a missile launcher or the ground surface, high level of temperature and pressure loads can be generated. And these impinging flows are generally found to be quite complex. The main applications of this problem include prediction of surface erosion and design of launcher systems. The key features of the flow field are plate shock, barrel shock, and jet boundary. Embedded between the plate shock and the solid surface is a region of subsonic and transonic flows similar to that found in the stagnation zone of blunt body in supersonic flow. Structure of this type of jet has been examined for many years both experimentally [1]-[14] and numerically [15]-[23].

Introducing a few on this issue, Rubel [15] presented numerical solutions for the normal impingement of inviscid axisymmetric jets with energy deficient cores revealing three distinct classes of behavior. Direct numerical simulation using both the three-dimensional and two-dimensional, time dependent Navier-Stokes equations was resorted to investigate V/STOL jet-induced interactions by Rizk and Menon [16]. Kim and Chang [17] studied numerically three-dimensional structure of a supersonic jet impingement on inclined plates using the Euler equations. Also Chow [18] numerically examined the problem of jet-plate interaction with inviscid analysis. Kitamura and

Iwamoto [19] studied numerically supersonic jet impingement under axisymmetric assumptions. And Sakakibara and Iwamoto [20] also investigated oscillatory mechanism associated with underexpanded jet impinging on plate. They have identified pressure oscillation, frequency, and separation bubble on the plate for different nozzle-plate distances.

While most of existing studies are confined to 2-D axisymmetric flows, Hong and Lee [21] presented numerical simulations of jet plume impingement onto a duct using Navier-Stokes equations. Lee [22] also gave numerical solutions for a VLS type missile launcher due to supersonic jet impingement. These kind of flow patterns are extremely complex and hard to obtain stable numerical solutions [23].

Having observed this, objectives of present numerical study are thus two folds: one is to capture unsteady nature of jet impingement structure while the jet undergoes a transitory process, the other is to overcome the inherent shock instability problem associated with Roe scheme to which the present CFDS scheme owes its ideas. Present work in particular focuses on the change of jet impingement structure as the distance between the nozzle exit plane and the flat plate varies between 3 to 6 nozzle exit diameters.

2. Numerical Method

The governing Navier-Stokes equations employed in the generalized coordinate system, (ξ, η, ϕ), are expressed for the conservative variable vector as

$$J^{-1}\frac{\partial q}{\partial t}+\frac{\partial}{\partial \xi}(\hat{F}+\hat{F}_v)+\frac{\partial}{\partial \eta}(\hat{G}+\hat{G}_v)+\frac{\partial}{\partial \phi}(\hat{H}+\hat{H}_v)=0 \tag{1}$$

The inviscid fluxes are linearized and split for upwind discretizations by

$$\triangle_{\xi} F=\tilde{A}\triangle q=(\tilde{A}^{+}+\tilde{A}^{-})\triangle q \quad \text{and} \quad \tilde{A}^{\pm}=\overline{M}\,\overline{T}\,\overline{\Lambda}^{\pm}\,\overline{T}^{-1}\,\overline{M}^{-1} \tag{2}$$

yielding

$$J^{-1}\delta q+\tilde{A}^{+}\nabla_{\xi} q+\tilde{A}^{-}\triangle_{\xi} q+\tilde{B}^{+}\nabla_{\eta} q+\tilde{B}^{-}\triangle_{\eta} q+\tilde{C}^{+}\nabla_{\phi} q+\tilde{C}^{-}\triangle_{\phi} q=0 \tag{3}$$

where $\delta q=q^{n+1}-q^{n}$. The strength of current formulation, termed as Characteristic Flux Difference Splitting (CFDS) scheme, is to enable one to switch the difference equation from the conservation form

$$\frac{I}{\Delta t}\delta q+\overline{MT\Lambda}\,\overline{T}^{-1}\,\overline{M}^{-1}\Delta q=0 \tag{4}$$

to characteristic form

$$\frac{I}{\Delta t}\delta\tilde{q}+\overline{\Lambda}\Delta\tilde{q}=0 \tag{5}$$

rather easily written here for one-dimensional case for the sake of simplicity. Details of the formulation and its applicability to characteristic boundary procedure are given in Ref. 24.

