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Experiment study on the burning rates of ethanol square pool fires affected by wall insulation and oblique airflow

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ABSTRACT

The effects of pool wall insulation condition and oblique air flow on the burning rates of ethanol square pool fires have been studied experimentally in a small-scale wind tunnel, which focused on the heat transfer process of the fuel pool system due to flame tilt and wall insulation. The results showed that the mass burning rate of a pool fire decreased when the pool wall was insulated, especially in the cases with larger airflow speeds. The maximum value of the mass burning rate without wall insulation reached approximately 2.3 times of that with wall insulation at an air speed of 2.93 m/s and a tilt angle of 0°. For both cases with or without wall insulation, the mass burning rates decreased with increase in pool sizes and increased with increase in airflow tilt angles. However, for the cases with wall insulation, the differences in the mass burning rates with different pool sizes are relatively small as the airflow speeds exceed 1.5 m/s, while the differences are relatively large for the cases without wall insulation. In addition, the turbulence of the flame fluid would be weakened when the pool wall was insulated.

1. Introduction

The fire hazards of liquid hydrocarbon fuels have been a serious safety concern, which is attributed to liquid hydrocarbons being ubiquitous throughout society, including in oil tanks, etc. A considerable number of studies [1–7] on both the practical and the fundamental aspects of pool fires have been conducted, which focused on the burning rate, the flame height and pulsation, the thermal radiation, the total kinetic energy, and the soot microstructure. However, the above studies mainly considered the cases of burning in a quiescent ambient condition. In practical scenes, most pool fires may burn under airflow environments, such as ambient wind in storage plants, etc.

Some reports had been focused on the effects of airflow on pool fires [8–12]. For a large pool fire, the influence of wind speed on the burning rate was negligible up to 2 m/s, but it had a certain effect at wind speeds higher than 2 m/s [8]. The results [9] of methanol square pool fires with transverse air speeds from 0 to 5.5 m/s showed that the burning rate of the smallest square pool (7.5 × 7.5 cm) monotonously increased with increased wind speeds, while the burning rate of the largest square pool (30 × 30 cm) was essentially invariant to this range of air speeds, and the intermediate-sized square pools showed a non-monotonic increase. The experiment of a small pool fire in a 1/20 reduced-scale tunnel [10–12] showed that the burning rates of methanol square pool fires decreased, while those of acetone and heptane square pool fires increased with increased air speeds.

It should be noted that in most previous studies, the burning pools were embed into the floor, so that the pool wall was not exposed to the surroundings and the tilted flame could not touch the pool wall. But in most practical scenes, the burning pools may be placed above the floor, such as the oil tanks in petrochemical enterprises, etc. In these scenarios, the tilted flame can touch the pool wall and this will enhance the heat transfer from pool to the fuel and then accelerate the fuel evaporation.

However, most of the above studies focused on horizontal cross airflow, but few considered the effect of tilt wind on fire behaviour. Several studies [13,14] had been investigated the effect of tilt wind on fire behaviours, but only focused on the flame spread rate, flame shape of solid fuel fires. The studies [15,16] on the effects of oblique air flow on burning rates of square ethanol pool fires showed that the mass burning rate increased with the increase of tilt direction and the pool wall heat effect became more obvious under oblique airflow, but they did not consider the effect of the pool wall

