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An experimental investigation into the effect of substrate slope on the continuously released liquid fuel spill fires

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ABSTRACT

The spread of burning fuel spilled from tanks or pipes during oil storage and transportation industries may threat other facilities nearby and trigger further accidents. In this paper, the effect of substrate slope on the continuously released liquid fuel spill fire was experimentally investigated, in a one-dimensional channel with different discharge rates and substrate slope angles. The time-varying burning area was recorded and analyzed, with 5 typical phases. It is observed that the maximum burning area increases largely with the increasing slope angle, while the steady burning area increases only a little. The steady burning rate, which equals the ratio of the discharge flow rate to the steady burning area, decreases with the increasing slope angle. It is proved that the burning rate for liquid fuel spill fire is much lower than that of pool fire with the same dimensions. The facilities and data presented in this work may provide a basis for the future modeling study of the liquid fuel spill fire on inclined surface.

1. Introduction

Liquid fuel spill fire is quite common in oil storage and transportation industries. When released and ignited, the spilled burning fuel may spread due to gravitational force. The burning area enlarges with time as the burning fuel spreading, thus posing a huge threat to tanks or facilities nearby, and causing further accidents. For example, the liquid fuel spill fire was observed in the Dalian oil spill accidents in 2010. It was reported that the spilled crude oil from a 1 m diameter pipe spread downslope soon after ignition. The burning area increased to at least 500 m^2 and the oil in a 100, 000 m^3 tank was ignited by the spill fire. The fire destroyed the pump room and the power distribution room at low-lying area, causing the accidents out of control (Jin et al., 2010). Thus, it is critical to investigate the time variation of burning area in a liquid fuel spill fire, especially on inclined surface, to effectively plan for the fire protection and the prevention of secondary disasters.

So far, the burning behavior of a pool fire within a certain area has attracted much attention. Empirical correlations for characteristic parameters of pool fire, such as burning rate (Babrauskas, 1983; Chatris et al., 2001), flame height (Hasemi and Nishihata, 1988), and thermal flux (Koseki and Yumoto, 1988) have been studied for decades. The effects of boundary conditions, such as lip height (Nakakuki, 2002), fuel thickness (Garo et al., 2007), and ambient conditions (Hu et al., 2011; Tu et al., 2013), on the pool fire have also been fully investigated. Those studies have provided basis for the liquid fuel spill fires. However, the fuel in a spill fire moves, which is quite different from the pool fire. Those results for the pool fire cannot be directly applied to the spill fire.

Some analytical models of liquid fuel spill fires spreading on water have been developed (Fay, 2003; ABS Consulting Inc., 2004; Lehr and Simecek-Beatty, 2004). However, very few experimental studies have been conducted to compare with the modeling results. In our previous work (Li et al., 2015), the continuously released *n*-heptane spill fire on water was experimentally investigated. The spill fire was divided into five observable phases: (I) fire propagation, (II) slight shrinkage in fire size, (III) quasi-steady burning, (IV) maintenance after discharge time, and (V) fire extinction. A modified gravity-viscous burning fuel spread model for the prediction of the time varying burning area was proposed and had been verified with the experimental results. Those studies mainly focuses on the spill fires on water. But for the spill fires on land, such as it occurred in Dalian oil spill accidents, the research is not adequate.

The spread of spill fires on land is severely affected by the

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terrain. The influence of substrate slope is quite critical. Mealy et al. (2014) tested the heat release rate of spill fire for instantaneously released gasoline, heptane, kerosene and ethanol on different substrates (concrete, wood, and carpet surface). The maximum burning area were analyzed with substrate initial temperatures and ignition delay times. But the role of substrate slope was not considered in their work. Simmons et al. (2004) measured the steady pool size of liquid fuel instantaneously spilled on inclined surface and then estimated the fuel thickness accordingly. However, the fuel was not ignited in his work.

In this paper, we present the experiments of continuously released *n*-heptane spill fires on inclined surface in a one-dimensional channel. The phases of the spill fire, the time varying burning area, the transition times, the steady burning rate and the fuel thickness are discussed with different substrate slopes and discharge flow rates.

