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Flowfield around Hypersonic MESUR Capsule

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ABSTRACT

The flowfield around a model of the Mars Environmental Survey (MESUR) Pathfinder probe traveling at a speed of Mach 10 was investigated by the electrical discharge method. The shock shape ahead of the capsule was visualized using a technique for visualizing 3-D shock shapes, then the streamline following the shock wave was visualized using a technique for observing streamlines crossing a shock wave. Subsequently, the expansion wave from the capsule shoulder was visualized by applying a technique for observing density changes. The flow pattern behind the capsule was then visualized by applying a technique for observing streamlines near a model surface. Finally, the flow pattern at a small angle of attack near the capsule shoulder was compared with one at zero angle of attack. These experiments qualitatively demonstrate spatial flow structures before and behind the hypersonic re-entry capsule. The techniques used in these experiments, known as the electrical discharge method, enable experimental investigations of spatial flow structures around the hypersonic re-entry capsule, which to date have been quite difficult to perform. These experimental results would be useful in comparing and verifying the results obtained by numerical calculations.

Keywords: Re-entry, Visualization, Streamline, Hypersonic flow, and Electrical discharge-method

1. Introduction

The purpose of this paper is to present the visualized spatial flow structure around a Mars Environmental Survey (MESUR) Pathfinder probe.

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. Few useful experimental techniques for extracting flow phenomena such as streamlines have been developed, except for the electron beam method[1,2], LIF[3,4], and some other methods[5]. For the reasons already given, 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[6~15] based on such investigations. However, the importance of the visualization data of flow structure is undeniable, and will help verify computational results.

The author and others have developed a unique technique called the electrical discharge method[16~20] for visualizing nearly all significant hypersonic flowfield phenomena, such as arbitrary 3-D shock waves (density changes), spatial streamlines at a distance from the model surface, spatial streamlines near the model surface, and boundary layers. 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, and shock/vortex interactions. The method permits the

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transformation of the energy of an applied electrical field into photons by generating inelastic collisions between the molecules and the electrons. Applying these electrical field results in very minor temperature increases in the gas, leading to very low levels of flow disturbance, as reported by M.Nishio.

This study applied this unique method to the visualization of the flow structure before and behind a model of the MESUR Pathfinder probe. The experiments were carried out by visualizing the shock shape ahead of the model, streamlines after the shock wave, expansion waves from the capsule shoulder, flow patterns just behind the model, and flow patterns near the capsule shoulder at a low angle of attack of 3°. The flow structure was clearly visualized through experiments based on the electrical discharge method.

2. Experimental Equipment

The sketch of the hypersonic gun tunnel used in these experiments is shown in Fig.1. The main characteristics of the tunnel are as follows: Mach number was 10, test duration was 10ms, and freestream density was $4.5\times10^{-3}kg/m^3$. Figure 2 shows the test section of the tunnel, including a capsule model, a model supporting system, and a hypersonic nozzle. As shown in Fig.2, the model was set. Figure 3 shows the electric circuit for generating electric field in the hypersonic flowfield. The model dimensions of the capsule is shown in Fig.4. This model is similar to MESUR Pathfinder probe.

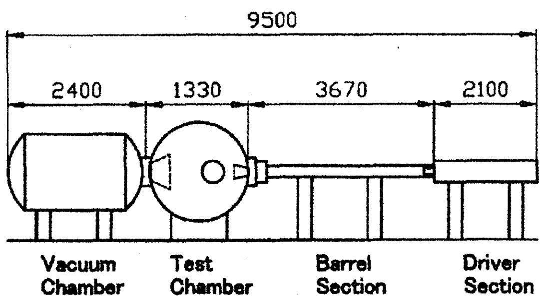


Fig.1 Sketch of hypersonic gun tunnel. (Unit: mm)

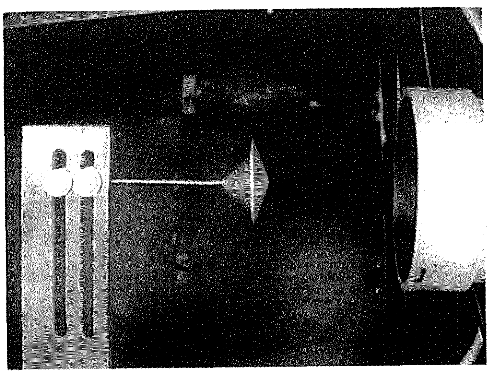


Fig.2 Test section including capsule model, hypersonic nozzle, and model supporting system.

