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Measurements of Capsule Wake Stabilization Times in a Hypersonic Gun Tunnel

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The wake stabilization time behind a hypersonic vehicle is very important in experiments focused on the near-wake studies in pulsed facilities at high-enthalpy and high-Mach-number conditions. Observations of such wake structure have been very difficult to obtain, and therefore, the experimental discussion about the stabilization time itself has also been elusive. The wake structure stabilization time was formulated by using dimensional analysis and the present experimental results. The experiments were carried out by observing free shear layers for capsule models similar to the Mars Environmental Survey Pathfinder probe. To visualize the wake structure, an electrical discharge method was used. From these investigations, it was found that the stabilization time of the wake structure was related to the Reynolds number, the model size, and the freestream velocity. A Mach 10 gun tunnel was used in these experiments.

Nomenclature

A = projected area of model
D = capsule maximum body diameter
k = proportionality constant
R_b = capsule maximum body radius
R_f = distance between free shear layer and symmetry axis
Re = Reynolds number
T = stabilization time of wake pattern measured from the beginning of stable uniform flow
T_0 = stabilization time of wake pattern measured from the beginning of flow obtained by a pulsed facility
T_1 = elapsed time from the beginning of flow obtained by a pulsed facility
T_2 = stabilization time of freestream measured from the beginning of flow
U = freestream velocity
α = constant
μ = viscosity coefficient
ρ = freestream density

I. Introduction

THE stabilization time of a hypersonic wake structure is a crucial problem when investigating such structures by using hypersonic pulsed facilities.

To promote space exploration from an aerodynamics point of view, the investigation of hypersonic flowfields is very important, and a large number of numerical studies focused on wake structures behind reentry capsules have been reported.[1–8] For 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 test duration of the order of some 10 ms or less. Because of this very short duration, a crucial problem occurs in that the wake structure behind hypersonic vehicles is unstable, although the flowfield ahead of the vehicles is considered to be stable. Figures 1a–1c show three shock shapes ahead of a capsule model of 70-mm diam vs elapsed flow times of 6.8, 9.8, and 14.8 ms, respectively, just after the beginning of a flow obtained by a hypersonic pulsed facility. These three shock shapes agreed perfectly with one another, as if indicating that the flow structures were stable. However, as will be seen later in this paper, the wake structures behind the capsule with elapsed times of 6.8 and 9.8 ms are unstable. In these cases, one must be very careful when investigating 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.

Despite the importance of the problem of the stabilization time for the wake structure, there have been very few investigations focused on stabilization time. This lack of experimental observations is because the wake structure characterization presents very difficult task under conditions of high speed, low density, and short duration of uniform flow as obtained in hypersonic facilities, such as a hypersonic shock tunnel, a ballistic range system, etc.

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

II. Experimental Equipment

In these experiments, the hypersonic gun tunnel shown in Fig. 2 was used as a pulsed facility. The experiments were carried out under nominal tunnel conditions, producing Mach 10 airflow with freestream density of 4.5×10^{-3} kg/m^3, freestream velocity of 1.5 km/s, static pressure of 70Pa, test duration of approximately 20 ms, and a unit Reynolds number of 1.7×10^6/m. The test gas was air. Figure 3 shows the test section of the tunnel, including a capsule model, hypersonic conical nozzle, pressure transducer, and model support system. These components were made of electric insulators to avoid the generation of an electric breakdown with the electrodes because 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 produce an electrical discharge in the hypersonic flowfield. The circuit was designed to operate while the hypersonic flow was being obtained.

