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Simulation of multiple pool fires involving two different fuels

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ABSTRACT

When two or more pool fires burn in close enough proximity to influence one another, the resultant combination is termed 'multiple pool fire' (MPF). Even though MPFs occur fairly often in chemical process industries, with highly destructive consequences, much lesser work has been done towards simulation, modeling, and control of MPFs than on stand-alone pool fires. Among the factors which strongly influence the interaction among the MPFs, and the consequent damage MPFs may cause, the most important is the type of fuel contained in the individual pools. This aspect affects the temperatures of the interacting flames, their soot production, and the resultant radiation load. However, studies to dynamically model this aspect have not been carried out so far. In this paper an attempt has been made, arguably the first of its kind, to explore the efficacy of computational fluid dynamics (CFD) in simulating the effect of fuel types on MPF clusters. A fair agreement has been found between the CFD simulation and the experimental findings reported by Vincent and Gollahalli (1995). The agreement between the experimental data and CFD simulation results is good considering the fact that the soot production has not been accounted by us.

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1. Introduction

When more than one pool fires occur close enough to influence each other, there is substantial impact on the burning rate of the fuel, the size of the flame, and the rate of heat transfer from the flame to the surroundings (Fukuda et al., 2005; Koseki and Yumoto, 1989; Liu et al., 2009; Vasanth et al., 2014a, 2014b; Vincent and Gollahalli, 1995). Quite often accidents involving multiple pool fires are recorded in a manner that makes the instances indistinguishable from stand–alone pool fires (Khan and Abbasi, 1998; Vasanth et al., 2014a). This creates an impression that accidents involving MPFs are few and far between. But a detailed study of past accidents reveals that such is not the case. Between 1950 and the present, hundreds of major MPF accidents have been reported worldwide (Hailwood et al., 2009; HSE, 2012; MIIB, 2012; Tauseef et al., 2011). As a result, perhaps, of the faulty reporting of accidents and the erroneous impression it has created that MPFs are a rare phenomenon, very few studies exist on the mechanism of MPF development and the factors that control it (Khan and Abbasi, 1997, 1999a, 1999b, 2002). Huffman et al. (1996) were among the first to note that pool fires may interact with each other when they observed that individual pool fires start to burn more intensely with higher flames when the distance between them is decreased. Several authors have subsequently reported different forms of interactive effects that distinguish MPFs in contrast to stand–alone pool fires (Chigier and Apak, 1975; Delichatsios, 2007; Fukuda et al., 2005; Hailwood et al., 2009; Steward and Tennankore, 1981; Sugawa and Takahashi, 1993; Weng et al., 2004).

In MPFs, the interaction of flames is influenced by several factors; the fuel type and pool spacing are the two most important (Vincent and Gollahalli, 1995). A competition for oxygen available in the interstitial space and radiation transfer from the neighboring flames are also among the important factors (Vincent and Gollahalli, 1995).

In recent years, CFD has emerged as a powerful technique which has the potential to handle the kind of complexities that are associated with MPFs. But, so far, only a few attempts have been made to use CFD in MPF simulation, essentially due to a lack of relevant experimental data. The reported studies encompass the work of Weng et al. (2004) and Satoh et al. (2007, 2008). The former group used large-eddy simulation (LES) to simulate the merging of flames, and found that numerical results agreed well with the

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experimental data. Satoh et al. (2007) also found that CFD–simulated profiles of isothermal surfaces of merging flames were quite similar to that which was found experimentally, including the critical merging distance. Later Satoh et al. (2008), found that the swirling conditions of fires in square arrays in the presence of wind were strongly influenced by the inter-fire distance in the array, the heat release rate (HRR), and the mass flow rate. A fire whirl is a vigorous atmospheric circulation, created when highly unstable, superheated, dry air near the ground breaks through the boundary layer and shoots upward in a swirling motion. This is also the result of an imbalance in the horizontal air flow that creates a positive vorticity cell. Fire whirls are generally associated with forest or city fires (Hassan et al., 2001; Satoh et al., 2001; Zhao et al., 2010).