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Nomenclature

L	pool edge length (cm)
A	fuel surface area (m^2)
c_p	specific heat (kJ kg^{-1} K^{-1})
m	fuel mass (g)
$\dot{m}'$	mass burning rate (gs^{-1})
$\dot{m}''$	mass burning rate per unit area (gm^{-2} s^{-1})
$\Delta\dot{m}''$	difference between with and without wall insulation (gm^{-2} s^{-1})
$\dot{m}''_{tilted}$	mass burning rate per unit area with oblique airflow (gm^{-2} s^{-1})
$\dot{m}''_{level}$	mass burning rate per unit area with horizontal airflow (gm^{-2} s^{-1})
k	value of $\dot{m}''_{tilted}/\dot{m}''_{level}$
θ	tilt angle (°)
H_g	gasification heat of the fuel (kJ kg^{-1})
H_v	latent heat of evaporation (kJ kg^{-1})
$\dot{Q}_{evp}$	net energy to evaporate the fuel (kW)
$\dot{Q}_{evp-without}$	net energy to evaporate the fuel without wall insulation (kW)
$\dot{Q}_{evp-with}$	net energy to evaporate the fuel with wall insulation (kW)
$\dot{Q}_{in}$	total heat transfer from the flame and surroundings to the fuel (kW)
$\dot{Q}_{out}$	energy loss from the fuel to the surroundings (kW)
$\dot{Q}_{frad}$	radiative heat transfer from flame to the fuel surface (kW)
$\dot{Q}_{fconv}$	convective heat transfer from the flame to the fuel surface (kW)
$\dot{Q}_{w-fuel}$	total heat transfer from the pool wall to the fuel (kW)
$\dot{Q}_{fw}$	heat transfer from the flame to the pool wall through the top surface (kW)
$\dot{Q}_{rad}$	radiative heat transfer from the tilt flame to the pool wall outside surface (kW)
$\dot{Q}_{conv}$	convective heat transfer from the tilt flame to the pool wall outside surface (kW)
$\dot{Q}_{cond}$	conductive heat transfer from the tilt flame to the pool wall outside surface (kW)
$\dot{Q}_{loss1}$	heat loss from the fuel to the surroundings through the pool wall (kW)
$\dot{Q}_{loss2}$	heat loss from the fuel surface to the surroundings through reradiation (kW)
v	airflow velocity (m/s)
T	wall temperature with wall insulation(°C)
T'	wall temperature without wall insulation (°C)
t	time (s)

Subscripts

with	with wall insulation
without	without wall insulation
f	flame
w	pool wall
l	leeward rim
s	streamside rim
w	windward rim

insulation, although it indicated that the insulation may mainly affect heat transfer [17,18].

The current experimental study focuses on examining if the wall insulation conditions would influence the burning characteristics of the pool fire under oblique airflow due to flame tilt and the extent of these effects compared to that without wall insulation. Then attempt to provide method on how to reduce the hazards of a liquid pool fire under such conditions. However, there are few relevant reports on this topic. The results may be helpful for estimating the mass loss and heat transfer of a pool fire under the coupling effects of oblique airflow and pool wall insulation.

2. Experimental setup and methodology

2.1. Experimental facility and condition

Fig. 1 shows the schematic diagram of the experimental setup. The cross-section area is 42 × 60 cm. The fuel used in the experiments was ethanol-C_2H_5OH, its properties are shown in Table 1. An ethanol flame generally produces little soot when combusting under normal atmospheric conditions; therefore, the flame emits relatively low levels of thermal radiation compared to yellow soot-producing flames. The stainless steel square pools with edge lengths, L, of 4, 6, 8, and 10 cm, a wall thickness of 1 mm and a depth of 1.5 cm were used based on the size in comparison with the cross-sectional area of the model.

As shown in Fig. 1, airflow was produced using a 0.75 kW wind fan positioned at one end of the wind tunnel, which generated downward wind with air speed up to 5 m/s. The angle θ represents the wind tilt direction. A KA12 four-channel anemometer with resolution of 0.01 m/s was used to measure the airflow speed inside the wind tunnel. In this work, airflow speeds ranging from 0 to 3.0 m/s were considered to provide relatively steady airflow. Turbulence intensity of the airflow was found to be less than ±6% at all test points.

The burning pool was placed on a horizontal support frame. An asbestos board with a thickness of 1 cm between the pool and the support frame was used to avoid the pool bottom heated by the flame and reduce heat loss from pool bottom. An electric balance with sampling intervals of 0.1 s and resolution of 0.01 g was positioned below the support frame to record the mass loss history of the fuel. Images of the flames were recorded with a 3.3 Mega pixels SONY HDR-PJ10 digital camera.

The experiments were carried out in a laboratory under the following ambient conditions: the temperature was 18 ± 2 °C, the pressure was 101 ± 5 kPa, and the humidity was 25 ± 15%. All of the test cases are specified in Table 2. Each test case was carried out at least three times. In each test, the door and the window were closed to avoid the influence of ambient wind, and the fan was switched on after all of the equipment and the fuel were set to the prescribed conditions. The fan and the data acquisition system were activated at the same time, then after approximately 30 s, the fuel was ignited. Each repeated test was conducted after the wind tunnel and fuel pan returned to the initial ambient conditions.

2.2. Heat balance of the fuel without pool wall insulation

Fig. 2 shows the schematic diagram of the heat balance in a liquid fuel pool fire without wall insulation under oblique airflow. Three K-type thermocouples with bead diameters of 1 mm and a resolution of 0.1 °C were soldered at the middle of the wall surfaces to measure the wall temperatures, which are according to the leeward wall temperature, T'_l, stream side wall temperature, T'_s, and windward wall temperature, T'_w, respectively. The fuel