Transient Ablation of Blunt Bodies at Angles of Attack

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An experimental investigation of transient ablation is presented, with particular emphasis on the transient shape changes of blunt bodies at angles of attack. Models were made of pure Teflon and Teflon mixed with glass powder, respectively. Initial body shapes were the flat-faced cylinder and the hemisphere-cylinder, respectively. The high-temperature region in which ablation occurs appears on the windward side of a body at angles of attack, and has great influence on the apparent recession depth results. It is revealed that the enhancement of heat transfer on the windward surface, as well as that on the front surface of the body, plays an important part during entry processes.

Nomenclature

D	= model diameter
l	= distance from the nozzle exit
M_∞	= freestream Mach number
p_0	= reservoir pressure
Re	= Reynolds number
T	= temperature
t	= time
(x,y,ϕ)	= cylindrical coordinates
α	= angle of attack
ΔX	= recession depth

Introduction

FOR high-speed entry of space vehicles into atmospheric environments, ablation is a practical method for alleviating severe aerodynamic heating. Several studies[1-5] have been undertaken on steady or quasisteady ablation. However, ablation is a very complicated phenomenon in which a chemical-physical process is associated with an aerodynamic one that involves changes in body shape with time. Therefore, it seems realistic to consider that ablation is an unsteady phenomenon. In the design of an ablative heat shield system, since the ultimate purpose of the heat shield is to keep the internal temperature of the space vehicle at a safe level during entry, both the transient heat conduction characteristics of the ablator and the change in body shape with time may be critical in the selection of the material and its thickness. The temperature distribution in the ablator, however, is greatly influenced by a boundary condition, i.e., the heat transfer rate through the body surface. In particular, the rate is governed mainly by both the instantaneous body shape and the history of shape change.

Popper et al.,[6] Tompkins et al.,[7] and Arai and Karashima[8] proposed numerical studies for ablating blunt-nosed axisymmetric bodies in which the effect of changes in body shapes is taken into account. In particular, Arai and Karashima took account of the second-order transition temperature of high molecular compounds. Arai et al.[9] pointed out experimentally the importance of thermal expansion. Nestler[10] presented results of high-pressure arc tests of carbon-carbon nose tips and investigated surface roughness, boundary layer transition, and two distinct types of nose sharpening. These investigations have been undertaken on transient ablation at no angle of attack. To the best of the authors' knowledge, the effects of initial body shape and angle of attack on transient ablation have been little undertaken.

The object of the present paper is to present experimental results of transient ablation of Teflon at low temperature, with particular emphasis on the instantaneous change in body shape at angles of attack and on the difference of materials.

Experiment

Test Facilities

The experiment was performed in a high-enthalpy hypersonic wind tunnel of the blowdown type,[11] which consists of the high-temperature furnace system, the wind tunnel system, and the evacuation system, respectively (see Fig. 1). The freestream conditions were: Mach number $M_\infty = 5.74$, stagnation temperature $T_{st} = 1020°C$, and stagnation (reservoir) pressure $p_0 = 1$ atm. Figure 2 shows the total temperature distribution along the centerline of uniform flow which was used in this experiment.

Models

Models were made of pure Teflon and mixed Teflon (in which glass powder and Teflon were mixed), respectively. Initial model shapes were a flat-faced cylinder and a hemisphere-cylinder, respectively. The diameter and the length of the model were 20 mm and 40 mm, respectively (see Fig. 3).

Measurements

Since the ablation phenomenon is essentially transient with the change in body shape, continuous data on the change in shape are required. In this experiment, the origin of the time axis is when the valve of the wind tunnel opens. We adopted the method for measuring the ablation rate, in which instantaneous shapes of an ablating model were measured by photographs taken every few seconds. Since the apparent ablation rate measured from the photographs includes the thermal expansion, it should be corrected in order to get the true ablation rate. From a standpoint of a real entry, how-

Presented as Paper 83-0583 at the AIAA 21st Aerospace Sciences Meeting, Reno, Nev., Jan. 10-13, 1983; submitted June 17, 1983; revision received Sept. 29, 1983.

