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Experimental study of continuously released liquid fuel spill fires on land and water in a channel

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ABSTRACT

Liquid fuel spill fires usually occur in the oil storage and transportation industries. The fire develops as the burning fuel spreads, posing a huge threat to the facilities nearby. In this paper, continuously released liquid fuel spill fires were experimentally investigated in one-dimensional channels with three different widths. The spread and burning behavior of the spill fire on water and on a horizontal steel plate were discussed in terms of the burning rate, spread rate and fuel thickness. The burning rate, estimated as the ratio of the discharge flow rate to the steady burning area, was slightly higher for the spill fire on water. The burning rate increased with the trench width, a similar tendency as that of the pool fire, but its value was much lower than that of the pool fire with the same dimensions. A method for estimating the burning fuel thickness at the flame front was proposed, and the estimated values corresponded well to the theoretical values calculated based on the balance between the gravitational force and surface tension. The spread rate of the spill fire was correlated as an exponent function of the ratio of the volumetric discharge flow rate to the trench width. The width of the one-dimensional liquid fuel spill fire mainly affected the burning rate and spread rate.

1. Introduction

Liquid fuel spill fires usually occur in the oil storage and transportation industries. In a loss of containment incident, the liquid fuel leaked from the tanks or pipes to an unconfined area may spread due to gravitational effects. When the fuel is ignited, the burning area will enlarge as the burning fuel spreads, possibly resulting in the further loss of containment by damaging other facilities nearby. For example, in the Dalian oil spill accidents in 2010, the fire zone enlarged to at least 500 m^2 after crude oil spilled from a 1-m diameter pipeline. The spreading fire destroyed the pump room and power distribution room and caused failure in the pipeline automatic control system. The fire fighters worked for 8 h to manually shut off the fuel supply. Fresh fuel was continuously fed to the spill fire, and the burning duration was thus extended (Guo et al., 2013). In addition to the accidents that have occurred on land, the spill fires also spread on water during the Dalian oil spill accident, and other offshore oil spill accidents, such as the Deepwater Horizon oil spill of 2010. Spill fires on water spread with the waves and currents and are a severe threat to vessels and platforms. Thus, investigating the spread and burning behavior of spill fires is important for assessing the consequences of the loss of containment in the oil storage and transportation industries.

Burning area changing with time is a distinctive characteristic for a spill fire. The movement of the fuel makes liquid fuel spill fires much more dangerous than pool fires, in which the fuel is nearly stationary and burns on a fixed area. However, unlike pool fires, which have been studied for decades with well-established theoretical/empirical models for the burning rate (Babrauskas, 1983; Chatris et al., 2001), flame height (Heskestad, 1983; Wang et al., 2017), and thermal flux (Mudan, 1987; Sun et al., 2015), liquid fuel spill fires have attracted less attention (Drysdale, 2011). Although a few analytical models of liquid fuel spill fires spreading on water have been proposed (Fay, 2003; ABS Consulting Inc., 2004; Lehr and Simecek-Beatty, 2004; Oka and Ota, 2008), most of the parameters and correlations in those models come from pool fires and may be not appropriate for describing a spill fire. Benfer (2010) and Mealy et al. (2014) conducted a series of spill fire experiments on concrete surfaces. For a fully developed spill fire (gravitational force balanced by surface tension), the fuel thickness was reported to be between 0.45 mm and 0.76 mm, which is much thinner than that of a pool fire. As a result, the burning rate in a spill fire was found to be much lower than that in a pool fire with the same dimensions (Li et al., 2015; Gottuk and White, 2016). Causes of the difference in the burning rate include heat losses due to the radiation through the thin fuel layer and the convection between the moving fuel and its

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Nomenclature

$A_{p(st)}$	Steady burning area, m^2	t_d	discharge time, s
D	trench width, m	t_{ini}	time of initial few seconds after release, s
g	acceleration due to gravity, m/s^2	u_f	initial fuel spread rate, mm/s
h_{ini}	average fuel thickness, m	σ	surface tension, N/m
h_∞	Frontal fuel depth, m	σ_{as}	the substrate-air interface tension, N/m
k	constant parameter, Eq. (6)	σ_{sl}	fuel-substrate interface tension, N/m
L_{st}	length of the steady burning area, m	σ_{al}	fuel-air interface tension, N/m
L_{max}	length of the maximum burning area, m	ω	linear burning rate, m/s
Q_{in}	Volumetric discharge flow rate, m^3/s	ρ_L	liquid fuel density, kg/m^3
t_{c3}	end time of phase IV, s	ρ_W	water density, kg/m^3
		Δ	fraction of the fuel above the substrate

substrate. (Zhao et al., 2016; Li et al., 2017).

