# Investigation of a Side Force Due to Ablation

W. C. Ragsdale* and E. V. Horanoff†
*Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, Md.*

## Introduction

THE injection of gases by ablation or transpiration into the boundary layers of bodies traveling at high speeds can influence aerodynamic forces by altering both the skin friction and the induced pressure due to boundary-layer displacement effects. Data from flight tests of re-entry vehicles have indicated the possibility of significant Magnuslike side forces due to the combined effects of ablation, spin, and angle of attack.[1] There does appear to be a definite mechanism for such a force. Due to thermal lag, the rate of ablation on a spinning body at angle of attack would be higher on one side of the body than on the other. The difference in the ablation rate on opposite sides of the body would lead to a difference in the boundary-layer induced pressure and produce a side force and moment. The side force in this case would act in a direction opposite to that of a classical Magnus force,[2] as illustrated in Fig. 1. Recent interest in the possible effects of ablation-induced side forces on re-entry vehicle stability led to an experimental investigation in the wind-tunnel facilities of the Naval Surface Weapons Center, White Oak Laboratory. The results of this test program provide insight into the influence of several important variables, in addition to establishing the magnitude of the side force under the chosen set of test conditions.

## Experiment

Ablating and nonablating spherically blunted cone models were tested at Mach 18 in the Naval Surface Weapons Center Hypervelocity Research Tunnel. Details of the configuration tested are shown in Fig. 2. Camphor was used as an ablating material and thin steel model shells were fabricated with a 0.32-cm layer of camphor covering 86.9% of the body length, as shown in Fig. 2. An aluminum shell was fabricated for the nonablating model. A steel nosetip was used for the ablating models as well as the nonablating model to avoid shape change effects in the region of highest aerodynamic heating. The static force measurements were made with a 4-component strain gage force balance which was designed for the test program and incorporated a mechanism for spinning the models.

The test procedure used was to spin the model to the desired rate while bringing the wind-tunnel supply pressure and temperature to the run condition. During this start-up period, the model was kept in a retracted position in the test cell of the open jet wind tunnel. When the run conditions were achieved, the model was injected into the tunnel flow and force data were recorded, while the angle of attack was swept at a rate of roughly 1.5 deg/s up to a maximum value which depended on the tunnel supply pressure. During most of the ablating model tests the sweep was halted for a few seconds at 10 and 25 deg angle of attack to look for possible transient effects. After completing the data sweep, it was necessary to return the model to a small angle of attack before retracting it from the tunnel flow. As a result, the amount of camphor ablated during the data sweep could not be determined. Usually, all the camphor was ablated during the wind-tunnel run and shutdown process. Observation via a television monitor indicated that the camphor-coated portion of the models remained fully coated throughout the data sweep. Models examined after two aborted runs indicated that roughly 20-30% of the camphor could have ablated prior to the data sweep as a result of exposure to the low-pressure test cell environment.

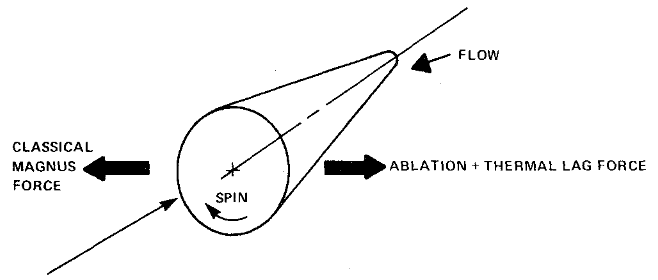


Fig. 1 Side force due to ablation and spin.

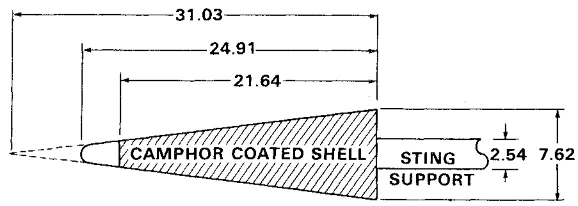


Fig. 2 Sketch of spinning cone model.

