Middeck Glovebox (MGBX)



# Fiber Supported Droplet Combustion-2 (FSDC-2)

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# FIBER SUPPORTED DROPLET COMBUSTION-2

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Abstract

Experimental results for the burning characteristics of fiber supported, liquid droplets in ambient Shuttle cabin air (21% oxygen, 1 bar pressure) were obtained from the Glove Box Facility aboard the STS-94/MSL-1 mission using the Fiber Supported Droplet Combustion - 2 (FSDC-2) apparatus. The combustion of individual droplets of methanol/water mixtures, ethanol, ethanol/water azeotrope, n-heptane, n-decane, and n-heptane/n-hexadecane mixtures were studied in quiescent air. The effects of low velocity, laminar gas phase forced convection on the combustion of individual droplets of n-heptane and n-decane were investigated and interactions of two droplet-arrays of n-heptane and n-decane droplets were also studied, with and without gas phase convective flow. Initial diameters ranging from about 2mm to over 6mm were burned on 80-100 μm silicon fibers. In addition to phenomenological observations, quantitative data were obtained in the form of backlit images of the burning droplets, overall flame images, and radiometric combustion emission measurements as a function of the burning time in each experiment. In all, 124 of the 129 attempted experiments (or about twice the number of experiments originally planned for the STS-94/MSL-1 mission) were conducted successfully.

The experimental results contribute new observations on the combustion properties of pure alkanes, binary alkane mixtures, and simple alcohols for droplet sizes not studied previously, including measurements on individual droplets and two-droplet arrays, inclusive of the effects of forced gas phase convection. New phenomena characterized experimentally for the first time include radiative extinction of droplet burning for alkanes and the "twin effect" which occurs as a result of interactions during the combustion of two-droplet arrays.

Numerical modeling of isolated droplet combustion phenomenon has been conducted for methanol/water mixtures, n-heptane, and n-heptane/n-hexadecane mixtures, and results compare quantitatively with those found experimentally for methanol/water mixtures. Initial computational results qualitatively predict experimental results obtained for isolated n-heptane and n-heptane/n-hexadecane droplet combustion, although the effects of sooting are not yet included in the modeling work. Numerical modeling of ethanol and ethanol/water droplet burning is under development. Considerable data remain to be fully analyzed and will provide a large database for comparisons with further numerical and analytical modeling and development of future free droplet experiments aboard space platforms.

## Background

Isolated, spherically symmetric, single droplet burning is the simplest example of non-premixed combustion that involves large molecular species typically found as components in liquid hydrocarbons used as transportation fuels. The simple, symmetrical, experimental configuration that can be obtained by removing the complicating effects of buoyancy provides an ideal venue for investigating, in fundamental detail, the complex physical and chemical processes involved in diffusion/mixing limited combustion of liquid fuels. These phenomenon include the effects of the multi-component nature of the liquid fuel, liquid phase internal circulation effects (effective liquid phase diffusivities), liquid phase combustion product absorption, diffusion flame dynamics, soot interactions in diffusion flame configurations, and radiative and diffusively controlled extinction processes. Furthermore, the spherically symmetric configuration can be perturbed in systematic and simply quantifiable fashion by imposing a slow gas phase convective flow relative to the droplet, and/or by introducing neighboring droplets in an array to investigate in a simple configuration the drop and flame interactions encountered in spray combustion.

Another paper in this L+1 proceedings describes the background and development of a full facility experiment, the Droplet Combustion Experiment (DCE), which can be utilized to investigate many of the above issues with experimental rigor[1]. For example, this facility was used on the MSL-1 mission to study the combustion of isolated n-heptane droplets in helium/oxygen at various oxidizer concentrations and ambient pressures and in shuttle cabin air at atmospheric pressure. The successful operation of DCE on a particular fuel and various ambient conditions is strongly dependent on developing experimental experience with large initial droplet diameters, larger than those which can be studied successfully in ground-based (droptower) or parabolic flight experiments. The Fiber Supported Droplet Combustion (FSDC) experiment was conceived as a much simpler, complementary facility that could not only provide the source of such data, but would permit cursory results on a myriad of liquid fuel compositions and droplet configurations, all within one flight mission. The use of fiber supported droplet combustion methods permits the study of large initial diameter droplets under quiescent conditions, as well as in the presence of forced gas phase convection. In addition, to studying individual droplet combustion phenomena, the interactions of multiple droplet flames with one another and with forced gas phase convection can also be investigated.

An FSDC experiment, FSDC-1, was first manifested as a multi-investigator endeavor during the STS-73/USML-2 mission in 1995. The mission profile consisted of seven separate sets of experiments: n-heptane single droplet combustion without forced flow, n-heptane droplet combustion with forced flow, methanol droplet combustion, methanol droplet-array combustion, methanol/dodecanol miscible binary-fuel mixture combustion, n-heptane/n-hexadecane binary-fuel droplet combustion, and methanol/water mixture droplet combustion. Due to crew-time limitations and safety considerations on the amount of liquid flammables that can be carried on board the Space Shuttle, each of these investigations were allotted a maximum of five droplet burns, with only two different mixture compositions for the bi-component fuels and two different flow velocities for the forced convection experiments. Although two sets of the planned experiments were unable to obtain data because of hardware malfunctions (n-heptane single droplet combustion without forced flow, methanol droplet-array combustion), the remaining components of the test matrices were very successful. The details of the experimental observations are reported and discussed in several publications[2,3,4,5,6,7,8,9].

The present FSDC-2 experiments were conducted aboard MSL-1 with slightly re-configured hardware to gather further scientific data on droplet combustion phenomenon and to extend the range of parameter values over which data were obtained during the USML-2 mission, both in terms types of fuels and initial droplet size.

Objectives

The general objectives of the droplet combustion experiments at the large diameters reported here focus on improving understanding of the mechanisms and the dynamics of burning liquid fuel droplets. The scientific justifications for these objectives are fully detailed elsewhere. The specific objectives of the FSDC-2 experiments themselves were as follows:

a) *Obtain new (first) data on the isolated droplet combustion behavior of n-heptane, n-decane, and ethanol over a range of initial droplet sizes from 2 to 6mm, in quiescent air, and to investigate the effects of relative gas phase convection on the combustion on individual droplets of n-heptane and n-decane.*

b) *Obtain new (first) data from droplet array experiments performed using n-heptane, and n-decane as fuels, and for a range of L/D ratios (where D is the droplet diameter and L is the distance between the droplets).*

c) *Obtain additional and complementary data (at mixture ratios not studied in FSDC-1) for isolated n-heptane/n-hexadecane and methanol/water droplet combustion in air, and new data on the isolated droplet combustion on ethanol/water azeotrope in air, over a range of droplet sizes from 2 to 6 mm.*

The co-investigators of each of these related projects and the relationship of each to other ongoing microgravity combustion projects are listed in Table 1. In addition to the FSDC-2 investigators, Drs. A. J. Marchese, and Bi-Li Zhang, former graduate students involved in this research at Princeton University and the University of California, San Diego, participated as FSDC Science Team Members during the MSL-1 mission.