III. Visualizing Principle of Wake Structure

To investigate wake structure stability behind hypersonic vehicles, models similar to a Mars Environmental Survey (MESUR)

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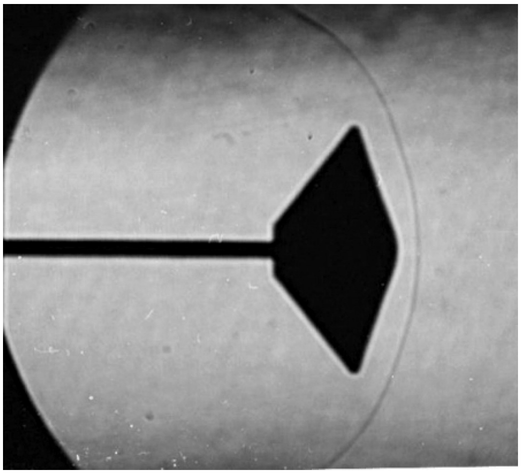
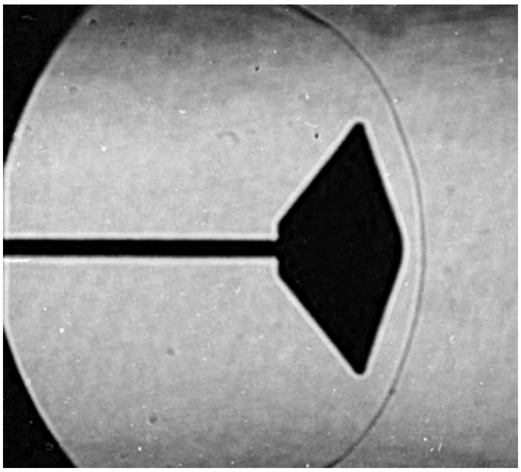
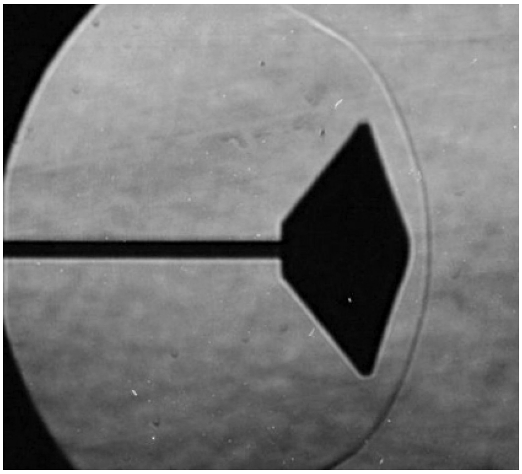


a) $T_1 = 6.8$ ms



b) $T_1 = 9.8$ ms



c) $T_1 = 14.8$ ms

Fig. 1 Capsule (70-mm-diam) shock shapes vs elapsed flow times in a Mach 10 gun tunnel.

Pathfinder probe afterbody configuration were used. A capsule model with a 70-mm diam is shown in Fig. 5. In this experiment, a thin plate with sharp leading edges was attached to the capsule as shown Fig. 5 to not disturb the upper part of the flow behind the capsule by the two wires attached to the cathode and anode as shown in Fig. 3. A pair of closely spaced cathode–anode electrodes are installed on the model surface, as shown in Fig. 5. 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 can be

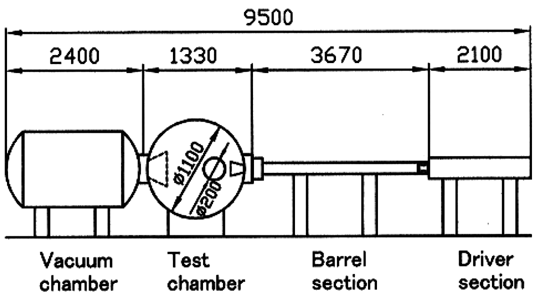


Fig. 2 Mach 10 hypersonic gun tunnel; dimensions in millimeters.

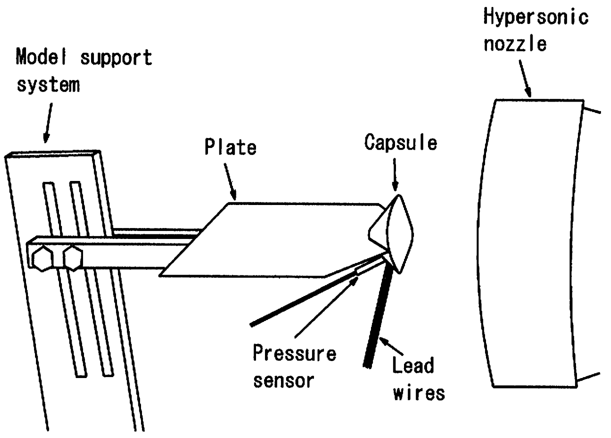


Fig. 3 Test section including a model, nozzle, pressure transducer, and model support system.