3. Shock Wave Visualization Ahead of the Capsule

The shock shape ahead of the model was visualized using one technique of the electrical discharge method. Figure 4 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. We applied an initial voltage of some 2kV to the pair of electrodes, generating a sheet shape electrical discharge path for some 1μsec between the electrodes. We obtained the shock shape on the plane made by the pair of electrodes. In this experiment, R1 and R2 were 0Ω and 500Ω, respectively. We visualized[16,17] the shock shape by the radiation contrast at the shock position in the sheet shape electrical discharge path. Figure 5 shows the visualized shock shape ahead of the model.

4. Streamline after Shock Wave

To visualize the streamline behind the shock wave generated ahead of the capsule, we applied the technique

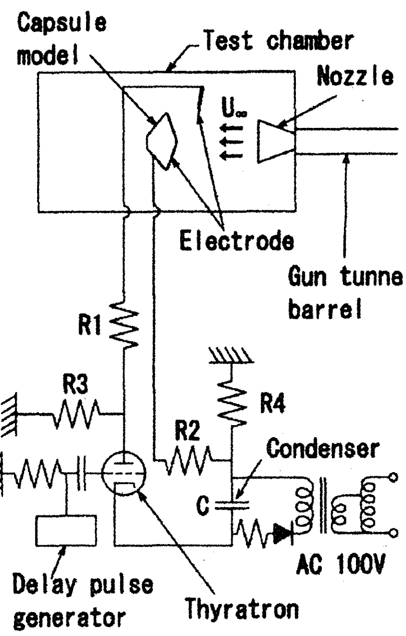


Fig.3 Electric circuit.

for visualizing streamlines crossing the shock wave. The principle behind the technique is as follows; as reported by M.Nishio[19], 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.6, 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 intensities from the drifting columnar discharge are not equal throughout the columnar discharge. The radiation intensities of the drifting electrical discharge change at the position Pn on the streamline where it passes through the intersection of the shock wave and the initial spark discharge. 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 as an example. Figure 7(a) shows the wedge shape, including its dimensions and a pair of needle electrodes. The visualized result is shown in Fig. 7(b). We 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.

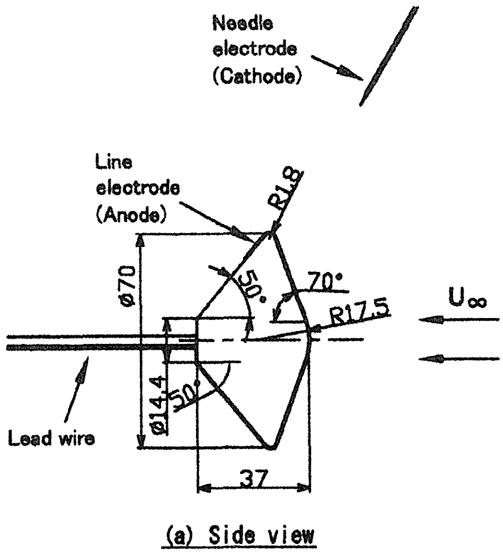


Fig.4 Model shape (Unit: mm) and arrangement of a pair of electrodes for visualizing shock shape ahead of the model.

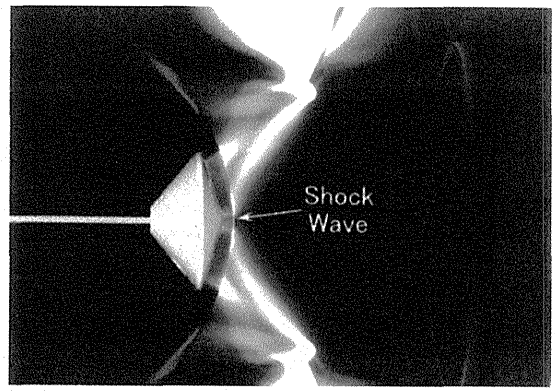


Fig.5 Visualized shock shape. Image of the capsule model is inserted in the photograph.

