Preliminary Investigation of Stagnation Point Liquid Injection Influence on Blunt Body Aerodynamics

William C. Woods, Dr. Kenneth M. Jones, and Noah N. Genzel
NASA Langley Research Center
Hampton, VA 23681-2199
Abstract

A preliminary investigation has been performed to determine the influence of stagnation point water injection on the hypersonic aerodynamic forces and moments for two-dimensional blunt bodies. This investigation was performed in the Langley 20-Inch Mach 6 Air Tunnel, and represents the qualitative first phase of a study to examine the potential benefits of water injection to reduce aerodynamic drag and aero-heating. Tests with a 4-inch diameter hemisphere cylinder and a 4-inch diameter cylinder with a span 1.5 times the diameter were performed over a range of free-stream unit Reynolds number from two million to six million per ft and of angle of attack (-5° to 5°) with water and gaseous nitrogen injection at the geometric stagnation point. The momentum flux ratio, that is, the ratio of the momentum flux of the jet to that of the free-stream flow, was varied from the non-blowing value of zero up to 0.00031 by maintaining the jet momentum fixed and varying the free-stream momentum, hence Reynolds number. The effect of water injection on the aerodynamic drag coefficient for the hemisphere cylinder was observed to be negligible as the momentum flux ratio was increased to 0.00017, but decreased significantly as this ratio increased above 0.00017; a nearly 50 percent reduction in drag occurred for a factor of two increase in momentum flux ratio.

Introduction

The effect of mass transfer by blowing or suction on the lifting capability of airfoils (or wings) has been studied for over 50 years. In the late 50's and through the 60's both fluid and gas injection at the stagnation point and around the forward face of entry bodies was experimentally studied for a variety of reasons: radio frequency attenuation, cooling, drag reduction, etc. Mass transfer proved to affect the flow about bodies with resulting changes in pressure distributions, forces, moments, and at supersonic - hypersonic speeds, heating distributions (e. g. references 1 through 6). It may be coincidental, but as ablating heat shields were developed, and adopted, with their natural ability to add mass to the flow field around a blunt body, artificial blowing studies tended to subside except for studies supporting Jovian entry (reference 7 for example) and aerobreaking for orbital plane change (e. g. references 8 through 10).

In the late 70's and early 80's some orbital transfer vehicle designs considered inflatable ballutes for lightweight high drag vehicles. Naturally, aeroheating levels and loads were a major concern. Stagnation point rocket exhaust was considered for both drag modulation and heating reduction. Figure 1, containing figures from references 8 through 10, presents results of stagnation point helium blowing studies performed in the Langley Research Center 22-Inch Mach 20 Helium Tunnel supporting ballute development. Figure 1(a) is a schematic diagram of how the bow shock varies with stagnation point blowing. The solid line shows the bow shock for no blowing. Low blowing produces a fluctuating bulge shown by the large dashed line. Increased blowing produces a large unsteady aerospike that can separate the flow off
the body. Eventually a mass flux balance between the free stream and the jet occurs producing a stable shock structure shown by the small dashed curve. This flow model was observed during the Mach 20 helium tests. Figures 1(b)-(d) summarize the helium results. Drag coefficient, as a function of momentum flux ratio, $C_\mu$, for these flow fields for 90° and 120° included angle bodies and two different expansion ratio nozzles is presented in Fig. 1(b). At $C_\mu = 0.01$ drag coefficient is roughly 1/10 the no blowing case ($C_\mu = 0$); at $C_\mu = 0.03$, $C_D$ was roughly 1/3 to 1/2 the no blowing case depending on the bluntness of the forebody. The focus of these studies at Mach 20 was the hope for high drag, at low fuel consumption, and low heating. At $C_\mu$ of 0.03, fuel consumption was excessive. However, additional tests at low blowing conditions indicated reduced pressure in the stagnation region (Fig. 1(c)) and possible surface cooling (Fig. 1(d)). These results indicate the capacity of stagnation point injection to affect drag, pressure, and heating.

