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HIGH-PRESSURE COMBUSTION OF BINARY FUEL SPRAYS

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Introduction

This is a joint research program, pursued by investigators at the University of Tokyo, UCSD, and NASA Lewis Research Center. The focus is on high-pressure combustion of sprays of miscible binary fuels. It involves construction of an experimental apparatus in Tokyo, mating of the apparatus to a NASA-Lewis 2.2-second drop-tower frame in San Diego, and performing experiments in the 2.2-second tower in Cleveland, with experimental results analyzed jointly by the Tokyo, UCSD, and NASA investigators. The project, initiated nearly one year ago, is a follow-on to a project on high-pressure combustion of single binary fuel droplets, initiated in December, 1990, which resulted in clarification of the near-critical three-stage combustion process, as published in ref. 1. The new project has now involved one period of drop-tower testing by Mikami at Lewis, in August, 1994, in which about 30 successful runs of video data were obtained on the combustion of pairs of fiber-supported droplets of mixtures of n-heptane and n-hexadecane, initially about 1 mm in diameter and separated by distances from 4 mm to 8 mm, at pressures up to 4 MPa.

Objective

The ultimate objective of this study is to obtain fundamental information relevant to combustion processes that occur in fuel sprays of practical interest at high pressures in internal combustion engines. Since practical fuels are multicomponent and derived from petroleum, the present work involves the model alkane mixture of n-heptane and n-hexadecane. Since burning droplets in sprays can interact with each other, the present work involves investigation of the effects of this interaction on flame shapes and droplet burning times. The small droplets in practical combustion chambers are not significantly influenced by buoyancy. Since such small droplets are difficult to study experimentally, the present work takes advantage of microgravity to lessen buoyancy and enable information about droplet interactions to be obtained by studying larger droplets. The results are intended to provide fundamental understanding that can be used in improving descriptions of practical spray combustion.

Experimental Apparatus and Procedure

Figure 1 shows a schematic diagram of the experimental apparatus. The pressure chamber has four windows that give two orthogonal views of the combustion process, a black-and-white backlit view from which the droplet sizes as functions of time are obtained and a color view which shows the flame surrounding the droplets. The backlight is in the plane of the droplet support fibers and is focused on the droplet nearest it. During each test, both of these views were recorded on VHS videotape by a fiberoptic link from the test package. Microgravity conditions were attained by dropping the pressure chamber and associated experimental equipment in a drop tower at NASA Lewis Research Center that provides 2.2 seconds of microgravity ($\sim 10^{-5}$ normal).

Before release of the experimental package, fuel droplets were formed at the end of 0.125 mm silica fibers from a high-pressure syringe driven by a stepping motor. Following release, immediately upon entry into microgravity the droplets were ignited. The ignition source was a hot wire (aluminum alloy, 0.2 mm diameter) formed into 2 mm diameter loops that surround the droplets. The hot wire was rapidly removed after ignition, leaving approximately 2 seconds of the 2.2 seconds to observe combustion. All processes, including droplet dispensing and ignition, were controlled by a microcomputer.

The initial droplet size was approximately 1 mm in diameter. This droplet diameter is nearly an order of magnitude larger than that of the suspending fiber, while also being small enough that complete burning could be observed in the available microgravity time. The ambient gas was air at a total pressure ranging from 0.1 MPa to 4.0 MPa. The binary fuel droplets were composed of mixtures of n-heptane and n-hexadecane with mass fractions of hexadecane ranging from 0 (pure heptane) to 1.0 (pure hexadecane). The subject fuels have

critical temperatures and pressures of 540 K, 2.74 MPa and 722 K, 1.53 MPa for heptane and hexadecane respectively. All experiments were performed with the ambient gas and the droplet initially at room temperature.

General Combustion Behavior

Figure 2 shows the flame around two droplets burning side by side at 0.1 MPa. The top photo is at an earlier stage of combustion and the bottom one at a later stage. Figure 3 is the corresponding history of the square of the droplet diameter, as obtained from the backlit camera view orthogonal to that of figure 2. The staged burning found for single droplets and explained previously (ref. 1) continues to exist for these droplet pairs. Resolution of the droplet diameter was achievable only up to 1.0 MPa. Above that pressure, flame radiation from soot washes out the backlight. However, the staged burning is still identifiable from the flame photographs; flame contraction occurs as hexadecane builds up at the droplet surface, then the flame grows again after the hexadecane begins to vaporize and burn. Dilution of the air with nitrogen suppresses soot formation and enables droplet-diameter histories to be resolved to somewhat higher pressures. In previous work with single droplets (ref. 1), such dilution was employed for this purpose.

