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Stabilization Time of Wake Behind Hypersonic Capsule

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ABSTRACT

A stabilization time of a wake structure behind a hypersonic vehicle is very important in an experiment on the flow structure by using pulsed facilities of high enthalpy or of high Mach number. However, observations themselves of such wake structure have been very difficult, and therefore, the experimental discussion about the stabilization time itself has also been very difficult. In this study the stabilization time of the wake structure was formulated by using the dimensional analysis and the present experimental results. The experiment was carried out by observing separation points and free shear layers just after capsule models similar to a MESUR pathfinder probe. To visualize the wake structure, one of techniques called the electrical discharge method was utilized. From these investigations it was found that the stabilization time of the wake structure was related to the Reynolds number, the model scale, and the freestream velocity. A hypersonic gun tunnel of Mach 10 was used in this experiment.

Keywords: Stabilization time, Wake, Hypersonic vehicle, and Electrical discharge method

Nomenclature

T = stabilization time of wake pattern measured from the beginning of stable uniform flow.
T0 = stabilization time of wake pattern measured from the beginning of flow obtained by a pulsed facility
T1 = elapsed time from the beginning of flow obtained by a pulsed facility
T2 = stabilization time of freestream measured from the beginning of flow
Rb = capsule radius
Rs = distance between separation point and symmetry axis
μ = viscosity coefficient
ρ = density of freestream
U = freestream velocity
D = projected area of model
A = projected area of model
Re = Reynolds number
k = proportionality constant
α = constant

1. Introduction

A stabilization time of a wake structure behind a hypersonic vehicle is a crucial problem in order to investigate the structure by using a hypersonic pulsed facility.

To promote a space development from aerodynamics points of view, the investigation about flowfields around hypersonic vehicles is very important, and a large number of numerical studies about wake structures behind re-entry capsules have been reported [1]-[8]. In case of experimental studies of high enthalpy and high Mach number flows, pulsed facilities, such as hypersonic shock tunnels or ballistic range systems, have usually been used. However, in general, these facilities have very short duration of the order of some ten milliseconds or of shorter than that. Because of this very short duration, there occurs a crucial problem that the wake structure behind hypersonic vehicles is unstable, although the flowfield ahead of the vehicles is considered to be stable. Figures 1 show three shock shapes ahead of a capsule model of 70mm diameter vs. elapsed times of 6.8ms,

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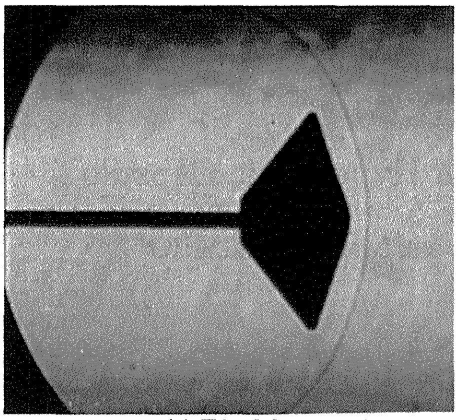
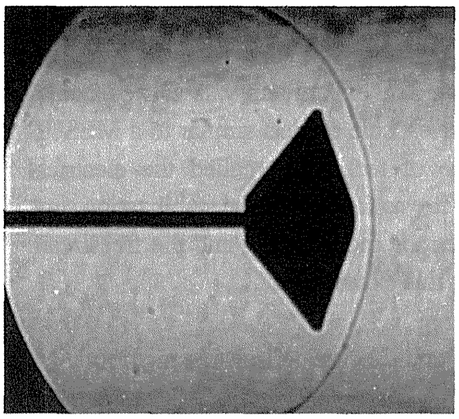
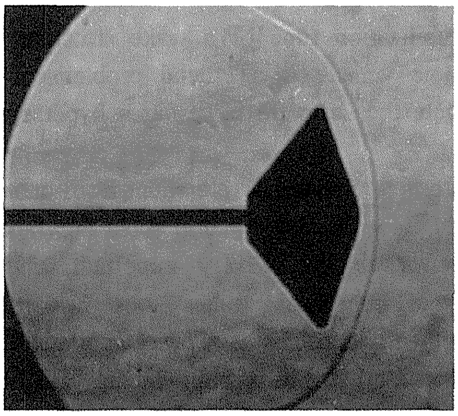


(a) T1=6.8ms



(b) T1=9:8ms



(c) T1=14.8ms

Fig.1 Shock shapes ahead of a re-entry capsule similar to MESUR model vs. elapsed times of 6.8ms, 9.8 ms, and 14.8ms, respectively, after the beginning of a hypersonic flow obtained by a gun tunnel of Mach 10. The capsule diameter is 70mm.