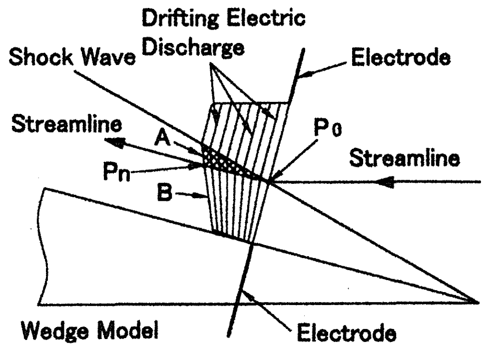
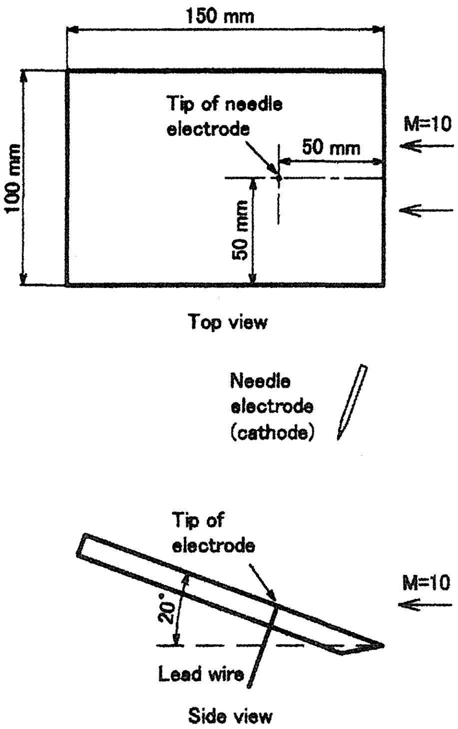
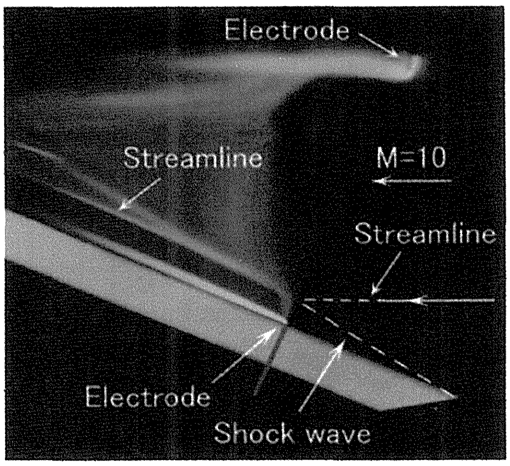


Fig.6 Illustration of visualizing principle for streamline after shock wave. A: The region above the streamline in the shock layer. B: The region below the streamline in the shock layer.



(a)



(b)

Fig.7 Visualization of streamline over wedge.
(a) Arrangement of wedge model with sharp leading edge and a pair of electrodes. (Unit: mm)
(b) Visualized streamline. Angle of attack is20° .

We undertook a visualization of streamlines around the capsule by applying the above technique. Figure 8 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

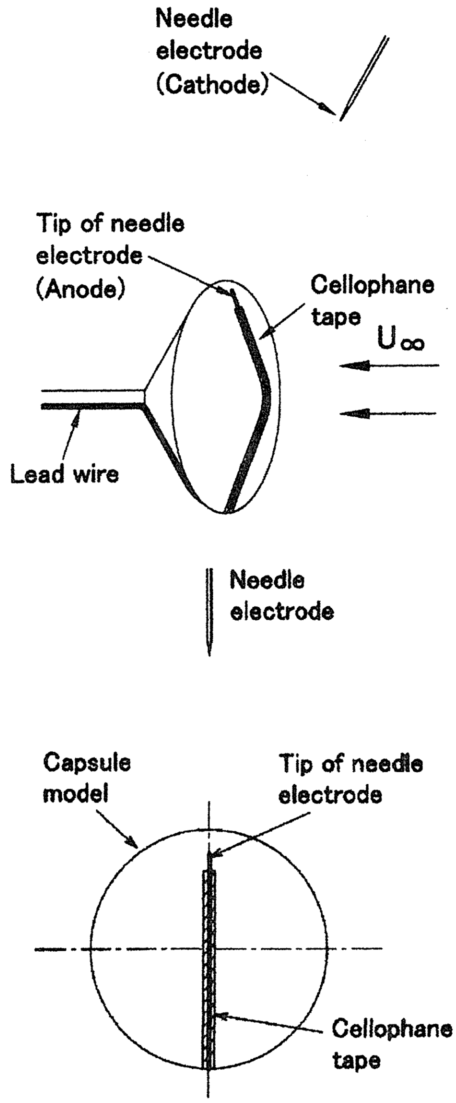


Fig.8 Arrangement of model and a pair of electrodes for visualizing streamline after shock wave.

experiments, R1 and R2 had the values 2kΩ and 0Ω, respectively. We applied an initial voltage of some 3kV to the pair of electrodes and generated a drifting columnar electrical discharge. Figure 9 gives the experimental results. In figures (a), (b), (c), (d), and (e), respectively, the five streamlines of different location were visualized. In order to observe the various streamlines, the position of the tip of needle electrode on the model surface was moved as shown in Fig.9. As is well known by hypersonic flow researchers, visualizing these streamlines to this point has been quite difficult. But now, these patterns can be visualized easily and simply as demonstrated by applying the electrical discharge method.