When the eigenvalue becomes zero in Eq. (5), there is no convective wave information traveling to that point as occurs in the stagnation line. Since the CFDS formulation also splits the eigenvalue as

$$\Lambda = \Lambda^{+} + \Lambda^{-} \tag{6}$$

this splitting is also susceptible to carbuncle problem when λ_1 becomes zero. When the velocity component parallel to the shock becomes zero, the associated eigenvalue matrix becomes

$$\overline{\Lambda} \cong \begin{bmatrix} u & & & & \\ & u & & & \\ & & u & & \\ & & & u+c & \\ & & & & u-c \end{bmatrix} = \begin{bmatrix} 0 & & & & \\ & 0 & & & \\ & & 0 & & \\ & & & c & \\ & & & & -c \end{bmatrix} \tag{7}$$

Thus it is necessary to prevent the eigenvalue component from becoming zero. This can be done via

$$\lambda = \lambda^{+} + \lambda^{-} = (\lambda^{+} + \varepsilon) + (\lambda^{-} - \varepsilon) \tag{8}$$

with a proper choice of ε. Sanders et al [25] recently found the H-correction method work well preventing the bow shock instability via

$$\lambda^{H}_{j+1/2,k} = \max(\lambda_{j+1/2,k},\ \lambda_{j,k+1/2},\ \lambda_{j,k-1/2},\ \lambda_{j+1,k+1},\ \lambda_{j+1,k-1/2}).$$

However, the shock instability occurs for 3-dimensional shock flows even if the entropy fixing is imposed as proposed by ether Harten or Sanders.

An alternative formulation of the flux term instead of Eq. (2) is employed in the grid-aligned shock area:

$$\triangle_{\xi} F = Flux_{\frac{1}{2}} - Flux_{-\frac{1}{2}} \tag{9}$$

where $$Flux_{\frac{1}{2}} = \frac{1}{2}[F_j + F_{j+1} - |\tilde{A}|(Q_{j+1} - Q_j)] \tag{10}$$

Here, $\tilde{A}$ is the same form in Eq. (2). The last term in Eq. (10), $|\tilde{A}|(Q_{j+1} - Q_j)$, means numerical dissipation and $|\tilde{A}| = \overline{M}\,\overline{T}\,|\overline{\Lambda}|\,\overline{T}^{-1}\,\overline{M}^{-1}$. The flux definition in Eq. (10) is similar in form to the Roe's flux definition. In the present study for supersonic jet impingement calculations, the entropy fixing formula in Eq. (10) takes

$$|\lambda| = \left(\frac{\lambda^2 + \varepsilon^2}{2\varepsilon}\right) \quad \text{if } |\lambda| < \varepsilon, \text{ and} \tag{11}$$

with $\varepsilon = 2.0$.

This entropy fixing is used when one detects the grid aligned with normal shock. The formulation in Eq. (2) is restored in the rest of the flow field except where the grid is aligned with a strong shock.

3. Results and Discussions

Supersonic jet impingement cases are run for a nozzle with chamber pressure Pt=1200 psia and chamber temperature Tt=2950 K. Figure 1 shows the computational model with the nozzle diameter of D=32.6 mm, and the nozzle-plate distance of H. The ratio of nozzle throat area to nozzle exit area is 7.38. The computational grid consists of 310000 grid points and of seven blocks. Also overlap grid technique is used at block interfaces. Figure 2 shows grid in symmetric plane and Fig. 3 yields enlarged grid in transverse plane parallel to the plate. A circle denoted with a solid line in Fig. 3 matches the nozzle exit plane in size. This grid system without singular line helps improve solution quality and convergence. The computational domain starts from the nozzle throat with Mach 1.0 condition. The boundary conditions of this nozzle throat are calculated from isentropic relations and perfect gas law. A specific heat ratio of 1.4 is used.