9.8ms, and 14.8ms, respectively, just after the beginning of a flow obtained by a hypersonic pulsed facility. These three shock shapes perfectly agreed with one another, as if, indicating that the flow structures were stable. However, as will be seen in Figs.11 later in this paper, the wake structures behind the capsule of the elapsed times of 6.8ms and 9.8ms are unstable. In these cases it must be very careful to investigate the wake structure. Therefore, it is very important to know the stabilization time of wake structures when hypersonic pulsed facilities of short duration are used.

In spite of this important problem of the stabilization time for the wake structure, there have been very few investigations about the time. This seems because that experimental observations of the wake structure were a very difficult task under conditions of high speed, low density, and short duration of a uniform flow obtained by hypersonic facilities, such as a hypersonic shock tunnel, a ballistic range system, etc.

Under these circumstances, the author has developed a method called the electrical discharge method[9]-[14] to visualize almost all important three-dimensional flow patterns around hypersonic vehicles under these difficult visualizing flow conditions mentioned above. The author has also developed a new technique of the electrical discharge method to observe the wake pattern behind hypersonic vehicles. The stabilization time of the wake structure has been investigated by utilizing the technique. Furthermore, a formulization of the stabilization time have been performed by using the dimensional analysis and the present experimental results.

2. Experimental Equipment

Figure 2 shows a hypersonic gun tunnel used in this experiment as a pulsed facility. In the figure, a sketch of the tunnel is included. The experiment was carried out under the conditions of the characteristics of the hypersonic tunnel which were the Mach number:10, freestream density:4.5 $\times$ 10^{-3}kg/m^3, freestream velocity:1.5km/s, static pressure:70Pa, test duration was some 20ms, and Reynolds number was 1.7×10^6/m. The test gas was air. Figure 3 shows the test section of the tunnel, including a capsule model, hypersonic nozzle, and model supporting system. These components were made of electric insulators to avoid a generation of a breakdown with electrodes since the flow structure was investigated by applying an electric field in the test section. Figure 4 shows the electrical circuit for generating an electric field to make electrical discharges in the hypersonic flowfield. The circuit was designed so as to operate while the hypersonic flow was being obtained.

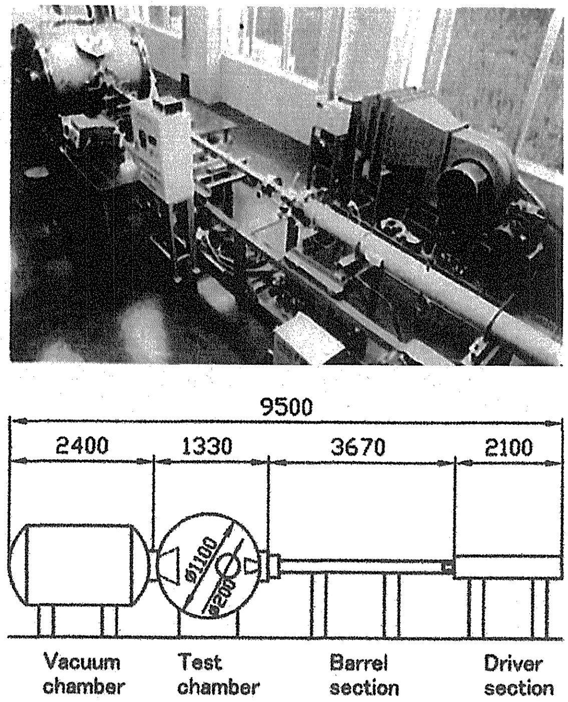


Fig.2 Hypersonic gun tunnel of Mach 10. A sketch of the tunnel is shown in the figure. (Unit: mm)

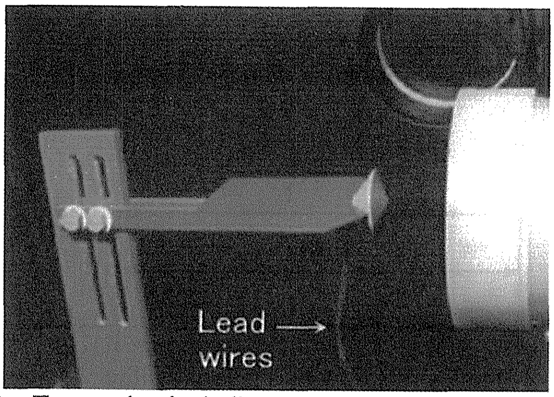


Fig.3 Test section including a model, nozzle, and model supporting system.

