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The First Electric Discharge Method for Visualizing Three-Dimensional Shock Shapes Around Hypersonic Vehicles

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Abstract

This paper describes a method for visualizing three-dimensional shock shapes around hypersonic vehicles using an electric discharge. The method is based on the following ideas. When an electric 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. Therfore, the three-dimensional shock shape can be visualized by taking the discharge photograph. In this paper, the theory of the visualization is established qualitatively by considering the relation among the radiation intensity from the electric discharge, excitation function vs. electron energies, and gas molecular number density. By establishing the theory of the visualization, it was found that there exists the most suitable experimental condition for visualizing shock shapes by using the method. By utilizing the result, three-dimensional shock shapes have been visualized successfully.

1. Introduction

To visualize 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 interferometer, shadowgraphs, etc., have been used as typical methods to visualize shock shapes. However, these methods are useful only for visualizations of two-dimensional shock shapes and shock shapes around bodies of revolution. Methods for visualizing three-dimensional shock shapes, such as the electron beam method and the vapor screen method, have been reported. The electron beam method by Muntz & Marsden (1963) and Maguire, Muntz & Mallin (1967) is suitable for the visualization of rarefied gas or extremely low-density gas. However, it is rather difficult to visualize shock shapes that are not extremely low density. In the vapor screen method by Scheuing (1961) and Rao (1971), there seemed to be the possibility of changing the characterisitics of the gas by mixing water.

Visualizations of three-dimensional shock shapes using electric discharge were tried by Kimura & Nishio (1977). They thought that when an electric 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. Therefore, the shock shape can be visualized by taking the discharge photograph. However, they did not have reasonable theoretical ideas why the radiation intensities

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become different from each other. Therfore, it was very difficult to select the suitable experimental conditions. Consequently, the visualizations of shock shapes were very difficult, and shock shapes were not visualized successfully, as mentioned by Nishio (1990).

In this paper, the author tries to establish the theory of the visualizing method qualitatively by considering the relation among the radiation intensity from the electric discharge and excitation function vs. electron energies, and gas molecular number density. By establishing the theory of the visualizing method qualitatively, it became possible to visualize three-dimensional shock shapes by the method.

2. Visualizing Prenciple

It is generally known that the radiation intensity from an electric discharge is related to the excitation functions vs the energy of the electrons drifting in the electric field and the molecular number density, as mentioned by Nishio (1990).

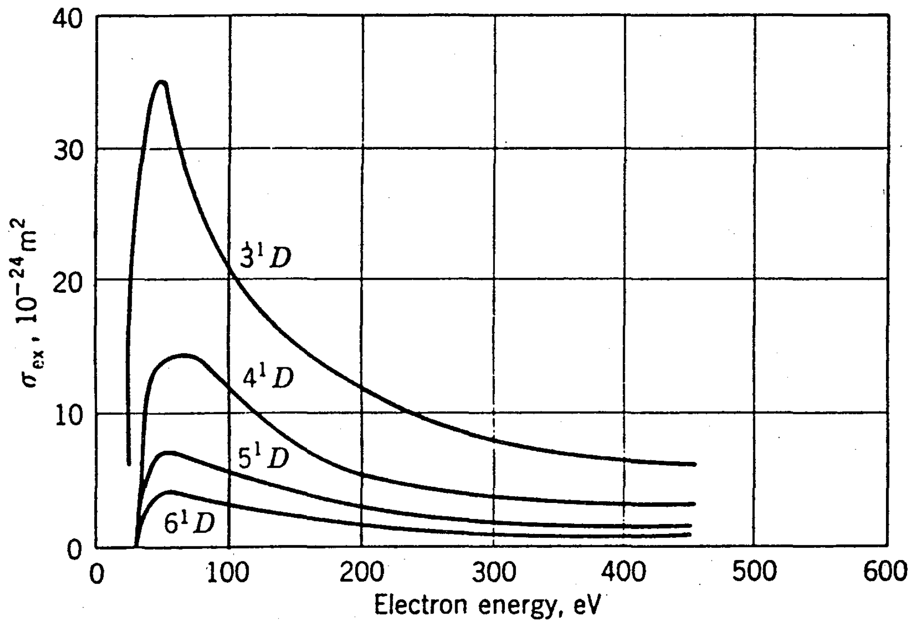

Fig.1 Typical curves for the excitation-collision cross sections as a function of the energy of the incident electrons.

Figure 1 by Nasser (1970) shows typical curves for the excitation-collision cross sections as a function of the energy of the incident electrons. The excitation cross sections are numerically equal to the excitation functions. The figure indicates that the excitation functions rise steeply according to increase of electron energies and the excitation functions drop rapidly just after reaching the maximums, and after that the excitation functions decrease gradually according to the increase of electron energies. As mentioned by Nasser (1970), the decline in all types of excitation functions after reaching the maximums can be explained purely qualitatively by considering the actual collision process that can be visualized by considering the interaction of the electro-magnetic fields of the two colliding particles. When the oncoming particle is a fast electron "wave," the period of interaction of the fields of the "waves" of both particles become very short. The amount of kinetic energy and momentum fransferred from the electron to the molecule also decreases. Hence, if the electron is too fast no "collision" takes place, as no appreciable interaction of fields is effective in the short time.

Now we consider a representative excitation function curve in arbitrary units vs. electron energy as shown in Fig.2. The radiation intensity I from an electric discharge is proportional to the product of the excitation function and the gas molecular number density. Therefore, the vertical scale in Fig.2 is replaced by the radiation intensity I as shown in Fig.3. In this case, the gas molecular number density is

