

Effect of Opposing Multiphase Jet on Hypersonic Flow Around Blunt Body

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Abstract. An experimental research has been conducted to investigate the flow control method using opposing jet with air and water as a fluid spike on a blunt body in hypersonic freestream at Mach number 7, using the Kashiwa hypersonic wind tunnel. The dynamic characteristics and instability of opposing jet were clarified. It can be seen from the comparison between the air opposing jet and the water opposing jet that a liquid jet seems more effective in generating fluid spike for reduction in the drag force and the heating rate on the body. Details of the flow field and the jet oscillation have been captured by Schlieren system with high-speed cameras. The experimental data reveal the interaction of the jet oscillation with the shock wave fluctuation. Such interaction has strong impact on the whole flow field structure and should be taken into consideration in the design of the active flow control system using the opposing jet method.

1. Background

The opposing jet has been attracting our research interest since it has been regarded as an effective flow control method for cooling, drag reduction, flow field modification and so on. Lots of the experimental and numerical studies have been conducted so far since the early 1950s.

Opposing jet, which is a kind of active flow control method, has advantages for reusability in comparison with a "physical" solid spike on a blunt body, which suffers from severe aerodynamic heating at its tip. The opposing jet works as a "virtual" spike, which extends forward into the incoming stream and forms the oblique shock wave at the tip of the spike. The pressure and temperature behind that oblique shock wave are much lower than those behind the detached bow shock wave on the blunt body without jet flow. As a result, significant reduction in the drag force and the thermal load are expected for a vehicle flying at hypersonic speeds. In addition, by switching off the opposing jet, the "virtual" spike instantaneously disappears. Such controllability cannot be expected for the solid spike.

Meyer and Nelson conducted the research on the active flow control by the opposing jet and the results showed that large reductions in heat transfer can be obtained by upstream injection[1].



Experimental study of Warren investigated the effectiveness of opposing gas jet from a spherical cone model in the Mach 5.8 wind tunnel. They found that the thermal load is effectively reduced by the gas injection[2].

The efficiency and performance of the flow control using opposing jet are explained in terms of the change in the flow field characteristics. The penetration length of the jet is one of the characteristic features of the jet flow. Daso, Preitchett and Wang conducted numerical and experimental studies on the opposing jets in the freestreams at Mach 3.48 and 4.0[3]. The results showed that the penetration length changes with the flow rate of the opposing jet. In some cases, however, the flow becomes unsteady and long penetration mode (LPM) and short penetration mode (SPM) were observed from the experimental data.

In most of the researches, gas is mainly considered for the injected fluid. When the length of the spike is not sufficient, the oblique shock wave formed from the tip of the spike hits the body surface, the severe peak pressure and peak heating are produced. To avoid such situation, the penetration length of opposing jet must be long enough. To realize a long virtual spike, the jet reservoir pressure must be high enough. Liquid or particle-laden gas seems promising for generating a long opposing jet, because its density is much larger than the gas and the strong inertia elongates the jet even in the presence of the free stream against it. Also, water jet can achieve a considerable cooling effect and protect the models from thermal damages, as shown in the Rashis' experiment[4].

Though the flow control by the opposing jet seems promising, Daso and Woods pointed out in their experimental study that the complexity and instability of the jet flow can have significant effect on the flow field structure, cooling effectiveness and the aerodynamic drag[5]. Experimental investigation on the cross-flow injection of liquid in Mach 6 flow by Beloki Perurena showed a coupling between the jet breakup and shock fluctuation. For the opposing jet, more complicated phenomena including jet oscillation, shock wave reflection and oblique shock wave/bow shock wave occurred in hypersonic flow[6].

The above review shows the researches on the use of liquid jet injection for flow field modification. However, few studies reported the details of the opposing jet flow dynamics and instability and our understanding on those is not satisfactory especially for the opposing jet of liquid in hypersonic flows. Thus, there remains a paucity of work on characteristics of opposing jet

In this paper, experimental studies were conducted to obtain the effect of opposing jet on hypersonic flow and details of the flow dynamic characteristics of opposing jets in order to gain a better understanding of its flow mechanism. This information should be helpful to advance the knowledge and application of opposing jets as a feasible method of flow control. The major objectives in the present study are 1) to visualize the opposing jet around the blunt body in hypersonic flow and capture the details of the flow field structure, 2) to analyze the flow dynamics, instability of opposing jet and its effect on hypersonic flow, 3) to compare the opposing air jet and opposing water jet.

2. Models and experiment apparatus

The test model is a blunt body imitating the Apollo capsule, as shown in Fig. (1a). The diameter of the model is 30 mm. The jet hole of 1mm diameter was drilled at the stagnation point. A tube was connected to a cavity inside the body from the back of the model. A flexible PVC tube was used to provide air or water from the reservoir outside of the test section at the atmospheric pressure. The water tank was set at the same height as the jet exit to avoid further acceleration of the water jet injection due to the gravitational force. The 3-D schematic of the model is shown in Fig. (1b). The photograph of the model installed in the test section is shown in Fig. 2. A spherical model was used to compare the flow structure of opposing jet around models with different shapes. The diameter of the spherical model is 30mm.