Experiment Description

All experiments were carried out in the Glovebox Facility on board the Spacelab using the FSDC-2 experimental apparatus (Fig. 1). Fuels were contained in fourteen modified, airtight commercial syringe cartridges. Because of fuel volatility, the loaded fuel cartridges were stowed in the shuttle only 24-h before launch. To operate the experiment, the fuel cartridge is screwed into the base of the experiment module. The crew turns a plunger screw, forcing fuel through two opposed hypodermic needles to the deployment site on a silicon fiber located between the needles and perpendicular to them. Numbered needle pairs, the fiber stretched between them and fuel cartridges may be seen in Fig. 1. After the fuel coalesces into a droplet of the desired size, the needles are slowly retracted to minimize contact of the liquid with the needle surfaces. The stretched droplet is then deployed by rapidly retracting the needles into the bottom of the chamber. Motions of the deployed droplet are allowed to dampen before the ignition button is depressed. This automatically raises a replaceable igniter wire into place on one side of the droplet (parallel to the fiber), approximately 3.5 mm from the fiber, and simultaneously provides DC electric current to the igniter. The igniter, seen on the chamber floor in Fig. 1, is a coiled loop of an aluminum alloy wire (resistivity 0.04 $\Omega$/mm) with a diameter of 0.25 mm and total length about 35 mm, carrying a current of approximately 3 amps. When the crew operator detects ignition visually, the igniter button is released, automatically retracting the igniter to the bottom of the test chamber.

Imaging data are provided by two video views, one a backlit view of the droplet and the other a perpendicular view of the flame. The backlight is comprised of five LEDs (620–670 nm), which reflect off a mirrored lens in the bottom of the experiment module. The video camera for the droplet view is attached to the Glovebox microscope. The second video camera, with a view essentially orthogonal to the microscope, records the droplet, the fiber, and the flame. All of the data were recorded using three 8 mm VCR's.

The taped camera images were analyzed using microcomputer-based imaging analysis systems. Reference 10 describes a typical example of the type of system employed. A frame grabber board is used to transfer video images of the backlit droplet to a microcomputer for analysis. The droplet image is differentiated from the background using various threshold-intensity-based algorithms. A two-dimensional projected area ($A_P$) is determined by counting individual pixels within the envelope of the droplet image. An equivalent droplet diameter, $D_{AP}$, can be determined as the diameter of a circle that yielded the measured projected area. In some cases a volume-equivalent diameter $D_v$, based on the assumption that the droplet is symmetric about the fiber has also been used to define the equivalent droplet diameter. In other cases, measurements of the major and minor axes of the droplet have been used to calculate an equivalent drop diameter. Each of the above reduction techniques have specific advantages and disadvantages, and the multi-investigator team continues to make cross-comparisons of the methodologies. For the purposes of the present paper, differences amongst results produced by the various methods are not relevant to the conclusions drawn.

In addition to the imaging data, two radiometers were employed in the experiments to measure radiant fluxes from the flame zone as a function of burning time. One radiometer (denoted as Radiometer 1) was used to detect radiant power fluxes in the wavelength range 0.6 - 40 microns. The other radiometer (denoted as Radiometer 2) was used to detect radiant power fluxes in the wavelength range 5.1 - 7.5 microns, which corresponds approximately to the wavelength range for thermal radiation emission from water vapor.

In experiments investigating the effects of forced flow, a dc fan (Fig. 1) generates an imposed forced flow. The fan induces airflow through a honeycomb (ten-to-one cell aspect ratio) inlet section and the experiment module, with the vectored direction collinear with the supporting droplet fiber. Uniform forced air speeds from 30 mm/s to 250 mm/s can be produced. When forced convection is imposed during an experiment, the droplets tend to move along the fiber. In order to "anchor" the droplet within the field of view of the imaging cameras, small ceramic (alumina glue) beads were placed along the SiC fibers at a spacing of 5 mm. This spacing also fixed the droplet separation distance during linear array tests at 5 mm for all the experimental runs. These beads were not present in the FSDC-1 experimental configuration. Further details of the apparatus and the experiment operation procedures can be found in Reference 4.

Each droplet combustion test occurred at pressures (0.996–1.107 bar), oxygen mole fractions (0.204–0.222), and relative humidity (39–46%) of the Spacelab environment.

Experimental Results Comparisons with Ground Based Data, and Analyses

Below, we summarize our initial findings and analyses concerning the study of pure alkane, binary alkane mixture, and alcohol isolated droplet burning in quiescent atmospheres, two-droplet array combustion in quiescent gas surroundings, and the effects of forced convection on droplet burning phenomenon. Much of the data presented are preliminary in nature, and further analyses are continuing. The qualitative features of results presented and discussed below are clear and independent of the continuing evaluations of the quantitative nature of the results. Quantitative interpretations may be modified by the continuing work. We therefore caution readers to contact the authors should they have interest in using the results from the experiments presented here quantitatively.

*Isolated Droplet Quiescent Gas Phase Studies*

*Pure Alkanes*

Isolated droplet studies without convection were performed using both pure n-heptane and n-decane as fuels. Normal heptane and decane are molecular species characteristic of liquid fuel carbon numbers found for species in gasoline, gas turbine, and diesel fuels. Burning n-heptane droplets allows a direct comparison between the fiber-supported data and the Droplet Combustion Experiment (DCE) obtained in the MSL-1 mission. This comparison includes examining the effects of the fiber on gasification rates and extinction, comparing the potential effects of the reduced gas volume surrounding the burning droplet in FSDC-2 (in comparison to that in DCE), and a comparison of burning heptane in air versus burning heptane in a helium-oxygen environment. Through several efficiencies in conducting tests in DCE, some tests not originally planned were conducted with cabin air rather than helium-oxygen mixtures. DCE experiments included tests using a similar filament suspension technique (that had no ceramic beads mounted on the filament). Thus, the combined FSDC-2 and DCE tests with n-heptane permit a number of cross-comparisons of results. Experiments with n-decane have never been performed in space environments before, although n-decane is a fuel that could be studied in DCE in the future. The quiescent, isolated droplet studies of n-heptane and n-decane also provide base cases for comparison with studies involving forced convection and 2-droplet arrays (discussed below). Both FSDC-2 and DCE tests result in excellent opportunities to evaluate the relationship of initial droplet size to gasification rate, flame dynamics, and extinction phenomena, particularly flame extinction induced by radiative heat loss from the droplet flame.

Fifteen single droplets of n-heptane were successfully ignited and burnt under quiescent gas conditions. Views of the droplets and radiometers exist for all the tests; no visible flame appears in the tests. However, the flame location can be estimated from local position of maximum radiation from the silicon fiber passing through the flame and the droplet surfaces. In some of the tests, bubbles formed inside the droplet while it was still burning. Initially, small bubbles usually grew to large bubbles (This growth maybe caused by small bubbles combining or by droplet heating.). The bubbles left the droplet at various times during the burning, but often a bubble with a volume approximately equal to the remaining fluid volume broke free in the last one or two seconds of the burn. Bubbles were present in studies with other fuels as well, and this observation appears to be more pervasive in the FSDC-2 experiments than was reported for FSDC-1 studies. Furthermore, the presence of the ceramic bead (FSDC-2 configuration only) appeared to enhance bubble formation, particularly in forced convection studies. The exact cause of these bubbles is still being investigated.

Preliminary measurements of droplet diameter as a function of burning time and extinction diameter as a function of initial droplet diameter have been made using the droplet views. These measurements cover a variety of initial droplet diameters ranging from 2.48 millimeters to 6.26 millimeters.

