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Convection-driven melting in an n-octane pool fire bounded by an ice wall

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ABSTRACT

An experimental study on an n-octane pool fire bound on one side by an ice wall was carried out to investigate the effects on ice melting by convection within the liquid part of the fuel. Experiments were conducted in a square glass tray (9.6 cm × 9.6 cm × 5 cm) with a 3 cm thick ice wall (9.6 cm × 6.5 cm × 3 cm) placed on one side of the tray. The melting front velocity, as an indicator of the melting rate of the ice, increased from 0.04 cm/min to 1 cm/min. The measurement of the burning rates and flame heights showed two distinctive behaviors; an induction period from the initial self-sustained flame to the peak mass loss rate followed by a steady phase from the peak of mass loss rate until the manual extinguishment. Similarly, the flow field measurements by a 2-dimensional PIV system indicated the existence of two different flow regimes. In the moments before ignition of the fuel, coupling of surface tension and buoyancy forces led to a combined one roll structure in the fuel. After ignition the flow field began transitioning toward an unstable flow regime (separated) with an increase in number of vortices around the ice wall. The separated regime started with presence of a multi-roll structure separating from a primary horizontal flow on the top driven by Marangoni convection. As the burning rate/flame height increased the velocity and evolving flow patterns enhanced the melting rate of the ice wall. Experimentally determined temperature contours, using an array of finely spaced thermocouples in the liquid fuel, were used to further investigate the two layer temperature structure; an upper layer (~8 mm thick) with steep temperature gradient in the vertical direction and a layer of low temperature in deeper regions. A hot zone with thickness of ~3 mm was present below the free surface corresponding to the multi-roll location. The multi-roll structure could be the main reason for the transport of the heat received from the flame toward the ice wall which causes the melting.

1. Introduction

The behavior and characteristics of pool fires have been studied for decades, including convective motions in the liquid. Understanding the controlling mechanisms of the liquid-phase convection in pool fires have aided fire researchers in explaining ignition and flame spread problems [1,2]. When the temperature of the liquid pool is lower than the liquid flash point temperature, liquid-phase convection becomes a key point for both ignition and flame spread process [3,4]. Due to the convection in the liquid phase, the heat required for creating a vapor concentration equal to the lean-limit concentration for a gaseous fuel-air mixture is removed, causing a delay in ignition [5–7]. Conversely, flame spread is powered by the convective flows in the liquid-phase [8]. This flow is mainly governed by surface tension and viscous forces and slightly by gravity [9,10]. A fairly recent scaling study on flame spread [11] presented flow structures and pulsating regimes indicating the magnitude of convection on the bulk and surface of the liquid fuels.

There is an extensive collection of both theoretical and experimental articles on the subject of flame spread, as reviewed by Glassman and Dryer [12]. However, few studies have addressed the transport phenomena in the liquid-phase throughout the burning time of the pool fires [13–15]. Furthermore, the effects of convective flow on the walls of the pool were dismissed until a new practical problem emerged; burning of oil spills in ice-infested regions e.g. burning of spilled oil in ice cavities or melt-pools. It is shown that removing the spilled oil in ice-infested regions is promising via in-situ burning [16–18]. This also opens up a new area of research related to understanding the influence of ice melting

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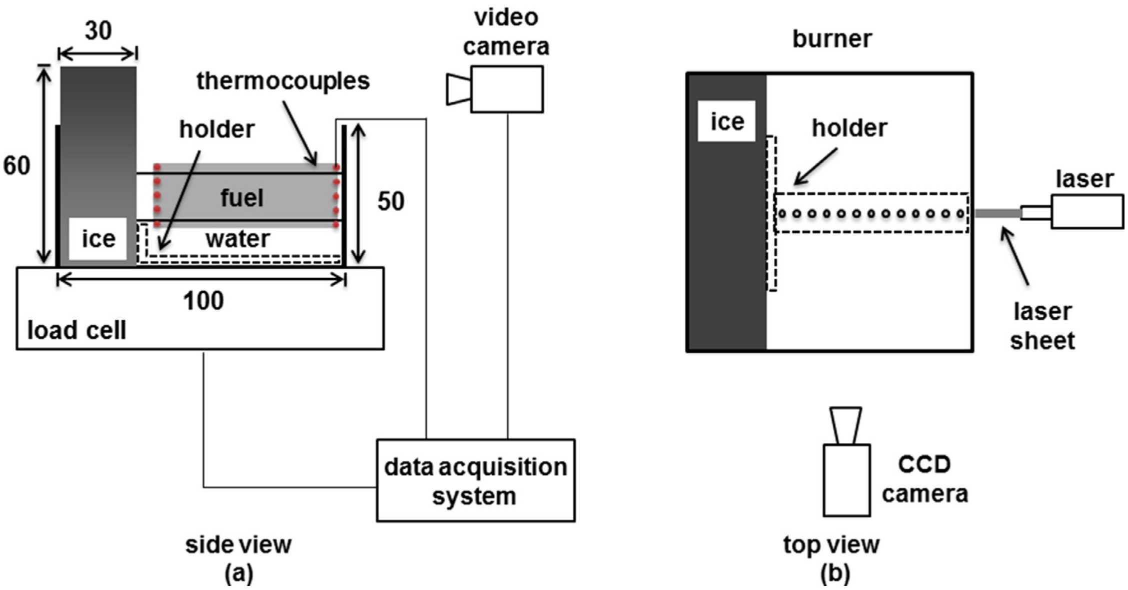

