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Transitional Behavior of a Supersonic Flow in a Two-dimensional Diffuser

Sehoon Kim, Hyungjun Kim, Sejin Kwon*

Division of Aerospace Engineering Department of Mechanical Engineering Korea Advanced Institute of Science and Technology, 373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea

Two-dimensional blow-down type supersonic wind tunnel was designed and built to investigate the transient behavior of the startup of a supersonic flow from rest. The contour of the divergent part of the nozzle was determined by the MOC calculation. The converging part of the nozzle, upstream of the throat was contoured to make the flow profile uniform at the throat. The flow characteristics of the steady supersonic condition were visualized using the high-speed schlieren photography. The Mach number was evaluated from the oblique shock wave angle on a sharp wedge with half angle of 5 degree. The measured Mach number was 2.4 and was slightly less than the value predicted by the design calculation. The initial transient behavior of the nozzle was recorded by a high-speed digital video camera with schlieren technique. The measured transition time from standstill to a steady supersonic flow was estimated by analyzing the serial images. Typical transition time was approximately 0.1sec.

Key Words : Supersonic Diffuser, MOC, Transition to Supersonic Flow, Ejector

Nomenclature

A^* : Nozzle throat area
M_1 : Mach number at nozzle exit
m : Air mass
P_0 : Stagnation pressure in air tank
R : Gas constant
T_0 : Stagnation temperature
V : Tank volume
δ : Wedge angle
γ : Specific heat ratio
θ : Oblique shock angle

1. Introduction

The performance of chemical and gasdynamic lasers depends upon the supersonic flow condition within the resonator cavity where the optical energy is extracted from the photon emitting species. Inducing a uniform reacting supersonic flow and quickly removing the combustion product gases upon completion of light emission from the resonator is an essential part of the design of a chemical laser system(Gross and Bott, 1976 ; Driscoll and Moon, 1997). The simplest method of inducing a supersonic flow in the lasing cavity is placing a vacuum device downstream of the cavity. Vacuum condition can be provided either by a vacuum pump or by a vacuum chamber equipped with an external vacuum pump. In both designs, the sizing of a vacuum device is determined by the transient behavior of the flow transition from rest to the fully supersonic state. Alternative method of a quick buildup of the supersonic duct flow is the high-speed ejection downstream the lasing cavity(Emanuel, 1976 ; Dutton et al., 1982). The ejector-diffuser for chemical lasers also finds applications in the high altitude environment test facilities for supersonic vehicles such as ramjets and upper stage rockets. The transient behavior of onset of supersonic flow in a converging-diverging nozzle also decides the

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* Corresponding Author,
E-mail : melody@kaist.ac.kr
TEL : +82-42-869-3721; **FAX** : +82-42-869-3710
Division of Aerospace Engineering Department of Mechanical Engineering Korea Advanced Institute of Science and Technology, 373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea. (Manuscript **Received** August 31, 2001; **Revised** October 16, 2001)

sizing of an ejector-diffuser (Merkli, 1976; Krause, 1981).

The purpose of supersonic flow in a lasing cavity is two-fold. One is to maintain a low-pressure level, typically around 10torr, within the resonator, so that the intermolecular distance is large enough for the optimum optical output. The other is to remove the product gas, once it completes transition, at a speed high enough for continuous lasing.

Despite the significance of the transitional behavior of a supersonic nozzle applied in the chemical or gasdynamic lasers, reports on the phenomena are scarce. In the present study, we intended to investigate the onset of a non-reacting supersonic flow in a blow-down type supersonic wind tunnel. We designed and built in-house a two-dimensional supersonic wind tunnel and tested its steady operation. The steady test was carried out for validation of the nozzle design.

Upon completion of the steady experiment, the flow transition from zero velocity to ultimate steady flowing supersonic condition was recorded by the high-speed digital motion picture schlieren system.

The data obtained in the present study can be used for the design of a pressure recovery system of a chemical laser or high altitude environment test facilities.

2. Supersonic Wind Tunnel

2.1 Nozzle design and steady test

The design of the supersonic nozzle followed a typical procedure. The contour of the subsonic converging part was determined so that the flow profile at the throat is uniform (Smith and Wang, 1944). In order to reduce the overall length of the nozzle, a two-dimensional bell shape contour was used for the supersonic divergent part of the nozzle downstream of the throat. The contour was determined by standard MOC method that is widely used in the supersonic nozzle design (Anderson, 1990).

