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Effects of oblique air flow on burning rates of square ethanol pool fires

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HIGHLIGHTS

- Flame detachment from the windward rim of the pools was observed.
- Flame wrapping around the fuel container was observed for downward wind conditions.
- The burning intensity is influenced by the wind direction and the wind speed.
- Heat transfer is the controlling factor in the burning intensity of a pool fire.
- The burning intensity is sensitive to the wind direction but the relationship is non-monotonic.

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ABSTRACT

The effects of downward airflow on the burning rate and/or burning intensity of square alcohol pool fires for different airflow speeds and directions have been studied experimentally in an inclined wind tunnel. An interesting flame-wrapping phenomenon, caused by impingement of air flow, was observed. The mass burning intensity was found to increase with the airflow speed and the impinging angle. The fuel pan rim temperatures were also measured to study the effect of wind direction and speed on heat transfer from the flame to the fuel source. A model based on heat transfer analysis was developed to correlate the burning intensity with the pan rim characteristic temperature. A good correlation was established between the model results and the experimental results.

1. Introduction

Liquid fuel fires occurring during industrial processes are serious safety concerns. Concerted efforts in fundamental research have been made in the past to understand the burning behavior of pool fires. These efforts have concentrated on the establishment of correlations between fire characteristics, such as the fuel burning rate, flame height and pulsation, soot formation and thermal radiation, with fuel characteristics, such as fuel type, depth, surface shape and size, and ambient conditions, including pressure, temperature, humidity and wind [1–3].

Liquid fuel fires can occur at many locations where sloping conditions are expected, such as in underground stores, mines, rail or road tunnels, and on hill sides. The speed and direction of the wind (either forced or natural), which are controlled by the surface inclination angle, may influence the pool fire combustion characteristics, such as burning rate, flame length, and flame tilt angle, which are of primary importance for fire safety in tunnels [4] as well as in wilderness fires and forest fires [5].

The dependence of the fuel burning rate and other related parameters on the pool size is a well-known phenomenon. Blinov and Khudiakov [6] studied the mass loss rate of hydrocarbon pool fires with diameters ranging from 0.0037 m to 22.9 m. They found that the rate of burning, expressed as the "fuel surface regression rate" R_S (mm/min), was high for small-scale laboratory 'pool' (0.01 m diameter or less), and exhibited a minimum at around 0.1 m. On the other hand, in the transitional and turbulent regime, the mass burning intensity, or the mass loss rate per unit fuel surface area, was observed to increase with the pool size [7,8] and can be modeled by an exponential function with an asymptotic limit as the pool size approaches infinity [9,10]. When pool fires are subjected to ventilation or cross air flows, the burning intensity has been observed by Hu et al. [8] to inversely vary with pool size of the range of 0.05–0.25 m.

Tieszen and O'Hern [11] studied the flame structure of methane fires and showed that the peak values of the turbulent kinetic energy occurred off-axis at a radial position of approximately 20% of the burner diameter. Radiation emission from pool fires has also

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Nomenclature

α	coefficient of correlation between $\Delta m'$ and ΔT_c ($g\,m^{-1}\,s^{-1}\,{}^\circ C^{-1}$)
C_p	specific heat ($kJ\,kg^{-1}\,K^{-1}$)
d	characteristic depth of fuel (m)
h	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
m	fuel mass (g)
$\dot{m}'$	fuel mass loss rate, or burning rate ($g\,s^{-1}$)
$\dot{m}''$	mass loss rate per unit fuel surface area, or burning intensity ($g\,m^{-2}\,s^{-1}$)
$\Delta\dot{m}''$	burning intensity change from quiescent to ventilated conditions ($g\,m^{-2}\,g\,m\,s^{-1}$)
L	length of the pool (m)
L_v	latent heat of evaporation ($kJ\,kg^{-1}$)
$\dot{Q}$	heat release rate (kW)
$\dot{q}_b$	heat feedback from pool rims to the fuel (kW)
$\dot{q}_{cond}$	conductive heat flux feedback (kW)
$\dot{q}_{conv}$	convective heat feedback (kW)
$\dot{q}_f$	heat feedback from flame to the exposed fuel surface (kW)
$\dot{q}_{fb}$	heat transfer to the fuel (kW)
$\dot{q}_{rad}$	radiative heat feedback (kW)
$\dot{q}_s$	rate of sensible heat consumed by warming up the fuel (kW)
S	area (m^2)
R	Pearson correlation coefficient
R_s	fuel surface regression rate
T	temperature (K)
ΔT_c	characteristic temperature rise above the fuel temperature (K)
t	time (s)
U_a	tunnel airflow speed ($m\,s^{-1}$)
U_{ar}	the airflow speed at the minimum mass loss rate ($m\,s^{-1}$)
θ	tunnel inclination angle, or the angle between the fuel surface and the air flow direction (°)