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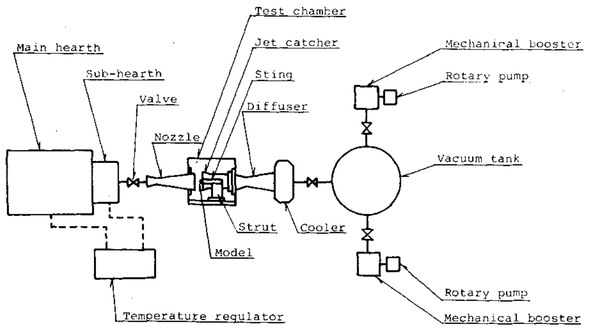

Fig. 1 Schematic diagram of test facilities.

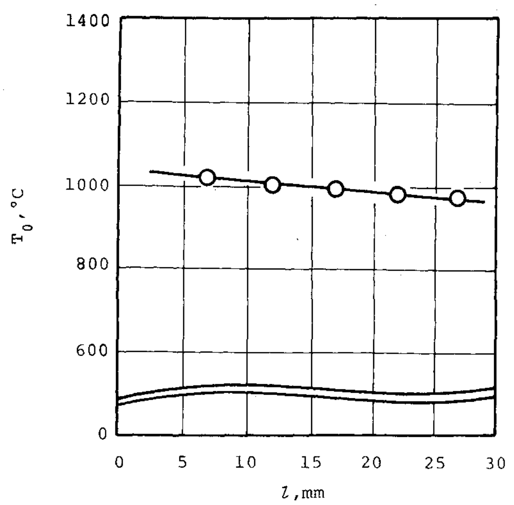

Fig. 2 Total temperature distribution along the centerline.

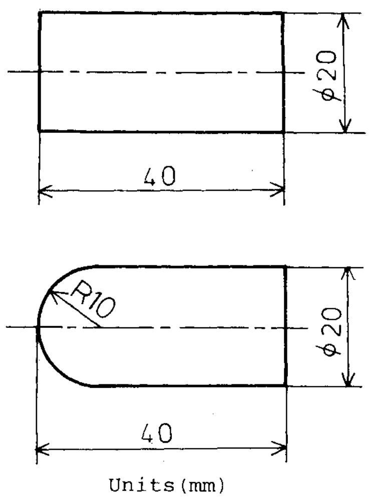

Fig. 3 Blunt body model.

ever, the apparent one is more important than the corrected one. Therefore, the apparent data are shown in the figures.

By using two camera positions (as shown in Fig. 4), photographs of side views and plan views from the bottom direction (windward) were taken in order to measure the ablation rate and shock shapes and in order to observe a high-temperature region on the windward side of the body.

Shock shapes were recorded using a single pass schlieren system. Shock shapes and instantaneous body shapes were read manually from photograph enlargements.

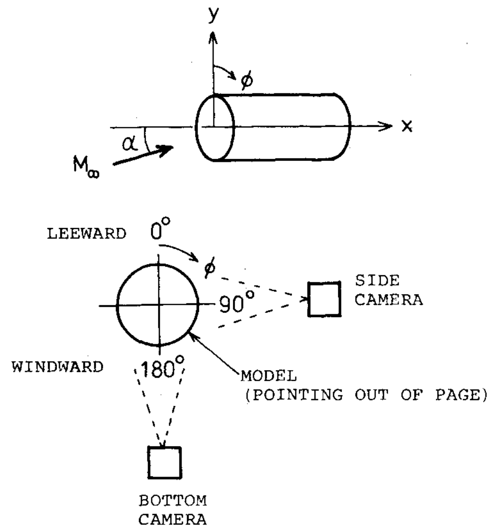

Fig. 4 Coordinate systems and camera positions.

Results and Discussion

Figures 5a and 5b show typical shape change histories for a hemisphere-cylinder and a flat-faced cylinder at no angle of attack, and at $\alpha = 12$ deg, respectively. Figures 6a and 6b show the instantaneous shock and body shapes for a flat-faced cylinder at $\alpha = 4$ and 12 deg, respectively. These figures show results of the pure Teflon models. There is little difference at first between shock and body shapes at $\alpha = 4$ deg and those at no angle of attack (not shown in figures). However, at about $t = 300$ s, there is a slight difference between two cases. At $\alpha = 12$ deg, asymmetries of body and shock shapes may be observed clearly with time elapsed. This trend may be observed more strongly in the case of the flat-faced cylinder than in the case of the hemisphere-cylinder. The qualitative reasons, which cause the differences, will be explained later. As a matter of course, since the Reynolds number in this experiment was within the region of laminar flow, both models became blunter. The same phenomenon was observed for the mixed Teflon models as well as for the pure Teflon ones.

