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Abstract

"Observations of Shock Diffusion and Interactions in Supersonic Freestreams with Counterflowing Jets"

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1) Concise statement of problem (its genesis and objectives).

One of the technical challenges in long-duration space exploration and interplanetary missions is controlled entry and re-entry into planetary and Earth atmospheres, which requires the dissipation of considerable kinetic energy as the spacecraft decelerates and penetrates the atmosphere. Efficient heat load management of stagnation points and acreage heating remains a technological challenge and poses significant risk, particularly for human missions.

An innovative approach using active flow control concept is proposed to significantly modify the external flow field about the spacecraft in planetary atmospheric entry and re-entry in order to mitigate the harsh aerothermal environments, and significantly weaken and disperse the shock-wave system to reduce aerothermal loads and wave drag, as well as improving aerodynamic performance. To explore the potential benefits of this approach, we conducted fundamental experiments in a trisonic blow down wind tunnel to investigate the effects of counterflowing sonic and supersonic jets against supersonic freestreams to gain a better understanding of the flow physics of the interactions of the opposing flows and the resulting shock structure.

2) Scope and methods of approach, with statement of contribution to the state of the art.

To gain a better insight into the flow physics of the interactions and shock dissipation of supersonics freestreams and counterflowing jets, tests were conducted in in trisonic wind tunnel with a maximum Mach number of 4.96. In addition to the baseline geometry of a 2.6% scale Apollo capsule, five counterflowing nozzles were built into the model which was tested in Mach 2.48 and 4.0 supersonic freestreams. Three of the nozzles are sonic while the other two are supersonic, with Mach numbers of 2.44 and 2.94, with the diameters of the nozzle exit areas varying from 0.25 to 0.5 inch to demonstrate the parametric effective of nozzle geometry. The flow rates of the counterflowing jets were also varied from 0.05 to less than 0.6 lb_m/sec, and the model was tested at three angles of attack, of -5 °, 0° and 9° to determine the effects of flow rate and angle of attack on the flow interactions and structure. The 2.6% scale Apollo model was instrumented with heat flux gauges, thermocouples, and pressure taps to quantify the flowfield. Schlieren system was also used to "see" the flowfield and capture the interactions and the resulting shock structure.

3) Summary of important conclusions.

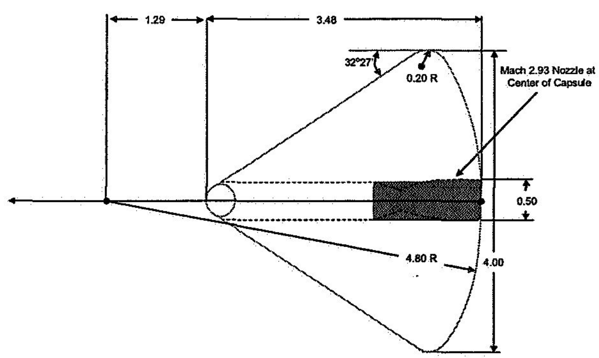
The Schlieren images of the tests show dramatic flow structure of the Mach 3.48 and 4.0 supersonic freestream-counterflowing jet interactions. It is seen that at the low jet flow rates of 0.05 and 0.1 lb_m/sec, the jet flow of both the three sonic nozzles and the two supersonic nozzles give the long penetration mode (LPM), the short penetration is observed at flow rates higher 0.1 lb_m/sec. The LPM is, in essence, a "pencil" of fluid embedded in the oncoming supersonic freestream, with the resulting flow structure being very unsteady and highly oscillatory. For the LPM interactions, the jet is seen to be nearly "fully expanded" resulting in an interaction that shows the bow shock to be very much dissipated or diffused, and it seen to be very unsteady and oscillatory in the Schlieren videos. The lack of definition of the bow shock in the traditional definition of shock waves is quite dramatic and could have several practical implications.

