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FLAME SPREAD ACROSS LIQUID POOLS*

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For flame spread over liquid fuel pools, the existing literature [1-9] suggests three gravitational influences: (a) liquid phase buoyant convection, delaying ignition and assisting flame spread; (b) hydrostatic pressure variation, due to variation in the liquid pool height caused by thermocapillary-induced convection; and (c) gas-phase buoyant convection in the opposite direction to the liquid phase motion. No current model accounts for all three influences. In fact, prior to this work, there was no ability to determine whether ignition delay times and flame spread rates would be greater or lesser in low gravity.

Flame spread over liquid fuel pools is most commonly characterized by the relationship of the initial pool temperature to the fuel's idealized flash point temperature, with four or five separate characteristic regimes having been identified [2]. In the uniform spread regime, control has been attributed to: (a) gas-phase conduction and radiation [2]; (b) gas-phase conduction only [10]; (c) gas-phase convection and liquid conduction [11], and most recently (d) liquid convection ahead of the flame [3]. Suggestions were made that the liquid convection was owed to both buoyancy and thermocapillarity. In the pulsating regime, complicated flow structures have been observed in both the gas and liquid phases with circulation around several centers; these flows, were attributed to combined thermocapillary and buoyant effects [1].

Of special interest to this work is the determination of whether, and under what conditions, pulsating spread can and will occur in microgravity in the absence of buoyant flows in both phases. One possible mechanism for pulsating spread in microgravity is if the "premixed gas - diffusive burning" pulsations are due to periodicity between gas-phase conductive and liquid-phase convective control, as suggested in [7]. A second possibility, which will be determined by these investigations, is whether pulsations may be induced in low gravity by the presence of slow, forced, gas-phase, flow.

The approach we have taken to resolving the importance of buoyancy for these flames is: (a) normal gravity experiments with advanced diagnostics; (b) microgravity experiments; and (c) numerical modelling at arbitrary gravitational level.

NORMAL GRAVITY EXPERIMENTS [12]: Most normal gravity flame spread tests were conducted inside a large metal glove box, 1.2 m long x 0.8 m wide x 0.65 m high which served to eliminate drafts from the room. The fuel tray, which was 300 mm long and 20 mm wide, was placed lengthwise in the center of the box and leveled on a platform. By placing aluminum inserts in the tray to raise its bottom, the depth of the tray could be varied from 12.5 mm to 2 mm. The inside walls of the tray were lined with 3 mm thick glass over the entire depth and length to reduce heat losses to the walls (the tray was 20 mm wide with the glass in place). The outer aluminum walls of the tray, as well as the bottom, were hollow, allowing a glycol-water solution to flow between them as a means of heating or cooling the tray. A standard CCD video camera recorded the flame, and the image was later digitized to allow mapping of the flame position vs. time. This semi-automated data conversion technique allowed detailed graphs of flame position vs. time for dozens of runs to be made with relative ease.

Experiments on pool depth effects (where buoyancy might be expected to be important) were carried out between temperatures of 13 °C and 21 °C, at approximately 1 °C intervals. For pools of 1-propanol at T_{Liq} = 17.3 °C, the 10 mm pool shows a slightly higher flame speed than the 5 mm pool (borne out in several runs), and both are well above that shown by the 2 mm deep tray. Furthermore, at this temperature, which is approximately the transition temperature from uniform to pulsating spread, the shallow pool clearly shows regular pulsations, while the others show only small amplitude irregular variations in spread rate. In fact,

* Portions of this paper are reprinted from references 5, 12, and 15.

we found definite, cyclic pulsations at temperatures as high as 18.4 °C for the 2 mm pools, which was thought to be above the transition temperature, but very uniform spread for the deeper pools. This difference in flame spread character with depth provides indirect evidence that there may be a weak liquid phase flow at these conditions that produces pulsations in a shallow fuel layer but yields uniform spread in deeper pools.