Figures 7a-d show the recession depth histories along the body centerline at $\alpha = 0$, 4, 8, and 12 deg for a flat-faced cylinder and for a hemisphere-cylinder, respectively. Figures 7a and 7b show results of the pure Teflon models, while Figs. 7c and 7d show those of the mixed Teflon models.

Pure Teflon Models

In the case of the flat-faced cylinder, the change history of ΔX and the duration of the minus recession depth at $\alpha = 12$ deg are very different from those at smaller angles of attack. On the other hand, in the case of the hemisphere-cylinder, those at $\alpha = 0$ and 4 deg are slightly different from those at $\alpha = 8$ and 12 deg. When the model at room temperature is suddenly exposed to a uniform high-enthalpy stream, large heat transfer takes place because of the large temperature difference. However, this heat is absorbed by the thermal capacity of the model itself and the surface temperature increases only slightly. Even though ablation occurs, the recession depth does not seem to be considerable at first. Therefore, the model length first increases because of thermal expansion. This qualitative explanation for the minus recession depth may be almost applicable to the case of the no angle of attack or the case of the small angles of attack. In the case of the hemisphere-cylinder, the recession depth exceeds the thermal expansion with about 50 s elapsed. The equilibrium state, in which the recession depth and the thermal expansion balance each other, exists for only about 10 s at all angles of attack. On the other hand, the duration of

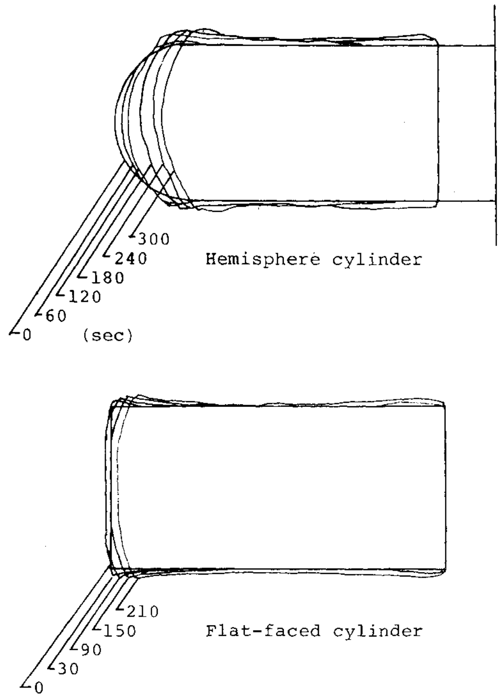

Fig. 5a Shape change history ($\alpha = 0$ deg, pure Teflon).

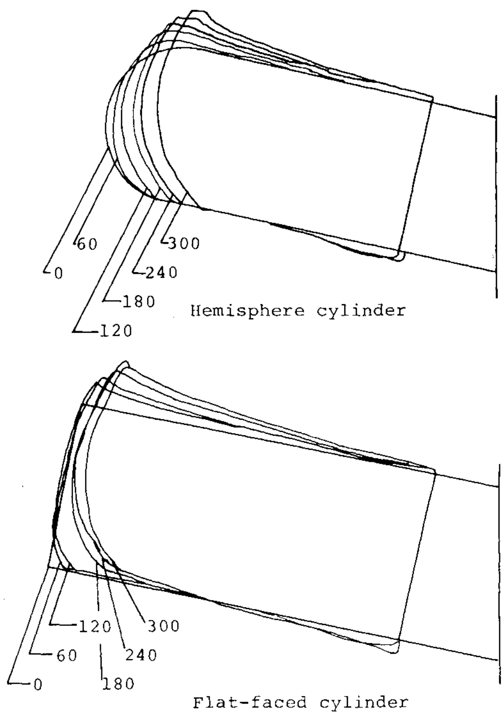

Fig. 5b Shape change history ($\alpha = 12$ deg, pure Teflon).

