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Fluid motion and energy transfer within burning liquid fuel pools of various thicknesses

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ABSTRACT

The burning characteristics and thermal-flow structures within laboratory-scale pool fires have previously been shown to be dependent on the pool's bottom temperature and the pool wall material. Relatively unexplored are the effects of the thickness of liquid fuel in the pool without ullage. These effects are explored experimental here using a 90 mm diameter quartz pool burning methanol in a quiescent environment for a range of bottom boundary temperature (*i.e.*, −4 °C to 50 °C). Three pools with fuel depth of 6, 12 and 18 mm were examined in terms of overall burning rate, flame height, and cross-sectional maps of mean temperature and in-plane 2-D velocity. It was shown that the burning rate and flame height for a specified pool bottom temperature increased with increasing pool depth, and shallower pools were more sensitive to pool bottom boundary temperature. Generally, the pool showed a distinct two-layer thermal structure with a near uniform upper layer, and a lower layer with a non-linear temperature gradient. The uniform layer was coincidental with a pair of standing counter-rotating vortices keeping this fluid well-mixed, while the lower layer had only a slow upward velocity associated with maintaining the liquid level. For the deepest pool, the thicknesses of the well-mixed and lower layers were essentially fixed, and the investigation showed that its velocity and non-dimensional temperature structures were independent of the bottom temperature. This independence was used to identify a regime of *thick-pools*, which allow the liquid to be modeled with relative simplicity. For shallow pools (*i.e.*, *thin-pools*), the thicknesses of these layers were dependent on the bottom temperature. Mechanisms for this behavior were proposed. Lastly, an energy analysis of the liquid beneath the well-mixed layer was able to explain the non-linear temperature profiles in that region as being a combination of vertical conduction and advection energy transfer.

1. Introduction

The burning of the vapor emitted from a horizontal layer of a flammable liquid results in a pool fire. This class of fire describes a large number of accidental combustion scenarios such as fuel spill fires, tank fires, and pan fires. As a result, pool fires have been the subject of considerable research since the 1950s [1–4]. These fires, as a multi-phase fluid mechanics phenomenon, include the gas phase where the reactions occur and combustion products are generated, and the liquid phase as the source of fuel. Relative to the liquid phase, the flame and gas phase fluid dynamics have typically attracted the bulk of interest among the fire researchers. The premise was that the liquid phase phenomena were relatively simple and had minor effects on the pool fire characteristics. However, since the burning rate of pool fire is controlled by the fuel evaporation rate from the liquid pool surface, attention has to be paid to the transport phenomena that receive and redistribute the energy within the liquid pool.

The liquid fuel requires energy to vaporize before it can burn; while initially that energy can come from the pool's internal energy, combustion is sustained by heat being fed back from the flame and hot combustion products to the liquid pool through various pathways. The details of these pathways, which have come to be referred to as convective, radiation, and conduction, have been qualitatively and quantitatively described in the literature [2,5–7]. The convection pathway is associated with the liquid and vapor interface and that the temperature of the gases and vapors directly above this interface are higher than the liquid surface [6–9]. The radiation pathway is associated with this same interface, but the energy coming directly from the flame and hot combustion products in its various wavelengths and directions relative to the liquid surface to be absorbed as a function of depth within the pool, or reflected from the surface [6,7,10]. The conduction pathway is

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associated with the non-direct path of convection and radiation heating the pool walls, and this energy is then conducted to the liquid-side of the walls before convection heat transfer introduces it into the fuel [11–13]. The absolute and relative magnitudes of the individual heat feedback pathways have been explored with respect to many variables such as fuel type, pool size, pool shape, material containing the pool, liquid bottom boundary condition, inclusion of obstacles protruding from the liquid surface, ullage (free board height), and transverse air speed [2,6,7,14–18].

In previous studies [18–20], it was shown that the burning characteristics of pool fire were also dependent to the liquid-side boundary conditions. The investigated parameters included the pool's bottom temperature and confining wall material. It was shown in [18,19] that burning rate and flame height increased with an increase in pool bottom temperature. The effect of the pool wall material, which directly impacted the conduction pathway, was to increase in burning rate and flame height as the thermal conductivity of the wall material was reduced [20]. A decrease in wall thermal conductivity prevented the heat from being conducted further into the solid wall and lowering the amount of heat available for transfer into the liquid. Furthermore, a lower thermal conductivity side wall accumulated heat in the top of the burner and facilitated fuel evaporation.

