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Characterization of flow field within the liquid phase of a small pool fire using particle image velocimetry technique

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ABSTRACT

Two-dimensional particle image velocimetry (PIV) technique is employed to measure the velocity field at the central cross-sectional plane within a round laboratory-scale liquid pool fire (90 mm diameter with 18 mm depth) burning under steady-state and quiescent environment conditions. The experimental technique and the results for the flow field within the liquid phase of pool are presented and their consistencies are discussed. It is shown that the experimental technique used in this study is capable to effectively characterize the flow and can provide useful information about fluid dynamics of the liquid phase of pool fire. The measured fluid velocity field depict that the upper region of the liquid pool is dominated by a pair of counter-rotating vortices while no fluid circulation is observed within the lower region of the pool where the flow velocity is uniformly low in value. Also, by decreasing the temperature at the bottom of the pool, the size of vortices and the ratio of the upper to lower layer thicknesses decrease. The sources of uncertainties associated with the experimental method (PIV) for this specific application are fully discussed to help in the design of similar experimental systems.

1. Introduction

The ignition of fuel vapor emitted from a horizontal layer of combustible liquid (such as fuels and solvents) results in a pool fire [1]. This is one of the most common forms of liquid fuel combustion often presents in accidental fires [2] and has been considered in the investigation of many fire scenarios such as spill fires, storage tank fires, and compartment fires. The large number of studies on both fundamental and practical aspects of this subject during the past few decades reflects the importance of pool fires to the fire safety engineering community [3].

Pool fires mainly involve two interactive phases: the combustible liquid pool (liquid phase) and the fire plume (gas phase). These two phases are coupled through fuel evaporation from the liquid pool (*i.e.*, the source of volatiles for combustion) and the energy transfer from the flame back to the pool. This relationship may be described as the liquid fuel must evaporate at the surface of the pool before burning, which requires energy, and the energy for evaporation is provided primarily by the heat transfer from the flame and hot combustion products to the liquid fuel. This energy is transferred to the liquid pool by radiation, convection and conduction [4,5]. The burning characteristics and the proportionality of various heat transfer pathways of pool fires depend on many pool parameters such as fuel type, pool size, ambient condition, etc. [3,4].

Most of the studies in the literature have focused on the flame-side of the pool fire and investigated the burning of liquid pools from the gas-phase perspective [3]. There is however some evidence that transport phenomena of the liquid phase are important in understanding of the overall system and can affect the burning characteristics of the pool fire such as burning rate and flame height [6,7]. Also, it is known that one of the heat pathways from the flame to the liquid phase is the heat transfer through the pool wall into the liquid fuel, known as the *conduction* pathway [5]. This heat pathway is particularly important for small-scale pool fires [8,9]. This energy is transferred from the pool wall to the liquid pool by convection, so the fluid motions within the liquid pool contribute to the energy distribution within the pool [10]. Another effect to be of interest in the liquid pool may be due to the energy that is radiated from the flame which is absorbed in the liquid layer and induces convective current within the liquid pool [11,12]. To understand the transport phenomena within the liquid phase of pool fire, the liquid velocity field needs to be determined, which is the main objective of the experimental methodology presented in this paper.

Particle image velocimetry (PIV) is used for this purpose, which is a non-intrusive optical flow measurement method that gives a

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two-dimensional flow field. This technique involves measuring the velocity of tracer micro-scale particles that are seeded into the fluid [13]. The basic assumption of this technique is that the particles follow the flow motion with negligible influence on the flow field [14]. In this technique, the fluid is seeded with particles and a light sheet is generated by an illumination source across a region of the fluid which is of interest. Then, the particles scatter light when they pass through this light sheet, and a camera collects an image of this scattered light. Focussing on a small region of the image, a representative displacement of the particles within the visualized plane between a pair of successive images is determined from image processing. Knowing the time difference between the successive images, the flow velocity is determined [13]. The flow field in the image plane is estimated by assembling all the velocity information from the small regions.

This paper is focused on the experimental method and to explore the feasibility and limitations of the implemented method (*i.e.*, PIV) for this specific application, which is the flow measurement in a complex system of pool fire. The experimental data was acquired under steady-state steady-flow conditions associated with maintaining the fuel level at the top edge of the pool. Quiescent ambient conditions and controlled lower fuel boundary temperatures were imposed during the experiments. The discussions on the experimental method presented in here can help in the design of experiments. Furthermore, the aim is for the experimental results to provide insight on the fluid dynamics within the liquid phase of a laboratory-scale methanol pool fire, which can be used for assessment of future experimental and numerical analysis on pool fires.