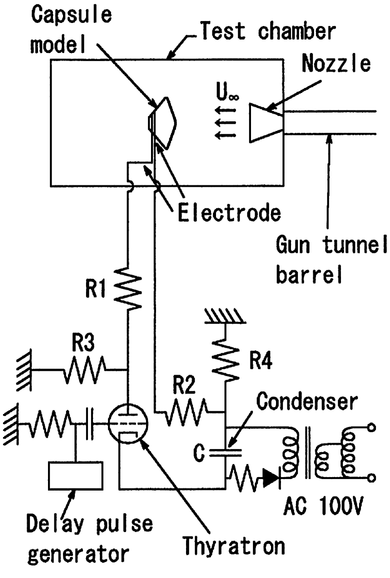


Fig. 4 Electric circuit for generating an electric field.

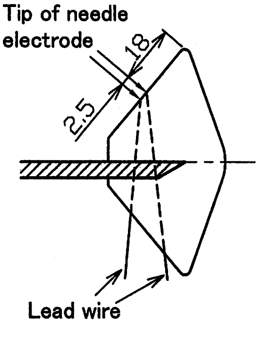


Fig. 5 Capsule model similar to the MESUR probe afterbody configuration; dimensions in millimeters; thin plate with a sharp leading edge attached to capsule.

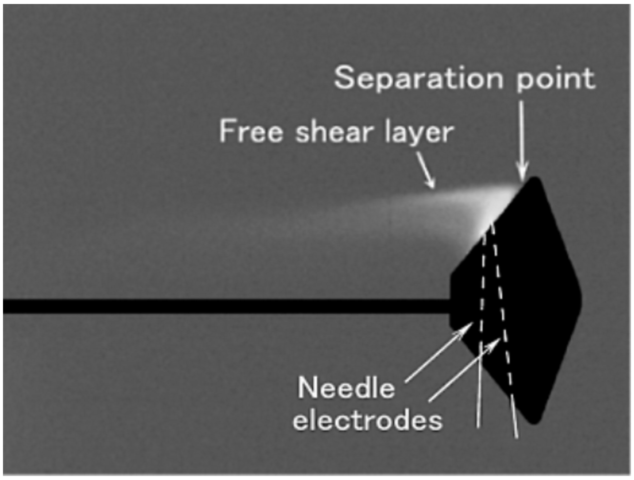


Fig. 6 Visualized result of separation point and free shear layer.

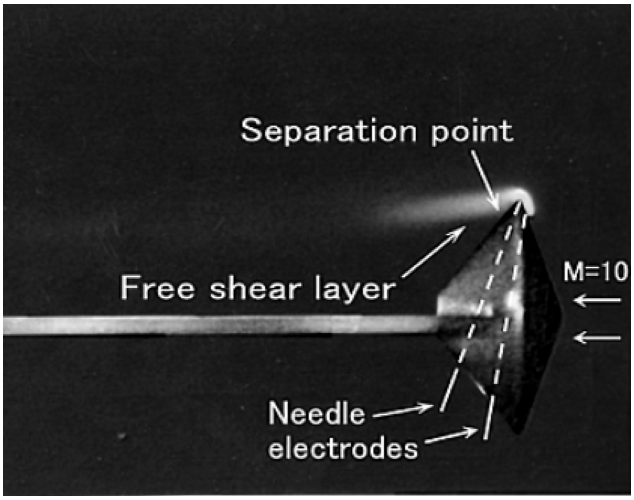


Fig. 7 Visualized result of separation point and free shear layer by different electrodes location.

