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Technical Notes

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Comparison of Droplet Combustion Models in Spray Combustion

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Nomenclature

D_{30} = volume-mean droplet diameter
R = fuel inlet tube radius
X = axial distance from inlet

Introduction

FOR a spray-burning combustor, experimental observations reveal that different spray combustion modes are present under various atomization conditions.[1] In a fine-droplet spray, fast evaporation of small droplets makes gas-phase combustion much more significant than droplet combustion and a diffusion gas-phase flame, with a relatively short spray length with respect to the overall flame length results. As spray droplets become larger, both individual droplet burning of large droplets and group burning of small droplets are possible, and a mixed combustion mode consisting of diffusion gas-phase flame and droplet combustion occurs. Massive droplet combustion with either envelope or wake flames are observed when the spray droplet size is further increased. It is also recognized that in the spray combustion process, droplets may undergo various subprocesses such as heat-up, vaporization, ignition, burning, and extinction according to their atomization conditions and local environmental conditions. As late as 1989, in the prediction of spray combustion, it was usually assumed that droplets could only evaporate [droplet evaporation model (DEM)] and that droplet-burning effects be neglected, since no suitable models were available to determine whether droplets should burn.[2-6] Recognizing that droplet burning did occur in spray combustion, Jiang and Chiu[7] initially employed local reactivity as the criterion for droplet burning, i.e., if the local gas mixture is oxidizer-rich, droplet burning is assumed once the droplets are heated up to the propellant's boiling point [droplet reactivity model (DRM)]. Thus, spray droplets may exhibit not only the vaporization mode, but also the burning mode. While DRM does offer a possible mode of droplet burning, there are, unfortunately, some imperfections associated with this model. Since only the local equivalent ratio is considered in this simple model, local gas temperature, oxidizer mass fraction, and droplet size become irrelevant to the determination of droplet burning. This obviously conflicts with droplet ignition study results.[8] As a remedy for this defect, Jiang and Chiu[9] further proposed that, in addition to local reactivity, droplet ignitability [droplet ignition model (DIM)] should also be considered. Both criteria are employed since the prediction of ignition alone does not automatically imply that subsequent droplet combustion is possible.[8]

This study compares the spray combustion characteristics predicted by the above three models with experimental observations resulting from various inlet mean droplet sizes. A simplified combustor, similar to that used for the spray Burke-Schumann diffusion flame, is assumed. The combustor possesses coaxial cylindrical tubes with fuel spray originating from the inner tube and an airstream between the inner and outer tubes. The tube rim is slightly enlarged for flame holding. Polydisperse sprays are employed, with three inlet volume-mean droplet sizes, 40, 60, and 100 μm in diameter, being selected to serve as bases for the computations in order to investigate the spray combustion characteristics of fine- and large-droplet sprays. The spray flame configurations and the axial fuel-consumption ratios predicted by the three models reveal detailed spray characteristics and overall combustion performance; information, which when compared with experimental observations, will determine the most accurate model.

Formulation

The Eulerian-Eulerian approach is adopted for the present two-phase flow computation. The governing equations include conservation equations for both gas-phase and droplet-phase flows. The conservation equations of mass, momentum, energy, species, turbulent kinetic energy, and turbulent dissipation rate are solved for gas-phase flow. The equations for droplet-phase flow of each droplet-sized group consist of the droplet number density equation (the continuity equation), droplet momentum equations, and the droplet energy equation.

Since DEM assumes only droplet evaporation and no droplet burning, fuel droplets act simply as fuel vapor source, and no air (or oxidizer) is directly consumed by droplet combustion. In DRM, droplet burning is determined based on local reactivity, which is represented by the local equivalence ratio. When the local equivalence ratio is less than unity, the environment is classified as oxidizer-rich and fuel droplet combustion is assumed to take place. When the local equivalence ratio is greater than unity, on the other hand, the environment is classified as fuel-rich and fuel droplets are assumed to only evaporate. In DIM, droplet ignitability is considered to determine the state of droplets in addition to local reactivity. The ignition criterion proposed by Law and Chung,[8] as well as the local equivalence ratio, are used simultaneously in the determination of droplet status. Note that their ignition criterion is only valid for the droplets in a quiescent environment, since the effects of convective flow on droplet ignition are not considered, making their model only a good approximation for flows without substantial velocity slip. Droplet combustion initiation is confirmed by first checking the local equivalence ratio in order to determine local reactivity; then, if local reactivity is in favor of droplet burning, the ignition criterion is applied to test droplet ignitability. Note that extinction may occur at a different point than that of ignition.

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Although DIM treats both points the same, the impact on the overall processes may not be significant since extinction occurs mainly for small droplets. In the three models, the transfer number, based on fuel mass fractions, and phase equilibrium being assumed at the droplet surface, are used in order to account for droplet evaporation in the droplet heat-up period, while the infinite-conduction model is employed for droplet heating.

