

Measurement of 3-D (Gas and Liquid) Flow Structures Generated by a Spreading Flame over n-Butanol

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ABSTRACT

This paper discusses a new 3-D experimental data that were obtained by a laser-sheet-particle-tracking (LSPT) technique for a spreading flame over n-butanol. The major heat-transfer process between the flame's leading edge and the liquid is a highly transient phenomenon involving both liquid and gas phases. These interact with each other through exchanges of momentum, heat, and mass. We improved our original 2-D LSPT and made it applicable to study 3-D measurement. Using this new 3-D LSPT we measured a series of velocity profiles in a pulsating flame spread over n-butanol at different distances above or below the liquid surface and obtained 3-D flow visualization in both liquid and gas phases. The new LSPT confirmed the existence of twin vortex flow on the liquid surface and deep in the liquid a few mm below the surface. These vortices gradually disappear as the laser sheet moves down from the liquid surface. A similar twin-vortex structure in the gas phase was also observed for the first time. These results proved that the convective flow in both liquid and gas phases is 3-D in nature in the three trays we have used.

Key words: Flame spread, Pulsating, Laser-sheet-particle tracking, Three-D measurement.

INTRODUCTION

This is a continuation of our previous work on flame spread over liquids [1-3], in which we focused mostly on the two-dimensional flow and temperature structures both in the gas and liquids. However, our recent preliminary study showed the spread phenomena to be rather three-D in nature. Thus, in this paper we focus on a new optical technique that allows us to measure transient three-dimensional structure of liquid flow and newly obtained representative data. Flame spread over liquids is of our current interest due to the fundamental curiosity of its

mechanisms and necessity of understanding the phenomenon and its impact on fire safety in liquid-storage tanks and accidental spills of flammable (e.g., crude oil and jet fuel) liquids. In the flame spread over liquids, liquid convection ahead of a flame spreading over liquids is unique and plays an important role in the spreading process. Because of the presence of liquid convection, the flame spreading process is complex in comparison to the flame spread over solids [3,4].

In our past studies [1,2,5], we focused on obtaining accurate and detailed measurements of flow (both liquid and gas), temperature (both liquid and gas) and gaseous fuel concentrations generated by the spreading flame. The flame spread phenomenon is highly transient, involving both liquid and gas phases that interact with each other through the exchanges of momentum, heat, and mass, and the critical transport of those quantities that occur in the gas and liquid phases within several millimeters of its interface and a few centimeters upstream from the flame's leading edge. Researchers have applied optical measurement techniques to reveal flow, temperature and fuel concentration distribution. Three major efforts have been made recently: (1) NASA applied a rainbow schlieren to visualize the liquid flow and an infrared camera to measure the liquid-surface temperature [6,7]; (2) Castillo et al. [8,9] applied a Schlieren technique to measure the liquid flow; and (3) in our laboratory we applied holographic interferometry to visualize the liquid flow [10,11] and a dual wavelength holographic interferometry to measure fuel concentrations in the gas phase [11]. In addition, NASA conducted a successful series of flame-spread experiments over n-butanol under microgravity and provided valuable experimental data [12] that revealed a twin vortex ahead of the flame's leading edge showing the 3-D nature of the spread phenomenon. Castillo et al. [8] also deduced from their Schlieren experiments that the theoretical predictions of the flame-spreading velocity turn out to be larger than the directly measured values. They concluded that the 3-D nature of the flow is induced by the test section walls that retard and cool the warm liquid moving ahead of the flame.

Despite these findings, unfortunately the currently available (all the above mentioned) techniques are at best 2-D. Thus, we put together an international collaboration among the University of Kentucky, Oita University and Kanagawa Institute of Technology to develop a 3-D measurement technique which can accurately and simultaneously measure the transient 3-D structures of flow, temperature and fuel concentration. As the first step toward this integrated multi-measurement technique, we developed a laser-sheet-particle tracking (LSPT) technique that can measure a transient three-dimensional flow distribution of both gas and liquid phases simultaneously. We applied this new LSPT to the flame spread tests over n-butanol because its flash point temperature is above room temperature. Thus the control of its subflash point temperature is relatively easy. In addition, flame spread over butanol possesses a typical flame spread character consisting of pulsating and uniform spread regions as a function of the initial butanol temperature.

