BI-COMPONENT DROPLET COMBUSTION IN REDUCED GRAVITY

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INTRODUCTION

This research deals with reduced-gravity combustion of bi-component droplets initially in the mm size range or larger. The primary objectives of the research are to study the effects of droplet internal flows, thermal and solutal Marangoni stresses, and species volatility differences on liquid species transport and overall combustion phenomena (e.g., gas-phase unsteadiness, burning rates, sooting, radiation, and extinction). The research program utilizes a reduced-gravity environment so that buoyancy effects are rendered negligible. Use of large droplets also facilitates visualization of droplet internal flows, which is important for this research.

In the experiments, droplets composed of low- and high-volatility species are burned. The low-volatility components are initially present in small amounts. As combustion of a droplet proceeds, the liquid surface mass fraction of the low-volatility component will increase with time, resulting in a sudden and temporary decrease in droplet burning rates as the droplet rapidly heats to temperatures close to the boiling point of the low-volatility component. This decrease in burning rates causes a sudden and temporary contraction of the flame. The decrease in burning rates and the flame contraction can be observed experimentally. Measurements of burning rates as well as the onset time for flame contraction allow effective liquid-phase species diffusivities to be calculated, e.g., using asymptotic theory [1]. It is planned that droplet internal flows will be visualized in future flight and ground-based experiments. In this way, effective liquid species diffusivities can be related to droplet internal flow characteristics.

This program is a continuation of extensive ground based experimental and theoretical research on bi-component droplet combustion that has been ongoing for several years. The focal point of this program is a flight experiment (Bi-Component Droplet Combustion Experiment, BCDCE). This flight experiment is under development. However, supporting studies have been performed. Because of space limitations, only some of the research performed over the last two years (since the 5th Microgravity Combustion Workshop) is summarized here (see below).

PROPANOL-GLYCEROL DROPLET COMBUSTION

In this research, reduced gravity experiments on combustion of propanol-glycerol mixture droplets were performed. Propanol-glycerol mixture droplets are of interest here because they are candidates for displaying Marangoni flows as as a result of solutal capillary stresses. Droplets were initially in the mm size range with initial glycerol mass fractions of 0, 0.05 and 0.2. All experiments were in O_2/N_2 ambients at standard temperature and pressure. The ambient O_2 mole fraction was 0.21 (air) or 0.5. Use was made of a NASA-supplied drop rig, and the experiments were performed at the NASA Glenn Research Center 2.2 s Drop Tower.

In the experiments, droplets initially about 1 mm in diameter were deployed onto silicon-carbide support fibers (about 12 μm in diameter). The droplets were ignited via a hot-wire ignition system, and droplets and flames were imaged using onboard video cameras. Droplet and flame size data were obtained from the video records using digital image processing routines. The experiments showed clear indications of flame contraction. Representative data on flame and droplet size variations are shown in Fig. 1 (the discrete data points). Also shown are computational results for droplet size variations with time (the thick line).

For analysis of the data, a computational model was developed to predict the transient buildup of glycerol at the surface of a droplet. This model assumed the gas phase was quasisteady, which was apparently the case in the experiments since flame-to-droplet diameter ratios were nearly constant after ignition. The model allowed for variable transport properties in the liquid phase. In addition, spherical symmetry was assumed in both the liquid and gas phases. In employing this numerical model, the gas-phase thermal conductivities and liquid species diffusivities were varied so that the computational results on burning rates and onset times for flame contraction matched the experimental results closely. This allowed effective species diffusivities to be estimated. The numerical model, which was based on an explicit finite difference scheme, employed nonuniform gridding to allow fine resolution near the droplet surface. This provided substantial decreases in computation time while still maintaining accuracy. A schematic of the nonuniform gridding is shown in Fig. 2. For clarity, all grid points are not shown in this figure.

Comparison of the experiments with the numerical model, as well as with an asymptotic model [1], suggests that convective mixing was present in the droplets. The liquid species diffusivities in the numerical model needed to be increased by as much as an order-of-magnitude in order to match the experimental results. For example, liquid species diffusivities were increased by about a factor of four for the data in Fig. 1. In an actual droplet, increases in effective diffusivities are generally caused by liquid convection. Because of the large differences in surface tension between glycerol and propanol, such convection was likely the result of solutalcapillary instabilities. In addition, the experiments exhibited extinction after flame contraction, which was unexpected for droplets in this size range. Details on this research are available in Ref. [2].