Most of the previous studies have focused on spill fires that were fully developed, and the results show significant differences between spill fires and pool fires. However, the studies focusing on the dynamic processes of spill fires were inadequate. In our previous work, an *n*-heptane spill fire on water in a 1-m-wide trench (Li et al., 2015) and a spill fire on an inclined steel plate in a 15-cm-wide trench (Li et al., 2017) were investigated experimentally. Through the experiment, the spill fire was divided into five observable phases: (I) fire propagation, (II) slight shrinkage in the fire size, (III) quasisteady burning, (IV) maintenance after the discharge time, and (V) fire extinction (Li et al., 2015). Experiments conducted in a trench can be treated as one-dimensional flow experiments, which are the basis for the comprehensive study of spill fires.

The spread and burning behavior of a one-dimensional spill fire can be affected by many factors, such as the substrate type and trench width, but the effects of these factors on spill fires have not been elucidated. In this paper, a comparison between a spill fire on water and a spill fire on land was conducted using continuously released *n*-heptane spill fires in trenches with three different dimensions. The effects of the trench width on the spread rate and burning rate of the spill fire were investigated. The scale issue of the spill fire was also discussed.

2. Experimental

The experiments were conducted in a large enclosed space. The ambient temperature during the experiments was 14–19 °C. The experimental facilities are shown in Fig. 1. The burning fuel spread in a 3-m-long steel trench with a 3-cm-high lip. Three different trenches with widths of 10 cm, 15 cm and 22 cm were used in the experiment. A 5-cm-high cooling water box was set beneath the trench surface (6 mm thick), with a volumetric inflow rate of approximately 12 L/min, in order to prevent boilover of the thin oil slick burning on metal plate. The inflow cooling water temperature was approximately 17 °C. The fuel, *n*-heptane, was drawn from a fuel tank by a peristaltic pump (Longer BT100-1F) through a flexible tube. The fuel spilled upward onto the steel trench through a V-shaped outlet (1 cm by 15 cm) so that the initial velocity could be neglected. A magnetic valve was installed between the V-shaped outlet and the tube to protect the pump from backflow after being powered off. An electronic balance was placed under the *n*-heptane tank to measure the real time volumetric discharge flow rate. The spilled *n*-heptane was ignited using a handheld burner near the outlet soon after the peristaltic pump was activated.

In total, 45 type-K (chromel-alumel) thermocouples were installed 2 cm above the trench along the central axis. The bead diameter and wire diameter of each thermocouple were 1 mm and 0.15 mm, respectively. The thermocouples were installed 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 other side (2.95 m). Three NI-9213-C series modules were used for data acquisition, with an acquisition frequency of 10 Hz. If there is a sudden rise/drop in a thermocouple, the location of this thermocouple is considered to be the current position of the flame front. The times when the burning fuel reached or left the location of the sensor was then recorded. The burning area can thus be computed as the product of the flame front position and the trench width. Two digital cameras were used to record the dynamic process from both the top view and the side view, with a frequency of 25 frames per second.

For a comparison, the burning fuel was spilled onto two different kinds of substrates: a horizontal steel plate to represent the land and a 1-cm-thick water layer. According to the trench width, the experiments

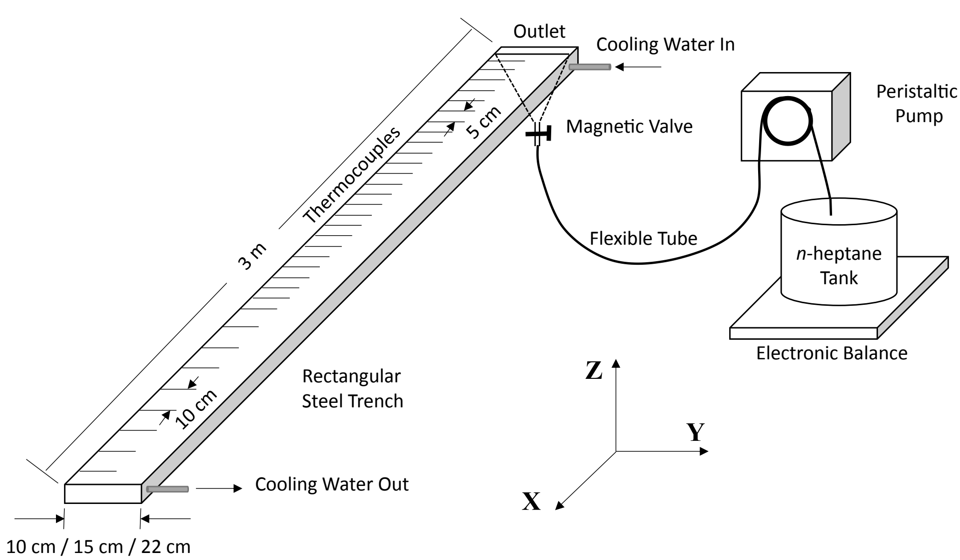

Fig. 1. Schematic of the experimental apparatus.