Calibration of ablation models for atmospheric entry thermal protection systems

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Venturing into Space requires large amounts of energy to reach orbital and interplanetary velocities. All this amount of energy is dissipated when space vehicles enter dense planetary atmospheres. The bulk of this energy is exchanged during the entry phase by converting the kinetic energy of the vehicle into thermal energy in the surrounding atmosphere, generating a heated plasma several times hotter than the surface of our Sun. Aerospace engineers rely either on catalytic or ablative materials to protect the spacecraft from the intense heat.

The characterization of ablation phenomena plays an important role in the development of theoretical models that can predict material degradation and recession of Thermal Protection Systems (TPS), both important aspects in the design of such aerospace systems. Experiments and models are often used to understand the physics of ablation and improve our predictive capabilities. On the experimental side, the stochastic nature of the data must be accurately described and modeled to produce reliable experimental data on which to base our analyses. On the modeling side, many different sources of uncertainties in the form of model parameters can affect the predictions considerably. Objectively characterizing and quantifying such uncertainties is important to make comparisons to experimentally observed quantities useful, providing a more consistent/quantifiable way of defining new research directions rather than informed guesses.

Overall, the process of inferring ablation parameters from experimental data poses many questions concerning our experimental capabilities as well as the assumptions in our models. In particular, the carbon nitridation reaction $\mathrm{C_s} + \mathrm{N} \rightarrow \mathrm{CN} + 0.34\mathrm{eV}$ on a solid (s) carbon surface is still hard to predict accurately at temperatures above 1000 K. The models found in the aerothermodynamics literature are derived empirically by fitting experimental data [2, 4, 7, 9, 5] which span several orders of magnitude and show great scatter. In many cases, not all aspects of the experimental facilities are completely understood. This issue adds important uncertainties to the inference process both in terms of experimental data and relevant physical processes considered to play a role under different experimental conditions. In this regard, severe lack of knowledge greatly affects our abilities to build predictive models.

Over the years, we have been continuously improving our tools and theoretical background on rigorous uncertainty quantification methods to tackle such challenging problem. In this work, we survey the evolution of our ablation research through three main developments: First, we show how we introduce parametric and experimental uncertainties in the calibration of a carbon nitridation model from plasma wind tunnel data [1]. Second, we incorporate model-form uncertainties by entertaining several different models that pertain to the gas and the gas-surface interface and assess their comparison with the experimental data in a stochastic framework [8]. Lastly, we discuss our recent development in merging the experimental data from molecular beam [3] and plasma wind tunnel to obtain a more comprehensive and detailed picture of nitridation reactions [6] while fully characterizing uncertainties in both cases.

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