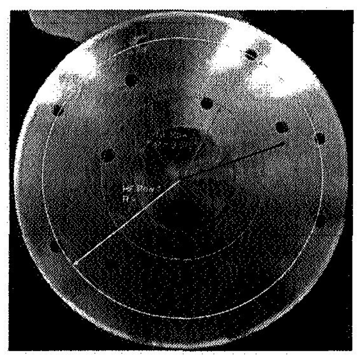
In contrast to the flow structure of the LPM interaction, the flow structure of the SPM interaction shows weaker but clearly defined complex shock structure. The jet is seen to be underexpanded and "plumes" into a barrel shock which interacts with the bow shock, emanating into a terminal shock and resulting into a supersonic jet stream similar to what has been observed in Type IV shock interactions. The shock standoff distance is seen to increase as the jet mass flow rate is increased, thus indicating a weaker shock strength, resulting much smaller jumps across the shock, and an attendant reduction in heat flux. However, for the observed reductions in heat flux, the process is different for the LPM and SPM jets, with the reduction from the SPM jet resulting, in part, from the cooling effects of the expanding jets. The trend in the heat flux data shows that the more the jet expanded, the lower the heat flux, up to some critical flow rate. The trend of the heat flux with flow rate is essentially the same for the two outer rows of heat flux gauges. The plot of the shock standoff distances is also given below. The broken section of the profiles represent the LPM jets for which the shock standoff distances can not be determined in the classical sense since the shocks are no longer discernable, at least in the context of the conventional definition.

For spacecraft and air vehicles in supersonic and hypersonic flows such as into entry and re-entry in planetary and Earth atmospheres, the observed flow interactions and flow structures could have many practical consequences with respect to mitigating the harsh aerothermal environments and aerodynamic performance. Plot of heat flux data shows the SPM interactions to very effective in reducing the aerothermal characterics of the Apollo model. In fact the data shows negative heat flux, indicating that the flow in the immediate vicinity of the heat shield was having a cooling effect instead of the shock induced heating that the model would have otherwise experienced. Such an effect could have a potential application in augmenting the traditional thermal protection systems (TPS) to significantly reduce the risk associate with the harsh aerothermal environment at entry and re-entry into planetary atmospheres, in addition to other potential aerodynamic benefits.

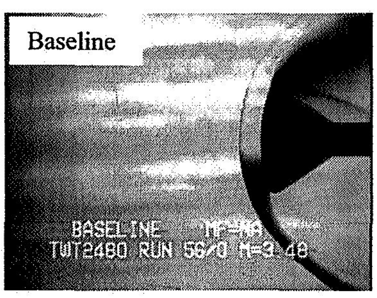
4) Statement of data used to substantiate conclusions, and free hand sketches of major figures to be used (no more than two pages).

The conclusions made above are based on the experimental results of supersonic flowfields with counterflowing jets. The complete set of data, including Schlieren videos and the potential benefits of the ccounterflowing jets as active flow control to mitigate the high risk of planetary atmospheric entry and re-entry, as well other potential benefits will be presented in the full paper.

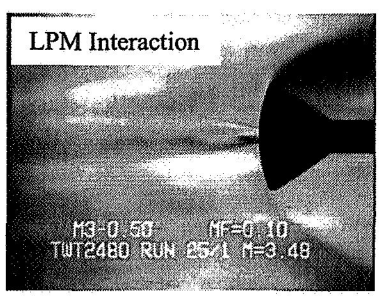




2.6% Scale Apollo Model
Showing Instrumentation



$M_\infty = 3.48$, $M_j = 2.94$, $M_{dot}=0.0$



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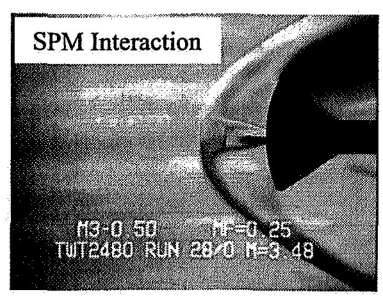

