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Experimental study and global correlation on burning rates and flame tilt characteristics of acetone pool fires under cross air flow

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ABSTRACT

This paper reports a new global relation developed to characterize burning behavior of acetone pool fire under crosswind ranged from 0 to 2.5 m/s with incremental change of about 0.5 m/s. With the increase of the cross air flow speed, results show that the enhancement rate of the mass burning rate relative smaller pool fires was higher than relative larger pool fires. And the overall mass burning rate of the pool fire increases linearly with the cross air flow speed from 0 to 0.5 m/s, the mass burning rate increase with the increase of cross air flow speed. Then it began to drop a bit slightly. Finally, the mass burning rate gradually increased as the cross wind speed increases from 1.5 to 2.5 m/s. A global correlation by introducing the diffusive transfer *B* number, with wind speed and pool dimension aspect ratio accounted for, is then developed for the mass burning rate of square acetone pool fires. The mean flame length of acetone pool fires is well correlated linearly with Froude number. And the tangent values of flame tilt angle with cross air flow can be correlated well by previous model.

1. Introduction

Pool fires present a serious fire hazard to industrial processes. Hydrocarbon pool fires have been studied for decades [1–12]; these works mainly concentrated on flame and buoyant plume characteristics, such as the mass burning rate [1–5], flame shape [5–7], temperature [8,9], thermal radiation [10–13], including wind [14–29] and pressure effect [30,31], with fuel characteristics, such as fuel type, and ambient conditions.

Mass burning rate (e.g., [1–5]) and flame shape [5–7], are two of the basic and important parameters of hydrocarbon pool fires. Physically, the mass burning rate is determined by heat transfer to fuel surface from flame on the basis of flame mechanisms involving in pool characteristic scale, which are both affected by the source characteristic (fuel type) as well as cross air flow speed. The most classical three-regime theory [2–4,19] based on the flame mechanisms: (a) fully laminar flame when the diameter of pool is smaller than 0.03 m, (b) transitional flame (laminar and turbulent) when the diameter of pool is between 0.03 m and 1 m, (c) fully turbulent flame when the diameter of pool is larger than 1 m. In the transitional and turbulent regime, the mass burning rate under quiescent conditions is as following [2,19]:

$$\dot{m}''_D = \dot{m}''_{\infty,D}(1 - e^{-k\beta D}) \tag{1}$$

This form was firstly recommended by Zabetakis and Burgess [32] in 1961, where $\dot{m}''_{\infty,D}$ is the burning rate for an infinite diameter pool fire, k is the radiative emission coefficient and the β is the mean beam length corrector.

For the cross air flow effect on burning behavior, previous works (e.g., [2,14-26]) have shown that the wind affects the burning behaviors of a hydrocarbon pool fire considerably. The cross air flow should enhance the turbulence and effect the heat transfer mechanism (Conduction, Radiation). Blinov [2] studied the effects of cross air flow on the burning rate of pool fire, which indicates the mass burning rate increase with cross air flow speed, that is,

$$\dot{m}'' - \dot{m}''_0 = (\dot{m}''_{\infty,v} - \dot{m}''_0)(1 - e^{-\gamma u}) \tag{2}$$

where $\dot{m}''$ is the mass burning rate under cross air flow, $\dot{m}''_0$ is the mass burning rate under quiescent conditions. $\dot{m}''_{\infty,v}$ is the asymptotic burning rate limit. γ is a parameter which is related to the wind speed enhancement.

For the effect of fuel type, Roh et al. [24,25] have studied experiments for small scale methanol, acetone, heptane pool fires (length from 4.5 to 14.5 cm) in a small scale model tunnel (0.4 m wide,

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Nomenclature

B	the diffusive transfer coefficient
C_p	specific heat of air at constant pressure
D	diameter of pool (m)
g	gravitational acceleration (m/s^2)
H_c	heat of combustion
H_g	effective heat of gasification
H_v	the latent heat of vaporization at the pool surface temperature
k	the radiative emission coefficient
L	the length of square pool rim (m)
L_R	the long side length of rectangular pool rim (m)
L_v	the latent heat of evaporation
ℓ_f	mean flame length (m)
$\dot{m}''$	the mass burning rate under cross air flow
$\dot{m}''_0$	the mass burning rate under quiescent conditions
$\dot{m}''_{\infty,v}$	the asymptotic burning rate limit
$\dot{m}''_{\infty,D}$	the burning rate for an infinite diameter pool fire
R_v	the mass burning rate enhancement rate
Ri	Richardson number
T_a	ambient temperature (K)
T_f	flame temperature (K)
u	cross air flow speed (m/s)
W_R	the short side length of rectangular pool rim (m)

