New Method for Visualizing Three-Dimensional Shock Shapes Around Hypersonic Vehicles Using an Electrical Discharge

Masatomi Nishio*
Kobe University, Nada, Kobe 657, Japan

This paper describes a new method for visualizing three-dimensional shock shapes around hypersonic vehicles using an electrical discharge. The method is based on the following ideas. When an electrical discharge is generated across a shock wave, the shock wave can be seen as a dark portion in the electrical discharge. The three-dimensional shock shape can be visualized by taking a discharge photograph in the rear direction of the flow. The method was developed to make it possible to visualize wide field shock shapes around vehicles using a single electrical discharge. First, a lateral shock shape over a wedge was visualized to investigate the accuracy of the shock shape obtained by the new method. The visualized result was compared with a schlieren photograph, and it was found that the results of both agreed sufficiently. This proved that the new method is a viable method for visualizing shock shapes. Next, a detached cross-sectional shock shape over a delta wing was successfully visualized. Cross-sectional shock shapes cannot be visualized by such optical systems as the schlieren method. Therefore, it can be concluded that the new method is superior for visualizing three-dimensional shock shapes.

Nomenclature

a = constant
E_1 = electric field generated by applied voltage
E_2 = electric field generated by ions
K = constant
N = ion number density
P = gas pressure
S = ionization efficiency
Vi = ionization potential
W = electron energy
x = distance from the shock position
ε = permittivity
ρ = electric charge density

Subscripts

s = in the shock layer
∞ = in the freestream

I. Introduction

THE visualization of three-dimensional shock shapes around hypersonic vehicles is very important for understanding the flowfield. However, there are few methods available for visualizing three-dimensional shock shapes.

Optical systems, such as the schlieren method, Mach-Zehnder interferometers, and shadow graphs, etc., have been used only for two-dimensional shock waves and for shock waves around bodies of revolution. However, these optical systems are not useful for three-dimensional shock waves because they can only visualize shock shapes by passing through the optical axes perpendicularly in the direction of the gradient of the gas density.

Methods for visualizing three-dimensional shock shapes, such as the electron beam method[1,2] and the vapor screen method,[3,4] have been reported. The electron beam method is suitable for the visualization of rarefied gas or extremely low-density gas. However, it is rather difficult to visualize shock waves that are not extremely low density. In the vapor screen method, there seemed to be the possibility of changing the characteristics of the gas by mixing water.

Recently, a method for visualizing three-dimensional shock shapes using an electrical discharge was reported by Kimura et al.,[5] and Kimura and Nishio.[6] The method is based on the following ideas. When an electrical discharge is generated across a shock wave, the radiation intensities from the two regions, one in the freestream and the other in the shock layer, become different from each other according to the difference of the gas densities. Therefore, the shock portion can be visualized by taking a discharge photograph. However, in practice, it is very difficult to select the suitable experimental conditions that make the two radiation intensities clearly different from each other. Therefore, up to now, the visualization of shock shapes has been very difficult, and shock shapes have not been visualized successfully. Moreover, this method visualizes only one position of the shock wave using one electrical discharge. Therefore, in order to obtain wide-field shock shapes, a large number of electrical discharges must be generated. This method requires a lot of time and it very troublesome. Therefore, a more superior visualizing method that can visualize three-dimensional shock shapes clearly and easily has been sought.

Our new method also utilizes an electrical discharge and is based on the following ideas. When an electrical discharge is generated across a shock wave, a dark portion at the shock position in the electrical discharge can be seen because we can make the energy of the electrons drifting in the electric field drop suddenly at the shock position. As a result of this, the level of electron excitation of the gas molecules at the shock position becomes very low and, therefore, the radiation intensity from the position becomes very weak. Consequently, a three-dimensional shock shape can be obtained by taking a discharge photograph either in front or behind the direction of the flow.

As an example of the efficacy of the new method, a detached cross-sectional shock shape over a delta wing traveling at a hypersonic speed has been visualized successfully. This cross-sectional shock shape cannot be visualized directly by optical systems such as the schlieren method, etc.

II. Visualizing Principle

When an electrical discharge is generated across a shock wave, a dark portion at the shock position in the electrical discharge can be seen. The shock position can be obtained by

Received March 10, 1989; revision received Dec. 19, 1989.

*Research Associate, Faculty of Engineering. Member AIAA.

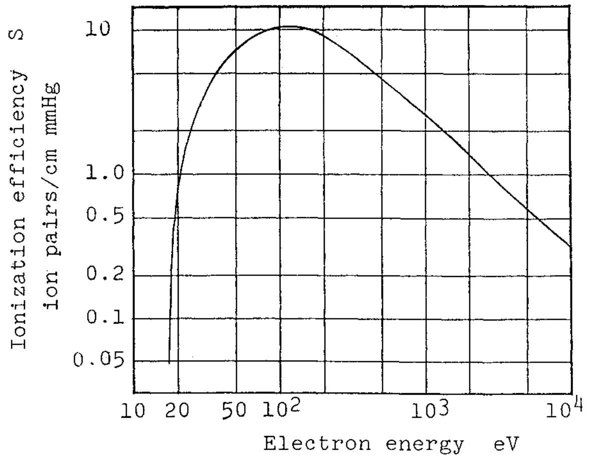


Fig. 1 Ionization efficiency curve as the function of electron energy.

taking a photograph of the electrical discharge. The reason the dark portion occurs is explained in the following.

It is generally known that the radiation intensity from an electrical discharge is related to the excitation functions vs the energy of the electrons drifting in the electrical field and the molecular number density.[7,8] The electron energy can be made very low at the shock position because the electron energy is proportional to E/P,[9] and that the electric field E can be made very small at the shock position is proven next.

