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Experimental study of the burning behaviors of thin-layer pool fires

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ABSTRACT

The thin-layer burning behaviors of gasoline, including the heat flux feedback to the burning surface, the penetrating thermal radiation, the temperature profile of liquid layer, and the burning rate were studied in experiments of thin-layer pool fires in square, fireproof glass trays. Experiments with four different tray sizes (side lengths of 30 cm, 40 cm, 50 cm and 60 cm) and four different initial liquid thicknesses of 6 mm, 9 mm, 12 mm and 15 mm were conducted. The results indicate that the heat flux feedback from the flame remained approximately constant, except during the ignition and extinguishment periods, and was also independent of the initial fuel thickness. The penetrating thermal radiation, on the other hand, increased with decreasing liquid layer thickness, gradually assuming rapid exponential growth. Furthermore, a boiling layer was formed during the initial burning period and its maximum depth was close to 3.0 mm. Four typical burning phases including pre-heating burning, steady burning, thin-layer burning and extinguishment were identified. The penetrating thermal radiation was the main cause of the burning rate decrease for thin-layer burning. These findings can provide a basis on which to build a real-time burning rate model for thin-layer burning.

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1. Introduction

Statistics show that fuel leakage accidents that occur during liquid fuel transportation frequently result in thin-layer burning incidents [1,2]. The thickness of such a liquid layer is usually on the order of millimeters because the liquid is not constrained by a physical boundary, as is the case for pool fires that occur in industrial settings, where leaks are confined by barriers constructed to contain leaks [3]. The burning area increases rapidly in thin-layer burning accidents, up to a certain leakage amount, and the ensuing thermal hazards are obvious [4,5]. For example, the accidental leakage from a tanker truck carrying 3.6×10^4 L of diesel in the Zhejiang Province of China resulted in a thin-layer fire accident with a burning diameter of more than 10 m (2016) [6]. In this accident, the driver lost his life and cars in the immediate area were damaged [6]. As a result, it is meaningful to study the burning behaviors of thin-layer burning.

Because pool fires related to liquid fuels are a safety concern, extensive research has been undertaken over several decades into fundamental aspects of the steady-burning behavior of pool fires. Topics of study include flame height [7], burning rate [8] and thermal radiation [9]. In addition to these fundamental aspects, specific environmental conditions such as high pressure [10,11], fuel thickness [12] and confined conditions [13] have also been studied. In comparison to the steady-burning of pool fires, thin-layer burning has not attracted much attention [14], even though this type of burning occurs frequently in industrial accidents [2]. Recent years, some scholars begin to show attention on thin-layer burning due to the increase number of thin-layer accidents. For example, we can find more descriptions on thin-layer burning in the third edition of *Fire Dynamics* and the fifth edition of *SFPE Handbook of Fire Protection Engineering* [3,14]. In these books, it is well known that the burning rate of thin-layer burning is smaller than that of pool fires. However, the reasons behind the burning rate decrease are still unclear. In thin-layer burning field, Garo et al. conducted a series of burning scale thin-layer experiments (0.15–2 m diameter) and built an one-dimensional heat transfer model to describe the decrease in burning rate for high-boiling-point fuels (boiling points above 100 °C) burning on water [15,16]. In his works, the radiative heat feedback was usually considered to be absorbed by the fuel surface due to opacity of crude oil [16]. Moreover, some elaborate models were also built by Inamura et al. and the absorption process on radiative heat feedback was considered [17–19]. However, the used absorption coefficient sometimes is usually unclear in their works and the effect caused by absorption on radiative heat feedback is still unknown. In recent studies, Farahani

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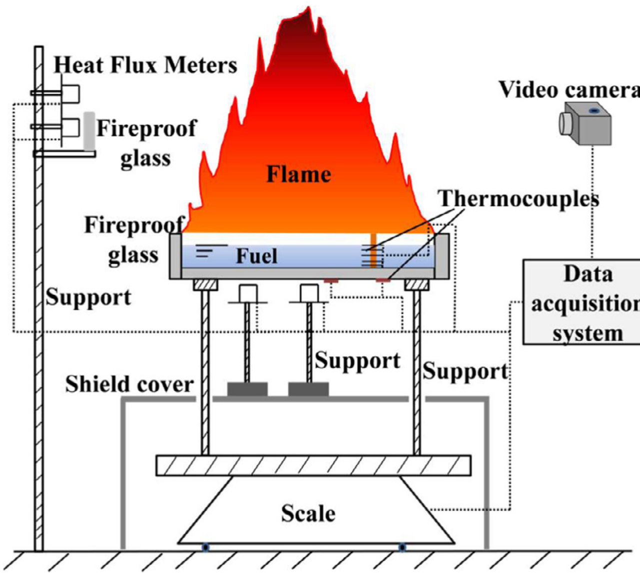

Fig. 1. Schematic of the experimental setup.