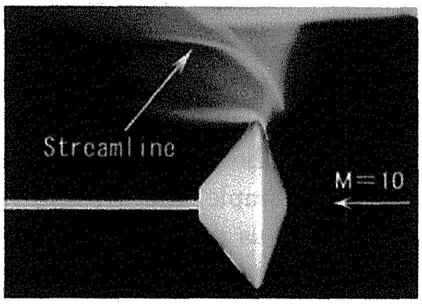
5. Expansion Wave from Capsule Shoulder

Theoretical investigations have made it clear that strong expansion waves issue from the shoulder of the capsule. In this study, these expansion waves were visualized by applying the technique for visualizing density changes. Figure 10 shows the configuration and positioning of the model and the pair of electrodes. An initial voltage of some 2kV was applied between the electrodes for approximately one microsecond, generating a sheet shape electrical discharge path. The visualized result is shown in Fig.11. We can see the two waves issuing from the capsule shoulder. In general, the flowfield in the expansion region is considered to be characterized by isentropic flow, with continuous generation of expansion waves. However, with measurements based on the electrical discharge method, the expansion waves were visualized as lines when the waves were powerful.

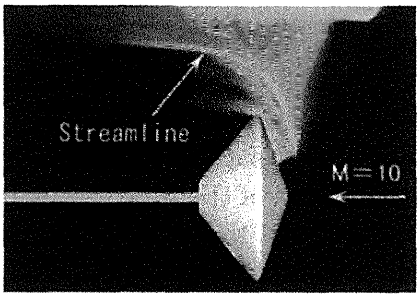
6. Flow Pattern Behind the Capsule

To visualize the spatial flowfield of the near-wake behind the hypersonic capsule, we applied the visualizing stream pattern technique near the model surface. The principle underlying the technique was described by M.Nishio[18]. When a high voltage is applied to the anode needle electrode while a freestream is being generated, ions are generated near the tip of the needle electrode. The ions drift according to the flow and radiate light due to the recombination between the ions and electrons. This radiating light can be used as a tracer indicating the flow pattern. We can then visualize the flow structure near the model surface by taking a photograph of the radiating light.

We applied the previously described technique to visualize the near-wake behind the capsule. The configuration and positioning of the model and anode electrode are shown in Fig.12. Voltages of 2kV~3kV were applied to the anode electrode when a freestream of Mach 10 was being achieved, and drifting radiations were generated. We took photographs of the drifting and radiating paths with a camera. The camera shutter was left open



(a)



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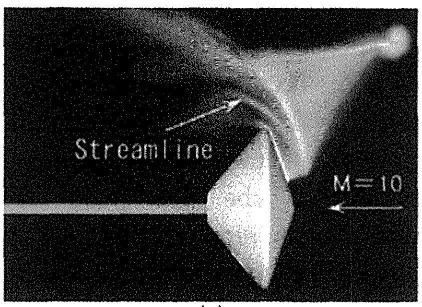

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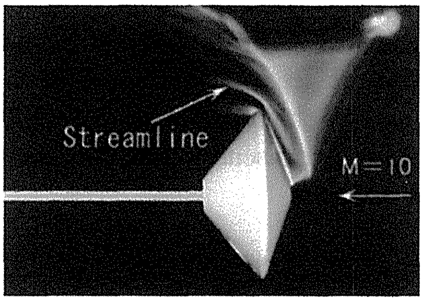

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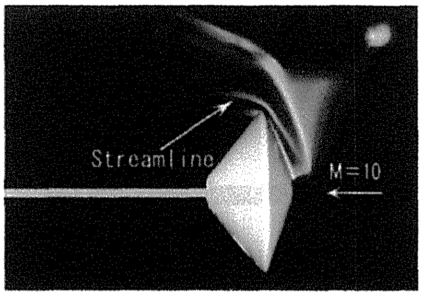

(e)

Fig.9 Visualized streamlines of various positions after shock waves.

during the experiment. The results are shown in Fig.13 (a), (b), and (c). In this experiment, the various photographs could be obtained by changing the applied voltage of 2kV to 3kV to the anode electrode on the model surface. As Fig. 13(b) shows, for example, the drifting radiation path which is used as a tracer demonstrates a comparatively apparent radiation contrast. We are able to consider that the radiation border of the tracer approximately indicates a single streamline. As Fig.13(a) shows, a dark portion is visible. Based on the experimental procedure, if a vortex exists in the flowfield, excited particles generated as tracers such as ions, cannot readily enter into the region of the vortex; thus resulting in the dark portion at the region of the vortex. In this respect, it is considered there possibly occurs a vortex at the dark portion. Moreover, just before the dark portion, it also appears that a separation may occur, as indicated in the figure. In discussions of the occurrence of a vortex, we must consider that the flow phenomena of vortices are generally unstable. However, it is hard to indicate the instability of the near-wake from the experimental results, since the camera shutter is left open during the experiment and all light from the beginning to the end of the radiating and drifting tracer is captured in a single picture. Use of a high-speed camera should make it possible to capture several framing pictures of sufficient short intervals of the radiating and drifting tracer, permitting further discussion of the instability of near-wake patterns.