NUMERICAL MODELING OF FIBER-SUPPORTED DROPLETS

Support fibers are commonly employed in microgravity droplet evaporation and combustion studies, and it is of interest to develop models of fiber-supported droplets. In this research, a numerical study of the Marangoni forces on a droplet supported by a fiber has been carried out for an evaporating methanol droplet in both dry air and humid air environments, with the focus being the development of instabilities that form early in the lifetime of a droplet. This modeling employed a finite-volume technique. A schematic of the fiber-supported droplet geometry considered here is shown in Fig. 3. The initial droplet-to-fiber diameter ratio was twenty for all cases considered.

The thermal Marangoni effect has a stabilizing effect, and it always drives the droplet surface toward an isothermal condition. The solutal Marangoni effect (from water absorption) is much larger in magnitude, and it tends to concentrate water on the surface. This tendency to concentrate water leads to surface waves and instabilities, which are relieved by diffusion of the water into the droplet interior. For 0.5 mm radius droplets (as measured from the fiber edge) the surface forces have generated liquid Reynolds numbers greater than one hundred. Figure 4 shows an instantaneous velocity field in a large droplet (the maximum velocity in Fig. 4 is about 20 cm/s). Also shown are water mass fraction profiles (y). At this instant in time, there are several vortices present in the droplet. These vortices are a result of the solutal Marangoni stresses.

Smaller droplets (initial radii of 0.005 mm) give qualitatively similar results, however the Reynolds numbers are reduced by size and diffusion damping influences. The numerical simulations are sensitive to droplet and supporting fiber size, and it appears that experimental verification and comprehensive numerical studies should be fully three-dimensional. It also appears that the solutal Marangoni flows are unstable to very small wavelengths, as suggested by previous linearized stability analyses [3]. Details on this research are available in Ref. [4].

MEASUREMENTS OF TRANSIENT DROPLET COMPOSITIONS VIA FIBER-OPTIC ABSORPTION SPECTROSCOPY

Experiments were performed to determine the time-dependent compositions of fiber-supported droplets initially in the mm size range. These experiments were performed to investigate mixing levels in bi-component droplets that are likely to have flows driven by solutalcapillary stresses. Droplets initially about 1 mm in diameter and composed of mixtures of methanol and acetone, or propanol and acetone, were investigated. Acetone was selected because its optical properties (i.e., absorption characteristics in the UV) are well characterized, while methanol and propanol are essentially transparent at a wavelength of about 270 nm, which is the peak wavelength in the spectral region where acetone absorbs strongly in the presence of polar liquids. The droplets evaporated in room air under normal gravity. The experiments employed thin optical fibers to carry light from a UV-Vis light source into and out of a droplet (Fig. 5). The time-dependent UV absorption spectrum of the liquid between the fibers was measured using a spectrometer coupled to one of the fibers, yielding the local transient acetone concentration.

Analysis of the experimental results [5] indicated that the droplets were well mixed while evaporating. This is likely a result of solutalcapillary flows that may have been induced as a result of water absorption into the droplets (the droplets evaporated in humid air). In addition, the data indicate that the more volatile component was preferentially evaporated. These trends are expected based on the relative vapor pressures of the components. Representative data are shown in Fig. 6 for a propanol-acetone droplet, where it is evident that the acetone concentration in the liquid decreased with time. Details on this research are available in Ref. [5].

FUTURE PLANS

Future ground-based research will include more drop tower experiments on reduced-gravity combustion of bi-component droplets initially about 0.8 - 1 mm in diameter. It is planned that these experiments will eventually employ flow-visualization so that droplet interior flowfields can be imaged during combustion. Experiments at UC Davis will include measuring local droplet interior compositions using absorption spectroscopy under conditions where Marangoni flows are both dominant as well as subdominant. A goal of these experiments is to provide data on mixing rates and liquid species fluctuations within droplets. Theoretical and computational studies will include development of a 3-d numerical model of fiber-supported droplet combustion, as well as further development of theory to predict effects of solutalcapillary stresses on droplet interior flows. Development of the BCDCE flight experiment will also continue.

ACKNOWLEDGEMENTS

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REFERENCES

1. Aharon, I. and Shaw, B. D., Combustion and Flame 113, 507 (1998).
2. Dee, V., and Shaw, B. D., AIAA paper 2001-0468.
3. Aharon, I., and Shaw, B. D., Physics of Fluids 8: 1820 (1996).
4. Dwyer, H. A., and Shaw, B. D., Combustion Science and Technology (in press).
5. Xiao, J. S., Wei, J. B., and Shaw, B. D., paper 43 presented at the 2nd Joint Meeting of the US Sections of the Combustion Institute, Oakland, CA (2001).