In recent years interest has been expressed in atmospheric transit (gun launch) at high initial velocities (30,000 ft/sec at sea level). The severity of this environment (i.e. high heating), and the possibility of deceleration due to high drag losses, has stimulated renewed interest in a basic series of hypersonic experiments to examine the effect of discrete liquid injection at the stagnation point of a blunt body on drag and heating. Due to limited resources, an experimental plan was formulated to provide a qualitative assessment by using simple, easily fabricated bodies and available water pressure to avoid extensive design and fabrication issues associated with complex systems/configurations. (A companion flight experiment was performed in the ballistic range at Eglin Airforce Base).

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>Angle-of-attack, (degrees)</td>
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<tr>
<td>$C_A$</td>
<td>Axial force coefficient, ($\text{Axial Force}/q_\infty S_{\text{ref}}$)</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Drag coefficient, ($\text{Drag}/q_\infty S_{\text{ref}}$)</td>
</tr>
<tr>
<td>$C_{D_0}$</td>
<td>Drag coefficient at $\alpha = 0^\circ$</td>
</tr>
<tr>
<td>$C_N$</td>
<td>Normal force coefficient, ($\text{Normal force}/q_\infty S_{\text{ref}} l_{\text{ref}}$)</td>
</tr>
<tr>
<td>$C_m$</td>
<td>Pitching moment coefficient, ($\text{Pitching moment}/q_\infty S_{\text{ref}} l_{\text{ref}}$)</td>
</tr>
<tr>
<td>$C_\mu$</td>
<td>Momentum flux ratio, ($m_{\text{jet}} V_{\text{jet}} / \rho_\infty V_\infty^2 S_{\text{ref}}$)</td>
</tr>
<tr>
<td>$l_{\text{ref}}$</td>
<td>Body diameter (axisymmetric), Body Height (2-D), inches</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass flow, ($\rho VA$), slugs/sec</td>
</tr>
<tr>
<td>$q_\infty$</td>
<td>Freestream dynamic pressure ($1/2 \rho_\infty V_\infty^2$), psi</td>
</tr>
<tr>
<td>$R$</td>
<td>Freestream unit Reynolds Number, ($\rho_\infty V_\infty / \mu_\infty$), 1/ft</td>
</tr>
<tr>
<td>$S_{\text{ref}}$</td>
<td>Reference area, base Area, sq. inches</td>
</tr>
<tr>
<td>$V$</td>
<td>Velocity, ft/sec</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density, slugs/ft$^3$</td>
</tr>
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</table>

**Research Apparatus**

**Models**

Desired characteristics for model geometry for the present study include a configuration whose hypersonic flow field and force and moment characteristics are understood; a geometry somewhat inexpensive to machine; and one having a relatively high drag coefficient. Two geometries were selected, a hemisphere cylinder and a quasi two-dimensional cylindrical leading edge slab model with a span 1.5 times the height to achieve near 2-D flow on the centerline. The 2-D cylinder slab model possesses only longitudinal curvature and provides a suitable surface for installing thin film gauges, etched on mylar film, for subsequent heating studies. Both models, fabricated from aluminum, have a 0.020-inch diameter hole drilled at the stagnation point with a 1/8 thick
walled tube bonded to a cavity behind this hole. Flexible tygon tubing was used to provide water at city water pressure (typically 75 psia) to the models. Model size (4-inch diameter) and wind tunnel balance (LaRC WTB HCF-04B) were selected for loads of sufficient magnitude (20 to 80 lbs axial load) to minimize any influence of the water injection system on force measurements (foulng or tare loads). Schematic diagrams of the models (without the water tube) are shown in figure 2. Photographs of the models installed in the test facility are shown in figure 3.

