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Methods for Visualizing Hypersonic Shock-Wave/Boundary-Layer Interaction Using Electrical Discharges

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Two methods for visualizing the spatial flowfield of hypersonic shock-wave/boundary-layer interaction were developed by utilizing the radiation of electrical discharges. One method visualizes boundary layers in hypersonic flow, and the other visualizes streamlines near wall surfaces in hypersonic flow. These two methods were applied to the visualization of hypersonic shock-wave/boundary-layer interaction, and the results confirmed that the two methods are useful for visualizing the spatial flowfield of hypersonic shock-wave/boundary-layer interaction. The experiments were carried out using a hypersonic shock tunnel, with Mach number of 10 and duration of 10 m · s.

I. Introduction

SHOCK-WAVE/BOUNDARY-LAYER interaction is one of the most important problems in hypersonic flow.[1–5] However, only a few methods, such as the oil-film method, have been developed for visualizing the flowfield. Because of this, surface flow visualization has been the main method used in visualization studies. However, the flowfield near the wall surface (the spatial flowfield) cannot be visualized by the oil-film method. It is difficult to clarify the phenomena of the flowfield solely on the basis of surface flow. To analyze the flow phenomena clearly, it would be very helpful to be able to visualize the spatial flowfield. Therefore, useful methods for visualizing the spatial flowfield of hypersonic shock-wave/boundary-layer interaction have been sought.

To visualize hypersonic flow, the author and others have developed methods for visualizing cross-sectional shock waves,[6,7] spatial streamlines,[8,9] temperature distributions,[10] and so forth, by utilizing the radiation of electrical discharges.

In this study, two methods for visualizing the spatial flowfield of hypersonic shock-wave/boundary-layer interaction were developed. To develop the two visualization methods, the author utilized the radiation of electrical discharges. One method visualizes boundary layers in hypersonic flow and the other method visualizes streamlines near a wall surface in hypersonic flow. These two methods were applied to the visualization of hypersonic shock-wave/boundary-layer interaction, and the results of visualization were demonstrated. The results confirmed that the two methods are useful for visualizing the spatial flowfield of hypersonic shock-wave/boundary-layer interaction.

II. Principle of Visualizing Boundary Layers

First, a method for visualizing boundary layers generated near the wall surface in hypersonic flow was developed by utilizing the radiation of an electrical discharge. The electric circuit used in these experiments is shown in Fig. 1. First, the principle of visualizing boundary layers in hypersonic flow needs to be described. To explain the visualization method, a wedge model in hypersonic flow is used. The arrangement of the wedge model and a pair of electrodes is shown in Fig. 2. In this case, a cathode needle electrode is set in a freestream. The anode line electrode is bonded to the surface of the model. The line electrode should be very thin so as not to disturb the flow. The line electrode is 0.1 mm thick and 2 mm wide. An illustration of the visualization principle is shown in Fig. 3. When an initial columnar spark discharge is generated between position A on the needle electrode and forward portion B on the line electrode by applying high voltage to the pair of electrodes, as shown in Fig. 3a, the ionized columnar discharge path drifts with the flow. This physical phenomenon has been proven by the spark-tracing method.[11] If a voltage is applied to the pair of electrodes while the ionized discharge path is drifting, the radiation from the drifting columnar discharge path also continues because of the continuous excitation of molecules by the electrons traveling from the cathode to the anode. Let us consider the drifting and radiating columnar discharge path after a certain amount of time has elapsed since the start of the initial columnar discharge. The drifting discharge path is curved at the boundary layer, as shown in Fig. 3b, because there exists a velocity distribution near the surface of the model. After a certain amount of time has elapsed after the stage shown in Fig. 3b, the distance between position B and position P on the radiating discharge path has become larger in comparison to the distance between position C on the line electrode in the downstream and position P as shown

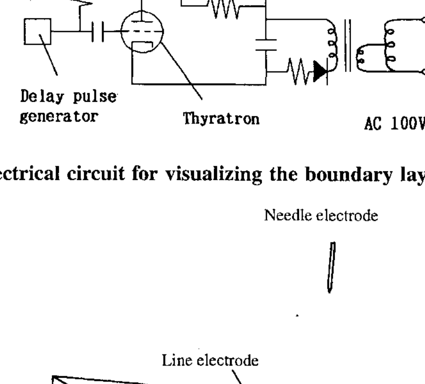

Fig. 1 Electrical circuit for visualizing the boundary layer in hypersonic flow.

