Aerodynamic Stability of Blunted-Cone Entry Vehicles

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ABSTRACT

The heat shield of a spacecraft provides protection against the extreme temperatures that result from aerodynamic heating on atmospheric entry. Additionally, the heat shield serves as an important aerodynamic component of the craft, providing the necessary drag and stability at hypersonic speeds. The shape of the heat shield used varies considerably between spacecraft, and spherical and blunted-cone geometries are often employed.

The `blunted-cone' heat shield has been developed through experimental design and computational simulation. Previous work (presented at IPPW7) [1] showed that a generic heat shield shape can also be mathematically derived and gave the maximum stabilizing aerodynamic torque of all possible shapes. The derived shape displays minimum variation in torque due to minor shape changes (such as those caused by ablation), and depends only on the center-of-mass of the craft. The shape corresponds closely to the 'blunted-cone' design already commonly used in entry vehicles. This previous derivation was performed for both free molecular (FM) and continuum flows. Importantly, both regimes yield an identical shape.

In the present work we extend the FM model to allow for finite entry speeds, i.e., the thermal motion of the gas molecules is considered. This is found to modify the shape, but at high Mach numbers these effects cause very little change to the derived shape. Analytical and numerical results of these effects will be presented.

Importantly, the previous work [1] only considered the limiting cases of free molecular and continuum flows. It is thus important to investigate flows in the transition regime, which lie between these limits. To this end, Direct Simulation Monte Carlo (DSMC) [2] simulations have now been used to (i) verify the behaviour of the derived shape in the FM regime, (ii) investigate the transition region between the FM and continuum regimes, and (iii) examine the influence of thermochemical effects. Simulations have been performed for both two-dimensional (for reference) and three-dimensional geometries, both with and without the inclusion of thermo-chemical effects. Excellent agreement with the previous analytical predictions is obtained in the FM regime. The same shape is found for much of the transition regime. However, deviations are observed as the continuum regime is approached – possible causes of these effects will be discussed.

The design of practical heat shields involves numerous competing factors, which include the expected heat load and the craft volumetric efficiency, in addition to aerodynamic stability. We thus emphasize that the presented results focus on only one component of this multi-objective problem. The presented results and simulations provide further information on the validity of the derived shape in Ref. [1]. By accounting for effects that are not analytically tractable (using computational simulations), the shape that gives maximum static stability is derived. This is obtained as a function of entry velocity, gas rarefaction and thermochemical effects.

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[1] E. C. Button, C. R. Lilley, N. S. Mackenzie and J. E. Sader, "Blunted-cone heat shields of atmospheric entry vehicles", *AIAA Journal*, 47, 1784-1787 (2009).

[2] Graeme Bird, Molecular Gas Dynamics and the Direct Simulation of Gas Flows, Oxford Engineering Science Series, 1994.