When an electrical discharge is generated across a shock wave, the rate of the nitrogen ion number densities generated in the shock layer and in the freestream can be estimated by the ionization efficiency[10] curve as the function of the electron energy, as shown in Fig. 1.[10] The ionization efficiency is numerically equal to the ionization cross section. In the range of low electron energy, Fig. 1 indicates that the ionization efficiency curve rises steeply and approximately linearly. Thus, the ionization efficiency S for electron energies below the maximum can be approximated by the following relation[10]:

$$S = aP(W - Vi) \tag{1}$$

The electron energy W is expressed by:[9]

$$W = K_1(E_1/P) \tag{2}$$

where K_1 is a constant and E_1 is an electrical field. From these, when voltage is applied to a pair of electrodes, the rate of the nitrogen ion number density N_s generated in the shock layer and the nitrogen ion number density N_∞ generated in the freestream is expressed by the following:

$$\begin{aligned} N_s/N_\infty &= S_s S_\infty \\ &= P_s[K_1(E_1/P_s) - Vi]/P_\infty[K_1(E_1/P_\infty) - Vi] \end{aligned} \tag{3}$$

In experiments, when the flow conditions are $P_\infty = 1$ mmHg and $P_s/P_\infty = 10$, if we make $E_1 = 400$ V/cm by applying a certain voltage to the pair of electrodes,

$$N_s/N_\infty \ll 1 \tag{4}$$

is realized because the value of S_s becomes almost zero since the electron energy W_s becomes smaller than the potential energy Vi. In this case, the strength of the electric field generated by the ions generated in the shock layer is negligible compared with the one in the freestream. Consequently, the electric field $E_2(x)$ generated by the ions in the freestream is expressed by:

$$E_2(x) = \frac{K_2}{4\pi\varepsilon}\int_{x_1=0}^{x_1=L}\frac{\rho(x_1)}{(x-x_1)^2}\,dx_1 \tag{5}$$

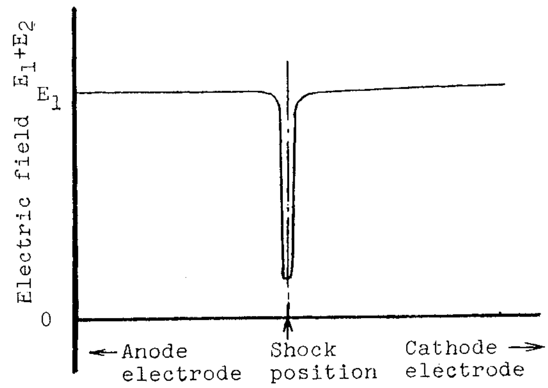


Fig. 2 Electric field distribution.

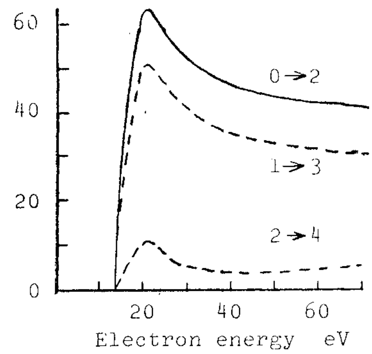


Fig. 3 Nitrogen excitation functions in arbitrary units vs electron energy.

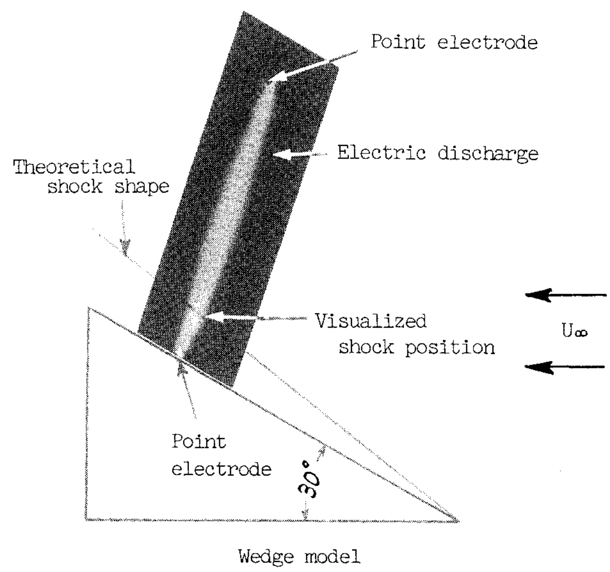
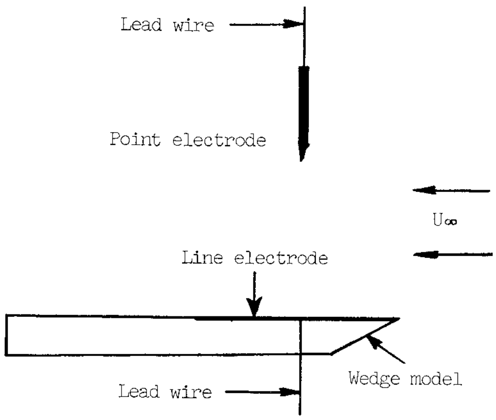


Fig. 4 Visualized shock wave over a wedge by the electrical discharge method.