The jet impinging distance H is varied for 3D, 4D, 5D, and 6D to illuminate the characteristics of the jet plume with the distance. Figure 4 shows Mach contours with contaminated shock structure, so called "carbuncle phenomenon" in symmetric plane. When a supersonic jet plume exhausts onto the plate, strong normal shock is formed upon the plate. Also the grid system used in numerical computation is aligned with this normal shock, which is known to cause the shock instability [26,27]. This shock instability is cured by fixing near-zero eigenvalues in the numerical dissipation term. Figure 5 exhibits Mach contours displaying shock shell, plate shock and Mach disk for various H. Those structures are formed and settled when the flow has reached nearly steady state. The structure of Fig. 5(a), however, has not settled to be stable in contrast to Figs. 5(b)-(d). As the distance H increases the shock structures are also stretched, but the distance between the plate and plate shock maintains nearly the same distance regardless of H.

Pressure distributions on the flat plate are presented in Fig. 6 for H=3D, 4D. The nozzle exit diameter is imposed on the figure with a bold circle to show the extent of highly concentrated wall pressure zone. The labels in Fig. 6 are with respect to the atmospheric pressure. Pressure contours form exact circles in spite of using the rectangular grid in the core zone. Figure 7 represents pressure history as a function of numerical iterations. As the plate is placed close to the nozzle, the computed wall pressure in Fig. 7(a) oscillates with large amplitude with respect to the mean value, yet barely maintaining periodicity of wall fluctuations. The amplitude of wall pressure fluctuations decreases as the distance increases, but the maximum mean pressure level at the plate is achieved when the distance is about 4D high. The frequency of the pressure fluctuations could be estimated from Fig. 7. In the steady zone, the frequency ranges from 6.0 kHz, 9.3 kHz and 10.0 kHz as the distance varies from 3D, 4D to 6D, respectively. The frequency is based on the conversion of the numerical iteration to the flow time which in turn is transformed from the CFL number. The CFL number depends on the grid cell spacing. So there is somewhat arbitrariness in converting iteration to the elapsed flow time. Nevertheless it is important to note that the jet impingement process fluctuates with a certain frequency on the order of 6-10 kHz at a close range. Note that the frequency of Sakakibara and Iwamoto [20] is approximately 20 kHz for a different jet condition.

Figure 8 shows heat flux distributions in radial direction for 4D case. Heat flux reaches its peak at X/R=0.8. Pressure distribution in radial direction in Fig. 9 exhibits typical pattern of supersonic jet impinging on flat plate [8]. In Fig. 9, the wall pressure measured is also denoted with a symbol, showing a good match between the prediction and the measurement. The pressure history at the center of the plate is presented in Fig. 10 collectively for the four different heights, showing the highest mean pressure occurs when H=4D. The thrust of the motor converges well in Fig. 11 for the four cases, yielding almost the same level of thrust at 300 lbs.

3. Conclusions:

Behavior of the complex, unsteady jet impingement flow is documented during its initial stage. The plate shock has been captured robustly with the addition of numerical dissipation when the shock is aligned with the grid line. The computed wall pressure compares well with the experimental data acquired recently at Anheung Proving Ground. The authors appreciate the professional efforts by Launcher, Propulsion, and Data Acquisition Teams.

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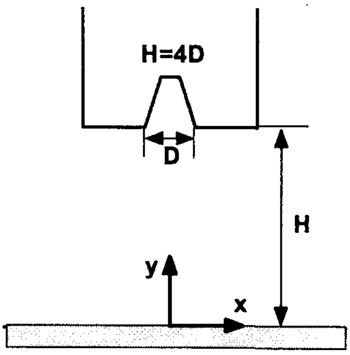


Fig. 1 Computational model.

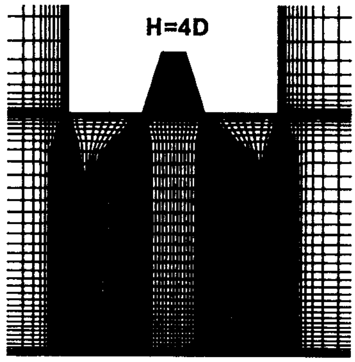


Fig. 2 Grid in symmetric plane.