The focus of the present study is on the pulsating flame spread over a small laboratory-scale open pool of n-butanol. This is of fundamental importance in determining the mechanism by which heat is transferred to the unburned liquid ahead of the flame. Our effort is to improve the current understanding of the twinning flow that was first reported by Ross et al. at the NASA Lewis Research Center [12] from their infrared imaging (IR) measurement data on the fuel-surface temperature. In that data the IR images revealed that the preheated distance ahead of the flame was much longer in microgravity than in normal gravity where no twin structure was observed.

EXPERIMENTAL METHODS

A schematic illustration of the experimental apparatus and setup for the LSPT technique used in this study is the same as our previous studies [1-2] and is shown in Figure 1. Pyrex fuel trays used have three different width (5, 10, 20 mm), each having 20 mm in depth x 300 mm in length. The initial fuel temperature was measured by placing a thermocouple at the center of the tray a few mm below the liquid surface. The x-axis was fixed along the fuel surface, the y-axis was fixed along the vertical direction, and the z-axis was normal to x-y plane. The flame's leading edge was moving with the origin along the centerline of the tray on the fuel surface (see Figure 1c).

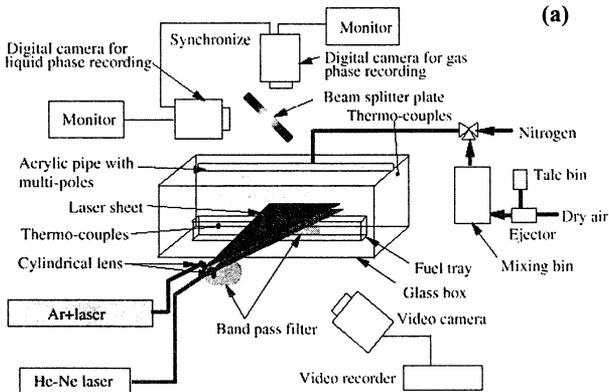


FIGURE 1 (a) A schematic illustration of the LSPT setup.

A small glass wool wick was placed at one of the ends and ignited by a small pilot flame; within a few seconds flame started to spread over the liquid. This ignition method gave us good

reproducibility in spread rate measurements. A 4-W Ar-ion laser was used as light source to form a 1-mm thick laser sheet by passing the beam through cylindrical lenses. Three positions of the laser sheet were chosen under the liquid surface at 2, 4 and 6 mm and two positions over the liquid surface in the gas phase at 1 and 2 mm as will be seen. Velocity profiles of the liquid and the gas convection were measured independently using the same LSPT technique.

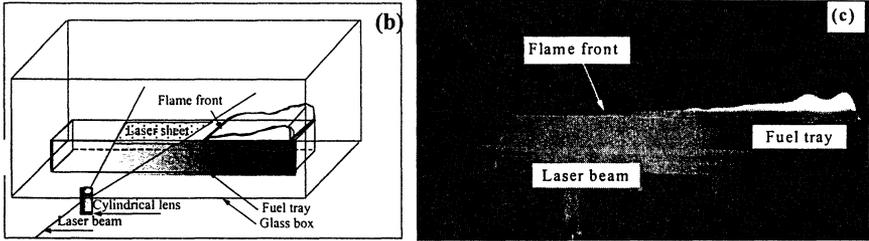


FIGURE 1(b) A schematic diagram of the fuel tray system. **(c)** A photograph of a spreading flame over the flame spread apparatus.

