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Transport phenomena within the liquid phase of a laboratory-scale circular methanol pool fire

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ABSTRACT

The effects of altering the lower thermal boundary condition of a methanol pool from −5 °C to 50 °C was investigated within a 90 mm diameter and 12 mm deep quartz burner under steady state burning condition in a quiescent air environment. Both the burning rate and the flame height were observed to increase by 15% with increasing bottom temperature over this range of bottom boundary conditions. The temperature and velocity within the liquid were measured by a single thermocouple traversed through the pool and PIV, respectively, in order to better understand the transport of mass and energy in the liquid. Temperature measurements revealed a distinct two-layer vertical thermal structure with the upper layer of the pool being almost uniform and near the boiling temperature of the fuel, while the lower layer experienced an increasing temperature gradient as the bottom boundary temperature was lowered. The thickness of the thermally uniform layer increased as the bottom temperature was increased. The measured fluid velocity showed a complementary two-layer structure with the upper layer being dominated by a pair of counter-rotating vortices that kept this portion of the liquid well mixed and transferred heat from the hot pool wall to the pool center, while the flow in the lower layer was uniformly low in value and vertical. A model was presented to aid in understanding the energy transfer within the liquid phase. In the lower layer, the Peclet Number was in the order of unity and required that the energy transfer throughout the liquid phase to be modeled as a combination of conduction and convection. Using this physical model, the change in burning rate over the full 55 °C change in bottom temperature was predicted within 2%, thereby supporting the proposed mechanism for energy transfer into the pool's depth.

1. Introduction

Liquid fuels are used in a multitude of applications due to their high energy density as well as their ease of transport and storage. As a result, the burning of liquid fuels in pools has been the subject of considerable research since the 1950s in order to better understand the phenomena and to develop safety strategies associated with fuel spills or tank stored fuels that are accidentally ignited. The steady and unsteady characteristics of pool fires, such as flame pulsation frequency, height, radiation levels, spread rate, energy transfer and the fuel-burning rate, have been reported under both quiescent ambient and transverse airflow conditions for a variety of fuels and pool geometries. A comprehensive review of these works can be found elsewhere [1], while more recent advances are captured in [2,3].

In the classical work of Blinov and Khudyakov [4], the rate of fuel burning was measured for different hydrocarbon fuels for a range of pool diameters. Of interest here is that the local fuel evaporation rate was reported as a maximum at the center of the pool and decreased toward the wall. This particular finding has not been universally observed and others [5] have stated that the maximum local evaporation rate was at the wall and decreased toward the pool center.

The reasons for these different observations have not been extensively discussed in the literature, but connections have been made to the relative importance of different mechanisms that bring the energy necessary to evaporate the fuel from the flame and product gases to the liquid. For example, soot producing fuels, such as heptane, emit high levels of thermal radiation to become a key pathway of heat feedback from the flame to the liquid fuel along with convection and conduction [6]. In general, radiation is seen as the dominant heat transfer mechanism for highly luminous fires, especially for large-scale pools [7]. Energy radiated to the fuel surface has been observed to be the highest at the center [8] and is attributed to creating the maximum local evaporation rate at that location. In contrast, for small-scale non-luminous pool fires, the heat transfer from the pool's wall to the liquid is seen as dominant [9] and results in the highest local evaporation rate to be at the

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wall. This perspective on the local evaporation rate focuses on where the energy enters the pool, but does not address any subsequent phenomena associated with its redistribution within the liquid, which is the topic central to the current research.

A significant barrier to developing a comprehensive and quantitatively relevant phenomenological model of pool fires from experiments is the large number of coupled parameters involved in establishing the burning of liquid pools. As a result, numerical modeling of pool fires is often seen as the more robust tool for predicting the key characteristics of pool fires, especially for large-scale pools. In developing numerical models, a key decision is the establishing of an appropriate region of interest or computational domain. Some models essentially ignored the liquid phase and only solved the reacting gas flow for a prescribed fuel mass flow rate being emitted from the pool surface at their computational boundary [10]. However, this mass flow should be determined by the requirement that the liquid fuel must evaporate before it burns, and that energy for evaporation comes from the flame and product gases. Therefore, the flow of fuel vapor at the inlet boundary is itself a part of the solution and some numerical models coupled it to the heat feedback from the flame to the fuel surface [11]. In this particular case, the solution domain remained restricted to the gas phase and it was assumed that all the energy transferred to the liquid was used to create an average evaporation rate without respecting spatial variations and redistribution within the pool's depth.

More complete numerical models have been developed including the liquid phase in the solution domain [12–14]. They determined the rate of fuel evaporation from liquid–vapor equilibrium at the fuel surface temperature. In these models, the liquid layer has been treated as a thermally-thick solid with one-dimensional heat conduction in the direction normal to the liquid surface [12,13]. Prasad et al. [14] modeled the liquid phase as columns of liquid traveling only in the direction normal to the surface at a constant velocity from inlet to the interface as required by the local surface evaporation rate. They set the velocity component parallel to the interface equal to zero.

