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Visualization of Flow Structure Around a Hypersonic Re-entry Capsule Using the Electrical Discharge Method

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Abstract : The spatial flowfield around a model of the re-entry capsule of the Mars Environmental Survey (MESUR) Pathfinder probe afterbody configuration traveling at a speed of Mach 10 was investigated utilizing the electrical discharge method. The shock shape ahead of the capsule was observed using a technique for visualizing 3-D shock shapes, then the streamline following the shock wave was observed utilizing a technique for visualizing streamlines crossing a shock wave. Subsequently, the flowfield behind the capsule was observed by applying a technique for visualizing flow patterns. From these observations, the spatial flow construction including the wake region such as a separation, free shear layer, and rear stagnation location behind the capsule was made clear. These experiments utilizing the electrical discharge method qualitatively demonstrated the spatial flow structure before and behind the hypersonic re-entry capsule, which had been very difficult to visualize. These experiments were carried out by using a pulsed facility of 18 ms duration.

Keywords : Hypersonic flow visualization, Electrical discharge method, Re-entry capsule, Wake, Flow structure, Hypersonic flow

1. Introduction

This paper presents the visualized flow structure before and behind a model which is similar to the Mars Environmental Survey (MESUR) Pathfinder probe afterbody configuration traveling at a speed of Mach 10 utilizing the electrical discharge method.

The difficulty of visualizing flow structures around hypersonic vehicles is the direct consequence of the characteristics of hypersonic flow obtained and used in laboratories: in general, very high speed, low density, and short duration. The experimental conditions clearly spell immense difficulty in developing visualization techniques for hypersonic flow structures. Thus, only a few useful experimental techniques for extracting flow phenomena such as streamlines have been developed, for example the Electron Beam Method by Larigaldie et al. (1998) and Laser Induced Fluorescence. For these reasons, recent investigations of flow structures around hypersonic vehicles such as re-entry capsules have been based primarily on computational investigations. A large number of worthy results have been reported based on such investigations, for example, Gnoffo et al . (1999), Mitcheltree et al. (1999), Moss et al. (1999), and Ivanov et al. (1998), et al. However, the importance of the visualization data of flow structure is undeniable, and will help verify computational results.

Concerning the investigation of the flowfield structure around the MESUR Pathfinder probe afterbody, a large number of papers have been reported. Dogra et al. (1994) investigated the effect of an afterbody sting on the wake structure for a generic configuration. In an investigation of the effect of chemistry in the wake structure, Dogra et al. (1995) reported that DSMC(Direct Simulation Monte Carlo) and Navier-Stokes calculations predicted a steady vortex in the wake region. Mitcheltree and Gnoffo (1995) calculated streamlines in the near wake region with non-ablating surfaces and showed the result including the vortex structure just behind the capsule. Moreover, Moss et al. (1999) reported the calculated aerodynamics with various angles of attack obtained by using the actual flight measured results. The above investigations were carried out mainly by calculation. Hollis and Perkins (1999) investigated the flow structure around a 70-deg sphere-cone planetary with a sting by using a Mach 10 perfect gas wind tunnel with a technique of oil flow and illustrated the transitional free shear layer from laminar to turbulent. They also mentioned that without flowfield diagnostics such as hot-wire surveys, or schlieren or electron-beam photography, which were not available in that study, definitive conclusions about the state of the free shear layer could not be made.

Under these circumstances, the authors and others have developed a unique technique called the electrical discharge method for visualizing nearly all significant hypersonic flowfield phenomena, such as arbitrary 3-D shock waves (Nishio 1990, Nishio 1992), spatial streamlines after shock wave (Nishio 1992), spatial flow patterns, and boundary layers (Nishio 1996). The electrical discharge method can also be used to visualize more complicated hypersonic flowfield phenomena such as shock/shock interactions, shock-wave/boundary-layer interactions (Nishio 1996), and shock/vortex interactions. The method permits the transformation of the energy of an applied electrical field into photons by generating inelastic collisions between the molecules and the electrons. Applying this electrical field results in very minor temperature increases in the gas, leading to very low levels of flow disturbance, as reported by Nishio and Hagiwara (1999).

This study applied this unique method to the visualization of the flow structure before and behind a model of the MESUR Pathfinder probe afterbody configuration. The experiments were carried out by visualizing the shock shape ahead of the model, streamlines after the shock wave, and flow patterns including the wake structure behind the model. The flow structure was clearly visualized through experiments based on the electrical discharge method.