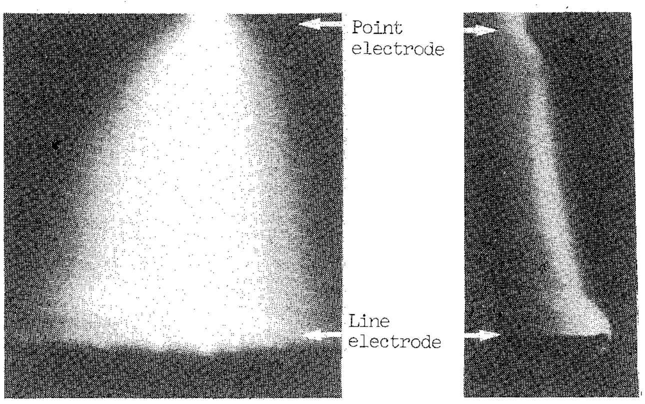
where $\rho(x_1)$ is the density of the electric charge at $x = x_1$, $x_1 = 0$ is the position of the shock wave, and L is the distance between the shock position and the cathode electrode in the freestream. In the present case, $\rho(x_1)$ is assumed to be zero at $x_1 < 0$. Furthermore, the shape of the electric discharge is assumed to be a one-dimensional streak.

Consequently, the electric field distribution obtained by adding the two electric field distributions E_1 and E_2 can be expressed by Fig. 2. This figure indicates that the electric field drops rapidly and becomes very small at the shock position.

Nitrogen excitation functions in arbitrary units vs electron energy is indicated in Fig. 3.[8] Judging from Fig. 3, when electron energy is lower than about 14 eV, which is the excitation potential of nitrogen, little electron excitation will



a) Arrangement of the wedge model and the pair of electrodes



b) Electrical discharge shape; the cathode point electrode is set in the freestream and the anode line electrode is bonded to the model surface

c) Electrical discharge shape; the anode point electrode is set in the freestream and the cathode line electrode is bonded to the model surface

Fig. 5 Electrical discharge shapes using point-line electrodes.

occur. We can make the electron energy at the shock position much lower than 14 eV, for the electric field at the shock position can be made small enough by applying suitable experimental conditions. Consequently, the dark portion appears at the shock position. Since the dark portion can be photographed not only from one side, but also from the rear or front, this new method should prove very valuable for the visualization of three-dimensional shock shapes.

As a practical example of this method, a shock wave over a wedge whose angle of attack is 30 deg is visualized and shown in Fig. 4. The electrical discharge is generated so as to cross the shock wave over the wedge by utilizing a pair of point-point electrodes. One of the point electrodes is set in the freestream and the other point electrode is installed in the wedge. The dark portion in the discharge column can be seen clearly at the shock position previously obtained theoretically. In this visualization, the electrical discharge has been photographed from the side. However, the electrical discharge can also be photographed from the rear by utilizing a mirror. Therefore, this confirms that the new method is useful for the visualization of three-dimensional shock shapes.

However, in the method utilizing the pair of point-point electrodes, only one shock position can be visualized by one electrical discharge. Therefore, in order to obtain a wide-field shock shape around hypersonic vehicles, a large number of electrical discharges must be generated. This requires much time and is very troublesome. Therefore, the authors tried to improve the method so as to obtain the wide-field shock shape by a single electrical discharge. For this purpose, a flat and wide electrical discharge shape was considered. If the electrical discharge shape around hypersonic vehicles is wide and flat, the wide-field shock shape can be visualized by a single electrical discharge. In order to generate such an electrical discharge shape, a pair of point-line electrodes were utilized. Moreover, it was considered that the point electrode should be used as the cathode and set in the freestream and the line electrode should be used as the anode and arranged on the model surface. In order to verify that such an arrangement of electrodes is suitable for generating a flat and wide electric discharge shape, the following experiment was carried out. The experiment was carried out under the conditions that the duration of the electrical discharge was about 10^{-6} s, and the initial applied voltage to the pair of electrodes was 2000 V. Figure 5a shows the arrangement of the wedge model and the pair of electrodes. The results are shown in Figs. 5b and 5c. In the case of Fig. 5b, the cathode point electrode is set in the freestream and the anode line electrode is bonded to the model surface. In the case of Fig. 5c, the anode point electrode is set in the freestream and the cathode line electrode is bonded to the model. The results indicate that the electrical discharge shape in the case of Fig. 5b was wide, but, in the case of Fig. 5c, it was not wide. From these results, in following experiments, the cathode point electrode was set in the freestream and the anode line electrode bonded to the model surfaces.

