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The Second Electric Discharge Method for Visualizing Three Dimensional Shock Shapes

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ABSTRACT

This paper describes a new method for visualizing three-dimensional shock shapes around hypersonic vehicles by 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. 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
: permittivity
: electric charge density

Subscripts

s : in the shock layer
∞ : in the freestream

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1. Introduction

The visualization of three-dimensional shock shapes around hypersonic vehicles is very important for understanding the flow field. 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.

As methods for visualizing three-dimensional shock shapes, 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 which 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.

A method for visualizing three-dimensional shock shapes using an electrical discharge was reported by M. Nishio.[5,6]. 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 which 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. The new method 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.

2. 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 taking a photograph of the electrical discharge. The reason the dark portion occurs is explained below.

It is generally known that the radiation intensity from an electrical discharge is related to the excitation functions versus the energy of the electrons drifting in the electric 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 below.

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,

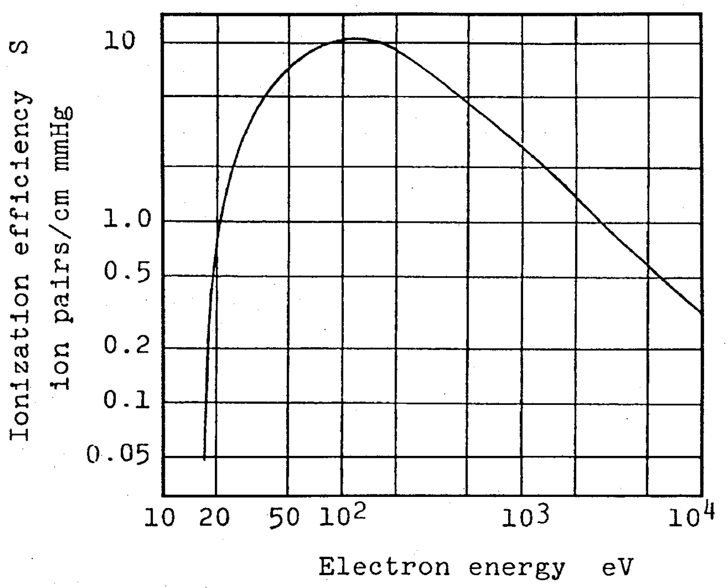


Fig.1 Ionization efficiency curve as the function of the electron energy.

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]

$$S = aP(W - Vi) \quad (1)$$

where a, P, W, and Vi are a constant, gas pressure, electron energy, and ionization potential, respectively. The electron energy W is expressed by the following.[9]

$$W = K_1 \frac{E_1}{P} \quad (2)$$

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 Ns generated in the shock layer and the nitrogen ion number density $N\infty$ generated in the freestream is expressed by the following.

$$Ns/N\infty = Ss/S\infty$$
$$= Ps\{K_1 \frac{E_1}{Ps} - Vi\} / P\infty\{K_1 \frac{E_1}{P\infty} - Vi\} \quad (3)$$

where the suffix s and ∞ are the shock layer and the freestream, respectively. In experiments, when the flow conditions are $P\infty = 1$ mmHg and $Ps/P\infty = 10$, if we make E_1 400 V/cm by applying a certain voltage to the pair of electrodes,

$$Ns / N\infty \ll 1 \quad (4)$$

is realized because the value of Ss becomes almost zero since the electron energy Ws 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 the following.

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

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 versus 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

