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# Thermochemical ablation modeling forward uncertainty analysis—Part II: Application to plasma wind-tunnel testing

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ABSTRACT

The coordination between modeling, simulations, and experiments is critical for the design of the thermal protections of space vehicles. This paper illustrates a proof-of-concept of the coupling between a thermo-chemical ablation model and modern uncertainty quantification techniques with the aim of rebuilding the ablative material tests performed in the inductively coupled Plasmatron facility at the von Karman Institute. In Part I of this two-part work we presented the thermo-chemical ablation model and studied the effect of its uncertain parameters on the simulation outcomes. The present analysis is devoted to understand the effects of the uncertain estimates of the plasma wind-tunnel test conditions on the final results of the ablation model. A two-step uncertainty analysis is performed: the impact of the experimental uncertainties on the plasma flow rebuilding is first analyzed; then, the obtained mean, variance and distribution of the free-stream conditions are used as input, together with the model uncertain parameters, for the uncertainty analysis of the ablation model. Our results show that the experimental uncertainties have a substantial impact on the ablation model output when surface nitridation is not considered among the surface reactions.

## 1. Introduction

Numerical simulations are widely used in modern engineering to reduce time, costs and error margins during the design phase of a complex system. The so-called validation process is what lies between the implementation of a numerical model and its effective use. This process, which is an essential practice in numerical modeling, pairs with the verification process in the effort that is made to assess the reliability of the obtained numerical results. Indeed, once the correct implementation of a model has been verified, it is fundamental to perform the validation step with the goal of answering the question: Are we solving the right equations to catch the relevant physics of the investigated phenomena? Experimental tests have multiple roles in this process: i) they define the test case to be numerically analyzed, also providing the input data set for the simulation; ii) they provide the experimental results to be compared with the numerical model output.

When dealing with thermal protection systems (TPSs) for atmospheric entry vehicles, ground testing in inductively coupled plasma (ICP) torches represent the best option to study the material response in a flight-relevant environment. In particular, this kind of test allows to accurately analyze complex gas-surface interactions, such as catalysis and ablation. The von Karman Institute (VKI) Plasmatron facility uses a state-of-the-art ICP torch [1]. Several experimental campaigns took place at the VKI over the past years to advance the fundamental knowledge of ablation phenomena; ablation tests of several materials, from pure graphite to newer low-density pyrolyzing materials, have been carried out in air/nitrogen plasmas in the Plasmatron [2–6]. The fully instrumented Plasmatron test chamber allows the monitoring of the free-stream conditions during the tests, as well as the measurements of interesting quantities such as sample recession rate, surface temperature, and spectrally resolved boundary layer emission. These features make the data collected from the ablation experiments rather unique, generating a wide data set for ablation models validation and updating. However, despite the overall fine tunability of the Plasmatron, the rebuilding of the actual plasma flow conditions is still a quite involved numerical process in which both measurement and modeling uncertainties might play an

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**Nomenclature**

| | |
|---|---|
| $\dot{m}_e$ | boundary-layer edge mass flux, kg/(m$^2$s) |
| $\dot{m}_e$ | surface mass blowing flux, kg/(m$^2$s) |
| $\dot{q}$ | heat flux, W/m$^2$ |
| $p$ | pressure, Pa |
| $T$ | temperature, K |
| *Greek symbols* | |
| $\beta$ | velocity gradient, s$^{-1}$ |
| $\varepsilon$ | coefficient of variation |
| $\gamma$ | reaction probability |
| $\varepsilon$ | integral emissivity |
| *Subscripts* | |
| cw | cold wall |
| c | test chamber |
| d | dynamic |
| e | boundary-layer edge |
| s | solid phase |
| w | gas-surface interface |
| $r$ | $r^{th}$ reaction |
| *Superscripts* | |
| Cu | copper |
| exp | experimental quantity |
| num | numerical quantity |
| $N_r$ | number of surface reactions |

important role. If data obtained from Plasmatron experiment are considered to be used for the validation of numerical tools, it is important to understand how the uncertainties on the rebuilding of these conditions affect the whole process.