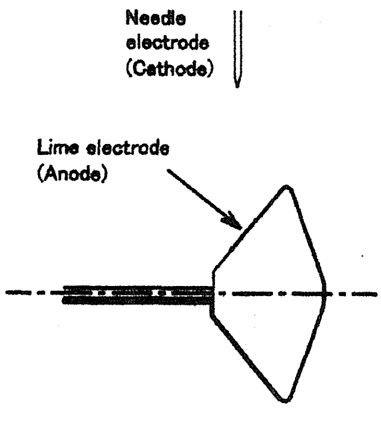

Fig.10 Arrangement of model and a pair of electrodes for visualizing expansion wave.

7. Flow Pattern near Shoulder with Angle of Attack

We also investigated the flowfield near the shoulder of the capsule with a small angle of attack. In this experiment, the flowfield was visualized for the case of 3° angle of attack. The shock shape and flow pattern are shown in Fig.14 and Fig.15, respectively. Figure 16 shows the case of zero angle of attack in order to compare with Fig.15. We can see that the flow pattern (streamline) near the capsule shoulder demonstrated in Fig.15 differs considerably from the one shown in Fig.16. For the flow direction near the shoulder, we can see that the two flow patterns differ markedly, although the angle of attack of the capsule shown in Fig.15 is very small. This suggests that the two flow structures after the shoulder would be considerably different even if the difference in angle of attack is very small.

8. Discussion

We have drawn a sketch of the flowfield around the re-entry capsule traveling at Mach 10 obtained by the results of Fig.5, Fig.9 and Fig.13. The illustration is shown in Fig.17. As this paper demonstrates, despite the difficulty of visualizations of spatial flowfields such as streamlines around hypersonic capsules, the techniques of the electrical discharge method make this a comparatively easy task.

In order to compare with the experimental results, the calculated shock shape and streamlines obtained by using the Finite Element Method are shown in Fig.18.

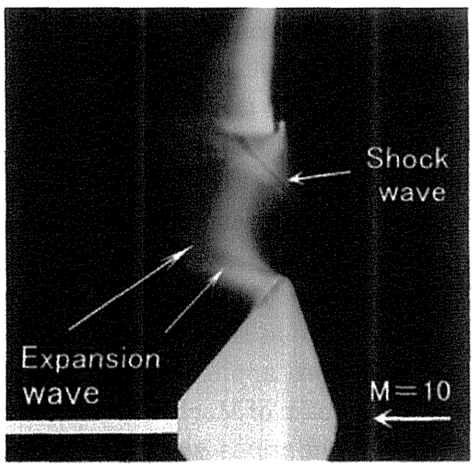

Fig.11 Visualized expansion wave.

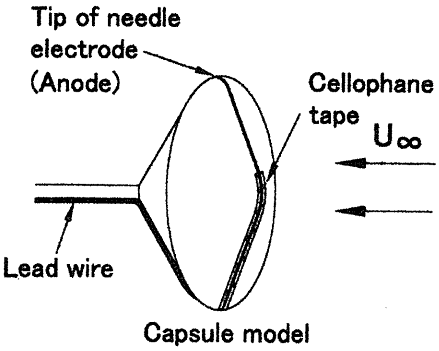

Fig.12 Arrangement of model and electrode for visualizing stream pattern just behind capsule.