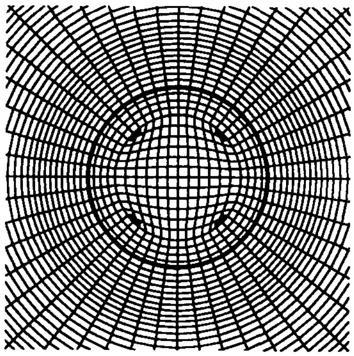


Fig. 3 Grid in transverse plane.

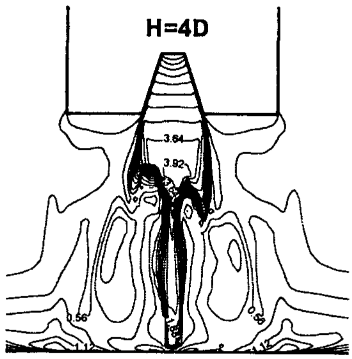
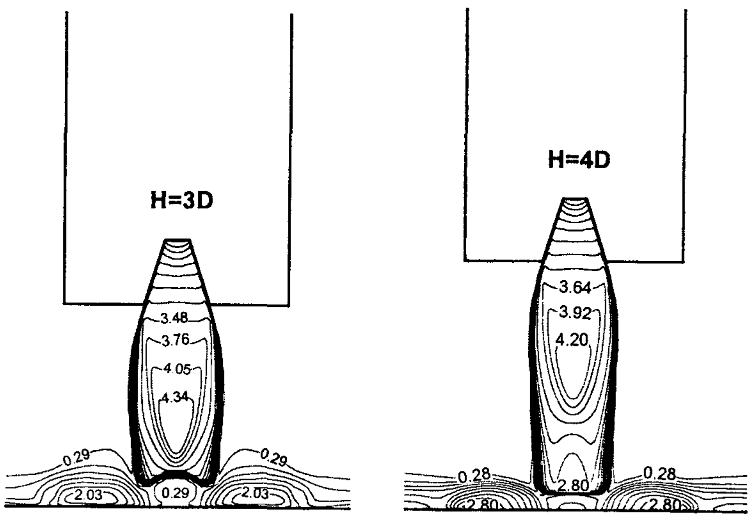
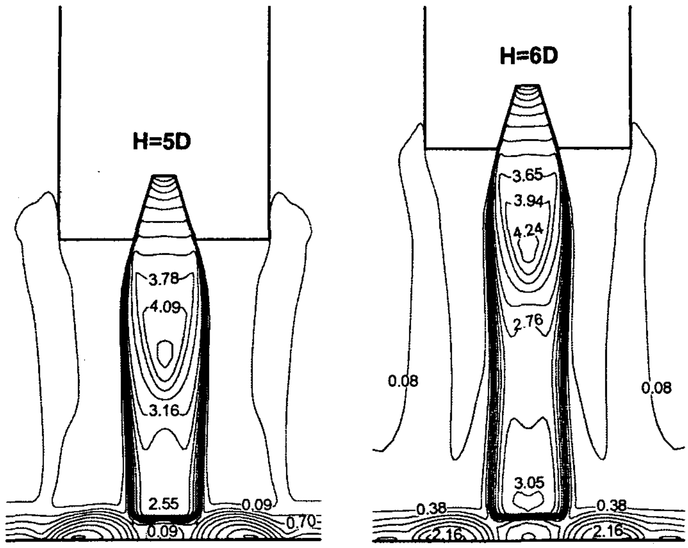


Fig. 4 Mach contours with conventional scheme.



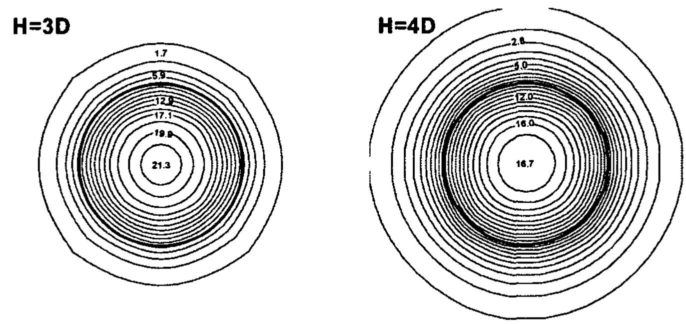
(a) H=3D (b) H=4D

Fig. 5 Mach contours in symmetric plane for varied distance H.