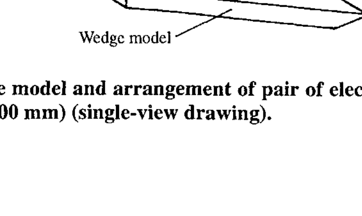

Fig. 2 Wedge model and arrangement of pair of electrodes (width of the wedge is 100 mm) (single-view drawing).

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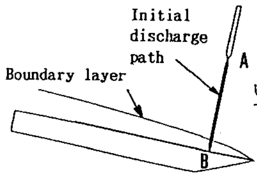
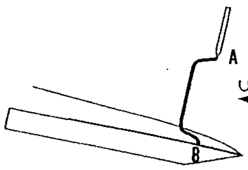
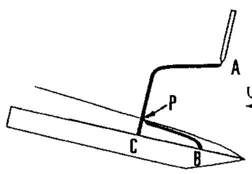


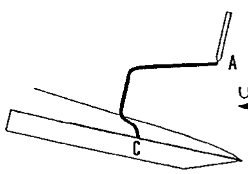
a) Initial electric discharge column



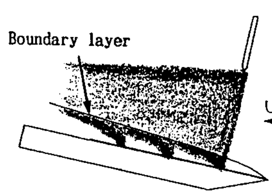
b) Drifting columnar electric discharge generated at time T_1 (T_1 is the time elapsed from the start of the initial columnar electric discharge)



c) As the distance between P and B becomes larger than that between P and C, the electrical resistance of PB becomes larger than that of PC



d) Electric discharge shape generated at time T_2 (T_2 is the time elapsed since the stage in Fig. 3c)



e) Drifting and radiating electric discharge obtained continuously from the start of the initial electric discharge

Fig. 3 Principle of visualizing the boundary layer in hypersonic flow.

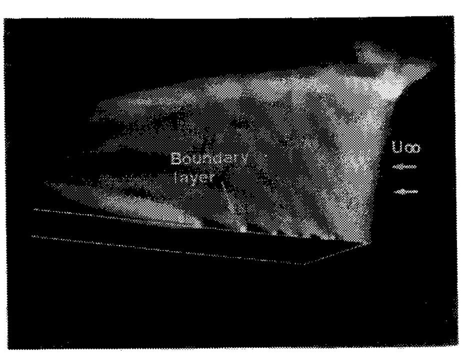


Fig. 4 Visualization of the boundary layer over a slightly blunted wedge in hypersonic flow (wedge angle of attack is 5 deg).

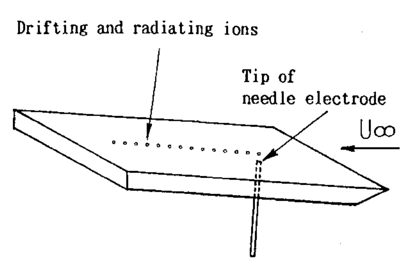
in Fig. 3c, where position P is the crossing position of the boundary layer and the drifting electric discharge path. In this case, as an anode position on the line electrode, position C on the line electrode in the figure, for example, may become a new anode position instead of position B on the line electrode. This is because the electrical resistance between position P and position B becomes larger than the electrical resistance between position P and position C, although the electrical resistances per unit distance are different from each other. Therefore, the new discharge path will become position A to position C by way of position P. If this radiating discharge path continues to drift, the same phenomenon will occur downstream as shown in Fig. 3d. This being the case, if the camera shutter is kept open while the drifting and radiating electrical discharge is being generated, the boundary layer can be visualized as illustrated in Fig. 3e by taking a photograph of the drifting and radiating electrical discharge path. Judging from the visualization principle, if the flowfield is not disturbed, the radiation from the drifting electrical discharge path will be connected smoothly at position P. In Figs. 3a–3e, the generation of the shock wave over the wedge has been excluded to make the illustration simpler.

By utilizing the electrical discharge method described above, visualization of a boundary layer over the wedge with a slightly blunted tip shown in Fig. 2 in hypersonic flow was performed. In the experiment, the angle of attack of the wedge was 5 deg. The result of visualization is shown in Fig. 4. Judging from the visualization principle described above, the boundary layer can be indicated as shown in Fig. 4. We can see that the radiations from the several anode positions on the line electrode are connected smoothly to each other at position P (see Fig. 3). Namely, the radiation from the drifting electrical discharge near the wedge surface is continuous at position P as illustrated in Fig. 3. If the boundary layer was violently disturbed, the radiation from the drifting electrical discharge would be discontinuous at position P. This being the case, it was confirmed that the visualized boundary layer was not violently disturbed.