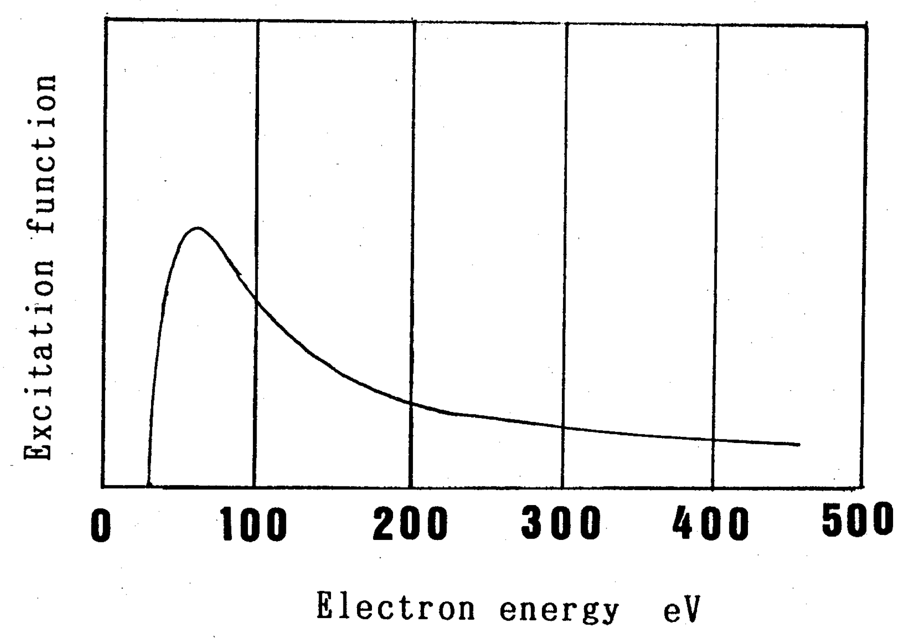

Fig.2 A representative excitation function curve in arbitrary units vs. electron energy.

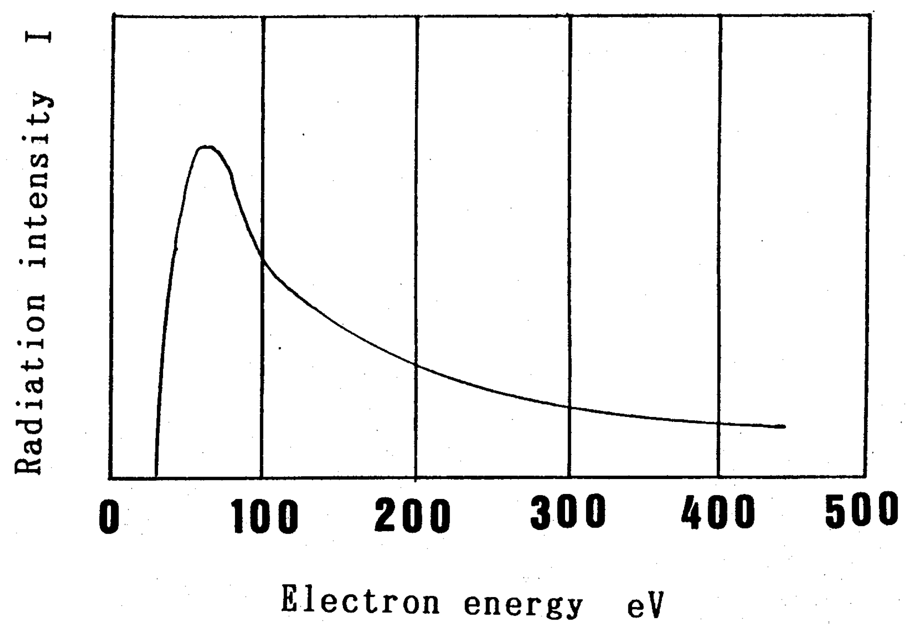

Fig.3 A rediation intensity curve in arbitrary units vs. electron energy.

a parameter. The electron energy W in an electric field is expressed by the following relation.

$$W \propto E/N \tag{1}$$

where E and N are electric field and the molecular number density, respectively. Consequently, the radiation intensity I vs. the electric field E is expressed as shown in Fig.4 by the parameter of the molecular number density N. In the figure, we can draw the different radiation intensity curves according to the different molecular number density N. However, the shapes of these curves are similar figures with each other, even though the molecular number density N is different.

We assume the case that there occurs a shock wave over a wedge and that an electric discharge is generated by applying a high voltage and it crosses the shock wave as shown in Fig.5. The radiation

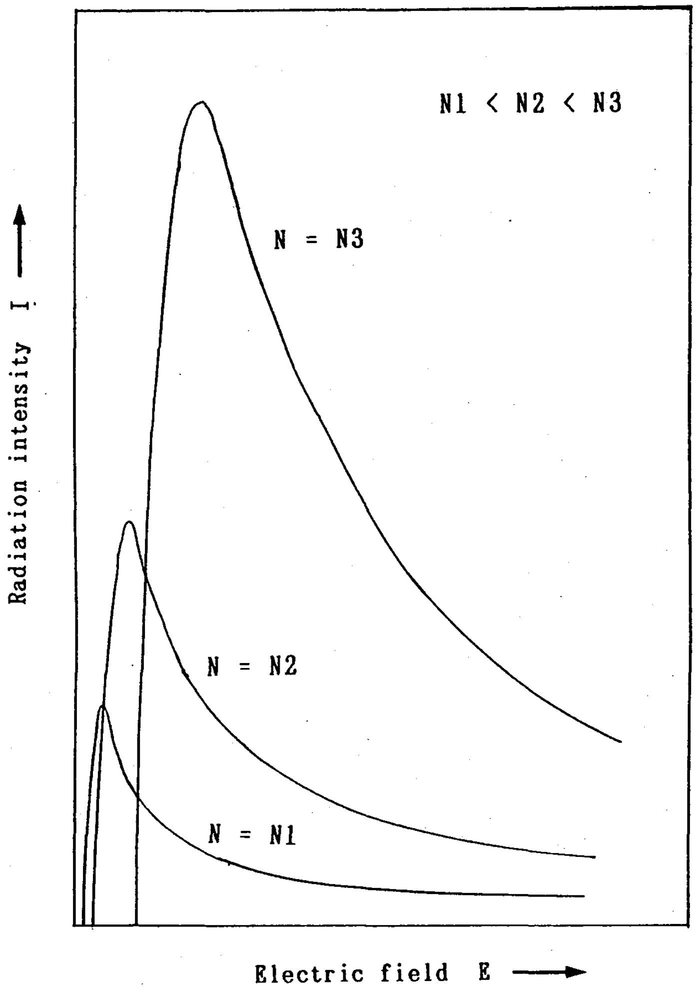

Fig.4 Radiation intensity I vs. electric field E by parameter of molecular number density N.