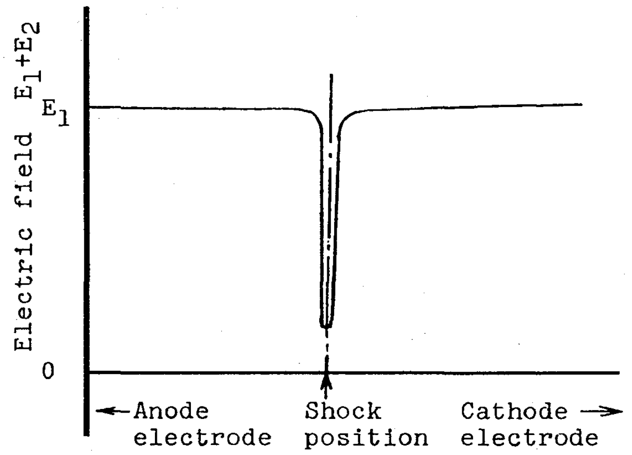


Fig.2 The electric field distribution

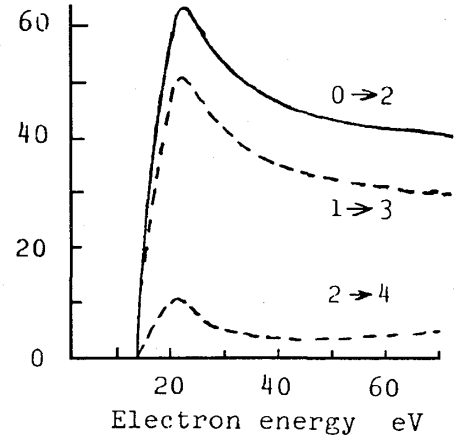


Fig.3 Nitrogen excitation functions in arbitrary units versus the electron energy.

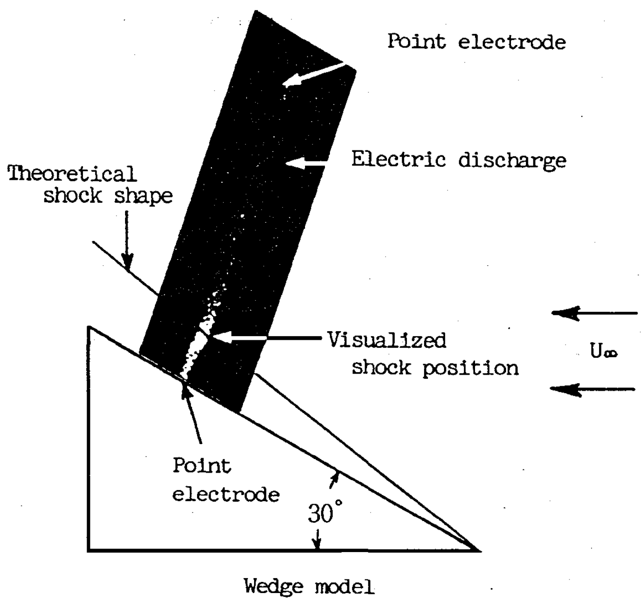


Fig.4 The shock wave over a wedge visualized by the electrical discharge method.

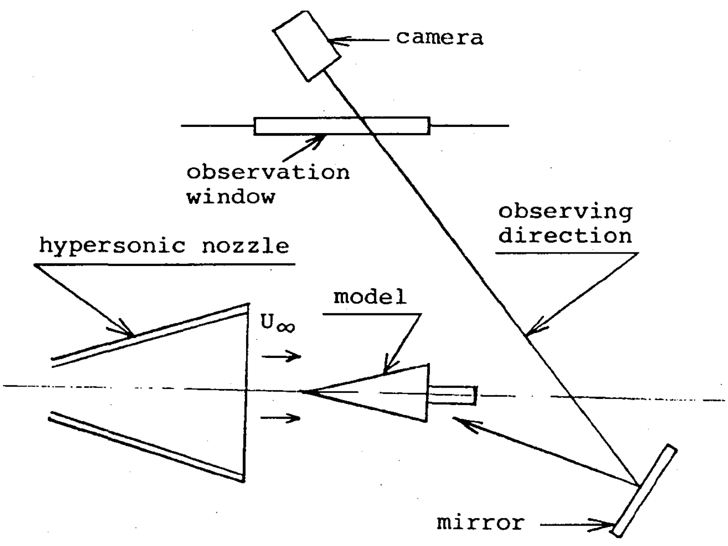


Fig.5 The observing direction of electrical discharges.

potential of nitrogen, little electron excitation will 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 the side, but also from the rear or front, this new method should prove very valuable for the visualization of three-dimensional shock shapes.

