ATOMIC OXYGEN INTERACTIONS WITH CARBON AT HIGH TEMPERATURES
RELEVANT TO ATMOSPHERIC ENTRY

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ABSTRACT

One of the major challenges associated with hypersonic flight is thermal protection system (TPS) design. Many hypersonic missions, such as those involving atmospheric entry, involve surface heat fluxes that are too extreme for reusable materials and require ablative TPSs (more colloquially called “heat shields”). Hypersonic flight through an atmosphere generates a thin, high-temperature, shock layer near the surface of a TPS. Within this shock layer, the gas is in a state of strong thermochemical non-equilibrium. The internal energy of the gas (rotational and vibrational) quickly increases and ultimately leads to dissociation of molecular species into atomic species. The hot boundary layer gas heats the TPS surface to temperatures that exceed 2000 K. In addition, as depicted in Fig. 1, the reactive atomic species (O and N) may react with the hot TPS surface. Reaction products are transported back into the flow, which in turn affects the chemical state of the boundary layer.

Hypersonic gas conditions of interest can vary widely depending on the flight altitude and velocity, as well as the geometry of leading edges and their location on the overall vehicle. Experimental measurements of the gas-surface and gas-phase chemistry relevant to the shock layer are incredibly difficult and expensive to perform, and ground-based experiments simply cannot reproduce such a wide range of flight conditions. Therefore, accurate and predictive models are required for use in computational fluid dynamics (CFD) simulations.

A detailed understanding of the mechanisms by which surface reactions proceed at temperatures relevant to hypersonic flight would enable more accurate modeling of the heat flux to and mass loss from the surface and allow for more efficient TPS design. The most important reactive species in the boundary layer is atomic oxygen, and most TPS materials are made from carbon or become carbon char when they are heated to high temperatures. Therefore, the key objectives of the research reported here are (1) to generate high-quality experimental data on the relevant O-atom reactions with carbon and (2) to incorporate the new data into an oxygen-carbon ablation model.

Interactions of ground-state atomic oxygen, O(3P), with three model forms of sp² carbon, highly oriented pyrolytic carbon (HOPG), vitreous (glassy) carbon, and a carbon fiber network (FiberForm), were investigated with a broad range of surface temperatures from 600 K to approximately 2200 K. Beams of 5 eV O atoms were directed at surfaces, and angular and translational energy distributions were obtained for inelastically and reactively scattered products using a rotatable mass spectrometer detector. The data suggest that the basic reaction mechanisms are the same on all forms of sp² carbon but that the morphology of the surface strongly affects the relative probability of the various reactive processes. The general gas-surface interactions and their temperature dependence are illustrated pictorially in Fig. 2. O-atom reactivity with an sp² carbon surface decreases at extreme temperatures. O atoms mostly stick and/or react at lower surface temperatures, while they tend to desorb promptly at high surface temperatures. The reduction in oxygen surface coverage reduces the reaction probability to form CO and CO₂. These species are produced mainly through thermal (Langmuir-Hinshelwood) reactions. Improbable Eley-Rideal reactions produce CO. Thus, the key reactions that remove carbon from the surface occur in thermal equilibrium with the surface regardless of the kinetic energy of the incident O atoms, suggesting that the incident beam may be treated simply as a supply of O atoms on the surface. The molecular-level scattering dynamics from the experiments have been incorporated into a new carbon ablation model.

Figure 1. Four coupled flow regimes in hypersonic ablation.

Figure 2. Pictorial representation of atomic oxygen interactions with sp² carbon at high temperatures.