NUMERICAL ANALYSIS OF INTERACTION BETWEEN SUPERSONIC JET AND PERPENDICULAR PLATE

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The numerical investigation of the interaction between the underexpanded supersonic jet and the perpendicular plate is carried out using the TVD numerical method. The wave structure in the flowfield and the pressure and temperature distributions on the plate surface are obtained by the numerical analysis. Especially, the influence of self-induced flow oscillation caused by the impinging jet and the characteristic of impinging jet are shown. From the result of the numerical analysis, it is concluded that the pressure and the temperature fluctuations on the plate surface strongly depends on the pressure ratio in the flowfield and the position of plate.

Keywords: Compressible Flow, Supersonic Jet, Impinging Jet, Mach Disk, Flow Oscillation

1. INTRODUCTION

The phenomenon of the interaction between the supersonic impinging jet and an obstacle is an important problem relating to some industrial engineering[1,2]. Especially, when the under-expanded supersonic jet impinges on the obstacle, it is well known that the self-induced flow oscillation occurs at the specific condition, namely the pressure ratio in the flowfield, the position of an obstacle and so on, and causes the noise problem. The many studies[3-6] had carried out for the oscillation phenomena caused by the interaction with perpendicular plate and the characteristic of the frequency and sound pressure level of a noise induced by the oscillation were cleared. But, it seems that the characteristics of the oscillated flowfield and the pressure or temperature fluctuation on the plate surface have to be more cleared to control the oscillation. This paper aims to clear the characteristics of the pressure and temperature fluctuation and the influence of several parameters of the flowfield during the under-expanded supersonic jet impinges on the perpendicular plate using the TVD numerical method.

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2. PROCEDURE OF NUMERICAL CALCULATION

The typical flowfield and the symbols used in this study are shown in Fig. 1. The name of shock wave in this figure is based on the Henderson's report[7]. As shown in this figure, the shock structure contained the Barrel shock, Mach disk and other shock wave are usually formed at the under-expanded condition. The flow structure is influenced by the pressure ratio ϕ (= p_0 / p_b, here, p_0 is a reservoir pressure, p_b is an ambient pressure) and the cell structure is formed when the ratio ϕ is sufficiently low. The standoff shock, sonic line and other pressure waves, furthermore, are formed ahead of a plate as a result of the interaction with a plate. In this study, the symbols D and x_p are defined as the nozzle exit diameter and the plate position.

In the numerical analysis, the x-y cylindrical coordinates system originated on the center of nozzle exit was considered as shown in Fig. 2. The basic equations used in this study are the compressible unsteady axisymmetric Euler's equations so that the inviscid gas is assumed. It can

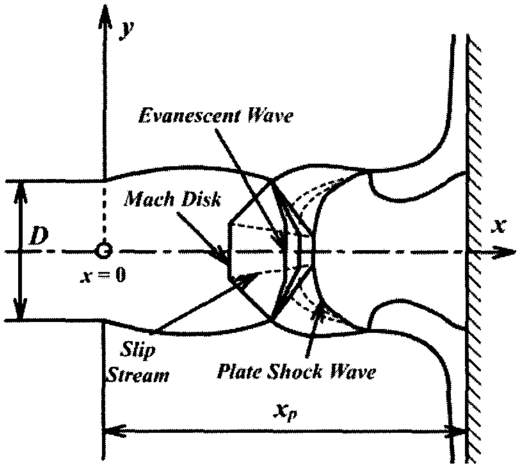


Fig. 1 Flow model and symbols

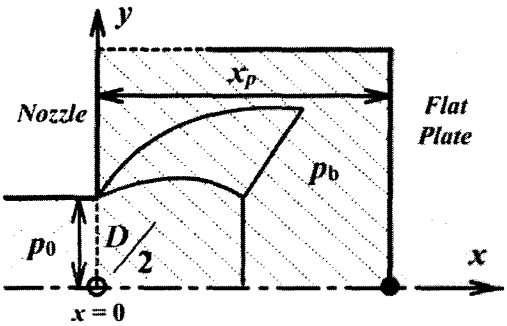


Fig. 2 Computational region and symbols

be written in the Eq. (1) by the nondimensional conservation forms.

