Transient Shock Waves in Supersonic Internal Flow

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ABSTRACT

When high-pressure gas is exhausted through nozzle exit to the atmosphere, expanded supersonic jet is formed with the Mach disk at a specific condition. In two-dimensional supersonic jets, the hysteresis phenomenon of the reflected shock waves is found to occur under quasi-steady flow conditions. Transitional pressure ratio between the regular reflection and Mach reflection in the jet is affected by this phenomenon. In the present study, experiments are carried out on internal flow in a supersonic nozzle to clarify the hysteresis phenomena for the shock waves and to discuss its interdependence on the rate of the change of pressure ratio with time. Flow visualization is carried out separately on the straight and divergent channels downstream of the nozzle throat section. The influence that the hysteresis phenomena have on the location of shock wave in a supersonic nozzle is also investigated experimentally.

Key Words : Internal flow, Hysteresis, Shock wave, Supersonic flow

1. INTRODUCTION

Hysteresis may be defined as the phenomenon of lagging of an effect behind its cause. Hysteresis phenomena are well known for external flows. Investigation of the effect of non-equilibrium condensation on hysteresis phenomenon of under expanded moist jets revealed that under-expanded moist air jet leads to less hysteresis of the jet, compared with the dry air jets [1]. However, hysteresis phenomenon of a supersonic internal flow for shock waves is yet to be clarified satisfactorily. From previous studies, it is understood that shock wave exists in supersonic part of a Laval nozzle and in some cases normal shock is also formed which results a sudden rise in temperature across the shock. Non-homogeneous temperature increase across the shock caused by boundary layer thickening ahead of the shock and resulting pre-compression prevents quasi 1-D evolution of flow downstream [2]. Due to multiple boundary layer interactions, the single shock disintegrates into a so called pseudo-shock system [3]. On increasing the nozzle pressure ratio, shock position is moved towards nozzle exit, and opposite of this phenomenon is also true.

The objective of the present study is to clarify the hysteresis phenomena for shock wave in a supersonic nozzle and to discuss the relationship between hysteresis phenomenon and rate of the change of pressure ratio with time. Influence of the hysteresis phenomena on the location of

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shock wave in the nozzle was also studied. Results obtained were compared with available numerically simulated data.

2. EXPERIMENTAL WORK

Schematic diagram of experimental apparatus is described in Fig. 1. Apparatus consisted of an air compressor, air drier, air reservoir, electronic control valve, plenum chamber and nozzle. Plenum chamber is placed upstream of nozzle. Test section is placed downstream of nozzle throat and optical glass windows are installed on both the side walls of test section for flow visualization.

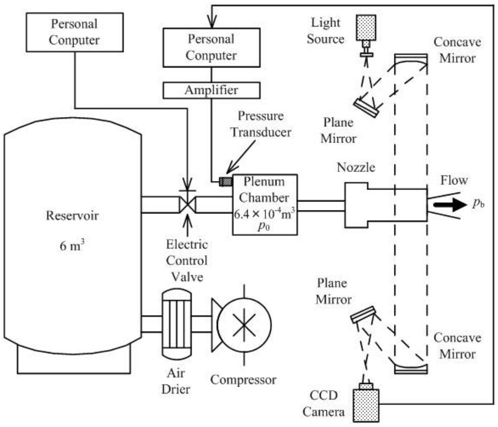


Fig. 1 Schematic Diagram for experimental setup

Fig. 2 shows the detailed nozzle configuration used in the present work. Nozzle was designed using the method of characteristics. Design Mach number of supersonic nozzle is M_e=2.0. Throat diameter is D_t=6.0 and exit diameter D_e=10.0mm.

Pressure ratio was continuously changed with time using electronic control valve. p_0 represents stagnation pressure of the plenum chamber and p_b, back pressure. For shock wave in straight part of nozzle (Case1), the range of pressure ratio was from 2.16 to 2.86. For shock wave in divergent part (Case 2), it is from 1.42 to 2.02.