The model shapes and the flow structures visualized by this technique will be helpful for verifying the computational results.

2. Experimental Equipment

The experiments were carried out under the test conditions defined by the characteristics of the hypersonic tunnel, which were: Mach number = 10, freestream density = 4.5×10^{-3}kg/m^3, freestream velocity = 1.5km/s, static pressure = 70Pa, test duration = 18ms and Reynolds number = 1.7×10^6. The test gas was air. Figure 1 shows the electrical circuit for generating electrical fields in the hypersonic flowfield. The circuit was designed so as to operate while the hypersonic flow of the tunnel was being obtained. The electrical circuit was quite simple, but permitted the visualization of various types of flow structure around hypersonic vehicles, just by selecting suitable values of the resistances R1, and R2 and a moderate value of applied voltage to the condenser C. It was possible to determine suitable values for the resistances and condenser during the actual undertaking of the experiment, thereby allowing them to be undertaken simply and easily.

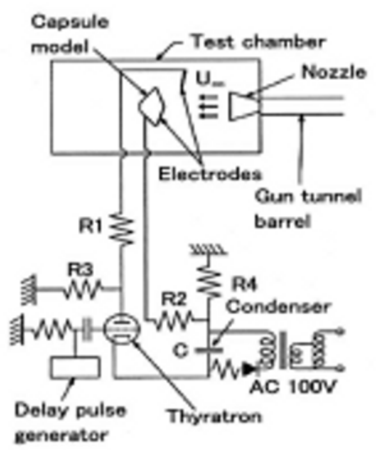
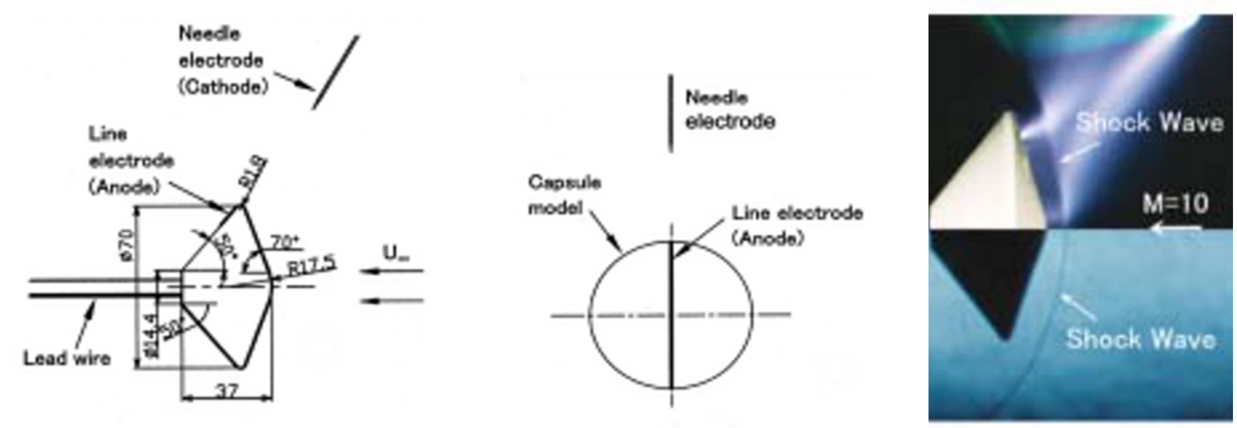


Fig. 1. Electric circuit.

3. Shock Wave Ahead of Capsule

The shock shape ahead of the model was visualized by the electrical discharge method. Figure 2(a) shows the arrangement of the model and a pair of electrodes. A needle electrode (cathode) was installed in the freestream and a very thin line electrode (anode) of some 100μm was bonded to the model surface. An initial voltage of 2kV was applied for 1μs to the pair of electrodes, generating a sheet-shaped electrical discharge between the electrodes. The shock shape on the plane made by the pair of needle-line electrodes was obtained. In this experiment, R1 and R2 were 0Ω and 500Ω, respectively. The shock shape was visualized by the radiation contrast at the shock position in the sheet-shaped electrical discharge path. Figure 2(b) shows the visualized shock shape ahead of the model.

To verify the correctness of the visualized shock shape by the electrical discharge method, it was compared with the result obtained by the schlieren method. The schlieren photograph is shown in the same figure and the results show a good agreement.