3. Experimental Equipment and Procedure

A hypersonic flow is generated by a hypersonic gun tunnel. The characteristics of the gun tunnel are as follows: Mach number=10, Reynolds number=2×10^4 cm^{-1}, freestream density=$4\times10^{-3}kg/m^3$, duration of freestream=10^{-2} sec., exit diameter of nozzle=15cm, freestream velocity=1000m/sec., and static pressure=1mmHg. 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

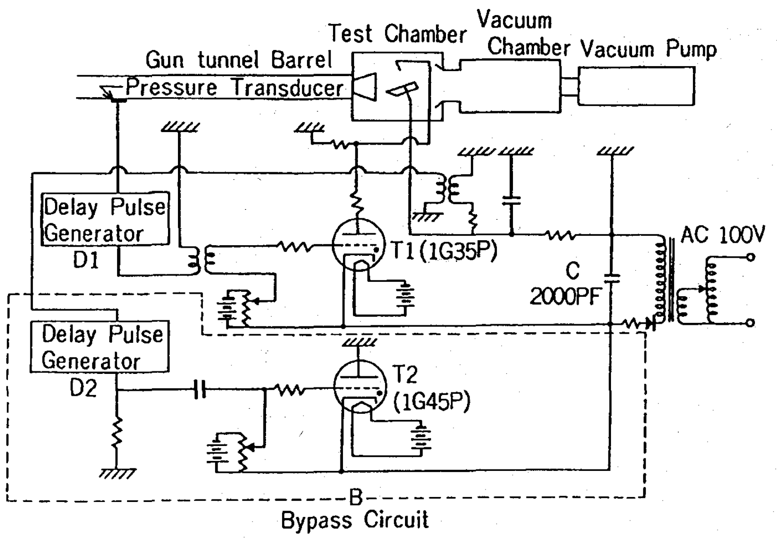


Fig.6 The electrical discharge circuit.

when cross sectional shock shapes are visualized. The observing direction is shown in Fig.5 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.6. 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.

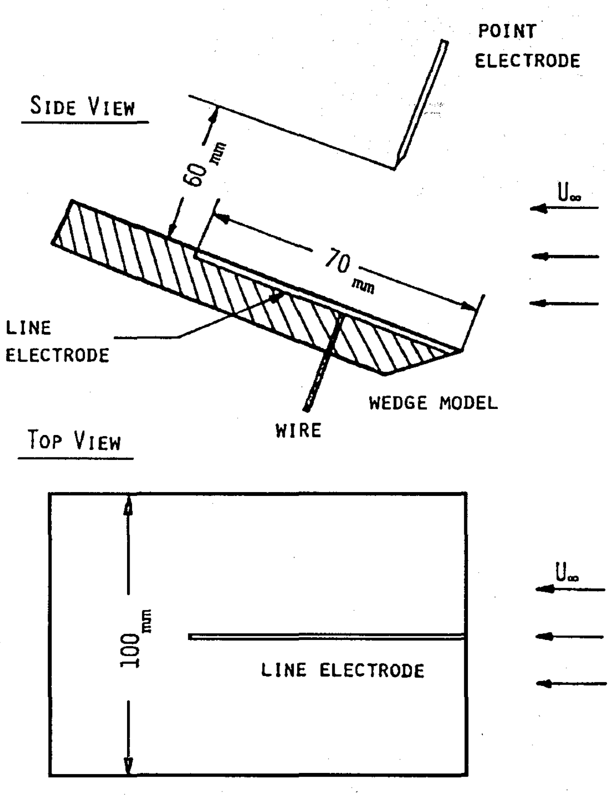


Fig.7 The arrangement of the wedge and the pair of point—line electrodes.

4. 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.7. In this experiment, the point electrode was used as the cathode and the line electrode was used as the anode. The point electrode was