Subscripts

0	under a quiescent condition
w	windward rim
s	side rim
l	leeward rim
a	ambient
f	flame
U	under wind condition
y	liquid
S	fuel surface
b	rims of the pool

been the subject of studies by many researchers for the purpose of fire hazard evaluation [2,12–14]. Measurements of burning rates for a circular pool (30 cm in diameter) exposed to a transverse airstream were also performed by Lam et al. [14]. Their main interest was to study the effects of obstructions placed either upwind or downwind of the pool and compare the results with those obtained without any obstruction.

Many studies on pool fire characteristics under cross airflows have been conducted in wind tunnels [7,15–20], where the airflow speed on level ground was considered. Woods et al. [16] reported that the burning rate of a small square pool (7.5 cm × 7.5 cm) increased monotonically by a factor of 2.5 when the air speed rose from 0 to 5.5 $m\,s^{-1}$. In contrast, the burning rate of a larger square pool (30 cm × 30 cm) was essentially unchanged over this range of air speeds.

In a sloped wind tunnel simulation study of combustion characteristics of forest fires [5], the rate of spread was observed to be linearly proportional to the slope angle in the range of 0–20° upward for various airflow speeds. Simcox et al. [20] numerically simulated the fire-induced flow of hot gases in a sloped escalator tunnel with wind blowing from a bottom inlet. They reported the so-called "trench effect" whereby the fire flame leans toward the inclined tunnel floor rather than extending upright toward the ceiling of the tunnel. This trench effect was experimentally verified by Drysdale et al. [21] in an inclined rectangular channel with burning paraffin-soaked cards. Again, the studies by Simcox et al. and Drysdale et al. both involved upward flows over inclined surfaces.

Fuel mass loss rate, or burning rate, is an important parameter in the evaluation of fire hazards. Most of the previous studies of pool fires under the influence of wind focused on the investigation of burning rate under horizontal wind direction that is parallel to the liquid fuel surface [7,8,15–20]. How the mass loss rate of a pool fire varies with wind direction inclined to the horizontal fuel surface remains a question. The objective of the study described in this paper was to search for answers to this question via an experimental investigation. The effect of downward wind direction and speed on the mass loss rate of alcohol pool fires was investigated. The study was conducted in a wind tunnel with a variable inclination angle. The controlled parameters of the experiments included the pool size, the tunnel air flow velocity and the tunnel inclination angle. The measured parameters included the temperature of the pool rims and the mass loss of the fuel. General observations were also made concerning the flame inclination and other characteristics that are influenced by the control parameters.

2. Burning rate of liquid fuels

Fire is a diffusion-controlled combustion process and the burning of liquid fuels is influenced by heat transfer for gasification [10]. The net gain of thermal energy due to radiation, convection and conduction feedback from the flame and the surrounding air to the fuel determines the amount of gasified fuel that participates in the flaming combustion process. The heat transfer to the fuel is defined as $\dot{q}_{fb}$, which includes the heat from the flame and the heat from the pool rims, $\dot{q}_f$ and $\dot{q}_b$, respectively. It is assumed that the heat from the flame is slightly different for quiescent conditions vs. ventilated conditions. The burning rate of liquid fuels is essentially controlled by the rate of heat transfer to the fuels [10]. The mass loss rate per unit area of a square pool liquid fuel can be written as follows:

$$\dot{m}'' = \frac{\dot{q}_{fb} - \dot{q}_s}{L_v S} = \frac{\dot{q}_{fb} - \dot{q}_s}{L_v L^2} \quad (1)$$

where L_v is the vaporizing latent heat; S is the pool area and L is the side dimension of the square pool; $\dot{q}_s$ (=$C_p m dT_y/dt$) is the rate of sensible heat consumed by warming up the fuel; and $\dot{q}_{fb}$ is the net heat transfer rate from the flame to the fuel:

$$\dot{q}_{fb} = \dot{q}_f + \dot{q}_b - \dot{Q} \quad (2)$$

where $\dot{q}_f$ is the heat transfer from the flame to the exposed fuel surface, $\dot{q}_b$ is the conduction heat transfer though the rim walls to the fuel and $\dot{Q}$ is the radiant heat loss via thermal radiation to the surrounding air. The heat transfer process associated with a typical pool fire is depicted in Fig. 1. In most cases, thermal radiation loss from the fuel surface is negligible because of its relatively low temperature, i.e.,

$$\dot{Q} \approx 0 \quad (3)$$