FINITE RATE HEAT-TRANSFER EFFECTS ON MULTIPHASE BURNING IN CONFINED POROUS PROPELLANTS

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Combustion in porous solid propellants is often affected by an increasing pressure difference (overpressure) between the burned-gas region and the gas deep within the pores of the material. In particular, this growing overpressure eventually causes a transition from "conductive" to "convective" burning. As a result of such a transition, the deflagration wave becomes significantly affected by the convective influences of the gaseous phase relative to condensed material. A number of different effects associated with two-phase flow in porous energetic materials have been studied in several theoretical investigations in which the rate of heat exchange between coexisting phases was considered to be infinitely large. Consequently, the temperatures of these phases are equal in this limit, resulting in a single-temperature model (*cf.* [1]–[4]). However, increasing convective-gas velocities in the two-phase regions reduce the degree of thermal equilibration between the coexisting phases. As a result, the one-temperature approximation becomes less accurate, and finite heat-transfer effects begin to play an increasingly important role. It has been shown in previous studies that the first effects of temperature nonequilibrium are felt in the multiphase reaction region, with the preheat zone remaining in thermal equilibrium to leading order(*cf.* [5]–[6]). Inclusion of two-temperature effects considerably complicates the analysis of the problem in the chemical boundary layer and, as the rate of interphase heat transfer decreases, temperature nonequilibrium spreads into the preheat region, thus requiring a separate analysis. In the present work we investigate analytically and numerically the finite heat-transfer effects for the regime in which the temperature nonequilibrium is confined to the reaction zone, for varying levels of a scaled interphase heat-transfer parameter. In particular, we are able to determine the upper limit of resistance to heat transfer, beyond which significant interphase temperature differences occur in the preheat region.

A physical description of the problem is shown in Fig. 1. The unburned porous solid lies to the left, while the burned-gas region lies to the right. These regions are separated by the reaction zone, which moves from right to left. This chemical boundary layer is characterized by temperature differences between the condensed and gaseous phases. In particular, the combustion process is modeled by a single-step exothermic reaction taking place in the condensed
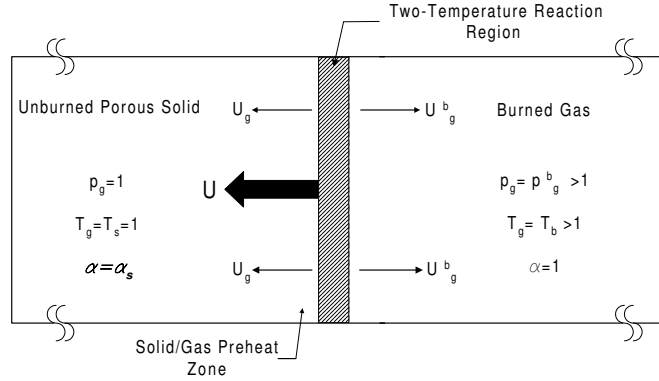
Figure 1: Physical illustration of the problem. Several variables change across the reaction zone; namely, the gas pressure p_g, gas and condensed temperatures T_g and T_s, and gas-phase volume fraction α.

phase, which converts condensed reactants into gaseous products. We employ activation-energy asymptotics to address separate problems outside and inside the reaction region. A combination of analytical and numerical approaches to the resulting reaction-zone problem is employed to obtain solutions in the chemical boundary layer for a wide range of parameters. Physically, a slower rate of temperature equilibration causes the thermal energy to accumulate in the reacting condensed phase. As a result, the local condensed-phase temperature inside the reaction zone may develop a local maximum that is higher than the final burned temperature. The burning-rate eigenvalue decreases with lower values of the scaled interphase heat transfer coefficient, as illustrated in Fig. 2, corresponding to a faster burning rate.

Increasing burned-gas pressure is shown to result in a higher buring rate, increasing temperature-nonequilibrium effects and, ultimately, a transition from conductive to convective burning. This transition has been observed even in the limit of temperature equilibrium; however, it is significantly sharpened when finite heat-transfer effects are taken into account. This is explicitly illustrated in Fig. 3, where the dimensional burning rate is plotted as a function of the burned-gas pressure. Since a steeper transition appears to be more consistent with available experimental data (*cf.* [7]), we conclude that inclusion of temperature-nonequilibrium effects is important in modeling and analyzing the transiton from conductive to convective burning.
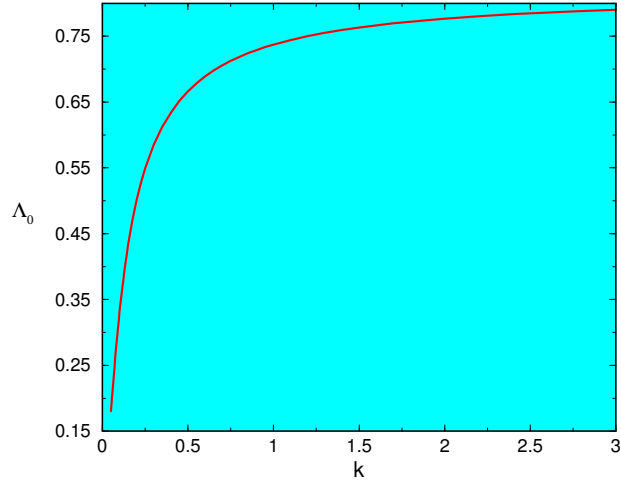
Figure 2: Numerical calculation of the leading-order burning-rate eigenvalue Λ_0 as a function of the scaled interphase heat-transfer coefficient k.
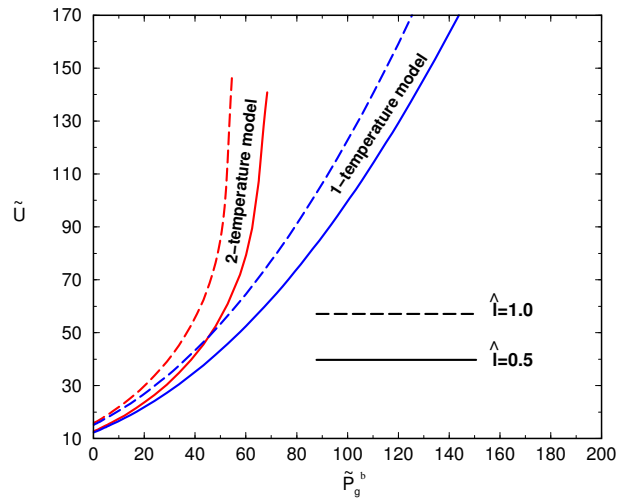

Figure 3: Dimensional burning rate $\tilde{U}$ plotted against the burned-gas pressure $\tilde{P}_g^b$ for two different values of the gas-to-condensed thermal conductivity ratio $\hat{l}$. Transition to the convective burning regime is noticeably sharper for the two-temperature model.

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