Model Applications to Solid-Fuel Ramjet Combustion

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Nomenclature

A_i = cross-sectional area of circular air inlet
A_p = cross-sectional area of circular fuel port
D, D_p = diameter of circular fuel port
G_{air} = mass flow rate of air per unit area through fuel port
L = axial length along fuel grain
L_p = length of fuel grain
P_c = combustion pressure
r = radial coordinate
R = radius of fuel port
T = temperature
T_{air} = inlet air temperature
T_{max} = maximum temperature in radial direction at a specified axial distance

Abstract

A PREVIOUSLY developed model for solid-fuel ramjet combustion with negligible radiation was applied to the combustion behavior of all-hydrocarbon fuels which exhibit significant gas-phase radiation. Theoretical predictions were compared to temperature field data taken by other investigators.

Contents

Details of the adaptation of the Spalding et al.[1,2] PISTEP II program to the solid-fuel ramjet combustor have been previously presented.[3] Comparisons with experiment (nonreacting flows and reacting flows with minimum gas-phase radiation effects) have been made for axial and radial variations in flame pattern, fuel regression rate, pressure and turbulence intensity, and the flow reattachment position. Temperature field data were not available for fuels which produced minimum radiation effects.

Earlier work with the model[4] had considered simple, finite rate kinetics, but the current work considered only mixing limited combustion. In addition, only convective heat transfer to the fuel surface has been treated. Incorporation of meaningful finite rate kinetics and radiation into the model greatly complicates the numerical calculations. However, the fuels proposed for use in solid-fuel ramjets often exhibit significant gas-phase radiation, and unburned carbon may exist due to incomplete combustion. The simple model currently developed may be able to provide limited, but meaningful, design information for the more complex fuel systems. In addition, the only solid-fuel ramjet combustion temperature field data[5] available for model validation were obtained for fuels which exhibit significant gas-phase radiation.

Schadow[5] has made measurements of temperature and species concentrations in a reacting solid-fuel ramjet. His experiments utilized an all-hydrocarbon fuel which results in significant radiative heat transfer to the fuel surface and higher fuel regression rates. Regression rate predictions using only convective heat transfer are too low for the radiative system. Therefore, the predicted regression rates along the length of the fuel grain from the model were arbitrarily increased by 30%. This cannot be expected to yield the correct axial variations in regression rate, but was done to obtain a more realistic value of the blowing parameter for the higher regression rate system.

Figures 1-3 present the theoretical temperature profiles compared to the data of Schadow[5] for different air mass fluxes and axial locations within the fuel grain. The theoretical temperature profiles are not for exactly the same L/D locations as the experimental data. The profiles at the nearest corresponding grid line have been presented.

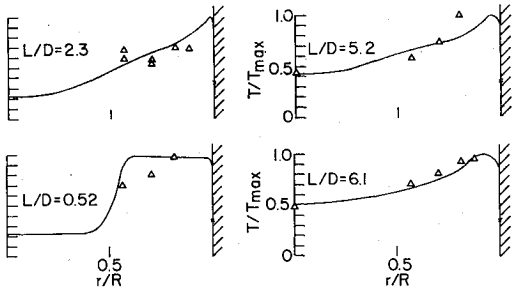

Fig. 1 Comparison of theory with temperature data of Schadow: G_{air} = 34.5 g/cm^2-s (0.49 lb$_m$/in.^{2}-s), P_c = 8.47 atm, D_p = 7.11 cm, L_p = 50.8 cm, T_{air} = 605 K, A_p/A_i = 2.74.

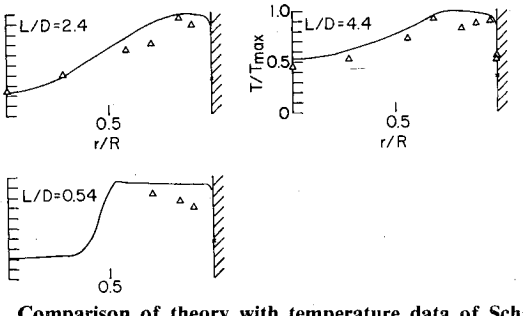

Fig. 2 Comparison of theory with temperature data of Schadow: G_{air} = 16.2 g/cm^2-s (0.23 lb$_m$/in.^{2}-s), P_c = 6.73 atm, D_p = 7.11 cm, L_p = 35.6 cm, T_{air} = 590 K, A_p/A_i = 3.55.