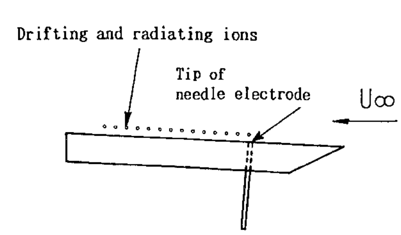
The conditions of the hypersonic shock tunnel used in these experiments were: Mach number = 10, duration = 10 m · s, freestream velocity = 1.5 km/s, and freestream density = 4×10^{-3} kg/m^3. The test gas was air. To generate a suitable electrical discharge for visualization, resistances R1 and R2 in the electrical circuit shown in Fig. 1 were set at 2 kΩ and 100 Ω, respectively. The initial high voltage applied to the pair of electrodes was 2 kV.

III. Principle of Visualization of Streamlines near the Wall Surface

To visualize a streamline near a wall surface in hypersonic flow, the radiation of an electrical discharge was utilized. The principle of the visualization method utilizing the radiation of electrical discharge is as follows. As illustrated in Fig. 5, a high voltage is applied to the anode needle electrode. In this case, ions are generated near the tip of the needle electrode. The ions drift according to the flow and they radiate light because of the recombination between the ions and electrons. Therefore, a streamline is obtainable by taking a photograph of the radiating light. A suitable number of ions must be generated near the tip of the needle electrode to be able to visualize the streamline. For this purpose, the electrical circuit shown in Fig. 6 was used. In this experiment, a streamline near the surface of the wedge was visualized. The wedge angle was 5 deg. The applied



Single-view drawing



Side view

Fig. 5 Principle of visualizing the streamline near a wall surface in hypersonic flow.

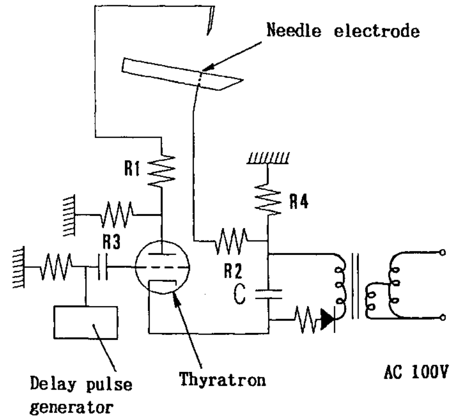


Fig. 6 Electric circuit for visualizing the streamline near a wall surface in hypersonic flow.

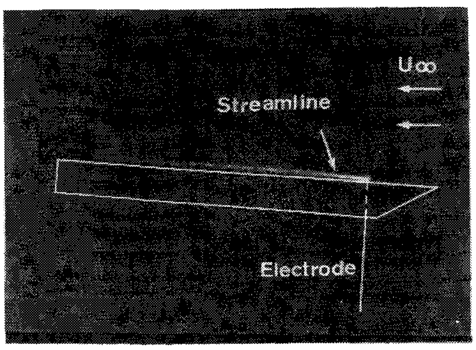


Fig. 7 Visualization of the streamline near the surface of a wedge in hypersonic flow (wedge angle of attack is 5 deg).

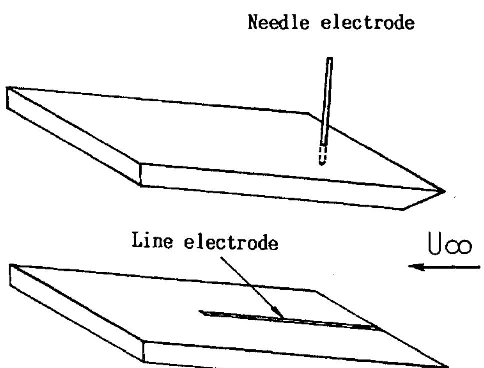


Fig. 8 Arrangement of two wedges and needle and line electrodes (single-view drawing).

voltage to the anode needle electrode was 2 kV. Resistances R1, R2, R3, and R4 were $\infty\ \Omega$, $0\ \Omega$, $200\ \Omega$, and $10\ k\Omega$, respectively. A visualized streamline near the surface of the wedge in the hypersonic flow generated by the shock tunnel is shown in Fig. 7. The result shows that the shape of the streamline is slender and is almost straight along the wedge surface. This indicates that the flow near the wedge surface was not violently disturbed.