Well into the pulsating region, at T_{Liq} = 14.1 °C, all three depths showed regular pulsations, and it is quite clear that the spread rate is dependent on pool depth. Again, the deeper pool shows a higher flame propagation rate, with the difference between 5 mm and 10 mm now somewhat enlarged compared to the 17.3 °C pool. Furthermore, it is clear that the pulsation wavelength is also strongly dependent on pool depth. Deeper pools exhibit much longer wavelength pulsations, in this case 4 pulsations over the 25 cm distance presented for the 10 cm deep pool, compared to 13 for the 2 mm deep pool.

The flame velocity in the "jump" portion of the cycle appears to be constant at about 12.5 cm/sec and therefore not to be a function of the pool depth, while the crawl velocity increased from 1 cm/sec at 2 mm deep to 3 cm/sec for fuel layers 10 mm deep. This indicates that the conditions in the gas phase are similar and controlling *during* a jump. Between jumps, the flame propagation is severely retarded for the shallowest pools, and the flame remains nearly stationary at times. This is most likely due to a hindered development of the subsurface eddy which preheats the liquid enough for the flame to spread further.

As shown by Williams [13], the velocity in the liquid phase, which is of the same order as the flame spread velocity, can be thought of as receiving contributions from both buoyancy and surface tension effects. His scale analysis shows that for shallow pools the dependence of the average flame spread rate should range from between h to h^3, depending on whether the dominant driving mechanism is surface tension or buoyancy, respectively (here, h is the boundary layer depth = pool depth for shallow pools). Experiments in which depth effects were reported only showed dependence from $h^{1/3}$ [9] to at most h [14]. While conceding that more than three depths should be studied to reliably establish a trend, the three depths we used indicate a linear dependence of average flame velocity on depth in the pulsating regime, and a less than linear dependence in the uniform regime. As noted above, there is no depth dependence on the jump velocity; the linearity arises from the increase in crawl velocity with depth. From this it seems that surface tension is the primary driving mechanism in the flow, with liquid-phase buoyancy of lesser importance than is attributed to it in Ref. 3. Further support for this conclusion is that, for shallow or deep pools, no one has witnessed anything approaching a cubic dependency, or even a higher than first-order dependency, on depth.

The pool depth has a strong effect on the pulsation wavelength, but there is no easily discernable temperature dependence. The depth effect may be due to a limitation imposed by the bottom on the size of the liquid circulation zone that slightly precedes the flame leading edge. This zone cannot fully develop in the shallow pools, and the flame catches up more rapidly. Drag on the bottom may also slow down this flow during each cycle, leading to more frequent pulsations but a lower overall velocity. This explanation is consistent with numerical predictions of more frequent pulsations for increasing values of liquid viscosity and/or decreasing surface-tension coefficient [6]. For the 2 mm deep pool, surface deformation may also be significant [8] and lead to the formation of roll cells; these cells could be the cause of the depth effect on pulsation. Future work is needed to resolve the subsurface flow in shallow fuel pools and to confirm this hypothesis.

Recently [15] we examined the temperature field using rainbow schlieren deflectometry (RSD) and the velocity field using particle image velocimetry (PIV) for uniform and pulsating flame spread using propanol and butanol as fuels. The RSD and PIV were recorded with standard CCD video cameras and S-VHS video recorders. The particle tracks, obtained using an 840 nm laser diode light sheet and 12 micron pliolite particles, on the video record were digitized, color coded, and time-averaged to assist analysis.

Figure 1 is a 35 mm still photograph, taken off the video records, of the RSD visualization of the refractive index gradients observed ahead of a left-to-right spreading flame in the pulsating regime. Figure 2 shows a 35 mm still photograph superposing 10 consecutive frames to reveal a 0.33 sec time-lapse picture of the flow field for the same conditions; in this case the flame moves from right-to-left. In order to determine the direction of the particle movement, the first frame was color coded red and the last frame was color coded blue; a gradual transition between the two was then performed on intermediate frames. The initial initial frame corresponds to when the flame was just visible on the right side of the photograph. Figure 2 suggests that the flow ahead of the flame has multiple, counter-clockwise rotating, centers.