Fig. 1. Schematic of the experimental setup. (a) side view of the tray showing the water and fuel layer bound by ice, shaded area corresponds to field of view (b) top view of the tray with PIV setup. The dimensions are in mm.

on pool fire burning dynamics, which is the focus of the current study.

In typical pool fires, bounded with rigid sidewalls, a portion of the heat produced by the flame transfers to the body of the fuel in deeper areas through the walls and creates upward convective flows in the liquid adjacent to the wall [19]. When the pool is bounded by walls of ice, the transport mechanisms are significantly altered [20]. Previous studies on burning of liquid fuels in ice cavities exhibited a convection-melt phenomenon which is referred as *"lateral cavity formation"*. During burning of liquid fuels inside ice cavities [20–22] the burning fuel was observed to melt the ice and create an ice lip. The ice melting process was found to be more significant in the regions of the fuel layer contact with the ice versus regions of flame impingement. The observations made during experiments of a previous study [23] supported existence of a flow close to the free surface of the fuel. It was hypothesized that the formation of lateral cavities is due to the convective flows in the liquid fuel layer driven by buoyancy and surface tension, relating to natural and Marangoni convection, respectively.

The objective of this study is to visualize the flow in the fuel layer using Particle Image Velocimetry (PIV) technique and to analyze the flow characteristics coupled with the temperature field. Exploring the extent of convective flows could explain the causes for melting of the ice and formation of the lateral cavity. Most oil spills happen in large size (pool size of several meters or larger) and involve multi-component fuels. The insight provided by laboratory-scale experiments on pure liquid fuels along with large scale pool fires in ice are useful to understand the controlling thermo-physical parameters and effect of the geometry [24]. It is envisioned that the results of this study can add to the current knowledge on the convection-driven melting process of ice.

2. Experimental setup

The experimental setup was developed to observe the melting of the ice and investigate convective flows within the liquid phase of an n-octane pool fire. A schematic of the experimental setup is shown in Fig. 1. The custom-made borosilicate glass tray used for the burning (2 mm wall thickness) was an open top square with outside dimensions of 100 × 100 mm and a depth of 50 mm. The liquid fuel used herein was n-octane, which has a Prandtl number well above unity (7.8), density of 703 kg/m^3 and a boiling point of 125°C as the liquid fuel . Each experiment used a 96 × 60 × 30 mm ice wall placed on one side of the tray as shown with dark color in Fig. 1a and b. In order to create ice wall free of visual imperfections, demineralized water was frozen using a directional freezing method, thus preventing the inclusions of gas bubbles and other impurities. A bracket-shaped holder (shown with dashed line in Fig. 1) was used to keep the ice wall fixed at the wall of the tray. A base-layer of water with initial temperature of 0-2°C was poured into the tray to a depth of 20 mm, followed by an n-octane layer that was 15 mm thick and had a temperature of 10-12°C. The tray was then placed on a load cell (0.01 g precision) to record mass loss. A camera was placed in front of the test setup to capture the flame heights during the burning process. A propane torch igniter was used to ignite the fuel layer after it was poured into the tray.

Preliminary tests with and without the ice wall were repeated three times to ensure the reproducibility of the results. The burning duration, mass loss, and flame height were experimentally determined. The flame height was measured by capturing random frames each four seconds from the videos of the tests. Then, the flame height was measured for each image via ImageJ [25]. The measured flame heights of each test were averaged to obtain an average flame height for the duration of the n-octane burning.

The velocity field on the mid-plane of the liquid fuel perpendicular to the ice wall was obtained by PIV measurements. The specifications of the PIV equipment used in this study are provided in Table 1. The liquid fuel in the tray was seeded with 10 μm silver coated hollow glass sphere particles. The particles specific gravity, relaxation time, and settling velocity were 1.1, 0.11 μs and 0.27 μm/s, respectively. The shaded area in Fig. 1a shows the field of view for the camera. The location of the laser sheet for the velocity measurements is shown in Fig. 1b. The camera was placed perpendicular to the laser that illuminated a thin light sheet in the flow.

Five thermocouples (K-type, wire and bead diameter of 0.10 mm and 0.25 mm) were also used to measure the temperature of the fuel in the vertical mid-plane perpendicular to the ice. These thermocouples were arranged vertically with 5 mm intervals (see Fig. 1a, with detail shown as solid circles). The ends of the thermocouple wires were parallel to the fuel surface to minimize conduction loss. The radiation loss was assumed to be negligible