Drag Reduction of a Noncircular Missile by Base Burning

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Nomenclature

A_b = base area
D = drag
I_{sp} = specific impulse, $D/\dot{m}_h$
$\dot{m}_h$ = mass-flow rate of hydrogen
P = freestream pressure
P_b = freestream velocity
ΔD = model drag without burning—model drag with burning
ρ_∞ = freestream density

Introduction

IN a series of experiments on supersonic base flows, Barr[1] discovered a complex flow pattern in a V-shaped channel attached to a back step. This flow pattern resulted whenever a uniform supersonic flow passing over a back step separated and reattached in the bottom of a v channel. A flow model based on detailed studies of Zumwalt[2] suggests that, in the process of reattachment, the shear layer emanating from the back step moves down into the corner, squeezes by the converging walls, and rolls its edges, and as a result, the vorticity vector gets aligned with the dominant direction of the flow (Fig. 1). In the bottom of the v channel, these counter-rotating vortices stay submerged in the outer flow. The effects of this vortex pair were observed not only downstream but also upstream into the near-wake region reaching almost to the back step. Zumwalt[3] also observed that one of the vortices slips under the other and they lie asymmetrically in the bottom of the v channel. Friedberg and Ahmed[4] later furthered the studies and found that these vortices were very stable and resulted in high levels of mixing when a secondary gas was injected in the base region. These vortices also increased the residence time and, therefore, offered a unique environment for sustained burning of hydrogen when injected in the base region of a back step. In addition, they also observed that the base pressure increased considerably in the presence of the v channels suggesting that the flow phenomena was a possible mechanism for the bleeding of higher pressure from the reattachment point to the base region.

In a subsonic flow regime, base flow is dominated by periodic formation and shedding of eddies in the wake; the base pressure is low, indicating high drag. With an increase in flow velocity, base pressure tends to decrease. However, for a given flow velocity and step height, it tends to remain uniform except when additional mass flow is injected into the separated region or when there is a temperature rise due to combustion. This increase in base pressure in turn lowers the base drag which is defined as,

$$D = (P - P_b)A_b$$

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After establishing the flame limits for a given ratio of boundary-layer thickness at the edge of the back step to the back-step height and hydrogen mass-flow rates for effective burning in small v channels attached to an open jet, it was observed that the base pressure rise due to injection alone was only 3% but increased to 15% with burning.[4] The present

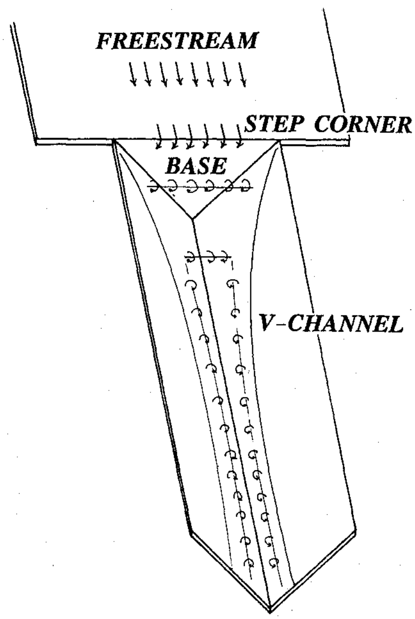

Fig. 1 V-channel flow model as indicated by oil streaks.

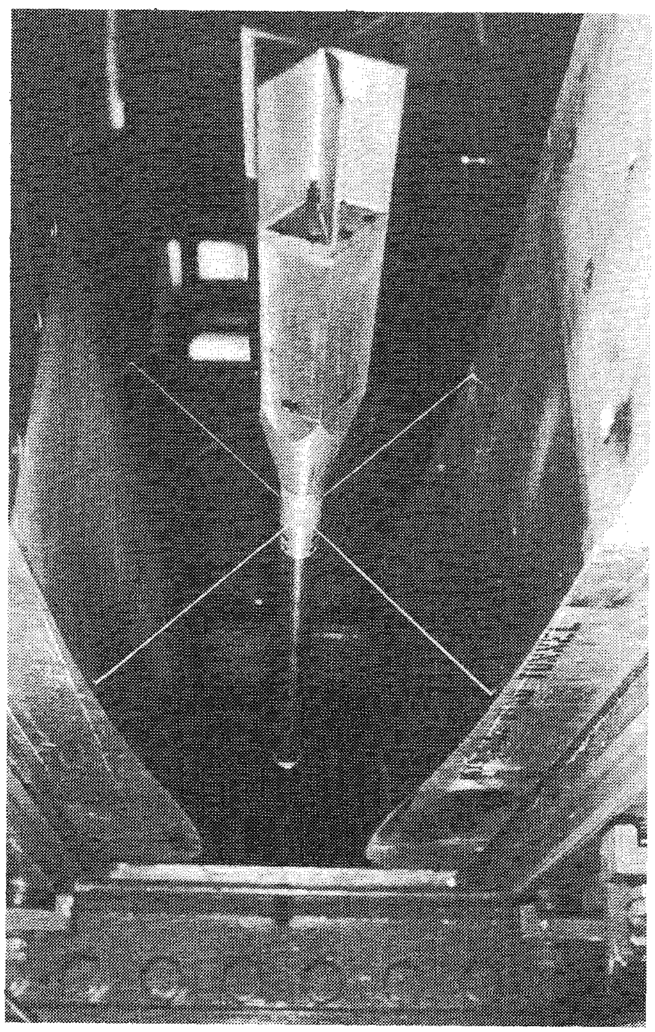

Fig. 2 Model mounted in the tunnel.