2. Experimental

The experiment was conducted in a large enclosed space. Fig. 1 shows the experimental facilities. The spill fire spread in a 3 m long, 15 cm wide steel trench, with a lip of 3 cm. A hydraulic jack was used to lift one side of the trench to change the slope angle from 0° to 4°. The slope was examined and rebalanced every time before each test with a digital angle ruler (BOSCH DNM 60L), to ensure that the angle was accurate and there was no inclination on the width direction. In order to prevent boilover of thin oil slick burning on metal plate, a cooling water box of 5 cm high was set just beneath the trench surface, with a volumetric inflow rate of about 12 L/min. A peristaltic pump (Longer BT100-1F) could provide a steady volumetric flow rate ranging from 0.02 μL/min to 500 mL/min. The fuel of *n*-heptane was drawn by a peristaltic pump from a fuel tank through the flexible tube. It spilled onto the steel trench through a V-shaped outlet (1 cm by 15 cm), so that the effect of initial fuel velocity on the burning fuel spread rate could be neglected. A magnetic valve was installed between the V-shaped outlet and the tube to protect the pump from backflow when it was shut down. Although the pump could show a real-time volumetric flow rate which was automatically calculated by the tube diameter and the rotate speed, an electronic balance was put under the *n*-heptane tank to measure the weight loss rate, to calibrate the displayed volumetric flow rate. Spilled *n*-heptane was ignited by a handheld burner near the outlet soon after the peristaltic pump was activated.

Two digital cameras were used to record the dynamic process from both the top view and the side view. Their frequency is 25 frames per second. The time-dependent position of flame front can be obtained by analyzing the RGB values of every pixel in the video images with horizontal gauges (Li et al., 2014). However, there might be errors mainly due to the view angle. For this reason, totally 45 type-K (chromel-alumel) thermocouples were used to measure the flame spread rate. The thermocouples, each with a bead diameter of 1 mm and a wire diameter of 0.15 mm, were installed 2 cm above the substrate surface along the central axis, with a spacing of every 5 cm from the outlet (zero) to 1.45 m, and every 10 cm from 1.45 m to the lower edge (2.95 m). Three NI-9213-C series modules were used for data acquisition, with acquisition frequency of 10 Hz. The time when the spread burning fuel reached or left the sensors' location can be recorded by the thermocouples for a change of the temperature. This means was also used by other authors to measure the flame spread rate of solid fuel (Liu et al., 2015). Fig. 2 shows the comparison of the time-dependent flame

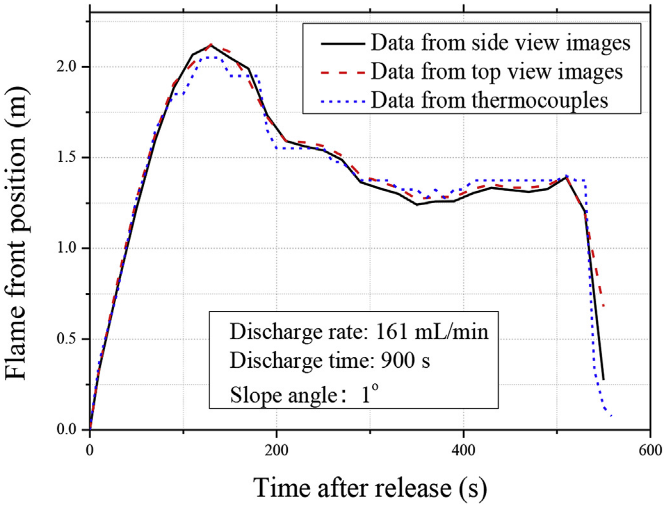

Fig. 2. Comparison of the time-dependent flame front position from the thermocouples and the digital cameras.

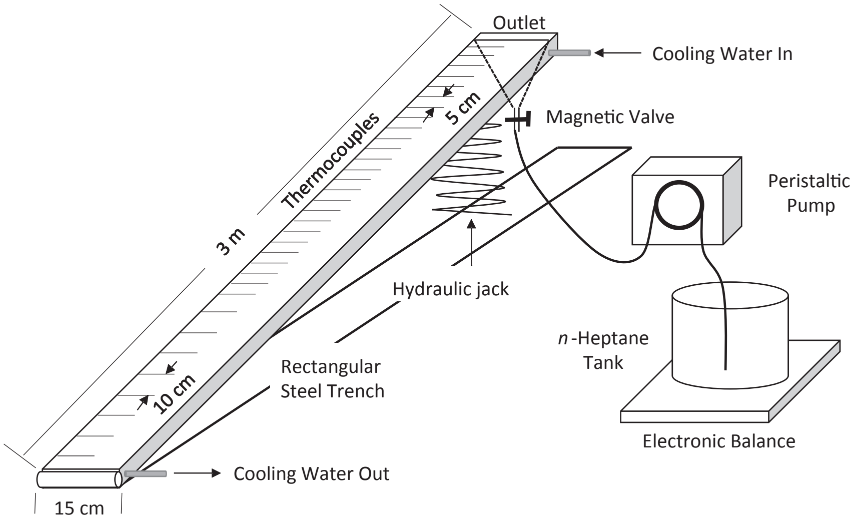

Fig. 1. Schematic of the experimental apparatus.