A Schlieren flow visualization system equipped with normal (30 frames per second) and high-speed cameras (60000 frames per second) was used in this experiment. For the cross-section imaging of the flow and the PSP (pressure sensitive paint) measurement, a laser light source (450nm, power Max. 2W) was used. The schematic of the experimental setup is shown in Fig. 3. Figure (3b) shows

the front view of the setup of the laser cross-section imaging, the laser light source was placed on the upside of the test section.

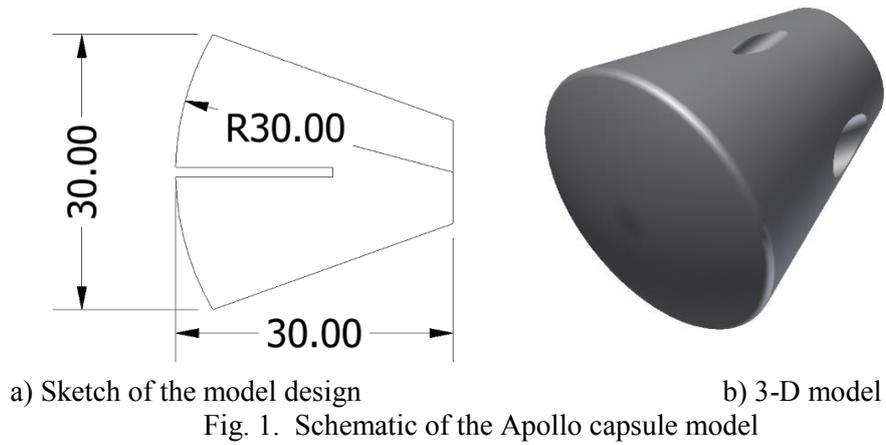


Fig. 1. Schematic of the Apollo capsule model



Fig. 2. Model in the test section

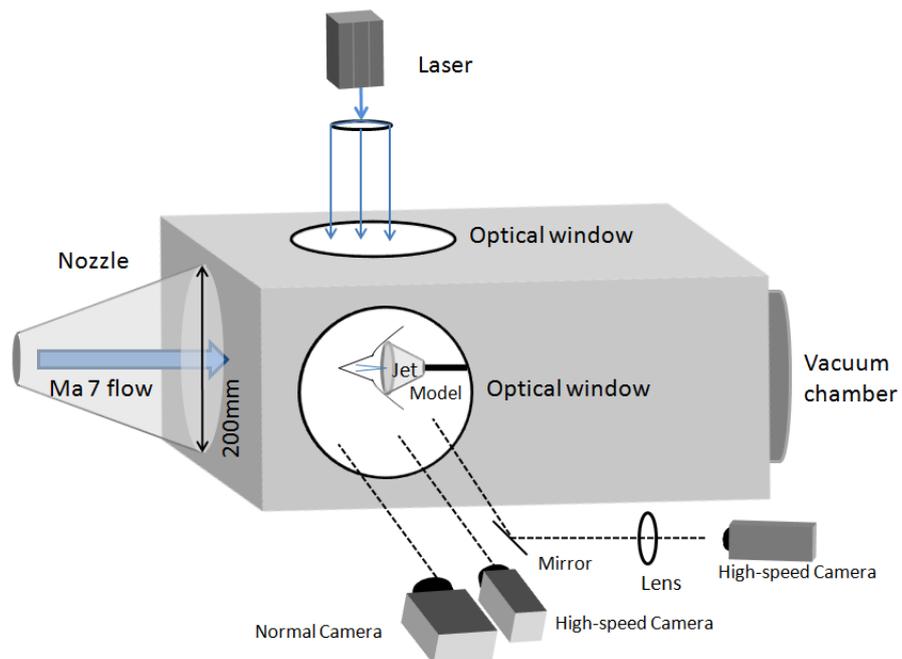


Fig. 3. Schematic of the experimental setup

3. Facility

The test facility used for the experiments is the Kashiwa Hypersonic and High-Temperature Wind Tunnel in the University of Tokyo[7]. It is a blow-down tunnel that operates at Mach number of 7 and 8. In the present study, the Mach 7 nozzle was used. Figure 4 shows the schematic description of the wind tunnel. The test model is injected after the steady hypersonic flow has been obtained. The tunnel conditions for this experiment are given in Table 1.

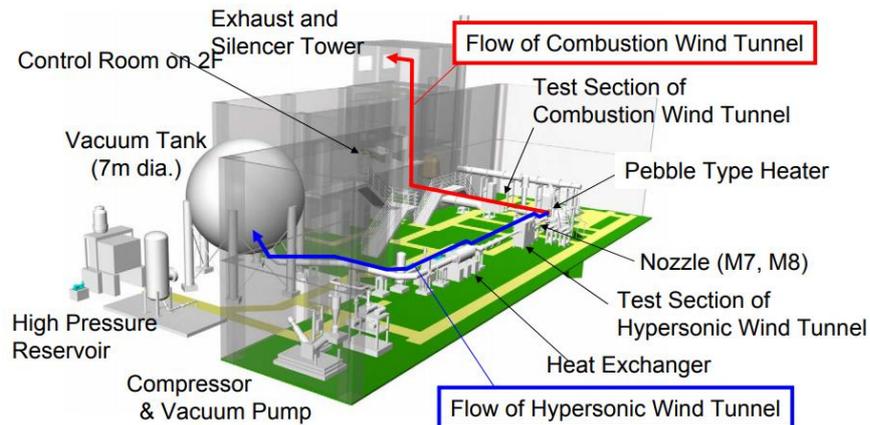


Fig. 4 Hypersonic and High Enthalpy Wind Tunnel at UT Kashiwa Campus (<http://daedalus.k.u-tokyo.ac.jp/wt/info/UTHYP.pdf>)