Results and Discussion

N-octane served as the fuel source with the numerical calculations being carried out at a fuel-air ratio of 0.0169, essentially a fuel-lean spray. The spray cone angle was 60 deg. Convective flow and droplet deformation effects on droplet vaporization rates are considered through the empirical correlation for convective flow. Droplet and gas mixture flows were set to the same velocity (25 m/s) at the combustor inlet in order to minimize convective flow effects on droplet ignition; effects not taken into account in the DIM droplet ignition criterion of the present study. Inlet droplets are assumed at room temperature (298 K). Inlet gas temperatures at inner fuel and outer airstreams were assumed to be 600 and 700 K, respectively.

The fuel-consumption ratio along the flow direction (Figs. 1–3), defined as the ratio of the axial fuel-consumption rate (including both vapor and liquid droplets) to the inlet total fuel-flow rate, serves as a basis for comparing the global predictions made by the three models. As shown in Fig. 1, discrepancies predicted by the three models are not significant for small-droplet spray (D_{30} = 40 μm). Among the models, DRM predicted the highest fuel-consumption ratio, while DEM predicted the lowest. All three models predicted a typical diffusion flame (not shown), which possesses a short spray length relative to the flame length. Here, fuel vapor produced by the center vaporizing droplets reacts with the outer air. This is in agreement with the experimental observations which showed a large envelope flame enclosing the center vaporizing droplets for small-droplet spray.[1] Since DEM ignores droplet combustion, droplets are assumed to just evaporate. On the other hand, depending on droplet combustion criteria, both droplet burning and evaporation may occur in DRM and DIM. Thus, deviations in the predictions made by the three models are mainly attributed to different droplet combustion treatments. According to droplet ignition studies,[8] droplet combustion with an envelope flame may occur for large droplets, but not for excessively small droplets, since fuel vapor produced by the latter may not be sufficient to initiate droplet burning. The DRM droplet combustion criterion of simply examining the local equivalence ratio may lead to a false

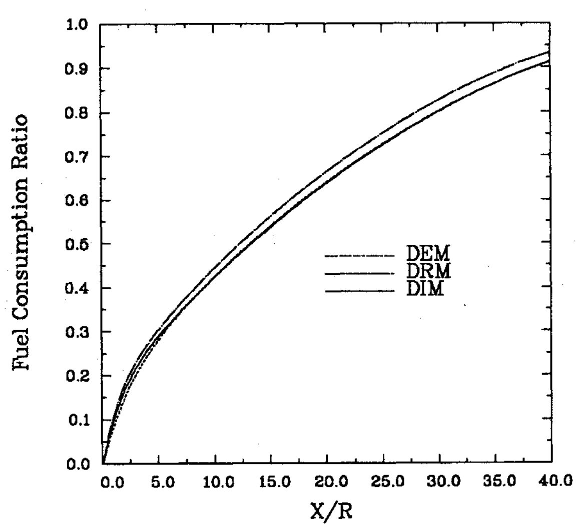

Fig. 1 Axial fuel consumption ratio (volume-mean droplet diameter = 40 μm).

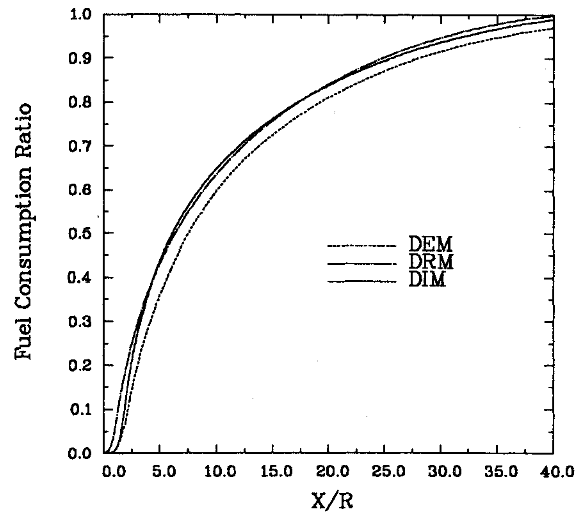

Fig. 2 Axial fuel consumption ratio (volume-mean droplet diameter = 60 μm).

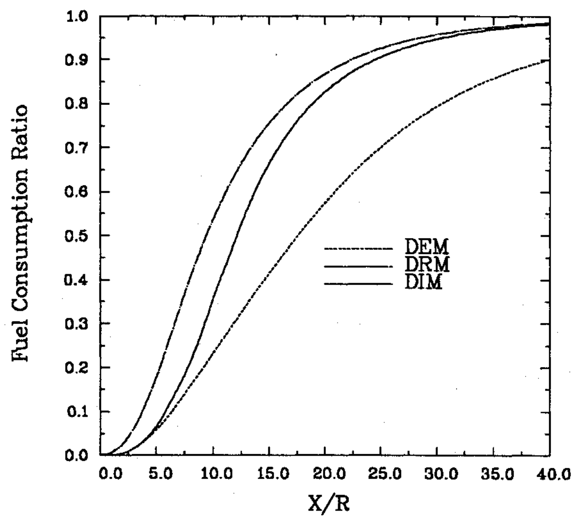

Fig. 3 Axial fuel consumption ratio (volume-mean droplet diameter = 100 μm).

prediction of droplet combustion for smaller droplets in a polydisperse spray, resulting in an overprediction of the fuel consumption ratio. Obviously, totally neglecting droplet combustion in DEM will result in an underprediction of the fuel consumption ratio, especially in the upstream region of the combustor where larger droplets possess better chances of being ignited.

