Study of Effect of Equilibrium and Finite-Rate Gas-Surface Interactions on Ablation of Graphite Material in Fully-Coupled Simulation between CHAMPS and KATS Solvers

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I. Extended Abstract

In this study, we develop a tight integration between a Near-Body Solver (NBS) in the framework of Cartesian Higher-order Adaptive Multi-Physics Solver (CHAMPS-NBS) [1] and a material response (MR) solver in the framework of Kentucky Aerothermodynamics and Thermal Response System (KATS-MR) [2]. The coupled interaction between the flow and material solvers is applied to explore ablation of graphite material under hypersonic conditions. Specifically, the focus of the study is made on exploring effects of different ablation modeling approaches on prediction of the material thermal response and surface recession.

Traditional material heating and ablation modeling approaches in uncoupled simulations, rely on engineering correlations to apply boundary conditions and account for attenuation of the incident heat flux due to increasing surface temperature and blowing of ablation products [3]. Equation (1) shows the correlation used to apply aerodynamic heat flux to the surface

$$\dot{q}''_{\text{aero}} = C_{H_0}\Omega_{\text{blw}}\left(h_r - h_w\right), \tag{1}$$

where C_{H_0} is the film coefficient computed in the flow simulation, h_r is the recovery enthalpy at the boundary layer edge, h_w is the gas enthalpy at the wall conditions and Ω_{blw} is the blowing correction, responsible for attenuation of the incident heat flux due to blowing of ablation products. Gas-surface chemical interactions in the traditional approaches are modeled assuming equilibrium chemistry and apply the so-called "bprime" ablation approach [4]. The "bprime approach assumes that the flow field around the material surface can be accurately modeled as a Couette flow, using a mass transfer analogy with Prandtl and Lewis numbers equal unity. In this approach, equal mass and heat transfer coefficients, $C_M = \rho_e u_e St_M = C_H = \rho_e u_e St_H$ are applied to evaluate ablation mass flux at the surface, given by the following correlation:

$$\dot{m}''_c = B'_c C_M \Omega_{\text{blw}}, \tag{2}$$

where B'_c is the non-dimensional ablation mass flux evaluated with assumption of chemical equilibrium in the boundary layer. Clearly, the assumptions of the engineering correlations, used in the uncoupled ablation simulation, do not take into account the shape change of the material as a result of surface recession, that would affect magnitude and distribution of the applied heat flux and pressure boundary conditions [5]. In addition, equilibrium chemistry assumption, as well as equal mass and heat transfer coefficients in modeling the ablation physics do not take into account the non-equilibrium effects and diffusion properties of the near-body gases and ablation products. The first part of this study aims at utilizing the coupled interaction between the flow and material physics to explore the effect of time and spatially varying boundary conditions on the material thermal response and surface ablation. In addition, assumption of the equal mass and heat transfer coefficients will be explored by explicit evaluation of the mass transfer coefficient from the near wall mass diffusion fluxes and applying it to compute the surface ablation.

Assumption of the equilibrium chemistry to compute the ablation rate of carbon material typically results in the deviation of surface recession from the experimental data. At low pressures and high heat fluxes, surface recession tends to be underpredicted with the equilibrium models, while at the low heat flux and higher pressures and opposite trend occurs and actual experimental recession turns to be lower than the predicted one [6]. In this study, we aim at