Greek symbols

γ	a parameter which is related to the wind speed enhancement
β	the mean beam length corrector
λ	related to the reciprocal of the latent heat of evaporation
θ	flame tilt angle from the normal direction

0.4 m high and 10 m long) under cross air flow (wind speed from 0 to 1.68 m/s). It is shown that the mass burning rate of methanol decrease with cross air flow, but the burning rate of acetone and gasoline pool fire showed different response to the longitudinal air flow. Hu et al. [18] also have studied the methanol and gasoline pool fires (length from 5 to 30 cm) under cross air flow (wind speed from 0 to 3 m/s). It is revealed that burning rate of methanol pool fires, except the 5 cm one, first decreased and then increased with the increasing of the longitudinal air flow speed from 0–3 m/s. and the gasoline pool fires increased monotonously with the increasing of the longitudinal air flow speed. It is also found recently that Hu et al. [19] have revealed experimentally that the burning rate of gasoline increase with the cross air flow, where γu is very small, Eq. (2) can be simplified as Eq. (3)derived from Blinov et al. [2].

$$\dot{m}'' - \dot{m}''_0 = (\dot{m}''_{\infty,v} - \dot{m}''_0)\gamma u \tag{3}$$

Hu et al. [18,19] analyzed further the burning rate of rectangular gasoline pool fires and provided a theory based on heat transfer mechanisms. It derived theoretically the mass burning rate enhancement rate due to a cross air flow vary linearly with the $2(L_R/W_R + 1)/L$, where L_R and W_R is the stream-wise and the cross-wise pool length respectively, the length of side wall plays a more important role in the enhancement of the burning rate due to the cross air flow than that of the perpendicular one. For the square pool fire, the burning rate enhancement rate with the cross air flow should

$$R_v = \frac{\Delta\dot{m}''}{u} = \lambda\frac{3L}{L^2} = \frac{3\lambda}{L} \quad \text{or} \quad \Delta\dot{m}'' = \frac{3\lambda u}{L} \tag{4}$$

where R_v is the mass burning rate enhancement rate, λ is related to the reciprocal of the latent heat of evaporation. So, the burning rate enhancement rate due to a cross air flow should vary linearly with the value of L^{-1} small pool fires. It is shown that the pool dimensions have a strong effect on the value of the burning rate enhancement rate due to cross air flow speed [18].

However, in all above tests, But there is still no report on how to quantify the cross air flow affect the burning rate enhancement rate of acetone pool fire considerably. How R_v and flame tilt characteristics changes with cross air flow speed in acetone pool fire needs to be quantitatively clarified by experiments. The mass burning rate including flame length and flame tilt angle, will be measured and correlated to clarify quantitatively enhancement rate difference in previous other hydrocarbon pool fire for a global models which is proposed with the classic mass transfer B-Number derived from Hamins et al. [12].

2. Experimental

Experiments are carried out with five square pools (length, L = 10 cm, 15 cm, 20 cm, 25 cm, 30 cm). Pool fires were burned with acetone. An electronic balance is used to record the mass loss history with resolution of 0.01 g. The uncertainty of the measured mass loss rate is estimated to be less than 3%. These pools were made by 2 mm thick steel board. Their depths are all 2.5 cm. In each test, the initial thickness of the fuel is the same. The pool is placed on the top of the fire prevention board. Which is positioned at experimental section of wind tunnel.

Experiments are carried out in combustion wind tunnel in University of Science and Technology of China. The wind tunnel is a total length of 20.2 m, as shown in Fig. 1. The crosswind ranged from 0 to 2.5 m/s with incremental change of about 0.5 m/s. More details of the experimental setup can be found in the previous report [18]. A four-probed parallel processing anemometer with accuracy of 0.01 m/s was used to measure the transient cross air flow speed. The flame geometry image was recorded by a digital CCD (Charge-Coupled Device) camera. Which the film speed is 25 f/s. Time series of flame images are decompressed into frames and processed. Each flame image frame is firstly converted to gray scale image and then to binary image using the Otsu method [14,26]. Each case was repeated three times to reduce random error. The error bars are determined based on the repeats of the experiments as we usually do. The data points in the figures are the mean value, meanwhile the error bar reflects the measured maximum value ranges during the repeats.

3. Results and discussion

3.1. Mass burning rate

Fig. 2 shown the typical mass loss rate derived from the measured data by the electronic balance, for the 30 cm square pool fire with the cross air flow speed of 2 m/s. The steady burning mass loss rate of the pool fire is deduced to be 35.9 g/m^2 s.

Fig. 3 presents the stretching flames of the 20 cm pool fire with increasing cross air flow speed. It was observed in the experiments that flame body tilt gradually with cross air flow speed increase, eventually be attaching to the ground with a cross air flow with