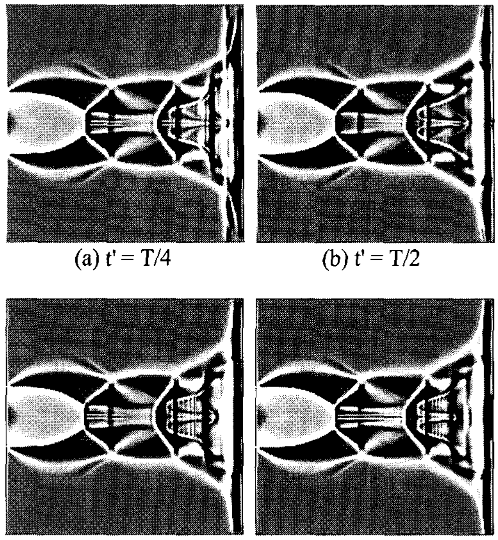
$$\frac{\partial U}{\partial t'} + \frac{\partial F}{\partial x'} + \frac{\partial G}{\partial y'} + W = 0 \qquad (1)$$

where,

$$U=\begin{bmatrix} \rho' \\ \rho' u' \\ \rho' v' \\ e' \end{bmatrix} \quad F=\begin{bmatrix} \rho' u' \\ \rho' u'^2+p' \\ \rho' u' v' \\ (e'+p')u' \end{bmatrix} \quad G=\begin{bmatrix} \rho' v' \\ \rho' u' v' \\ \rho' v'^2+p' \\ (e'+p')v' \end{bmatrix} \quad W=\frac{1}{y'}\begin{bmatrix} \rho' v' \\ \rho' u' v' \\ \rho' v'^2 \\ (e'+p')v' \end{bmatrix}$$

The symbol ' denotes the non-dimensional quantities which are nondimensionalized by the nozzle exit diameter D and the reservoir condition p_0, ρ_0 and a_0.

Equation (1) is solved by the TVD method[8] with the operator splitting technique[9]. The square grid such as $\Delta x = \Delta y$ is used and the time step Δt is decided by the CFL condition. In this numerical analysis, the influence of viscosity is neglected because the influence of viscosity is not concerned for the fundamental characteristic of pressure fluctuation for impingement with the perpendicular plate.



(a) t' = T/4 (b) t' = T/2

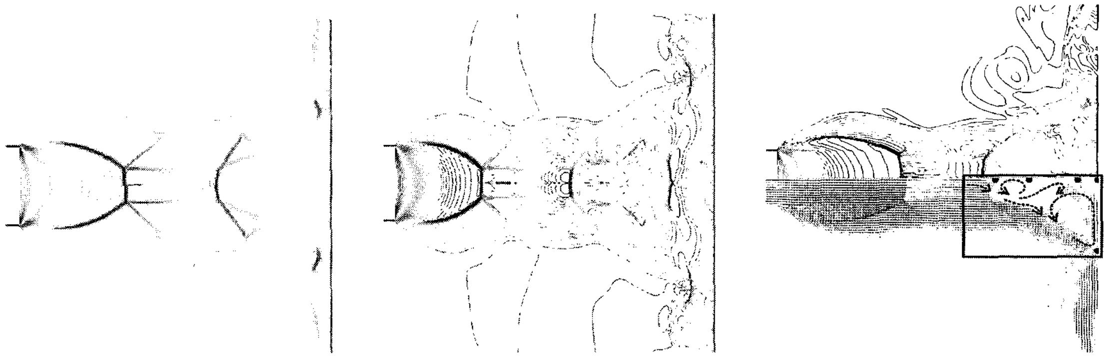
(c) t' = 3T/4 (d) t' = T/4

Fig. 3 Typical computed shadowgraphs at several times for a cycle of flow oscillation ($x_p/D=4, \phi=6$)

For the numerical calculation, the initial conditions are as follows ; the sonic jet of exit Mach number M_e=1, the ratio of the specific heats k=1.4, the position of plate x_p/D=2-7. The pressure ratio of reservoir pressure p_0 and the ambient pressure p_b is varied in the range of $2 \leq \phi$ $(=p_0/p_b) \leq 20$.