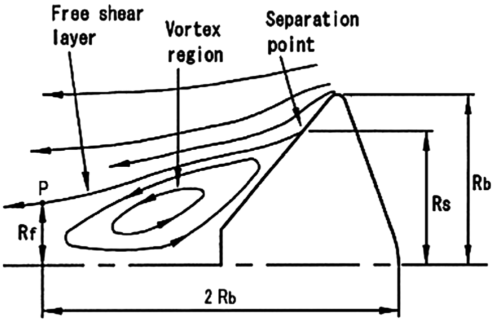


Fig. 8 Separation point and free shear layer.

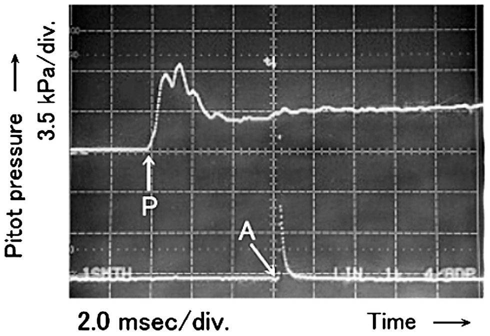


Fig. 9 Observation of elapsed flow time: P, beginning of flow and A, beginning of electric discharge.

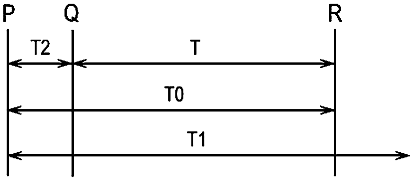


Fig. 10 Time relations for T, T_0, T_1, and T_2: P, beginning of a flow by a pulsed facility; Q, time when a stable uniform flow is established and R, time when a stable wake pattern is established.

obtained by measuring the radiating light. As an example of this visualization method, the wake flow pattern behind a capsule in Mach 10 air is shown in Fig. 6. Figure 6 indicates a wake structure including a separation point and a free shear layer just after the separation point.

To verify the accuracy of the visualized flow pattern shown in Fig. 6, another experiment was performed by generating an electrical discharge at a different location of the model, as shown in Fig. 7. The separation point shown in Fig. 7 agreed well with that of Fig. 6, and the shape of the free shear layer in Fig. 7 agreed well with that of Fig. 6. The radiating particles in Fig. 6 were produced inside the recirculation region. On the other hand, radiating particles shown in Fig. 7 were produced outside the recirculation region. From these results, it can be concluded that the flow pattern obtained by the present method is reasonably correct.

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 position P of the free shear layer at the distance $2R_b$ from the capsule nose as shown in Fig. 8 was investigated. To express the position P numerically, the value R_f/R_b was examined, where R_b and R_f are the capsule maximum radius and the distance of the free shear layer measured from the symmetry axis, respectively. It was defined in this study that the wake structure was stable when the value R_f/R_b was considered to be approximately constant. The purpose of this paper is to investigate the stabilization time, not to show the wake structure such as the lip shock, recompression shock, etc. For this purpose, the authors consider it sufficient to show the data of the present paper. The authors have already visualized the three-dimensional flowfield including a rear stagnation point by using the electrical discharge method. However, the authors do not think it is necessary to use those data to obtain the stabilization time, which is the present purpose of this study. The elapsed flow times T_1 were examined by measuring the stagnation pressure history at the capsule nose. An example is shown in Fig. 9.