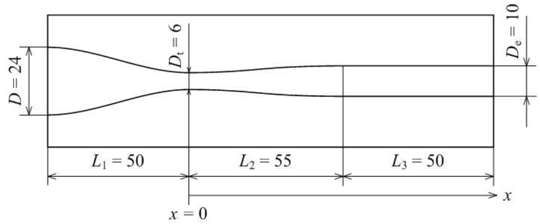


Fig. 2 Nozzle geometry (all dimensions in mm)

Rate of change of pressure ratio with time is from 0.107 (1/s) to 0.437 (1/s) for Case 1 and from 0.112 (1/s) to 0.338 (1/s) for Case 2. Compressed dry air is discharged from nozzle exit through the plenum chamber. Flow field was investigated by Schlieren technique. Visualization and measurement of pressure ratio were conducted simultaneously. Location of first shock wave L was obtained from Schlieren pictures. With the experimental conditions, it is found that a time delay exists for the response of change of flow to the change of pressure ratio at $\triangle\dot{\phi}$ > 0.229 (1/s) for Case 1 and $\triangle\dot{\phi}$ > 0.338 (1/s) for Case 2. Results were determined from the change in position of shock wave in the nozzle.

3. NUMERICAL SIMULATION

Computational Fluid Dynamics simulations were carried out under conditions that replicate the experimental investigations of hysteresis phenomena of shock waves in the straight part of nozzle. Flow was treated as compressible, viscous, unsteady and turbulent. Governing equations were the conservation forms of mass, momentum and energy. Axisymmetric, mass averaged, unsteady, Navier-Stokes equations, with the two-equation *k-w* SST (Shear-Stress Transport) turbulent model were used in the computation. Governing equations are discretized spatially with a finite volume scheme. For time derivatives, an implicit multistage time stepping scheme, which is advanced from time t to time $t+\triangle t$ with a 2nd order Euler backward scheme for physical time and implicit pseudo-time marching scheme for inner iteration, is used.

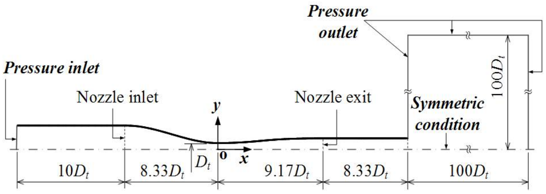


Fig. 3 Computational domain and boundary conditions

Computational domain and boundary conditions for simulating the hysteresis phenomena in the straight part of Laval nozzle are illustrated in Fig.3. Axisymmetric geometry is considered. Boundary conditions used are inlet total pressure and outlet static pressure respectively. Adiabatic no-slip conditions are applied at the walls. For ensuring domain independent solutions, the upstream domain is extended straight to a distance of $10D_t$ upstream from nozzle inlet. The downstream extends straight to $8.33D_t$ from the nozzle exit and then extends again to the distance of $100D_t$ both in the x and y directions.

A structured mesh was employed in computations. Grid independence of solutions was checked. Grids were densely clustered in near wall regions to capture the flow features in boundary layers. A solution convergence was obtained when residuals for each conserved variables were reduced to below the order of magnitude 4. Net mass flux was also checked and there was only an allowable imbalance through computational boundaries. Fig. 4 shows the procedure for the process of the startup transient, in which pressure ratio is increased.

Steady supersonic flow of $\phi=\phi_{st}$ is computed and resulting solutions are used as initial conditions for the first step of the process of

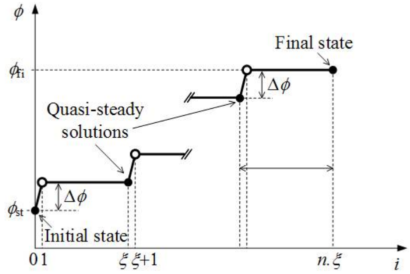


Fig. 4 Simulation of startup transient

startup transient. In the second step, pressure ratio is increased by $\triangle\phi$ and computation is repeated until the transient process is completed, thus leading to a quasi-steady state, as indicated by the black circle. The computed quasi-steady solutions are used again as initial conditions for next step. Consequently final quasi-steady solutions are obtained for the pressure ratio of ϕ_{fi}. Conversely for the shutdown transients, wherein the pressure ratio is decreased; the final quasi-steady solutions are used as the initial conditions. In the present study, ϕ_{st}=2.17, ϕ_{fi}=3.02, $\triangle\phi$=0.029 and ξ=2000. Through such a series of computations, the quasi-steady solutions obtained during startup and shutdown transients are compared to investigate hysteretic behavior of shock waves generated in the straight part of the supersonic nozzle.