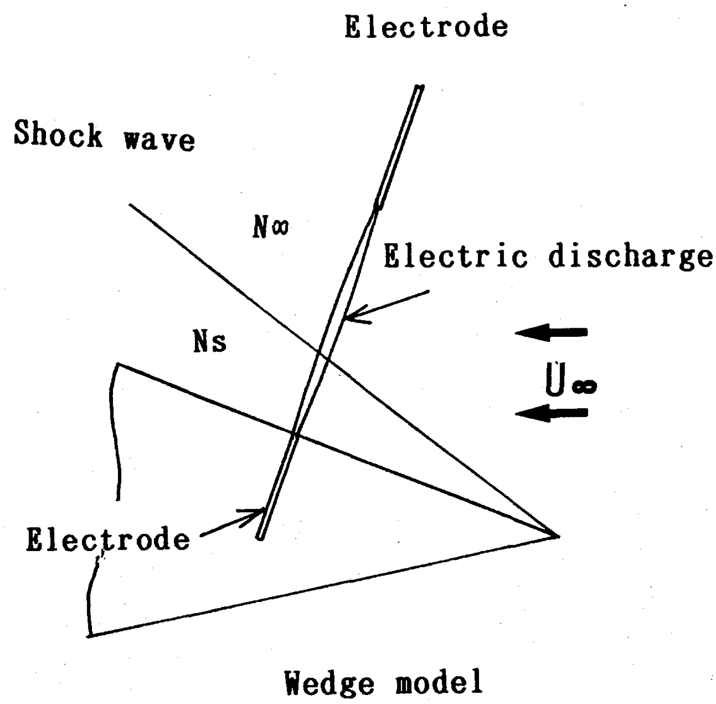

Fig.5 Illustration of. a shock wave over a wedge crossed by an electric discharge.

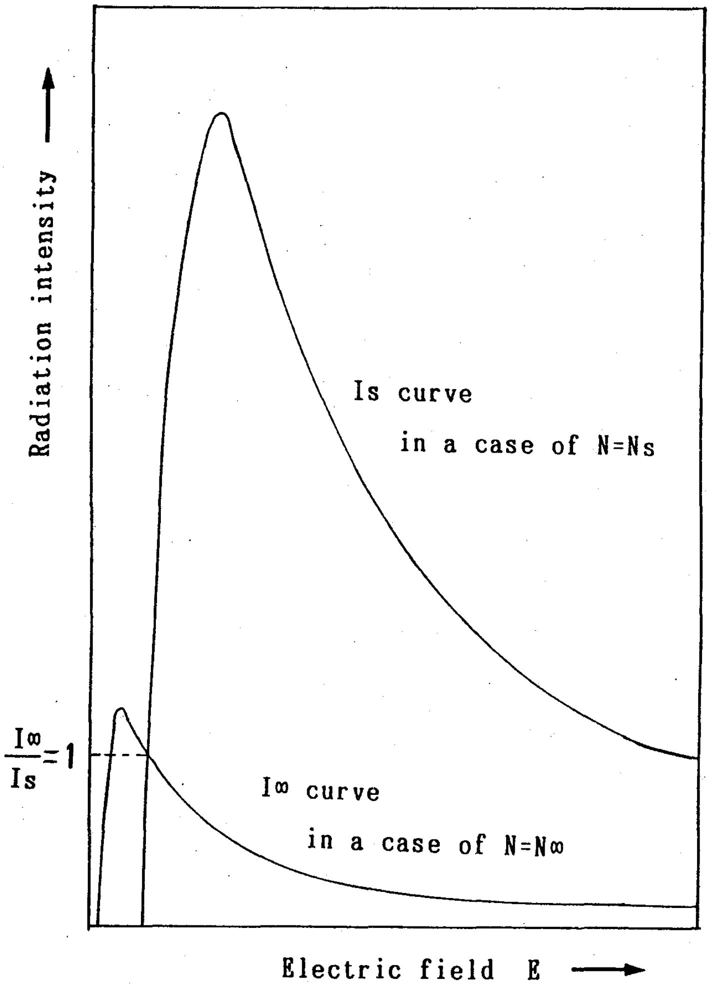

Fig.6 Radiation intensity curves from the two regions, one in the freestream and the other in the shock layer.

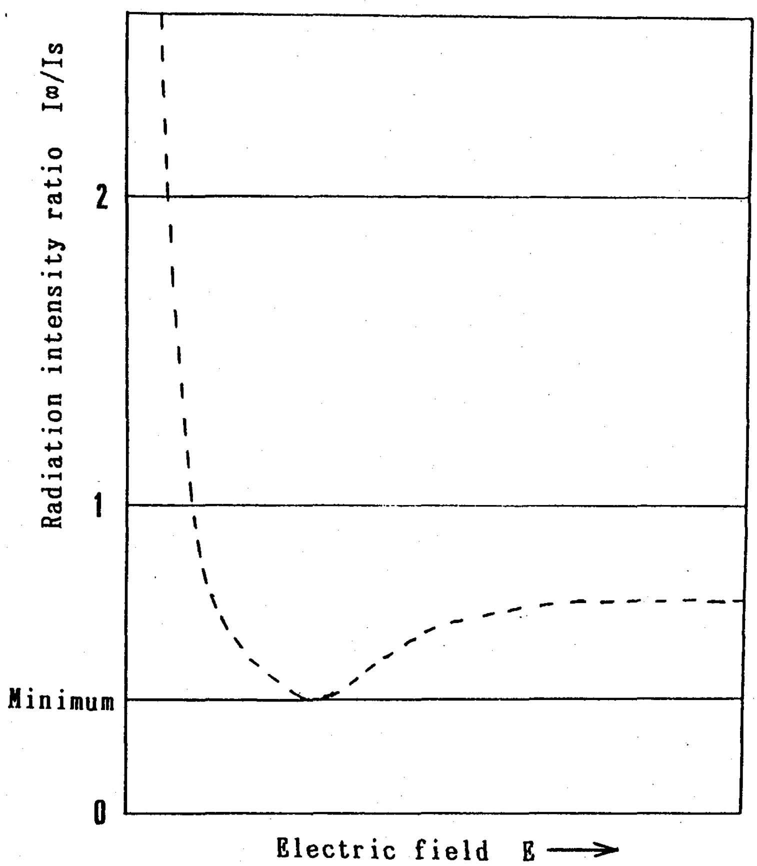

Fig.7 Relation between radiation intensity ratio I∞/Is and electric field E.

intensity I∞ from the freestream differs from the radiation intensity Is from the shock layer because of the following reasons.

