



## Effects of altering the liquid phase boundary conditions of methanol pool fires

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### ABSTRACT

Fuel burning rate, flame height and temperature distributions within the liquid phase of a methanol pool fire were measured to investigate the impacts of altering the pool's liquid-side boundary conditions. The conditions changed were the temperature at the bottom of the pool and the material used for the pool walls (either quartz or aluminum). These materials were chosen for their different thermal conductivities, which affect one of the pathways for heat transfer from the flame to the pool. The experiments were conducted under steady state and quiescent ambient conditions. It was observed that the burning rate increased linearly with increasing the bottom boundary temperature, and that the aluminum pool was significantly more sensitive to this parameter than the quartz pool. Due to the coupling between burning rate and flame area, the flame height showed similar behavior to boundary temperature and pool wall material variations. For either type of wall materials, the temperature distribution showed a vertical structure of two distinct layers with one layer being nearly uniform and the other having a relatively steep gradient. The arrangement of these layers was unexpectedly opposite for the different wall materials. For the aluminum vessel the pattern was thermally well-mixed in the lower part of the pool and the steep temperature gradient near the surface, while for the quartz pool the thermally well-mixed region was at the top. These observations lead to proposing the existence of non-1-D fluid motion in regions of high convective heat transfer from the walls. Irrespective of the underlying mechanism, these differing temperature distributions suggested that the liquid phase is not as simple as what has been typically modeled in the literature.

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### 1. Introduction

The ignition of fuel vapor emitted from a horizontal layer of combustible liquids results in a pool fire. This class of diffusion flames can be either laminar or turbulent depending on its buoyant interactions with the surroundings and ambient air motion [1]. In general, pool fires are complex systems due to combining combustion, heat and mass transfer, and fluid dynamics involving two phases. Interest in pool fires is derived from scenarios of the accidental ignition of open fuel storage vessels or fuels spills. A good understanding of these phenomena is required for designing safe fuel storage or effective suppression systems.

The liquid fuel's burning rate, expressed either as the mass rate of fuel consumed or its usual surrogate quantity of mass rate of evaporation of fuel from the pool ( $\dot{m}_b$ ), requires an analysis of the transport phenomena of the overall two-phase system. The liquid fuel must evaporate before burning, which requires energy. The source of this energy is primarily the heat transfer from the flame and the hot combustion products to the liquid fuel. Part of the energy that arrives at the pool may also be lost or gained to

the surroundings from the confining walls and the bottom surface of the pool depending on the direction of the temperature gradient, which affects the energy balance in the system and the burning rate [2].

The practical and fundamental aspects of pool fires have been the focus of considerable research over the past few decades. Previous experimental studies showed that the burning characteristics of pool fires are affected by variations in burner size, geometry and material, fuel type and ambient conditions [3]. Blinov and Khudyakov [4] conducted experiments on different pool sizes and hydrocarbon fuels. Using concentric ring burners, they found that the local vaporization rate per unit area ( $\dot{m}_b''$ ) was highest in the center and decreased toward the outer pool walls. For square polymethylmethacrylate pool fires, a monotonic decrease in  $\dot{m}_b''$  was observed from the pool center to its edges [5]. Akita and Yumoto [6] challenged these findings by observing the opposite trend, while affirmed that pool size and fuel type were important parameters of pool fires. Hamins et al. [7] also measured  $\dot{m}_b''$  in a concentric ring burner and found that the burning rate per unit surface area was almost constant throughout the fuel surface.

These different spatial variations in  $\dot{m}_b''$  reported in the literatures [4–7] have been attributed to the dominant mode of heat transfer being different. Heat is transferred to the pool in the forms

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of radiation, convection and conduction. The relative contributions of different heat transfer pathways depend on geometrical parameters such as the pool dimensions [7], burner material, lip height [8] and the structure of the flame including its shape, soot volume fraction, temperature and species concentration distributions [2]. Considering just one of these parameters, it was observed that conduction dominates the heat transfer back to the liquid fuel for small pools [9]. As the pool size increases the importance of conduction decreases and convection becomes more important, while for yet larger pools, with a characteristic length greater than  $\sim 1$  m, radiation heat transfer dominates [10]. The key point being that the breadth and interdependencies of variables that can affect a pool fire beside the destructive nature of pool fires especially the large scale ones has resulted in experiments providing an incomplete understanding of the phenomena and provided limited predictive capacity.