Figure 2 compares some of the FSDC-2 and DCE measurements of average gasification rate for n-heptane droplet combustion in air with ground-based experimental data and recent numerical modeling results[13]. One notes that the average gasification rate decreases with increasing initial droplet size, both experimentally and computationally. Furthermore, the FSDC-2 and DCE experimental measurements at about 4-mm initial droplet size are in excellent agreement with one another. Consistent with the interpretation of similar behavior for methanol droplet combustion[11] and DCE data for n-heptane[12], Marchese et al.[13] conclude that this result is due to energy losses from the flame structure from both luminous (soot) and non-luminous radiation (hot gas products). At initial drop sizes larger than about 3.5 mm, non-luminous effects appear to dominate. The non-luminous loss reduces the flame temperatures sufficiently that the formation rate of gas phase soot formation is suppressed, and the resulting flame is non-sooting.

However, other average gasification rates measured for n-heptane drops in the FSDC-2 experiments, particularly those which contained substantial numbers of bubbles, appear to be much larger than expected from the results presented in Fig. 2. It should be noted that bubbles appeared in the liquid phase in the DCE tests only as a result of introduction through the fuel supply needles themselves, while bubbles appeared to form and grow in size throughout the burning history in some of the FSDC-2 experiments. The source for these peculiarities continues to be investigated.

Normal heptane droplets were observed to burn for as little as six seconds in some tests, and longer than thirty seconds in other test. The droplet burning time does not always increase as the square of the initial drop diameter. While experiments at smaller initial droplet sizes burned to completion, as initial droplet size was increased, the droplet flame was observed to extinguish with a finite diameter droplet remaining. Figure 3 displays the "extinction" diameter found in different initial diameter experiments. Theory would predict that one should observe the qualitative relationship shown in Figure 3, based upon the increased radiative loss effects with increasing drop diameter. Further evaluation of these results and comparisons with theory are continuing.

Successful experiments were also performed using isolated pure n-decane droplets, and some results are presented here, primarily for comparison with two-drop array observations discussed below. Figure 4 compares the burning histories of three single n-decane droplets of different initial in FSDC-2. The quality of the experimental data for the variation of the square of droplet diameter with burning time is typical of FSDC-2 experiments with n-decane as well as with the other fuels studied. The observed scatter in the data results from two factors: 1) difficulty in determining the edge of the droplet because of flame radiation (especially close to ignition) and non-uniform backlighting combined with soot generation; 2) vibration of the droplet due to the nucleation and growth of the vapor bubbles. The slope of the curve at any point in Figure 4 is the instantaneous gasification rate constant, k. The average gasification rate constant, $k_{avg}$, reported in Fig. 1 and elsewhere in this paper, is the average slope over a burning period of linear behavior in the data, typically, 10% to 90% of the total droplet burn time. The initial burning time is defined to be when the droplets anchor after ignition. From the results in Fig. 4, the average gasification rate constant for n-decane in air clearly decreases with increasing diameter, similar to the behavior noted in studies of n-heptane described above. The average gasification rate for the smallest droplet, 0.76 $mm^2/s$, is close to the average gasification rate constant for smaller 1 mm initial diameter droplets ($k_{avg} \sim 0.7$ $mm^2/s$) burned in drop tower experiments. During combustion, bubbles were observed to nucleate within the fuel droplet near the bead of the droplet. These bubbles grew during combustion and became a significant volume of the droplet near the end of the burn. Many of the bubbles burst near the end of combustion, which caused a sharp, drop off in droplet diameter measurements at the end of a test (Figure 4).

*N-heptane/n-hexadecane Mixtures*

Liquid fuels used in practical devices such as internal combustion engines and gas turbines are blends of several hundred molecular structures, having a wide range of chemical and physical properties. These binary component alkane experiments address the effects on gasification rate, flame dynamics, and extinction phenomenon which are related to the fuel component interactions resulting from volatility differences among molecules of similar structural type (normal alkanes). Normal heptane and hexadecane differ widely in volatility, with heptane being the more volatile species. The large volatility difference allows study of phenomena associated with transient liquid species diffusion and component volatility differences. After ignition of a heptane-hexadecane droplet, heptane is initially preferentially vaporized from the droplet with most of the hexadecane remaining in the liquid phase. As the droplet decreases in size, the liquid surface mass fraction of hexadecane increases with time, causing rapid droplet heating as the surface mass fraction of hexadecane closely approaches unity. This heating reduces the droplet vaporization rate and causes the flame to contract until liquid heating is completed, at which time vigorous vaporization of both droplet components begins and the flame grows in size again. The onset time for a flame contraction can be used to estimate liquid species diffusivities in burning droplets[14]. In addition, transient processes associated with flame contractions can apparently cause extinction of large droplets[4] as well as variations in sooting[15] and gasification rates[14].

The present experiments complement previous ones[4] that were performed in FSDC-1 during the STS-73/USML-2 flight in 1995. As with FSDC-1, the FSDC-2 experiments focused upon studying initially large droplets, allowing the study of chemical and physical phenomena over length and time scales that cannot be achieved in ground-based experiments. The FSDC-2 experiments were performed with the following specific objectives:

1. *The initial liquid compositions in FSDC-1 were limited to initial heptane mass fractions (Y) of 0.90 and 0.60. To more fully test theories on bi-component droplet combustion, other compositions needed to be investigated. The FSDC-2 experiments utilized Y = 0.95 and Y = 0.80.*

2. *Measurements of flame radiant energy output rates were made with FSDC-2 (this measurement was not available in FSDC-1). These measurements provided new and useful data on radiant outputs of the weak flames associated with combustion of large heptane-hexadecane droplets, and the measurements allowed determination of whether flames had actually extinguished. Because of the very dim flames encountered with FSDC-1, it was not possible to determine when flame extinction had occurred. The radiometer data also provided information on the occurrence of flame contractions.*
3. *Unexpected extinction and sooting behaviors were observed during the FSDC-1 experiments. For example, larger droplets appeared to soot weakly only shortly after ignition, with sooting becoming negligible prior to extinction. In addition, extinction in larger droplets seemed to be induced by flame contractions. These phenomena merited further study.*

Twenty-two droplets were deployed, ignited and burned in the FSDC-2 heptane-hexadecane experiments, with 11 droplets having Y = 0.95 and the remainder Y = 0.8. Initial droplet sizes ranged from about 1.8 mm to about 6 mm. The larger initial droplets extinguished at large diameters (a few mm). These droplets could be re-ignited after extinction, much as is described for the ethanol results reported below. Only limited representative data and results are presented here, as analyses are continuing.

In both the FSDC-1 and FSDC-2 experiments, flames were detected by the video cameras only for times shortly after ignition, after which the flame luminosity was too low to record. Even glowing of support fiber was not evident in the video images after the initial ignition transients. These factors suggest that flame temperatures were very low for the mixture fractions and droplet sizes studied here. The square of the droplet diameter (d) and radiometer data as a function of burning time are shown in Fig. 5 for a droplet (Y = 0.95) initially about 1.8 mm in diameter. After ignition, the $d^2$-t plot is essentially linear until an interior bubble exits the droplet, causing a sudden decrease in droplet size. As in the case of the pure alkane studies, small bubbles were present in many of the heptane-hexadecane droplets prior to ignition. After the bubble exits, the $d^2$-t plot is again essentially linear with nearly the same slope as prior to the bubble exit. The plot also exhibits a temporary decrease in slope at about 3.5 s, likely associated with the flame contraction phenomenon typical of bi- component combustion. The gasification rate prior to the flame contraction is about 0.64 $mm^2/s$. This gasification rate, in conjunction with asymptotic theory[14] yields the effective liquid-phase species diffusivity $D \approx 9 \times 10^{-9}\ m^2/s$.

