Downstream pressure variation induced hysteresis in the scramjet isolator

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Hysteresis phenomenon in scramjet has been observed in combustion experiments. Its mechanism was seldom investigated. Present works aim to specify the conditions when hysteresis phenomenon occurs in cold flow experiment. Experiments were conducted in a direct-connect isolator part with a ramp in Mach 3 flow. Two different condition in the exit of isolator were considered. The experimental results show that the hysteresis phenomenon appears. It is a hysteresis of position of separation region induced by back pressure. We consider that it is the interactions between the upstream disturbances, for example incident shock wave-induced separation bubble, and downstream separation region induced by back pressure cause the flow separation hysteresis.

Nomenclature

Tr = throttling ratio
t = time
$p/P0$ = normalized pressure

I.   Introduction

AS the key part of scramjet, the isolator connects the inlet and the combustor. Its key function is to prevent the static pressure rise and pressure oscillation that associates with combustor operation from inlet unstart. In isolator duct is complex flow, including shock wave/boundary layer interactions and boundary layer separation[1]. This interesting field led to many researcher efforts that aim to explore the flow mechanism. Base on the axial symmetry isolator with constant area, Walrtup and Billig developed an empirical relationship between the shock train length and the pressure distribution in the shock train region[2]. For the rectangle isolator with constant area, Bement et al. developed a similar relationship between the shock train length and the pressure rise[3].

The flow patterns and performance in the scramjet has been investigated thoroughly. However, some new phenomena occur in the combustion experiments of scramjet in recent years. Goyne et al.[4] studied the vitiation effects on dual-mode scramjet performance and observed a hysteresis phenomenon that the flow pattern are different at the same equivalence ratios dependent on the whether the equivalence ratio was increasing or decreasing. Juntal Chang et al.[5] also observed hysteresis phenomena in direct-connect scramjet engine experience. In the numerical studies, Baurle[6] and Dalle[7] also observed the hysteresis phenomena. Draw a conclusion from the above literatures, the hysteresis phenomena occurs in the combustion experiences, which will exert an important influence on the performance of design condition of scramjet engine. However, its mechanism is still unclear.

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These experiences conduced in the above studies are based on whether a scramjet engine test or direct-connect scramjet engine. The combustion of fuel provides flow condition on the outlet of isolator. However, it is not clear that whether the hysteresis phenomenon occurs if a back pressure is imposed on the outlet of isolator directly. The focus of this paper aim to present the hysteresis phenomena in the cold flow experience based on the rectangle isolator with constant area and analyze preliminarily its mechanism.

I. Experimental setup

The experiments were conducted using the direct-connect experiment system at Institute of Mechanics of Chinese Academy of Sciences. The isolator was designed a constant area duct with a ramp located at the upstream of observation window. As shown in Figure 7Figure 1, experimental system was consisted of plenum, nozzle part, isolator duct and downstream part. The nozzle part, a two dimensional Laval nozzle with an exit of 40×80 mm, was used to accelerated the air to Mach 3. The isolator duct had a length of 470 mm and the observation window downstream had a length of 230 mm. The ramp had a bottom side length of 37.5 mm and a sweepback of 10 degree. The downstream part with a length of 390 mm had a rectangle to circle part and a converging part. A flow plug which can move at a speed of up to 22 mm per second located at the exit of converging part. 21 pressure survey point and 20 pressure survey point was distributed at the upper wall and bottom wall respectively.