The both radiation intensities I∞ and Is from the two regions, one in the freestream and the other in the shock layer are expressed by the two curves as shown in Fig.6. In this case, Ns is larger than N∞. where N∞ is the molecular number density in the freestream and Ns is the one in the shock layer. The figure shows that I∞ is larger than Is when the electric field E is small enough. I∞ and Is become equal at the electric field value where the two curves cross with each other. We can not visualize the shock position in this case. Moreover, if the electric field becomes larger than the value, Is becomes larger than I∞. From these relations described above, the radiation intensity ratio I∞/Is vs. the electric field E is

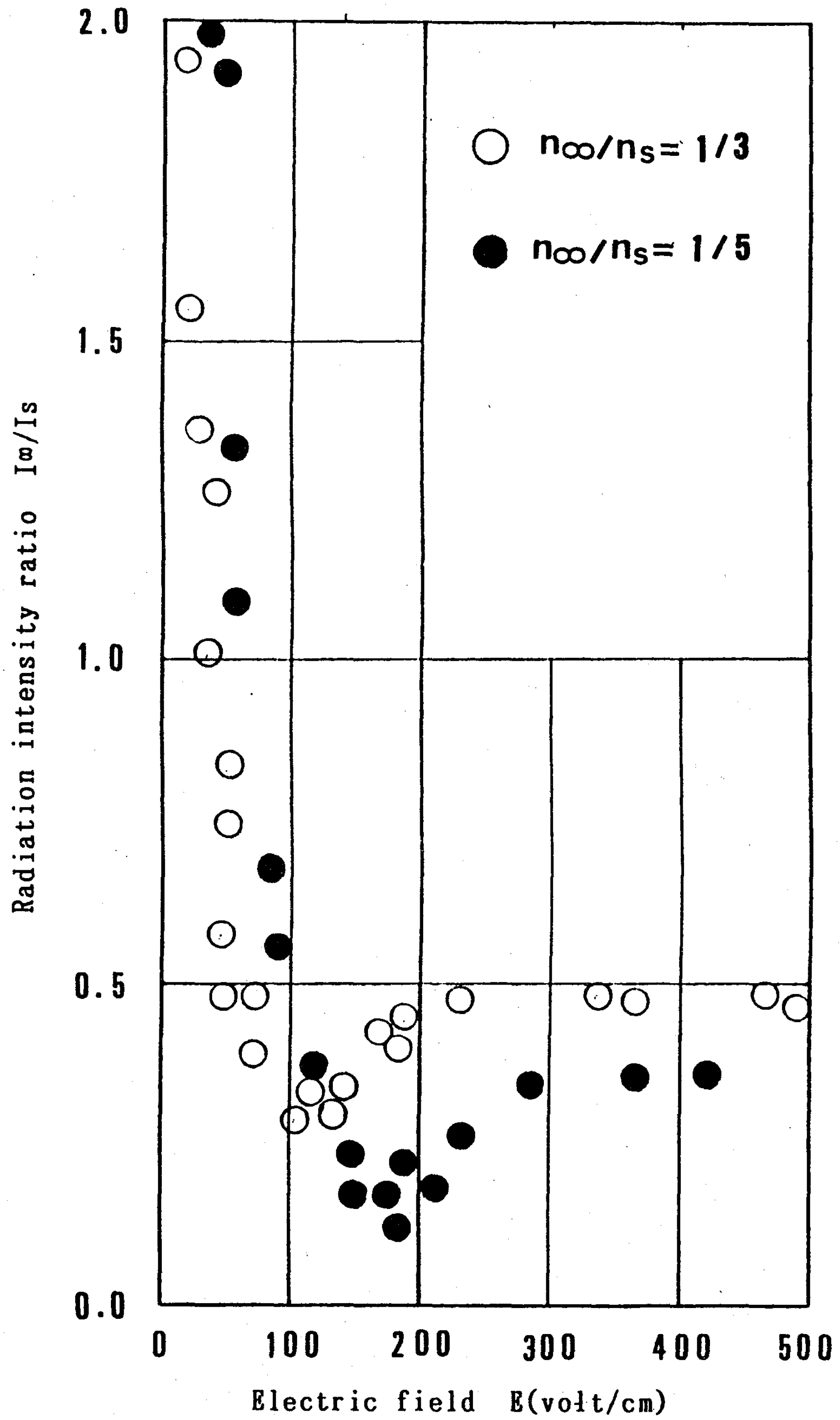

Fig.8 Relation between radiation intensity ratio I∞/Is and electric field E obtained experimentally.

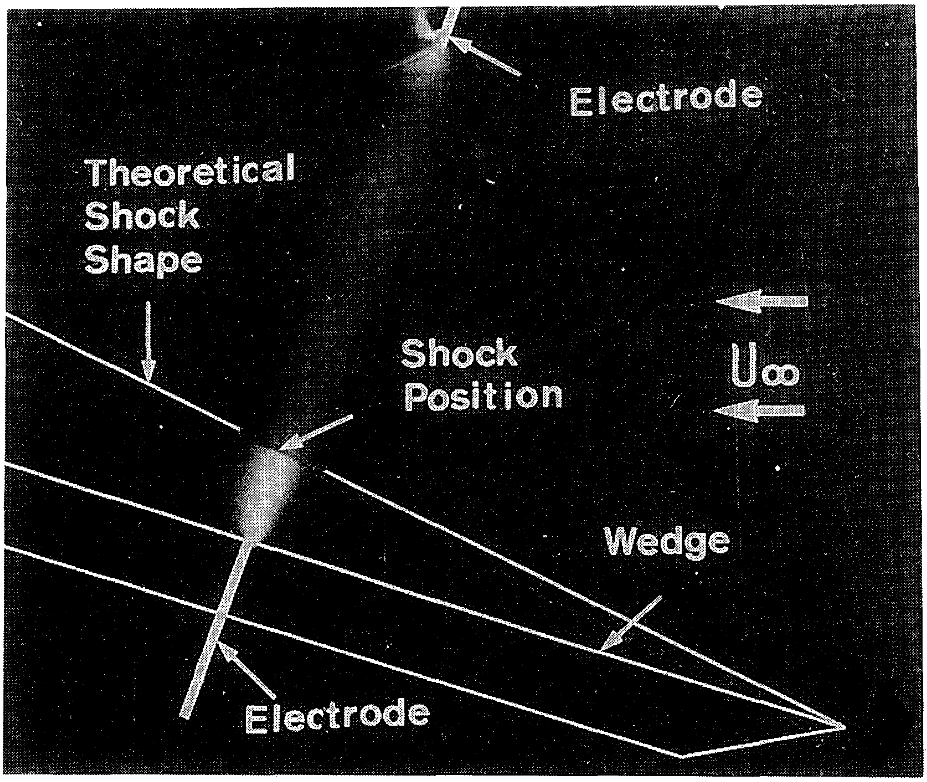

Fig.9 Result of visualization of Shock position over a wedge model.