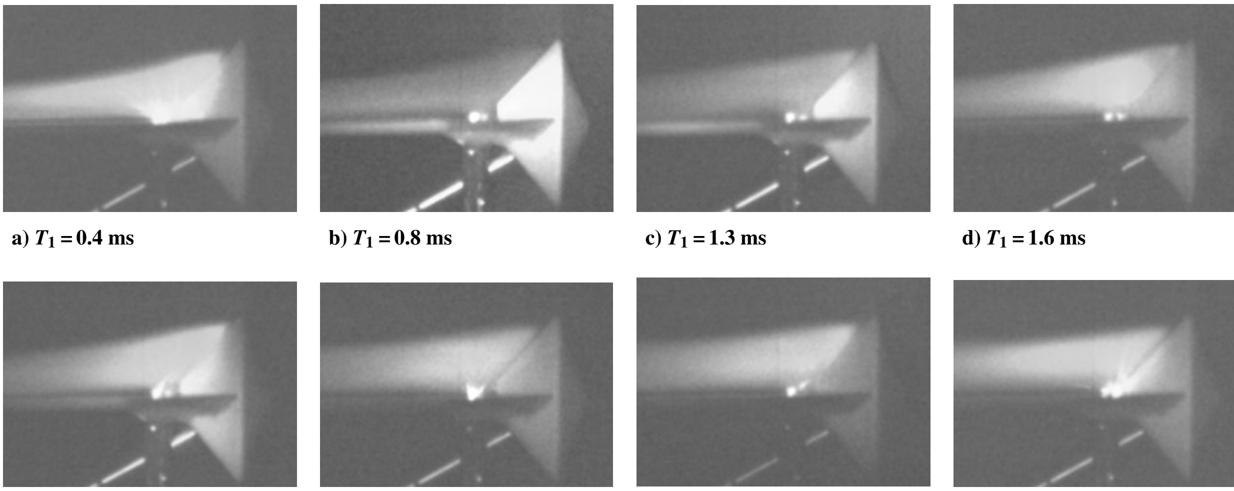
IV. Wake Structure Behind Three Models of Different Sizes

Wake patterns vs elapsed time T_1 from the beginning of the flow obtained by the present hypersonic gun tunnel experiment was investigated by observing the position P of the free shear layer after the separation. An illustration of the relation between the times T, T_0, T_1, and T_2 is shown in Fig. 10. The observations were carried out for different diameter models of 35, 50, and 70 mm. The corresponding experimental results are shown in Figs. 11, 12, and 13, respectively. These experimental results are read and arranged as shown in Fig. 14.

From Fig. 13, the following results are obtained. In the case of the 35-mm-diam capsule, the R_f/R_b value becomes stable when T_1 is approximately 3.5 ms. Also, in the cases of the 50- and 70-mm-diam capsules, the R_f/R_b values become stable when T_1 are approximately 6.5 and 14.5 ms, respectively.

V. Formulization of Wake Stabilization Time

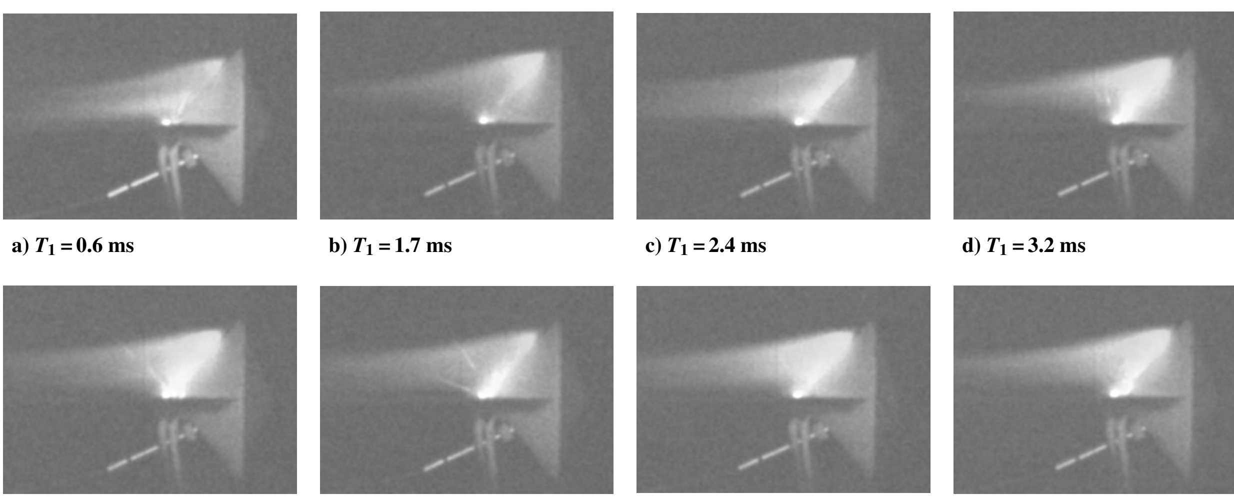
An equation for the wake stabilization time T behind hypersonic vehicles was determined by using the already discussed experimental results and dimensional analysis.