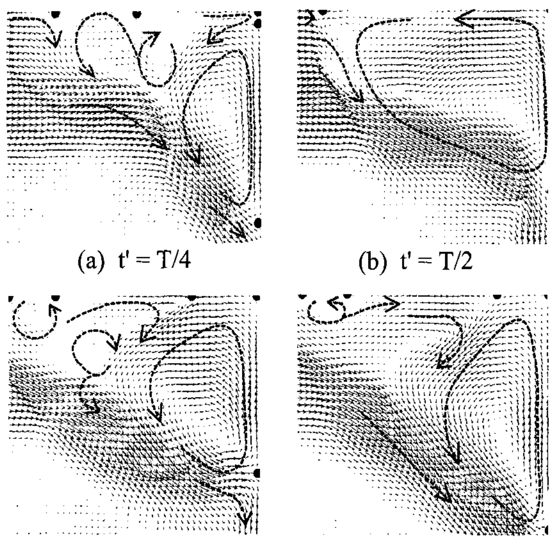
3. NUMERICAL RESULT AND DISCUSSION

Typical computed shadowgraph is shown in Fig. 3 and the numerical condition is indicated in the figure. These figures are the results at several times in the one periodic time T of the oscillation. In our past paper[10], we had confirmed that the numerical results had good agreed with our schlieren photographs so that these numerical results are proper because of same program. In Fig. (a), the plate shock is formed ahead of plate and weakens with increasing of time, in Fig. (d) begin to grow again. In this case, the Mach disk is a



(a) $x_p / D = 4, \phi = 6$ (b) $x_p / D = 5, \phi = 6$ (c) $x_p / D = 5, \phi = 10$

Fig. 4 Typical isopycnics during flow oscillation



(a) t' = T/4 (b) t' = T/2

c) t' = 3T/4 (d) t' = T/4

Fig. 5 Typical velocity vectors at several times for a cycle of flow oscillation (x_p / D=5, ϕ=10)

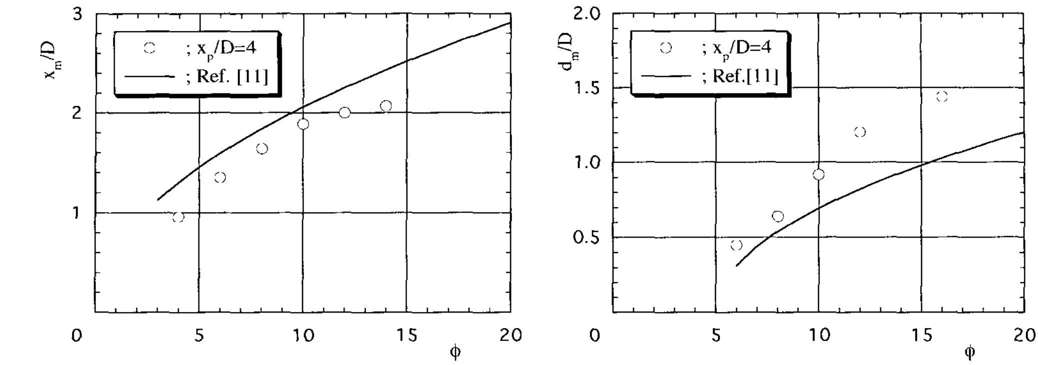
stationary and the secondary shock at downstream of the Mach disk and the plate shock ahead of a plate oscillate.

Typical isopycnics are shown in Fig. 4. These figures are the instantaneous isopycnics during the oscillation. In Fig. (a), the two sub-tail plate shock waves are formed at the vicinity of a plate and observed in other cases. This shock wave decreases the flow speed from the supersonic to subsonic and divides the flow into two directions. In Fig. (b), the size of the sub-tail plate shock is larger than the case of Fig. (a) and the small plate shock is formed ahead of a plate. The velocity distribution around the plate locally changes for these shock waves.