3. Visualizing Principle of Wake Structure

To investigate a stability of wake structure behind hypersonic vehicles, models similar to a Mars Environmental Survey (MESUR) Pathfinder probe were used. A model shape of 70mm capsule diameter is shown in Fig.5(a). In this experiment, a thin plate with sharp leading edges was attached to the capsule as shown in Figs.5(b) and 5(c) so as not to disturb the upper part of the flow behind the capsule by the two (cathode and anode) leading wires as shown in Fig.3. The surface of the plate was located on the symmetry axis. A pair of

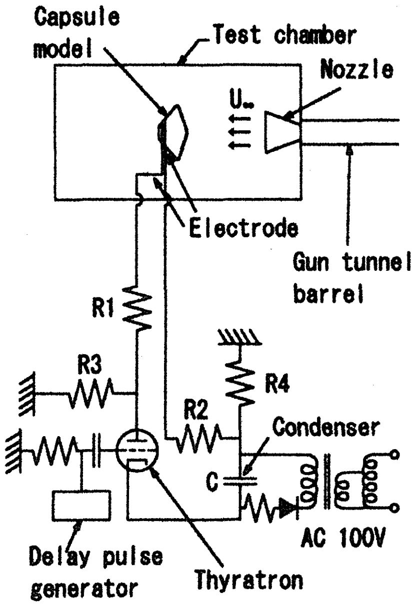
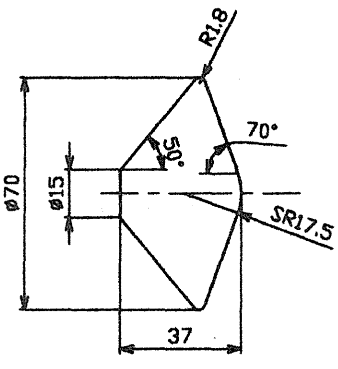


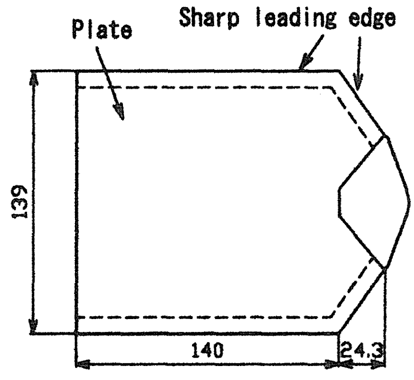
Fig.4 Electric circuit for generating an electric field.

cathode-anode electrodes of a very little distance are installed on the model surface as shown in Fig.5(c). The visualizing principle of wake structure is as follows. When an electrical discharge is generated between the electrodes, excited particles such as ions are made. These excited particles will drift according to the flow direction, radiating light. Thus, the flow pattern will be obtained by taking the radiating light. As an example of this visualizing method, a flow pattern of wake behind a capsule traveling at Mach 10 was shown in Fig.6. Figure 6 indicates a wake structure including a separation point and a free shear layer just after the separation point.

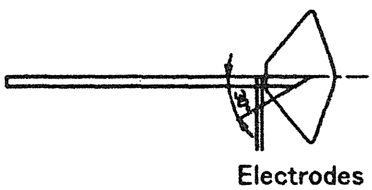
In this study, as a method to investigate the stabilization time of the wake structure vs. the elapsed time from the beginning of the uniform flow, the location of the separation point and the direction of the free shear layer just after the separation were examined. Concerning the location of the separation point vs. the elapsed time, the value Rs/Rb was observed, where Rb and Rs were the capsule radius and the distance of the separation point measured from the symmetry axis, respectively. The direction of the free shear layer was examined at the location Di of some L/Rb=1 shown in Fig.7, where L was the distance from the capsule nose. It was defined in this study that the wake structure was stable when both the location of the separation and the direction of the free shear layer were considered to be approximately stable.



(a)



(b)



(c)

Fig.5 A capsule model similar to MESUR probe afterbody configuration and its dimensions.(Unit:mm) A thin plate with sharp leading edges is attached to the capsule.

4. Wake Structure Behind Three Models of Different Scale

Wake patterns vs. elapsed times T1 from the beginning of the flow obtained by the present hypersonic gun tunnel was investigated by observing the separation location and the free shear layer just after the separation point. An illustration about the relation among the times T, T0, T1, and T2 is shown in Fig.8. The observation was carried out under the condition of different capsule diameters of 35 mm, 50 mm, and 70 mm, respectively. The experimental results were shown in Figs.9, Figs.10, and Figs.11, respectively.

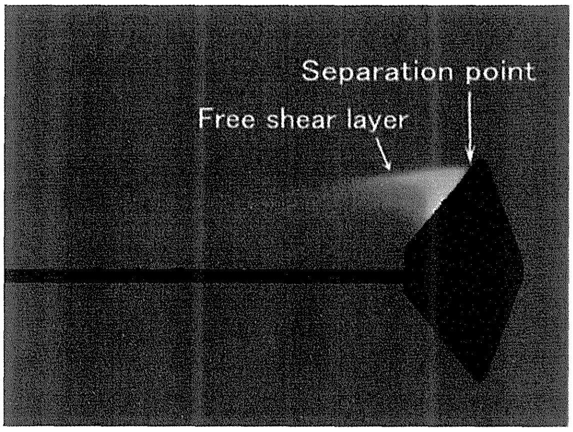


Fig.6 Visualized result of separation point and free shear layer.