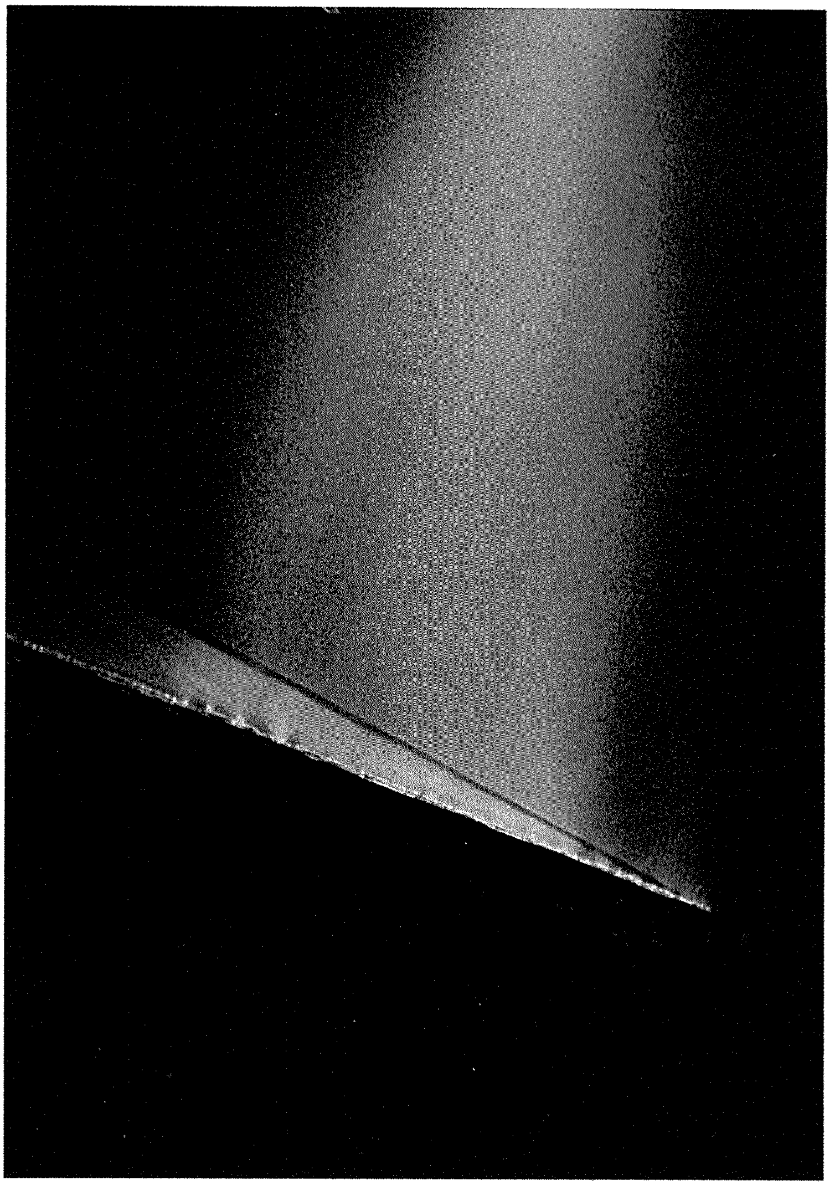
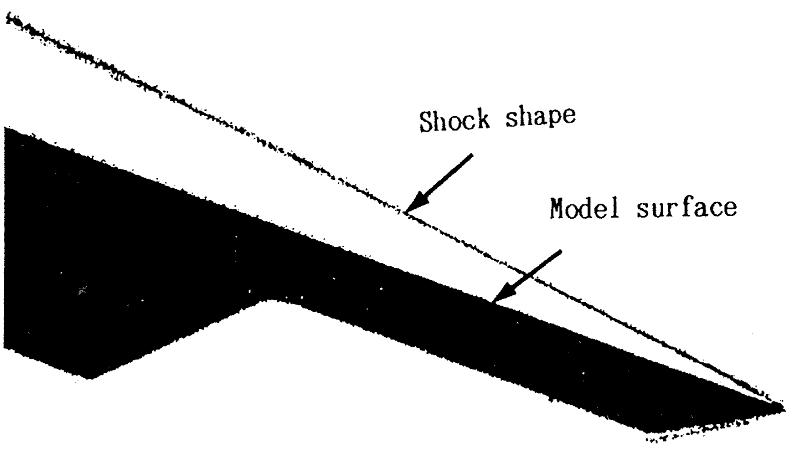


Fig.8 The visualization of the lateral shock shape over the wedge in the hypersonic flow by using an electrical discharge.
(a) The photograph of the visualized shock shape.



(b) The schlieren photograph.