In comparing figs. 1 and 2, notice that the flow penetrates to the full depth of the pool, unlike the temperature field. Thus, as might be expected, the use of methods responding to *thermal* variations, such as RSD or interferometry, to infer the *flow* patterns, can be misleading. From the video records, the flame position never surpassed a surface location of elevated temperature indicated by the color change along the surface. These results are consistent with the findings of Ito et al [3] who used holographic interferometry to determine the temperature field. The distance at which surface flow is seen ahead of the flame exceeded that of the temperature field. The set of measurements implies that the flame advances only to that position where the surface temperature rises to the flash point; however, the flow head clearly surpasses this location and the flame's leading edge throughout the pulsating spread cycle, consistent with the conclusions of refs. 6-7.

Similar measurements were made in the uniform spread regime. The RSD indicates elevated liquid temperatures penetrate less distance both into the pool depth and ahead of the flame. The PIV also shows liquid-phase convection does indeed exist a short distance ahead of the flame. Most likely then convection is the dominant heat transfer mechanism all the way to the flash point even in the uniform spread regime, a conclusion which is consistent with ref. 3.

MICROGRAVITY EXPERIMENTS [5,12]: We performed a series of normal and microgravity (μg) experiments in the NASA Lewis 5.18 second Zero Gravity Facility. A 15 cm diameter, 1 mm deep tray was mounted inside a 113 liter pressure vessel for both safety purposes and to permit the oxygen concentration to be varied. The base of the tray was machined from ceramic material to minimize heat losses and ease ignition from a small nichrome, electrically-heated wire (250 μm diameter) cantilevered over the tray. To provide a reproducible fill level, and to minimize pre-drop evaporation, the pool was filled by gravity just before the drop. Multiple safety systems were employed as described below. The sole instrumentation was top and side view cameras, operating at 24 f/s and 50 f/s, respectively, and a thermocouple to determine the initial system temperature. The slow speed of the cameras was required due to the low luminosity and thinness of the flame. Following the test, the flame spread rate was determined from the visible flame diameter as a function of time through the use of a digitized motion analyzer.

A major problem with μg, fluid experiments is the control of the liquid surface, whose shape is determined by a balance of gravitational and surface tension forces, i.e. the static Bond number, $Bo=\rho^{*}g^{*}l^{2}/\sigma$, where ρ is the liquid density, g is the gravitational acceleration, l is the characteristic vessel dimension, and σ is the surface tension. For propanol, Bo, based on a 7.5 cm radius, is about 1800 in normal gravity and 0.0018 in microgravity. As such, the liquid surface transitions from a "flat" configuration in normal gravity to one of constant curvature, related to its contact angle. Scale analysis and drop tower experiments in both the 2.2 sec and 5 sec facilities were performed in partially and completely filled cylinders to estimate the transition and settling time. For simple comparison to normal gravity results and due to the limited μg time, the surface curvature and transition time needed to be minimized. The use of very shallow (1.6 mm) pools in completely full trays provided such minimization; also the contribution to spread of gas-phase buoyancy was isolated by a comparison of normal and microgravity flame spread characteristics.

Although the leading edges were virtually identical in appearance, the trailing shape of the microgravity flame was nearly parallel to the pool surface, indicating the suppression of buoyancy. For conditions where the corresponding normal-gravity flame spread was uniform, the microgravity spread was also uniform, at rates comparable to the normal gravity flames. The similarity of normal and microgravity spread in the uniform regime indicates that (a) buoyancy-driven motion in either phase had no influence on uniform flame spread, (b) radiation effects on spread were probably small for this scale experiment (the large change in flame height made no difference), and therefore (c) liquid conduction, gas conduction or thermocapillary-induced liquid motion were the controlling parameters. Normal gravity results described above suggest the latter is the controlling parameter.