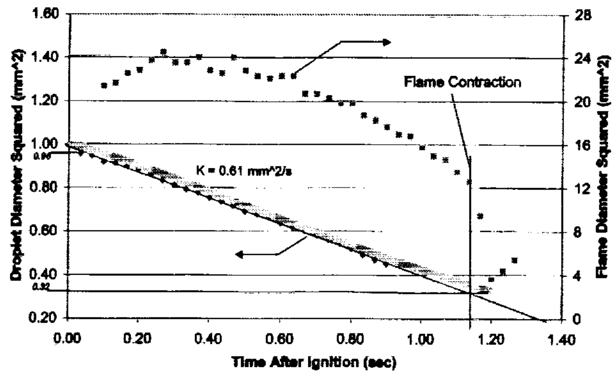

Figure 1. Propanol-glycerol droplet combustion data.

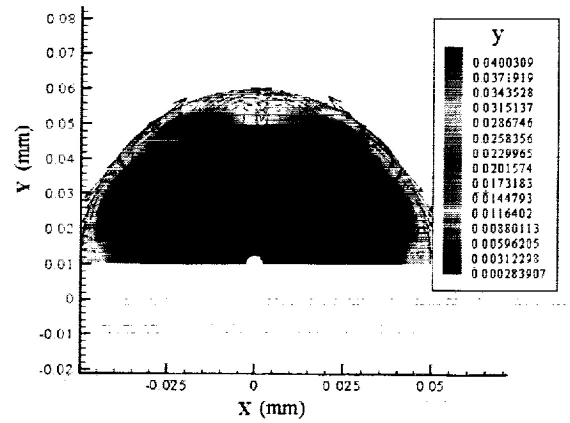

Figure 4. Water mass fraction (y) contours and velocity vectors (cm/s).

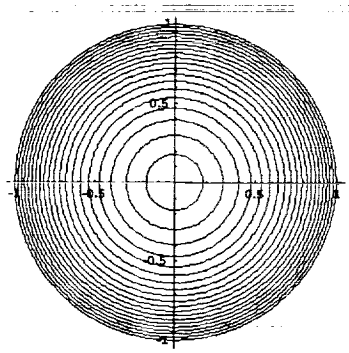

Figure 2. Nonuniform computational grid.

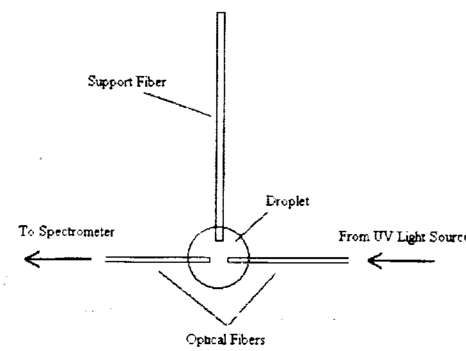

Figure 5. Schematic of the droplet spectroscopy setup.

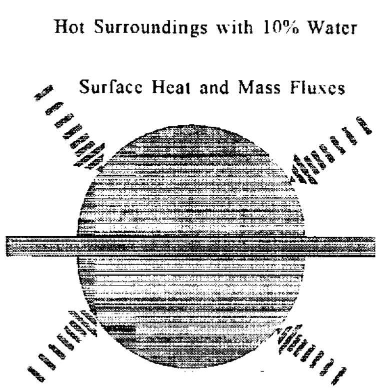

Figure 3. Schematic of a fiber supported droplet.

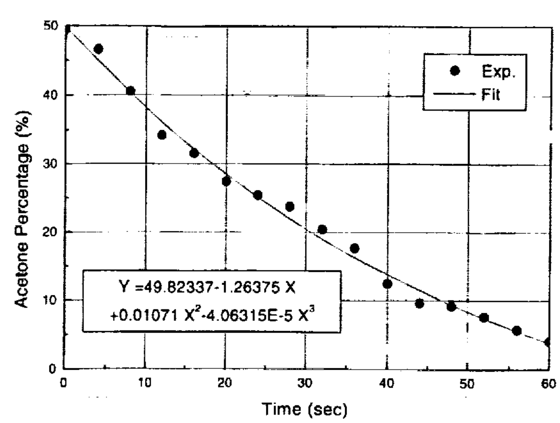

Figure 6. Acetone mass fraction vs. time.