For D_{30} = 60 μm spray, the fuel consumption ratio predicted by DEM is smaller than those predicted by DIM and DRM (Fig. 2). An examination of spray combustion modes revealed that a diffusion flame, with fuel vapor provided by vaporizing droplets dispersed in an area extending from the inner fuel-rich zone up until the outer airstream region, was predicted by DEM (not shown), while DRM predicted droplet combustion in the outer airstream region in addition to a relatively narrow gas-phase combustion zone located between the inner fuel-rich zone and the outer airstream region. The gas-phase combustion zone predicted by DRM is not so wide as that predicted by DEM, because those droplets penetrating into the airstream (fuel-lean) region are assumed to begin burning immediately, with no resultant fuel vapor leading into global gas-phase combustion. DIM predicted a gas flame similar to that of DRM, except that smaller droplets do not burn in the airstream such that multidroplet combustion, supported by some vaporizing droplets, extends from the main flame at several spots. The same phenomenon was also observed experimentally for large-droplet spray.[1] Since some of the fuel droplets penetrating into the airstream do not burn in DIM, its fuel consumption ratio is slightly smaller than that predicted by DRM. As compared to experimental observations, where droplet combustion was observed outside of the gas-phase combustion zone for large-droplet sprays,[1] DRM and DIM gave better qualitative descriptions of the spray combustion modes than did DEM, with DIM providing the most detailed gas-flame configuration.

For D_{30} = 100 μm spray, the fuel consumption ratio predicted by DEM is substantially lower than those predicted by DIM and DRM, with that predicted by DRM being higher than that predicted by DIM in the upstream region of the combustor. The spray combustion modes predicted by DRM and DIM, droplets with envelope flames outside of the main gas flame for large droplet sprays, are in agreement with experimental observations, while that predicted by DEM, a broader diffusion flame enclosing vaporizing droplets, is not. Note, however, that for a polydisperse spray, where mean droplet size is large, there exist droplets that are too small to be ignited. This explains why the fuel consumption ratio is overpredicted by DRM in the upstream region. Considering this aspect of spray combustion modes, DIM does give more appropriate predictions. On the other hand, DEM underpredicts the fuel consumption ratio as much as 20% at the middle part of the combustor because it fails to predict droplet burning, which is a significant combustion mode for large droplet spray.

Conclusions

Three droplet combustion models, including DEM, DRM, and DIM, have been evaluated for spray combustion through a qualitative comparison of their predictions with experimental observations. The three models accurately predict the experimentally observed spray diffusion flame for small droplet spray, giving similar global combustion performances. For large droplet sprays, DRM and DIM predictions, droplets with envelope flames outside of the main gas flame, remain in agreement with experimental observations, while DEM predicts a diffusion flame without droplet combustion. In addition, DEM predicts a lower combustion performance in comparison to those predicted by the other two models. DRM accurately predicts droplet combustion for large-droplet sprays, but overpredicts the combustion performance of a polydisperse spray, with the predicted gas-flame falsely excluding multidroplet combustion of small droplets. DIM is able to effectively model an adequate flame configuration, something the other two models fail to do. For large-droplet sprays, DIM successfully predicted single droplet combustion of large droplets, multidroplet combustion of small droplets, and external group combustion. Among the three models, it may be concluded that DIM is the most accurate model for spray combustion. For an even more realistic prediction of spray combustion, the droplet ignition criterion in DIM should include the effects of transient droplet heating and surrounding convective flow; work that is currently in progress.

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Measurement and Analysis of a Small Nozzle Plume in Vacuum

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Introduction

THERE is continuing development of small thrusters that operate on electrical power for both primary and auxiliary satellite propulsion. As a part of this development, a study is in progress to gain a better understanding of thruster-satellite interaction and design considerations in placing electric thrusters on satellites. Of particular interest is the prediction of thruster-plume expansion, especially in the off-axis region where the plume may impinge on spacecraft surfaces. The problem is being approached numerically, by modeling the nozzle flow and plume on both the continuum and molecular level, and experimentally by making plume flowfield measurements in a vacuum facility.

In prior work,[1] the flow of nitrogen in a nozzle was computed with two numerical techniques. One, based on continuum theory, numerically solved the Navier-Stokes equations for compressible flow. The other, based on a stochastic model of kinetic theory, used the direct-simulation Monte Carlo (DSMC) method. Each was applied to solution of a low-density, viscous gas flow in a converging-diverging nozzle of conical shape that simulated flow in a resistojet. This work demonstrated that the numerically intensive DSMC technique could be applied readily to a low-density nozzle flow, where the flow varied from continuum at the throat to rarefied at

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