Table 1. Tunnel operation conditions in present experiment

Mach Number	7.0
Unit Reynolds No. (1/m)	1×10^5
Stagnation Temperature	540-670 K
Stagnation Pressure	950 kPa
Test Duration	Max. 60s
Nozzle Exit	200mm dia.
Uniform Flow Core Size	120mm dia.
T_0 of Jet Injection	299.15K
P_0 of Jet Injection	101 kPa

4. Result and Discussion

The discussion is divided into two parts. The first part is the test results of opposing air jets, the second part is results of opposing water jets..

4.1. Air opposing jet

Figure 5 is the Schlieren images of the flow field when the model was set in the Mach 7 freestream without the jet injection. The bow shock wave is clearly seen. This picture was taken by a normal video camera and the knife-edge is placed vertically. The separated flow was seen behind the edge of the shoulder of the model.

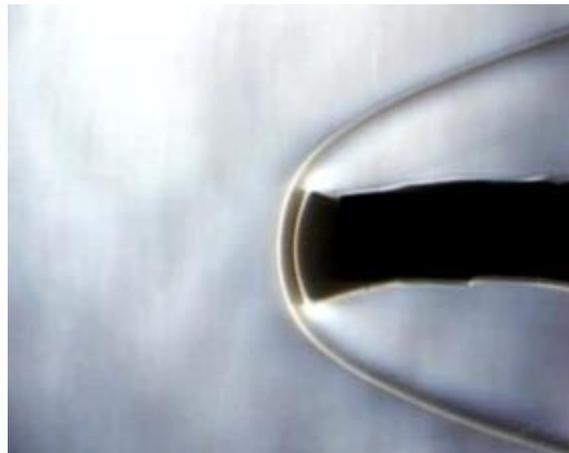


Fig. 5. Schlieren image of the flow field with no jet injection

Figure (6a) and (6b) shows snapshots of the Schlieren pictures in the case of the longest virtual spike obtained by the air jet injection. Here the penetration length is defined as the maximum distance between the pointed end of the jet and the surface of the model. The schematic of opposing jet flow filed is shown in Fig. (6c). The interface of the detached shock wave and bow shock can be seen at the position where the bow shock and the jet induced shock interact. The jet stream impinges the shear layer and the shock wave reflection can be seen in (6b), the high-speed Schlieren image Figure.

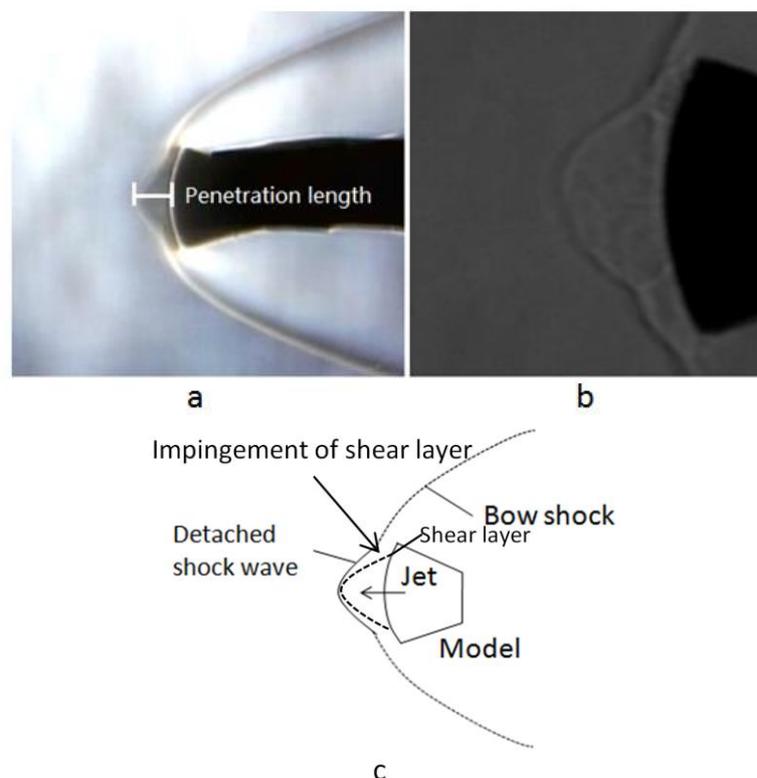


Fig. 6. Penetration length of opposing jet from normal-speed Schlieren system(left) and high-speed Schlieren system(right)

Figure 7 is a comparison of the Schlieren images from normal-speed camera(30 frames/sec) and high-speed camera(60,000 frames/sec, 256×128 pixels). The exposure time of high-speed camera was

1 μ s. These images were taken in the same blow and show the time history of the flow structure for the flow field with air jet injections at the attack angle $\alpha=0^\circ$. From high-speed Schlieren images, it is noticeable that there exist significant jet oscillation and unsteadiness at the front of the nose of the model. The phenomenon is one of the most important dynamic characteristics to show the instability of the opposing jet in hypersonic freestream. The mechanism or explanation of oscillation and instability remains unclear. One possible mechanism is the transition of the boundary layer flow on the nozzle wall from laminar to turbulent [8].

