International Journal of Thermal Sciences 115 (2017) 89–103

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

A refined methodology to determine the spatial and temporal variation in the emissivity of diffusion flames

Vinay C. Raj, S.V. Prabhu*

Department of Mechanical Engineering, Indian Institute of Technology, Bombay, India

A R T I C L E I N F O

Article history:
Received 23 March 2016
Received in revised form
13 December 2016
Accepted 16 January 2017
Available online 31 January 2017

Keywords:
Spatial
Temporal
Emissivity
Temperature
Infrared thermography

A B S T R A C T

Flame emissivity is an important parameter in the study of pool fires. A refined methodology is developed to determine the spatial and temporal variation in the flame emissivity of pool fires. Limitations of earlier methodologies include an assumption of axisymmetrical flame and the obtained data being spatially and temporally averaged. Experiments are performed with diesel and gasoline as the fuel for pool diameters of 0.3 m–1.0 m. Flame emissivity is obtained based on the calculation of flame transmissivity using an infrared camera with reference to electrically heated thin metal strips. Average emissivity is determined for the multi-averaged image of 80 instantaneous images. Complete spatial emissivity and temperature distribution are obtained. Vertical centerline emissivity matches reasonably well with the average emissivity reported in the literature.

1. Introduction

A pool fire is defined as a turbulent diffusion flame burning above a horizontal pool of vaporizing hydrocarbon fuel. Buoyancy is the controlling transport mechanism. Radiation from the flame is due to the hot combustion products formed during the combustion process and hence flame emissivity is a combination of emissivity of soot and hot gases. Emissivity of pool fires depends on various parameters such as pool diameter, fuel type, temperature, and soot and species concentration. Fires that occur in petrochemical industries or during the transportation of hazardous materials (like spent fuel casks) put the industry members, transport workers and the general public at risk. The effect of flames on process equipments can result in spillage of chemicals or radioactive materials resulting in a major disaster.

According to the regulations adopted by the International Atomic Energy Agency (IAEA) (Safety Standards No. TS-R-1 (1990)) [1], the radioactive packaging must undergo an exposure for 30 min in a thermal environment that provides a heat flux at least equivalent that of a hydrocarbon fuel/air fire in sufficiently quiescent ambient conditions to give a minimum average flame emissivity coefficient of 0.9 and an average temperature of at least 800 °C, fully engulfing the specimen, with a surface absorptivity coefficient of 0.8 or that value which the package may be demonstrated to possess if exposed to the fire specified.

In an effort to understand and minimize the hazards, it is important to characterize pool fires by accurately and reliably measuring emissivity and temperature of pool fires. Several investigators have reported studies on pool fires. Preliminary studies of pool fire have shown, the temperature variation in large pool fires to be greater than the specified average temperature of 800 °C.

Emissivity of pool fires is primarily determined by the following methodologies:

1.1. *Methodology 1*

Hottel and Sarofim [2] determined the flame emissivity from species concentration using look up tables to evaluate the emissivity of the combustion gases of a fire. Felske and Tein [3] and Taylor and Foster [4] established a simple analytical model for determining the total emissivity of a luminous flame and showed the relative importance of gas and soot emission. These theoretical models predict radiation from diffusion flames utilizing either Mie theory for soot particles or the well established wide band theory for radiating gases. These models require the knowledge of various parameters such as soot volume fraction, optical properties and flame temperatures. Complete information of these parameters is

---

* Corresponding author. Department of Mechanical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai, Pin: 400 076, India.
E-mail address: svprabhu@iitb.ac.in (S.V. Prabhu).

http://dx.doi.org/10.1016/j.ijthermalsci.2017.01.016
1290-0729/© 2017 Elsevier Masson SAS. All rights reserved.

Nomenclature

a,b	Empirical constants
C_1, C_2	Planck's constant
D	Pool diameter (m)
DPF	Diesel Pool Fire
F	View Factor
GPF	Gasoline Pool Fire
Δh_g	Total heat of gasification (kJ/kg)
I	Intensity obtained from thermal camera ($W/m^2.sr$)
$\dot{m}''$	Mass loss rate per unit area (kg/m^2s)
OS	Object signal
$\dot{q}''$	Heat flux (kW/m^2)
T	Temperature (K)

Subscripts

b	Body
bf	Body through flame
$conv$	convection
f	Flame
$loss$	Conduction losses
rad	Radiation
rr	Re-radiant
t	Total
∞	Ambient; Infinite

Greek symbols

ε	Emissivity
σ	Stefan Boltzmann Constant (W/m^2K^4)
τ	Transmissivity
λ	Wavelength (m)

usually not available and data reduction becomes extremely difficult under such circumstances.