Figure 5 presents the change of velocity vector distribution with time in the marked region in Fig. 4(c) and the self-induced flow oscillation occurs at this condition. The separation bubble is observed and the complicated flowfield is formed in this case. The size and position of a circulation flow, the stagnation point changes with time. From these figure, the flow velocity is decreased and the flow direction is divided into two direction because of sub-tail plate shock wave formed around the lower stagnation point. On the other hand, the stagnation point at the center of plate remains during oscillation occurs. It is remarkable that the structure of the separation bubble is varies due to occur the self-induced flow oscillation

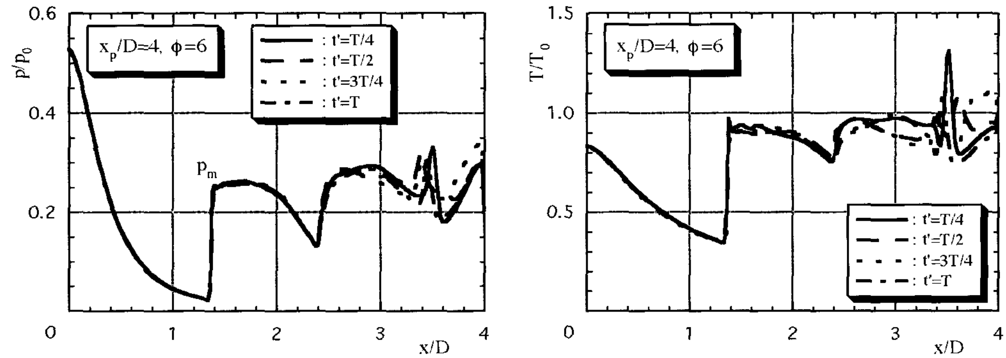
The relation between the nondimensional position and diameter of the Mach disk x_m/D, d_m/D and the pressure ratio ϕ are shown in Fig. 6. The plotted symbol indicates the numerical result for x_p/D=4 and the solid line shows the result of Addy's equation[10] which means the result of free jet. The value of x_m/D increases with increasing of ϕ and reduces by comparison with the free jet. On the other hand, the value of d_m/D exceeds from the result of free jet.

The pressure and temperature distributions on the jet axis are shown in Fig. 7. The numerical condition is indicated in the figure. In the Fig. (a), the symbol p_m denotes the pressure behind the Mach disk. The pressure and temperature on the jet



(a) Position x_m / D (b) Diameter d_m / D

Fig. 6 Relation between nondimensional position and diameter of Mach disk x_m / D, d_m / D and pressure ratio ϕ



(a) Pressure distribution (b) Temperature distribution

Fig. 7 Typical pressure and temperature distributions on jet axis ($x_p / D = 4, \phi = 6$)

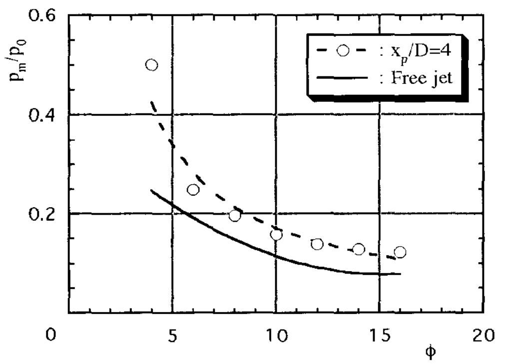
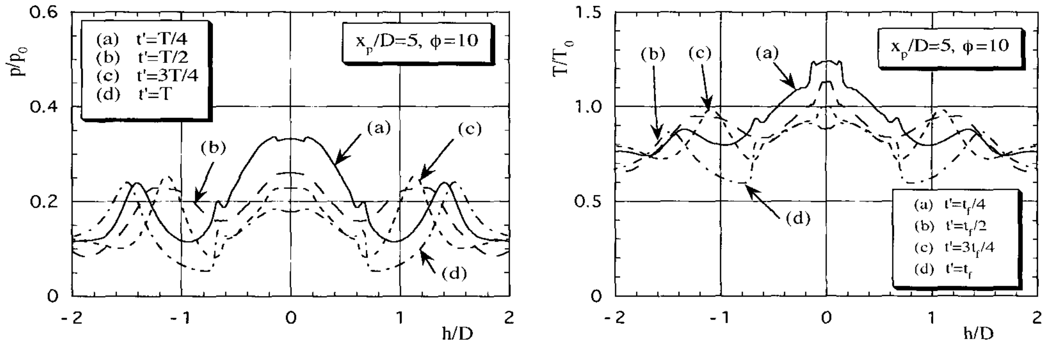


Fig. 8 Relation between nondimensional pressure at behind Mach disk p_m / p_0 and nondimen sional position of plate x_p/D

axis decrease with the increasing of distance x/D as like the isentropic change and recover by the Mach disk, as if the self-induced flow oscillation occurs. In this case, the Mach disk and the secondary shock wave are stationary and the plate shock oscillates along the jet axis.