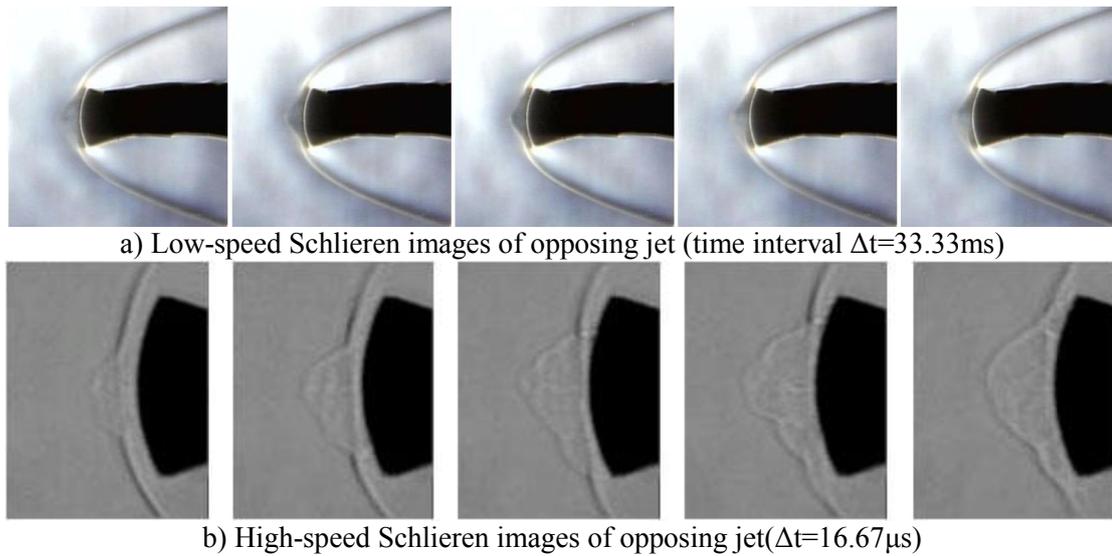


Fig. 7. Comparison of Low-speed and High-speed Schlieren images

However, such oscillations cannot be captured by the normal-speed Schlieren video. As can be seen in high-speed Schlieren images, the irregular compression wave generated by jet-free stream interaction appears in different positions during its oscillation. The high-speed Schlieren images at 60,000 frames/s successfully captured the oscillatory motion with the period of 250 μ s.

Figure 8 shows the penetration length fluctuate with time. Though the jet penetration is not necessarily symmetric with respect to the centerline as shown in Fig. 7, we define the most upstream point as the pointed end of the jet. From Fig. 8, which shows the part of the results used for measuring the distance between the pointed end of the jet and the surface of the model for 1000 frames of the Schlieren video, it can be seen that the amplitude of the fluctuation is about 10mm and the frequency is estimated at about 3963 Hz though the fluctuation is not perfectly periodic.

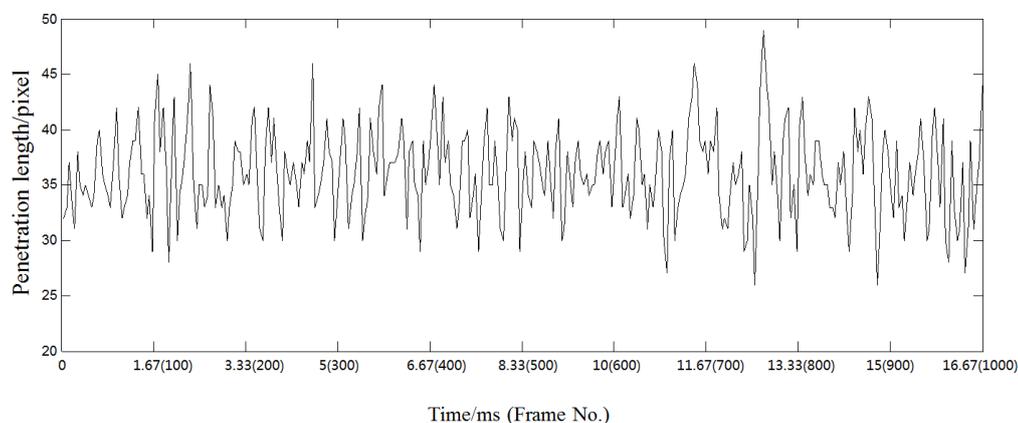


Fig. 8. Penetration length of air opposing jet fluctuation

Figure 9 is a series of the images of the jet/shock interaction, it can be seen from the figure that the jet oscillation interacts with the bow shock and the intersection of compression wave and bow shock locates on the model surface. The penetration length changes, and the feature of the jet expansion changes from one to another. The intersection of both waves kept moving reciprocally on the surface and the contour of bow shock fluctuated in a synchronizing manner. This indicates the presence of a correlation between the jet oscillation and the shock fluctuation. Such fluctuation may change the pressure distribution on the body and may cause unfavorable forces and/or moments on the body. For the design of the flow control system by the opposing jet, such unsteady behavior of the jet must be taken into account to avoid the unexpected effects on the body.