The radiometer data presented in Fig. 5 show increases after the igniter was turned on, with very sharp increases after droplet ignition. Following ignition, the radiant heat fluxes grow and then decrease, with slight increases apparent after the flame contraction has occurred. Interestingly, the shapes of curves in these radiometer data are qualitatively similar to flame diameter data published for drop-tower experiments with heptane-hexadecane droplets initially about 1 mm in diameter[14].

Figure 6 report similar data for a larger droplet, 2.9 mm diameter. After an initial the bubble exits, the $d^2$-t plot is again essentially linear until a flame contraction appears at about 10.5 s. The gasification rate prior to the flame contraction is about 0.66 $mm^2/s$ for this droplet. A similar analysis with asymptotic theory yields $D \approx 8 \times 10^{-9}\ m^2/s$. The D values corresponding to the data in Figs. 5 and 6 are very close to the D values determined from the FSDC-1 experiments.

Unlike the data in Fig. 5, the radiometer values for the droplet in Fig. 6 did not increase after the flame contraction. Rather, the data decreased to low values prior to the disappearance of the droplet (from complete evaporation) at about 16.5 s. Cusps are apparent in the radiometer data at flame contraction as well as shortly after the droplet had completely vaporized. Radiometer data following the latter set of cusps indicates that cooling rates of the gas increased substantially after the droplet had completely vaporized.

While not shown here, it is noted that droplet diameter data indicate the largest droplets extinguished at large diameters corresponding to the droplet sizes expected at the onset times for flame contractions. The radiometer data show cusps at these same times, followed by strong decreases in radiometer outputs, indicating that gas-phase chemical heat release had abruptly stopped and that the gases were rapidly cooling. Gasification rates were also observed to decrease as droplets became larger, with the largest droplet exhibiting gasification rate constants roughly 30 % lower than the smaller droplets (prior to flame contractions). Finally, it is noted that interesting soot shell dynamics were observed in these experiments; these behaviors are presently being evaluated.

Further data analyses remain to be performed. The droplet diameter data will be analyzed to determine the liquid species diffusivities that apply to all droplets burned in the experiments. In addition, the radiometer data will be further analyzed and compared with theoretical predictions of radiant heat losses from spherical droplet flames with particular attention being paid to the transient effects caused by transient liquid species diffusion. Recent numerical modeling of the n-heptane/n-hexadecane droplet combustion, including detailed gas phase chemistry and non-luminous radiation[13], qualitatively shows many of the phenomena observed in the FSDC experiments and that observations are particularly responsive to liquid phase transport within the droplets and radiative loss from the flame structure. Additional modeling efforts will be necessary to produce quantitative predictions of both ground and flight microgravity data.

*Simple Alcohol and Alcohol/Water Mixtures*

Methanol and methanol/water have been extensively investigated in drop towers and FSDC experiments primarily because the fuel itself is a relatively simple hydrocarbon for which physical and chemical properties are relatively well known, and the material has no propensity to form soot. Methanol also offers a unique opportunity to study dissolution of combustion products in the liquid phase (primarily water) and binary multicomponent combustion behavior with one of the components being non flammable. Methanol/water droplet combustion experiments from FSDC-1 and FSDC-2 have recently been analyzed and compared against the predictions of a detailed numerical model[9]. In FSDC-2, two additional levels of water content (15% and 30% by mass) were studied by performing experiments at several different initial drop sizes (a total of thirteen successful experiments in all).

Overall, both pure methanol and methanol/water droplets of 2 to 7 mm were studied. In some cases, droplets burned for over 40 seconds and flame extinction was observed at small but finite droplet diameters. In other cases, droplets ignited, but the flames rapidly extinguished. Numerous asymptotic and numerical modeling studies have addressed the prediction of droplet burning phenomena in microgravity for methanol, particularly the extinction phenomena[6,8,9,16]. In the most recent work[9], both FSDC-1 and FSDC-2 experiments are compared against the results of a detailed numerical model, which simulates the time-dependent, spherically symmetric combustion of a multi-component liquid droplet in an infinite oxidizing environment. The model includes detailed chemistry, multi-component molecular diffusion and non-luminous radiative heat transfer. The model quantitatively reproduces (without modifications or adjustments) measured gasification rate, flame position and extinction diameter for a wide range of initial diameters and initial water contents. Radiative heat loss is significant in experiments with initial diameters greater than 3 mm, resulting in a decreased gasification rate and a non-linear increase in extinction diameter. Figure 6 shows that, both numerically and experimentally, the extinction diameter increases with increasing initial droplet size. At smaller initial sizes, the dissolution of water (a combustion product) into the liquid fuel droplet leads to the increased extinction diameter. At larger initial diameters, radiative loss from the flame structure becomes an important factor. Moreover, at 6-mm initial diameter, radiative losses result in entirely transient burning, with extinction occurring after only a few seconds of combustion. The critical extinction diameter of 6 mm, predicted numerically in a previous study for methanol droplet combustion[8] in 1-atm air, was verified experimentally. Figure 7 shows that importance of considering non-luminous radiative loss in predicting the flame diameter for large-diameter methanol droplet combustion. Non-luminous radiative effects also result in decreased gasification rate with increasing initial drop diameter even at initial diameters smaller than 3.0 mm.

Ethanol and Ethanol/water azeotrope mixture were also studied in FSDC-2 experiments. Ethanol has been proposed as a fuel for investigating the droplet combustion behavior of azeotropes[17] and sooting effects in microgravity droplet combustion[18]. As in the case of methanol, the physical and chemical properties of ethanol itself, as well as the intermediates present in its combustion are reasonably well known, compared to those of liquid alkanes. The azeotrope mixture is mostly ethanol (96% ethanol, 4% water), limiting the amount of water that can be absorbed as combustion products of absolute ethanol droplets. Finally, the sooting nature of this fuel has pressure sensitivities qualitatively similar to that of n-heptane, but shifted to a higher range of pressures. For example, droplet combustion of this fuel produces no soot at atmospheric pressure and 21% oxygen index in nitrogen. At three atmospheres, however, sooting is profuse at the same oxygen index. The present FSDC-2 experiments provide first observations of ethanol combustion ion microgravity at large drop sizes.

Figures 9 and 10 display the average gasification rate and extinction diameters for ethanol as functions of initial droplet size. Figure 10 includes average gasification rate data taken on ethanol in the NASA-Lewis 2.2 s droptower[19]. The results show that both average gasification rate and extinction diameter are related to the initial droplet size in manners similar to n-alkanes and methanol. However, ethanol does not soot at these conditions (as does n-heptane), and cannot absorb large amounts of combustion products during its combustion history (as does methanol). The ethanol experiments were particularly interesting in that large initial droplets that burned and underwent extinction could be re-ignited. The gasification rate of the re-ignited droplet was reduced in comparison to the prior burn. The re-ignited droplet was observed to sometimes burn to extinction again, with an extinction droplet size that could again be re-ignited. The observed gasification rate would again be slower than for the prior burn. Eventually, the re-ignited droplets would burn to completion. In one case, the initial droplet burned and extinguished, and this sequence was repeated 5 times until the droplet was fully consumed. The extinction diameters for droplets that were re-ignited were quite similar in their relationship to the ignited initial drop diameter, as were similar data for droplets ignited only once. Apparently, the amount of water dissolved into the liquid phase over multiple burns does not accumulate sufficiently on a volume-averaged basis to affect extinction. The averaged water content cannot be more than that in the azeotrope mixture (4% water). Even slight increases in average water content, however, appears to reduce the average gasification rate. Data analyses are continuing and a numerical model to for to compare results with the data is in development.