A non-intrusive holographic interferometer technique conducted in [21] showed that during transient burning the liquid thermal structure experienced noticeable fluctuations in temperature values due to Rayleigh convection. Also, a flow visualization in the liquid fuel presented in [22] showed the existence of Rayleigh convection in the fuel layer during unsteady burning of liquid pools. Both studies [21,22] investigated luminous pool fires (*e.g.*, toluene and kerosene) and attributed the Rayleigh convection within the liquid phase to in-depth radiation absorption. The steady thermal and flow structures within the liquid phase of a methanol pool fire in [18] detected large scale mixing motions and a two-layer thermal structure. However, not noticeable small liquid circulations were observed within the liquid layer of the non-luminous methanol pool fire.

The results to be presented here are driven by the same objective of developing a better understanding of the effects of the liquid-side conditions on the pool fire. This paper is an experimental exploration on the effects of the depth/thickness of the liquid fuel layer, independent of ullage, in the case of a circular quartz-walled, laboratory-scale methanol pool fire operating in a quiescent environment with specified bottom boundary temperatures. The resulting pool fires are characterized by their steady-state mass burning rate and flame height, as well as the two-dimensional thermal and velocity structures observed on a cross-sectional plane within the liquid fuel. A further objective of this study was to check for the existence of a regime of pools depths (*i.e.*, *thick* or *thin* pool) that have thermal-flow characteristic near the surface that were independent of pool depth and bottom boundary conditions. The existence of such a regime would significantly reduce the complexity of modeling the liquid boundary conditions of pool fires.

2. Experimental approach and methodology

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 [23]. Steady-state, steady-flow burning conditions were established during the experiments by maintaining a constant fuel level in the pool. The temperature at the bottom of the liquid layer was held constant in order to stabilize the liquid phase boundary condition. The tests were conducted in a quiescent environment with no transverse airflow and at atmospheric pressure.

2.1. Burner

A schematic diagram of the burner used in this study is shown in Fig. 1. The burner was circular with an inner diameter of $d = 90$ mm and different depths of $L = 18, 12, 6$ mm (referred to as deep, medium, and shallow pools, respectively). The pool 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 relative 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 −10 °C and 50 °C. This provided a controllable boundary condition at the bottom of the pool.

2.2. Fuel delivery system and burning rate measurement

The fuel-burning rate is normally defined as the rate fuel mass is consumed in the process of combustion, but is quantified here by the surrogate quantity of the flow rate of fuel needed to maintain a steady fuel level in the pool. In these experiments, this level was the top edge of the wall in order to eliminate any effects of ullage (*i.e.*, lip height effects) [14,24,25]. As shown in Fig. 2, the fuel delivery system transmitted the methanol from an open atmospheric tank to the liquid pool, and it consisted of a level sensor, a controller, and a pump. An ultrasonic level sensor (Model 098-10001, ML-101, Cosense Inc.) monitored the fuel level, 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. The fuel level readings were used in a custom-designed software controller (LabWindows/CVI, National Instruments Corporation) at a rate of 100 Hz. The fuel level value was compared in the controller with the pool depth, *L*. A peristaltic pump (MasterFlex L/S digital driver with Easy Load II head, Cole Parmer Canada Inc.) flow rate was set with an accuracy of 0.01 ml/min accordingly to eliminate the difference between the pool depth and the fuel level.

There was a transient period after ignition for the steady thermal structure within the pool to be established (*i.e.*, a warm-up period) [24,26]. While some researchers suggested that the pool fire could reach a steady-state burning rate in less than a minute [27], others proposed a relatively longer warm-up period of around 20 min [28]. Hamins et al. [7] reported that under constant-level condition, the mass burning rate reached a nearly constant value

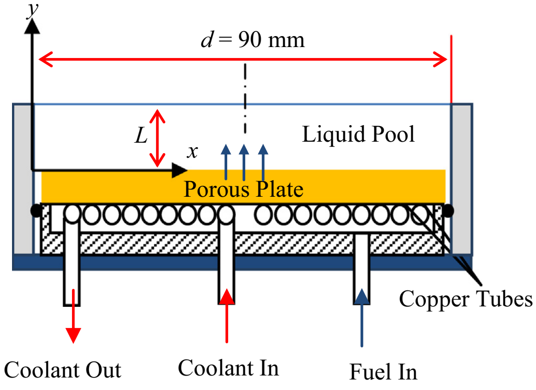

Fig. 1. Section view of the burner used in this study.