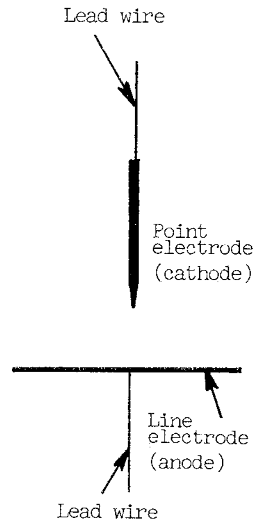
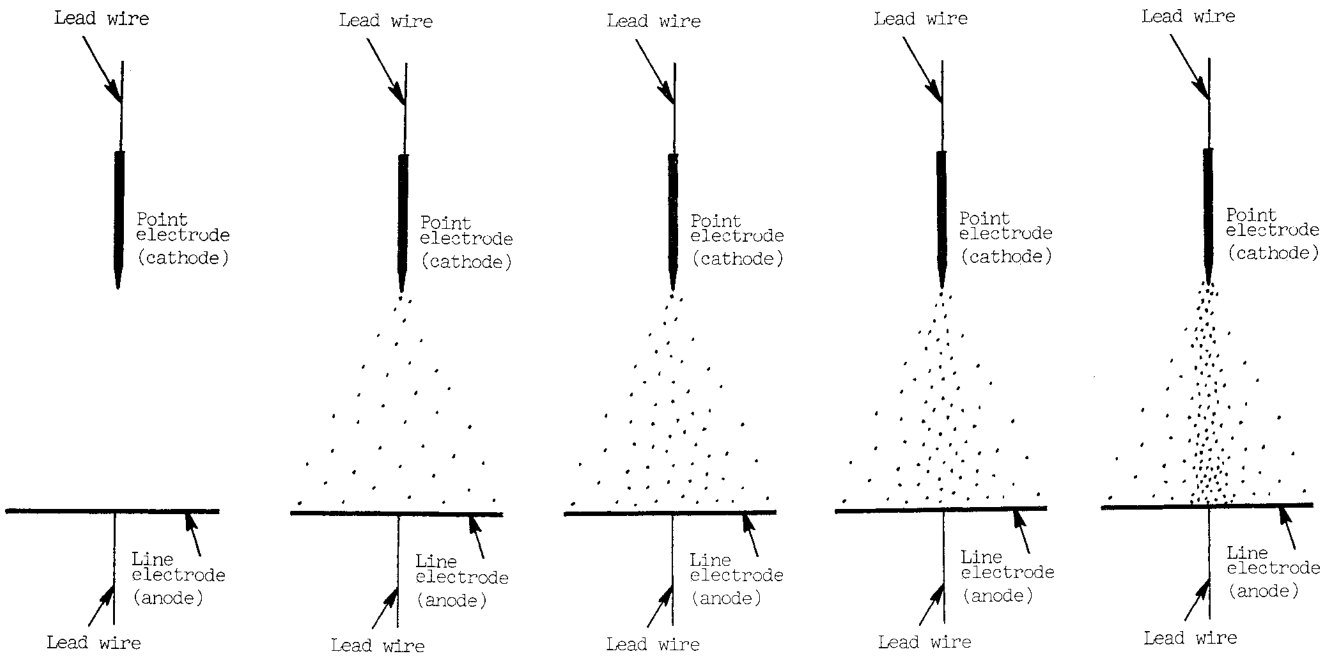


Fig. 6 Arrangement of the point (cathode)-line (anode) electrodes.

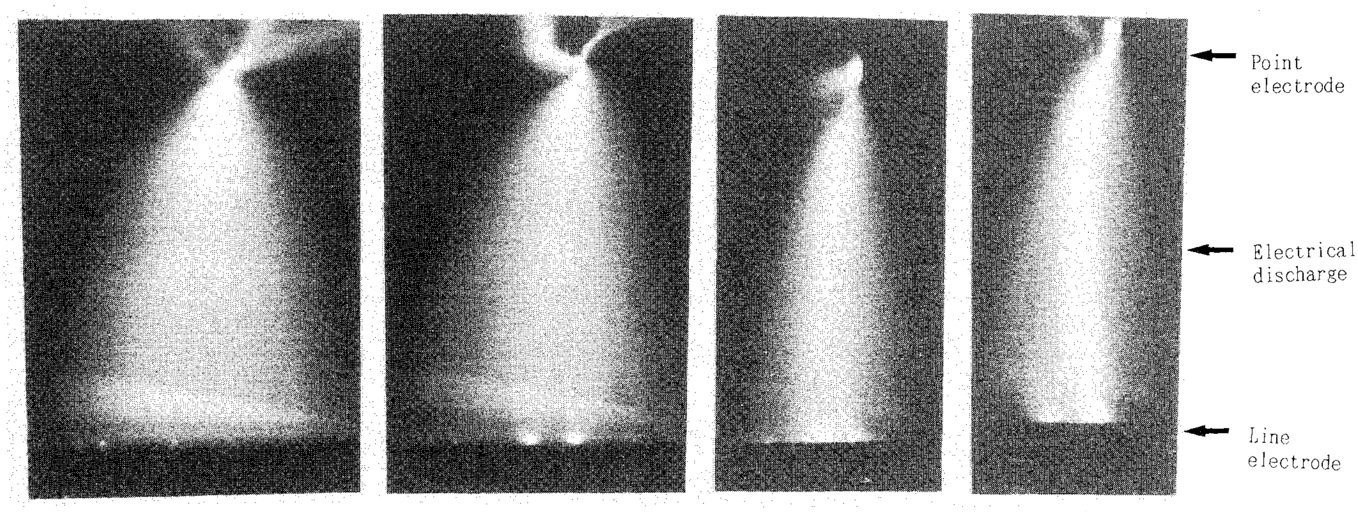
Ion density in the electrical discharge path was considered the main factor that affected electrical discharge shape. To verify this, the following arrangement of the point (cathode)-line (anode) electrodes was considered, as shown in Fig. 6. Before the breakdown of the electrical discharge, the electric field distribution between the pair of electrodes is generated only by an applied voltage to the pair of electrodes. The values of the electric field strength near the line electrode are almost equal with each other, although there might be a little difference according to location. Therefore, in the initial stage of electrical discharge, a wide electrical discharge shape will be observed, although the radiation intensities from the electrical discharge are very low. However, the values of the electrical field strength near the line electrode are not perfectly equal with each other. Therefore, the ion density at one place is slightly larger than at other places. At this stage, if the absolute quantity of the ions at the place is large enough to form an electrical field and, therefore, if the ions attract the electrons travelling from the cathode to the anode, more electrons would pass through the place in the next stage. Consequently, the ion density at the place becomes much larger than the other places because further ionization would occur at that place. Therefore, many more electrons pass through the place, exciting the molecules at the place. As a result of this, according to the development of the electrical discharge, the radiation strength at the place where a large number of electrons pass through becomes much larger than the other places. Consequently, a slender, columnar electrical discharge shape will be observed. The illustration of the development of the electrical discharge shape just described is shown in Fig. 7. The dots in the figure indicate ions. Before the breakdown of the electrical discharge, there exist no ions between the pair of electrodes, as shown in Fig. 7a. Figure 7b shows the initial stage of the electrical discharge. Figure 7c is the stage following Fig. 7b, and Fig. 7d is the stage following Fig. 7c. Figure 7e shows the last stage of the electrical discharge. The phenomenon just described occurs easily when the absolute quantity of the ions generated in the electrical discharge is large enough to form an electric field and, therfore, when the ions attract the electrons travelling from the cathode to the anode. If the electric current is very small during the electric discharge and, consequently, if the absolute ion number generated in the electrical discharge is small enough, the electrical discharge shape will remain in the state of Fig. 7b. From this result, it was confirmed that we must make the ion density between the pair of electrodes very small to generate a wide, flat electrical discharge shape.