This bell shaped nozzle has been proven to result in a uniform velocity profile at the exit while holding the overall nozzle length at minimum (Anderson, 1990; Hodge and Koenic, 1995) by superimposing expansion waves and compression waves along the nozzle surface. The nozzle shape and the characteristic lines from the calculation are presented in Fig. 1. The geometric data of the nozzle design are summarized in Table 1. In the design of the nozzle, the size of the air reservoir set upper limit of the nozzle size.

Table 1 Geometric data of the wind tunnel

Contents	Specification
Area ratio	3
Design Mach number	2.64
Throat area	2.5m × 2cm
Test-section area	2.5cm × 6cm
Window	15.5cm × 5.5cm

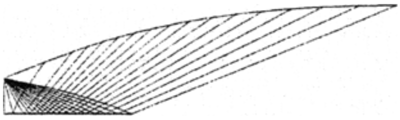


Fig. 1 MOC design

2.2 Run time estimation

The air reservoir supplying the pressurized air to the nozzle has a volume of $2m^3$ at a maximum pressure of 10bar. Therefore, the operation of supersonic nozzle is severely limited. By assuming isentropic expansion through the nozzle, it is possible to estimate the total run time of the nozzle during which the supersonic flow fills the divergent part of the nozzle. From an elementary gasdynamic calculation taking friction inside the supply piping into account, the minimum reservoir pressure at which the nozzle flow is fully supersonic is 268.6kPa. The supersonic flow fully occupies the divergent part of the nozzle until the reservoir pressure drops to 268.6kPa from its initial pressure. More accurate estimation of the operation time can be calculated from the following equations.

$$\frac{dm}{dt}=\sqrt{\gamma/R}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)}\frac{A^*P_0(t)}{\sqrt{T_0(t)}} \quad (1)$$

$$P_0(t)\,V=m(t)\,RT_0(t) \quad (2)$$

$$P_0(t)\,/\,T_0(t)^{\frac{\gamma}{(\gamma-1)}}=\text{const.} \quad (3)$$

By integrating this system of equations with respect to the reservoir pressure, we obtained the run time of 15seconds.

At the exit of the nozzle, a constant cross sectional duct with rectangular dimension of 2.5cm×6cm is attached for visual observation of the supersonic flow field produced by the nozzle. To test the steady flow characteristics of the flow field, flow Mach number was calculated from the measure value of the oblique shock angle on a wedge with a half angle of 5 degree. The oblique shock wave was photographed using schileren technique as shown in Fig. 2.

The Mach number is calculated from the following equation by substituting the wedge half angle and the shock wave angle.

$$\tan\delta=2\cot\theta\frac{M_1^2\sin^2\theta-1}{M_1^2(\gamma+\cos 2\theta)+2} \tag{4}$$

Here, δ is wedge angle and θ is measured oblique shock angle with M given.

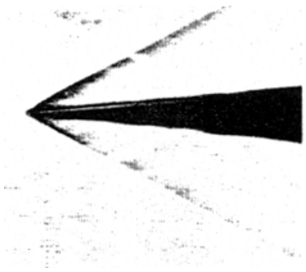


Fig. 2 Schlieren image of oblique shock on a sharp wedge

2.3 Numerical Simulations

FLUENT code was used to test the transition behavior of the supersonic nozzle and diffuser. The turbulence model and the numerical scheme of the original code were used as was provided by the package. Only the boundary conditions and the initial conditions were supplied to accurately describe the condition of the problem in the present study. The results of the numerical simulation will be discussed along with the experimental results in Sec. 3.2.

