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An experimental and modeling study of continuous liquid fuel spill fires on water

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ABSTRACT

The spread of burning fuel spilled from oil product containers during offshore storage and transportation may cause large damage and trigger further accidents. Some analytical models already exist to predict the spread and burning behavior of liquid fuel spill fires, however, few experimental studies have been conducted to verify the model results. In this paper, continuous *n*-heptane spill fire experiments were conducted in a rectangular trench covered with water. The burning area, fuel spread rate, and thermal flux with different discharge flow rates and ignition delay times were investigated by both experimental and modeling means. The spill fire burning area, with 5 typical phases during burning, has a quasi-steady value which is directly proportional to the discharge rate but irrelevant to the ignition delay times. The steady burning rate, as the ratio of discharge rate over burning area, was estimated. A spread model was modified to simulate the spread of continuous liquid fuel spill fires in a one-dimensional channel, based on the balance between gravity and viscous forces. A cuboid solid flame model was used to compute the thermal flux from spill fires. The burning fuel spread and the heat flux calculated by the models agree with the experimental results.

1. Introduction

The offshore storage and oceanic shipping of large volumes of flammable liquids bring a potential hazard of spill fires due to liquid fuel release. When spilled and ignited, the burning fuel flowing on water may threaten and damage the vessels, fuel tanks and/or other facilities nearby, and trigger further accidents. It is critical to investigate the spread, burning, and thermal flux of liquid fuel spill fires to effectively plan for fire protection and prevention of secondary disasters in fuel processing industries.

Experiments of liquid fuel fire on water have mostly focused on the burning behavior of the pool fire within a certain burning area. Improved empirical correlations have been widely proposed by researchers to describe the pool fire characteristic parameters such as burning rate (Babrauskas, 1983; Chatris et al., 2001), flame height (Hasemi and Nishihata, 1988), and thermal flux (Koseki and Yumoto, 1988). These pool fire studies have provided good basis for the research on liquid fuel spill fires. Large-scale spill fire experiments, with a total release volume ranging from 3 m^3 to 66.4 m^3, were mostly performed in the 1970s and 1980s (Luketa-Hanlin, 2006). Recently, in order to eliminate the pollution from oil spill accidents, offshore experiments have been conducted to investigate “in situ burning” of oil spills (Evans, 2001). Those experimental studies paid more attention to instantaneous spills (a single, or batch release), however, in some oil spill accidents, if the fuel supply is difficult to cut off, a continuous release will feed the fuel while burning, and makes it more dangerous. Only few experiments have been conducted to study the continuously released spill fires. In our previous work (Li et al., 2014), although the phenomenon of one-dimensional liquid fuel spill fire on water was described and discussed, little quantitative work has been carried out.

Analytical models of liquid fuel spill fires have been widely investigated. Fay developed an analytical model to study LNG and oil spills at sea in the event of an oil tanker rupture on or below the water level, based on the balance between gravity and inertial

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forces (Fay, 2003). ABS Consulting Inc. proposed a model based on Webber's solutions of shallow water equations (van den Bosch and Weterings, 1997) and lubrication theory, taking the impact of resisting force into consideration (ABS Consulting Inc., 2004). Lehr quantitatively estimated the spread rate, maximum slick size, burning rate, duration and effective thermal radiation of both hypothetical LNG and fuel oil spill fires (Lehr and Simecek-Beatty, 2004). These models usually consist of several sub-models, including liquid fuel release, oil spread on water or ground, vapor dispersion, formation of pool fire and flame models to calculate radiation flux. The maximum size of the burning area and thermal flux level can be estimated based on these models. Discussion of those models can be found in the literature (Oka and Ota, 2008; Qiao et al., 2006). However, very few experimental studies have been conducted to compare with the modeling results.

In this paper, we present the experiments of continuous *n*-heptane spill fires on water in a one-dimensional channel to explore the spread and burning behavior of spill fires with different discharge flow rates and ignition delay times. The modified viscous fuel spread model was exploited for the prediction of burning area. A solid flame model to calculate the thermal radiation level was established and compared with the experimental results. The potential consequences in an oil spill fire situation can be predicted using the combination of these two models.