*Two Droplet Array Studies*

While the results of single droplet studies are relevant to practical combustion devices, in practice, droplets, do not burn in an isolated manner. Instead, droplets interact with each other during combustion. Droplet arrays represent the next logical building block in the development of a spray model. During the FSDC-2 experiments, several experiments on two-droplets arrays of droplets at a known distance from each other were conducted. The results from binary droplet tests with n-decane as fuel are compared here with single droplet experiments with decane reported earlier. Both experiments were in a quiescent ambient.

In general, the droplets studied were near-spherical with slight elongation along the axis of the fiber (the ratio of the maximum and minimum diameters was typically no more than 1.2). The two droplets moved on the fiber as a result of combustion interactions, and this combustion-induced phenomenon was coined the Thomas "twin" effect. The droplets initially moved apart along the fiber during ignition and anchored to the fiber ceramic bead on the side of the droplet nearest to each other. After ignition, the droplets drifted together and became anchored to the bead on the side facing away from each other. During many of the tests, soot particles formed during ignition. The soot gave evidence of unexpected recirculating flow patterns in the vicinity of the droplets. Between the droplets in the array, soot particles were observed to approach the droplets somewhat parallel to the fiber and then rapidly move radially away from the droplets. The motion of the soot particles suggests the existence of strong liquid-phase motion during combustion. Internal, liquid phase flow patterns have also been observed in the single droplet experiments discussed earlier, but generally were less developed.

Figure 11 shows the gasification rate history for both droplets in the two-droplet array (separation distance, ~7-mm between the center of the droplets, anchored immediately after ignition. The burning is relatively symmetric in the present case, with a lack of symmetry in other tests typically due to the bubble nucleation and growth, especially for smaller size (< 3 mm initially) droplets.

Figure 11 also shows the instantaneous gasification rate constant, K, for the two drops. In general, significant errors are encountered when differentiating experimental data. Both Miyasaka and Law[20] and Mikami et al.[21] differentiated a polynomial fit of the experimental data to determine K. We found, however, that the polynomial fit did not accurately describe the experimental data over the entire burning history and could produce errors in K when differentiated. Also, simply smoothing and differentiating the data produced very scattered plots of $K(t/D_0^2)$. The K values in Figure 11 are determined by performing a modified cubic spline curve fit on the experimental data. In the present case, the data are divided into equal increments of $(t/D_0^2) = 0.15$. Third order polynomial fits are then performed on the data in each interval subject to the constraint that the values along with the first and second derivatives are continuous at each node point.

Figure 11 shows that K is nearly constant or just slightly increasing over a significant portion of the burn. This is in contrast with previous work[20,21] which show that the gasification rate constant increases continuously as the relative separation distance (inter-droplet spacing, L, normalized by the instantaneous droplet diameter, D) increases during burning. The results are, however, consistent with recent droptower work that shows that most of the curvature in the droplet history ($D^2$ vs. t) occurs early in the lifetime and that K is nearly constant over (most of) the droplet lifetime.

Figure 12 shows a comparison of the burning histories and gasification rate constants for one of the droplets in Figure 11 (left) with a nearly identical sized single droplet (initially). Clearly, the average gasification rate of the droplet in the array is smaller than for an isolated single droplet. The interaction effect is the largest when the normalized separation distance, L/D (L/D increases with increasing $t/D_o^2$) is largest. The difference decreases as L/D increases, approaching zero at the end of the burn. The surprising point in Fig. 12 is that the gasification rate constant for the single droplet also decreases with time.

*Forced Convective Studies*

Relative droplet/gas velocities exist in practical, spray combustion applications. The influences of slow, purely forced convective velocities on the burning characteristics of two-droplet linear arrays of n-decane in air are discussed here. Droplet gasification rates and flame dynamics were experimentally measured for a range of imposed velocities, and droplet initial sizes. The results are compared here with single droplet combustion under similar flow conditions. The separation distance between the two droplets were nominally 5 mm, and the upstream and downstream droplet initial sizes were varied independently between 2 and 5 mm. Figure 13 shows the gasification rate histories of isolated, single droplets as a function of imposed flow velocities. The instantaneous droplet diameter is obtained by measuring the major and minor diameter of the droplet from the backlit images and then computing D as the cube root of the major diameter times the square of the minor diameter. The $D^2$ versus time curves in Fig. 13 are not linear. However, the noise in the data precluded us from obtaining instantaneous gasification rates. The average gasification rate constant, $K = d(D^2)/dt$), computed from linear least-square curve fits to the portion of the curve prior to the vapor bubble explosion (to be discussed below) are 1.3, 1.4, 1.5, 1.5, and 1.4 mm2/s for the imposed flow velocities of 11, 15, 15, 20, and 25 cm/s, respectively. The gasification rate in general increases with the increasing flow velocity. There are insufficient data to derive a statistically significant correlation between K and other independent dimensionless numbers, such as the Reynolds number. During the experiments, it was observed that the droplet anchored itself on the ceramic bead at its forward leading edge. A few seconds into burning, a small vapor bubble formed on the ceramic bead and continued to grow before bursting. The time at which the bubbles burst is marked with a vertical line in Fig. 13. The vapor bubble formation was rapid and vigorous during the forced convective burning. In this case, the anchoring bead is less shielded by the liquid droplet than under quiescent burning conditions where the bead is centered within the droplet. With reference to Fig. 13, we note that two competing effects influence the observed droplet size and $d^2$-t history displayed in the figure. The size decreases due to vaporization, but increases due to bubble growth. The actual mass vaporization rate is likely somewhat higher than that implied by the average K determined from Fig. 13.

Figure 14 shows the burning histories for a typical 2-droplet array test. As in the case of single droplet combustion, the ceramic beads cause vapor bubble nucleation and growth within both the upstream and downstream droplets. The time at which the vapor bubbles break is marked by a vertical line. The average gasification rate constants calculated prior to the vapor bubble release are plotted against the Reynolds number for the single droplet and the linear array droplets in Figure 15. This plot clearly shows that droplet interaction reduces the individual gasification rates of both the upstream and downstream droplets. The downstream droplet, which is embedded in the wake of the upstream droplet most of its lifetime, shows a larger reduction in gasification rate, as much as 30%, compared to a single droplet burning under the same imposed velocity.