Total Burning Times

Single-droplet results from previous work (ref. 1) are shown in figure 4. In that figure, X denotes the mole fraction of oxygen in the oxygen-nitrogen atmosphere, and Y_0 is the mass fraction of hexadecane in the liquid fuel. Consider first the results shown in figure 4 for pure heptane ($Y_0 = 0$) and for pure hexadecane ($Y_0 = 1$). For the former, the droplet total burning lifetime decreases with increasing pressure up to 3.0 MPa, but for the latter there is a minimum lifetime at about 2.5 MPa. This behavior is consistent with a minimum lifetime occurring in this atmosphere for pure fuels at pressures somewhat above the critical pressure (2.74 MPa for heptane and 1.53 MPa for hexadecane). A minimum may thus be expected for heptane in figure 4 at a somewhat higher pressure. In theory, the more vigorous the combustion is, the closer to the critical pressure will the minimum lie. This prediction is in agreement with present experimental results on the burning of single droplets of pure heptane in air, as shown in figure 5. In air, the combustion is more vigorous than in the diluted atmosphere, and the minimum total burning time for heptane in figure 5 occurs very near its critical pressure.

Figure 4 shows that in diluted atmospheres the total burning times for mixtures typically exceed those of the pure fuels, and the burning time decreases with increasing pressure, so that there is a pressure at which the burning time reaches a minimum value, then this pressure is higher than that for the pure fuels. Figure 5 shows that these conclusions continue to apply in

undiluted air. The curve in figure 5 for $Y_0 = 0.33$ suggests that the burning time may achieve a minimum at about 5.0 MPa. At higher values of Y_0 , the minimum may be expected to occur at lower pressures and to approach a value somewhat above 1.53 MPa as Y_0 approaches unity. These results on total burning times of single droplets of binary fuel mixtures are thus exhibiting a consistent pattern.

The effects of droplet spacing on the dependence of droplet burning time on pressure are shown in figures 6 and 7 for two different initial hexadecane mass fractions. It is seen in these figures that droplets separated by eight times their initial diameter burn under microgravity conditions in air almost as if they were single isolated droplets. However, droplets separated by four times their initial diameter burn more slowly as a consequence of the droplet interactions. In addition, the magnitude of the effect of the interaction decreases with increasing pressure. For $Y_0 = 0.33$, at a pressure of 5.0 MPa there is almost no effect of interaction on the total burning time at spacings as close as four times the initial droplet diameter. Further work is needed to explain these observations properly. It may be noted, however, that if effects of interactions are assumed to become noticeable at spacings in fixed proportion to the flame diameter, then in theory at low pressures there is no pressure dependence, while for supercritical burning the spacing for a given magnitude of perturbation should vary inversely with pressure.

Future plans

About 30 successful drops were made in the first series of runs. The parameter space of the problem, however, is too large for significant conclusions to be drawn from so few tests. Two additional series of drops therefore are planned, with about 60 tests in each series. Since the apparatus is now working reliably in the tower, it is anticipated that practically all of these future drops will be successful. The principal parameters to be varied are the droplet spacing, the mass fraction of hexadecane in the fuel, and the pressure. Hexadecane mass fractions of 11% and 33% will be studied at smaller droplet spacings, and measurements will be made at higher hexadecane mass fractions. At pressures of 0.1 MPa, 1.0 MPa, 2.0 MPa, 3.0 MPa, 4.0 MPa and nearly 5.0 MPa, droplet spacings will be varied between about 1 mm and 8 mm. Conditions will be determined under which individual flames surround each droplet and under which one single flame surrounds both droplets, as a function of pressure. In addition, the influence of the droplet separation distance on the burning rate will be measured. Information relevant to testing predictions of cloud burning and of individual-droplet burning thereby will be obtained. Very little data of this type are available at pressures approaching supercriticality. The results should therefore help to improve understanding of spray combustion under conditions of practical interest in engines.

References

1. Mikami, M., Kono, M., Sato, J., Dietrich, D.L., and Williams, F.A., "Combustion of Miscible Binary-Fuel Droplets at High Pressure under Microgravity," *Combustion Science and Technology*, Vol. 90, pp. 111-123, 1993.