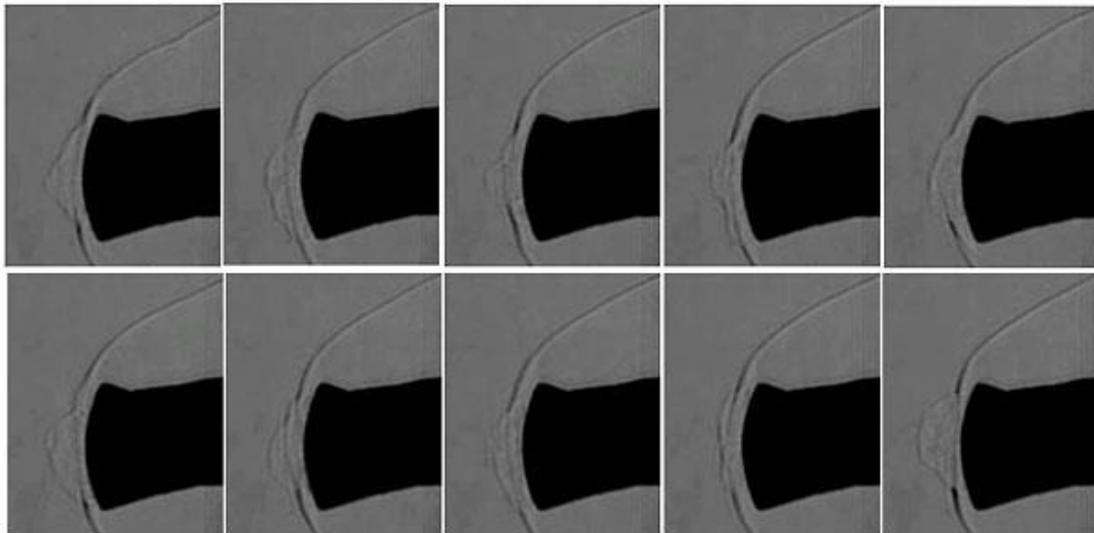


Fig. 9. Schlieren images of jet/shock interaction

The experiment for a spherical model was also conducted for comparison. Figure 10 is a time series of Schlieren images of the flow field. The penetration length for the spherical model is longer than that of capsule model. These results suggest that shape of model, in other words, the nose radius has obvious impact on the jet dynamic characteristics and oscillation.

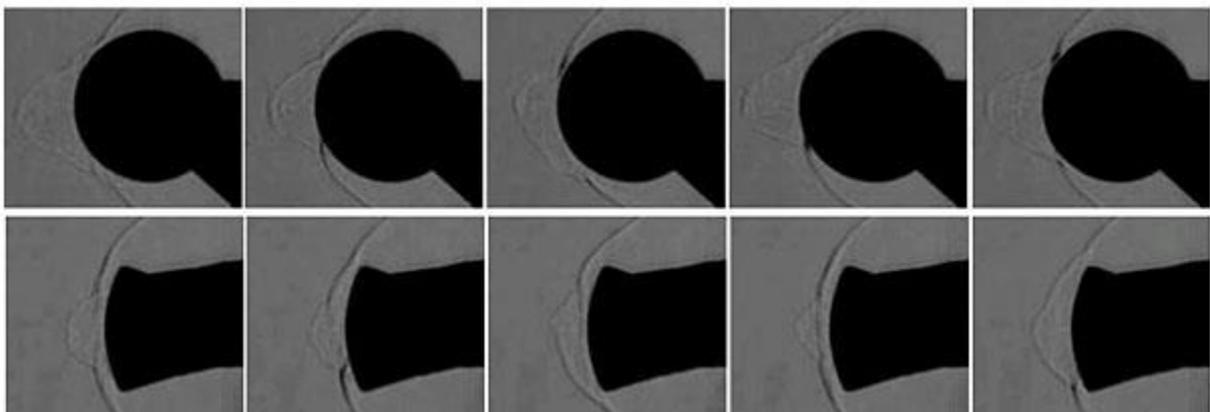


Fig. 10. Flow field of opposing jet on spherical model and capsule model

4.2. Water opposing jet

In this case, the opposing jet is injected into the stagnation pressure behind the normal shock wave, which is 14.58 kPa not 950 kPa. The jet stagnation pressure of 101 kPa is sufficiently high to generate

the jet. However, once the tip of the opposing jet goes out of the shock layer over the body, it is exposed to the freestream stagnation pressure. Consequently the air opposing jet can change the shape of the detached shock wave but cannot make a long penetration. As mentioned above, it needs high jet reservoir pressure for air opposing jet to realize a long penetration length to avoid impingement of the shear layer (see Fig. 6c), which can be danger for the surface of hypersonic vehicles. It seems reasonable to use liquid such as water for generating a long spike of the opposing jet. Since it is easier to obtain higher jet momentum with its density much larger than the gas, the penetration length of liquid jet is expected to be longer than that of gas jet. The dynamic characteristics and instability of liquid jet should be investigated in the same way as in the case of the air jet.