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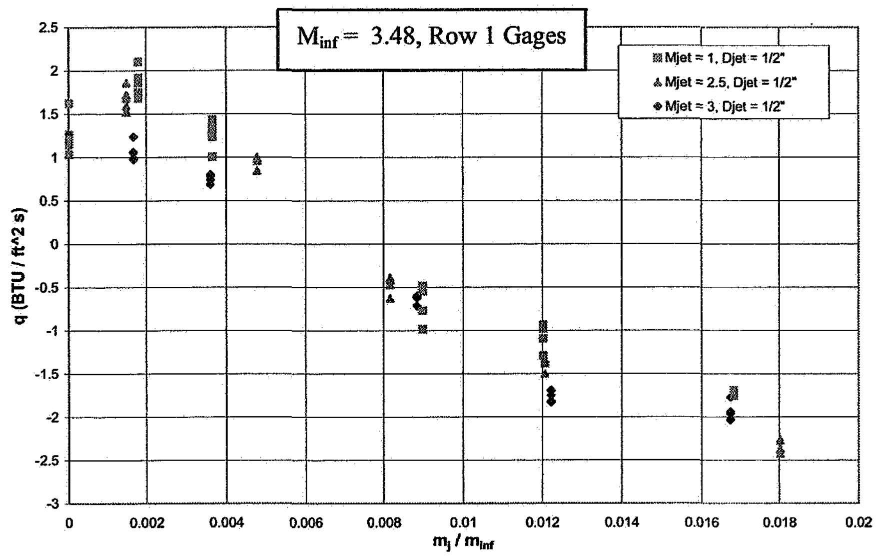

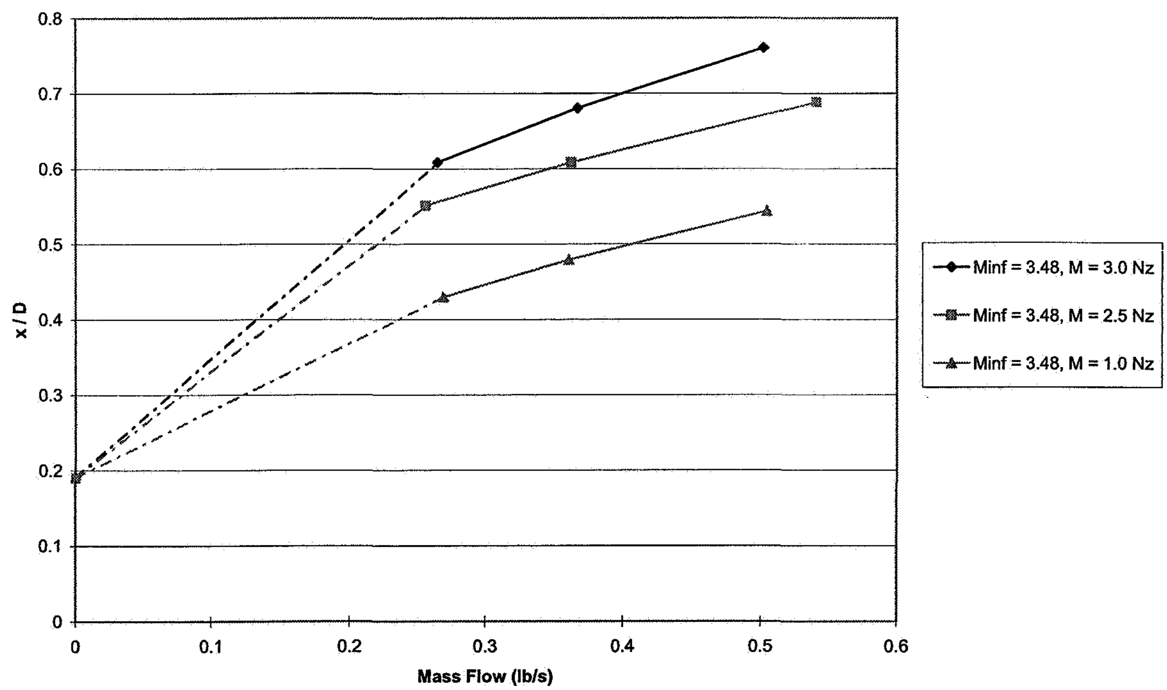

Shock Standoff Distance vs Mass Flow Rate Mach 3.48 Freestream and 0.5" Diameter Nozzles