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FLUID MANAGEMENT OF AND FLAME SPREAD ACROSS LIQUID POOLS

H. D. Ross[1] and F. J. Miller[2], [1]NASA Glenn Research Center; MS 500-115, 21000 Brookpark Road, Cleveland, OH 44135-3191; Howard.D.Ross@grc.nasa.gov; [2]National Center for Microgravity Research; MS 110-3, 21000 Brookpark Road, Cleveland, OH 44135-3191

INTRODUCTION

The goal of our research on flame spread across pools of liquid fuel remains the quantitative identification of the mechanisms that control the rate and nature of flame spread when the initial temperature of the liquid pool is below the fuel's flash point temperature. As described in [1,2], four microgravity (μg) sounding rocket flights examined the effect of forced opposed airflow over a 2.5 cm deep x 2 cm wide x 30 cm long pool of 1-butanol. Among many unexpected findings, it was observed that the flame spread is much slower and steadier than in 1g where flame spread has a pulsating character. Our numerical model, restricted to two dimensions, had predicted faster, pulsating flame spread [3] in μg. In a test designed to achieve a more 2-D experiment, our investigation of a shallow, wide pool (2 mm deep x 78 mm wide x 30 cm long) was unsuccessful in μg, due to an unexpectedly long time required to fill the tray [4].

As such, the most recent Spread Across Liquids (SAL) sounding rocket experiment had two principal objectives: 1. determine if pulsating flame spread in deep fuel trays would occur under the conditions that a state-of-the-art computational combustion code and short-duration drop tower tests predict, and 2. determine if a long, rectangular, shallow fuel tray could achieve a visibly flat liquid surface across the whole tray without spillage in the μg time allotted. If the second objective was met, the shallow tray was to be ignited to determine the nature of flame spread in μg for this geometry. For the first time in the experiment series, two fuel trays – one deep (30 cm long x 2 cm wide x 25 mm deep) and one shallow (same length and width, but 2 mm deep)-- were flown. By doing two independent experiments in a single flight, a significant cost savings was realized. In parallel, the computational objective (work conducted at Univ. of California at Irvine by W. Sirignano and collaborators) was to modify the code to improve agreement with earlier results. This last objective was achieved by modifying the fuel mass diffusivity and adding a parameter to correct for radiative and lateral heat loss [5].

GROUND-BASED TESTING AND RESULTS

The following types of flame spread experiments were performed in 1g and in μg prior to the sounding rocket flight: (a) flame spread across shallow pools (2 mm deep, 20 mm wide, and 165 mm long) in ambient air and in enriched O_2 subject to a 30 cm/s opposed flow inside a flow duct; and (b) flame spread experiments as in (a) but with a deeper trays (10 & 25 mm) in μg at varying temperatures. As discussed later, tests were also performed to validate a new fluid filling technology.

Flame spread results: The pool width was selected based on recent work that showed that the 20 mm wide pools suppress unstable flame front shapes that appear in 80 mm wide trays [6], and on the need to fit two trays into the flow duct. The length was selected based on available test time and room in the experimental chamber. The trays were filled with 1-butanol in 1g, and then ignited after release in μg. For the 2 and 10 mm deep trays, the experimental realization of pulsating flame spread across a flammable liquid in μg was accomplished for the first time [5]. For the shallow tray at either gravity level, the pulsation frequency increases as O_2 concentration increases, until the flame spread character becomes uniform at sufficiently high O_2 concentration (e.g. 25-26%), as shown in Fig. 1.

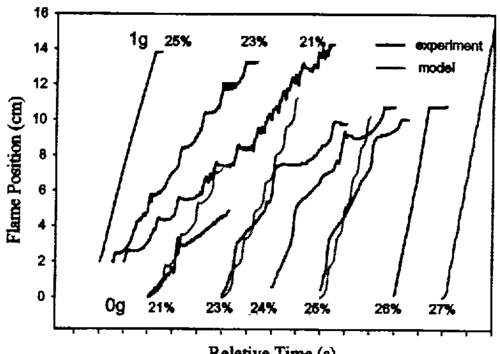


Figure 1. Flame position for a 2 mm deep tray.