The flow field of water injection into Mach 7 flow is shown in Fig. 11. The attack angle for each run was 0° . As expected, longer virtual spike was formed for the water opposing jet and sharper conical shock wave was formed at the tip of the water jet. That oblique shock wave did not hit the surface of the blunt body when the penetration length reaches its maximum. The dark spots and regions in the Schlieren images indicate the presence of the liquid water. The water jet is well confined by the conical shock wave without spreading. The cone angle and the contour of conical shock wave in the Schlieren images seem relatively stable. Interaction between conical shock wave and bow shock can be seen near the rims of model. However, it can be seen clearly that the water jet bent downward due to both the gravity force and the aerodynamic force. Once the water spike inclines downward by the gravitational force, the asymmetric aerodynamic force bends it further.

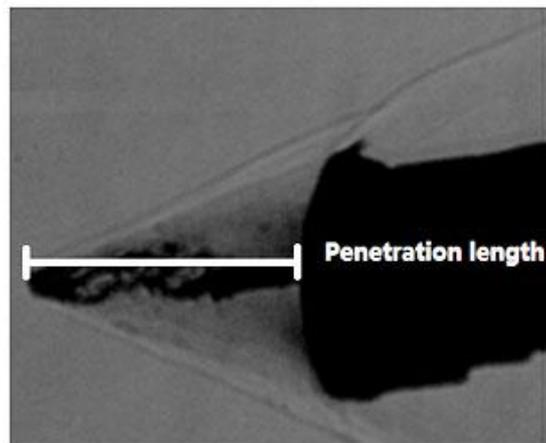


Fig. 11. Schlieren image of opposing jet and its penetration length

From the Schlieren images, the penetration length of water opposing jet is measured to be about $1.05 D$, where D is the diameter of model. Comparison is made between water jet and air jet in Fig. 12. We can see the penetration length of water jet is much longer than that of air jet (about $0.3D$). For the water tank was set at the same height as the jet exit, and the reservoir pressure of water jet was the same as that of the air jet. These results suggest that a liquid jet may be more effective than the gas jet from a viewpoint of the virtual spike effect. In the present experimental setup, the sonic jet was only tested as the opposing air jet. The effect of the jet exit Mach number should be investigated as well as the air jet stagnation pressure in the future.

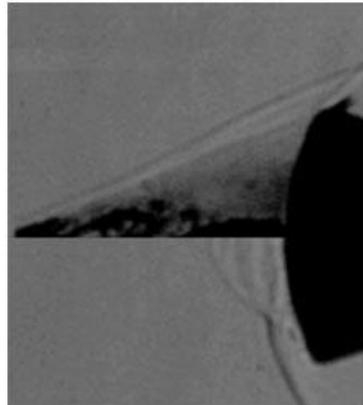


Fig. 12. Comparison of penetration length of water(upper) and air opposing jet

Figure 13 is the time history of the flow field of water jet captured by high speed camera, the snapshot was taken each 40 frames ($\Delta t=666.67\mu s$). It can be seen from the images that the water jet is unstable and oscillates at a relatively low frequency. The length and width of jet change along with time. Fig. 13(e) shows that when the penetration length was shorter than a certain value, the jet impinged on the model surface and the oblique shock wave hit the model, inducing the shock reflection. Complex interactions exist among the oblique shock wave, reflection shock and bow shock. Strong impact of the jet oscillation on the shock separation area can be seen from the enlarged view in Fig. 14. In addition, the frequency of the water jet oscillation is estimated at 66.65Hz, which can be calculated from the Fig. 15. Break up and bending of the water jet caused the fluctuation indicated as the second peak in Fig. 15.

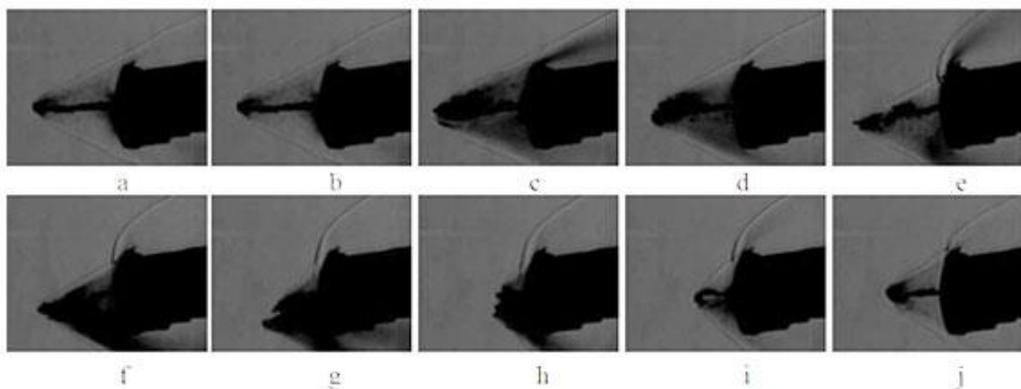


Fig. 13. Schlieren images of water opposing jet(interval of 40 frames, $\Delta t=666.67\mu s$)