a) $T_1 = 0.4$ ms b) $T_1 = 0.8$ ms c) $T_1 = 1.3$ ms d) $T_1 = 1.6$ ms

e) $T_1 = 2.0$ ms f) $T_1 = 2.5$ ms g) $T_1 = 3.7$ ms h) $T_1 = 7.4$ ms

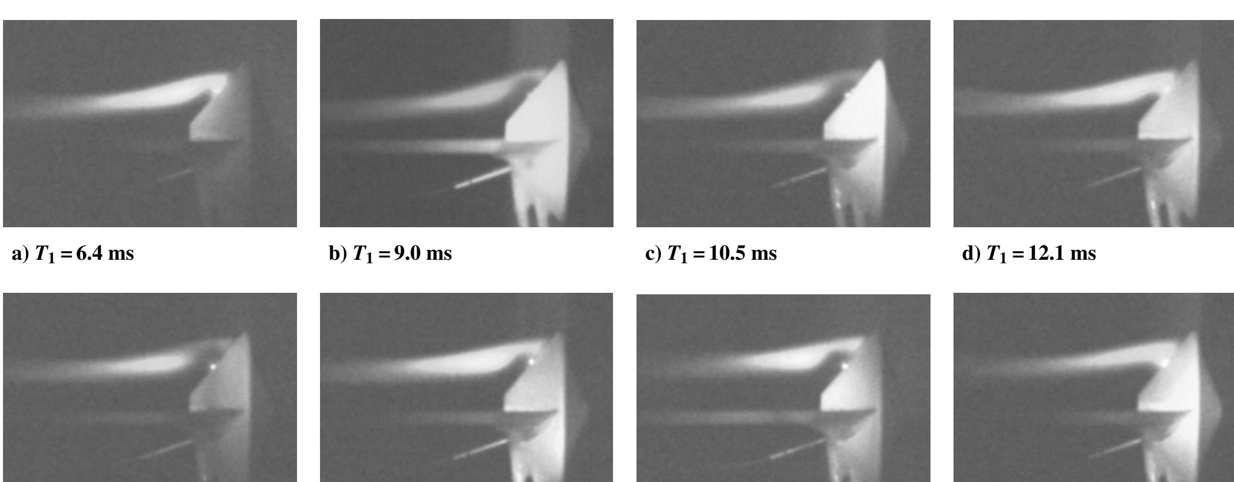
Fig. 11 Wake structure vs elapsed flow time T_1 for a 35-mm-diam capsule.



a) $T_1 = 0.6$ ms b) $T_1 = 1.7$ ms c) $T_1 = 2.4$ ms d) $T_1 = 3.2$ ms

e) $T_1 = 3.8$ ms f) $T_1 = 4.4$ ms g) $T_1 = 6.7$ ms h) $T_1 = 9.7$ ms

Fig. 12 Wake structure vs elapsed flow time T_1 for a 50-mm-diam capsule.



a) $T_1 = 6.4$ ms b) $T_1 = 9.0$ ms c) $T_1 = 10.5$ ms d) $T_1 = 12.1$ ms

e) $T_1 = 12.3$ ms f) $T_1 = 12.8$ ms g) $T_1 = 14.0$ ms h) $T_1 = 16.0$ ms

Fig. 13 Wake structure vs elapsed flow time T_1 for a 70-mm-diam capsule.