briefly obtained as shown in Fig.7. Figure 7 showns that the value of I∞/Is becomes minimum at a certain value of E. The reaspn of the occurrence of the minimum value can be explained than the excitation functions drop rapidly just after reaching the maximums and after that, the excitation functions decrease gradually according to the increase of electron energies, as mentioned before.

To verify the above qualitative predictions, the relations between the value of the radiation intensity ratio I∞/Is and the electric field E are investigated experimentally. In these experiments, electric discharges crossed shock waves were photographed at various values of electric field, and the radiation intensities in the freestream and the shock layer were read by using densito-meter. Figure 8 shows the experimental results of the value of I∞/Is vs. the electric field E when E when N∞/Ns are 1/3 and 1/5. In the case of a constant value of N∞/Ns, Fig.8 indicates that I∞/Is is larger than unit when the electric field E is small enough. I∞/Is becomes unit at a value of electric field E. In the region just over the value of E, I∞/Is becomes minimum. After that, I∞/Is becomes nearly constant according to the increase of the value of E. There experimental results are just like the qualitative ones.

In the case of I∞/Is=1, the shock shape can not be visualized since there exists no radiation contrast at the shock position. when the electric field is small enough, it seems to be suitable for the visualization of shock shapes since I∞/Is=1 is realized. However, to generate the electric discharge under the condition of small electric field, a great amount of electric current should be required. Consequently, the flowfield would be disturbed and the visualization of shock shapes would not be successful. Therefore, it is considered to be suitable to select the electric field value which makes the value of I∞/Is minimum.

Figure 9 shows a shock position over a wedge model obtained experimentally by using the suitable experimental condition. The result indecates that the shock position is visualized exactly and clearly. The electric discharge can be photographed not only in the side, but also in the rear. Therefore, the present method can visualize three-dimensional shock shape.

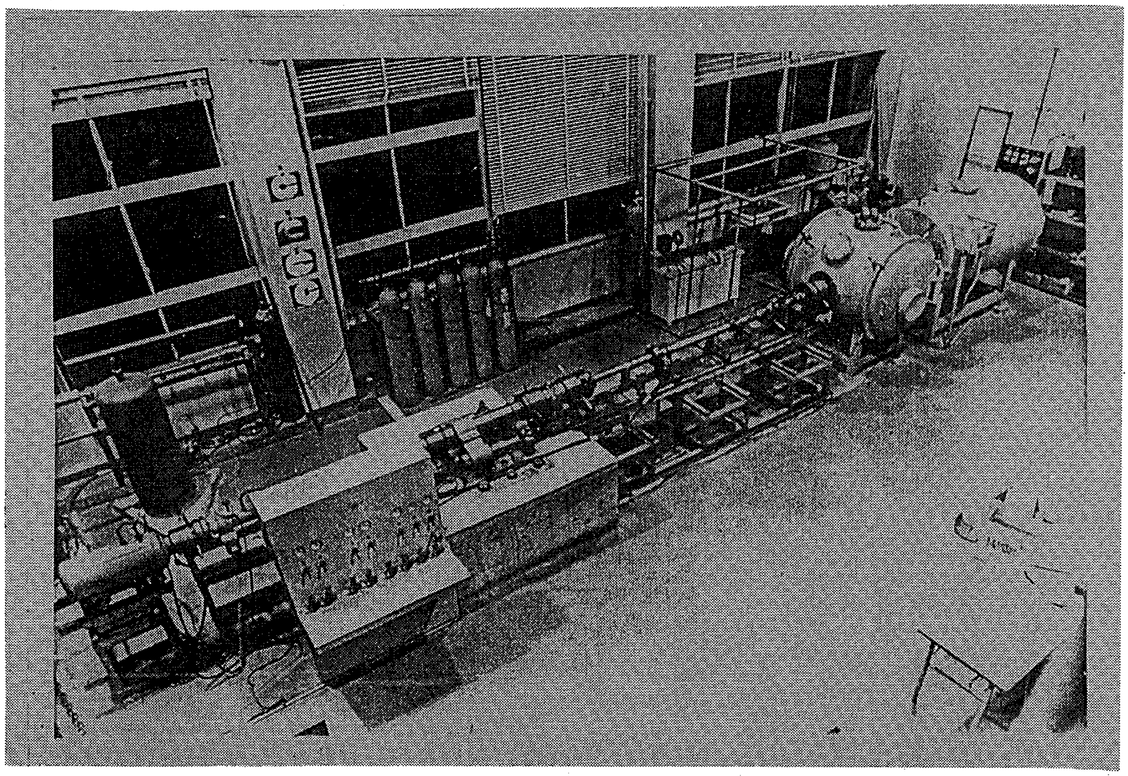

Fig.10 Hypersonic tunnel.

