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Effects of convective motion in *n*-octane pool fires in an ice cavity

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ABSTRACT

The effects of convective flows in *n*-octane pool fires in an ice cavity were investigated and it was found that a new set of parameters to the classical problem of bounded pool fires arises under these unique conditions. To systematically understand these parameters, two sets of experiments were performed by burning *n*-octane in cylindrically shaped ice cavities of 5.7 cm diameter. The first set of experiments was intended to provide a clear understanding of the geometry change of the cavity and displacement of the fuel layer. The results of these experiments showed that the rate of melting of the ice walls were higher in areas where the fuel layer was in contact with ice than in places where the flame was present. Due to the melting of the ice walls, a ring-shaped void was formed around the perimeter of the cavity. In the second set of experiments, the change in the temperature of the fuel layer was measured by use of multiple thermocouples at different locations inside the ice cavity. The results of the temperature analysis showed that the lateral temperature gradient of the fuel layer was an increasing function of time, whereas the vertical temperature gradient was a decreasing function of time. Using these experimental results, two dimensionless numbers (Marangoni and Rayleigh) were calculated. The Marangoni number represents the surface tension driven flows in the fuel layer and the Rayleigh number represents the buoyancy driven flows in the fuel layer. The results of this study showed two major convective phases; in the first half of the burning time, the buoyancy driven flows (Rayleigh) were dominant, while Marangoni convection was dominant in the second half of the burning time. The role of these mechanisms in affecting the flow and melting the ice is discussed.

1. Introduction

The study of flow within liquid fuels and pool fires has been of general interest for numerous decades both from a fire safety and from a scientific point of view. The phenomenology and understanding of the controlling mechanisms of liquid flow in pool fires have aided fire researchers in recommending methods to lessen the risks associated with use of liquid fuels. Liquid-phase convection in pool fires was one of the main subjects of investigation in the 1955–1980 research period and extensive studies of ignition and flame spread indicated a connection with the motion in liquid fuels [1,2]. Specifically, it was shown that the rate of flame spread in liquid fuels with an initial temperature below the fuel's flash point temperature is governed by liquid-phase convection [3]. The liquid fuel flow pattern was first documented by Burgoyne et al. [4] during experiments of flame spread over alcohol pools. They attributed the motion in the liquid to buoyancy effects. Later, studies revealed that both surface tension and buoyancy were the driving forces in the flame spread of the liquids fuels and the surface tension was predicted to be the dominant parameter [5–7]. It was found that the liquid-phase convection in flame spread is driven by surface tension (Marangoni or thermo-capillary flow) initially, after which buoyancy forces and, to a much lesser degree, evaporation and thermal expansion are the driving forces [8]. However, further studies revealed the significant role of surface tension driven flows during the flame spread process [9–11]. Although extensive work on convective flow in the flame spread process has been undertaken, only a few studies have addressed the transport phenomena throughout the burning of pool fires [12–14].

In a typical pool fire (contained with sidewalls), a portion of the heat produced by the flame transfers to the body of the liquid fuel in deeper areas through the rim of the pan, thereby creating local convective flows [15]. When the rigid walls of the pan are replaced with walls of ice, the transport mechanisms are significantly altered. Such a situation will arise for example during clean-up of oil spills in the Arctic using the in-situ burning method [16]. In two previous studies on burning of liquid fuels in ice cavities, a phenomenon that is referred as *"lateral cavity formation"* was observed. During burning of liquid fuels in ice cavities [17] and ice channels [18] (where the fuel was surrounded by walls of ice), the burning fuel was observed to penetrate radially into the ice. The size of the lateral cavity formed on

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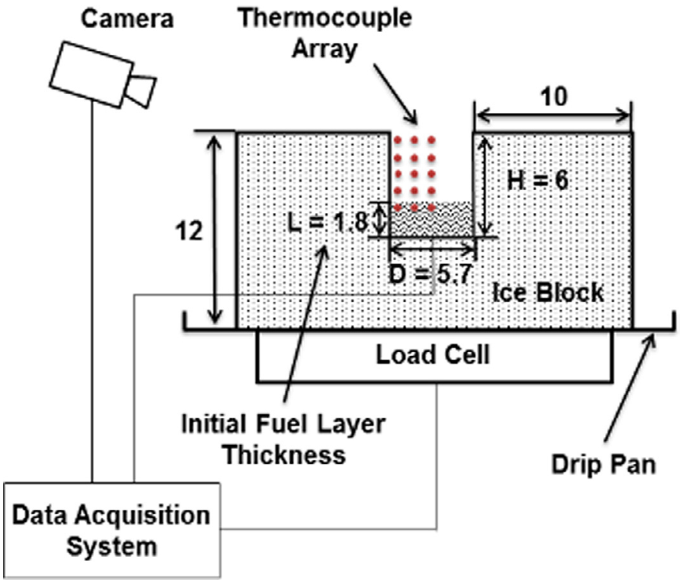

Fig. 1. Schematic of the experimental setup. The numbered dimensions are in cm with an uncertainty of ±0.05 cm for D and ±0.1 cm for H and L.

the circumference of the original cavity by the fuel layer was found to vary with fuel type, and different geometric configurations of the ice.