Side view

Front view

(a) Arrangement of model and pair of electrodes and model dimensions in mm.

(b) Upper photograph is electrical discharge. Lower one is schlieren.

Fig. 2. Visualization of shock wave.

4. Streamline After Shock Wave

To visualize the streamline after the shock wave generated ahead of the capsule, we applied the technique for visualizing streamlines crossing the shock wave.

The principle of the technique, as reported by M. Nishio (1992), is as follows: when a columnar spark discharge is generated across a shock wave by the application of high voltage to a pair of point to point electrodes, as shown in Fig.3, and the application of voltage between the electrodes is continued after the spark discharge, the columnar discharge drifts with the flow, radiating light. In this case, the radiation intensity from the drifting columnar discharge is not equal throughout the columnar discharge. The radiation intensity of the drifting electrical discharge changes at

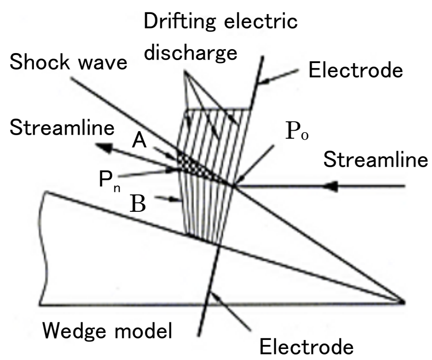


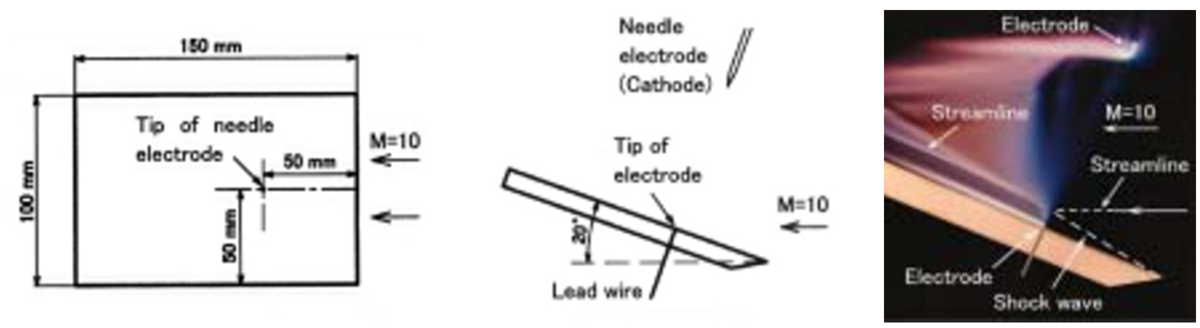
Fig. 3. Illustration of visualizing principle for streamline after shock wave.

the position Pn on the streamline coming from the intersection Po of the shock wave and the initial spark discharge. From this, the radiation contrast appears between A and B regions where A is the region above the streamline and B is the one below the streamline.

Therefore, the streamline can be obtained by taking a photograph of the continuous drifting columnar discharge.

Visualization of a streamline over a wedge with a sharp leading edge was performed to show the correctness of the visualization result. Figure 4(a) shows the wedge shape, including its dimensions and a pair of needle electrodes. The visualized result is shown in Fig. 4(b). We can see that the visualized streamline in the shock layer is nearly parallel to the wedge surface, corroborating the accuracy of the streamline visualized by the present method. The approximate streamline over the wedge is easily obtained through conventional modeling and calculations. However, visualizing such streamlines in hypersonic flow by experimental techniques has been very difficult, even for the case of a very simple flow structure. Such visualization is now made possible by the development of the electrical discharge method.

The visualization of streamlines around the MESUR model was carried out by applying the above technique. Figure 5 shows the configuration and placement of the model and a pair of electrodes. In principle, since we can obtain one streamline at a certain location through one experiment, the two electrodes are moved and positioned at suitable positions to permit visualization of several different streamlines crossing the shock wave. In these experiments, the values of R1 and R2 were 2kΩ and 0Ω, respectively. An initial voltage of 2kV was applied to the pair of electrodes generating a drifting columnar electrical discharge. Figure 6 gives the experimental results. In the figures (a), (b), (c), (d), and (e), five streamlines of different location were visualized. As is well known by hypersonic flow researchers, visualizing these streamlines to this point has been quite difficult. But now, these flow patterns can be visualized easily and simply as demonstrated by applying the electrical discharge method.



