Overheating Anomalies during Flight Test due to the Base Bleeding

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Abstract: In this paper we present the results of the analytical and numerical studies of the plume interaction with the base flow in the presence of base out-gassing. The physics-based analysis and CFD modeling of the base heating for single solid rocket motor performed in this research addressed the following questions: what are the key factors making base flow so different from that in the Shuttle [1]; why CFD analysis of this problem reveals small plume recirculation; what major factors influence base temperature; and why overheating was initiated at a given time in the flight. To answer these questions topological analysis of the base flow was performed and Korst theory was used to estimate relative contributions of radiation, plume recirculation, and chemically reactive out-gassing to the base heating. It was shown that base bleeding and small base volume are the key factors contributing to the overheating, while plume recirculation is effectively suppressed by asymmetric configuration of the flow formed earlier in the flight. These findings are further verified using CFD simulations that include multi-species gas environment both in the plume and in the base. Solid particles in the exhaust plume (Al_2O_3) and char particles in the base bleeding were also included into the simulations and their relative contributions into the base temperature rise were estimated. The results of simulations are in good agreement with the temperature and pressure in the base measured during the test.

Keywords: Base heating, base bleeding, plume recirculation.

1 Introduction

Recent test flight with single motor first stage design posed significant challenge in predicting base environment using both shuttle space flight database and CFD code. The post flight detached LES performed for this configuration revealed plume recirculation at the level substantially below one required for observed overheating. To gain further insight into root causes of the observed overheating and to facilitate the prediction of the thermal environment for the next generation of the heavy lift vehicle the following analysis was performed.

2 Problem Statement

A model of the vertically stacked rocket with single motor first stage was built in CFX and simulated for a number of time instants during the flight. The base flow sub-domain was next simulated with increased resolution. Mesh adaptation was used to resolve flow mixing in free share layers as shown in Fig. 1a. The k–ω based Shear-Stress-Transport (SST) model and BSL Reynolds stress model were used in simulations. The results of the simulations in the absence of the base bleeding and Al_2O_3 particles in the plume were in agreement with earlier detached LES performed for this geometry by one of the authors (FC) showing base temperatures corresponding to the aerodynamic heating and plume recirculation at the level of few percent. Further insight into the root causes of the observed phenomenon was provided using topological analysis of the base flow that demonstrated strong asymmetry of the flow, when the region of plume recirculation with the relatively high temperature is very small and pressed against the plume boundary preventing plume recirculation mixing with the main volume of the base. This configuration of the trapped based flow is formed earlier in the flight. Next, relative contributions of the radiation, plume recirculation, and base bleeding into the base heating were estimated using Korst theory [2], showing that base bleeding may be one of the key factors that determine base overheating observed in the test flight.

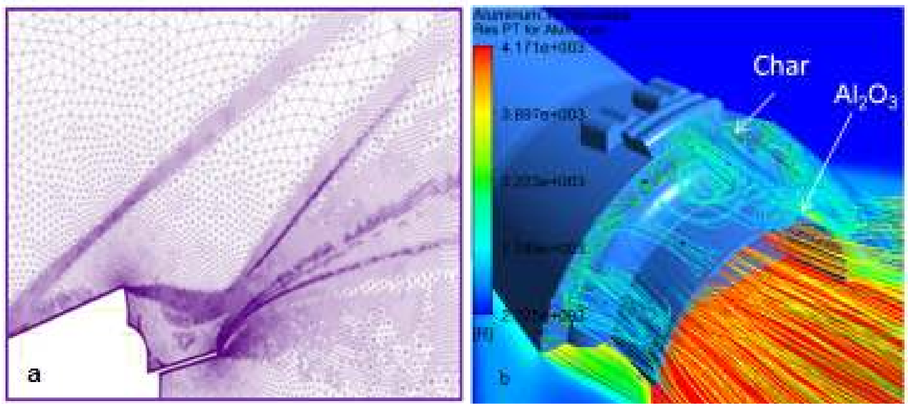

Figure 1: (a) Mesh Adaptation showing the location of mixing layers; (b) Char and Al_2O_3 particle trajectories are shown together with the contour plot of the temperature in the plane of symmetry.

To verify these findings a model of chemical kinetics of the pyrolysis of the TPS was developed [3] to determine chemical composition, temperature, and mass flow rate of the base bleeding. Parameters of the bleeding determined from the chemical kinetics analysis were next substituted into the CFD simulations. The results of the simulations of the base flow with base bleeding confirmed significant increase of the base temperature in agreement with the test flight data.

2 Conclusion and Future Work

Theoretical analysis and CFD simulations performed in this research revealed that the base heating anomalies observed in a recent test flight can be attributed to the following factors: small volume of the base flow in a single motor first stage configuration; significant base bleeding of hot chemically active components and char trapped in the base; and strong asymmetry of the base flow with relatively small region of plume recirculation. An additional important factor that influence the overheating measured during the flight is a strongly non-uniform distribution of the hot flow in the base, which is mainly concentrated along the base walls for both base bleeding and plume recirculation.

The methodology of the base flow analysis developed in this research is currently being transferred, extended, and adopted for base flow in nozzle clusters.

References

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