There are some disadvantages to these ice deformations from a practical point of view. For example, the deformation will allow a portion of the oil to drift underneath the lateral cavity. This is presumed to be a potential factor in reducing the burning efficiencies by preventing the exposure of air to the trapped oil. A decrease in the burning efficiency leads to larger amount of oil residue. In addition, the confined residue in the cavity would be harder to collect and, as a result, increase the cost of the post-burn clean-up during in-situ burning operations. In particular, if the residue stays untreated, it could be encapsulated due to freezing of the water in colder seasons and potentially remain in the ecosystem for years.

The hypothesis to explain the formation of lateral cavities is that the penetration into the ice is caused by flows in the liquid fuel layer. The observations made during the previous experiments validated the existence of a flow close to the free surface of the fuel. The driving forces behind the flow in the liquid fuel are anticipated to be buoyancy and surface tension, relating to natural and Marangoni convection, respectively. However, the relative contribution of each of these mechanisms should be studied in order to figure out the influence that these convective flows within the fuel layer have on the formation of lateral cavities in the ice walls.

The objectives of this study are therefore to understand the convective motions in the fuel layer (role of thermocapillary and natural convection) and to relate these to the lateral cavity formations during in-situ burning of liquid fuels in ice cavities. It is envisioned that the results of this study could give a solution toward higher efficiency of in-situ burnings in Arctic condition.

2. Experimental procedure

Figure 1 shows the experimental setup with *n*-octane in a 5.7 cm diameter ice cavity. Each experiment used an ice block with a circular cavity excavated in its center. The depth (H) and initial fuel layer (L) were chosen based on the data obtained from preliminary tests to prevent overflow and spillage during the burning of the fuel. The ice block was placed on a drip pan on top of a load cell (precision of 0.01 g) to record the mass loss of the fuel. Then, 30 ± 0.1 g *n*-octane was added to the cavity (with no water base-layer) and a propane torch igniter was used to ignite the fuel layer immediately after *n*-octane had been poured into the cavity.

Two sets of experiments were performed to collect data for analysis. In the first set, 10 identical tests were conducted where the only varying parameter was the burning duration. In the first experiment, *n*-octane was allowed to burn only for 1 min and then it was extinguished by covering the ice cavity with a lead. The second experiment was extinguished after 2 min and so on. After each test the ice blocks were cut in half and a photograph was taken from the cross section. In addition, measurements of the ice cavity geometry were made by processing the images. These tests were intended to give an understanding of the process of geometrical changes of the ice and lateral cavity formation. In addition, the free surface of the fuel was tracked visually by the camera that was positioned on top of the ice block. Also, the interface of the fuel–water was calculated based on the fuel layer thickness at each time stamp. The fuel layer thickness was also calculated based on the diameter of cavity and the remaining mass of the fuel (load cell data). In the second set of experiments three thermocouples (type K, gauge 36, and 0.13 mm diameter protected by ceramic tubes with a 1–2 mm exposed junction) were placed inside the cavity as shown with solid circles in Fig. 1. These tests were repeated five times with the thermocouple (TC) array placed at different elevations in the cavity to create a temperature map of the liquid fuel within the cavity. A more detailed description of the TC implementation is given in Section 3.2.

3. Results and analysis

Measurements of the mass loss over time as well as the images taken from the cavity were used to measure and analyze the geometry change of the cavity and the thickness of the fuel layer. The results are reported in Section 3.1. along with a discussion on lateral cavity formation. The temperature profile of the fuel layer was obtained by using different arrangements of TCs inside the cavity and within the fuel layer. The results of the temperature analyses are reported in Section 3.2. A discussion on convective flow within the fuel layer and the effects of the fuel layer on melting of the ice follows in Section 3.3.

3.1. Cavity change

The geometry change of the original cavity in ice during combustion of liquid fuels has been reported to be an important reason in affecting the burning rate and efficiency of a liquid fuel [17]. However, the exact changeover of the cavity into its final shape and formation of lateral cavity was not addressed in earlier studies [17,18]. In order to provide a detailed observation of the geometry change of the ice cavity, 10 experiments with similar initial condition were performed as explained in Section 2. Figure 2 shows the change in the cavity geometry and labels the relevant dimensions associated with the geometry changes.

As shown in Fig. 2, at any instance during the burning of the *n*-octane pool, the ice walls of the cavity were melting and the diameter of the cavity was constantly increasing. However, it was observed that the rate of melting of the ice walls were higher in areas the fuel layer was in contact with ice as compared with places where the flame was present. The melted ice created a semi-hemisphere void inside and around the circumference of the cavity. Thus, a lateral penetration of the fuel layer was observed around the perimeter of the original cavity. The final diameter of the cavity measured at the location of the fuel layer (D) was 15.8 cm whereas the diameter at the top surface of ice (D') was 13 cm. This translates into a partial penetration length (defined as $\frac{D-D'}{2}$) of roughly 1.4 cm for a 10 min burning period. Note that the total penetration (calculated from original position of the ice wall) of the fuel layer was larger (about 5 cm) than the partial penetration length. With this estimation, the area of the fuel layer would