3. Results and Discussions

3.1 Start up transition to supersonic flow

Though it takes a very short time from the start of the supersonic diffuser to the onset of a fully

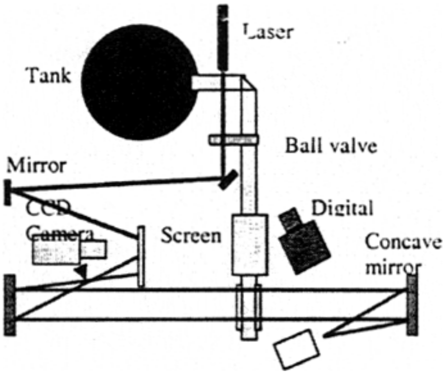


Fig. 3 Setup for laser timing mark

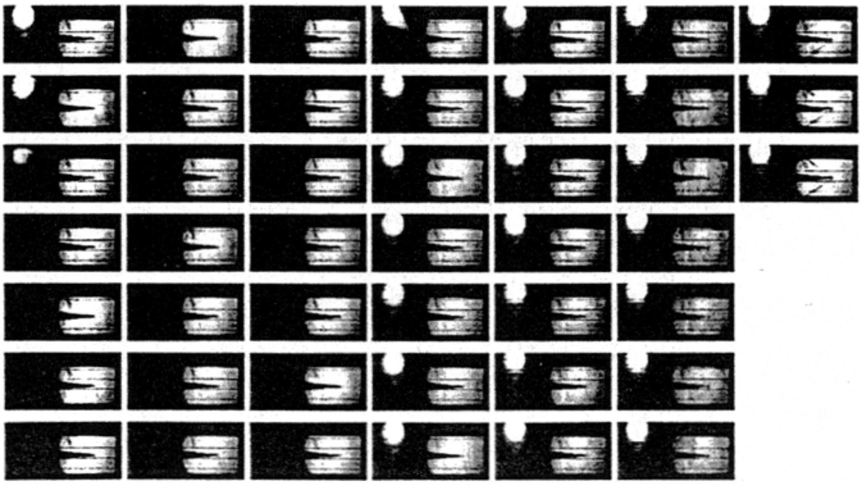


Fig. 4 Series video images during the startup

developed supersonic flow, the behavior of this transition has significance in designing supersonic nozzles. Especially, in a chemical laser, the transition characteristics of the supersonic nozzle determine the size of vacuum devices.

In this study, the flow transition was recorded by a high-speed digital video camera running at a flaming rate from 1000 to 2000 fps. To help visual observation, a wedge was placed in the test section downstream of the nozzle.

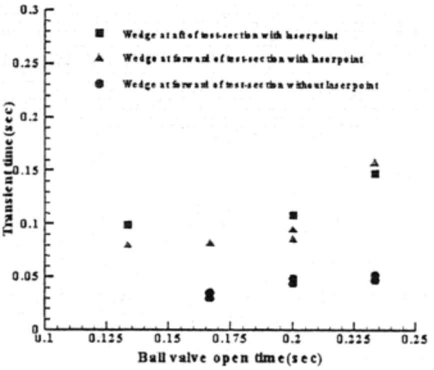
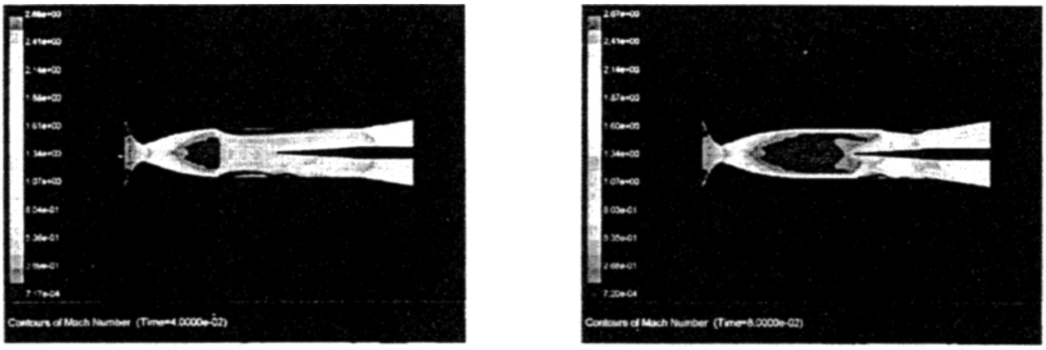


Fig. 5 Transition time dependence on the valve opening speed

To accurately mark the time of the nozzle startup, a laser beam was overlaid on the video images. Laser beam after a couple of steering mirrors falls on the screen, where the schlieren also forms the image of the supersonic nozzle flow. Upon the startup of the nozzle by opening the valve, the laser beam is blocked and the timing mark disappears on the image as in Fig. 4.