Top view   Side view

(a) Arrangement of wedge model with sharp leading edge and pair of electrodes. (Unit: mm)   (b) Visualized streamline.

Fig. 4. Visualization of streamline over wedge.

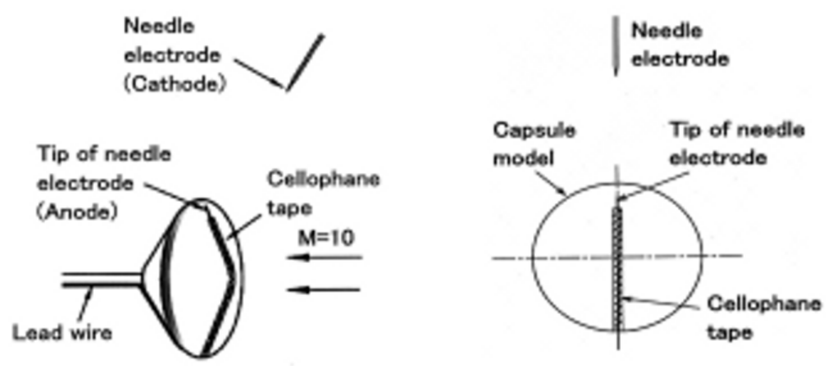
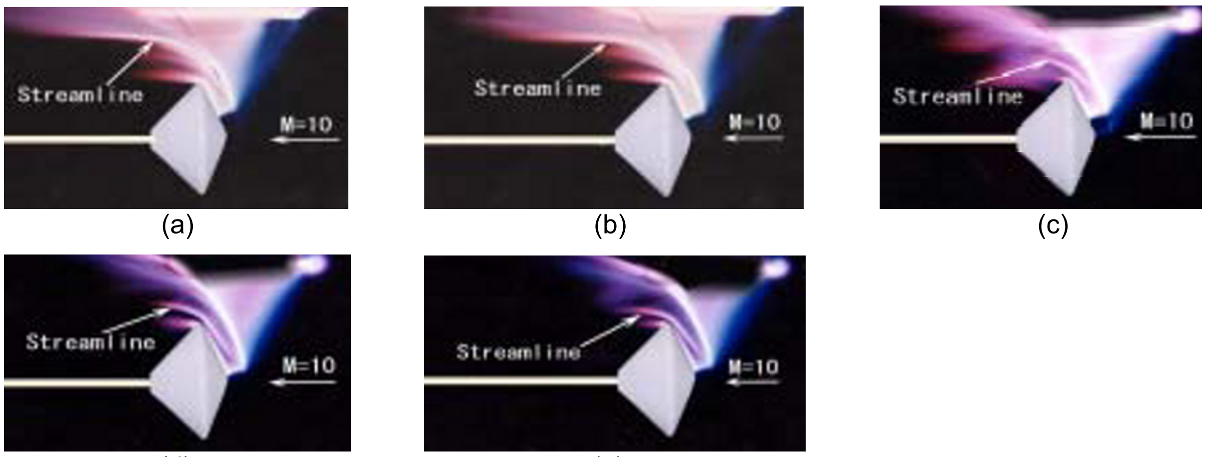


Fig. 5. Arrangement of capsule model and pair of electrodes for visualizing streamline after shock wave.



(a) (b) (c)
(d) (e)

Fig. 6. Visualized streamlines after shock wave ahead of capsule.

5. Flow Structure Behind Capsule

Flow patterns behind the capsule were investigated. To visualize the streamline and the re-circulation region including a separation, free shear layer, and reattachment location the following technique was used. As an example, an arrangement of a model and a pair of electrodes is shown in Fig.7. The tips of the two electrodes were arranged just at the model surface so as not to disturb the flow. The distance between the tips was made very small(2.5mm to 5.0mm). When a voltage was applied between the electrodes, excited particles were produced near the tips. Figure 7 shows the radiation in the case of no flow. When this electric discharge is generated in the flow, these excited particles are drifted by the flow, radiating light. Although the radiation is very little, it can be observed by using an image intensifier. This radiation can be used as a tracer and the flow pattern is obtainable by using the technique.