Note deals with the application of base burning in v channels attached to the base of a noncircular missile for base-drag reduction.

Experimental Facility And Model

All experiments were conducted at Mach 2 in a Wichita State University 23×23-cm supersonic blowdown wind tunnel. Air for all tests was supplied from storage tanks of 20-m^3 capacity and a maximum storage pressure of 1724 kN/m^2. To reduce the humidity of air in the test section, a water cooled heat exchanger and a centrifugal water separator were installed just downstream of the compressor. Gaseous hydrogen for base burning was supplied from a commercial high-pressure cylinder at room temperature. Hydrogen mass-flow rate was monitored by a set of calibrated in-line flow nozzles. Pressure drop across the nozzle was measured by a differential-type pressure transducer.

Since the termination of a flat surface into a v channel was a prerequisite for the stable vortices to form in the v channel, a hexagonal cross-section missile was designed primarily to facilitate the utilization of six v channels in the base of the missile. This geometry guaranteed the formation of the vortex system in the bottom of the v channel where hydrogen was injected and burned. To reduce the interference due to reflected shock waves, the overall length of the model with the v channels attached was 300 mm, which was less than the distance at which the shock waves reflected from the tunnel walls were anticipated to hit. This was later confirmed by schlieren images. The model width (across flat sides) was 51 mm and was designed to slide on an upstream support to which strain-gauged flexures were attached for drag measurement (Fig 2). The balance was calibrated before and after each series of tests for possible dc shift and hysteresis. Six v channels with v angle of 60 deg were soldered to a steel base plate that was attached to the model base. Each v channel was 76 mm long and 24 mm deep. In the middle of the base plate, a spark igniter was inserted through a 4-mm hole. Hydrogen was uniformly supplied to each channel separately from a built-in manifold.

Under the given capacity of storage tanks, a typical run time was approximately 14 s for a Mach 2 flow. Tunnel stagnation pressure and temperature were held constant at 483 kN/m2 and 293 K, respectively, resulting in a test Reynolds number of 20×10^6 based on model length. After the flow was established in the test section, the hydrogen supply valve and an analog X/Y plotter were activated to record the output from the strain-gauge balance. The spark igniter was used only momentarily to the ignite hydrogen. Force data were obtained from the time histories, specific impulse and hydrogen mass-flow rate were calculated after each run.

Results And Discussion

The time histories of the test runs indicated that the injection alone was contributing very little to the changes in drag readings and that a large part of the reduction was due to burning. This is possibly due to the presence of v channels in the base that act as splitter plates and therefore increase the base pressure. Because of the physical constraints of the model size and the difference in the type of flows (axisymmetric vs three dimensional), no attempts were made to measure model drag without v channels.

During the initial tests, difficulty was encountered in achieving stable burning due to the small reaction time of hydrogen. To increase the residence time of hydrogen in the base region, flow deflectors were installed on each supply port to direct hydrogen toward the bottom of the v channels. Stable burning was thus achieved for all hydrogen supply pressures. These deflectors also served the purpose of eliminating the axial momentum of the hydrogen jet, which would have otherwise opened the wake or altered the vortical flow within v channels.

Analysis of time records and flow parameters indicated that the error in the hydrogen mass-flow measurement remained below 4% and the drag readings were observed to be repeating well within 3%. The overall error was estimated to be < 5%.

The percentage drag reduction and specific impulse is plotted against the nondimensionalized hydrogen mass-flow rate in Fig. 3. An average drag reduction of 30% was achieved with this method of base burning proving the effectiveness of v channels as an alternate method of wake modification. In addition, a very high specific impulse was also achieved which is compatible with the analytical results of Zumwalt et al.[5]

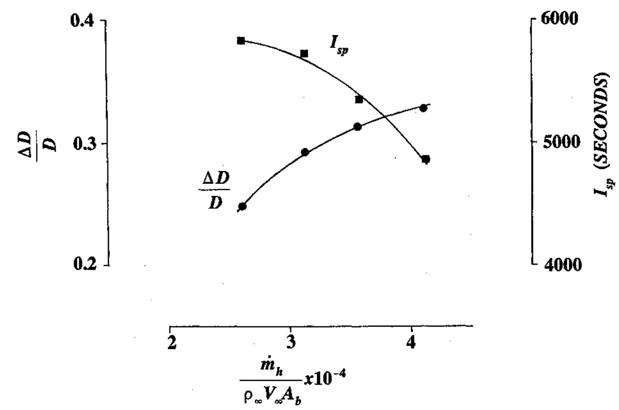

Fig. 3 Effective drag reduction and specific impulse obtained at different nondimensionalized hydrogen mass-flow rates.

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Solar Sail Trajectories at the Lunar L_2 Lagrange Point

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Introduction

THE concept of solar sailing came to fruition in the mid-1970s when it was adopted by NASA as a possibility for a comet Halley rendezvous mission.[1] During this time much work was carried out on the optimization of two-body solar sail dynamics for interplanetary trajectories.[2] More recently, interest has arisen in "exotic" solar sail trajectories with novel mission applications. Work by Forward[3] has shown that high-performance solar sails may have useful applications for terrestrial communications purposes. Currently, McInnes and Simmons are investigating large new families of solar sail

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