The high pressure air was supplied by a big enough chamber and then flow into plenum. In the current experiments, the total pressure and total temperature were 1.7 MPa and room temperature respectively.
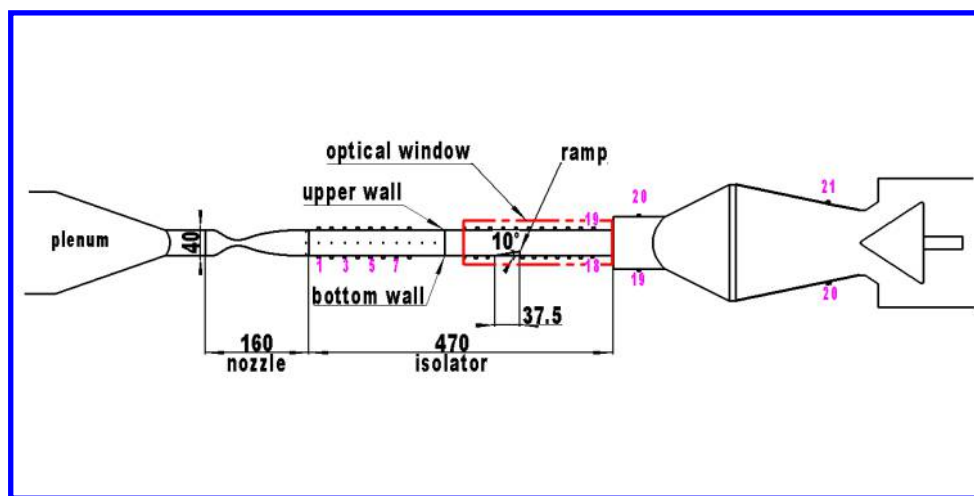

Figure 1 Schematic of direct-connect experimental system.

II. Experimental Results

The flow patterns and pressure distributions along the wall of isolator duct at different throttling ratio conditions are discussed in present section. The throttling ratio are defined as following:

$$Tr = \frac{throttling\ aera}{total\ area} \times 100\% \tag{1}$$

A. Case 1

In present case, an intermittent plug movement test was carried out. The plug moves to the first position when the tunel starts. After staying for one second, the plut moves to the second postion. In a same way, the Tr will finally increases to 44.91%. And then, the plug backtracks. The corresponding Tr increases from 32.16% to 44.91% and then decreases to 32.16%. Figure 2 shows the schlieren photographs of typical moments. Figure 2 a)-c) correspond the increasing process of Tr and Figure 2 c)-(e) correspond the decreasing process of Tr.

As Figure 2 b) and d) show, although the throttling ratio are same in two different moments, the flow patterns are clearly different. It means that the flow structures are determined not only by the throttling ration(or back pressure) but also by the history effect. The hysteresis phenomenon appears in present case. The flow patterns at typical moments are described as follow.

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At Tr = 32.16%, the flow pattern is shown at Figure 2 a). Several Mach waves occur in the upstream of location A due to the joint between nozzle and isolator. The ramp locates at B. The shock wave C generated due to the ramp B interacts with the boundary layer on the upper wall, which induces the separation bubble D. The shock wave C1 reflects from a upstream weak shock wave. Downstream the ramp B is an expansion fan E and a strong shock wave appears downstream. At Tr = 32.16%, the shock train leading edge G arrives at the downstream position of optical window. The separation region F presents on the upper wall.

As Tr increases to 38.27%, the flow pattern is shown in Figure 2 b). The shock train leading edge G and separation region F move upstream. At the same time, the separation region F1 appears on the bottom wall. As Tr further increases to 44.91%, the flow pattern changes a lot as shown in Figure 2 c). The size of separation bubble D increases. Separation region F and expansion fan E disappear. Separation region F1 spreads to the trailing edge of ramp B. A shock wave H occurs and impinges into the separation bubble D.

As Tr decreases from 44.91% to 38.27%, it is clear that the separation region F1 still connects with the training edge of ramp as shown in Figure 2 d). In other words, there exists a hysteresis phenomenon in the process of growth and decrease of Tr.