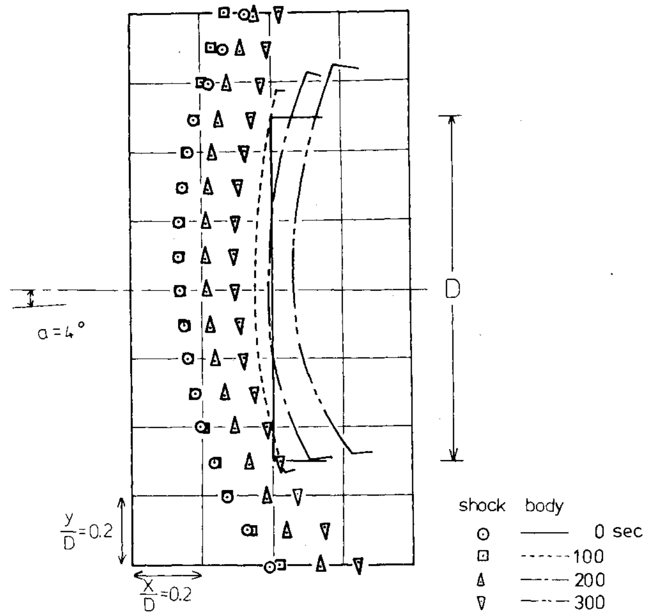

Fig. 6a Instantaneous shock and body shapes ($\alpha = 4$ deg, pure Teflon).

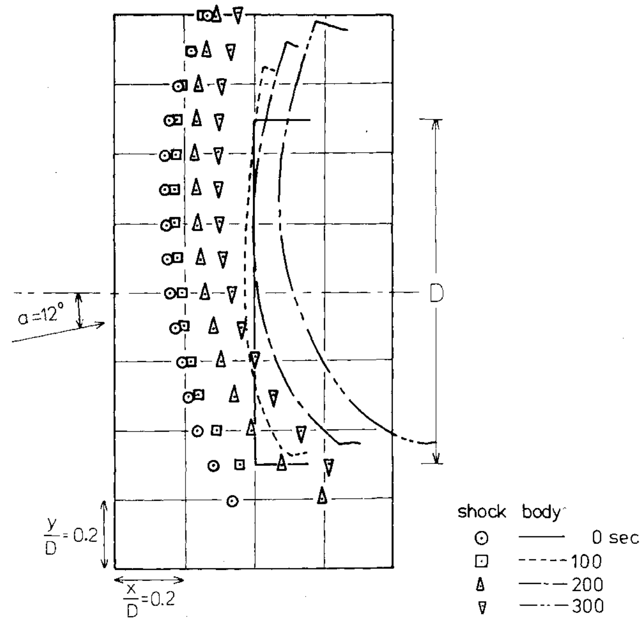

Fig. 6b Instantaneous shock and body shapes ($\alpha = 12$ deg, pure Teflon).

the minus recession depth is much wider in the case of the flat-faced cylinder than in the case of the hemisphere-cylinder. At no angle of attack, this is more than 150 s, and at $\alpha = 12$ deg, it is over 180 s. The equilibrium states continue during $t =$ 20-80 s at no angle of attack and during $t = 20$-140 s at $\alpha = 12$ deg. The equilibrium position at $\alpha = 12$ deg moves slightly forward in comparison with the case of no angle of attack, i.e., the thermal expansion effect at angles of attack is greater than that at no angle of attack. Particularly, that at $\alpha = 12$ deg is much more considerable than that at other angles of attack. The effect of thermal expansion on the recession depth results at $\alpha = 12$ deg is very different from that at smaller angles of attack. That effect becomes slightly smaller at about $t = 80$ s, however, it increases again during $t = 100$-140 s. This phenomenon may be explained by photographs, shown in Ref. 12, which show developments of the high-temperature region on the windward side of the bodies. Ablation occurs at the body shoulder on the windward side with time elapsed, and consequently, that on the windward side grows rounder than that on the leeward side. At the same time a high-temperature region may be observed on the windward side of the bodies. This causes the body temperature to increase, and, consequently, the thermal expansion effect to be considerable. Also, the high-temperature region expands with time elapsed