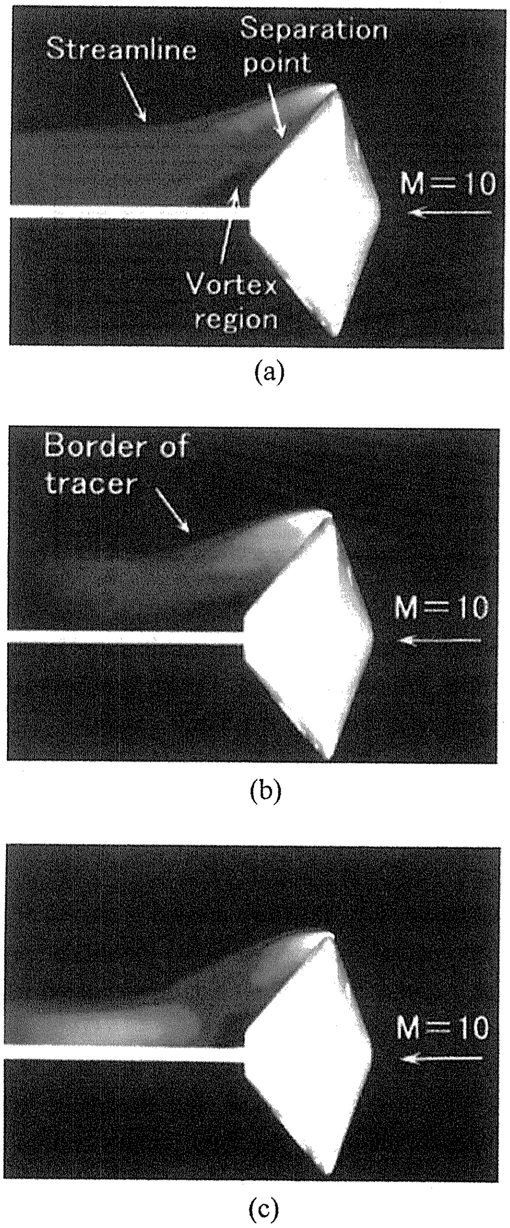

Fig.13 Visualized stream patterns of different positions behind capsule.

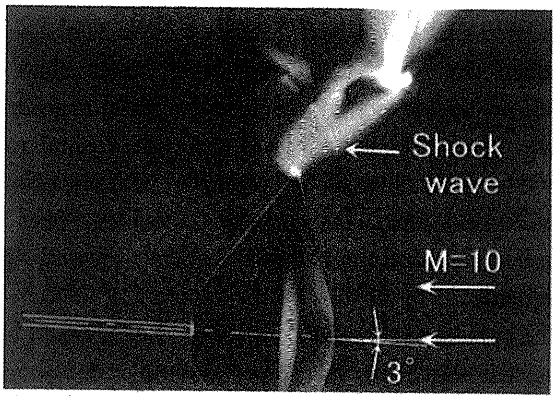

Fig.14 Visualized shock shape near capsule shoulder with a 3° angle of attack.

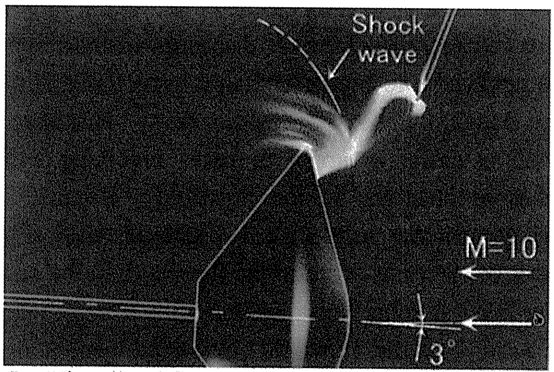

Fig.15 Visualized flow pattern near capsule shoulder with a 3° angle of attack. Shock wave obtained by Fig.14 is illustrated in this picture.

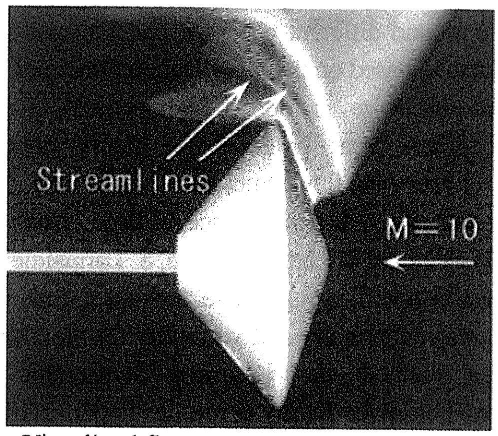

Fig.16 Visualized flow pattern near capsule shoulder with 0° angle of attack.

The calculation was carried out under the conditions of Mach number=10, freestream velocity=1.5 km/s, static pressure=70 Pa, and density=4.5×10^{-3} kg/m^3. The viscosity coefficient is obtained by the Sutherland equation.

The ratio Dex/Dth of the shock stand-off distances of the experimental and theoretical results was nearly 1.0. (Dex: experimental shock stand-off distance. Dth:

calculated shock stand-off distance.) The vortex region obtained by the calculation was larger than the experimental one, and the calculated separation point was a little upward compared with the experimental result. Concerning the flow patterns (streamlines) ahead of the capsule and near the capsule shoulder, both the experimental and calculated results showed good agreement.