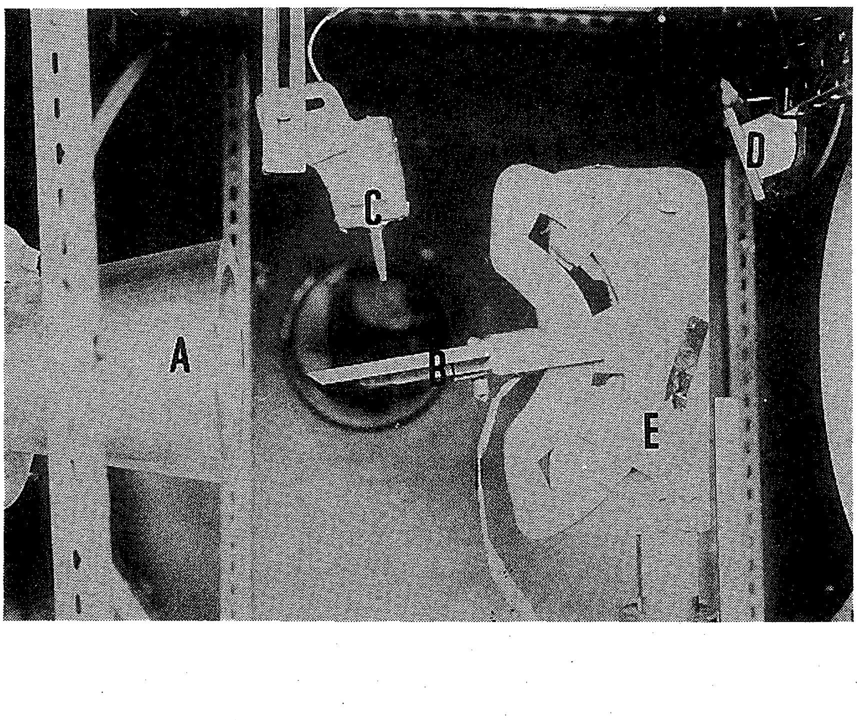

Fig.11 Test section of the hypersonic tunnel.
A:Hypersonic nozzle, B:Model, C:Electrode, D:Mirror, E:Model supporting. system.

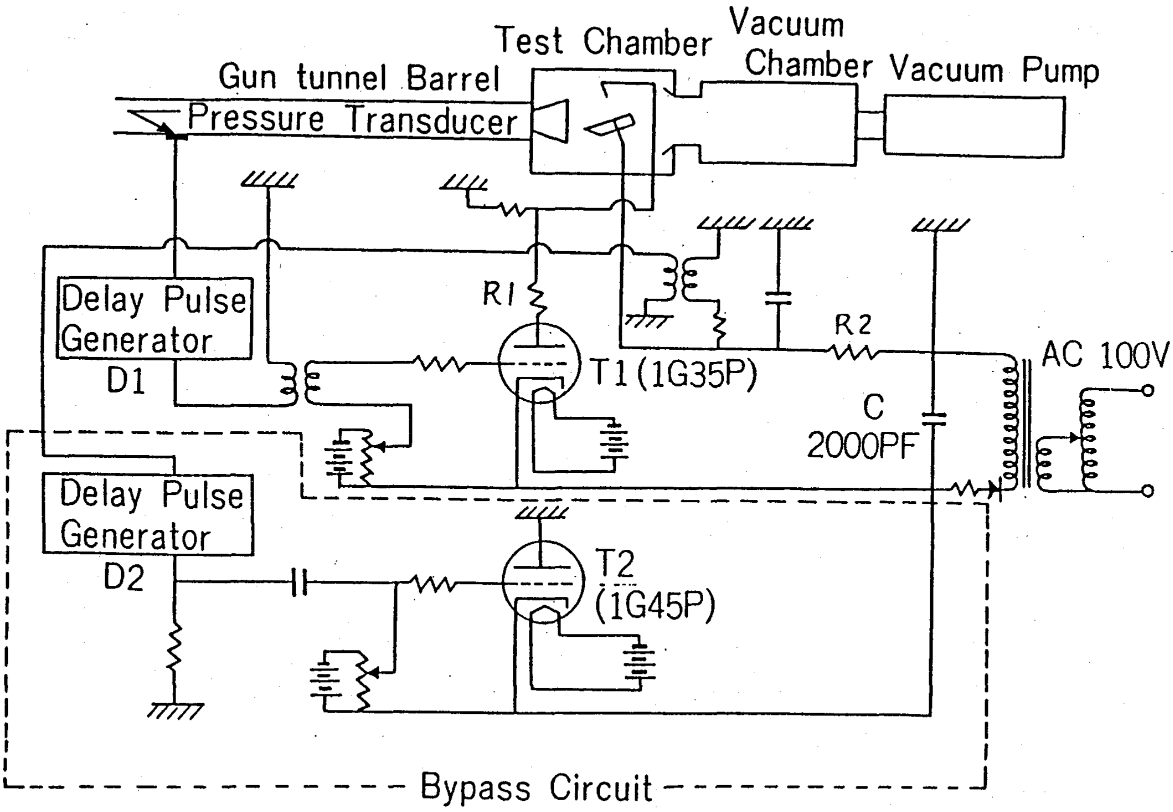

Fig.12 Discharge circuit.

3. Experimental Instruments

A hypersonic flow is generated by the hypersonic tunnel shown in Fig.10. The characteristics of the tunnel are as follows: Mach number is 10, the freestream velocity is 1000 m/sec, the freestream density is 4×10^{-3} kg/m^3, the static pressure is 1 mmHg, the flow duration is 10^{-2} sec, and the diameter of the exit of hypersonic nozzle is 0.15 m. The test section of the tunnel is shown in Fig.11. A mirror is used when three-dimensional shock shapes are visualized and a camera is set just outside the observation window. The camera is set open during the experiment, and therefore, the exposure time of the film is equivalent to the duration of the electric discharge itself. The electrical discharge circuit is shown in Fig.12. An electric discharge is generated by the circuit while the hypersonic flow is obtained.

4. Visualizations of Shock Shapes

To visualize a wide field of a shock shape by a single electric discharge, the method of a pair of point-line electrodes by Nishio (1990) were used.

First, a shock shape over a wedge was visualized to investigate the accuracy of the shock shape by the present method. The arrangement of the wedge and the pair of electrodes is shown in Fig.13. The result of the visualization is shown in Fig.14. For comparison, a schlieren photograph of the shock shape obtained under the same experimental conditions is shown in Fig.15. The results of both agree sufficiently. From this, it is confirmed that the present method using the electric discharge can bisualize shock shapes precisely.