IV. Visualization of Shock-Wave/Boundary-Layer Interaction

As an example of the visualization of the flowfield of interaction between a shock wave and a boundary layer, the flowfield generated by the two wedges shown in Fig. 8 was visualized. This flowfield configuration is of practical importance in air-breathing inlets. The result of visualization is shown in Fig. 9. A drawing explaining the photograph was created as shown in Fig. 10 with the aid of the shock shapes shown in Figs. 11a and 11b. Figure 11a shows the interaction of two shock waves generated by the upper wedge and the lower wedge. Figure 11b shows the reflected shock wave from the lower wedge surface. These shock shapes were obtained by the radiation of electrical discharges.[6,7] From the results of the experiment, we came to understand that the flowfield generated by shock-wave interaction is completely different from the flowfield when there is no shock-wave interaction, as shown in Fig. 4. Namely, Fig. 9 shows that the radiations from several anode positions on the line electrode are not connected smoothly with each other. This means that the drifting electrical discharge path is discontinuous. Judging from the visualization principle, the radiations from the several anode

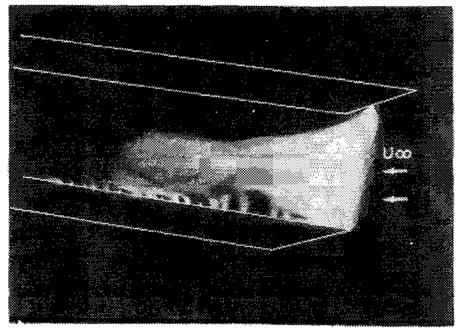


Fig. 9 Visualization of flowfield of shock-wave/boundary-layer interaction in hypersonic flow.

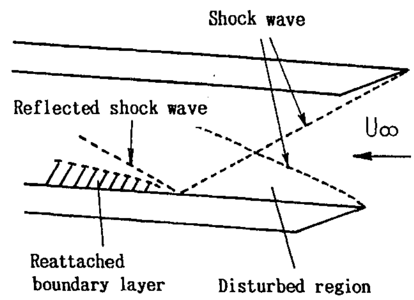
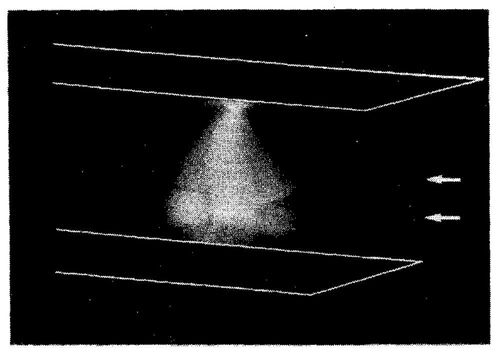
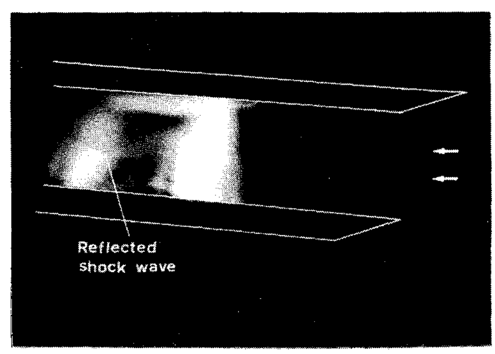


Fig. 10 Flowfield obtained by visualization.



a) Shock–shock interaction



b) Reflection of shock wave from wedge surface

Fig. 11 Visualization of shock waves caused by the radiation of electric discharges.