This is consistent with the model (thin red lines on Fig. 1) and our earlier conclusion that gas-phase phenomena (not just liquid-phase phenomena) contribute to the onset or elimination of pulsating spread [6]. The pulsation frequency in 1g is higher than in μg, even at elevated O_2 concentration, and the transition to uniform spread occurs at slightly higher O_2 concentration in the μg experiments. Thus, while O_2 concentration and shallow pool depth can yield similar flame spread character at either gravity level, they alone cannot render the spread behavior identical in μg and 1g in the pulsating spread regime. In tests with the 10 mm deep pools, the sequential transition through all three subflash flame spread regimes -- from pseudo-uniform to pulsating to uniform spread -- was achieved in μg. As was predicted by the model, pulsating spread for the deeper 10-mm pools appears to be achievable only in a narrow band of O_2 concentrations (between 23 and 25%) in μg.

For the 25mm deep pools, a temperature-controlled tray was employed. We conducted μg experiments at fuel temperatures from 23 °C to 26 °C and O_2 concentrations from 21 to 25 %. For 21% O_2, steady flame spread rates between 1 cm/s (23 °C) and 2 cm/s (27 °C), as shown in Fig.2, were obtained in the 3 s that the flame had spread far enough from the igniter to be reliably tracked. As the O_2 level was increased, two new phenomena were noted. At O_2 levels of 23% and 24% the flame wobbled side to side as it spread. This was not classical pulsating spread, in which the flame brightness increases markedly just before the flame (or a large part of its front) jumps, but a higher speed, side-to-side wobble. At 25% O_2, regardless of temperature, the flame-front shape changed from convex to concave, i.e., the edges along the sides of the flame led the portion in the middle. This is the first time such a flame shape was observed in our tests (though it has been seen with solids' flame spread). A preliminary 3D version of the model, however, predicted such a shape.

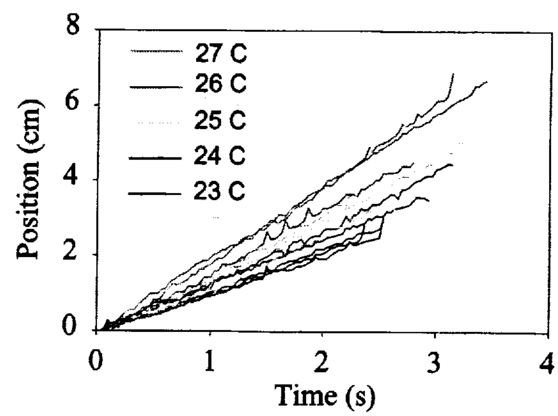
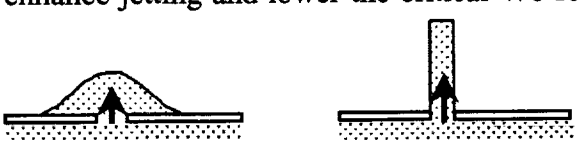


Figure 2. Flame position vs. time for a 25 mm deep tray in mg

Fluid filling re-design and testing: Each experiment on the sounding rocket required 1-butanol to be pumped from a reservoir into an open tray in μg. For the 25 mm deep tray, 1-butanol was pumped into one end of the tray and allowed to fill the tray lengthwise by inertial and capillary forces (as had been done on previous flights). The same design could not be used for the 2 mm shallow tray because the time required for fuel spreading exceeded the available microgravity time. This conclusion was reached based on both the previous sounding rocket experiment as well as additional tests that were run in a freely floated rig on the NASA low-gravity aircraft. With such a configuration, the rate at which liquid spread and wetted the shallow tray bottom was measured to be less than 1 mm/s, so that the time needed to completely cover the 300 mm long tray, with filling from one end, was excessive. The 'free float' approach was vital to reach this conclusion, as the observed spread rate was much faster in a 'bolted down' configuration on the aircraft, owed to the latter's much higher residual acceleration and g-jitter.

A redesign was then performed for the shallow fuel tray and a manifold was utilized, from which fuel slowly issued from 10 small capillary holes (of diameter 0.33 mm) located 2 cm apart along the tray bottom. From a theoretical perspective, if the Weber[1] number of the fuel leaving each hole is too large, then the fuel stream leaving the hole will jet, i.e. it will no longer stick to the fuel tray bottom (as in Fig. 3a), but proceed in a column away from the tray (Fig. 3b). This can be avoided by filling with a sufficiently small fuel velocity leaving each hole. If, however, the velocity is too small, then not enough fuel would be pumped into the tray in the allowable (2 minutes) time in microgravity. In addition, it was necessary to choose the fill holes' diameter small enough such that the pressure drop through them was much larger than through the manifold to assure an even distribution of fuel along the tray bottom, but making the holes more prone to jetting (since V increases for small holes with the same volume flow rate). Further complicating the design was the possibility that one or more fill holes might clog with debris or bubbles, and potentially increase the Weber number of the others above the critical value. Numerous 1g tests were performed with upward and downward facing holes. This design was tested in the free-float rig, with transparent parts utilized initially to visualize the flow in the manifold and capillaries. Later tests were also performed with a metal tray bottom whose anodized surface roughness matched that planned for flight. The degree of roughness was optimized based on sessile droplet tests performed in 1g and μg that examined the rate of spread of liquid along a flat surface.