In general, though, there is a lack of information about the liquid phase in pool fires and this has forced modelers to use simplifying assumptions that are sometimes inaccurate or unrealistic, such as using an infinitely deep or a stationary liquid layer.

There is evidence in the literature that the liquid side of the pool fire is not as simple as assumed in previous models. Vali et al. [15] studied pool fires by varying the liquid side boundary conditions and found that the burning rate and flame height of methanol pool fires were strongly affected by pool wall material and the lower boundary temperature of the liquid. Based strictly on the thermal structure of liquid phase, Vali et al. [15] proposed the possibility of the existence of large-scale mixing motions within the liquid pool that were strong enough to influence the energy transfer from hot surfaces to the bulk of liquid fuel.

Others have raised the importance of the non-uniform evaporation rates, and as such the liquid surface may experience convection induced by both buoyancy and thermocapillary forces [16]. This phenomenon is well known in the flame-spread stage of pool fires. The region beneath the flame is hotter than other regions and motion is induced by thermocapillary stresses on the fuel surface from hot to cold regions to accelerate the flame spread over the liquid fuel layer [17,18]. To simulate steady pool fire burning, the system was modeled as a free surface liquid layer over a cold solid base that was heated from above by a non-uniform heat source [19]. This work showed that for liquids with a Prandtl number of unity or larger, under conditions which were similar to the steady burning of liquid pools, thermocapillary and buoyant flows were induced within the liquid layer.

Following on from a previous study [15], this paper considers the flow within the liquid phase. The velocity field within the liquid phase of a laboratory-scale pool is measured using particle image velocimetry (PIV). The aim of this paper is to contribute to overall understanding of liquid pool fires by investigating the potential of large-scale motions within the liquid pool. Coupled with the measured temperature distribution within the pool, the transport of energy in the pool is considered, which elucidates how a specified lower liquid boundary temperature can influence the burning rate of the fuel. A further aim of this paper is to provide experimental results for a well-characterized pool fire under steady and prescribed burning conditions that can be used for validation of numerical models.

2. Experimental setup and methodology

Experiments were conducted under steady-state, steady-flow conditions associated with maintaining a constant fuel level in the pool while burning. The pool was kept full of liquid fuel to the top edge of the confining walls to eliminate any effects of ullage [20]. The temperature at the bottom of the liquid layer was held at a prescribed constant temperature. The tests were conducted in a quiescent environment with no transverse airflow and at atmospheric pressure. The fuel used in this study was methanol (CH_3OH) which at atmospheric pressure has a flash point of 11 °C and boiling point of 64.7 °C [21]. The flames produced in these conditions were translucent blue and emits low levels of thermal radiation [6].

2.1. The burner

A schematic of the burner used in this study is shown in Fig. 1a. The burner was circular with an inner diameter of 90 mm and a depth of 12 mm. The burner wall was made of 2.5 mm thick quartz tube (95 mm outer diameter), which was exposed to the room conditions on the outside. The bottom of the burner was made of 3 mm thick porous bronze plate with an average pore size of 10 μm. The porous plate provided a uniform inlet fuel flow into the bottom of the pool while it was heated/cooled from underneath by a heat exchanger. The heat exchanger was a flat spiral coil made of 6 mm diameter copper tube that was in contact with porous plate. The fluid circulated through this coil was 50% ethylene glycol 50% water solution and its temperature was set by a water bath (Model 12111-21, Cole Parmer Canada Inc.) controllable between −20 °C and 50 °C. As shown in Fig. 1a, the fuel was supplied to a cavity occupied by the heat exchanger beneath the porous plate.

2.2. Fuel delivery system and burning rate measurement

Fuel was supplied to the burner at a rate to keep the fuel level within the burner constant. Assuming that the evaporated fuel from the pool was burned completely in the flame, the burning rate was estimated by measuring the fuel flow rate to the burner. The schematic diagram in Fig. 1b shows the fuel delivery system consisting of an ultrasonic level sensor (Model 098-10001, ML-101, Cosense Inc.), a custom-designed software (LabWindows/CVI, National Instruments Corporation) PID controller, and a peristaltic pump (MasterFlex L/S digital driver with Easy Load II head, Cole Parmer Canada Inc.).

The level sensor monitored the fuel height with an accuracy of 0.01 mm in a small (6 mm diameter) non-combusting, inter-connected shunt-pool located immediately adjacent to the main pool as shown in Fig. 1b. Then, the peristaltic pump was used to set the flow rate of the fuel with an accuracy of 0.05 mg/s to compensate the evaporated fuel of the pool and keep the fuel level steady. The fuel flow rate transferred to the pool was measured as the set