**Facility**

*NASA LARC 20-Inch Mach 6 Tunnel*

The NASA Langley 20-Inch Mach 6 Air Tunnel, selected for this investigation, is a blowdown facility with a 20-inch by 20-inch square test section that operates at a fixed Mach number of 6, using dry air as the test medium. Typical test conditions in this facility include nominal freestream unit Reynolds numbers from 0.5 to 9 million/ft. Model angle of attack can be varied in a pitch-pause mode from –5° to 55°, depending upon the length and position of the model in the test section. The design of the injection system permits the pitch-pause sequence at sideslip angles up to 5°. Run times are typically several minutes with a maximum time of approximately 15 minutes. For additional information on this facility see reference 11.

As previously mentioned, to expedite this study, existing city water at constant pressure was utilized (approximately 75 psi). An instant on/off valve, remotely operated from the tunnel control room provided water control and an in line gage measured pressure levels on a run to run and day to day basis to account for variations in city pressure. Accordingly, to vary the momentum flux ratio tunnel test conditions were varied (Reynolds number and free stream momentum) run to run. Table 1 lists test conditions and accompanying momentum flux ratios (Cμ) for both the liquid and gaseous nitrogen spikes produced for each condition.

The test procedure included tare runs with no water injection and tare runs with water injection over the angle-of-attack range. During a tunnel run water was turned on intermittently at each angle to minimize the amount of fluid introduced into the tunnel system. Therefore, at each α, both water off and water on data was obtained. Base pressure was measured and base pressure corrections applied to the axial data.

**Discussion of Results**

The effect of water injection on the hemisphere cylinder flow field is shown in Fig. 4. This is a series of schlieren photographs taken for a range of Cμ from 0 to approximately 0.0003. The initial photograph (Fig. 4(a)) corresponds to no water injection and a unit Reynolds number of 2 x 10^6/ft, Cμ = 0. Figures 4(b) through 4(e) are schlieren photographs taken at tunnel conditions for Reynolds number of 6 x 10^6/ft to 2 x 10^6/ft and water injection pressure of 75 psi resulting in a range of Cμ from approximately ,0001 to .0003. Liquid spikes (water spikes as opposed to aerospikes or solid spikes) from 0.16 nose diameter to 1.32 nose diameter in length were produced. In addition, it was observed that the flow field is quite complex and is unsteady. This was not surprising, but since liquid injection tests had not previously been conducted in this tunnel and considering the low pressure environment whether the water would remain liquid or immediately vaporize was unknown. It appears from the schlierens there is a substantial liquid stream and there was no fluid residue in the tunnel after the test.

Figure 5 shows the effect of 5° angle of attack on this complex flow field for R/ft = 2 x 10^6 and Cμ = 0.0003. By comparing Figs. 5 and 4(e) (α = 0°, Cμ ≈ 0.0003) some indication of how angle of attack (i.e., 3 dimensionality) compounds this already complex flow field is gained. Varying the angle of attack from zero significantly reduces the length the water spike is able to extend upstream and the spike takes the form of that observed at zero angle of attack for a lower value of Cμ (compare to Fig. 4(b)).

The effect of water injection on the longitudinal aerodynamic coefficients is shown in Figure 6, where Cα, C_N, and C_m are shown as
functions of angle of attack. As observed in Fig.
6(a) for $C_\mu > 0.0002$ (liquid spikes > 0.3D), a
significant reduction in $C_A$ occurs; for example
a 45% reduction in $C_A$ occurs at $\alpha = 0^\circ$ as $C_\mu$ is
increased to 0.00031. Similarly, significant
variations occur for both normal and pitching
moment as $C_m$ is increased beyond 0.0002.

The significance of these results is
summarized in Fig. 7 where $C_{D_0}$ (i.e. $C_A$ at $\alpha =
0^\circ$) is presented as a function of $C_\mu$. For these
limited results two distinct linear trends appear.
Momentum flux increases from zero (non-
blowing) to 0.00016 show little influence on
$C_{D_0}$, but a point of departure occurs around $C_\mu =
0.00016$ to 0.00017. For $C_\mu > 0.00016$ a near
linear reduction in $C_{D_0}$ with $C_\mu$ occurs and $C_{D_0}$ is
reduced to 55% of the no blowing value. The
effectiveness of the water spike for drag
reduction is clearly indicated.