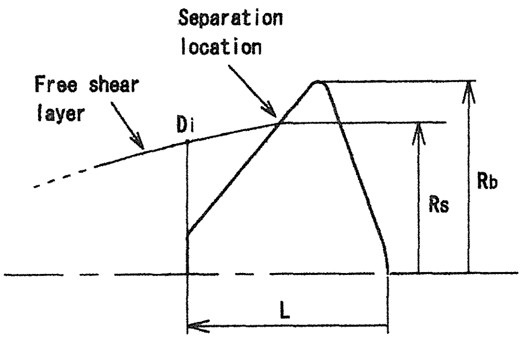
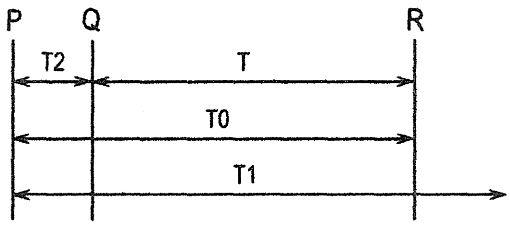


Fig.7 Sketch of model and wake.



P: Beginning of a flow by a pulsed facility.
Q: Time when a stable uniform flow is established.
R: Time when a stable wake pattern is established.

Fig.8 Relation among T, T0, T1, and T2.

In the case of the 35mm capsule diameter shown in Fig.9, the followings can be seen. The location of the separation point and the direction of the free shear layer just after the separation are unstable till the elapsed time T1 of some 0.5ms just after the beginning of the flow. However, after the elapsed time of 0.6ms, both the matters become nearly the same location and the same shape, indicating the same flow pattern. Namely, the ratio Rs/Rb becomes nearly the same value of 0.91 after the elapsed time T1 of 0.6ms. However, before the elapsed time of 0.5ms, the ratio Rs/Rb is smaller than the value of 0.91 and the ratio is changing, indicating the wake pattern is unstable. From these results the stabilization time T0 of the wake pattern measured from the beginning of the flow obtained by the present hypersonic gun tunnel is considered to be between the elapsed times of 0.5ms and 0.6ms in the case that the capsule diameter is 35mm.

In the case of the diameter of 50mm shown in Fig.10, the followings can be seen. The location of the separation point and the direction of the free shear layer are unstable till the elapsed time T1 of some 1.8ms just after the beginning of the flow. However, after the elapsed time of 2.3ms, both the matters become nearly the same location and the same shape, indicating the same flow pattern. Namely, the ratio of Rs/Rb becomes nearly the same value of 0.92 after the elapsed time T1 of 2.3ms. However, before the elapsed time of 1.8ms, the ratio Rs/Rb is smaller than the value of 0.92 and the ratio is changing, indicating the wake pattern is unstable. Also, the direction of the free shear layer are nearly parallel to the symmetry axis at the position of some L/Rb=1 when the elapsed time T1 is larger than some 2.3ms. However, the direction becomes to tend toward the symmetry axis, and the direction becomes unstable, when the time T1 is smaller than some 1.8ms. From these results the stabilization time T0 of the wake pattern measured from the beginning of the flow obtained by the present hypersonic gun tunnel is considered to be between the elapsed times of 1.8ms and 2.3ms in the case that the capsule diameter is 50mm.

In the case of the 70mm diameter shown in Fig.11, the followings can be seen. The location of the separation point and the direction of the free shear layer are unstable till the elapsed time T1 of some 12.8ms. However, after the elapsed time of 13.8ms, both the matters become nearly the same location and the same shape, indicating the same flow pattern. Namely, the ratio Rs/Rb becomes nearly the same value of 0.92 after the elapsed time T1 of 13.8ms. However, before the elapsed time of 12.8ms, the ratio Rs/Rb is smaller than the value of 0.92 and the ratio is changing, indicating the wake pattern is unstable. Concerning the direction of the free shear layer, the same matter occurs as the case of the 50mm diameter model at around the time T1 of 13.3ms. From these results the stabilization time T0 of the wake pattern measured from the beginning of the flow obtained by the present hypersonic gun tunnel is considered to be between the elapsed time of 12.8ms and 13.8ms in the case that the capsule diameter is 70mm.

5. Formulization of Stabilization Time of Wake

A formulization of the stabilization time T of the wake structure behind hypersonic vehicles in the experiment using pulsed facilities was made by using the dimensional analysis and the above experimental results.

