Numerical Computation of Flame Spread over a Thin Solid in Forced Concurrent Flow with Gas-Phase Radiation

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I. Introduction

Concurrent-flow flame spread over a thin solid in purely forced flow with gas-phase radiation is examined numerically. The computational model solves the two-dimensional, elliptic, steady and laminar conservation equations for mass, momentum, energy, and chemical species (oxygen, fuel, carbon dioxide, and water vapor). Gas-phase combustion is modeled via a one-step, second order finite rate Arrhenius reaction. Gas-phase radiation considering gray non-scattering medium (CO$_2$ and H$_2$O) is solved by S-N discrete ordinates method. A simplified solid phase treatment assumes a zeroth order pyrolysis relation and includes radiative interaction between the surface and the gas phase.

The formulation in this work is similar to that in [1] except that we have included gas-phase radiation. It has been shown that in low-speed flows [2, 3] that gas-phase radiation is amplified and can become important in the flame energy balance. The solution procedure is also different from that in [1] in that the entire flame domain is solved using elliptic equations rather than the mixing elliptic-parabolic approach used in [1].

The flame configuration is shown schematically in Fig. 1. The coordinates are fixed with respect to the fuel burnout point ($x = y = 0$) and steady state solutions are sought. The equation of transfer for radiation is solved by S-N discrete ordinates method [4, 5, 6]. An evaluation has been made which reveals that one-dimensional $S_2$ scheme (2 ordinates) and two-dimensional $S_2$ scheme (4 ordinates) give poor accuracy for the radiative flux, but the difference between two-dimensional $S_4$ scheme (12 ordinates) and two-dimensional $S_6$ and $S_8$ schemes (24 ordinates and 40 ordinates, respectively) is small. Consequently, the two-dimensional $S_4$ scheme is chosen to simulate gas-phase radiation based on the balanced consideration of numerical accuracy and computational cost.

II. Results and Discussion

In this section, we will present selected results of a purely forced, concurrent-flow spreading flame with gas-phase radiation at 15% O$_2$, $U_r = 6$ cm/sec. The properties chosen are the same as those in Ref. 1. Comparison with the results neglecting gas radiation will also be made.

Fig. 2 shows nondimensional radiation heat flux vectors (nondimensionalized by $\sigma T^4_{inc}$). It reveals the multidimensional characteristics of radiation. The net radiation heat flux vectors all point outward, meaning heat is lost from solid fuel and flame zone to ambient. Fig. 3 shows contours of nondimensional $\nabla \cdot q_r$ term in the energy equation (nondimensionalized by $\sigma T^4_{inc}/\delta$, where $\delta$ is thermal diffusion length).
diffusion length). Because the flame is optically thin, little absorption takes place and the $\nabla \cdot q_r$ term is positive which implies local heat loss.

In the rest of this paper, we will compare the flame structures of corresponding cases with and without gas radiation. Fig. 4 shows nondimensional temperature contours (nondimensionalized by $T_r$). Fig. 5 shows fuel reactivity contours. Comparing the cases in Fig. 4 and Fig. 5, we see that the flame temperature decreases and flame size shrinks when gas radiation is included. A similar finding was reported in opposed-flow flame spreading [2, 7]. Fig. 6 gives the solid fuel surface heat fluxes from conduction (convection) and radiation and the summation of the two. It shows that conduction heat flux is lowered when gas radiation is included since flame temperature decreases. The net radiation flux is negative indicating heat loss from solid surface. However, the loss in gas radiation case is less than that when gas radiation is neglected. This is because with part of the gas radiation is absorbed by solid fuel. The competition of the conductive heat gain and the radiative heat loss results in approximately equal net heat flux to the solid fuel for the two cases. As a result, the flame spread rates are almost equal (0.38 cm/sec with gas radiation vs. 0.42 cm/sec without gas radiation), despite the large difference of gas phase flame structure. It should also be pointed out that because of the flame temperature decrease, the computed condition (15% $O_2$, 6 cm/s) is a near-limit flame (5 cm/s is not flammable) when gas radiation is included. The same condition is well within the flammable domain when gas radiation is ignored [1].

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References