## Conclusions

FSDC-2 planned to conduct 52 total experiments, using single droplets and nine different fuels or fuel mixtures. Each experiment was to have involved the combustion of a single isolated droplet of between 2mm and 6 mm in diameter in cabin air. One-hundred-twenty-seven (127) experiments were conducted, of which 123 resulted in producing test data. In addition to investigating the full range on initial droplet sizes with each fuel, seventeen experiments were conducted using two droplets, spaced about 1 cm apart, to study droplet-droplet interactions during combustion. These experiments yielded science that was originally planned for the flight of FSDC-1 on the STS-73 USML-2 mission in 1995. In the two-drop array studies, the drops were forced apart by ignition process, and then as the drops burn, they are forced together by the reduced vaporization on the adjacent sides of the drop. We named this effect, the "Thomas Twin Effect", after Don Thomas who was operating the experiment. Single droplet studies have yielded extensive and new information for gasification rate and extinction phenomena for the various fuels studied and on the effects of forced convection on droplet burning. Three presentations of this work to the science community have occurred over the last twelve months, and results from the methanol/water droplet combustion studies have been published archivally. Analyses of single droplet pure and binary mixture, forced convective, and two-droplet array studies are continuing and will be the subject of future archival publications

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*Archival Publications*

1. Marchese, A.J., Colantonio, R.O., "Radiative Effects in Space-Based Methanol/Water Droplet Combustion Experiments", 27th Symposium (Intn'l) on Combustion, The Combustion Institute, Pittsburgh, PA. 1998. In Press.
2. Marchese, A.J., Dryer, F.L. and Nayagam, V., "Numerical Modeling of Isolated n-Alkane Droplet Flames: Initial Comparisons with Ground and Space-based Microgravity Experiments", *Combust. Flame*, 1998. In Press.

*Other Preprints and Presentations*

1. Nayagam, V., Calvert, M.E., Colantonio, R.O., and Dietrich, D.L., "Forced Convection Burning of Two-Droplet n-Decane Linear Arrays in Microgravity", Proceedings of the 1998 Central States Section of the Combustion Institute.
2. Marchese, A. J., "Microgravity Droplet Combustion", University of Delaware Fluid, Particulate and Environmental Seminar Series, Newark DE, October, 1997.
3. Marchese, A.J. and Dryer, F.L., "Detailed Kinetic Modeling of Microgravity n-Alkane Droplet Flames", Eastern States Sectional Meeting of the Combustion Institute, East Hartford CT, October 1997.
4. Dryer, F.L., "Recent Studies of Liquid Hydrocarbon Droplet Combustion Aboard the Columbia Space Shuttle", University of Wisconsin, Madison, Nov. 19, 1997.
5. Williams, F.A., "Experiments on Droplet Combustion in the Space Shuttle", National Fire Prevention Association (NFPA) Meeting, San Diego, CA, December 8, 1997.
6. Zhang, B.L., "Theoretical Analysis of Heptane Droplet Combustion for Comparison with Results from the Shuttle Spacelab During The MSL-1 Mission", 36th AIAA Aerospace Sciences Meeting, Reno, NV, January 13,1998.
7. Marchese, A.J. and Dryer, F.L. "Detailed Numerical Modeling of Liquid Droplet Combustion Experiments Conducted Aboard Microgravity Science Laboratory-1", 36th Annual Aerospace Sciences Meeting, Reno, NV, January 13, 1998.
8. Dryer, F.L., "Liquid Hydrocarbon Droplet Combustion Aboard the Columbia Space Shuttle", Vanderbilt University, Nashville, TN, February 20, 1998.
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10. Nayagam, V. and Williams, F. A., "Dynamics of Diffusion Flame Oscillations Prior to Extinction During Low Gravity Droplet Combustion," 7th International Conference on Numerical Combustion, 30th March – 1st April, 1998, York, England.

**Table 1.** FSDC-2 Investigators and their relationship to funded projects

| *Investigator* | *Experiment Responsibility* | *Relationship to funded microgravity research programs* |
|---|---|---|
| Prof. Forman A. Williams<br>University of California, San Diego | Principal Investigator of overall program | Droplet Combustion Experiment (DCE) |
| Prof. Frederick L. Dryer<br>Princeton | n-heptane - no flow, methanol/water mixtures<br>ethanol/water mixtures | DCE |
| Prof. Benjamin D. Shaw<br>University of California, Davis | n-heptane/n-hexadecane,<br>internal circulation visualization | Bi-Component Droplet Combustion |
| Dr. Daniel Dietrich<br>NASA Lewis Research Center | n-heptane and n-decane two-droplet arrays | Droplet Array Interactions |
| Mr. John Haggard<br>NASA Lewis Research Center | n-heptane - no flow | DCE, FSDC-1 co-Investigator |
| Dr. Vedha Nayagam<br>Analex Corporation | forced flow effects, n-heptane, n-decane | DCE - Project Scientist<br>FSDC-1 co-Investigator |
| Dr. Ron Colantonio<br>NASA Lewis Research Center | ethanol/water azeotrope | DCE - Deputy Project Scientist* |

- Current responsibilities are: High Speed Systems Office, NASA-Lewis Research Center

