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Spread and burning behavior of continuous spill fires

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ABSTRACT

Spill fire experiments with continuous discharge on a fireproof glass sheet were conducted to improve the understanding of spill fire spread and burning. Ethanol was used as the fuel and the discharge rate was varied from 2.8 mL/s to 7.6 mL/s. Three ignition conditions were used in the experiments; no ignition, instantaneous ignition and delayed ignition. The spread rate, regression rate, penetrated thermal radiation and the temperature of the bottom glass were analyzed. The experiments clearly show the entire spread process for spill fires. Further, the regression rate of spill fires at the quasi-steady burning was lower than that of pool fires and the ratio of the spill fires' regression rate to the pool fires' regression rate was found to be approximately 0.89. With respect to the radiative penetration and the heat conduction between the fuel layer and the glass, a regression rate expression for spill fires was developed based on some modifications on existing expressions for pool fires. In addition, a complete phenomenological model for spill fires was developed by combining the characteristics of spread and burning. The model was verified by the experimental data and found to predict the spread process for spill fires with reasonable accuracy.

1. Introduction

Overflows and leakage from oil product containers during storage and transportation may cause large damage and trigger further accidents especially in the case of ignition [1,2]. It is important for risk management to investigate the fuel spread, burning, and thermal radiation of spill fires. The spill fire has two main aspects: the spread behavior and the burning behavior. At present, some models have already been established to predict the spread and burning behaviors. For the fuel spread, the spread of LNG and oil on water or on land has received considerable attention the past few decades [3,4]. In these studies, different versions of pool spread model based on various simplifications have been provided and these have been summarized by Webber et al. [5]. For the fuel burning, many experiments with burning diameters ranging from around 0.01 m to around 80 m have been carried out to study the steady-state burning rate [6]. Based on these experiments, empirical models have been established, and these are gathered and discussed by, for example, Babrauskas [7] and Ditch et al. [8]. As a result, the existing models for spread and burning can lay a foundation for spill fire research.

To date, the combination of the spread and the burning has been taken into account by some researchers and a 'complete' model for spill fires has been proposed [4]. In these models, it is obvious that the fuel consumption due to burning is crucial in the spread process, and the quasi-steady burning is directly determined by the burning rate of the spill fire for a certain discharge rate [9]. However, the burning rate of pool fires is directly considered that of spill fires in some cases, even though this has been proved wrong by Gottuk et.al [10] and Mealy et al. [11]. They found that the burning rate of spill fires is lower than that of pool fires and in some situations the ratio of the spill fires' burning rate to that of pool fires is less than 0.5. Gottuk and White provided a depth coefficient that was introduced to modify the pool fires' burning rate model in the newest edition of the SFPE Handbook for Fire Protection Engineering [12]. Still, they did not further discuss the reason for the decrease of the burning rate. In their descriptions, the available experimental data for continuous spill fires are not sufficient to explain the burning rate decrease because the temperature of the substrate and the transmitted thermal radiation were not measured [12]. However, spill fire accidents often evolve into the continuous discharge situations, as exemplified by the "7.16" oil pipeline fire accidents of Dalian [13]. As a result, continuous discharge spill fires should be paid more attention to and the burning rate's decrease should be further discussed.

Herein, some continuous spill fire experiments were conducted to

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Nomenclature

ΔH_e	heat of gasification (kJ/g)	w_t	real-time regression rate (m/s)
Q_{dis}	fuel discharge rate (cm^3/s)	w_∞	a peak regression rate (m/s)
R	spread radius (cm)	w_s	steady regression rate (m/s)
R_{max}	maximum spread radius (cm)	q_f	heat feedback (kW/m^2)
S_{st}	steady burning area (cm^2)	q_{cov}	convective heat feedback (kW/m^2)
T	fuel temperature	q_{pe}	penetrated thermal radiation (kW/m^2)
T_a	ambient temperature (K)	q_{out}	heat loss of fuel layer (kW/m^2)
T_b	fuel boiling point (K)	h	fuel thickness (mm)
Y_s	smoke yield	h_{min}	minimum fuel thickness (mm)
c_p	fuel specific heat (kJ/(gK))	g	gravitational acceleration (m/s^2)
c_g	glass specific heat (kJ/(gK))	k	spread coefficient
		ρ_g	fireproof glass density (kg/m^3)
		t	Time (s)

display the entire spread process and burning behaviors. In order to find the main reasons leading to the regression rate decrease, the penetrated thermal radiation was measured by using the transparent fireproof glass. Then the heat loss of fuel layer was estimated and an empirical regression rate model is provided by some modifying an existing pool fire model. In the end, a basic spill fire model is developed that describes the entire spread process.