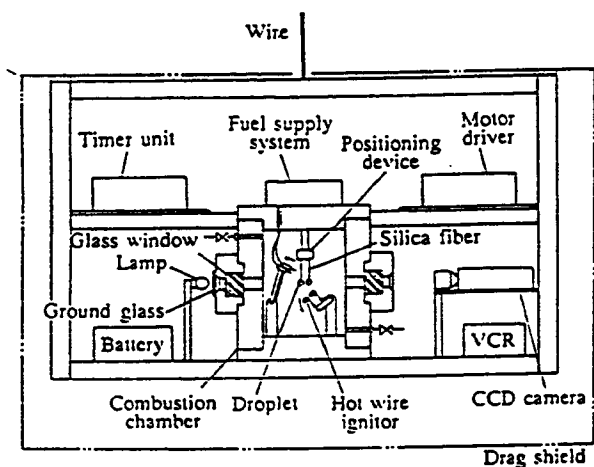


Figure 1 Schematic diagram of the experimental apparatus.

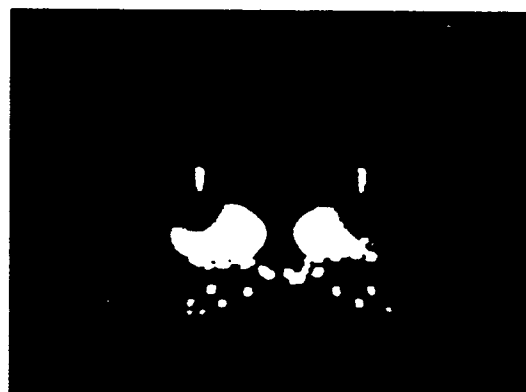
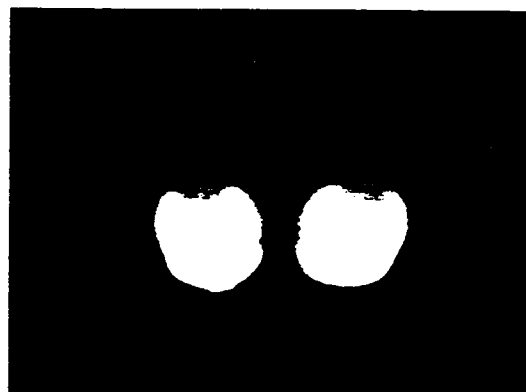


Figure 2 Photograph of a pair of burning droplets with an initial hexadecane mass fraction of 33%, initially 0.93 mm in diameter, separated by a distance of 0.8 mm, burning in air at 0.1 MPa.

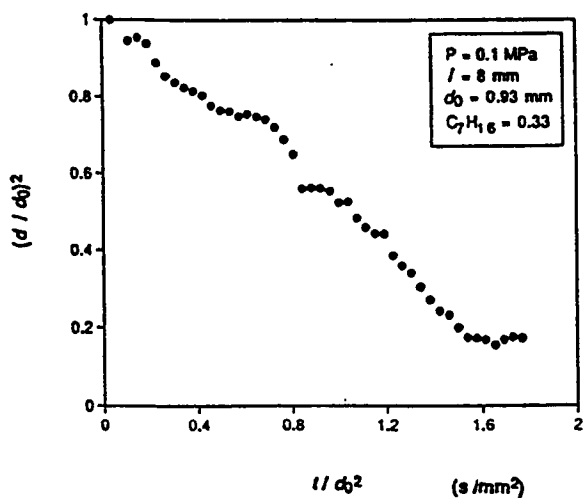


Figure 3 The square of the droplet diameter d as a function of time for the test shown in figure 2.

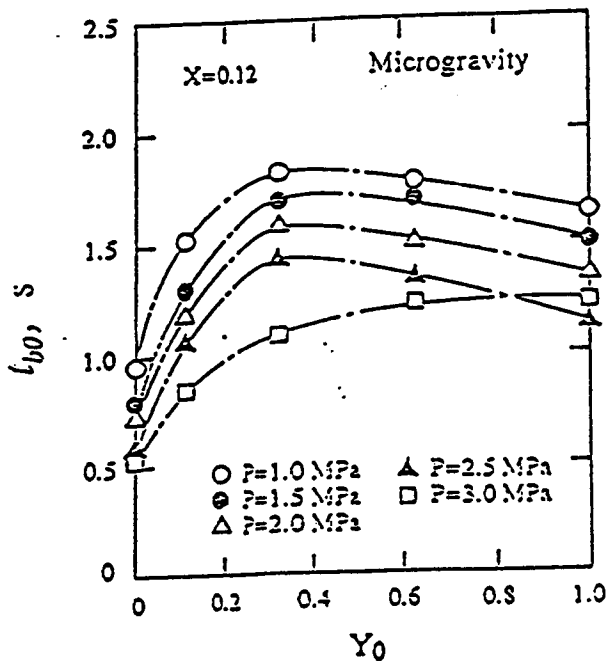


Figure 4 Dependence of the droplet lifetime, t_{b0} , at different ambient pressures on the initial hexadecane mass fraction, Y_0 .