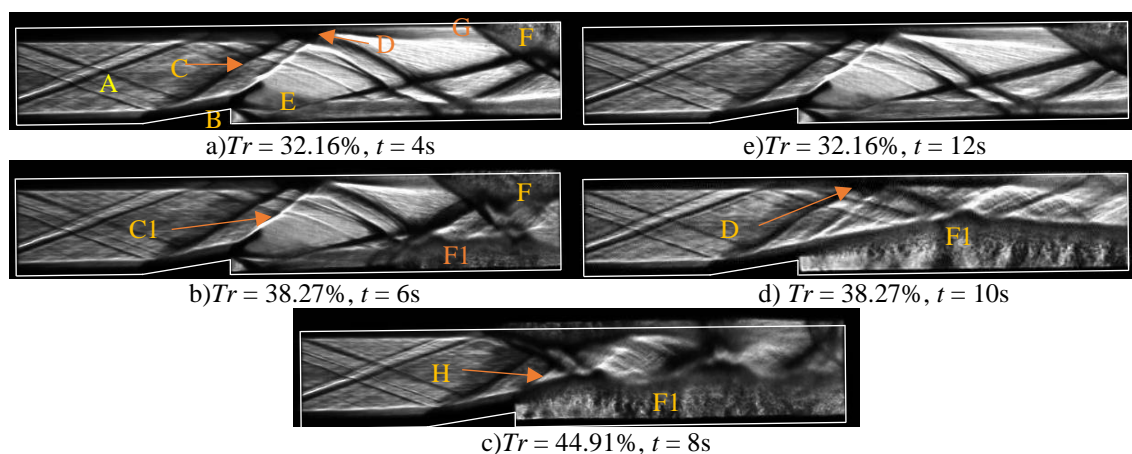As Tr further decreases to 32.16%, the same flow pattern return to original state.

a)Tr = 32.16%, t = 4s

e)Tr = 32.16%, t = 12s

b)Tr = 38.27%, t = 6s

d) Tr = 38.27%, t = 10s

c)Tr = 44.91%, t = 8s

Figure 2 Schlieren photographs showing the flow patterns at various Tr.
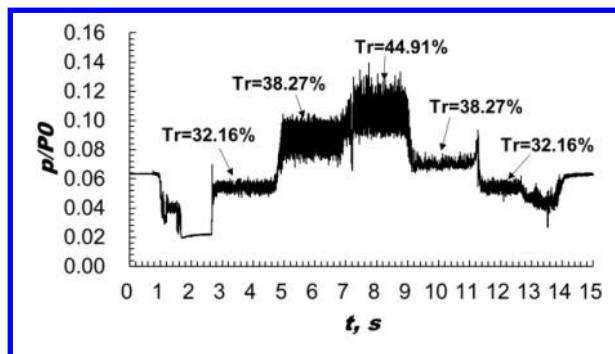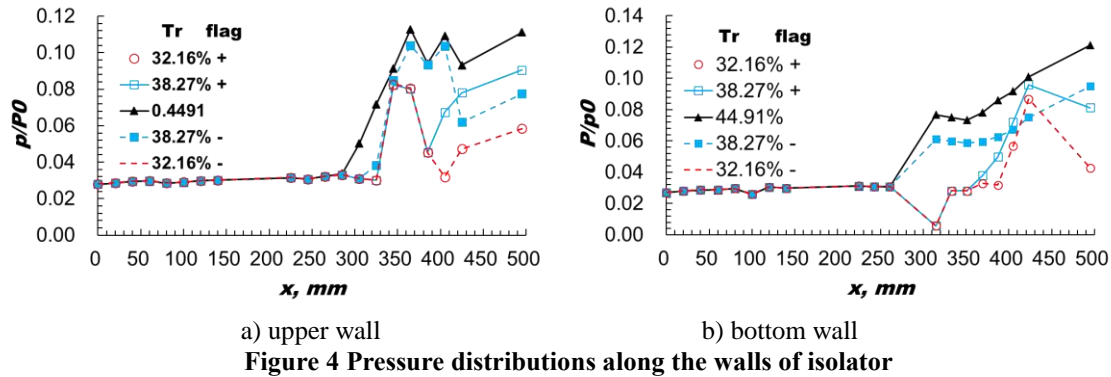

Figure 3 The histories of pressure at the 20th transducer on the upper wall.