2. Experimental setup and methodology

Fig. 1 shows a schematic diagram of the main components of the experimental setup. The custom-designed burner was manufactured at the University of Alberta, which had an inner diameter of 90 mm with a depth of 18 mm. The pool was kept full of liquid methanol to the top edge of the quartz wall during the experiments. The outer side of the wall was exposed to ambient that was quiescent without any noticeable air motion. The fuel was supplied to the pool from the bottom which was made of a 3 mm thick bronze porous plate to provide a uniform inlet fuel flow into the pool. The bottom plate and inlet fuel were kept at a prescribed temperature to establish a constant temperature boundary condition. This was accomplished using a copper tube heat exchanger that recirculated coolant underneath of the bronze plate. The coolant (50% ethylene glycol 50% water solution) temperature was set by a water bath (Model 12111-21, Cole Parmer Canada Inc.) controllable between −10 °C and 50 °C. The temperature at the bottom of the pool was measured in multiple locations using a Type-K thermocouple probe (TSS series, Omega Engineering Inc.) with an exposed 0.25 mm junction, which was traversed using a 2-axis motorized stage (UniSlide model, Velmex Inc.). Then, an area-averaged value was obtained from the measurements and reported as the pool bottom boundary temperature.

The fuel delivery system drew methanol (the liquid fuel) from an open atmospheric tank and delivered it to the liquid pool in a controlled manner. This system consisted of a level sensor, a software controller (shown as the computer in Fig. 1), and a pump. The ultrasonic level sensor (Model 098-10001, ML-101, Cosense Inc.) monitored the fuel level in real time with an accuracy of 0.01 mm in a small (6 mm diameter) non-combusting, interconnected shunt-pool located immediately adjacent to the main pool. Then, the fuel level readings were sent to a controller (custom-designed software developed using LabWindows/CVI, National Instruments Corporation) every 0.1 s. The fuel level value was compared in the controller with the pool depth set point, which was from the bottom of the pool to the top edge of the pool wall. The flow rate of the peristaltic pump (MasterFlex L/S digital driver with Easy Load II head, Cole Parmer Canada Inc.) was set with an accuracy of 0.01 ml/min accordingly to eliminate the difference between the pool depth and the fuel level. Analog voltage signals (conversion factor of 3 ml/min per volt) were sent from a computer controlled data acquisition system (miniLAB 1008™, Measurement Computing Corporation) to the pump every second to update the fuel flow rate (the controller output to the pump was based on 10 successive level measurements).

The light sheet for PIV was produced by a scanning system (NT59-874, Edmund Optics) that was composed of two mirrors of which one was fluctuating at 500 Hz and distributing the laser beam (LRS-0532-TF, 1.6 W, 532 nm, Laserglow Technologies) to illuminate the central cross-sectional plane within the pool. A lens (100 mm focal length, 25 mm diameter, ThorLabs) located at its

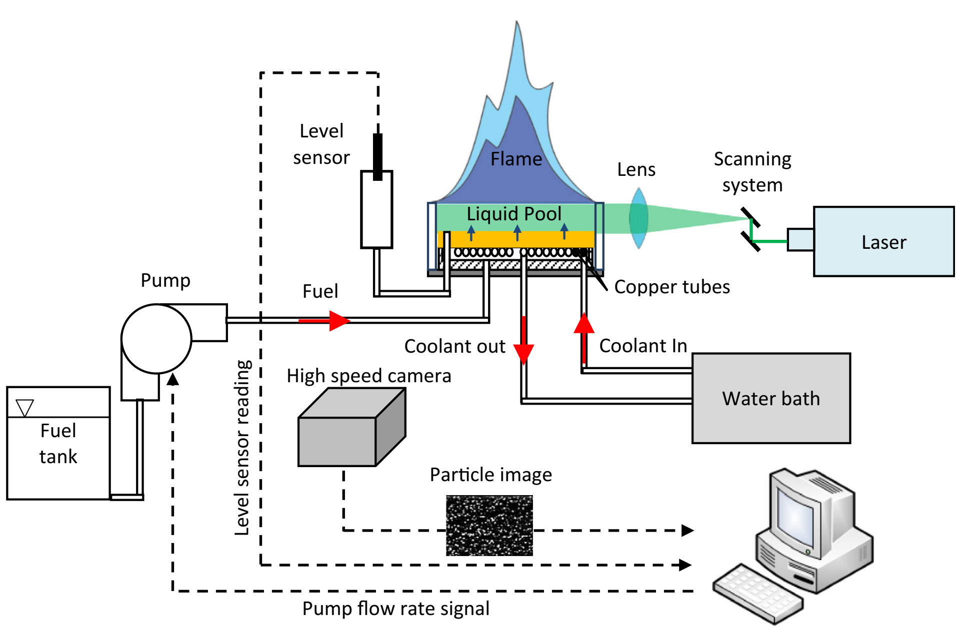

Fig. 1. Schematic diagram of the experimental setup.