The stabilization time T measured from the beginning when a uniform flow is established, is considered to be the function of the freestream velocity U, density ρ, viscosity coefficient μ, and model projected area A. Thus

$$T = T(U, \rho, \mu, A) \qquad (1)$$

The dimensional analysis is made for the above relation. Then, T will be expressed by the following.

$$T = kD(\mathrm{Re})^{\alpha} / U \qquad (2)$$

where α and k are constant values, and D and Re are the dimension of a model such as the diameter of a capsule and the Reynolds number, respectively. In this case, there is the relation of

$$T = T0 - T2 \qquad (3)$$

Therefore,

$$T0 - T2 = kD(\mathrm{Re})^{\alpha} / U \qquad (4)$$

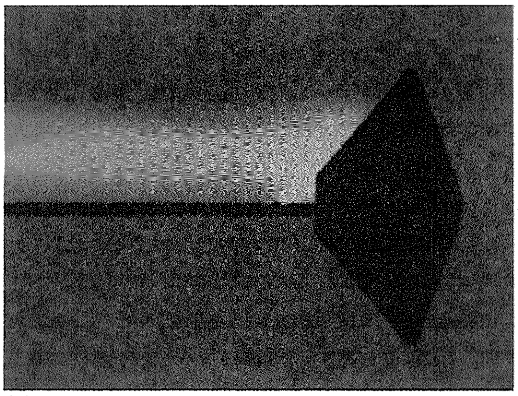
From the above experimental results already obtained, the values of k, α, and T2 become 1.69×10^{-8}, 2.01, and 0.44ms, respectively.

From this, the stabilization time T(second) of the wake structure is formulated approximately as the following expression.

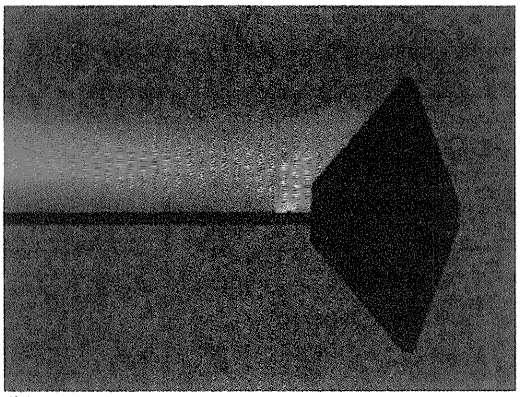
$$T = 7.29 \times 10^{-24} D(\mathrm{Re})^{5.04} / U \qquad (5)$$

6. Conclusion

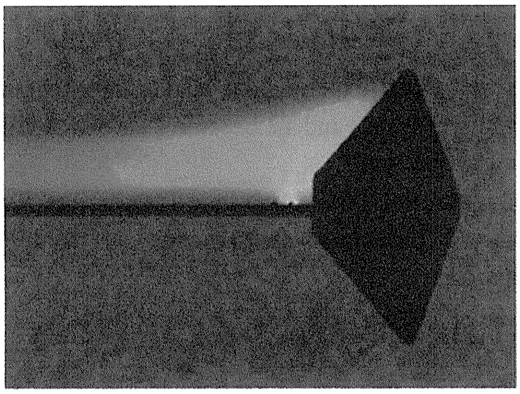
The stabilization time T of the wake structure behind hypersonic vehicles just after a uniform flow was formulated approximately by using the dimensional analysis and the present experimental results. To investigate the time, the location of the separation point and the free shear layer just after the separation were observed. The experiment was carried out utilizing a technique for observing the flow pattern behind hypersonic models. The technique was one of the electrical discharge method and was developed by the author. The experiment was performed by using the three