In the subsequent study, the influence of ion density on electrical discharge shape was investigated. For this investigation, the authors tried to observe the electrical discharge shape by varying the electric current, which is considered to affect the value of ion density. The variation of the electric current of the electrical discharge has performed by changing the resistance in the electrical circuit shown in Fig. 12. In these experiments, the duration of the electric current was about 10^{-6} s. Duration was controlled by using a bypass circuit in the electric circuit shown in Fig. 12. The arrangement of the wedge model and the pair of electrodes was as shown in Fig. 5. The experiments were carried out under the conditions that the model was in a freestream with a velocity of 1000 m/s and the wedge angle was 0 deg. The relation between electrical discharge shape and electric current is shown in Figs. 8. The electrical discharges in parts a–d of Fig. 8 were obtained with electric currents of 1, 3, 10, and 50A, respectively. The iris of the camera was adjusted to make each photograph of similar brightness, but in reality,



a) Before the breakdown b) Initial stage c) Next stage of stage b d) Next stage of stage c e) Final stage

Fig. 7 Illustration of the development of the electrical discharge shape.



a) 1 A b) 3 A c) 10 A d) 50 A

Fig. 8 Electrical discharge shapes vs electric currents.

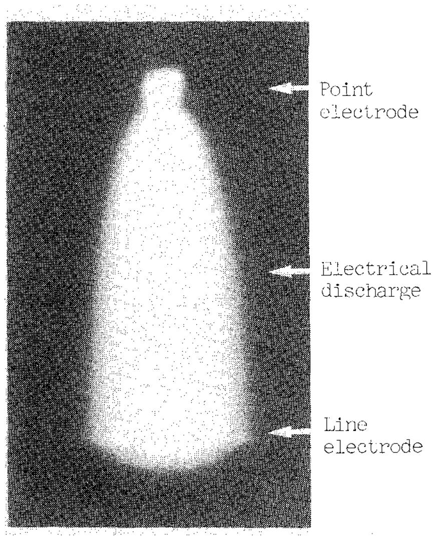


Fig. 9 Electrical discharge in the case that the radiation intensity from the electrical discharge is too strong.

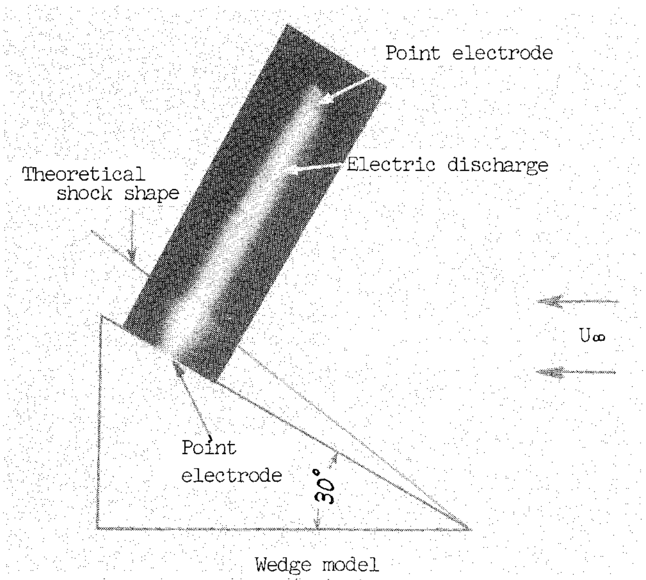


Fig. 10 Electrical discharge obtained by setting the anode electrode in the freestream and the cathode electrode on the model surface.

the larger the electric current, the greater the brightness of the electrical discharge. However, to visualize shock shapes, we must photograph the electrical discharge at a suitable brightness because we cannot visualize the shock position when the radiation from the electrical discharge is too great and halation of the film occurs, as shown in Fig. 9, even if the dark portion is generated at the shock position. For this reason, visualization is carried out by varying the setting of the iris of the camera. From Fig. 8, it can be concluded that when the electric current is large, the electrical discharge shape becomes slender, and when the electric current is small, it becomes wide. Consequently, in the case of the visualization of shock shapes using a pair of point-line electrodes, it was proven that the electric current should be as small as possible.

However, the preceding discussion of electrical discharge shape pertains only when the effect of ion diffusion is negligible because the duration of the electrical discharge is short enough and the ion density generated in the electrical discharge is not extremely large. If the ion density is extremely large and the duration is long, the electrical discharge shape will become wide due to ion diffusion. However, if the ion density is extremely large and the duration of the electrical discharge is long, the flowfield will be disturbed and, therefore, the visualization of the shock shapes would not be

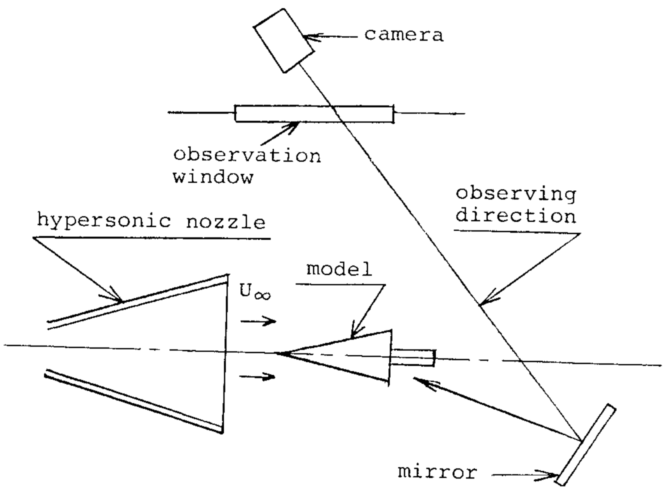


Fig. 11 Observing direction of electrical discharge.