Figure 3 shows the histories of pressure at the 20th transducer on the upper wall. It shows that violent fluctuation occurs at Tr = 38.27% and 44.91%, while gentle fluctuation presents at other throttling ratios.

The pressure distributions along the upper wall and bottom wall is shown in Figure 4. It is mean pressure over a period of time at a throttling ratio. The symbol '+' represents the increasing process and '-' represents decreasing process. The pressure increases very slowly along the streamwise direction in the upstream ramp B. The pressure distributions shown in Figure 4 corresponds to flow pattern shown in Figure 2. Therefore, two pressure distributions line at Tr =38.27% doesn't coincide, which mean a hysteresis phenomenon.

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a) upper wall　　　　　　　　　　b) bottom wall

Figure 4 Pressure distributions along the walls of isolator

A. Case 2

   To be compared with the last case and to eliminate the return error of plug movement, the plug will moves continuously in present case. And the throttling ratio is from 26.6% to 63.9%. Figure 5 shows the schliren images at typical moments. It can be found that the flow patterns are similar to the last case, which mean the types of plug movement have little effect on flow field. More importantly, the hysteresis phenomenon can also be found in present case as shown in Figure 5 b) and f).
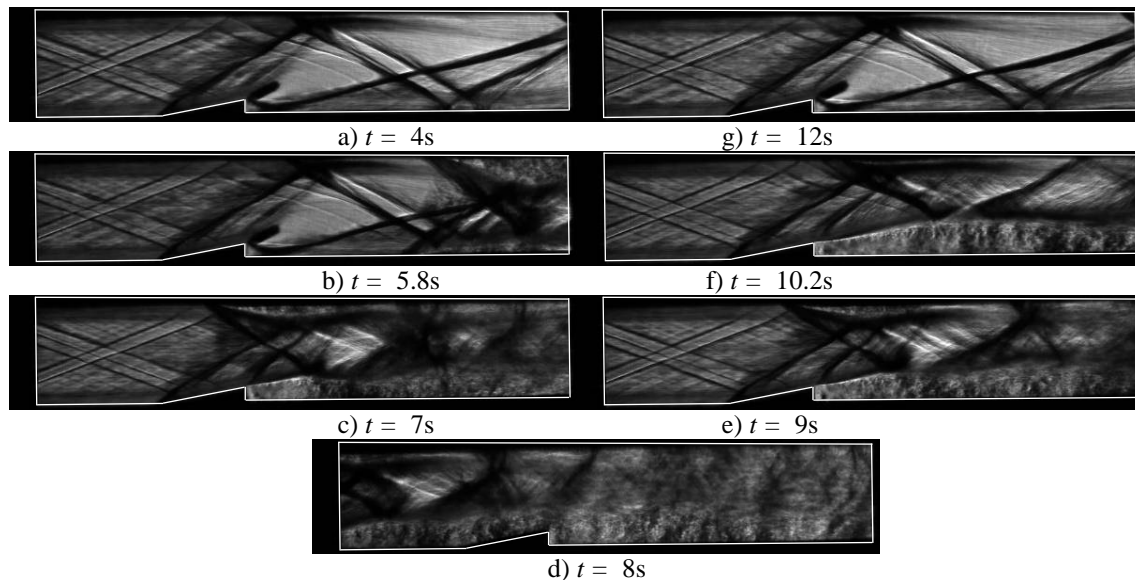

a) $t = 4$s　　　　　　　　　　g) $t = 12$s

b) $t = 5.8$s　　　　　　　　　　f) $t = 10.2$s

c) $t = 7$s　　　　　　　　　　e) $t = 9$s

d) $t = 8$s

Figure 5 Schlieren photographs at typical moments

   To comfirm the hysteresis exactly, the characterstic of oscillation can be dicussed. The joint time-frequency analysis results of the most downstream pressure signal on the lower wall are shown in Figure 6. In this figure, the color represents the mean-square amplitude of the power sprctral. The red block corresponds to the virlent oscillation.