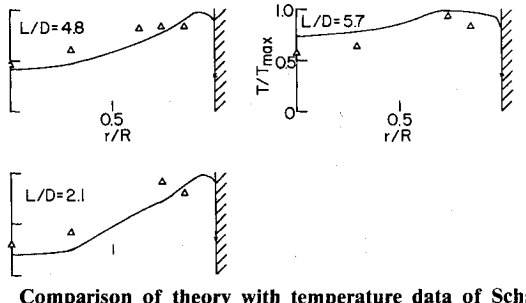

Fig. 3 Comparison of theory with temperature data of Schadow: G_{air} = 13.4 g/cm^2-s (0.19 lb$_m$/in.^{2}-s), P_c = 6.8 atm, D_p = 7.11 cm, L_p = 50.8 cm, T_{air} = 550 K, A_p/A_i = 3.20.

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Figure 1 presents data for the high mass flux condition. The model predicts more complete mixing and, therefore, more uniform temperatures in the recirculation zone ($L/D=0.52$) than the data. In the region near reattachment ($L/D=2.3$), the experimental data indicate an apparent "two-flame" zone. It is possible that just upstream of reattachment, one flame may exist very close to the wall and another could result, farther from the wall, from the recirculating, reacting shear layer. However, the data of Schadow have not been corrected for radiation effects and an L/D of approximately 2.0 should be the most downstream location of reattachment for the inlet step height employed. If this "two-flame" region is characteristic of the flow near reattachment, then the model fails to predict this detail. There could be several reasons for this possible weakness in the model. Radiation is neglected in a system which produces large amounts of radiation. In addition, the turbulence model and/or the boundary conditions specified on the fuel surface for shear stress could result in a "smearing-out" of the species distributions in the radial direction near the wall where large property gradients exist. Downstream of reattachment, where the boundary layer develops ($L/D=5.2$, 6.1), the profiles are in better agreement with experiment. The centerline temperature increase with axial distance is reasonably predicted.

Similar results for lower air fluxes can be observed in Figs. 2 and 3. The model, without radiation-convection coupling to determine the fuel regression rate, predicted a stronger dependence of regression rate on air flux than obtained experimentally. This will also affect the predicted temperature profiles. The model does correctly predict the increasing boundary-layer thickness with resulting peak temperatures farther from the wall and higher centerline temperatures as the air flux is decreased. The regression rate variation with axial distance is different for the all-hydrocarbon system than for the convection-dominated polymethlymethacrylate (PMM) fuel system. The model does a reasonable job of predicting this profile for PMM.[3] For both fuels, the regression rate increases from the head-end to near the reattachment zone and then decreases. Farther downstream the PMM regression rates (and the model predictions) continue to decrease and/or level off, whereas the all-hydrocarbon regression rates begin to increase again.

The model assumed mixing limited and complete combustion so that "products" consisted only of H_2O and CO_2. This is obviously an oversimplification, but perhaps warranted when compared to the other simplifications employed in the model. Schadow[5] has measured with a probe the radial variation in moles of free O_2 per mole of N_2 at the exit plane of the fuel grain. A comparison of his data with the model is presented in Fig. 4. Schadow[5] found that in order to

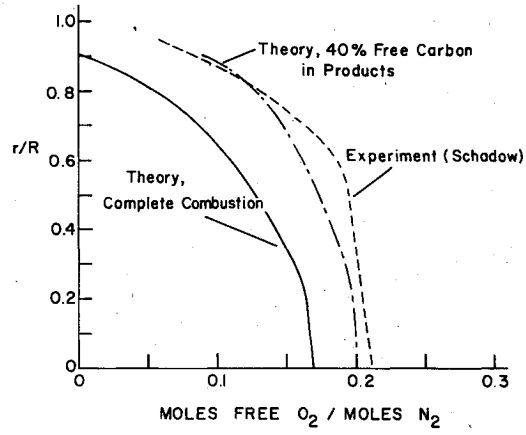

Fig. 4 Comparison of theory with concentration data of Schadow.

predict the correct variation in combustion temperature with mixture ratio in the fuel port, 40% of the carbon present had to be assumed as unreactive soot particles. As a qualitative attempt to compare the model (with infinite rate kinetics and no free carbon) with the data of Schadow, 40% of the carbon in "CO_2 products" was assumed unreactive. The oxygen from the CO_2 was combined with the unreacted O_2 to produce a new profile for the moles of "free" O_2. The results are presented in Fig. 4 and show reasonable agreement with experiment.

Acknowledgment

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References

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