Talc particles were dispersed uniformly over the fuel surface for the measurement of gas phase convection. Aluminum particles of $15 (\pm 5) \mu\text{m}$ diameter were mixed with the liquid for the measurement of liquid convection. Some aluminum particles floated on the liquid surface and others entered into the liquid. The total mass of aluminum particles used were less than 0.1 grams so that the particles had little effect on the fuel properties. A high-speed camera system with an ultraviolet lens and an image intensifier having a speed of 500 frames/s was used to obtain the velocity profiles. The trajectories of these particles were recorded by the high-speed video camera, which was connected to a video system and a TV monitor for the real time observation of both the flow field and spreading flame.

RESULTS AND DISCUSSION

The test section width plays an important role in the flame spread mechanism because of the effect of the wall on the heat-transfer process. In order to study this effect we used three-test section widths: 5, 10, and 20 mm and kept the other dimensions the same. As the flame began to propagate, the preheated region extended ahead of the flame. It then developed two symmetric vortices that rolled up toward the sidewalls while the preheated liquid at the center continued to proceed upstream of the flame. Later, when the gaseous fuel-air mixture over the liquid surface reaches the lean flammability limit, the flame accelerates forward in the premixed gas layer and

covers the twin vortices. Our other paper [13] will discuss the fuel concentration profiles formed in the gas phase just ahead of the flame's leading edge. The existence of this side-flow structure was first reported by Miller and Ross [6] using a 20-mm wide tray. We confirmed for all the three tray-width cases that the preheated liquid extended ahead of the flame with twin vortices flow structure (Figures 2, 3a and 4).

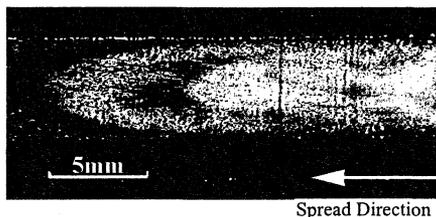


FIGURE 2 Top view of LSPT image of liquid flow 1 mm below surface (tray width: 5 mm).

It was found that the length of the preheat zone ahead of the flame is inversely proportional to tray width. Both buoyancy and surface-tension forces likely govern this flow circulation. Once the flame leading edge reaches the front of the liquid convection zone, it stops or decelerates to start another cycle. We also observed that the flame inclination angle defined in references [10,11] is smaller in the acceleration step than in deceleration because the flame acceleration only occurs when the gaseous fuel-air mixture is within the flammability limit [13]. Figures 3 shows two different 2-D particle-tracking images (a) before jumping and (b) after jumping, which were obtained by LSPT for the 10 mm wide tray 1 mm below the fuel surface. Figure 4 shows four different 2-D LS particle-tracking images; (a) is 1 mm below the fuel surface, (b) is 2 mm below the fuel surface, (c) is 3 mm below the fuel surface and (d) is 5 mm below the fuel surface. Figure 5, a schematic of the figure 4 results and a side view of the liquid flow along the centerline, reveals the formation of complex twin vortices in the liquid.

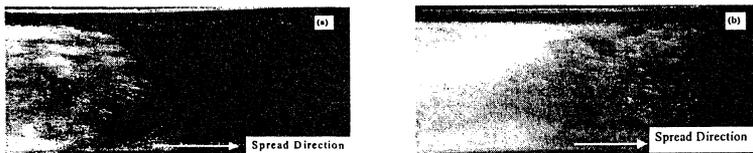


FIGURE 3 Two different top view images of liquid flow visualized by LSPT, both at 1 mm below the fuel surface. (a) before jumping and (b) after jumping.