   When Tr increases, an unstable stage comes out from $t = 5.65$s to 5.95s. However, the unstable stage disappears while Tr decreases, which means whether the flow fields are oscillating or not is determined by the history effects of throttling ratio in special range of Tr.
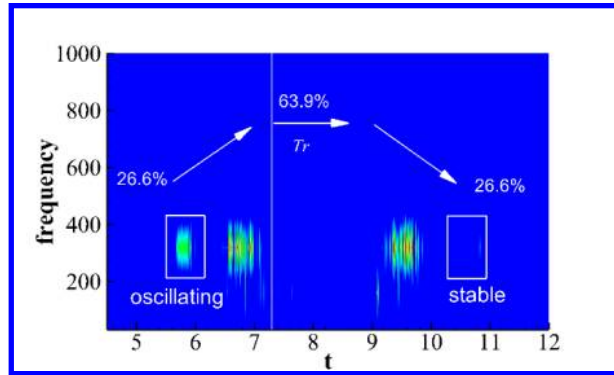
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Figure 6 Wavelet analysis of the most downstream pressure signal on the lower wall showing the hysteresis mhenonmenon.

IV.   Analysis

Previous studies[3-6] shown that hysteresis phenomenon occurs in combustion experiments. They presented the hysteresis phenomenon in the combustion mode transition of scramjet but didn't point out the reason why hysteresis occurs. However, in present experiments, there is no combustor. The hysteresis can not be caused by combustion.
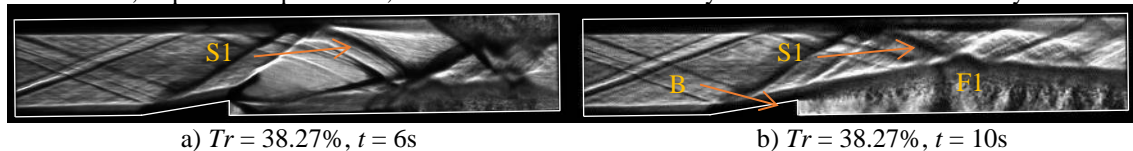

a) $Tr = 38.27\%$, $t = 6$s   b) $Tr = 38.27\%$, $t = 10$s

Figure 7 Flow field of case 1.

As shown in Figure 7, taking a closer look to schlieren images, it can be found that the reflected shock wave S1 and the ramp B are the main structures in isolator. The separation region F1 seems to be attracted by shock S1 so that it can maintain until Tr decreases to much lower value. Combining our numerical studies(not presented here), an incident shock wave can cause a flow separation hysteresis in constant area isolator, which will be presented in other papers. Therefore, we consider that such flow hysteresis appears because of the interactions between an upstream disturbances and downstream pressure variation, such as incident shock wave, ramp and even cross jet. Such phenomenon is called flow separation hysteresis in present works. It manifests as a position hysteresis of separation region induced by back pressure.

V.   Conclusion

The hysteresis is detrimental to the control of hypersonic vehicles. In present work, the cold flow experiments were conducted in a rectangular cross section isolator with a two-dimensional ramp. The results indicate that there exists a new hysteresis in cold flow in present isolator when the throttling ratio or back pressure increases and then decreases.

We consider that it is the interactions between the upstream disturbances and downstream pressure variation cause the flow separation hysteresis. It is a hysteresis phenomenon of position of sepration region induced by back pressure.

Acknowledgments

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All of the preceding information is required. The journal issue number ("No. 11" in Ref. 1) is preferred, but the month (Nov.) can be substituted if the issue number is not available. Use the complete date for daily and weekly publications. Transactions follow the same style as other journals; if punctuation is necessary, use a colon to separate the transactions title from the journal title.

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