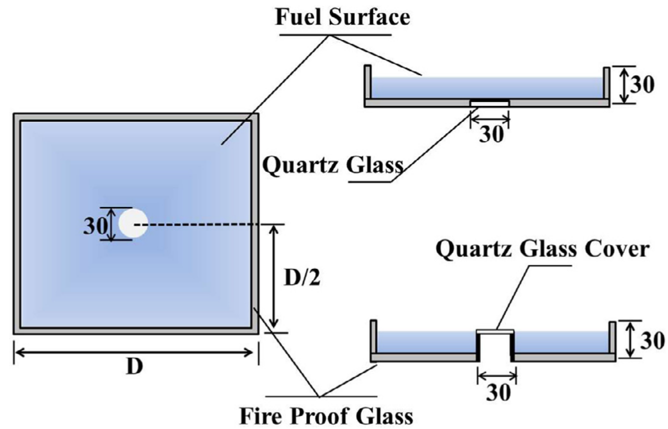

Fig. 2. Detailed structure of the two types of pans. The numbered dimensions are in mm.

et al. and Vali also pointed out that the heat transfer in liquid layer and liquid motion due to uneven heating should be further studied in thin-layer burning [20,21]. More importantly, Vali stressed the radiative absorption effect on temperature distribution and on formation of vortex in the liquid layer [21]. Therefore, thin-layer experiments are needed to study the radiative heat transfer process in the liquid layer.

The purpose of this study is to improve understanding of thin-layer burning by using different scale experiments to determine the factors that are responsible for the decrease in the burning rate. Thin-layer fire experiments were conducted in square trays of different dimensions (30 cm, 40 cm, 50 cm and 60 cm), with various initial fuel thicknesses (15 mm, 12 mm, 9 mm and 6 mm). In the experiments, the heat flux feedback (HFF), the penetrating heat flux (PHF) and the temperature profile of the liquid layer (TPLL) were measured and analyzed to provide a qualitative explanation for the variations in the thin-layer burning rate.

2. Experimental setup and models

2.1. Experimental setup

The experimental setup was designed to investigate the burning behaviors including the heat flux feedback (HFF) from the flame, the penetrating heat flux (PHF), the temperature profile in the liquid and the burning rate. A schematic of the experimental setup is shown in Fig. 1. Four configurations of custom-made square trays with side dimensions of 30 cm, 40 cm, 50 cm and 60 cm, and with an inner depth of 3.0 cm were used. The side wall and the bottom of the custom-made square trays were all made of fireproof glass (thickness = 5 mm) and stick together by fireproof adhesive. The pool bottom was transparent and some part of heat radiation can penetrate the bottom directly. The trays could be separated in two types according to the structure and function: the first was used to measure PHF and the second was used to measure HFF, as shown in Fig. 2. In order to improve the accuracy of the experiments, the glass sheet at the measurement position was replaced by a quartz glass sheet (first type) and a quartz glass cover (second type). The height of the quartz glass cover (second type) is 16 mm (in Fig. 2). The custom-made square trays were supported by four legs and each contact area between the glass and the leg was around 1 cm^2. Meanwhile, asbestos was used between the bracket and the trays to reduce the heat loss due to heat conduction. Herein the trays could be considered to be exposed in the air. This method was used by Inamura et al. [17] and Hu et al. [22] to measure the HFF. The fuel used was 120# gasoline. The properties of gasoline and fireproof glass were shown in Table 1.

In the experiments, the PHF and the HFF were measured using water-cooled heat flux meters (SBG 01) with a nearly hemispherical wide view angle and the layout is shown in Fig. 3. The maximum range of the heat flux meters is 50 kW/m^2 and the accuracy is more than 95%. The temperature profile in the liquid layer was obtained using five K-type thermocouples with a diameter of 0.5 mm, which were fixed at different positions in the centerline of the liquid pool. The measurement uncertainty of these thermocouples is less than ±2.2 °C when the measurement temperature is less than 227 °C and the specific layout is shown in Fig. 3.

The thin layer burning platform was placed on a Sartorius load cell and an acquisition module was used to collect the data in time. The detail measurement is shown in our previous study [23]. Moreover, a digital camera (Sony HDR-XR260E) was placed in front of the experimental setup to capture the flame height and the processing method relied mainly on the flame brightness as described by Muñoz et al. [24]. A propane torch igniter was used to ignite the fuel layer.

The thin-layer burning experiments were conducted in a large-scale 30 m × 14 m × 9 m (L × W × H) chamber. During the experiments, the windows and the door were closed to reduce the influence of wind, but were not sealed. The indoor temperature was 30 ± 3°C and the humidity remained around 75 ± 10% during the experiments. Each experiment was performed twice. The specification of the experimental conditions is shown in Table 2.

2.2. Heat transfer models

To simply explain thin-layer burning behaviors, the main heat transfer mechanics for a thin-layer burning provides the basic concepts as shown in Fig. 4, which is adapted from Hamins et al. [25]. In addition, the liquid layer is divided vertically into two parts: the boiling layer (BL) and the temperature gradient layer (TGL) based on Vali's work [21].

In general, the burning rate is determined by the received net heat from the boiling layer in which the fuel evaporates directly. According to energy conservation, the heat available at any given time for evaporation is given by Eq. (1):

$$\dot{Q}_e = \dot{Q}_{\rm conv} + \dot{Q}_{\rm rad} + \dot{Q}_{\rm cond} - \dot{Q}_{\rm heat} - \dot{Q}_{\rm loss} - \dot{Q}_{\rm ref} \quad (1)$$

where $\dot{Q}_e$ is the total net heat directly used to evaporate, $\dot{Q}_{\rm conv}$ is the convection heat between the flame and the fuel layer, $\dot{Q}_{\rm rad}$ is

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