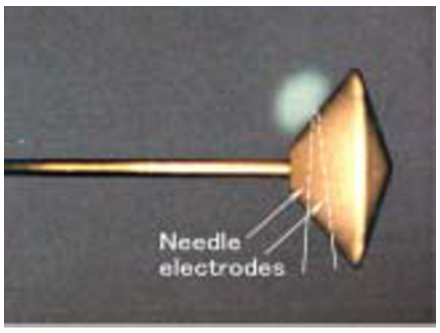


Fig. 7. Arrangement of model and electrodes, and radiation of electric discharge without flow.

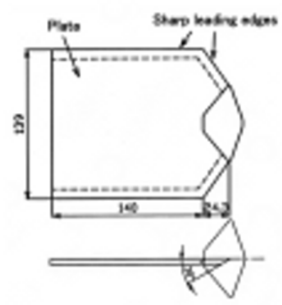
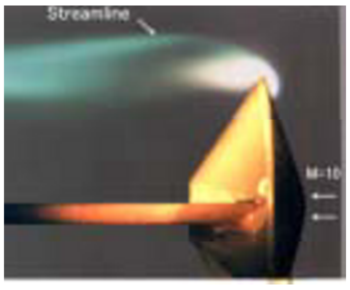


Fig. 8. Arrangement of capsule and plate. (Unit : mm)

A. Streamline

The streamline after the capsule was investigated using the technique described above. The arrangement of the model with a plate is shown in Fig.8. This plate separates the upper flowfield and the lower one behind the model. The plate has sharp leading edges so as not to disturb the flow. The experimental result was shown in Fig. 9(a). As shown in the figure, the upper part of the drifting radiation path which was used as a tracer demonstrated a large radiation contrast. We are able to consider that the radiation border of the tracer approximately indicates a single streamline. The radiation strength of Fig. 9(a) may be considered to be too large. However, actuary, it is not so large. Fig. 9(b) is the same picture as Fig. 9(a). The difference between the two pictures is the sensitivity of the camera. When the electric discharge is generated, the radiation looks like Fig. 9(b) to the naked eye. Another experimental result of streamline obtained by a different location of electrodes was shown in Fig. 10.



(a) Visualized streamline by using image intensifier camera.

(b) Same electrical radiation as;(a) no intensifier.

Fig. 9. Visualization of streamline.

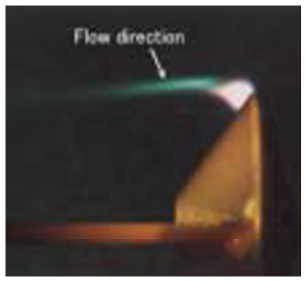


Fig. 10. Visualization of flow direction.

B. Separation Point and Free Shear Layer

The separation point behind the capsule was investigated. The experimental result is shown in Fig. 11. The explanation of the flow structure is illustrated in this figure. From this experimental result it was found that the separation behind the capsule occurred very soon just after the capsule shoulder.

Further experiments were carried out about the separation from a different point of view. The experimental result is shown in Fig. 12. From the figure we can draw an illustration of the flow structure as shown later in this paper. The experimental flow structure shown in Fig. 11 and Fig. 12 agreed well concerning the separation position and the flow direction of the shear layer just after the separation.

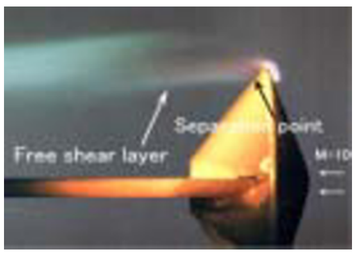


Fig. 11. Visualization of separation point and free shear layer.

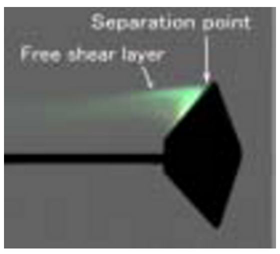


Fig. 12. Visualization of flowfield inside the re-circulation region.