| | RUN NO. | REYNOLDS NO. PER METER | SPIN RATE rps | ABLATION |
|---|---|---|---|---|
| x | 1 | $1.6 \times 10^6$ | 5.0 - 5.8 | NO |
| x | 2 | 1.5 | 2.7 - 2.9 | NO |
| x | 3 | 1.6 | 8.7 - 9.8 | NO |
| x | 4 | 1.2 | 5.5 | NO |
| o | 5 | 1.6 | 5.3 - 4.1 | YES |

FLAGS INDICATE DATA TAKEN AT FIXED $\alpha$

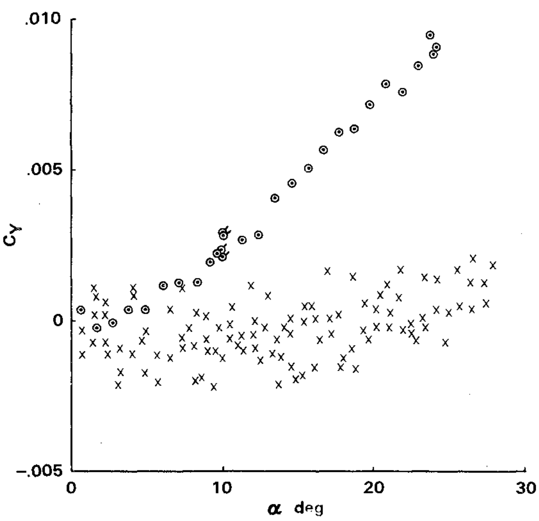


Fig. 3 Comparison of side force data with and without ablation.

## Results and Discussion

The side force data obtained from the wind-tunnel tests are shown in Figs. 3-5, as plots of yaw force coefficient, $C_Y$ (ref. area = initial base area) vs angle of attack. Data taken during the pauses in the angle-of-attack sweep at 10 and 25 deg are indicated by flagged symbols.

Received May 9, 1978. 
Index categories: Supersonic and Hypersonic Flow; LV/M Aerodynamic Heating and Ablation; LV/M Aerodynamics.
*Aerospace Engineer, Aerodynamics Branch. Member AIAA.
†Mechanical Engineer, Aerodynamics Branch.