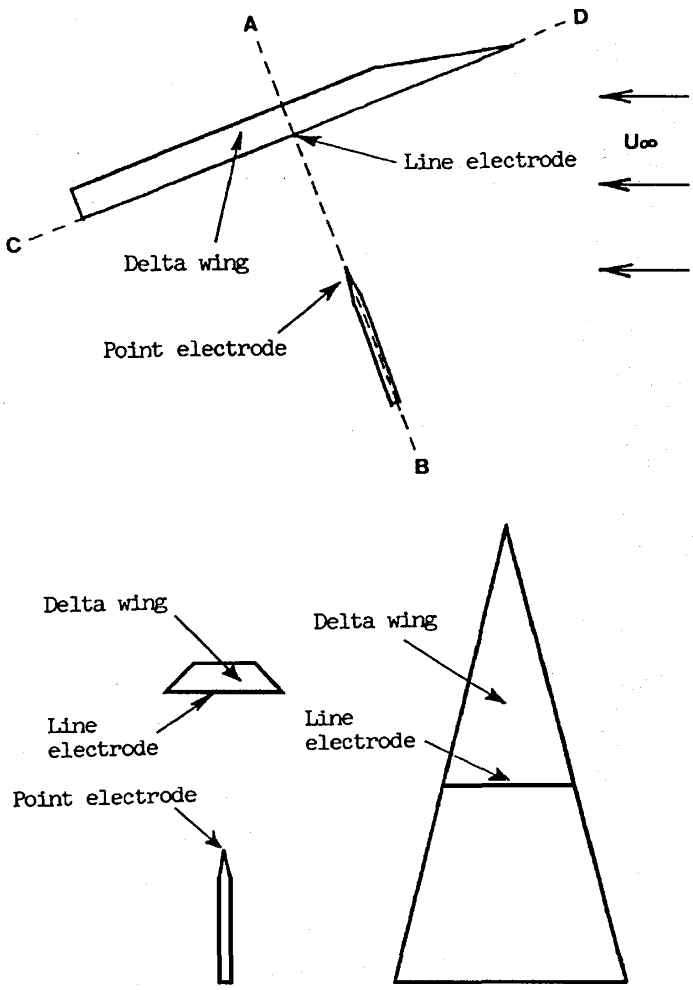


Fig.9 The arrangement of the delta wing and the pair of electrodes

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°. Gap between the pair of electrodes was 60 mm. Iris of the camera was F=1.4, and film speed was ASA 3200. The initial voltage applied to the pair of electrodes was 2000 volts, and the electric current was 1 A. The result of the visulization is shown in Fig.8(a). 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.8(b). The results of both agree sufficiently. From this, it was proved 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.9. The apex angle of the delta wing was 25° and the angle of attack of the model was 20°. The result of the visualization is shown in Fig.10. The photograph indicates that a detached shock shape over the delta wing was visualized successfully.

5. Conclusions

The visualization of three-dimensional shock shapes around hypersonic vehicles is very important for understanding the flow field. 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.

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 proved that the new method is suitable for the visualization of shock shapes. Second, a cross-sectional shock

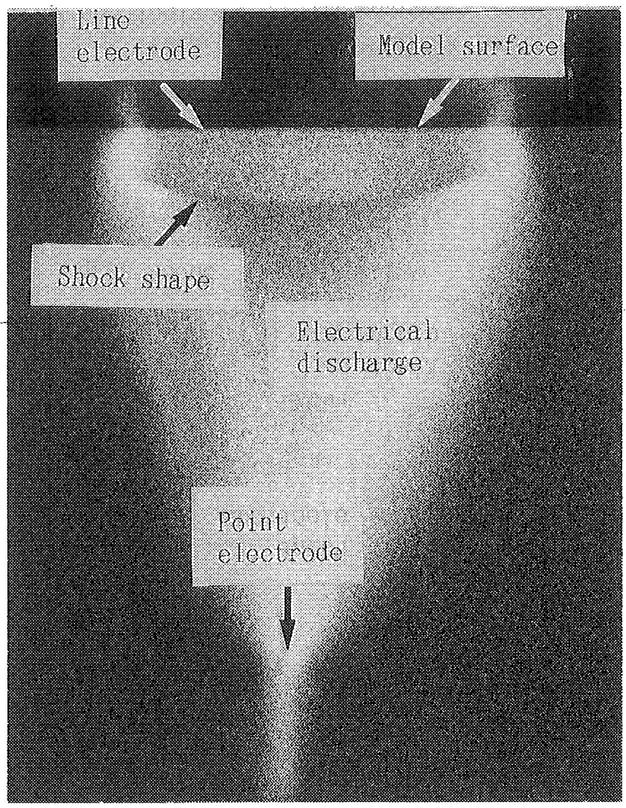


Fig.10 The visualized cross-sectional shock shape over the delta wing in the hypersonic flow.

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.

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