In contrast, pulsating flame behavior in microgravity, where buoyant flows in both the liquid and gas phases are negligible, was never observed. Instead, independent of O_2 concentration, fuel or diluent type, the initial conditions which gave rise to pulsating flame spread in normal gravity coincided with those causing extinguishment in a quiescent, microgravity environment. In those cases where the flame did spread to the edge of the tray, the microgravity flame subsequently collapsed "bottom-up," i.e. toward the luminous region farthest from the pool, until the remaining flame was very thin and blue at a distance of 10-15 mm from the pool surface. After this collapse, the flame lifted very slightly away from the pool, and its luminosity steadily diminished, disappearing at low O_2 concentrations before the end of the test.

In a second series of microgravity tests, the fuel tray was changed from being circular to a trough with dimensions 15 cm x 2 cm x 1 cm deep. In this case 1-butanol in air and 1-propanol in 17% O_2 were used as the fuels, since they produce pulsating flames at room temperature. To test whether the extinction condition can be changed and whether pulsating spread can occur in the presence of a forced air flow in microgravity, a series of tests was conducted with a fan providing a slow, opposed flow of 10-25 cm/sec, as measured with a TSI hot wire anemometer. *This flow regime is inaccessible in normal-gravity flame spread due to the induced buoyant flows.* Initial experiments confirmed that the change of tray geometry from a shallow, axisymmetric pool to a deep, linear pool did not affect the previous conclusions regarding microgravity flame spread behavior under quiescent conditions: the aforementioned pulsating/extinction and uniform/uniform correspondence was maintained in the new pool when comparing normal/microgravity behavior. However, with the opposed air flow the flame was sustained in microgravity where under quiescent conditions it had extinguished. This agrees with studies of microgravity flame spread over solids, in which slow, opposed flow lowers the limiting oxygen index [16]. Unlike solids though, the flame stand-off distance remained immeasurably close to the pool surface until extinction. For solids, surface re-radiation has been cited as contributing principally to the extinction [17] , but the low surface temperature of the pool makes this an unlikely mechanism. These differences suggest that other factors, perhaps gas-phase radiative losses [16], conductive losses to the environment or the pool [6], and/or low oxygen transport rates [18], are contributing to flame extinction of liquid pools in microgravity.

The character of the flame spread with opposed flow was unsteady, and to some extent pulsating, with the frequency of the pulsations comparable to those observed in normal gravity. It was determined that the fan swirl was also approximately of this frequency (no flow straightener was used), so a definite statement that classical pulsating spread was observed is not yet justifiable. The flames appeared very responsive to the air flow; when the air flow weakened, so did the flame, to the point that it nearly extinguished. Therefore, the tests showed conclusively that the flame spread behavior was tied to the air flow, furthering proof that subflash microgravity flame spread is not controlled entirely by liquid convection.

NUMERICAL MODELLING: Our recent computational studies have addressed unsteady, axisymmetric and planar open pool configurations. The transient numerical model uses the SIMPLE algorithm [19] with the SIMPLEC modification [20]. This method uses primitive variables (u, v, p, h), a staggered mesh, and the hybrid-differencing scheme. The continuity equation is satisfied by solving the pressure-correction equation in the SIMPLE algorithm. A "phase-split" solution technique is used in that the gas and liquid phases are solved separately. At the gas/liquid interface, Dirichlet-type boundary conditions from the solution of the liquid phase are used for the solution of the gas phase, while Neumann conditions from the gas phase are used for the upper boundary of the liquid phase. Accurate modelling of the reaction zone requires a fine numerical mesh not only in the reaction zone itself, but also in the region between the reaction zone and the liquid surface (to predict accurately the liquid surface heating ahead of the flame). In order to save computer time, a partially-adaptive grid scheme is used to move the fine mesh region along with the spreading flame in the radial direction. Convergence of the governing equations is optimized by underrelaxation and extra iterations of the pressure-correction equation.

The effects of blackbody radiation, surface tension, gravity level, variable density and thermophysical properties, vaporization, and finite-rate chemical kinetics are included in the computational model. Infinitely-fast chemical kinetics (i.e., the flame sheet approximation) cannot be assumed because the flame leading edge is premixed. The model assumes that the liquid surface remains flat and horizontal at all gravity levels. Solutocapillary forces and recession of the liquid surface due to vaporization are neglected.