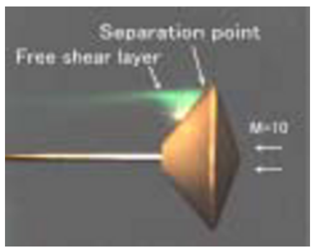


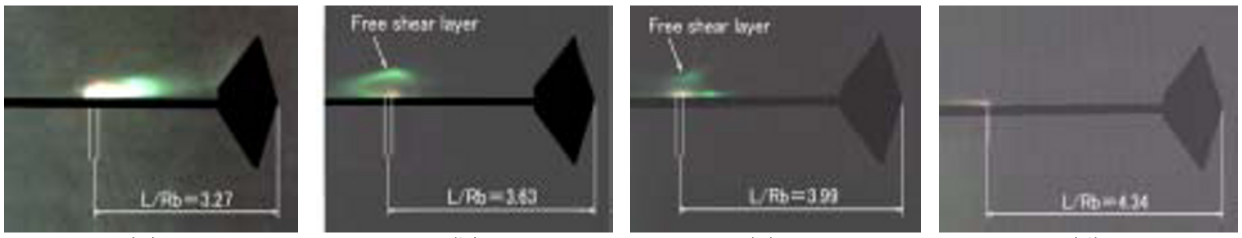
Fig.13. Visualization of separation point using sting.

These visualized flowfields showed that the separation occurred very soon after the capsule corner and that the flow direction (angle of the model surface and free shear layer) after the separation was very large. We could guess from these experimental results that the vortex region behind the capsule would be considerably large one, as will be discussed later in this paper.

In these experiments a plate with sharp leading edges was used instead of a thin sting for fear that the lead wires used for generating an electrical discharge might disturb the flowfield. In the next experiment the difference of the location of separation points and free shear layers just after the separation between the two cases using the plate and the thin sting was compared. Figure 13 showed the experimental result using a thin sting of Rs/Rb=1/14. (Rb:radius of capsule and Rs:radius of sting) From the comparison, it was found the separation position and free shear layer using the plate were nearly the same as those of the sting.

C. Free Shear Layer and Reattachment Region

Further investigations of the flow structure about the rear stagnation region were carried out. As shown in Fig. 14, the electrodes were positioned at four different locations L/Rb=3.27, L/Rb=3.63, L/Rb=3.99, and L/Rb=4.34, respectively. L is the distance between the capsule nose and electrodes. Each electrode was positioned at the center of the plate. The experimental results are shown in Fig. 14 (a), (b), (c), and (d), respectively. These results indicate the followings: when L/Rb was 3.27,



(a) (b) (c) (d)

Fig. 14. Visualization of flow pattern near symmetry axis. L : distance between capsule nose and electrodes, Rb : radius of capsule.

the apparent re-circulation flow toward the capsule was generated and that the flow moved toward the separation position near the capsule shoulder. When L/Rb was 3.63, it was confirmed that there was a free shear layer at a considerable distance from the symmetry axis. Also, at the left side of the electrodes position the flow from the neighborhood of the free shear layer comes down abruptly toward the symmetry axis. When L/Rb was 4.34, the flow near the symmetry axis moved toward the downward. Judging from these experimental results, it was considered that the location of rear stagnation was at around L/Rb=4.

6. Discussion and Conclusion

The flow structure obtained in these investigations is illustrated in Fig. 15. As far as the authors know, this is the first spatial flow structure before and behind a hypersonic re-entry capsule which was obtained by visualization. As is well known by hypersonic researchers the visualization of spatial hypersonic flow structures has been an extremely difficult task although it is very important in order to promote space developments from the aerodynamics point of view. However, the electrical discharge method has made it possible to obtain such flowfield visualization.

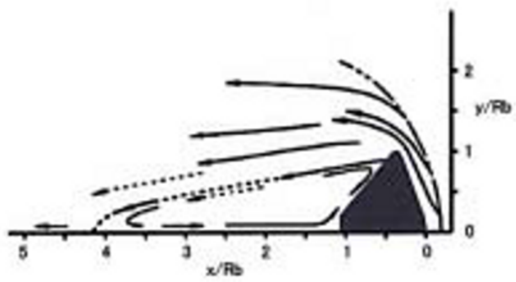


Fig. 15. Experimental flow structure around hypersonic capsule obtained by visualization. Dotted lines are conjectural illustration. x : axial distance from stagnation point measured along symmetry axis, y : radial distance from symmetry axis.

The free shear layer attachment occurred at around L/Rb=4. However, considering from the experimental result in Fig. 14, the rear stagnation region might be unstable, although the shock shape ahead of the capsule and the separation point seemed to be nearly stable during the test time and they occurred at the same locations, respectively.

In these experiments air has been used as a test gas. However, carbon dioxide seems to be preferable to air, although the experiment becomes a little difficult.

The model shape used in this study was similar to the MESUR Pathfinder probe afterbody configuration. However, the electrical discharge method is applicable to any kind of model shapes.

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