An alternative approach used to study pool fires is to solve the problem numerically. In contrast with the case when the fuel flow rate can be specified for modeling a typical gas co-flow burner [11], the inlet fuel flow rate of pool fire is itself one of the unknowns. In pool fires, liquid fuel is vaporized from the surface before it mixes with surrounding air and burns in a diffusion flame. The rate of evaporation is controlled by the energy transport in the system. Some of the previous numerical models did not consider this coupling of the flame feedback and the evaporation rate (burning rate) to simplify their model. They defined the solution domain as the gas phase above the liquid fuel surface and specified a constant vaporized fuel flow rate at the liquid fuel surface [12]. Others determined the pool fire evaporation rate from the heat feedback of the flame to the fuel surface only from the gas phase solution [13]. They assumed constant temperature and evaporation rate at the fuel surface. To make it more accurate, some numerical models were developed by considering a full coupling between the liquid and gas phase. They typically solved the temperature field within the liquid phase, and determined the local evaporation rate from gas-liquid equilibrium at the fuel surface. However, they applied various models and boundary conditions for the liquid side. Hostika et al. [14] treated the liquid layer as a “thermally-thick solid” regardless of any convection within the liquid pool. To solve the unsteady burning of small to medium scale pools, Novozhilov et al. [15] applied a one-dimensional heat transfer equation and neglected the transverse temperature gradients compared to the gradients in the direction normal to the liquid surface. Considering the motion within the liquid phase, Prasad et al. [16] modeled a laminar methanol pool fire by assuming two-dimensional energy equation but one-dimensional liquid motion. They assumed that the liquid only had a vertical velocity component normal to the fuel surface. They also neglected any velocity variations in the vertical direction and considered the liquid pool to be made of columns that are moving at a constant local velocity from the fuel inlet to the top. This model still needs more improvements since there is evidence [17] that suggests transverse motions within and on the surface of liquid fuel may be important. For example, the non-uniform evaporation rates at the liquid surface observed with the spatial variations in  $\dot{m}''_b$  may result in temperature and consequently surface tension gradients, which induces thermocapillary convection or Marangoni motion with velocity components parallel to the liquid surface [18]. Hiquera [19] modeled a steady free surface liquid layer over a cold solid base when it was heated from the top non-uniformly through its surface. This work showed that for the liquids with a Prandtl number of unity or larger, under the problem conditions which were similar to the steady burning of liquid pools, thermocapillary and buoyant flows were induced within the liquid layer.

To help the efforts to improve the modeling of pool fires, further experimental data are required for validation. While the

experimental measurements for the gas phase of the pool fire can be found in the literature for validation of the numerical models [7], insufficient data is provided for the liquid-side. One of the important characteristics that can have profound effects on the numerical modeling is the use of realistic boundary conditions. For example, Prasad et al. [16] assumed that the liquid phase is infinitely extended from the bottom, which is not practical. The effects of applying these kinds of boundary conditions and different simplifying models for the liquid side were not considered in previous works, which left the liquid-side of the pool fire underrepresented in the literature. The current experimental study focuses on assessing the importance of the liquid phase boundary conditions of the pool fire and examine if the boundary conditions on the liquid side would influence the burning characteristics of the pool fire. The approach taken here is to alter the pool-side boundary conditions in terms of prescribing the temperature at the bottom of the pool and changing the thermal conductivity ( $k$ ) of the pool's confining walls, and then measure the system's response in terms of burning rate, flame height, the temperature distributions within the liquid, and the heat required for the steady burning.

## 2. Experimental setup and methodology

The experiments were conducted under steady-state, steady-flow conditions. An exploded view of the square burner and a schematic diagram of the setup used to achieve these conditions are shown in Fig. 1a and b, respectively. The pool dimensions were  $75 \times 75$  mm and 14 mm depth. The confining walls were 3 mm thick and made of either quartz ( $k_q = 1.3 \text{ W m}^{-1} \text{ K}^{-1}$ ) or aluminum ( $k_{al} = 238 \text{ W m}^{-1} \text{ K}^{-1}$ ) [20], where the confining walls were subjected to quiescent ambient at room temperature.

The fuel that evaporated from the top of the pool for combustion was continuously replaced by injecting fuel through the pool's bottom surface, which was made of 3 mm thick porous stainless steel plate (1100-10-12-.125-2-A Sheet 316LSS, Mott Cooperation). A pore size of  $4 \mu\text{m}$  provided an even fuel mass flux across the bottom inlet boundary. By using a level sensor, controller and pump, the fuel supply rate was adjusted to maintain a stationary fuel level in the pool. An ultrasonic level sensor (098-10001, ML-101, Cosense) with an accuracy of 0.01 mm measured the fuel height in real time in a small (6 mm diameter) non-combusting, inter-connected shunt-pool located immediately adjacent to the main pool. A custom-designed software (LabWindows/CVI, National Instruments) PID controller synchronized this liquid level reading to a peristaltic pump (MasterFlex L/S digital driver with Easy Load II head, Cole Parmer), which was also used to set the flow rate of the fuel stored in an open tank at room conditions. As shown in Fig. 1a, a plate heat exchanger located beneath the porous plate was used to control the temperature of the entering fuel and the bottom of the pool. Either heated or chilled water from an adjacent water bath was circulated through one of the heat exchanger's serpentine. The fuel-side of the heat exchanger was a closed-end serpentine channel to distribute the fuel to all regions under the porous plate. The water bath (12111-21, Cole Parmer) that was used to control the water temperature was set between  $5 \text{ }^\circ\text{C}$  to  $55 \text{ }^\circ\text{C}$  and had an uncertainty of  $\pm 0.5 \text{ }^\circ\text{C}$ .

The fuel used in this study was methanol, which at atmospheric pressure has a flash point of  $11 \text{ }^\circ\text{C}$  and boiling point of  $64.7 \text{ }^\circ\text{C}$  [21]. The flames produced in these conditions were translucent blue and emits low levels of thermal radiation compared to yellow soot-producing pool fires (e.g. heptane) [7]. In order to eliminate the effects of the pool lip [22] the fuel in the burner was maintained at its top edge. The surrounding ambient air conditions for all experiments were quiescent.

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