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Measurement of geometric and radiative properties of heptane pool fires

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ABSTRACT

The objective of the present work is to characterize heptane pool fires for pool diameters ranging from 0.1 m to 1.0 m, in a quiescent environment. Characterization of pool fires is done by determining various parameters such as the mass burning rate, puffing frequency, flame height, optical thickness, spatial distribution of emissivity and temperature, irradiance and fire safety distance. Measurement of the instantaneous mass burning rate indicates the presence of two steady states: an initial steady state and a bulk boiling steady state. The mass burning rate is found to decrease with increase in the free board height. Flame height is determined based on the definition of intermittency. Puffing frequency is obtained from the visible images by tracking the vortical structures in flames. The obtained results for the flame height and puffing frequency match well with the correlations presented in the literature.

Flame emissivity is determined from the mass burning rate as well as a refined technique that determines the transmissivity of the electrically heated strips placed behind the flame. Radiative properties such as temperature distribution and irradiance at a distance are calculated from the thermal images. The irradiance at a distance obtained using the infrared camera is compared with Schimdt-Boelter gauge. The effect of fire size on the optical thickness, radiative fraction and fire safety distance has been examined.

1. Introduction

A pool fire may be defined as a diffusion flame burning above a pool of vaporizing hydrocarbon fuel where buoyancy is the predominant transport mechanism. Air, from the surroundings, diffuses into the reacting zone resulting in combustion. Processing industries, such as the paint industry, make use of *n*-heptane as a solvent. They incur the risk associated with the occurrence of pool fires. Knowledge of the radiative environment of potential fire scenarios is very helpful for planning fire-fighting strategies. This allows for determination of whether a particular fire can be approached or not. It also allows for determination of which equipments to be used and what strategy should be employed in an emergency response plan [1].

Significant progress has been made in understanding the mass burning rate and heat feedback mechanisms to pool fires in quiescent air. The reviews by Joulian [2], Steinhaus et al. [3] and Hu [4] elaborates the state of the art research and addresses various characteristics of pool fires such as the burning rate, heat feedback mechanism, flame morphological characteristics, radiation and soot production. Despite the enormous body of work on large scale pool fires, there are still significant uncertainties in our understanding of such fires and capabilities to predict their behavior [3]. Extensive research, conducted over the last few decades in understanding the burning characteristics of liquid pool fires, is summarized below.

1.1. Mass burning rate

Mass burning rate is defined as the mass of fuel consumed per unit area per unit time. For gasoline pool fires, Babrauskas [5] observed that the mass burning rate increased for diameters up to 2 m and was nearly constant thereafter. Blinov and Khudyakov [6] observed that the burning rate for single-component fuels initially decreases at a rapid rate, reaches a minimum and finally increases with diameter before reaching their asymptotic value for large diameters. Parameters such as environmental conditions and lip height also affect the mass burning rate.

Mass loss rate is routinely measured as the decrease in the height of fuel [7] or decrease in the weight of the pan containing the fuel [8]. However, Hamins [9] obtained the mass burning rate indirectly by determining the heat feedback to the fuel surface. The analysis was carried out by applying a heat balance in the liquid fuel of the pool fire for a quasi-steady state system. Fig. 1 shows the mass burning rate of *n*-heptane pool fire reported in various literature [7,9–16]. It is

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Nomenclature

a,b	Empirical constants
A	Area of pool fire (m^2)
$A1$	Pixel Area
$A2$	Sensor Area
C_p	Specific heat capacity, ($J/kg\ K$)
D	Pool diameter (m)
E	Emissive power (W/m^2)
f	Puffing frequency (Hz)
F	View Factor
g	acceleration due to gravity (m/s^2)
h	Heat transfer coefficient (W/m^2K)
Δh_g	Total heat of gasification (kJ/kg)
HPF	Heptane Pool Fire
I	Intensity obtained from thermal camera ($W/m^2.sr$)
k	Thermal conductivity (W/mK)
L	Flame Length (m)
$\dot{m}''$	Mass loss rate per unit area (kg/m^2s)
OS	Object signal
Q	Heat released (W)
Q^*	Non-dimensional heat release rate
$\dot{q}''$	Heat flux (kW/m^2)
r	Radial distance (m)
T	Temperature (K)
x,y	Coordinates in the flame plane
X/D	Non-dimensional radial distance
Y/D	Non-dimensional distance along the axis of the flame
Z	Distance between the flame and sensor plane
Z/D	Non-dimensional distance parallel to the flame plane