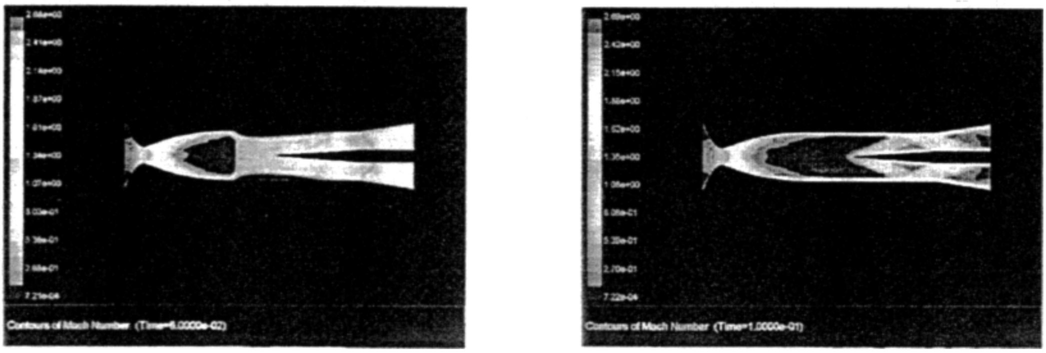
Figure 4 the series of video images during the startup operation of the nozzle. The bright circular spots on the upper left corner of the frame are timing mark signature. Nozzle starts up at the instant when the timing mark disappears. From Fig. 7, it takes 36 frames from the startup to the full development with clear formation of oblique shock wave in the bottom of the rightmost image.

Analyzing the time marks over repeated experiment with different valve opening speeds, we obtained the correlation between the valve opening speed and the transition time for the



(a) 0.04 sec after startup

(c) 0.08 sec after startup



(b) 0.6 sec after startup

(d) 0.1 sec after startup

Fig. 6 Simulation results of the onset of supersonic flow within the diffuser section startup. Figure 5 shows this relationship.

It is clear from Fig. 5 that the transition time is relatively independent of the valve opening speed. However, when the valve opening speed is very slow, choking at the valve precedes the choking of the nozzle and unexpected flow condition develops. This undesired condition could be avoided if the valve opening speed of less than 0.225 second is used for the actual experiments. Present experimental setup allows repeatable valve opening speed of 0.2~0.3 second with ease.

For the cases in which the valve opening time was below the liming condition, the transition time was relatively constant and ranged from 0.05 to 0.1 second. However, the transition time tend to increase as the test wedge moved further downstream.

3.2 Results of the numerical simulations

The simulation results of FLUENT on the startup of a supersonic flow in the nozzle and the diffuser are presented in Fig. 6. As the time passes after the startup of the nozzle, the supersonic region expands from downstream of the diverging part of the nozzle. After 0.06 second, the supersonic region fully fills the divergent part of the nozzle and expands into the diffuser part. 0.08 seconds later, the flow inside the diffuser becomes supersonic up to the wedge. However, the flow right on the wedge surfaces is not uniformly supersonic. Fully supersonic flow fills the overall length of the diffuser after 0.1 second (d).

5. Conclusions

In the present study, a supersonic nozzle-diffuser was designed and fabricated. The startup of a supersonic flow field within the diffuser with emphasis on the transition was observed visually by the high-speed schlieren system. Accurate timing was recorded by a laser timing mark and the overall transition time from the standstill to the fully developed supersonic flow was around 0.1sec with slight variance depending upon the insertion point of a wedge in the diffuser. The effect of valve opening speed was insignificant within this transition time. As a result, it can be argued that the onset of the flow in the duct mainly initiated by the pressure wave unless the choking at the valve last more than the transition time.

Numerical simulation using a commercial code (FLUENT) resulted in a transition time of 0.1 sec that is comparable to its measured value. It was noted that the simulation predicts the transition behavior of the diffuser satisfactorily although no modification to the code was made for the simulation.

The results obtained in the present study can provide data for sizing the vacuum devices that are essential subsystems of a chemical laser or a high-altitude high-speed environment test facility.

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