An uncertainty quantification (UQ) analysis on a CFD ablation model was presented in Part I of this two-part work. The influence of the model uncertain parameter on the final outcomes of the model was studied in this first analysis. The investigation considered a non-pyrolyzing carbon-based TPS material exposed to a subsonic high-enthalpy flow, and we focused on the forward stagnation-point ablation of a spherical sample. A CFD stagnation-line code featuring an ablative boundary condition served as the deterministic simulation tool to study the flow and the gas-surface interaction. For that analysis, flow conditions representative of those of the ablation experiments performed in the VKI Plasmatron were selected. However, these inlet conditions for the ablative CFD simulations were considered as unequivocally defined in the study. In this second part of the work we want to reanalyze the same test case and perform an new ablation-model UQ analysis including also uncertainties on the inlet conditions (see Fig. 1). These additional uncertainties come from uncertain experimental (plasma flow) measurements through the flow rebuilding procedure. Then, the *two-step approach* in Fig. 1 has been thought of to evaluate their effect on the final predictions.

With this complementary analysis we would like to draw the reader's attention to the following questions: Do the experimental uncertainties significantly affect the ablation model outcomes? Is a better characterization of the test environment required before we can use the experimental data for numerical code validations? Being the answers to these questions sought through a modern UQ approach, the paper thus constitutes a proof-of-concept of an advanced numerical platform, which can be applied to future Plasmatron experimental data.

The article is arranged as follows. Section 2 recalls briefly the uncertainty analysis tools, thoroughly described in Part I of this work. Section 3 presents the VKI Plasmatron and gives a description of a typical experimental setup used for the test condition measurements. Section 4 presents the experimental-numerical procedure in use at the VKI for the determination of the free-stream conditions. In addition this section lists and quantifies the uncertainties present in this procedure. The two-step UQ analysis is then performed in section 5. First, the UQ analysis on the rebuilt test conditions is performed, providing the distributions of the stochastic free-stream inlet conditions to be used in the stagnation-line ablative analysis; then, the ablation model UQ analysis is carried out. Finally, section 6 discusses the results and draws the conclusions.

## 2. Recall on uncertainty analysis tools

Uncertainty Quantification techniques aim to efficiently characterize the variability of quantities of interest (QoIs) with respect to the uncertainties of the system. Consider a given quantity of interest $\phi(\xi)$ varying with respect to the system uncertainties $\xi$ (characterized by their probability density functions), then the main issues one faces are the computation of the statistical moment of $\phi(\xi)$ and the fulfillment of the so-called sensitivity analysis to identify a hierarchy in the influence of the different uncertainties. Several classes of methods exist to address this problem. In this paper, as done in its first-part companion, we will refer in particular to non-intrusive methods. This means that the variability of $\phi(\xi)$ with respect to $\xi$ is estimated by sampling $\phi$ with different specific values of the uncertain conditions $\xi$, and that all these computations are then post-processed to estimate the statistical moments.

Two different non-intrusive techniques, already presented in Part I of the work, are used here to propagate the physical uncertainties through the system under consideration. A

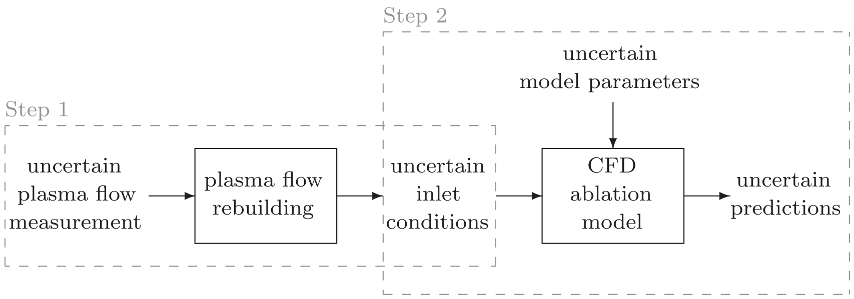

**Fig. 1.** Sketch of the two-step procedure applied. The test free-stream conditions (uncertain inlet conditions for CFD) link the two steps.

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