Next, a shock wave generated between two wedges was visualized. The arrangement of the model and the pair of electrodes is shown in Fig.16. The result of the visualization is shown in Fig.17. The figure indicates that the shock shape is visualized clearly. To visualize such cross-sectional shock shape is very important for understanding the flowfield around complicated hypersonic vehicle shapes as well as fundamental ones. From this, it is confirmed that the present method is useful for the visualizatins of

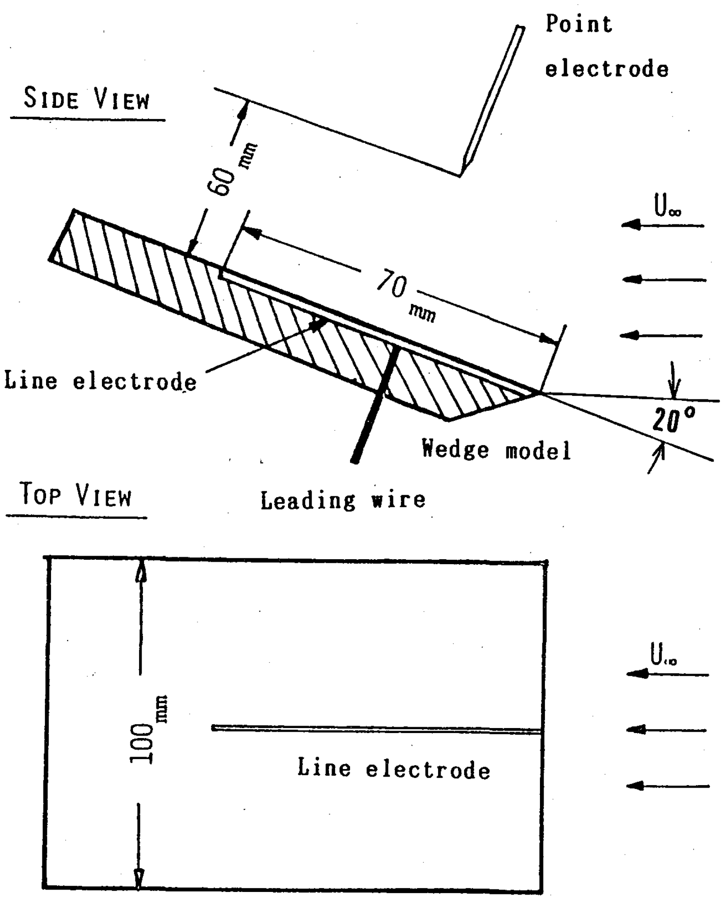

Fig.13 Arrangement of wedge model and pair of electrodes.

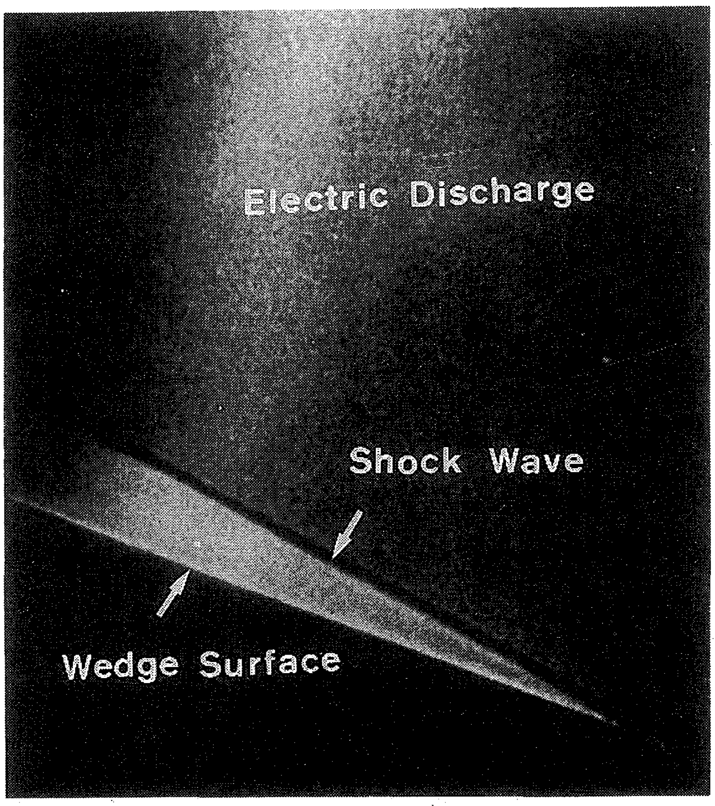

Fig.14 Visualized shock shape over wedge.

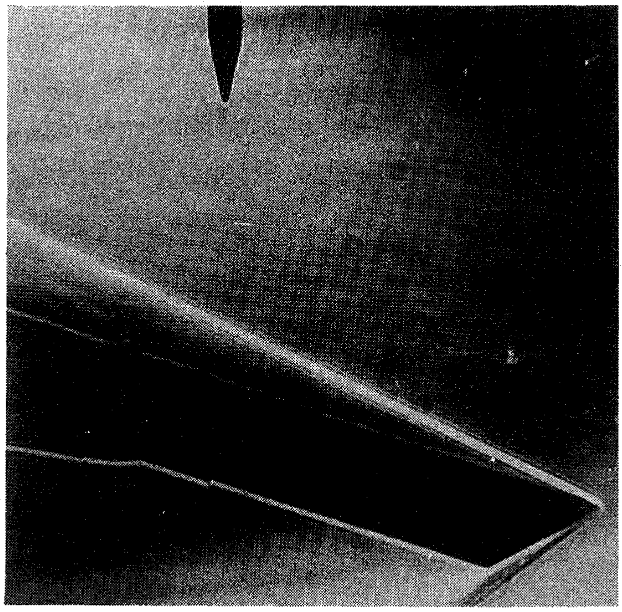

Fig.15 Schlieren photograph.