From the 1g tests a critical Weber number of between 5 and 10 was found, with the higher numbers applying to downward facing holes. Although one might expect gravity to enhance jetting and lower the critical We for downward facing holes, in fact it tends to pull the liquid into a hanging mound that absorbs some of the jet momentum. For upward facing holes the fluid does not mound, but gravity does act to pull down on a fluid column. Thus, it was unknown how the fluid would behave in microgravity; if it wetted the surface well, it might jet more easily than in either 1g configuration. The KC-135 tests were not able to answer this question directly because the pump used for filling the trays was a positive displacement pump with two pistons. Thus, the We number was not constant over the whole pump cycle. An average critical We number of 3 was found in microgravity, though the instantaneous value was higher. From all of these tests, the liquid pumping rate was optimized, such that the shallow tray could be filled completely within 42 seconds in μg. As the aircraft test periods were less than this requirement, a complete test in μg was performed for the first time in the sounding rocket experiment itself.



(a) We << We_{crit} (b) We >> We_{crit}

Figure 3. For low We liquid adheres to the tray bottom (a); for high We it breaks free into a jet.

SOUNDING ROCKET TESTING

[1] Weber number is the dimensionless ratio of inertial to surface tension forces, We = $\rho V^2 D/\sigma$, with ρ the liquid density, V the mean velocity, D the hole diameter and σ the surface tension.

A sequence of operations was selected such that two or three tests could be run. After the deep tray was filled with liquid, the shallow tray was filled during the time period normally allotted to the damping of liquid motion in the deep tray. After both trays were full, the opposed airflow fan was energized, followed by two 'smoke wires' to visualize near-surface and bulk streamlines in the air flow, and then the deep tray was ignited and flame spread was observed. As in our other sounding rocket experiments, particle image velocimetry and rainbow schlieren deflectometry (RSD) were utilized to observe the liquid-phase flow and temperature fields in the central portion of the deep fuel tray. In addition, infrared (IR) thermography provided the surface temperature in the same region of the tray. After the flame spread and extinguished in the deep tray, the smoke wires were de-energized, and viewing and ignition switched to the shallow fuel tray. Diagnostics for this tray included only flame imaging, IR thermography, and strobe-light imaging to check for fuel spills during flame spread.

The sounding rocket flight took place on February 12, 2001, and so the data have not yet been analyzed in detail. An initial condition was selected as air at 1 atm and 25 C. The fluid management designs were successful as the trays filled completely and yielded a flat liquid surface. Upon sequential ignitions, each tray remarkably exhibited pulsating flame-spread behavior, which was anticipated for the shallow tray based on drop tower tests and modeling, but never before seen in previous μg experiments for the deep tray. Finally, the detailed diagnostics all performed nominally and yielded novel observations. The IR showed that twin vortices formed with the deep pool in both 1g and in μg during the crawl phase of the pulsating spread; similar vortices formed with the shallow pool in 1g, but surprisingly not in μg. Instead a long preheat region was observed in μg during the crawl phase of the pulsating flame spread in the shallow tray. The RSD showed vortices in the liquid phase of the deep tray that resembled those seen in 1g, a finding very different than that observed in earlier sounding rocket flights.

SUMMARY

The fluid management design achieved the largest-ever flat rectangular free liquid surfaces in μg, without jetting or spilling of any liquid. A classical manifold design can be made to work well in μg, if attention is given to the Weber number limitations and to the spreading characteristics on the tray surface. Pulsating spread in μg, heretofore never seen, has now been achieved for several pool depths, O_2 concentrations, and temperatures. For fixed pool depth, pulsation frequency increases with O_2 concentration and temperature until a limit is reached, and spread becomes rapid and uniform. On the other hand, pulsation frequency decreases with pool depth for all O_2 concentrations and temperatures. Modeling improvements have yielded sharply better agreement with experiments, though experimental flame spread across liquid pools continues to exhibit some behaviors that are unpredicted.

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