2. Methodology

2.1. Experiment

Fig. 1 shows a schematic diagram of the experimental apparatus. A total 35–100 L *n*-heptane was released continuously with different discharge flow rates, from a sliding vane pump into a rectangular trench. The liquid fuel was ignited immediately or at some time delay after release, as specified in Table 1. The concrete trench was covered with a layer of water 5 cm deep. The trench was 12 m long, 1 m wide and 15 cm deep. A torch burner was used to ignite the liquid fuel at the nozzle, which was installed over the water surface and was 21 mm in diameter. In order to observe the flame features of the *n*-heptane spill fire, a Digital Video (Sony HDR-XR260E) was used to record the flame image with the aid of horizontal and vertical gauges. The length of burning area and the flame height, which was defined as the median value of the flame tip height in 5 s, were obtained through image processing, as described in the previous study (Li et al., 2014). Radiant flux sensors (Captec, TS-30) were used to measure the heat flux on the side region of the flame.

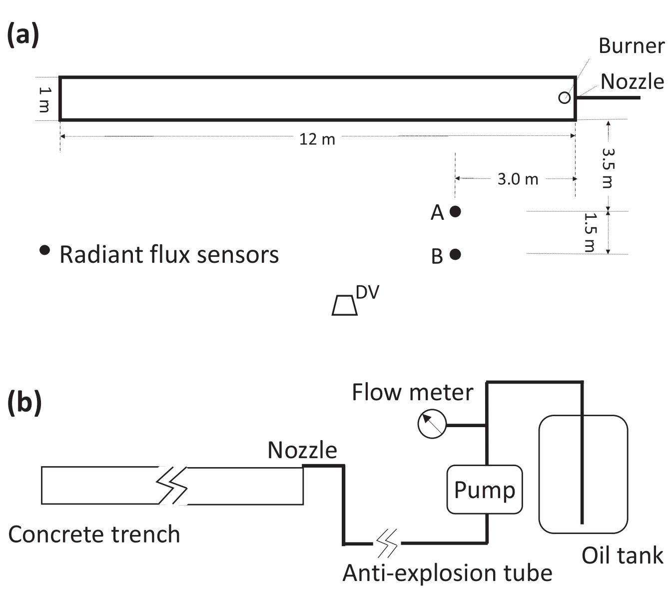

Fig. 1. Schematic diagram of experimental apparatus. (a) and (b) are the top and the side view of the continuous spill system, respectively.

Table 1
Specification of the testing conditions.

Test number	Total volume V_t (L)	Discharge rate Q_{in} (L/min)	Discharge time t_d (s)	Ignition delay t_{ign} (s)
1	35	10	210	0
2	35	15	140	0
3	35	20	105	0
4	50	25	120	0
5	60	30	120	0
6	35	40	52.5	0
7	80	40	120	0
8	50	20	150	40
9	80	20	240	60
10	100	20	300	90
11	35	20	105	∞
12	35	40	52.5	40
13	35	40	52.5	60
14	35	40	52.5	90
15	35	40	52.5	∞

The experiment was conducted outdoors at the test site of State Key Laboratory of Safety and Control for Chemicals in Qingdao, China. The ambient temperature was around 10 °C, and the wind speed was less than 0.2 m/s.

2.2. Models

The fuel spread model and the thermal radiation model to predict the burning area and thermal radiation level of spill fires are discussed separately in this section. The sketch of burning fuel model is shown in Fig. 2.

2.2.1. Burning fuel spread

For an oil film on the water surface, the spread rate of the slick is usually governed by four different forces, which are gravity, inertial, friction, and surface tension. It is proved that the spread can be divided into three regimes according to the balance of these forces: (i) gravity-inertial regime, (ii) gravity-viscous regime, and (iii) surface tension-viscous regime (Fay, 1971). For the spreading oil slick on water, the inertial force in the horizontal direction is of order $\frac{\rho_l u^2}{L}$, and the viscous force is of order $\frac{\mu u}{h^2}$ (Williams, 1994), where ρ_l is the density of liquid fuel, μ is the viscosity of the liquid, L is the length of the oil slick, u is the liquid fuel spread rate, and h is the average thickness of oil film. In the situation of burning fuel spread presented in the experiment, the fuel spread rate is of order 0.1 m/s and the fuel thickness is about 2–3 mm. The viscous force was much larger than inertial force. It was the gravity-viscous effects that mainly dominate the fuel spread rate.

Hoult proposed the one-dimensional spreading law for gravity-viscous regime in the form of slick length as a function of the time t since the oil was instantaneously released at the origin of the spread, the volume V_t of the oil spill and the physical properties of the oil and water (Hoult and Suchon, 1970):

$$L = k_v\left(\frac{\Delta g V_t^2 t^{3/2}}{\nu^{1/2}}\right)^{1/4} \quad (1)$$

where k_v is an empirical constant which value is recommended to be 1.5, g is the acceleration due to gravity, υ is the kinematic