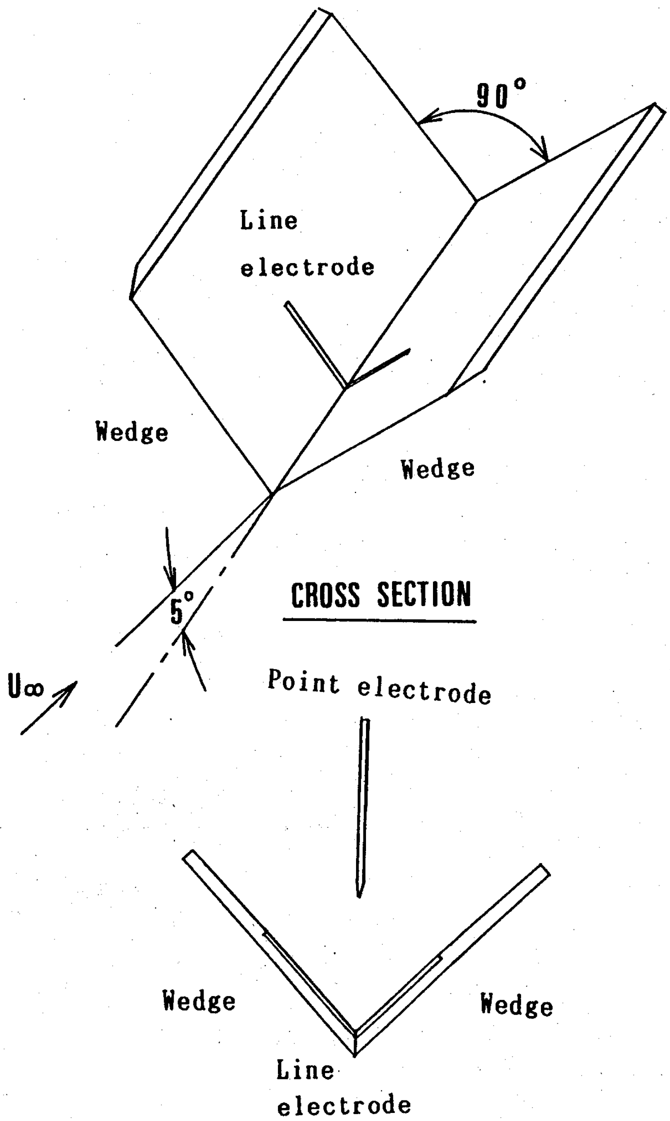

Fig.16 Arrangement of two wedge models and pair of electrodes.

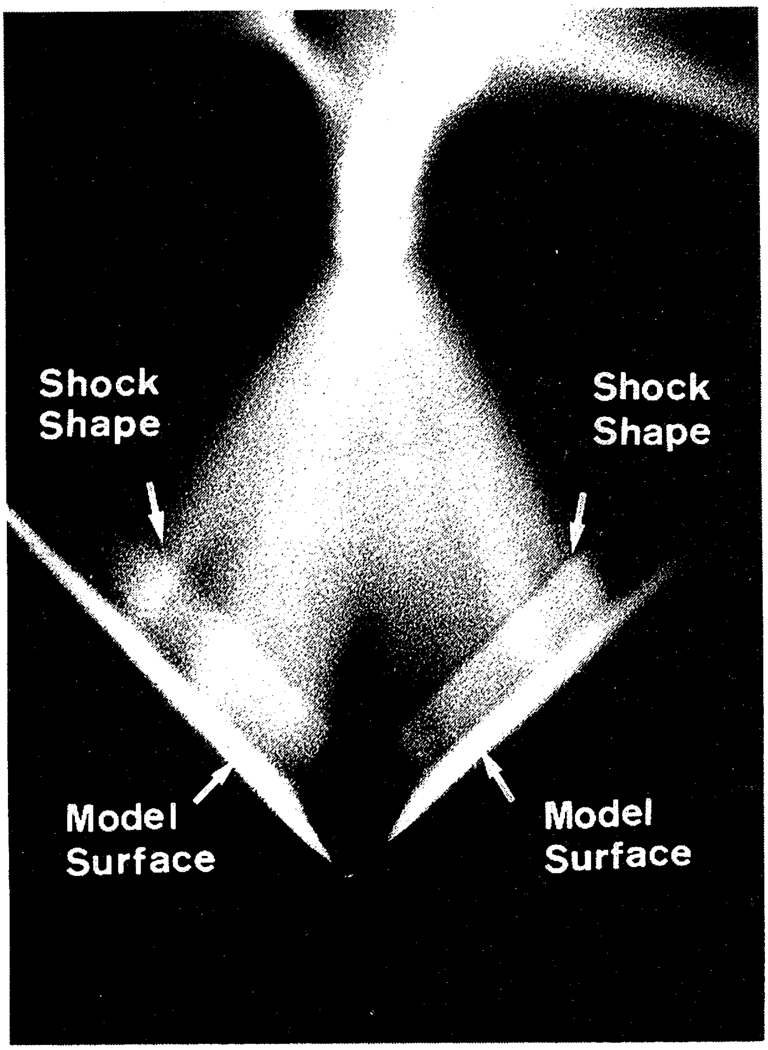

Fig.17 Visualized shock shape generated between the two wedges.

three-dimensional shock shapes.

5. Conclusions

This paper described a method for visualizeing three-dimensional shock shapes around hypersonic vehicles using an electric discharge. The method is based on the following ideas. When an electric 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. Therefore, the three-dimensional shock shape can be visualized by taking the discharge photograph. In this paper, the theory for the visualization of shock shapes was established qualitatively by considering the relation among the radiation intensity from the electric discharge, the excitation function vs. electron energies, and the gas molecular number density. By establishing the visualizing theory, it was found that there is a suitable experimental condition. The shock generated between two wedges was visualized successfully by utilizing the suitable experimental condition. The shock shape can not be visualized by optical systems, such as the schlieren method. From this, it was confirmed that the present method is useful for the visualization of three-dimensional shock shapes.

References

1. Kimura, T. and Nishio, M., "Visualization of Shock Wave by Electric Discharge," AIAA Journal, Vol. 15, No.5, 1977, pp.611-612.
2. Maguire, B., Muntz, E., and Mallin, J., "Visualization Technique for Low-density Flow Field," IEEE Transactions on Aerospace and Electronic System, Vol.AES-3, No.2, 1967, pp-321-326.
3. 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.
4. Nasse, E., Fundamentals of Gaseous Ionization and Plasma Electronics, Wiley-Interscience, 1970, pp. 73.
5. Nishio, M., "New Method for Visualizing Three-dimensional Shock Shapes Around Hypersonic Vehicles Using an Electrical Discharge," AIAA Journal, Vol.28, No.12, 1990, pp.2085-2091.
6. Rao, D., "Delta Wing Shock Shape at Hypersonic Speed, "AIAA Journal, Vol.9, No.10, 1971, pp. 2093-2094.
7. Scheuing, R., "Outer Inviscid Hypersonic Flow With Attached Shock Waves, "ARS Journal, Vol.31, No.4, 1961, pp.486-505.