2. Methodology

2.1. Experimental set-up

Fig. 1 shows the schematic diagram of the experimental apparatus. The fireproof glass was selected as the spread surface because it could provide a level surface for fuel spread. In addition, the radiative penetration could also be measured due to the transmittance property of the glass. The fireproof glass was 1 m long, 1 m wide and 10 mm thick. A 10 mm diameter hole was punched at the center of the glass to allow for connecting a tube. The ethanol was released continuously with different discharge flow rates from a fuel container to the surface of the fireproof glass by a peristaltic pump. A balance (Sartorius) with a range from 0 kg to 35 kg with an accuracy of 0.1 g was used to measure the residual ethanol mass. Then the discharge rate can be calculated by analyzing the average change in mass over a period of time. Three water-cooled heat flux gages were installed under the glass and used to measure the transmitted thermal radiation. They were separately located 5 cm, 15 cm and 25 cm away from the center of the glass. In addition, three patch thermocouples were positioned symmetrically with respect to the heat flux gages at the center of the glass. Finally, ten K-type thermocouples were arranged at the vertical axis of the glass surface and the separation distance between each was 10 cm. During the experiments, the fuel spread rate and the flame height were recorded by two digital video recorders (Sony HDRXR260E). By analyzing the red, blue, and green (RGB) values of every pixel, the flame area (R > 180, G > 90, B > 70) could be captured and then the flame height and burning area could be determined.

It was an important work to keep the glass surface level because a small inclination would have a significant effect on the spread behavior. Before each experiment, a levelling instrument with an accuracy of 0.01° was used to check whether the surface is level. And then we used the pump to input water first to confirm whether the water can spread uniform on the glass surface.

The spill fire experiments were performed in a large test hall (30 m×14 m×9 m). During the test, the doors and windows were closed, but not sealed. Each experiment was repeated three times. The experiments were conducted at around 28 ± 4 °C. The ethanol spill was; (1) ignited immediately, (2) ignited after a certain delay after the release, and (3) not ignited, as specified in Table 1.

2.2. Model descriptions

The spread process is controlled by the force of gravity, viscosity and friction [14]. There are many different models in the spread field because of different understanding and different simplifications. The integral spread model on land is developed in PHAST considering the pool spread, vaporization and heat conduction [15].

$$\frac{dR}{dt} = k\sqrt{g(h - h_{min})} \tag{1}$$

where R is the spread radius(m), t is the spread time(s), g is the acceleration due to gravity (m/s^2), h is average fuel thickness(m), k is an empirical constant whose value can be determined from experimental data. h_{min} is the minimum spread fuel thickness which is provided for some fuels in PHAST [15] and the value can be calculated using the experimental data.

The fuel front spread rate becomes zero when the thickness of the pool reaches its minimum height ($h= h_{min}$). Many authors, including Brambilla and Manca [16] and Webber [17], have declared that it is a mistake for spread on land to neglect the friction part. However, the effect of friction would decline significantly for longer duration spills based on the Manning formula with the flow being under the laminar flow condition. Therefore, it is reasonable to select Eq. (1) as a basic model to assess the ethanol continuous spread process. Compared with the spread, there are many special phenomena for spill fires, such as the shrinking phenomenon which cannot be predicted by the spread model. In addition, the quasi-steady burning area is determined by the burning rate for long time burning. Combined with the above descriptions for the entire spread and burning process, the whole spread

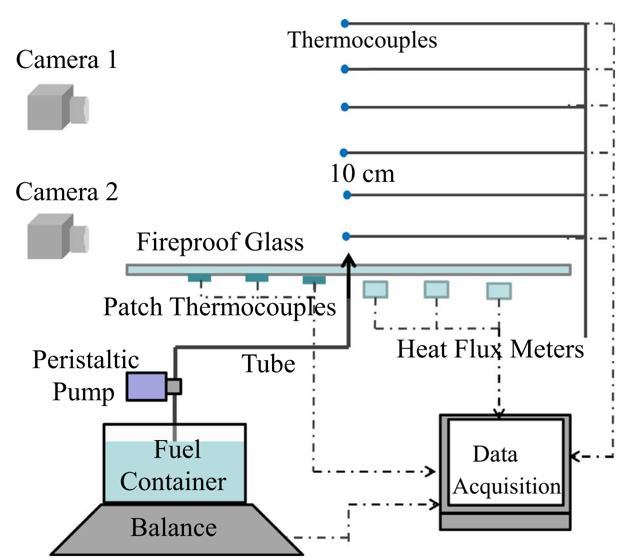

Fig. 1. Schematic diagram of the experimental apparatus.