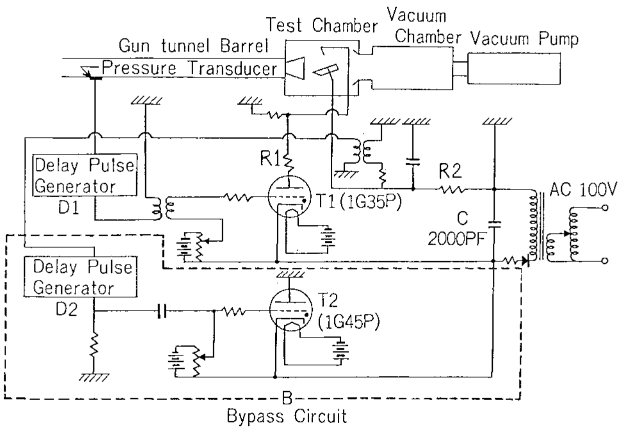


Fig. 12 Electrical discharge circuit.

successful. Based on this, regarding visualization using the new method, we must limit our discussion to the case when the effect of ion diffusion is negligible.

Concerning the visualizing principle using an electrical discharge, a more detailed consideration is discussed. The appearance of the dark portion at the shock position may be due to the deflection of the light axes out of the electrical discharge because of the density at the shock position. Further experiments were carried out by changing the polarity of the pair of point-point electrodes to investigate the possibility of the influence of the deflection of the light axes. If the dark portion appears because of the deflection of the light axes, it was considered that the appearance of the dark portion would have nothing to do with the polarity of the electrodes. Figure 4 shows an electrical discharge obtained by setting the cathode electrode in the freestream and the anode electrode on the model surface. Figure 10 shows an electrical discharge obtained by setting the anode electrode in the freestream and the cathode electrode on the model surface. The dark portion appears at the shock position clearly in the case of Fig. 4; the dark portion does not appear in the case of Fig. 10. From these results, it can be concluded that the influence of the deflection of the light axes out of the electrical discharge would be negligible regarding the new visualizing method.

III. Experimental Equipment and Procedure

A hypersonic flow is generated by a hypersonic gun tunnel. The characteristic of the gun tunnel are as follows: Mach number = 10, Reynolds number = 2×10^4 cm^{-1}, freestream density = 4×10^{-3} kg/m^3, duration of freestream = 10^{-2} s, exit diameter of nozzle = 15 cm, freestream

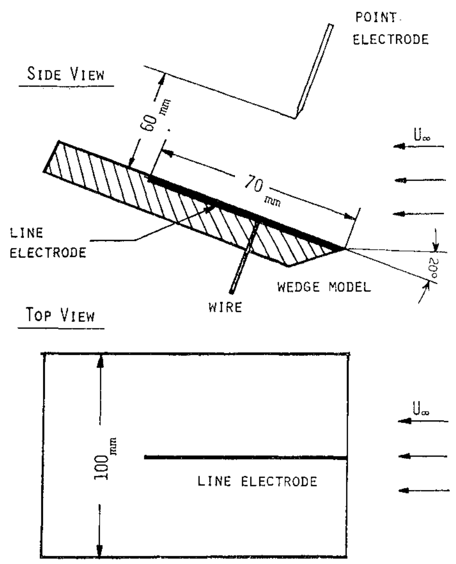
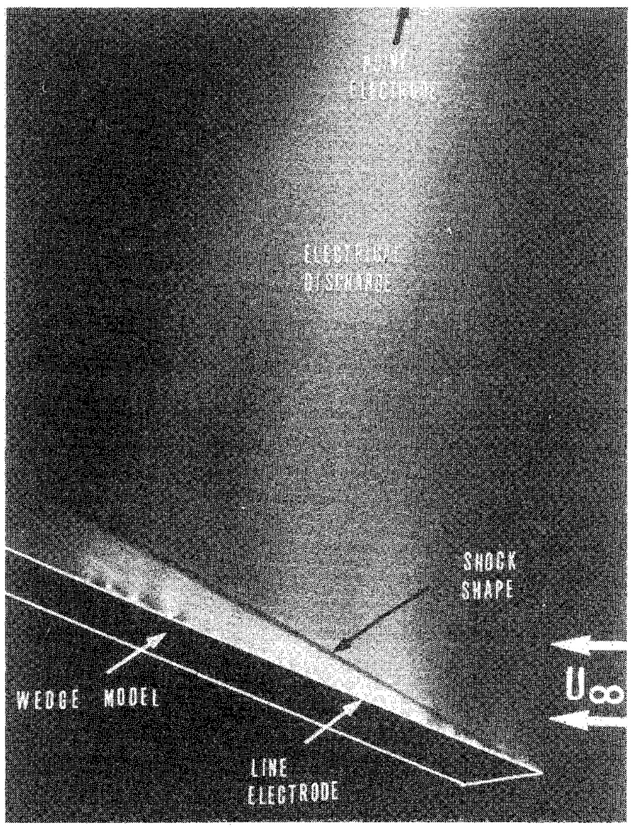
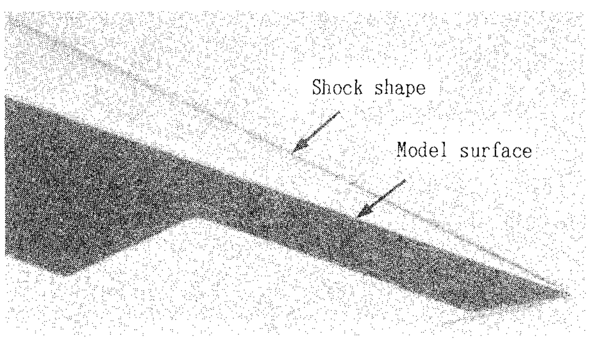