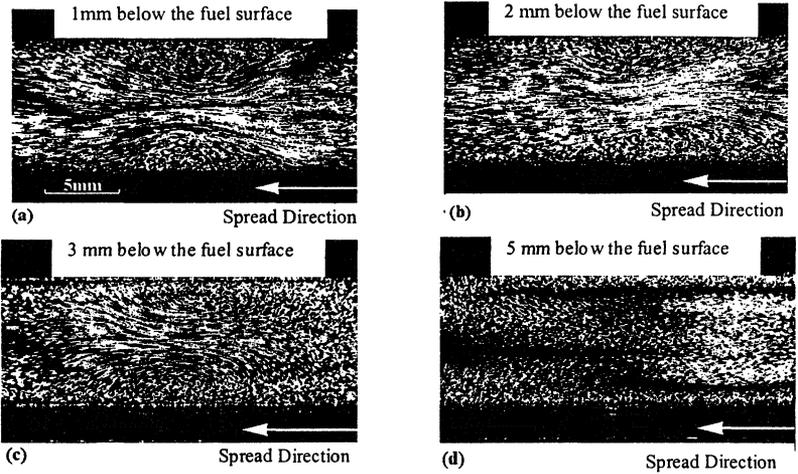


FIGURE 4 Four top images of liquid flow visualized at four different depths from the liquid surface using LSPT (tray width:10 mm).

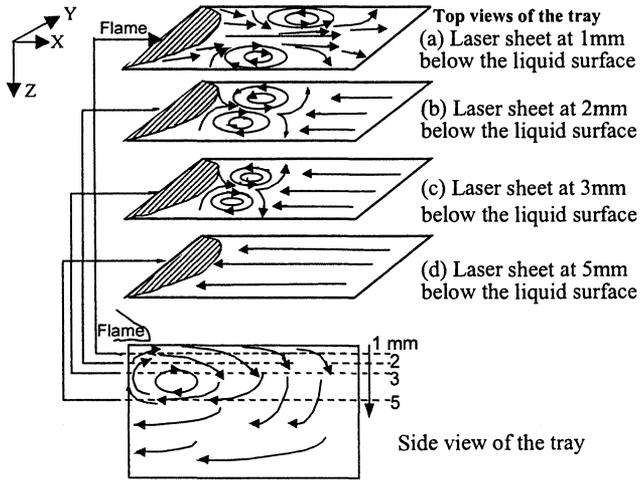


FIGURE 5 A schematic illustration of 3-D liquid flow structure constructed from LSPT images shown in Figure 4.

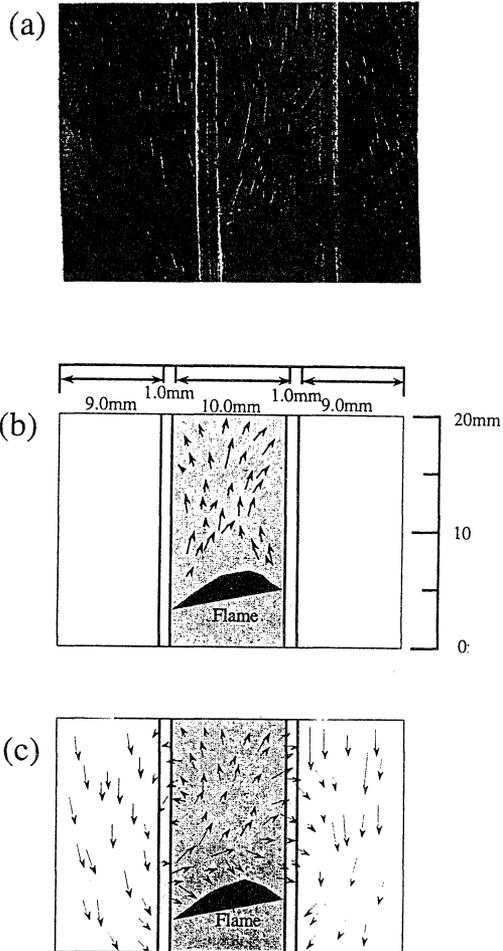


FIGURE 6 (a) LS particle tracking image, (b) A schematic of 2-D flow profiles in liquid-phase 0.5mm below the liquid surface (liquid temperature 21.5 °C), and (c) 2-D flow vector map in the gas-phase 0.5mm above fuel surface (air temperature 34.4 °C).