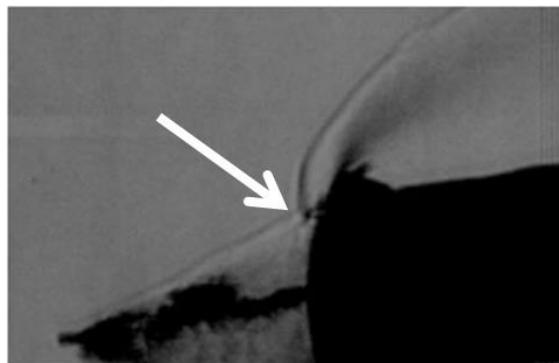


Fig. 14. Zoom in view of oblique shock wave/shock reflection/bow shock interactions

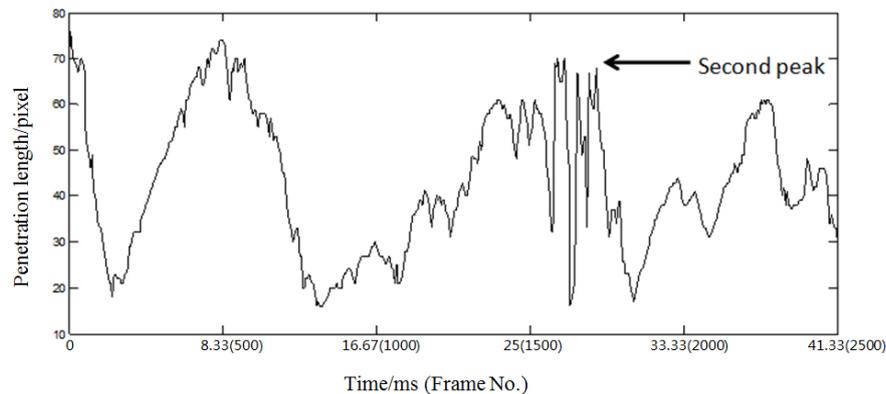


Fig. 15. Penetration height of water opposing jet oscillation

The enlarged view also shows that water flow over the rim of the capsule model and entered the wake flow area. The behavior of the injected water itself seems to be complicated and no explanation has been given up to this present time. In addition, it is reported by Rashis[4] that water jet is promising for cooling the re-entry vehicles. However, such uneven cooling can cause extra problem in the heating environment over the vehicle. Detailed investigation needs to be done on the water jet individually. The boundary of water jet is indiscernible in the Schlieren images due to the interaction with shock wave. On the other hand, the information of the cross-sectional image of the flow with jet is expected to be helpful for understanding the water jet behavior.

Flow visualization method using the laser sheet to obtain cross-section distribution, called as the laser cross-section imaging hereinafter, was performed. The schematic of laser cross-section imaging is shown in Fig. 16. It can be seen that the water spike forms an oblique shock wave at the tip and there is a recirculation region behind the oblique shock wave. Laser beam passing through a lens to fan out into a line, creating a cross-section through the flow. The water scatters the laser light towards the camera. Figure 17 is a time series of the jet cross-section taken by the high speed camera(5000 frames/sec, exposure time=198 μ s). The contour of water opposing jet can be seen from Fig. 17 clearly, the conical water jet well covered the model surface. The scattering of laser lights indicates the zone, where the liquid water or ice pieces exist. Most of the water stayed in liquid and solid state without turning into vapor, even the pressure in the test section is extremely low.