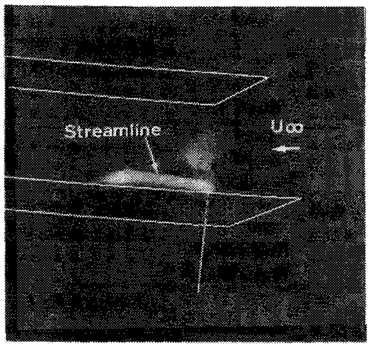
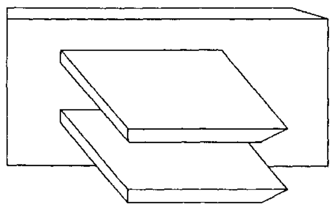
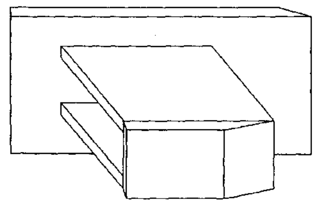


Fig. 12 Visualization of the flowfield near the wedge surface under the condition of hypersonic shock-wave/boundary-layer interaction.



ı) Wall at one end of the two wedges



ı) Two walls at both ends of the two wedges

Fig. 13 Model geometry.

ositions on the line electrode must be connected smoothly with ach other if the flowfield is not disturbed. Based on this, the flow in ıe forward region from the interacted shock wave is considered to e disturbed. From Fig. 9, it is also considered that the flow behind ıe reflected shock wave is reattached to the wedge surface.

Further investigation of the flowfield of interaction between a hock wave and a boundary layer was performed by using the vi- ɹalization method of a streamline near the wall surface. The result f visualization is shown in Fig. 12. In Fig. 12, the shock posi- on was obtained by an electrical discharge,[6,7] as shown in Fig. 11. 'he result shows that the visualized streamline is thick and curved in ɔmparison with the result shown in Fig. 7. Based on the differences etween the two results, it appears that the flowfield in the forward ·gion from the interacted shock wave was considerably disturbed.

V. Discussion

We can perceive the spatial flowfield in Figs. 9 and 12, but in eneral, the visualization of the hypersonic spatial flowfield is very fficult. In particular, as shown in Fig. 13, when there exists a side all at one end or at both ends of the two wedges, visualizing the in- ɜr flowfield becomes very difficult. However, we have proven that ır methods utilizing the radiation of electrical discharges can visu- ize even this kind of inner flowfield by using an optical-fiber scope. oreover, when the model geometry is as shown in Fig. 14, it is con- ɹered possible to obtain the spatial flowfield near the wall surface ' just setting the needle (cathode) and line (anode) electrodes at a itable position as illustrated in the figure. Therefore, we confirmed at our methods utilizing the radiation of electrical discharges e useful for visualizing hypersonic shock-wave/boundary-layer teraction.

There are many important factors that must be considered to per- rm the successful visualization of boundary layers in hypersonic ›ws by our method utilizing the radiation of an electrical discharge. ıe most important point would be to generate an initial columnar

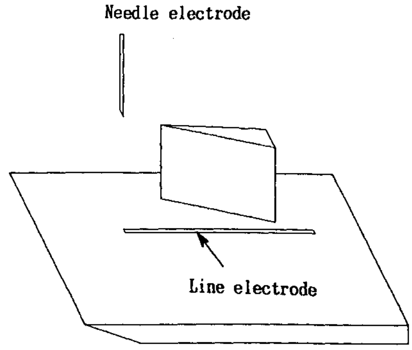


Fig. 14 Model geometry and arrangement of electrodes.

electric discharge path between the pair of electrodes. If the initial columnar electric discharge path cannot be generated successfully in the flowfield, visualization will not be successful. To generate the initial columnar discharge path, the electron velocity traveling from cathode to anode must be sufficiently fast compared to the freestream velocity. The mean electron velocity depends mainly on the applied voltage, the gap length of the pair of electrodes, and the freestream density. In this experiment, the mean electron velocity was calculated as about 100 km/s and the freestream velocity was 1.5 km/s. If the freestream velocity became much faster in this experiment and the freestream density became much higher, we would have to apply a much higher voltage to the pair of electrodes. In this case, the experiment would become more difficult.

VI. Conclusion

Shock-wave/boundary-layer interaction is an important problem in hypersonic flow. In the study being reported, two methods for visualizing the spatial flowfield of hypersonic shock-wave/boundary-layer interaction were developed. To develop these two methods, the author utilized the radiation of electrical discharges. One method visualizes boundary layers in hypersonic flow and the other visualizes streamlines near the wall surface in hypersonic flow. These two methods were applied to the visualization of hypersonic shock-wave/boundary-layer interaction, and the results of visualization were demonstrated. On the basis of these results, the two methods were confirmed to be useful for visualizing the spatial flowfield of hypersonic shock-wave/boundary-layer interaction.

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