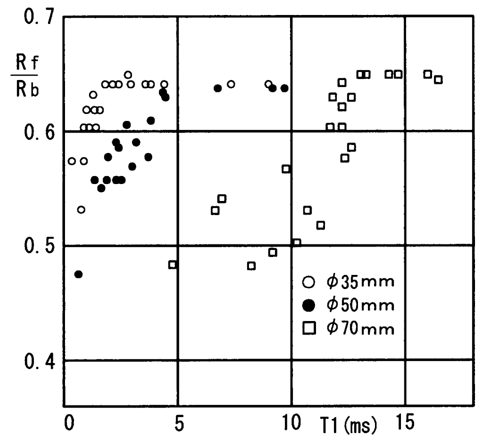
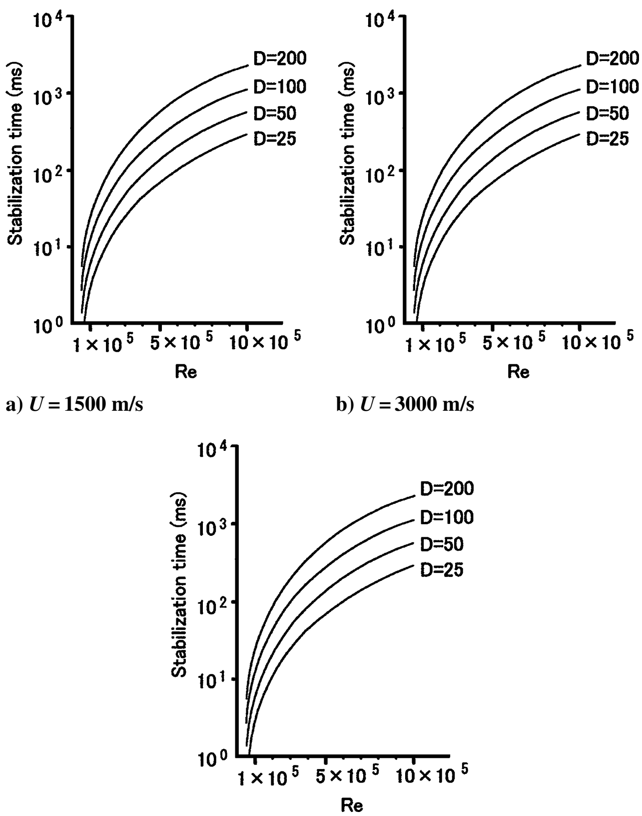


Fig. 14 Relation between R_f/R_b and elapsed flow time T_1.



a) $U = 1500$ m/s

b) $U = 3000$ m/s

c) $U = 5000$ m/s

Fig. 15 Stabilization time that plots Eq. (5).

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

Thus,

$$T = T(U, \rho, \mu, A) \tag{1}$$

The dimensional analysis is made for relation (1). Time T will be expressed by

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

where α and k are constants, D is a model dimension such as the capsule diameter, and Re is the Reynolds number, which is defined as $Re = \rho_{\infty}U_{\infty}D/\mu_{\infty}$. In this case,

$$T = T_0 - T_2 \tag{3}$$

Therefore,

$$T_0 - T_2 = kD(Re)^{\alpha}/U \tag{4}$$

From the earlier experimental results, the values of T_0 are approximately 3.5, 6.5, and 14.5 ms when the diameters D are 35, 50, and 70 mm, respectively. If these values including the Reynolds number and the freestream velocity are substituted in relation (4), then the values of k, α, and T_2 become 1.69×10^{-8}, 2.01, and 1.94 ms, respectively. From this, the stabilization time T (seconds) of the wake structure is formulated approximately as

$$T = 1.7 \times 10^{-8} D(Re)^{2.0}/U \tag{5}$$

The stabilization time that plots Eq. (5) is shown in Fig. 15, with D in millimeters.

VI. Conclusions

The stabilization time T of the wake structure behind hypersonic vehicles was formulated approximately by using dimensional analysis and the present experimental results. To investigate the stabilization time, the locations of the free shear layer after separation were observed. The experiments were carried out by using a technique for observing the flow pattern behind hypersonic models. The particular technique was the electrical discharge method previously developed by the first author. The experiments were performed by using three different model sizes of a configuration similar to the MESUR capsule in Mach 10 flow. From these investigations, the wake stabilization time T can be defined with the expression $T = 1.7 \times 10^{-8} D(Re)^{2.0}/U$, which relates the stabilization time to the Reynolds number, the model size, and the freestream velocity.

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