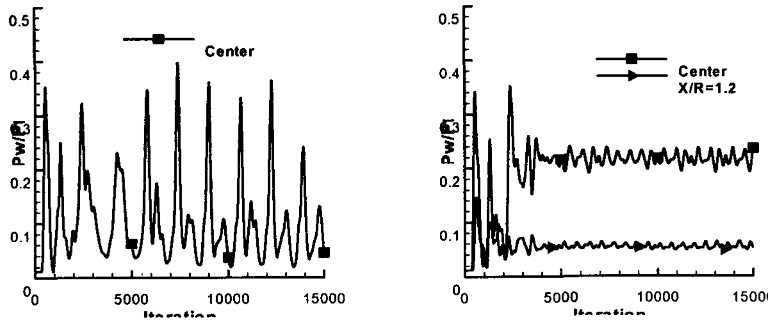
(c) H=5D (d) H=6D

Fig. 5 Mach contours in symmetric plane for varied distance H.



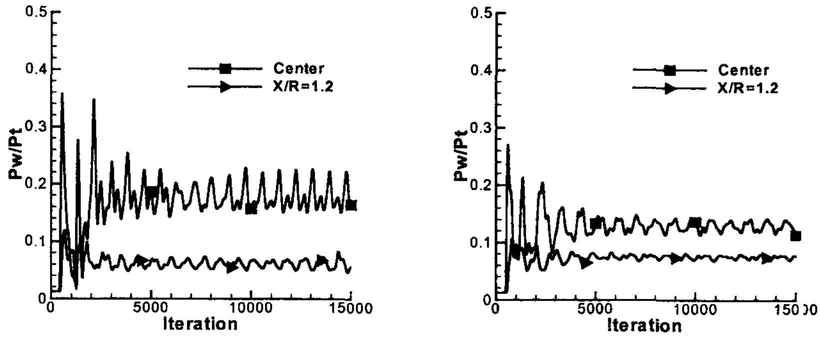
(a) H=3D (b) H=4D

Fig. 6 Pressure distributions on the flat plate(atm.).



(a) H=3D (b) H=4D

Fig. 7 Pressure history for varied distance H.



(c) H=5D (d) H=6D

Fig. 7 Pressure history for varied distance H.

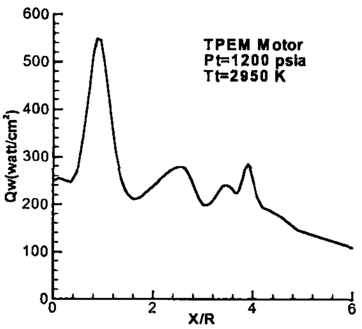


Fig. 8 Heat flux distributions in radial direction for H=4D.

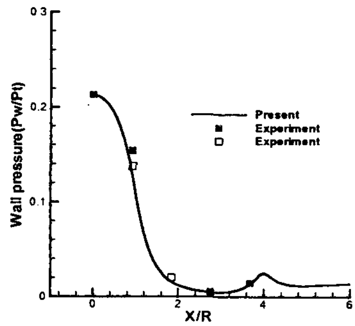


Fig. 9 Pressure distributions in radial direction for H=4D.

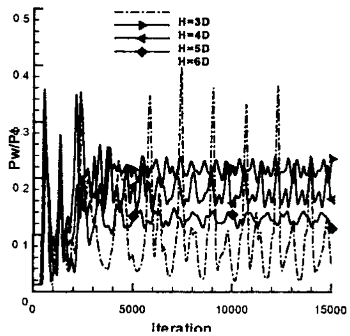


Fig. 10 Pressure history comparisons.

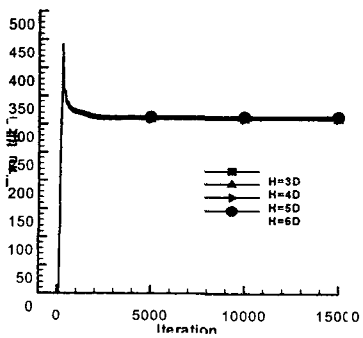


Fig. 11 Thrust history comparisons.