For comparison purposes limited tests were
conducted using dry nitrogen for stagnation
point blowing. Figure 8 is a schlieren
photograph showing the effect of blowing with
nitrogen gas at approximately the same pressure
(75 psi) as the water jet and a tunnel free stream
unit Reynolds number of $2 \times 10^6$/ft. At these
conditions the water spike was 1.3 body
diameters (Fig. 4(e)). The corresponding
nitrogen spike is greatly defuse and only 0.16D
in length, even though the momentum flux ratio
$C_\mu$ is 0.00058; i.e. over approximately 5 times
the $C_\mu$ value for a comparable water spike
(reference Fig. 4(b)). The effect of $N_2$ blowing
on the aerodynamic coefficients (Fig. 9) is about
the same as for a water spike of 0.16D
corresponding to $C_\mu$=0.00011.

Figure 10 presents schlieren photographs,
from the limited tests on the quasi-2D shape
showing the effect of water injection on the flow
field. The shock stand off distance for the no
injection case (Fig. 10(a)) is approximately
twice that observed for the hemisphere cylinder
(Fig. 4(a)), as expected. These tests were
conducted for a tunnel free stream Reynolds
number of $2 \times 10^6$/ft corresponding to a $C_u =
0.00016$. Figure 10(b) shows the effect on the
flow field of water injection at a pressure of 75
psia. The water spike length is roughly half the
cylinder diameter (0.5D), which is comparable
to a water spike for a $C_u \approx 0.00016$ to 0.00022
on the axisymmetric (hemisphere cylinder)
configuration. For the same Reynolds number
and water pressure on the axisymmetric
configuration a $C_\mu = 0.00031$ and a water spike
of 1.32D occur. The flow appears un-
symmetrical; however, the flow is highly
unsteady, and this schlieren photograph is at a
frozen instant in time. The effect of this flow
field on the aerodynamics is shown in Fig. 11.
No drag reduction occurs as $C_\mu$ is increased from
zero to 0.00016, consistent with the
axisymmetric results for $C_\mu < 0.0002$. The
increase in $C_N$ and $C_m$ is also comparable to
the previous results for $C_\mu < 0.0002$.

Future Plans

To provide direct comparison between liquid
and solid spikes a series of solid spikes with
various fairings at the spike body interface have
been fabricated. Testing has been initiated, but
results were not available at the time of this
publication. Two such configurations are shown in figure 13.

Concluding Remarks

Tests were conducted in the LaRC 20 Inch
Mach 6 Air Tunnel using stagnation point water
injection for a hemisphere cylinder and quasi 2-
D cylindrical leading edge body to examine the
effect of geometric stagnation point water
injection on the measured aerodynamic
coefficients. The influence of water injection on
aerodynamic coefficients for the hemisphere
cylinder was negligible as the momentum flux
ratio was increased to approximately 0.00016 to
0.00017. Aerodynamic drag coefficient
decreased significantly as this ratio increased
above 0.00017. (A nearly 50 percent reduction
in drag occurred for a factor of two increase in
momentum flux ratio.) Variation in momentum
flux up to 0.00031 produced liquid spikes up to
1.32 times body diameter with drag reduction
occurring for liquid spikes greater than 0.3 times
body diameter. Limited tests with a quasi 2-D
body produced results consistent with those for
the hemisphere cylinder. Limited tests with
gaseous nitrogen indicated a liquid spike to be
more effective than a gaseous spike, as would be expected.