Fig. 13 Arrangement of the wedge and the pair of point-line electrodes



a) Visualized shock shape



b) Schlieren photograph

Fig. 14 Visualization of the lateral shock shape over the wedge in the hypersonic flow by using an electric discharge.

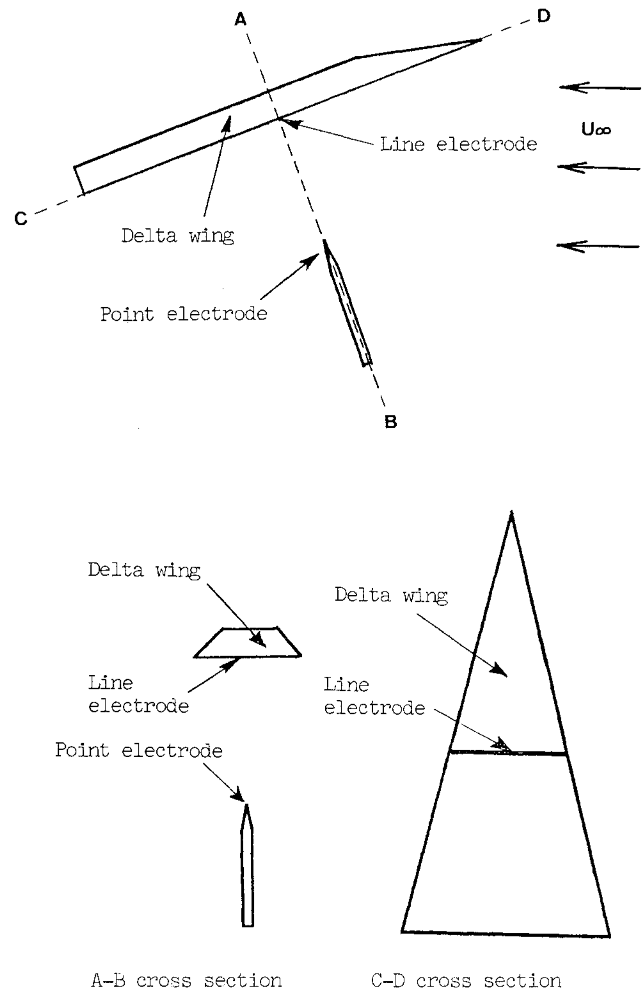


Fig. 15 Arrangement of the delta wing and the pair of electrodes.

velocity = 1000 m/s, and static pressure = 1 mmHg. Since high electric voltage is applied between the pair of electrodes, the hypersonic nozzle, models, etc., are made of electric insulator. A mirror is used when cross-sectional shock shapes are visualized. The observing direction is shown in Fig. 11, and a camera is set just outside the observation window. The camera is set open, and, therefore, the exposure time of the film is equivalent to the duration of the electrical discharge itself.

The electrical discharge circuit is shown in Fig. 12. The experimental procedure using the circuit is as follows. The pressure transducer made of titanic acid balium in the barrel of the gun tunnel receives a signal from an incident shock wave in the barrel. This pulse becomes an input signal to the delay pulse generator (D1). The signal is delayed in this pulse generator so as to generate the electrical discharge while the freestream is being obtained. The delayed pulse acts on the thyratron (T1). When the thyratron is operated, the electric circuit is closed and high voltage is applied between the pair of electrodes by the electric charge stored in the condenser (C1). After that, an electrical discharge occurs naturally. The bypass circuit (B) is set to control discharge duration. In the bypass circuit, the signal generated by the electrical current of the electrical discharge acts on the delay pulse generator (D2) and the delayed pulse acts on the thyratron (T2). Consequently, the electric charge in the condenser is released to the ground and the electrical discharge between the pair of electrodes is finished. One of the electrodes is placed in the freestream and the other electrode is installed on the model surface. The electrical discharge generated between the pair of electrodes is photographed with the camera.