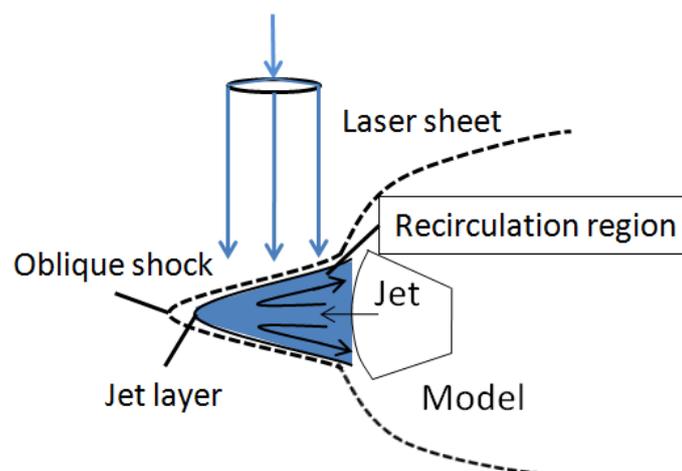


Fig. 16. Schematic of laser cross-section imaging

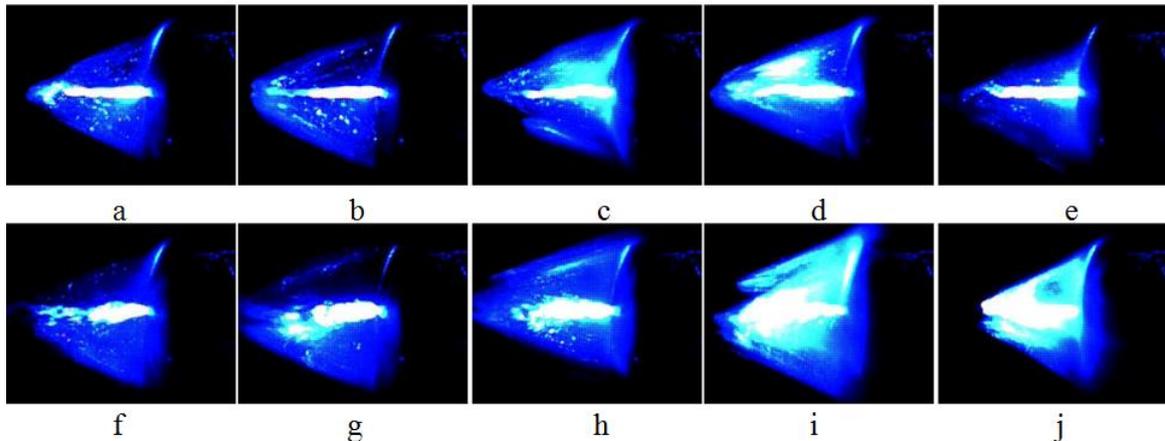


Fig. 17. Laser cross-section images of water jet($\Delta t=200\mu s$)

This observation suggests that phase change cooling can be also available for thermal protection. In the Fig. 17(c), at the moment after the penetration height reached its maximum and began to back to the jet outlet, part of the water seems to be 'peeled' off the conical surface and no longer confined by the water. The contour of oblique shock was unstable and began dispersing. Such breakup process of liquid jet was found in hypersonic cross flow by Beloki Perurena[6]. The results of Beloki's research indicates the correlation between jet breakup and shock fluctuation.

4.3. Visualization of air spike using Pressure-sensitive Paint technology

The above work shows that different kinds of visualization methods have been used in this research including Schlieren photography and laser cross-section imaging. In order to obtain detailed and quasi-quantitative/quantitative results of opposing jet, a trial experiment of using binder-less Pressure sensitive paints technology[9] was conducted to realize the measurement of the pressure distribution of opposing jet. The dye probes was absorbed by some small inorganic spherical porous particle (Godd ball, B-25C, Suzuki Yushi Kougyo, Japan). Such particles were seeded into the jet. It can be seen from the Fig. 18 that the signal of the luminescence of dye probe molecules was captured near the tip of the air 'virtual' spike. Figure (18b) shows the enlarged view of PSP signal.



Fig. 18. PSP signal of PSP particles in the air jet

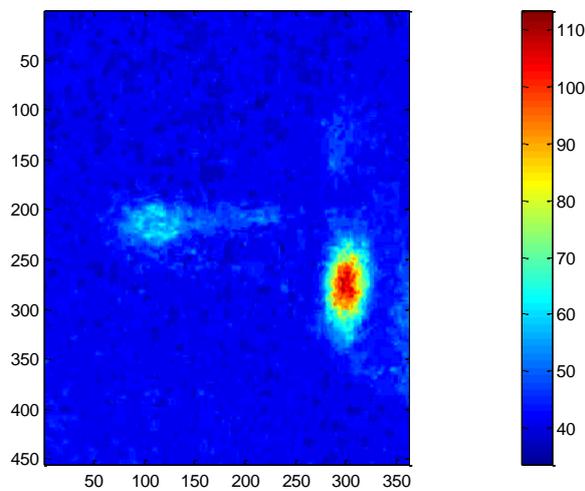


Fig. 19. Post-processed image of PSP signal

Figure 19 is the post-processed image of PSP signal. The light blue area is the PSP signal. A piece of tape coated with PSP powder was used as the object of reference for camera focusing. However, it can be seen from Fig. 19 that the intensity of PSP signal is low and the signal/noise ratio is not sufficient for flow visualization of opposing jet and calculation of pressure distribution. The PSP system will be improved in the near future for further research.

5. Conclusion

Experimental research was conducted to investigate the effect of opposing jet on hypersonic flow around the blunt body. The major conclusions are as follows:

- 1) The flow structure of opposing jet around the blunt body in hypersonic flow is visualized in this research. With the aid of high speed camera, the details of opposing jet-free stream interaction and jet instability have been captured. As a result of analyzing the Schlieren data, it was revealed that the jet oscillation and instability has a strong impact on the shock separation area.
- 2) Comparison of air opposing jet and water opposing jet was done. The penetration length of air jet is shorter than that of water jet. Frequency of air jet oscillation is larger than that of water jet oscillation. These results suggest that a liquid jet may be more effective than the gas jet from a viewpoint of the virtual spike effect.
- 3) Flow visualization methods including laser cross-section imaging and Pressure-sensitive paint technology were explored and new information about opposing jet was obtained in this research. Results of the laser cross-section imaging reveals the complicated water jet behavior. Trial experiment for binder-less PSP measurement of opposing jet was performed. The image of PSP signal indicates that PSP technology has potential to be used for quantitative measurement of opposing jet in hypersonic flow.

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