1.2. Methodology 2: mass burning rate

Babrauskas [5] applied energy balance at pool surface as given below:

$$\dot{m}''\Delta h_g = \dot{q}''_{rad} + \dot{q}''_{conv} + \dot{q}''_{rr} + \dot{q}''_{loss} \tag{1}$$

Wall conduction losses ($\dot{q}''_{loss}$) and re-radiant heat losses ($\dot{q}''_{rr}$) are usually small and hence neglected. In radiatively dominant pool fires (large diameters), heat received by convection ($\dot{q}''_{conv}$) can be neglected. Thus,

$$\dot{m}'' = \frac{\dot{q}''_{rad}}{\Delta h_g} = \frac{\sigma\varepsilon_f T_f^4}{\Delta h_g} \tag{2}$$

For a pool of infinite diameter, $\varepsilon_f = 1$;

$$\dot{m}''_\infty = \frac{\sigma T_f^4}{\Delta h_g} \quad \Rightarrow \quad \frac{\dot{m}''}{\dot{m}''_\infty} = \frac{\frac{\sigma\varepsilon_f T_f^4}{\Delta h_g}}{\frac{\sigma T_f^4}{\Delta h_g}} = \varepsilon_f \tag{3}$$

Thus, emissivity is determined by obtaining the ratio of mass burning rate of particular diameter to the mass burning rate of a pool fire of infinite diameter.

1.3. Methodology 3: inference of flame emissivity with reference to a body

Infrared thermography has been used by various researchers to determine the emissivity and temperature distribution of pool fires. The method developed by Cuchi et al. [6] makes use of the transmissivity of the flame to determine the emissivity of pool fires. Thermal images of pool fire were captured with the infrared camera placed in three different positions as shown in Fig. 1:

- Position 1: Image of the reference body is taken at an angle less than 45° normal to the reference body.
- Position 2: Image is taken of the reference body as seen through the flame (normal to reference body).
- Position 3: Image of the flame alone (by removing the reference body).

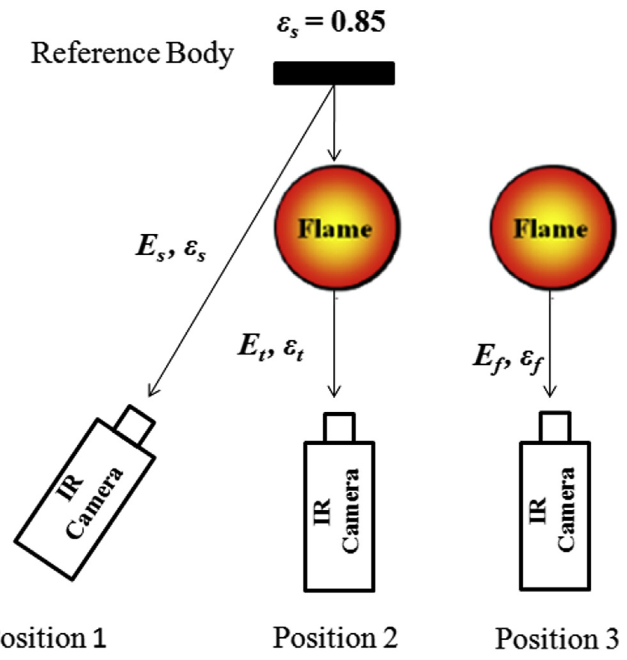

Fig. 1. Schematic of the positions of IR camera used in the methodology developed by Cuchi et al. (2003).

The detailed mathematical model for obtaining the emissivity is given in Cuchi et al. [6] and Sudheer and Prabhu [7,8]. A brief overview of the algorithm is given below:

The camera at position 1 measures the reference body intensity. The camera when arranged at position 2 measures the infrared radiation equal to the sum of the infrared radiation from the flame (I_f) and the infrared radiation proceeding from the body, when this radiation crosses the flame (I_{bf}):

$$I_{total} = I_f + I_{bf} = \sigma\varepsilon_t\left(T_t^4 - T_\infty^4\right) \tag{4}$$

The IR-camera placed at position 3 collects only the infrared radiation proceeding from the flame (I_f)