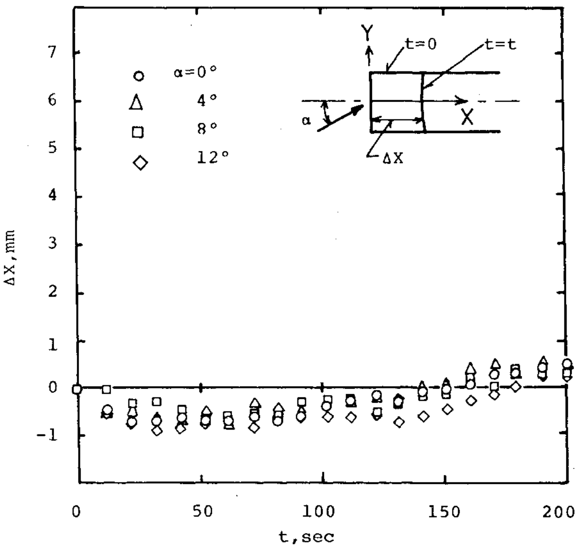

Fig. 7a Recession depth history along the body centerline; flat-faced cylinder (pure Teflon).

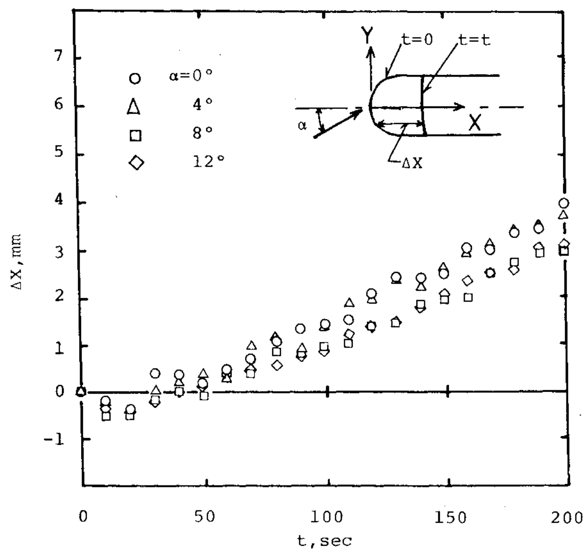

Fig. 7b Recession depth history along the body centerline; hemisphere-cylinder (pure Teflon).

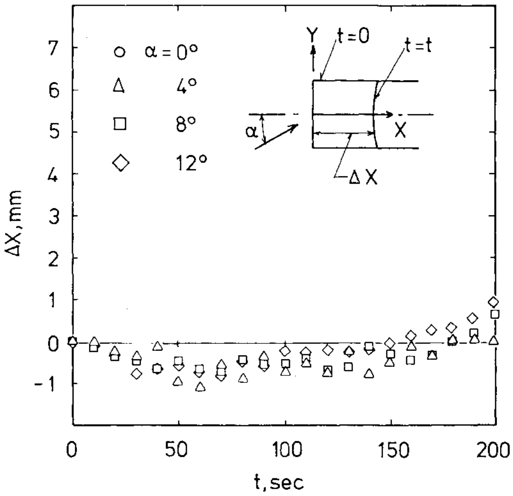

Fig. 7c Recession depth history along the body centerline; flat-faced cylinder, mixed Teflon (glass 25%).

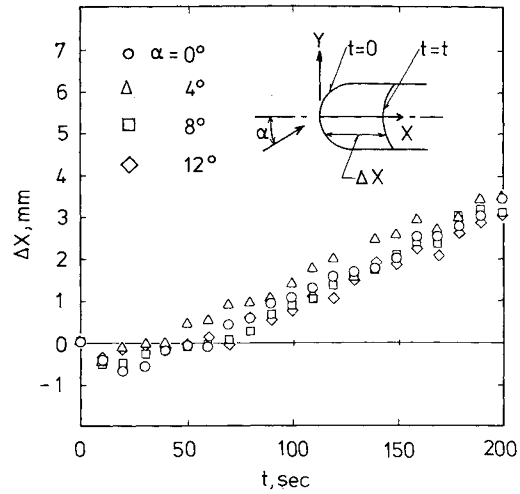

Fig. 7d Recession depth history along the body centerline; hemisphere-cylinder, mixed Teflon (glass 25%).