The relation between the nondimensional pressure behind the Mach disk and the pressure ratio ϕ is shown in Fig. 8. The value of p_m decreases with the increasing of a distance x/D.From these results, it is noticed that the pressure p_m behind of the Mach disk exceed the result of a free jet and does not exceed the reservoir pressure p_0.

The pressure and temperature distributions on the plate surface are shown in Fig. 9. In Fig. (a), the maximum pressure is observed at the plate center, but the secondary peak is formed at h/D=1.5 and h/D=-1.5. The stagnation bubble causes this peak pressure and this result corresponds to the other report[4]. As shown in Fig. 5, the stagnation point at the center of plate remains during the oscillation occurs in this condition so that the maximum



(a) Pressure distribution (b) Temperature distribution

Fig. 9 Typical pressure and temperature distributions on plate surface ($x_p / D = 5,\ \phi = 10$)

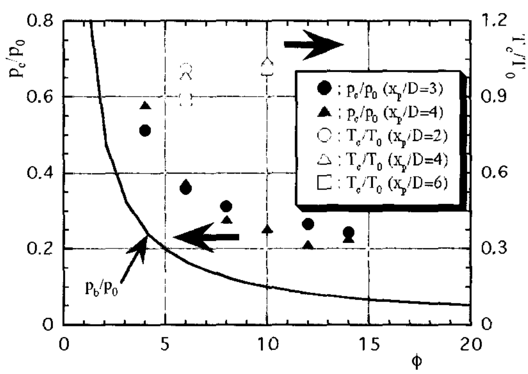


Fig. 10 Relation between nondimensional Pressure P_c/P_0 and temperature T_c/T_0 on center of plate and pressure ratio ϕ

pressure is observed at the plate center. If the of stagnation bubble becomes larger, the stagnation point at the center of plate may disappear so that the pressure at the plate center will decrease. The pressure, furthermore, fluctuates by the self-induced flow oscillation, but the change of amplitude of the secondary pressure peak is smaller than that of plate center. In Fig. (b), the characteristic of temperature distribution is a similar to result of Fig. (a).

Figure 10 shows the relation between the averaged pressure and temperature p_c / p_0, T_c / T_0 at the center of a plate and the pressure ratio ϕ. The value of p_c / p_0 and T_c / T_0 mean the averaged value of maximum and minimum results during a cycle of oscillation. The plotted symbol indicates the numerical result and the solid line shows the nondimensional ambient pressure p_b / p_0. The value of p_c / p_0 decreases with the increasing of the pressure ratio ϕ and position x_p/D. On the other hand, the value of T_c / T_0 increases with the increasing of the pressure ratio ϕ and decreases with increasing of the position x_p/D. It is remarkable that the averaged pressure p_c / p_0 and temperature T_c / T_0 depend on the pressure ratio ϕ and the nondimensional position of a plate x_p/D.

4. CONCLUSION

The self-induced oscillation during the under-expanded supersonic jet impinges on the perpendicular plate is investigated by the numerical calculation in this study. The characteristics of a wave structure, the pressure and temperature fluctuations on the plate surface are discussed. The conclusions are summarized as follows.

(1) The wave structure is a similar to the case of the free jet and the Mach disk or the plate shock oscillates along the jet axis. The position of Mach disk reduces and the diameter increases by comparison with the result of a free jet.

(2) The stagnation bubble is formed under almost conditions of this study. When the self-induced flow oscillation occurs, the recirculating region and a number of stagnation point and the stagnation position change with time.

(3) The pressure at behind the Mach disk p_m / p_0 decreases with increasing of pressure ratio ϕ and approaches to the result of the free jet.

(4) The averaged pressure on the plate center p_c / p_0 decreases with the increasing of position x_p/D and the pressure ratio ϕ. On the other hand, the

averaged temperature on the plate center T_c / T_0 increases with the increasing of the pressure ratio ϕ . It is concluded that the averaged pressure p_c / p_0 and temperature T_c / T_0 strongly depends on the pressure ratio ϕ .

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