It is predicted that at normal gravity, the temperatures in the reaction zone are generally higher and the reaction zone thinner than at microgravity. The flame standoff distance is slightly smaller at normal gravity than at microgravity, but the reason for this is not as clear as with flame spread over solids. Without the effects of surface tension, flame spread rates decrease with increasing gravity level. When surface tension is included, flame propagation is either uniform or pulsating depending on the gravity level and initial pool temperature.

Pulsating spread of the precursor flame in front of the main body of the diffusion flame is caused by the formation of a recirculation cell in the gas phase in front of the flame leading edge (see Figure 3). This recirculation cell is formed by a combination of opposed flow in the gas phase due to buoyancy and concurrent flow in the liquid phase due to thermocapillary forces. At microgravity, a recirculation cell may still form in front of the flame leading edge solely due to the surface-tension-driven shear flow. However, the strength of this recirculation cell is relatively weak compared to that at normal gravity. Therefore, periodic flame pulsations are not predicted at microgravity.

Hot gas expansion plays a significant role in the flame pulsation process by causing the periodic destruction of the gas-phase recirculation cell. Large hot gas expansion velocities oppose the flow of fresh oxygen to the reaction zone. Both a lack of oxygen due to the hot gas expansion and quenching by the liquid surface leads to the extinguishment of the precursor flame. When hot gas expansion is not included in the simulations, small backward and forward pulsations of the precursor flame still occur at normal gravity due to the presence of the recirculation cell in front of the flame leading edge. However, the recirculation cell structure remains intact throughout the pulsation cycle, and the precursor flame is extinguished due to quenching by the liquid surface.

The presence of both opposed flow (e.g., due to buoyancy) and concurrent flow (due to thermocapillarity) in front of the flame is required for periodic flame pulsations to occur. Since the flame spread rate increases with initial pool temperature (due to a larger concentration of fuel vapor in the gas phase), the region of liquid surface heating ahead of the flame decreases. Without appreciable liquid surface flow ahead of the flame, a recirculation cell does not form in front of the flame leading edge; therefore, flame pulsations do not occur for initial temperatures near the flash point.

FUTURE WORK: Numerical simulations to date have used fuel properties of n-decane. In the future, alcohols such as methanol will be simulated to help explain the fundamental differences in flame spread characteristics between hydrocarbon and alcohol fuels. The effects of gas-phase radiation and diluent type will also be investigated.

In normal gravity experiments, we will continue to perform flow and temperature field visualization studies for several pool sizes over a range of temperatures. In addition we plan to do rocket-based microgravity experiments. The three principal areas will be: a. The effects of deeper and longer pools; b. the effects of small levels of forced gas-phase flow, both opposed and concurrent, in both the uniform and pulsating spread regime; and c. the effect of fuel type on flame spread.

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FIGURE 1: RSD Visualization of a butanol-air flame at 23 C. Flame spreads from left to right. The pool depth is 1 cm.

FIGURE 2: PIV of a butanol-air flame at 23 C. Flame spread is from right to left. Time lapse is 0.33 sec. Pool depth is 1 cm; note that the field of view of this picture is different than that of Figure 1.