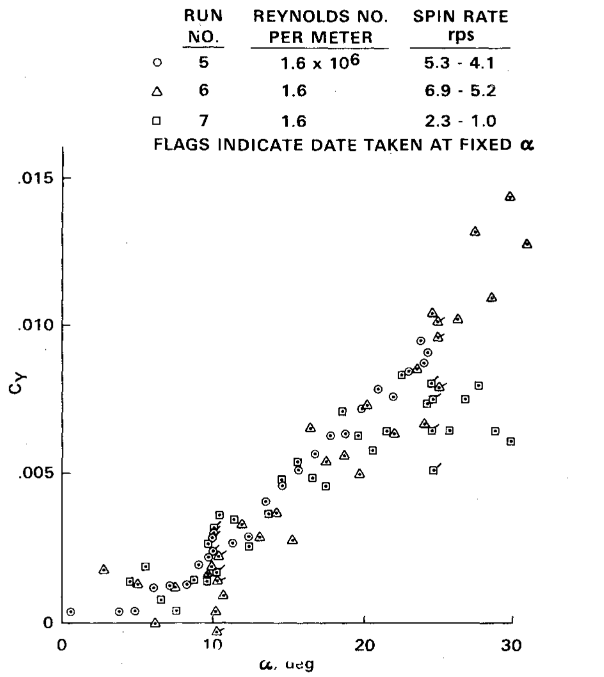


**Fig. 4 Comparison of side force data with ablation at different spin rates.**

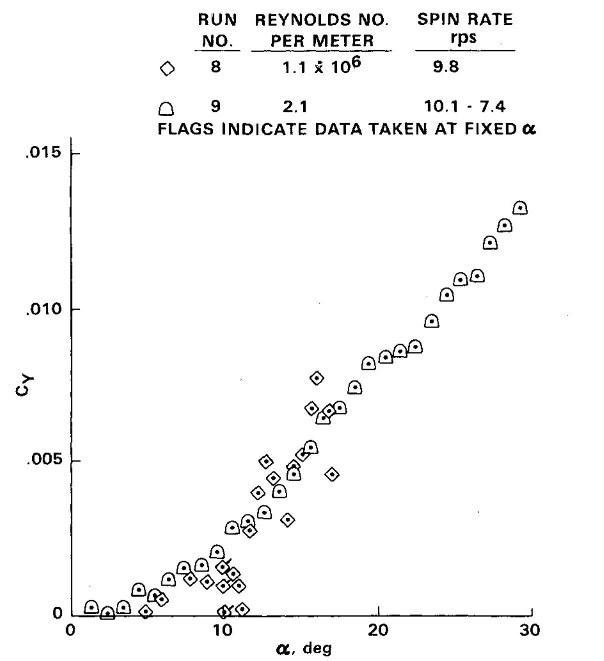


**Fig. 5 Comparison of side force data with ablation at different Reynolds numbers.**

A comparison of data from the nonablating model tests with data from one of the ablating model tests is shown in Fig. 3 and a significant side force due to ablation is clearly indicated. The ablating model data also indicate that the side force is a strong function of the angle of attack—nonlinear up to about 10 deg and linear at higher angles. In Fig. 4, data from three tests made with ablating models at different spin rates are compared. No significant effect of spin rate is seen over most of the angle-of-attack range; although above 25 deg angle of attack the side force data for spin rates between 1 and 2.3 rps are significantly lower than the data taken at higher spin rates. Thus, for camphor ablation at the test conditions reported here, the side force due to ablation was independent of spin rate at speeds greater than 1-2 rps for angles of attack up to 25 deg. In Fig. 5, data from two tests made at different Reynolds numbers are compared and show no significant effect of Reynolds number over the range investigated. It should be noted that completely laminar boundary layers are expected over the entire range of test conditions available in the Hypervelocity Research Tunnel.

The data show the angle-of-attack behavior of the side force due to ablation to be very similar to that of the normal force, and the magnitude of the side force to be roughly 1% of the normal force. The response of the camphor ablation to changes in angle of attack was evidently quite rapid since the data taken at fixed angles of attack do not indicate any large lag effects. The data for spin rates of 1-2.3 rps definitely follow a different trend beyond 25 deg but it is not clear whether this indicates a lag effect or is due to the low spin rate.

In the wind tunnel, positive angle of attack was nose-up and the direction of spin was clockwise, looking upstream. The direction of the observed side force was to the right, looking upstream, which is in agreement with the qualitative mechanism for the ablation-induced side force previously mentioned.

The center of pressure of the side force was also measured but due to the fact that the force was very small, accurate results were not obtained. In general, the experimental data indicate the side force center of pressure to be located 50-60% of the body length from the nosetip and independent of the angle of attack.

Normal force and pitch center of pressure measurements were also made and the results for the ablating models were in good agreement with those for the nonablating models. The normal force data were in good agreement with classical Newtonian flow theory. The center of pressure data for the ablating models showed small shifts ($<1/2\%$ of body length), while the angle of attack was held constant at 10 and 25 deg. These shifts are believed to be due to the effect of shape change.

## References

[1] Waterfall, A. P., "Effect of Ablation on the Dynamics of Spinning Re-Entry Vehicles," *Journal of Spacecraft and Rockets*, Vol. 6, Sept. 1969, pp. 1038-1044.

[2] Vaughn, H. R. and Reiss, G. E., "A Magnus Theory," *AIAA Journal*, Vol. 11, Oct. 1973, pp. 1396-1403.

# Mixing of a Transverse Jet with a High Mach Number Stream

R. Rosen* and D. W. Harvey†
*McDonnell Douglas Astronautics Company, Huntington Beach, Calif.*

## Nomenclature

| | |
|---|---|
| $c,\gamma$ | = mass and molar concentration, respectively |
| $c_{crit}$ | = fraction of injectant within $\gamma_{min}$ ellipse |
| $g$ | = ratio of $x$ and $y$ dimensions of $\gamma_{min}$ ellipse |
| $M$ | = ratio of molecular weights of injectant to freestream |
| $M_j$ | = molecular weight of injectant |

Presented as Paper 78-27 at the AIAA 16th Aerospace Sciences Meeting, Huntsville, Ala., submitted Feb. 13, 1978; revision received May 4, 1978. 

Index categories: Supersonic and Hypersonic Flow; Airbreathing Propulsion.

*Senior Engineer/Scientist.

†Senior Engineer/Scientist. Member AIAA.