4. RESULTS AND DISCUSSION

4.1 Experimental Results

Schlieren photographs of flow fields for straight channel and divergent channel are given by Fig. 5 and 6 respectively. Rate of change of pressure ratio with time ($\triangle\dot{\phi}$), for the straight channel and divergent channel are 0.131 (1/s) and 0.138 (1/s) respectively. In both figures, left side sequence represents increasing process of pressure ratio and right side represents the decreasing process of pressure ratio. As seen from these figures, there are differences between

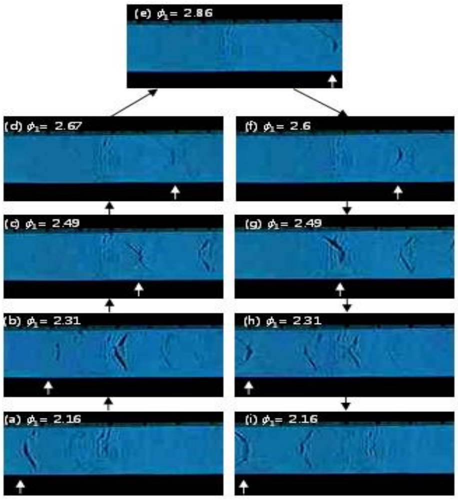


Fig. 5 Schlieren photographs in straight channel

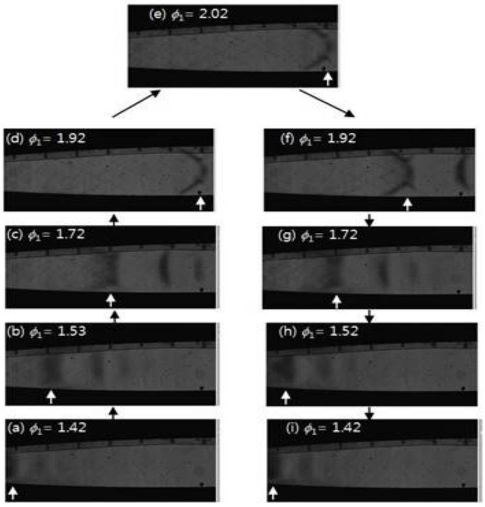
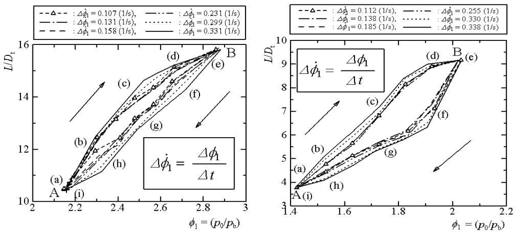


Fig. 6 Schlieren photographs in divergent channel

the locations of the first shock wave even at the same pressure ratio.

Fig. 7 (a) shows the effect of $\triangle\dot{\phi}$ on the location of first shock wave (L/Dt), measured from nozzle throat, in the range from 0.231(1/s) to 0.331(1/s). The hysteresis loops exist at the course between A and B. Variation between A and B follow the same course below $\triangle\dot{\phi}$=0.289 (1/s).

For Case 2, the experimental results explaining the effect of rate of change of pressure ratio

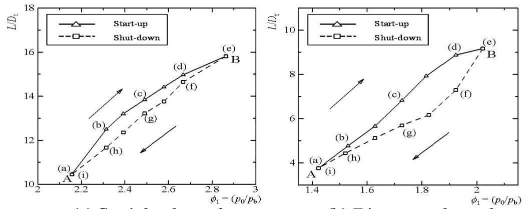


(a) Straight channel (b) Divergent channel

Fig. 7 Effect of rate of change of pressure ratio in straight and divergent channels

with time, $\triangle\dot{\phi}$ on the location of the first shock wave L/Dt is shown in Fig.7(b). Here, $\triangle\dot{\phi}$ is in the range from 0.112 (1/s) to 0.338 (1/s). Here too hysteresis loops exist at the course between A and B and variation between A and B follow the same course below $\triangle\dot{\phi}$=0.318 (1/s).