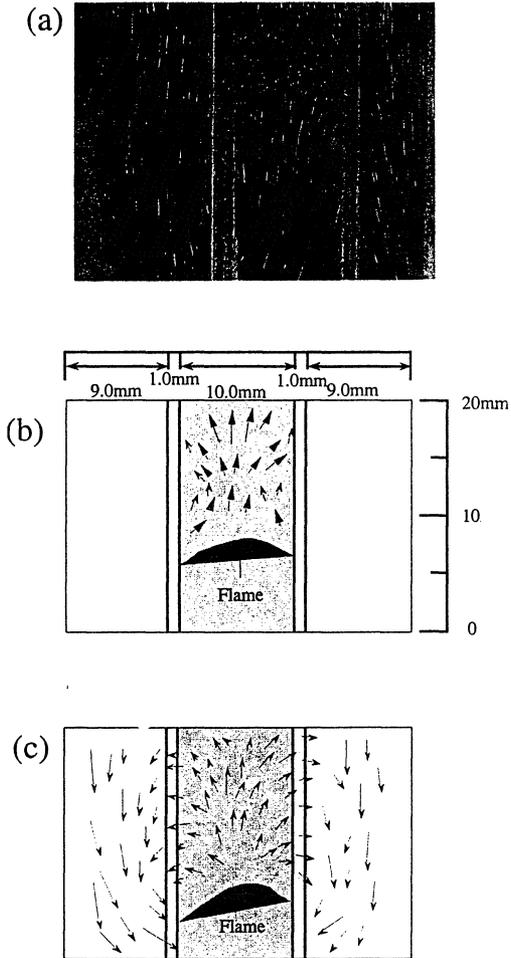


FIGURE 7 (a) LS particle tracking image, (b) A schematic of 2-D flow profiles in the liquid-phase 1 mm below the liquid surface (liquid temperature: 21.1 °C), and (c) 2-D flow vector map in gas-phase 1 mm above fuel surface (air temperature: 24.2 °C).

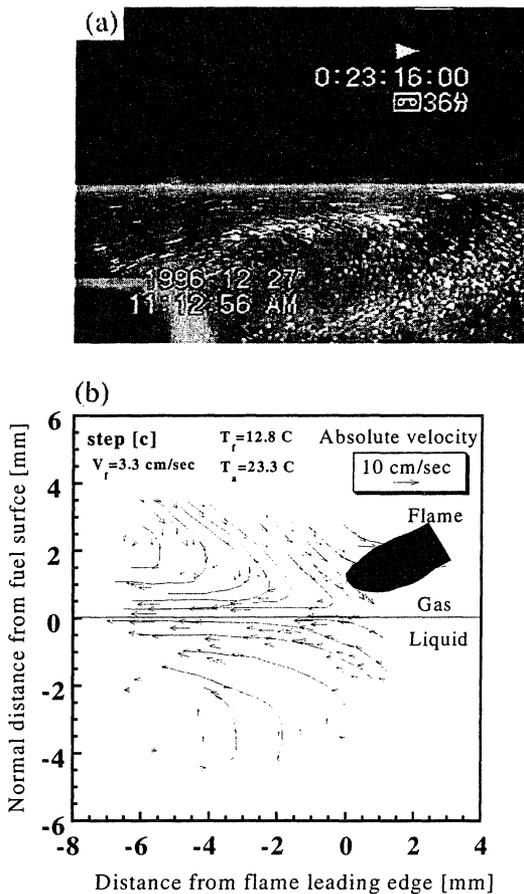
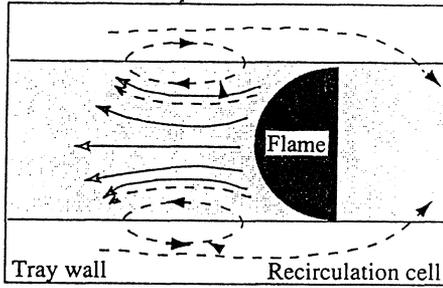


FIGURE 8 (a) LS particle tracking side view image, (b) A schematic of 2-D flow profiles in the gas and liquid (air temperature: 23.3 °C).