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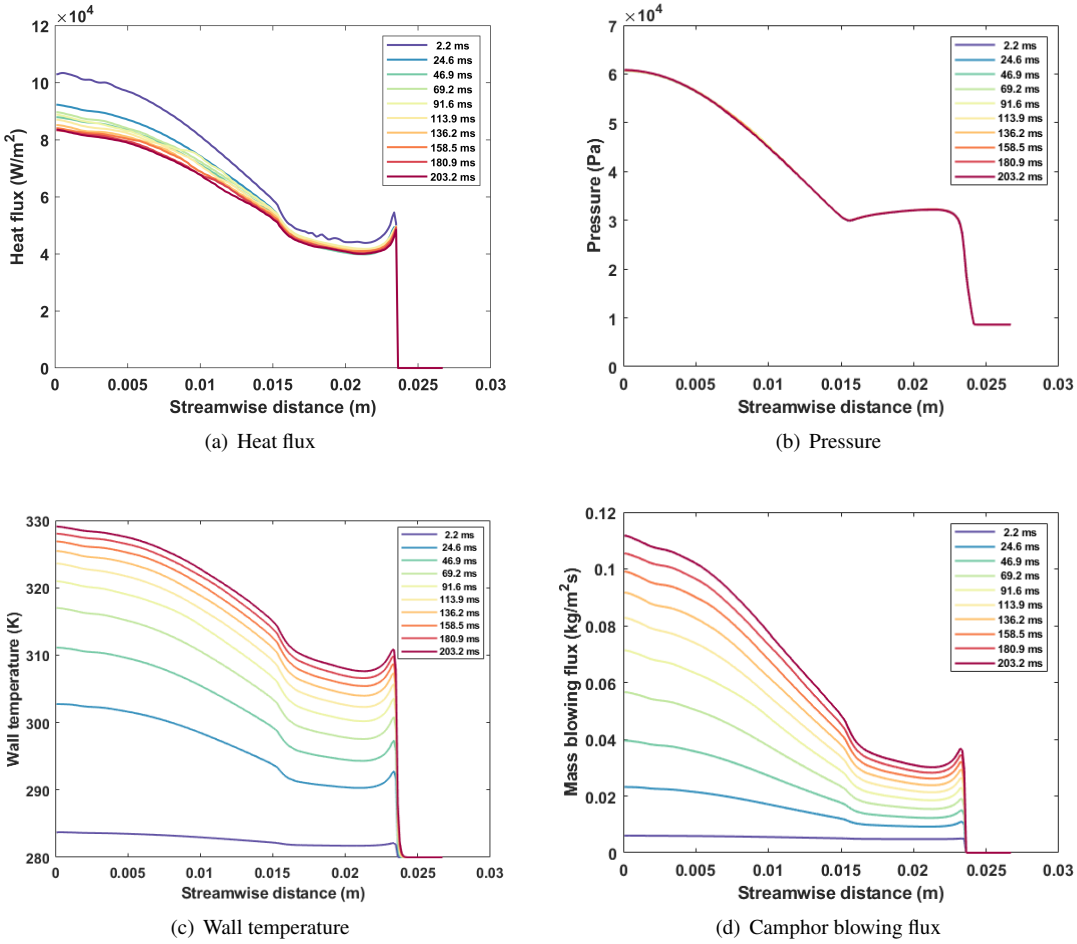
applying state of the art finite-rate gas-surface chemistry models [7, 8] for carbon oxidation and sublimation to study ablation of graphite material. The obtained results will be compared to the experimental data and numerical results presented by Chen et al. [9] and Bianchi et al. [10].

The current work relies on the previous study where CHAMPS-NBS was tightly coupled to a one-dimensional material response solver with surface ablation to simulate sublimation of Camphor material in hypersonic flow [11]. In addition, the material response solver KATS-MR has recently been benefited from a three-dimensional mesh deformation scheme and was verified against ablation workshop results Zibitsker et al. [2]. In the current state of the art of the coupling work, CHAMPS and KATS solvers were already coupled to a level where a two-dimensional material with surface chemistry can be simulated without recession of the wall. Namely, the material interacts with the flow solution as a conjugate heat transfer problem and in addition, solves surface balance and chemistry equations to compute the ablation blowing fluxes and pass back to the flow solver the updated surface blowing and pressure. Figure 1 shows the preliminary simulation results of CHAMPS-KATS coupled simulation of Camphor sublimation at Mach 6 flow. In this test case, Phoebus capsule geometry is covered by a 2.5 mm thick layer of Camphor above a copper sub-structure. The original conditions and geometry of the simulation are provided in [12].



(a) Heat flux

(b) Pressure

(c) Wall temperature

(d) Camphor blowing flux

Fig. 1 Preliminary results from coupled CHAMPS-KATS simulation of Camphor sublimation, with conditions taken from [12]

To summarize, in this study we develop a fully-coupled simulation between CHAMPS and KATS solvers and aim at exploring ablation of graphite material at hypersonic flow conditions, based on the experiment of Chen et al. [9]. Specifically, we aim at exploring various assumptions of the engineering correlations used to model material ablation in uncoupled regime. In addition, we plan to compare the equilibrium ablation chemistry of graphite material to the state of the art finite-rate oxidation and sublimation models.

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