Subscripts

∞	Ambient; Infinite
b	Body
bf	Body through flame
f	Flame
i, j	Pixel location
r	Radiative
t	Total
TC	Thermocouple

Greek symbols

ε	Emissivity
$\kappa\beta$	Absorption-extinction coefficient(m^{-1})
σ	Stefan Boltzmann Constant (W/m^2K^4)
ρ	Density (kg/m^3)
τ	Transmissivity

Non-dimensional numbers

$\mathrm{Pr} = \frac{\mu C_p}{k}$	Prandtl number
$\mathrm{Re} = \frac{\rho VD}{\mu}$	Reynolds number

perplexing to observe that the mass burning rate for a particular pool diameter has been reported sometimes more than double.

1.2. Effect of lip height

Freeboard height or the lip height is the distance between the top of the pan to the top of the fuel level. Babrauskas [5] observed that the lip height significantly influences the convective and radiative heat flux when the liquid level is allowed to run down in the vessel. A fundamental study elucidating the effect of lip height on the burning rates and on flame size of small scale fires have been investigated by Dlugogorski and Wilson [17]. They measured the burning rates of ethanol fires in copper, mild steel and glass vessel for diameters less than 7 cm. They observed that the onset of fuel boiling in copper and steel cylinders dramatically altered the mass burning rates. The effect of lip height on mass burning rate of heptane pool fires has not been studied. This is essential to explain the difference in the mass burning rates reported throughout the literature.

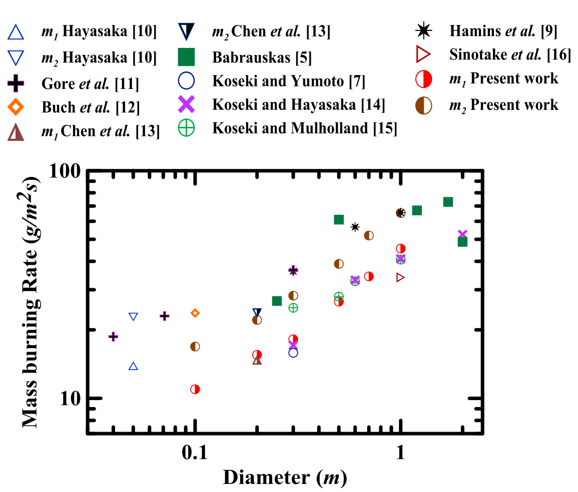

Fig. 1. Mass burning rate of heptane pool fires.

1.3. Puffing frequency

Malalasekara et al. [18] defined puffing as quasi-periodic oscillations of the diffusion flame front near the axisymmetric source of a fire with the formation of large scale flaming vortical structures. The frequency at which puffing occurs is called puffing frequency. Various researchers have determined the puffing frequency from visual as well as thermal images obtained using high speed cameras. Cetegen and Ahmed [19] recorded the pressure fluctuation across the face of the burner by means of a pressure tapping located at one quarter of the way along the burner diameter. The puffing frequency was determined by means of a frequency analyzer. They concluded that puffing is a result of buoyant flow instability which arises due to strong interaction of the toroidal vortex formed at a short distance above the burner surface. Equations (1a) and (1b) are used to determine the puffing frequency, as given by Cetegen and Ahmed [19] and Malalasekara et al. [18] respectively.

$$f = \frac{1.5}{\sqrt{D}} \tag{1a}$$

$$f = \frac{1.68}{\sqrt{D}} \tag{1b}$$

Experimental investigations have been carried out to determine the pulsation frequency of pool fires of different aspect ratios in sub-atmospheric pressures [20]. Hu et al. [21] demonstrated that the Rayleigh-Taylor instability and puffing instabilities are the main reason for the necking-in and the periodic oscillatory behavior. The dominant instability mechanism transits from the extended Rayleigh-Taylor instability to the puffing instability with increase in pool size and lip height.