Top View
($z \approx 1.5\text{mm}$)



Side View

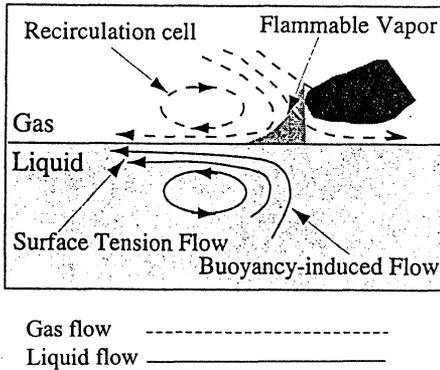


FIGURE 9 Illustrations of gas and liquid flow induced by a pulsating flame spread.

The twin vortices shown in Figure 5 were observed for all three tray-width cases. The formation of the fully developed twin vortices requires a certain pool depth, roughly 2.0 cm. When the pool depth is less than 0.5 cm, there is no circulation in the liquid. When the depth is between 0.5 cm and 2 cm, the liquid circulation is formed, but somewhat affected by the depth. Figures 6(a) and 7(a) show two LS-particle-tracking images obtained respectively 0.5 mm and 1mm below the liquid surface. Figures 6(b) and 7(b) show two 2-D-liquid-flow vector-diagrams obtained respectively 0.5 mm and 1 mm below the liquid surface. Figures 6(c) and 7(c) show two 2-D-gas-phase-flow vector-diagrams obtained respectively 0.5 mm and 1 mm above the liquid surface. Figure 8(a) shows a side view image obtained by LSPT and 8(b) is the schematic

of figure 8(a). Figure 9 shows two schematic illustrations of gas and liquid flow structures obtained by figure 8. Comparison of Figures 6(b) to 6(c) and Figures 7(b) to 7(c) suggest that roughly a 60 to 70 percent correlation between 2-D liquid-flow vector and 2-D gas-flow vector for each case. This indicates that the gas flow near the liquid surface is influenced by the liquid surface-flow that is strongly influenced by the liquid surface temperature near the flame leading edge.

Figure 9(b), a side view of liquid and gas flow profiles, shows the formation of twin vortex, one in the liquid and the other in the gas and each circulates in the opposite direction suggesting an interaction between the liquid flow and the gas flow. We speculate the liquid convection as the main cause for this interaction because both the inertia force and the sensitive heat (thermal inertia) of liquid are much greater than those of the gas. In our forthcoming paper [13], we show experimental data that demonstrate a strong correlation between the profiles of gas-phase fuel-vapor concentration and the liquid surface temperature, another evidence that the pulsating spread is controlled by the liquid convection.

CONCLUDING REMARKS

- (1) We found twin circulation cells existed in the liquid as the mirror image of the gas-phase-flow structure. Our LSPT revealed the flow profiles both in gas and liquid ahead of the flame to have a complex 3-D structure. Under the microgravity, the liquid convection observed in this paper won't exist, because a longer preheat length ahead of flame needs to keep the flame to spread.
- (2) The thermocapillary force in the liquid phase can affect the airflow field within a height of approximately 1.5-mm above the fuel surface. The airflow, which moves over 1.5 mm above the fuel surface, is affected by the shape of the flame front. If the flame front is symmetric, the air also moves symmetrically. However, if the flame front is asymmetric, the air prefers to move in the direction of the protruding side of the flame. In the liquid phase, two circulation cells are formed as the mirror image of the gas-phase-flow structure.

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