References


6. Charczenko, Nickolai; Hennessey, Katherine

Table 1

<table>
<thead>
<tr>
<th>P, psi</th>
<th>T, °R</th>
<th>M</th>
<th>R/ft x 10^6</th>
<th>( C_\mu ) sphere H(_2)O</th>
<th>( C_\mu ) sphere N(_2)</th>
<th>( C_\mu ) 2-D H(_2)O</th>
<th>Sphere H(_2)O spike</th>
<th>Sphere N(_2) spike</th>
<th>2-D H(_2)O spike</th>
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<tr>
<td>125</td>
<td>910</td>
<td>5.97</td>
<td>2</td>
<td>0.00031</td>
<td>0.00058</td>
<td>1.320D</td>
<td>0.160D</td>
<td>0.5D</td>
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<tr>
<td>180</td>
<td>910</td>
<td>5.97</td>
<td>3</td>
<td>0.00022</td>
<td>0.00016</td>
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<tr>
<td>250</td>
<td>910</td>
<td>5.97</td>
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<td>375</td>
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<td></td>
<td>0.160D</td>
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</table>


1(a) Changes in bow shock structure due to jet flow.

1(b) Variation of drag coefficient with rocket plume momentum flux ballute OTV.

1(c) Effect of jet flow on forebody pressures.

1(d) Effect of jet flow on ballute model surface temperatures.

Figure 1. Effects of stagnation region gas injection for ballute configuration in Mach 20 helium (taken from refs. 8-10).

Figure 2. Sketch of the axisymmetric and 2-D models.
3(a) Axisymmetric model.

3(b) Quasi 2-D model.

Figure 3. Tunnel installation of models.

4(a) $C_{\mu} = 0$, $R = 2 \times 10^6$/ft.

4(b) $C_{\mu} = 0.00011$, $R = 6 \times 10^6$/ft.

4(c) $C_{\mu} = 0.00016$, $R = 4 \times 10^6$/ft.

4(d) $C_{\mu} = 0.00022$, $R = 3 \times 10^6$/ft.
Figure 4. Effect of momentum flux ratio for water injection on the axisymmetric model flow field at Mach 6 in air.

$C_\mu = 0.00031$, $R = 2 \times 10^6$/ft.

Figure 5. Effect of angle of attack on axisymmetric model flow field at $M = 6$ in air with water injection (compare to Fig. 4(e)).

$C_\mu = 0.00031$, $R = 2 \times 10^6$/ft, $\alpha = 5^\circ$

Figure 6. Effect of momentum flux ratio and angle of attack on axisymmetric model aerodynamic coefficients at Mach 6.

6(a) Effect of $C_\mu$ and $\alpha$ on $C_A$.

6(b) Effect of $C_\mu$ and $\alpha$ on $C_N$.

6(c) Effect of $C_\mu$ and $\alpha$ on $C_m$. 
Figure 7. Effect of momentum flux ratio on axisymmetric model $C_{D,0}$ at Mach 6.

Figure 8. Effect of stagnation point $N_2$ injection at Mach 6 in air; $C_{\mu} = 0.00058$, $R = 2 \times 10^6$/ft (compare to Figs. 4 (b), (c)).

Figure 9. Effect of $N_2$ injection and angle of attack on axisymmetric model aero-coefficients at Mach 6.

9(a) Effect of $C_{\mu}$ and $\alpha$ on $C_A$.

9(b) Effect of $C_{\mu}$ and $\alpha$ on $C_N$ & $C_m$.

10(a) $C_{\mu} = 0$.

10(b) $C_m = 0.00016$.

Figure 10. Effect of momentum flux ratio due to water injection on the 2-D model flow at Mach 6, $R = 2 \times 10^6$/ft.
The diagrams illustrate the effects of water injection on the aerodynamic coefficients of a 2-D body.

11(a) Effect of $C_\mu$ and $\alpha$ on $C_A$ of the 2-D body.

11(b) Effect of $C_\mu$ and $\alpha$ on $C_N$ and $C_m$ of the 2-D body.

Figure 11. Effect of water injection and angle of attack on 2-D model aerodynamic coefficients at Mach 6.

12(a) Axisymmetric model with 4-inch spike.

12(b) Axisymmetric spike model with 45° interface.

Figure 12. Tunnel insulation photographs of solid spike models.