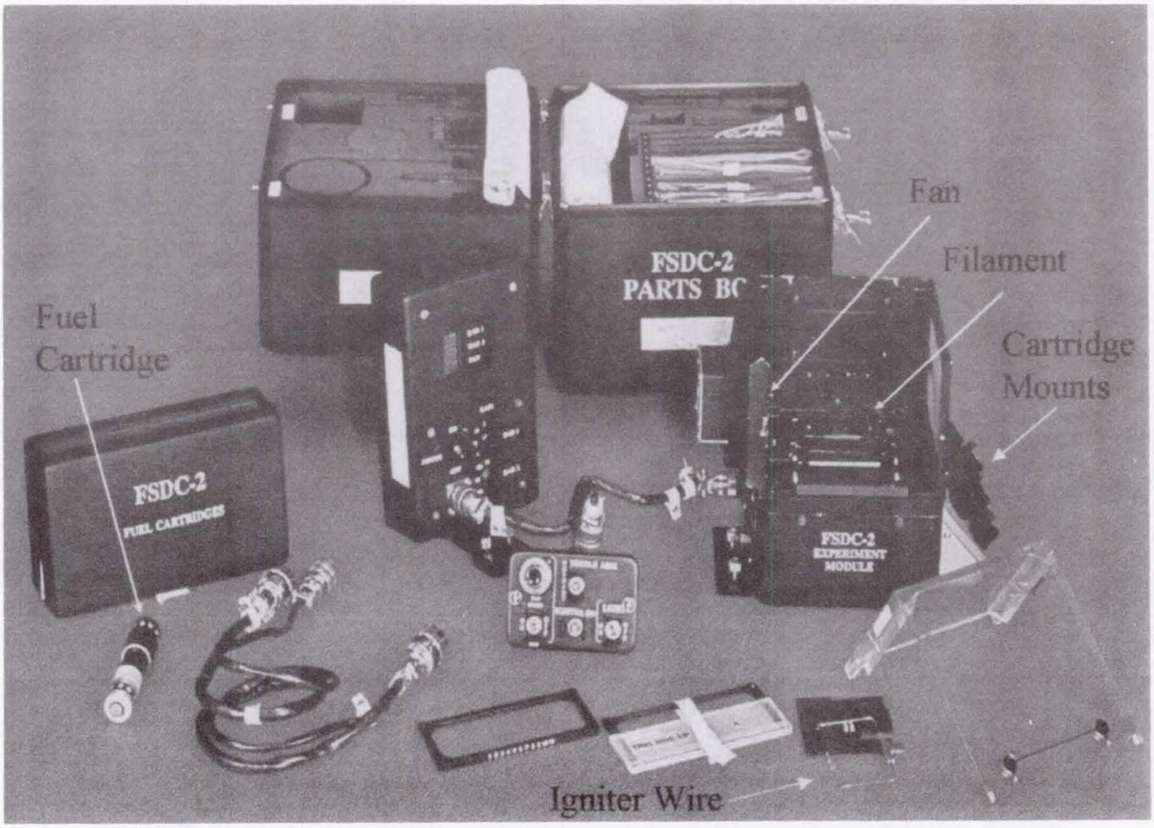


**Figure 1** FSDC-2 Hardware

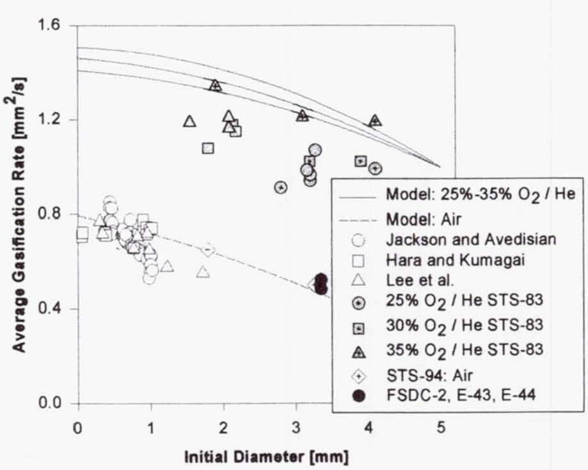


**Figure 2** Average burning rate as a function of initial diameter for n-heptane burning in air.

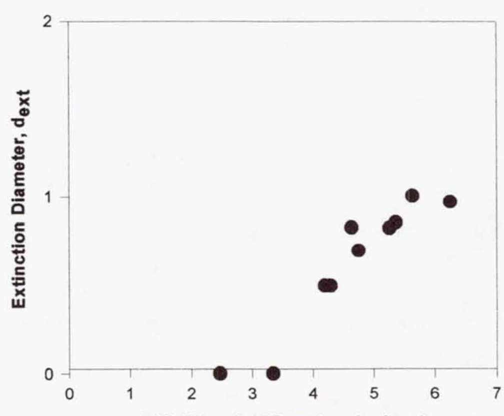


**Figure 3** Extinction diameter as a function of initial diameter for n-heptane combustion in air.

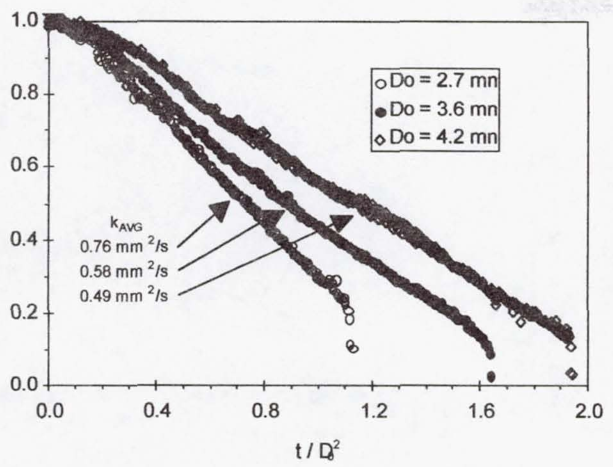


Figure 4 Single n-decane droplets burning in FSDC-2.

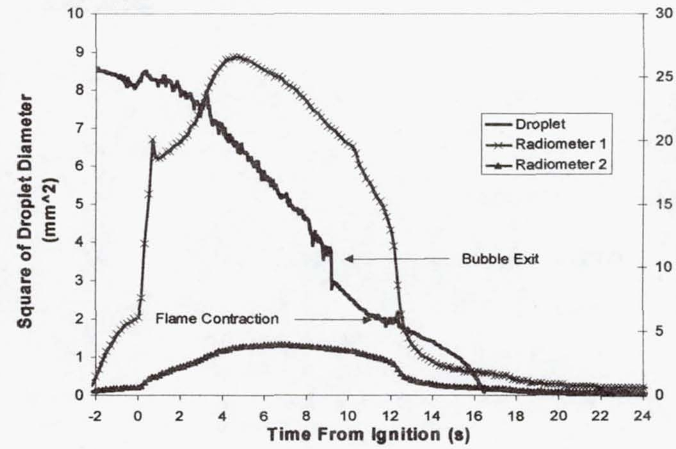


Figure 5 Droplet diameter and radiometer data for a heptane-hexadecane mixture droplet burned in the FSDC-2. The initial heptane mass fraction (Y) was 0.95.

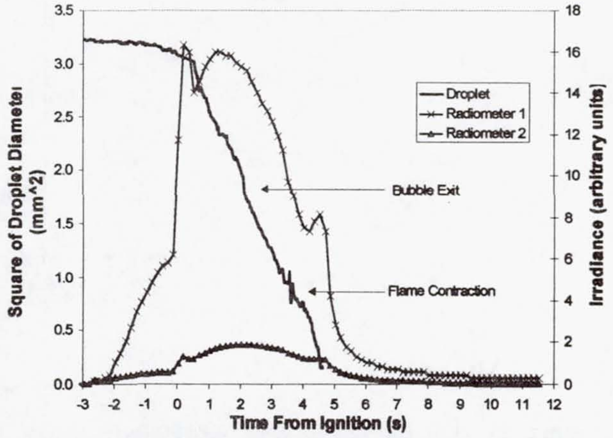


Figure 6 Droplet diameter and radiometer data for a heptane-hexadecane mixture droplet burned in the FSDC-2. The initial heptane mass fraction(Y) was 0.95.

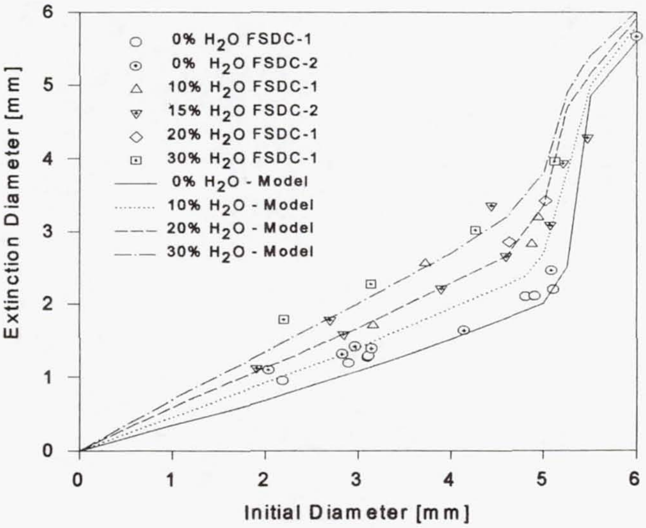


Figure 7 Extinction diameter as a function of initial diameter for methanol/water mixtures.