The present experiments are carried out at Mach 10 by using the electrical discharge method. In order to generate the electrical discharge, we need to generate an electrical brake down in flow. To do this, there must exist in advance at least several electrons/cm^3 in the flowfield. In this respect, the electrical discharge method appears more applicable to higher enthalpy hypersonic flows or larger Mach number hypersonic flows. Because this method is easier to apply in cases involving a large number of electrons in the flowfield. Because it is easier to generate an electrical discharge when a large number of electrons occur in the flowfield. In the case of higher Mach number flows, we may find a larger number of electrons in the flowfield. However, generating an electrical discharge becomes more difficult at highly rarefied gas densities.

While the present investigation of flow structure used a model of the MESUR Pathfinder probe, the flow structure around different types of model shapes should be obtainable, based on the visualization principles of the electrical discharge method. The electrical discharge method offers great potential for future efforts to visualize hypersonic flow structures.

For more effective performance of flow visualization using the electrical discharge method, S. Larigaldie[5] et al. have demonstrated a suggestive technique that would permit greater flexibility and versatility for the electrical discharge method in visualizing hypersonic flow structures. For lower density or rarefied hypersonic flows, it may be very useful and effective for visualizing hypersonic flow structures if the electrical discharge method can be combined with the simultaneous use of an electron beam. For higher density hypersonic flows, simultaneous use of the electrical discharge method and an ultraviolet laser capable of exciting molecules and generating a relatively modest number of electrons may prove eminently useful.

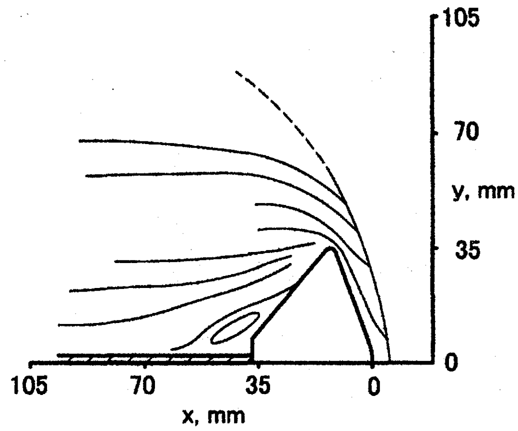

Fig.17 Sketch of streamline around capsule obtained by the results of Figs.5, 9, and 13.

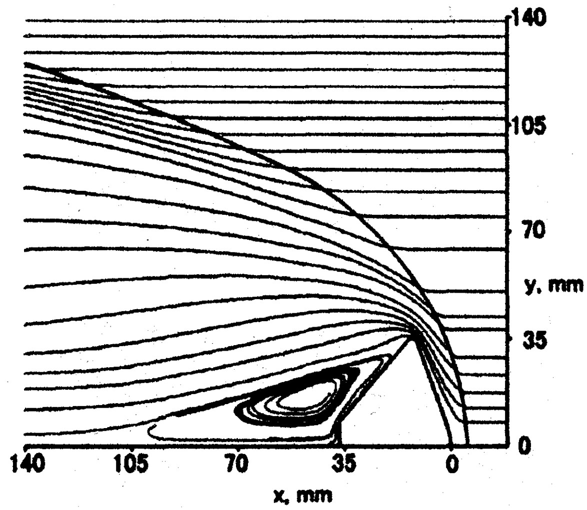

Fig.18 Shock shape and streamlines calculated by the Finite Element Method. (Mach number=10, freestream velocity = 1.5km/s, static-pressure = 70Pa, and density = 4.5×10^{-3}kg/m^3)

9. Conclusion

The qualitative flow structure around a model of the Mars Environmental Survey (MESUR) Pathfinder probe traveling at a speed of Mach 10 was investigated using the electrical discharge method.

In this study, the shock shape ahead of the capsule, the streamline after the shock wave, the expansion wave from the capsule shoulder, the flow pattern behind the capsule, and the flow pattern near the capsule shoulder at a small angle of attack were visualized. These experiments qualitatively demonstrated the spatial flow structure before and behind a hypersonic re-entry capsule. The visualized result was compared with the calculated one obtained by the Finite Element Method. Both the results showed good agreement except the location of vortex just behind the capsule.

Based on visualization principles of the electrical discharge method, the flow structures around various model shapes should be obtainable. The method offers great potential in the visualization of flow structures about hypersonic vehicles.

The electrical discharge method may be even more effective and useful in visualizing hypersonic flow structures when applied in combination with an electron beam or an ultraviolet laser.