Fig. 8(a) and (b) show the relationships between L/Dt and pressure ratio ϕ in case of occurrence of hysteresis phenomena for Cases 1 ($\triangle\dot{\phi}$=0.131 (1/s)) and 2 ($\triangle\dot{\phi}$=0.138 (1/s)), respectively. In both figures, symbols from (a) to (i) correspond to those in Figs. 5 and 6. The figures confirm the existence of two values of L/Dt in the ranges of ϕ=2.16 - 2.86 for Case 1 and ϕ=1.42 - 2.02 for Case 2.



(a) Straight channel **(b) Divergent channel**

Fig. 8 Hysteretic behavior: location of Mach disk

4.2 Computational Results

In order to confirm the existence of hysteresis phenomena for shock wave in supersonic nozzle, a computational study is conducted in a range of pressure ratio from ϕ=2.17 to 3.02. Fig. 9 shows computed density contours in the straight part of the nozzle for the range of ϕ=2.2 to 3.02. Results

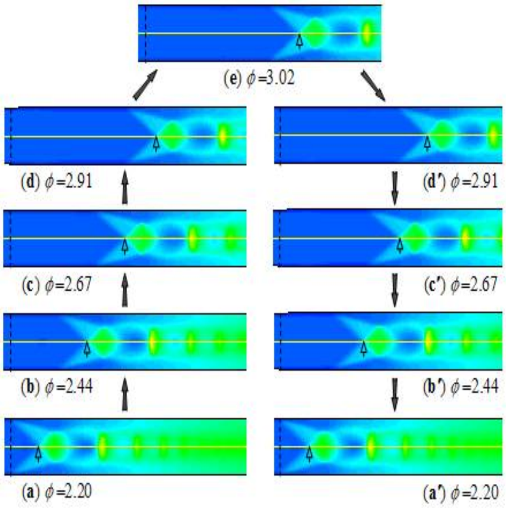


Fig. 9 Density contours illustrating hysteresis phenomena in straight channel

confirmed the formation of shock wave in the straight part of the nozzle, and some normal shocks are also formed due to sudden rise in temperature across the shock (6, 7). During the startup transient of supersonic nozzle flow, at pressure ratio ϕ=2.2, the oblique shock wave (first shock) is located just at the beginning of the straight part of the nozzle. As ϕ increases to 3.02, the first shock wave moves downstream with stronger magnitude. At ϕ =3.02 which corresponds to final steady state in startup transient, the computed flow field is nearly same to that employed as the initial conditions in the shutdown transient. In the shutdown transient, as ϕ decreases again to 2.2, the shock wave moves upstream and the strength seems to be stronger than those found in the startup transient. From a series of computations, it is found that the location and strength of the first shock wave is significantly different in both the processes of the startup and shutdown transients. This clearly revealed that there exist a hysteretic behavior in the formation of shock wave in the straight part of the supersonic nozzle for the range of pressure ratio ϕ =2.2 to 3.02.

5. CONCLUSIONS

Experimental and computational studies were done to investigate the hysteretic behavior in the formation of shock waves in supersonic nozzle. Axisymmetric, unsteady, compressible Navier-Stokes equations have been solved numerically to simulate the flow field concerned with hysteretic behavior in both the processes of shutdown and startup transients of supersonic nozzle flow. Hysteresis phenomena for the location of shock wave in a supersonic nozzle were investigated experimentally. Results confirmed the hysteresis phenomenon for shock wave in the Laval nozzle at a certain specific condition. Relationship between hysteresis phenomenon and the range of rate of change of pressure ratio with time was shown experimentally. Existence of hysteretic behavior in the formation, both the location and strength, of shock wave in the straight part of the supersonic nozzle with a range of pressure ratio has also been confirmed numerically.

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