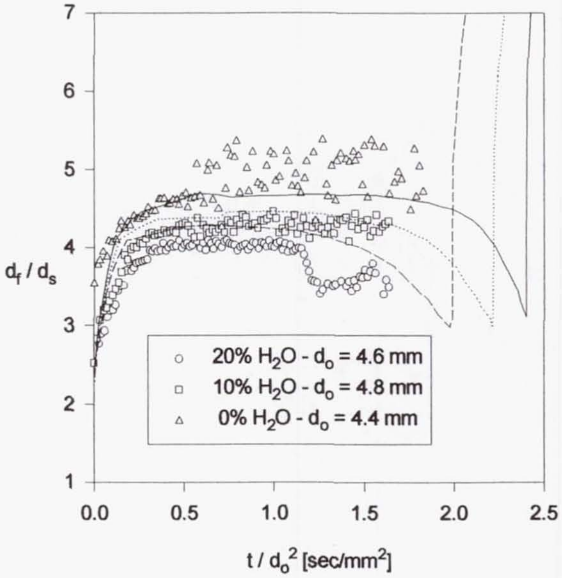


**Figure 8** Measured and calculated flame position for 5 mm methanol/water droplets with varying initial water content.

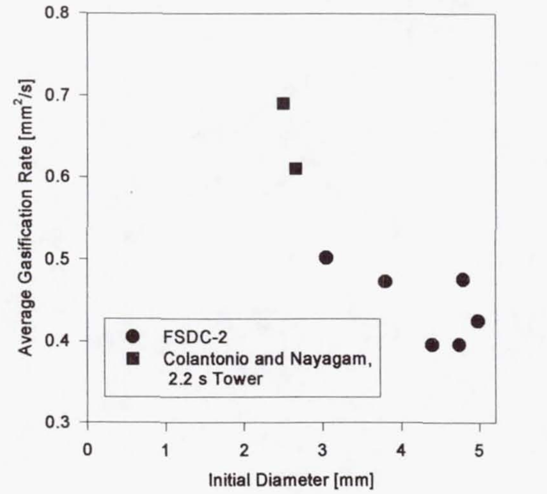


**Figure 9** Extinction diameter as a function of initial diameter for ethanol in FSDC-2.

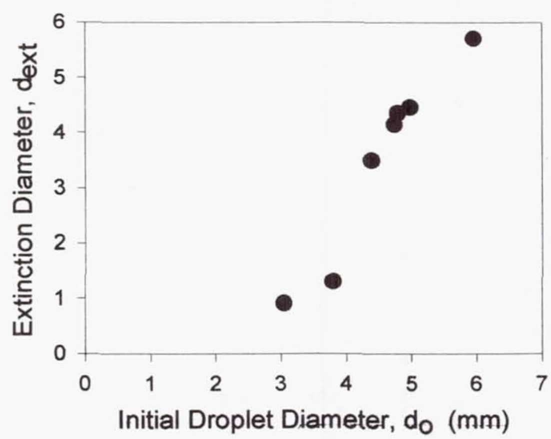


**Figure 10** Average burning rate as a function of initial diameter for ethanol burning in air.

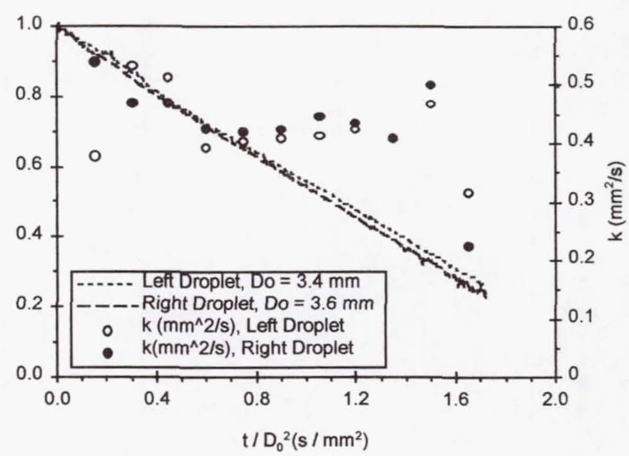


**Figure 11** Burning rate history for both n-decane droplets of a two-droplet array with an initial separation distance of approximately 7 mm.

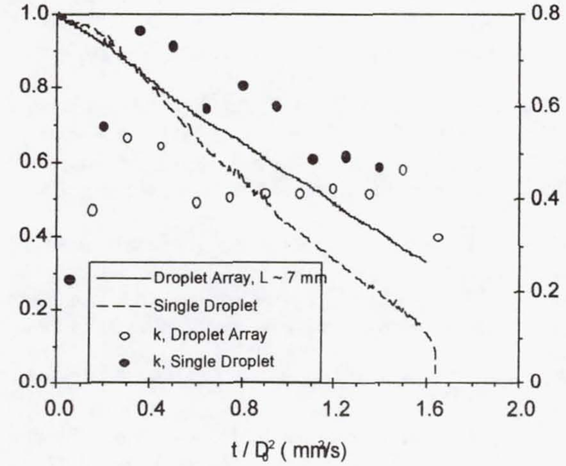


**Figure 12** Burning history and instantaneous burning rate comparison of a single droplet and droplet array in FSDC-2. The initial droplet size was approximately 3.7 mm for both droplets in the array and the single droplet.

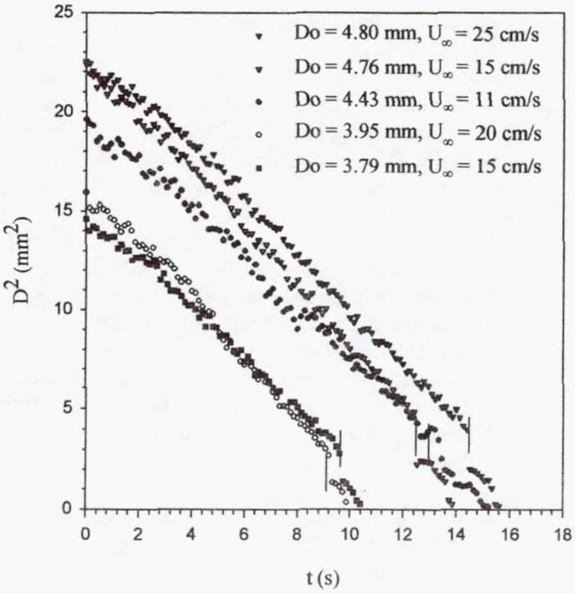


**Figure 13** Droplet diameter squared versus time for single n-decane droplets in a forced convective field.

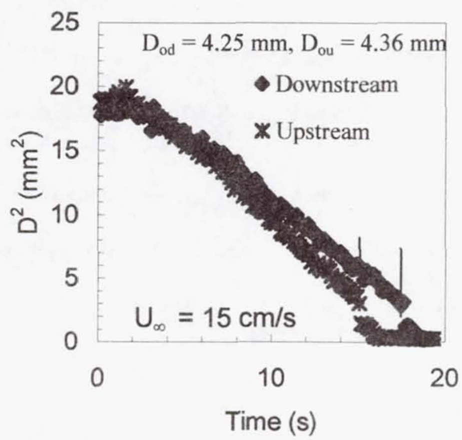


**Figure 14** Burning history of a two-droplet linear Array under forced convection.

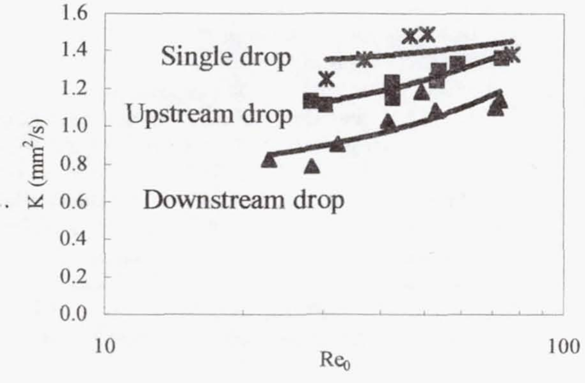


**Figure 15** Average burning rates for single and two-droplet, linear arrays as a function Reynolds

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