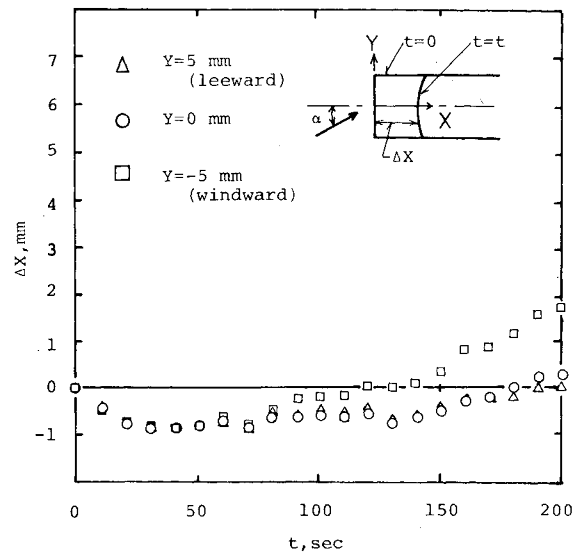

Fig. 8a Surface recession history; flat-faced cylinder ($\alpha = 12$ deg, pure Teflon).

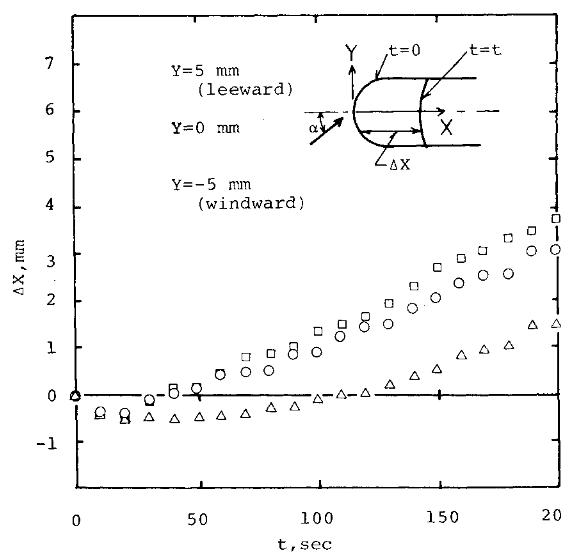

Fig. 8b Surface recession history; hemisphere-cylinder ($\alpha = 12$ deg, pure Teflon).

and causes the internal temperature to increase rapidly. This phenomenon was observed more considerable in the flat-faced cylinder than in the hemisphere-cylinder.

Mixed Teflon Models

We may qualitatively explain phenomena for mixed Teflon models as well as those for pure Teflon models. However, there is a little difference in the dependence on angles of attack. In the case of the flat-faced cylinder, minus recession depths become small, contrary to pure Teflon models with angles of attack increased. When ablation occurs, Teflon and glass are isolated from each other. Teflon is sublimated and injected into the boundary layer. However, glass is melted and stays near a stagnation point. The shear force along the centerline due to the boundary layer is smaller at smaller angles of attack. Therefore, melted glass stays easily. However, melted glass off stagnation point goes out from the inside of the bodies like the spallation and flies away downstream. Therefore, mixed Teflon models became more conical than pure Teflon models. This seems to be caused by weak spallation from a weak char layer.

Figures 8a and 8b show the surface recession histories at $\alpha = 12$ deg for a flat-faced cylinder and for a hemisphere-cylinder, respectively. These figures show recession depth results of pure Teflon models at $Y=5$ mm (leeward), $Y=0$ mm (centerline), and $Y=-5$ mm (windward). In the case of the flat-faced cylinder, there is little difference between the result at $Y=0$ mm and that at $Y=5$ mm. On the other hand, in the case of the hemisphere-cylinder, there are slight differences between that at $Y=0$ mm and that at $Y=-5$ mm. The difference of the surface recession between both models seems to be caused by the difference of heat transfer due to the difference of initial body shapes.

Conclusions

Transient ablation of the "pure" and "mixed" Teflon models is investigated at low temperature, with emphasis on the transient shape changes of blunt bodies at angles of attack. Recession depth results are governed mainly by angles of attack, materials, and initial body shapes. However, initial body shapes are most effective. The high-temperature region appears on the windward side of the body due to instantaneous body shape changes at angles of attack, and has great influence on recession depth results.

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