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Modelling the view factor of a 'grain-like' observer near a tilted pool fire via planar approximation approach

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ABSTRACT

Modelling the view factor, F, of a 'grain-like' observer near a tilted pool fire assumed to be cylindrical in shape, requires the observer (on the same ground level as the pool fire) to be as close as possible to the flame surface so that the flame surface is viewed as a plane. The orientation of the observer is to receive a maximum view, with the view factor integrated over the flame area seen by the observer. The derived expression for F was expressed in terms of standard functions and sensitive parameters: α, defined to ensure the observer receives a maximum view of the flame surface and β, the angle of inclination of the differential observer plane. Results from a planar approximation to F are compared with those of PHAST 7.2 simulated results in MATLAB. The values of the planar approximation to F was found to increase with increasing β. This suggests that the larger the value of β, the more the radiation received by a near observer. For $\beta = 48.961^\circ$, horizontal distance, $X = 30\,\text{m}$, $\alpha = 0.01$, flame length, $L = 12.14\,\text{m}$, tilt angle, $\theta = 55.17^\circ$, and pool diameter, $D = 5\,\text{m}$: planar and PHAST 7.2 approximations to F were found to coincide up to 6 significant digits and differ by 3.2×10^{-8}. The close agreement between both approximations depend heavily on the choice of flame properties and sensitive parameters. Interestingly, this result may depend sensitively on the choice of parameters, leading to prediction of planar approximation to F much higher or lower than those of PHAST 7.2 approximations. The advantage of this approach is that a knowledge of the plane where the largest concentration of radiation is located will help minimise loss of lives to fire hazards and improve the efficiency of risk safety assessment/management.

1. Introduction

Driving towards a safer, smarter and greener world in the face of emerging industrialisation cannot be achieved without proper safety precautions in the design, construction and operation of liquid hydrocarbon storage facilities, as poor management of accidental releases of liquid hydrocarbons could result in large/small scale pool fires, emitting thermal radiation which could be dangerous to lives and property.

A pool fire (whose geometry is normally assumed to be cylindrical in shape) is the most important type of fire hazard when compared to other fires because of its sheer devastating potential and ability to cause maximum damage in process industries [1]. This is very common in scenarios such as the rupture of pipelines transporting fuel and in the huge volume

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of fuel stored in tanks. It may also arise as a result of leakage or spillage of flammable substances; cracks in vessels or pipelines including abrupt temperature or pressure changes in operating systems [1].

Mannan [2] defined a pool fire as that which occur when flammable liquid spills onto the ground and is ignited. This could be in form of trench fire or fire in a liquid storage tank and may also occur on water whose surface contains the spilled flammable liquid. Additionally, Fay [3] defined pool fire as a diffusion flame driven entirely by gravitational buoyancy. Invariably, a buoyant diffusion flame whose fuel is configured (shaped/formed together) horizontally could be regarded as a pool fire.

Pool fires, which could either be modelled as “large pool” or “small pool” depending on the size of the pool diameter, require careful determination of fire dynamics from evolution time to extinction period. In other words, there is a need for an in-depth understanding of the nature of combustion, pool spreading, dependence of radiation intensity on flame shape, turbulence and temperature at various flame zones.

It’s noteworthy that the dependence of radiation intensity on flame shape and existence of flame zones in effective management of fire hazards, cannot however, be determined without proper conceptualisation of pool fire characteristics: composition of liquid fuel, size and shape of fire, duration of fire, mass burning rate, average flame surface emissive power, atmospheric transmissivity and view factor.

The view factor which of interest in this paper depends on the shape and size of the flame including the position and orientation of the target. In particular, consider an observer at some target position from the flame: the configured proportion of all the radiation that reaches the observer from the flame surface is called the view factor of the flame. Hence, it will not be surprising that the dependence of view factor on the shape and location of the flame relative to the target is of great interest.

Several analytic methods have been used to determine the view factor of pool fires [4]. In particular, [5] employed analytic techniques to determine the view factor of tilted cylinders while [6] observed that available methods of analytic solution for predicting view factors of tilted cylinders with circular cross-section and other simple shapes are restricted to certain locations and orientation of the target. View factor prediction methods (which divide the flame surface into small parallelogram) [7] for a tilted cylinder with target located at ground level, directly under the flame and part of the cylinder surface directly contained within the view field of the target have been criticised by [6], who observed that, the method made no allowance for the differences in area of these parallelograms as their positions change around the circumference of the cylinder.

In order to address these restrictions, [6] developed an area integral for view factor which is evaluated numerically and could cover any geometrical shape by dividing the entire flame surface into triangular area elements which are calculated and summed vectorially provided the triangles have been defined. This numerical method could be used to calculate view factor for modelling radiant heat flux from irregular shapes. Interestingly, its accuracy depends upon the number of triangular mesh elements since the denser the mesh, the more accurate it becomes and the greater the computational time.

More generally, the view factor between the flame surface and the target (observer location) is calculated over the flame surface that is visible from the location and orientation of the observer. It was derived by application of Lambert’s cosine rule [8] and is given by

$$F = \iint_{A_1} \frac{\cos\beta_1 \cos\beta_2}{\pi d^2} dA_1. \tag{1}$$

Here, F is the view factor, β_1 is the angle between the local normal to the flame element and the line joining this element to target position, β_2 is the angle between the unit normal specifying the orientation of the elemental target and the line joining the target to the flame element, d is the distance from the flame surface element to the target element, dA_1 is the area of flame surface element, and A_1 is the area of the flame surface that can be viewed from the location and orientation of the target.

A restriction to (1) is that any contribution for which $\cos\beta_1$ or $\cos\beta_2$ is negative is neglected. In other words, it is required that $\cos\beta_1 > 0$ and $\cos\beta_2 > 0$ in order to be used in the above calculation. We have assumed that the pool fire is on the ground level, and at the same level as the observer. Also, the volume and shape of the cylinder does not change as it tilts to greater angle by greater wind velocity. The observer height is also assumed to be negligible - ‘grain-like’.

Our objective in this paper is to determine the expression for the view factor of a ‘grain-like’ observer near a pool fire where the flame surface as ‘seen’ by the observer is approximately planar. Invariably, we require the observer to be as close as possible to the flame surface so that the flame surface is viewed as a plane and the observer receives a maximum view of the flame. In fact, we would expect that the closer the observer is to the flame surface, the more planar the flame surface appears and the higher the view factor (the configured proportion of all the radiation that reaches the observer from the flame surface) of the observer gets. This to a great extent distinguishes our approach in this paper to those found in literature ([9]–[10]) since a better view factor calculation allows for a better risk assessment of the safety of pool fire and how best to minimise the level of radiation damage that can result from it especially for a near observer. It is also of interest to characterise how the incident angle of radiation affects the configured proportion of all the radiation that reaches the observer from the flame surface. We intend to address this in this paper by identifying and analysing some sensitive parameters: α and β. Our research in this paper was motivated by a question raised by DNV GL London UK, in an *Industrial Day Presentation, March 2015* at the University of Bath, UK. In this presentation they noted that numerically integrating