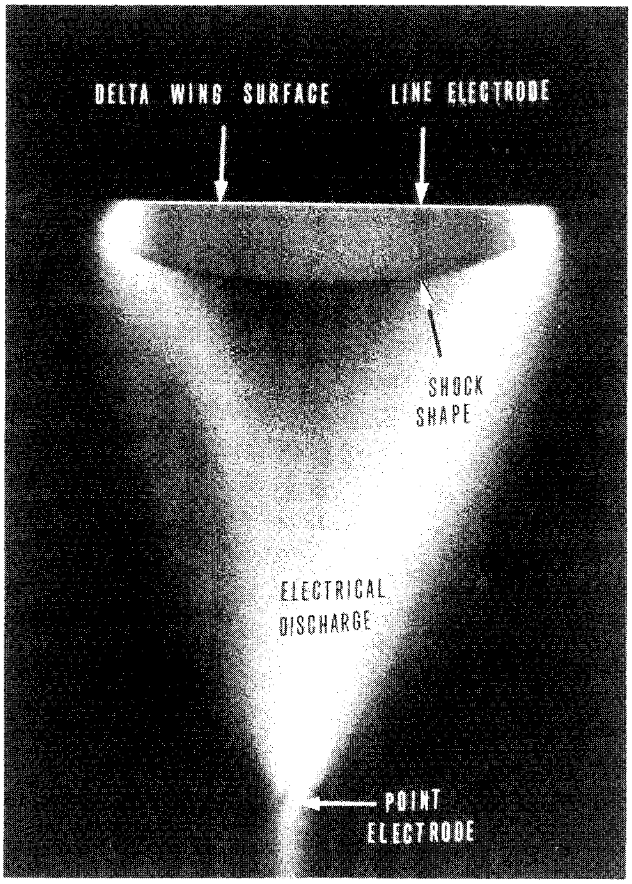


Fig. 16 Visualized cross-sectional shock shape over the delta wing in the hypersonic flow.

IV. Visualizations of Shock Shapes

Shock shapes over hypersonic vehicles have been visualized by using the new electrical discharge method. As examples, two visualizing results will be described.

First, a lateral shock shape over a wedge model was visualized in order to investigate the accuracy of the shock shape obtained by the new method. The arrangement of the wedge and the pair of point-line electrodes is shown in Fig. 13. In this experiment, the point electrode was used as the cathode and the line electrode was used as the anode. The point electrode was set in the freestream and the line electrode was attached to the model surface in order to obtain wide-field shock shapes with a single electrical discharge. The line electrode was made thin enough not to disturb the flowfield over the model. The thickness of the line electrode was 0.1 mm. The experiment was carried out under the conditions; wedge angle was 20 deg. The gap between the pair of the electrodes was 60 mm. The iris of the camera was F = 1.4, and the film speed was ASA 3200. The initial voltage applied to the pair of electrodes was 2000 V, and the electric current was 1 A. The result of the visualization is shown in Fig. 14a. A dark portion, which is the shock position, is clearly visualized in the wide electrical discharge shape. For comparison, a schlieren photograph of the shock shape obtained under the same experimental conditions is shown in Fig. 14b. The results of both agree sufficiently. From this, it was proven that the new method is suitable for the visualization of shock shapes.

Second, visualization of a cross-sectional shock shape over a delta wing was carried out. The arrangement of the delta wing and the pair of electrodes is shown in Fig. 15. The apex angle of the delta wing was 25 deg and the angle of attack of the model was 20 deg. The result of the visualization is shown in Fig. 16. The photograph indicates that a detached shock shape over the delta wing was visualized successfully.

V. Conclusions

The visualization of three-dimensional shock shapes around hypersonic vehicles is very important for understanding the flowfield. However, it has been very difficult to visualize them, and few available visualizing methods have been reported. For this reason, the authors have suggested a new method for visualizing three-dimensional shock shapes.

The method is based on the following ideas. When an electrical discharge is generated across a shock wave, the shock wave can be seen as a dark portion in the electrical discharge. The three-dimensional shock shape can be visualized by taking a discharge photograph either in front or behind the direction of the flow.

Moreover, the authors tried to improve the method so as to obtain wide-field shock shapes with a single electrical discharge. For this purpose, a wide and flat electrical discharge shape was considered. In order to generate such an electrical discharge shape, a pair of point-line electrodes was utilized.

As examples of the new method using an electrical discharge, two visualizing results were discussed. First, a lateral shock shape over a wedge was visualized and the result was compared with a schlieren photograph. The results of both agreed sufficiently. From this, it was proven that the new method is suitable for the visualization of shock shapes. Second, a cross-sectional shock shape over a delta wing was visualized successfully.

The cross-sectional shock shape cannot be visualized by optical systems such as the schlieren method, etc. Therefore, we confirmed that our new method using an electrical discharge is superior in visualizing three-dimensional shock shapes.

References

[1]Muntz, E., and Marsden, D., "Electron Excitation Applied to the Experimental Investigation of Rarefied Gas Flows," *Rarefied Gas Dynamics*, Vol. II, edited by J. A. Laurmann, Academic, New York, 1963, pp. 495–526.

[2]Maguire, B., Muntz, E., and Mallin, J., "Visualization Technique for Low-Density Flow Fields," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-3, No. 2, 1967, pp. 321–326.

[3]Scheuing, R., "Outer Inviscid Hypersonic Flow With Attached Shock Waves," *ARS Journal*, Vol. 31, No. 4, 1961, pp. 486–505.

[4]Rao, D., "Delta Wing Shock Shape at Hypersonic Speed," *AIAA Journal*, Vol. 9, No. 10, 1971, pp. 2093–2094.

[5]Kimura, T., Nishio, M., Fujita, T., and Maeno, R., "Visualization of Shock Wave by Electric Discharge," *AIAA Journal*, Vol. 15, No. 5, 1977, pp. 611–612.

[6]Kimura, T., and Nishio, M., "Measurement of Shock Waves Around a Delta-Wing Semicone," *AIAA Journal*, Vol. 18, No. 7, 1980, pp. 843–844.

[7]Engel, V., *Ionized Gases*, Oxford University Press, Oxford, UK, 1965, p. 220.

[8]Alferof, V. I., Okerblom, T. I., and Sarantsef, A. I., "Experimental Study of Vortex Flow about Low Aspect Ratio Wings and Circular Cones at $M = 2$," AN SSSR. *Mekhanika Zhidkosti i Gaza*, Vol. 2, No. 5, 1967, pp. 113–121.

[9]Engel, V., *Ionized Gases*, Oxford University Press, Oxford, UK, 1965, pp. 122–123.

[10]Engel, V., *Ionized Gases*, Oxford University Press, Oxford, UK, 1965, pp. 62–63.