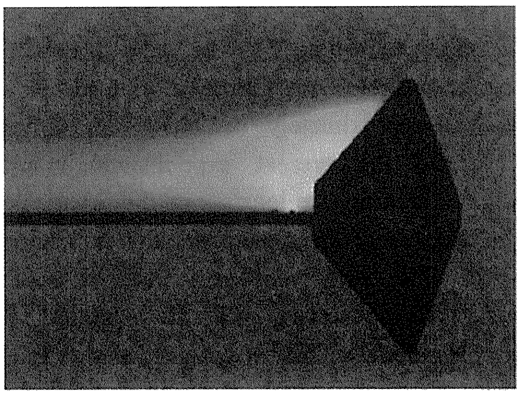
(a) T1=0.3ms



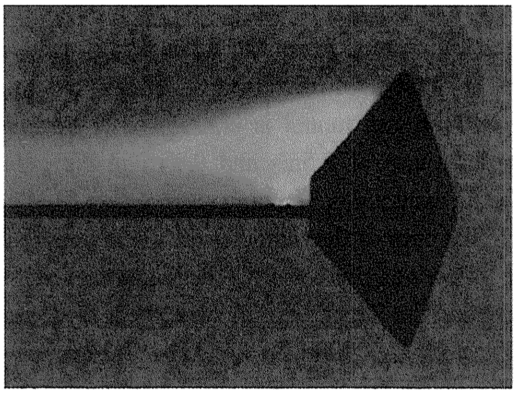
(b) T1=0.5ms



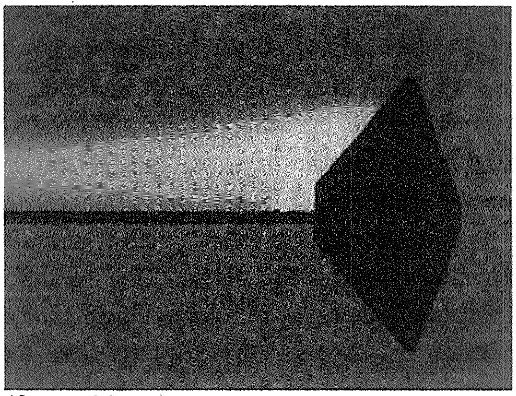
(c) T1=0.6ms



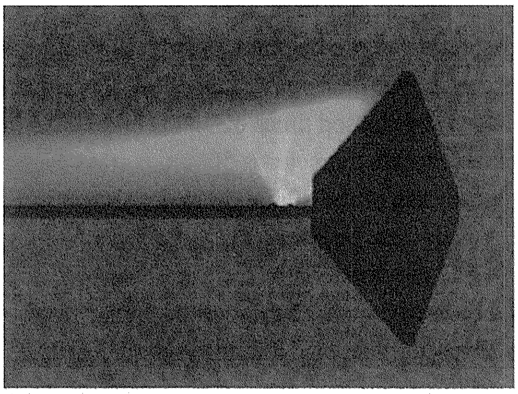
(d) T1=0.8ms



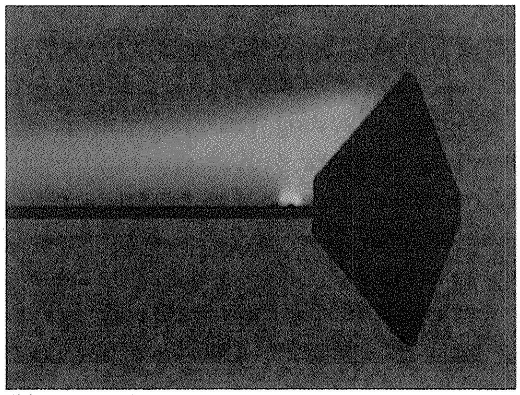
(e) T1=1.8ms



(f) T1=6.8ms

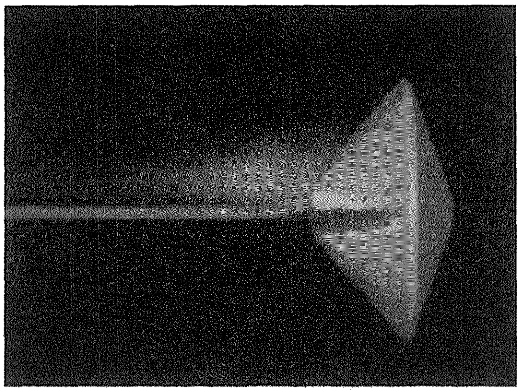


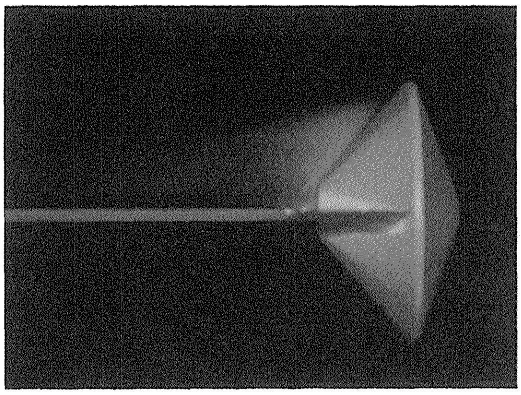
(g) T1=9.8ms

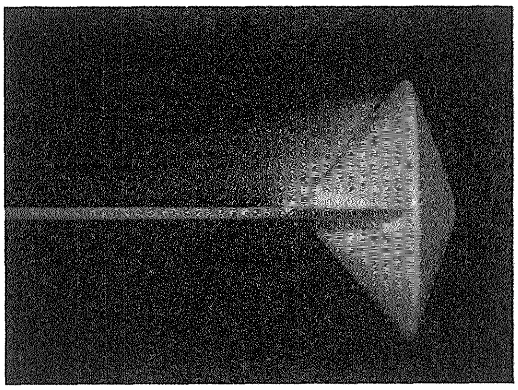


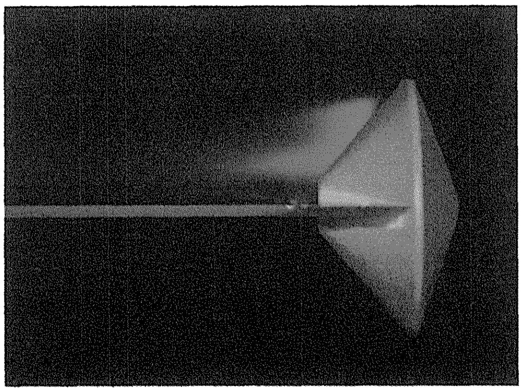
(h) T1=14.8ms