Appendix: FEM(Finite Element Method) simulation

The FEM(Finite Element Method) simulation was carried out. First, basic formulation for FEM used in this study is described.

The axi-symmetric governing equations of compressible fluid can be written as follows.

$$\frac{\partial U}{\partial t}+\left(\frac{\partial F_1}{\partial x}+\frac{\partial F_2}{\partial y}+\underline{\frac{F_2}{y}}\right)-\left(\frac{\partial G_1}{\partial x}+\frac{\partial G_2}{\partial y}+\underline{\frac{G_2'}{y}}\right)=0 \qquad (1)$$

The underlined terms are particular terms for axi-symmetric problem when the x-axis is a symmetry axis. U, F_1, F_2, G_1, G_2, G_2' are expressed as follows:

$$\left.\begin{aligned} U &= \langle \varrho \quad \varrho u_x \quad \varrho u_y \quad \varrho e \rangle \\ F_1 &= u_x U, \\ F_2 &= u_y U \\ G_1 &= \langle 0 \quad \sigma_{xx} \quad \sigma_{xy} \quad u_x\sigma_{xx}+u_y\sigma_{xy}-q_x \rangle \\ G_2 &= \langle 0 \quad \sigma_{xy} \quad \sigma_{yy} \quad u_x\sigma_{xy}+u_y\sigma_{yy}-q_y \rangle \\ G_2' &= \langle 0 \quad \sigma_{xy} \quad \sigma_{yy}-\sigma_\theta \quad u_x\sigma_{xy}+u_y\sigma_{yy}-q_y \rangle \end{aligned}\right\} \qquad (2)$$

where, ρ is density, u_x, u_y are x, y component of velocity, and e is energy per unit mass. σ_{xx}, σ_{yy}, ... are stress component, and q_x, q_y is the heat flux. Equation (1) expresses the conservation law of mass, momentum of x, y-direction, and energy according to the order of variables in bracket < >, respectively.

Next, we consider the boundary conditions $U=\overline{U}$ on the surface *Su*, and $G_1 n_x + G_2 n_y = \overline{P}$ on the surface *Sp*, where n_x, n_y are x, y component of outward normal vector on the surface. The weighted function w, which takes value 0 on *Su*, is multiplied on equation (1), and this equation is integrated over the analytic area A. By using Gauss's divergence theorem, this equation finally becomes as follows.

$$\begin{aligned}\int_A w\frac{\partial U}{\partial t}dA &= -\int_A w\left(\frac{\partial F_1}{\partial x}+\frac{\partial F_2}{\partial y}\right)dA \\ &\quad -\int_A\left[\frac{\partial w}{\partial x}G_1+\frac{\partial w}{\partial y}G_2\right]dA+\int_{SP} w\overline{P}dS \\ &\quad \underline{-\int_A w\left(\frac{F_2'}{y}-\frac{G_2'-G_2}{y}\right)dA} \end{aligned} \qquad (3)$$

$dA=2\pi y dx dy$, in the case of axi-symmetric problem. (if underlined terms are omitted, and dA is put $dxdy$, the equation becomes 2-dimensional problem). In this analysis, the stress (pressure) term contained in G_1, G_2 does not have differential form.

The *SUPG* method with respect to the weighted function w, and artificial diffusion terms are introduced for the stable calculation. In addition, explicit time integration scheme is used by making diagonal matrix for the left side of eq.(3) in order to economize memory and calculation time. The calculated velocity field is shown in Fig.19.

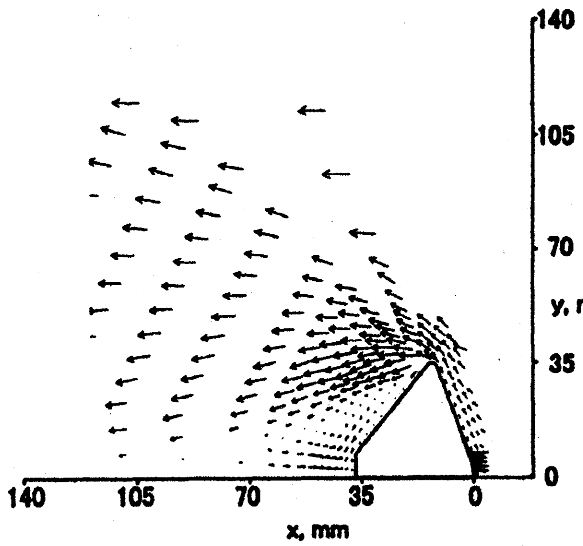

Fig.19 Calculated velocity distribution.

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