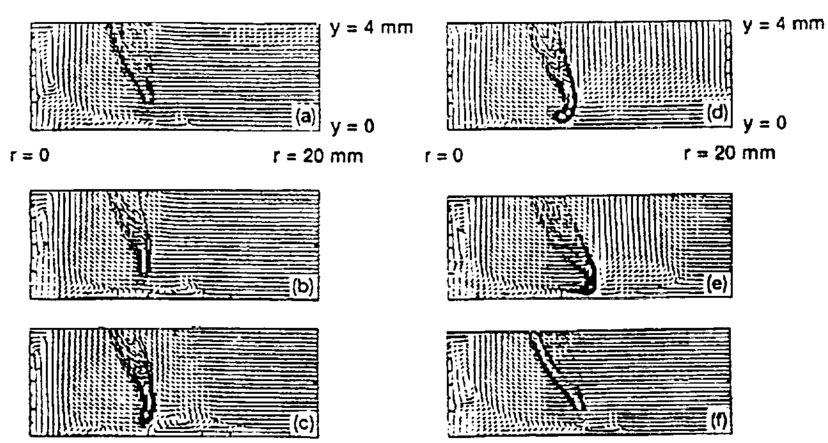
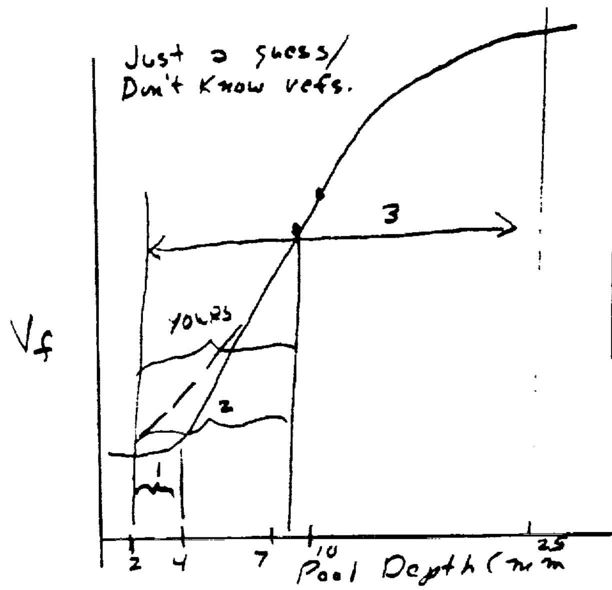


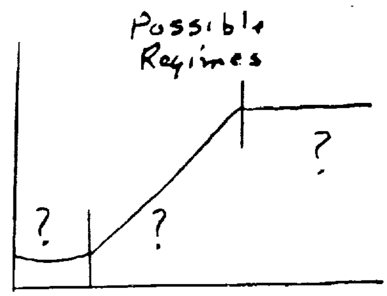
Figure 3.—Flow pattern and flame structure for one flame pulsation at normal gravity. In (d)-(f), the recirculation cell structure in front of the flame leading edge is destroyed during the premixed burning portion of the flame. Hot gas expansion opposes the flow of fresh oxygen to the reaction zone, and the flame moves backwards (as if it were being extinguished). The gas expansion rate decreases after the flame propagates through the premixed region, and, subsequently, the buoyant forces recover to provide fresh oxygen to the reaction zone.

See Color Plate F-5

COMMENTS

Question (Sandra Olson, NASA Lewis Research Center): You commented that there is no consensus as to the effect of pool depth on spread rate. Your data, for pools 2-10 mm deep, agrees qualitatively with literature data for 1-7 mm deep pools (i.e., linear relation). The other two references cited; 2-4 mm and 2-25 mm (I think) show no effect or a 1/3-dependence relation, respectively. Could you comment further on the trend with depth, specifically if it is possible that for the ranges studies each may be valid, which may help interpret controlling mechanisms of flame spread?





Answer: The question of how flame spread velocity varies with pool depth has been studied by several researchers with mixed results. We believe that the work with very shallow pools missed a depth dependence by collecting too few data points, and then plotting them on a log scale. The linear relation we described was based on 3 data points; we readily conceded in our paper that was insufficient to draw firm conclusions. Eventually one expects the flame spread rate to become independent of pool depth, at least in normal gravity (i.e., the pool could be considered "deep"). Previous work suggested that a pool depth of 1 cm would meet this criterion. It is met based on thermal penetration depth, but not momentum considerations: our PIV showed the vortex reaches the pool bottom.

Question (S. Raghu, SUNY at Stony Brook): In the flow pattern in the liquid resembles that during surface wave propagation have any studies been done from this perspective?

Answer: No one has yet measured quantitatively the extent of surface deformations or waves during flame spread. At the same time, we know they exist. Estimates suggest deformation is on the order of 1 mm, therefore deformation may be quite significant for shallow pools. Our PIV results suggest that some form of surface wave exists and affects the flow pattern in 2 mm deep pools, but not in 10 mm deep pools.