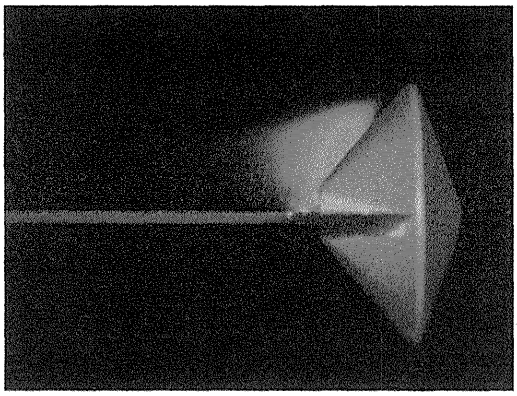
Fig.9 Wake structure vs. elapsed time T1 in case of 35mm diameter capsule.

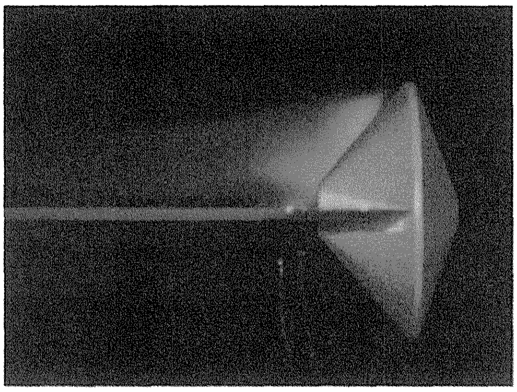

(a) T1=0.4ms

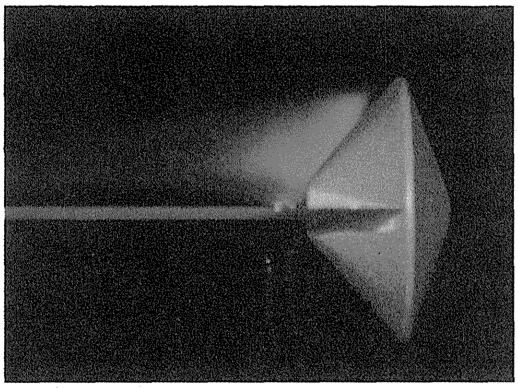

(b) T1=0.6ms


(c) T1=0.8ms


(d) T1=1.3ms


(e) T1=1.8ms


(f) T1=2.3ms


(g) T1=2.8ms

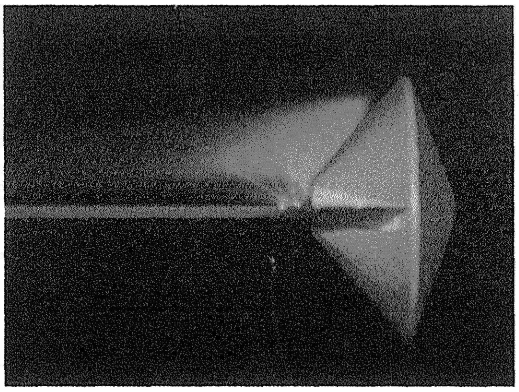
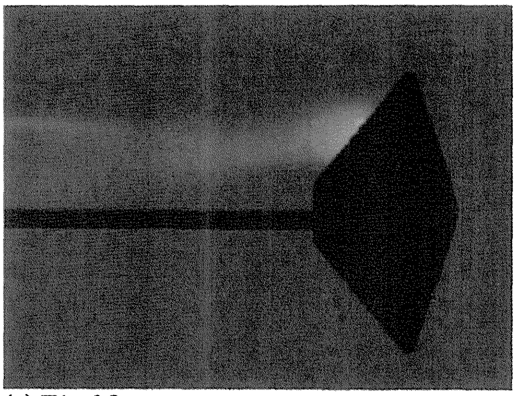
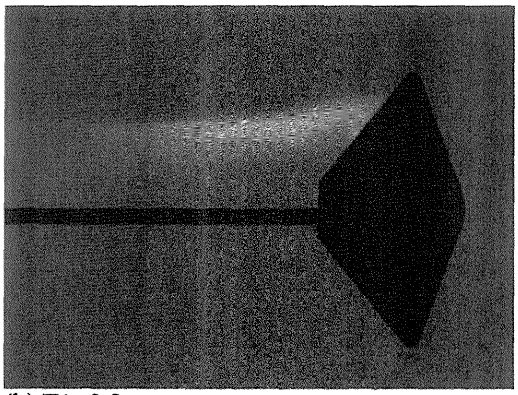
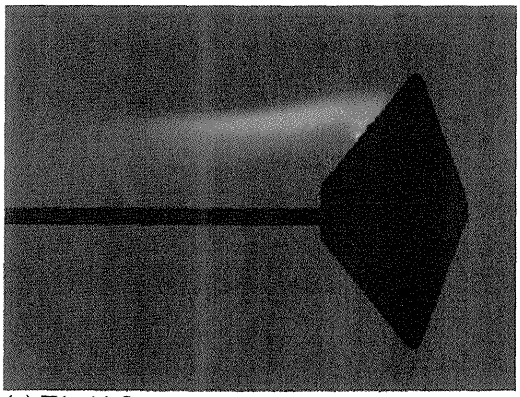
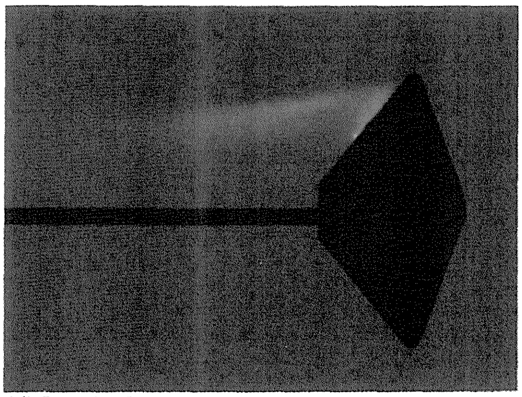