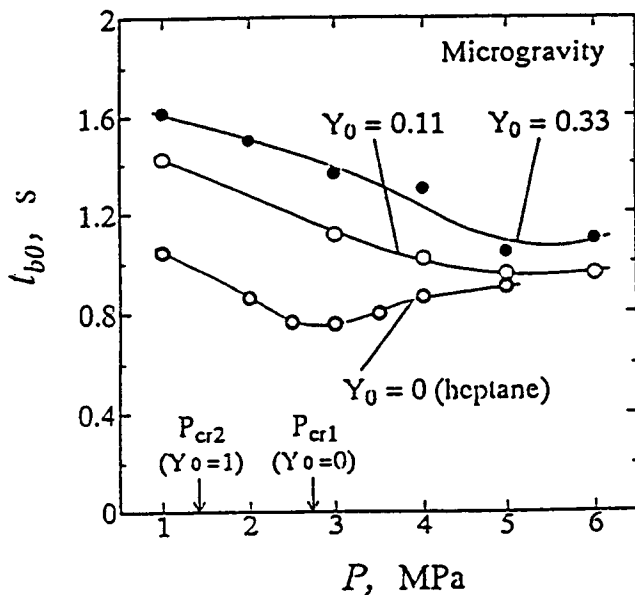


Figure 5 Dependence of the droplet lifetime, t_{b0} , on the ambient pressure, P , for three different values of the hexadecane mass fraction, Y_0 .

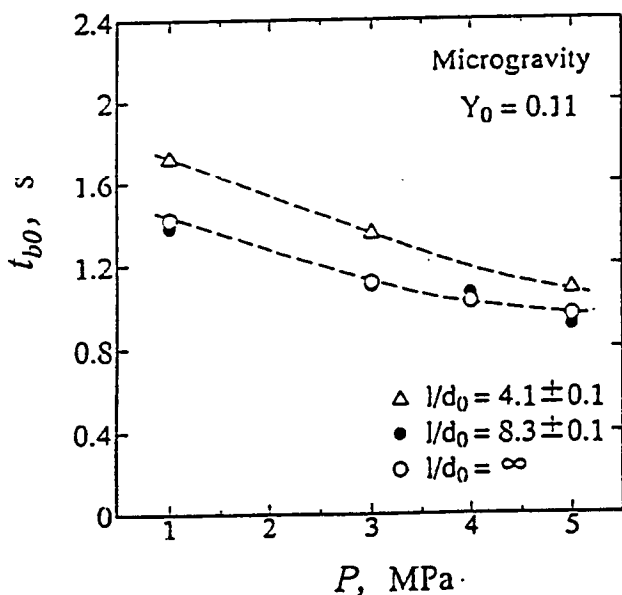


Figure 6 Dependence of the droplet lifetime, t_{b0} , on the ambient pressure, P , for three different ratios of the droplet spacing, l , to the initial droplet diameter, d_0 , for an initial hexadecane mass fraction of $Y_0 = 0.11$.

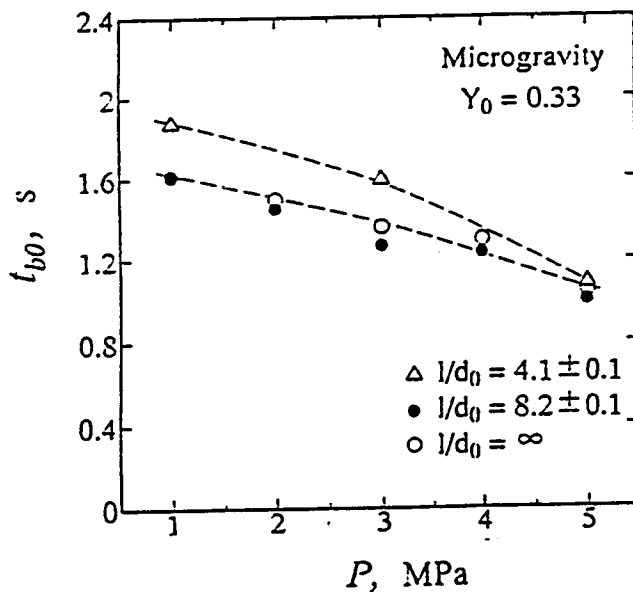


Figure 7 Dependence of the droplet lifetime, t_{b0} , on the ambient pressure, P , for three different ratios of the droplet spacing, l , to the initial droplet diameter, d_0 , for an initial hexadecane mass fraction of $Y_0 = 0.33$.