(h) T1=4.8ms

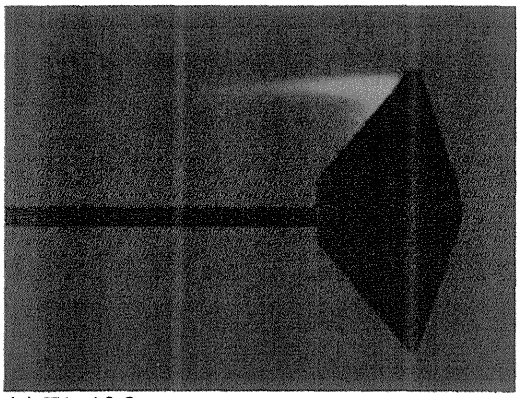
Fig.10 Wake structure vs. elapsed time T1 in case of 50mm diameter capsule.

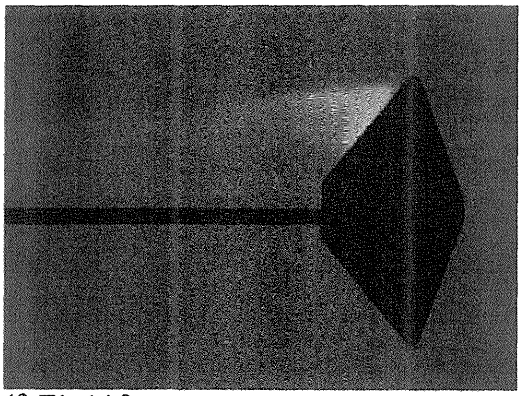

(a) T1=6.8ms

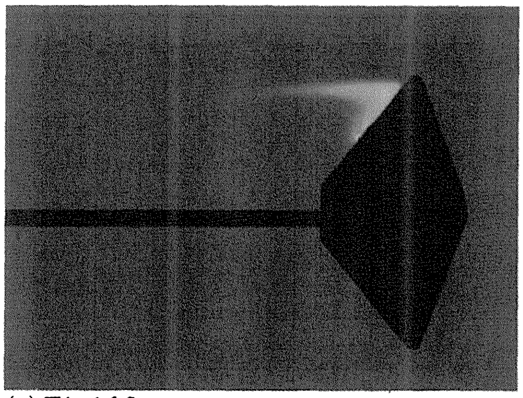

(b) T1=9.8ms


(c) T1=11.8ms


(d) T1=12.8ms


(e) T1=13.8ms


(f) T1=14.8ms


(g) T1=16.8ms

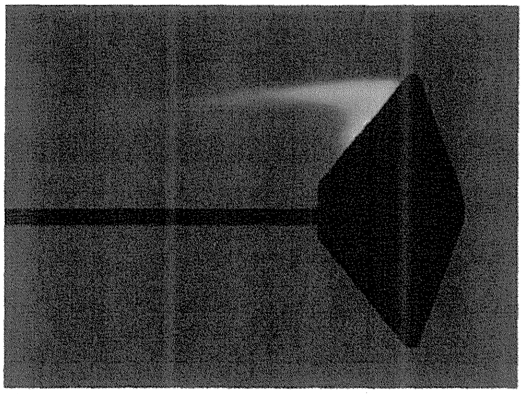

(h) T1=19.8ms

Fig.11 Wake structure vs. elapsed time T1 in case of 70mm diameter capsule.

different model scales similar to a MESUR capsule in a hypersonic flow of the Mach 10. From these investigations the time T became as the following expression.

$T = 7.29 \times 10^{-24} D (Re)^{5.04} / U$

From this expression, it could be considered that the stabilization time of the wake structure behind hypersonic vehicles was related to the Reynolds number, the model scale, and the freestream velocity.

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