In this paper we report attempts to study the effects of two different fuels (iso-octane and Jet A) on the interaction of the concerned MPFs using CFD. It is perhaps the first attempt of its type, and has been made because the behavior of MPFs is known to be affected by the nature of the fuels involved in the MPFs. This, in turn, is expected to play a role in determining what minimum separation distance must be kept between pools of liquid to prevent interaction should the pools accidently catch fire. As the studies described in his paper reveal, separation distance between the fuel tanks holding lighter fuels should be more than the separation distance between the tanks holding heavier fuels because lighter fuels have higher evaporation rates and may lead to more intense inter-fire interaction than the fuels with lesser evaporation rates. The interaction causes heat feedback, influences the air flow field and, consequently, the fuel burning rate.

For validation, the experimental data obtained by Vincent and Gollahalli (1995) was chosen from among the various experiments done on MPFs, because –

1) The study of Vincent and Gollahalli (1995) is one of the very few in which the impact of interaction between a cluster of liquid pool flames has been studied using two different types of fuels.
2) The temperature, flame height, burning rate, and peak radiation of the pool fires were studied in greater detail than in other experiments, providing the depth and breadth of data that was adequate for effective CFD simulation.

2. Methodology

For the CFD simulation, standard k-ε model was used for turbulence as it has been found more effective, in comparison to other turbulence models, by the authors (Vasanth et al., 2013). P1 radiation model, also known as Gibb's model, was used for radiation modeling as it has been found to be effective by several other authors (Prasad et al., 1999; Raithby, 1991; Snegirev, 2004). Combustion was modeled using eddy dissipation concept (EDC) (Magnussen, 1981). The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used for pressure velocity coupling (Blazek, 2001; Versteeg and Malalasekera, 2007), and the finite volume method was used for the second order discretization of the governing equations.

In the experiments performed by Vincent and Gollahalli (1995), five circular pools of 25.4 cm diameter and 10 cm depth were employed with octane and jet A as the fuels. Center to center separation distance between the pools was 40 cm. We have studied kerosene instead of jet A for two reasons. First is that jet A is not included in the material data-base of the CFD code FLUENT 6.3 used by us. The second reason is that the compositions of jet A and kerosene are similar except that jet A contains a few additives in the form of corrosion inhibitors, and anti icing agents not normally put in kerosene. Otherwise, various key properties such as flash point, flammability, boiling point and specific gravity of the two fuels are very similar: the flash point for both Jet A and Kerosene is 100 °F; both have similar flammability classification (Class II); both boil between 330 and 550 °F; and their specific gravities are very close to each other (0.81 and 0.83).

A 3D domain which was 450 × 450 × 450 cm was set up with five circular pools arranged symmetrically as shown in Fig. 1a and b. Grid sensitivity analysis (Table 1) was performed to find the optimum grid size. It showed that refinement of grid beyond a certain size does not result in any appreciable improvement in the accuracy of the simulation results; only the computational time goes up. The total number of nodes that resulted from meshing of the domain using the optimal grid size was 2,051,760.

2.1. Boundary conditions

The conditions imposed at different boundaries (marked A – G), for both the simulations (Fig. 1a) were as follows.

2.2. Boundaries A, B, C, D, and E

Since flow velocity and/or flow rate were not known at the boundaries marked A, B, C, D, and E and they were at a great distance from the pool fire epicenter, it was assumed that pressure is atmospheric at these boundaries (gauge pressure set to zero). Hence atmospheric pressure was used to calculate inlet velocity using Bernoulli's equation. This enabled the calculation of other flow variables, too.

2.2.1. Boundary F

This refers to the impermeable surface represented by the ground. A no-slip condition was imposed for this, because viscous fluids will have zero velocity relative to this solid boundary.

2.2.2. Boundary G

The pools were modeled such that the octane or kerosene vapors were assumed to enter the domain, at the rate equal to their respective burning rates, from the boundary G. The burning rates of octane and kerosene were calculated using the model proposed by (Babrauskas, 1983) because it has been shown earlier (Brambill and Manca, 2009; Drysdale, 2011) that the Babrauskas' model gives better predictions for the burning rate if experimental data is available for evaluation of absorption extinction coefficient (k) and mean beam length corrector (β) ((Brambill and Manca, 2009; Drysdale, 2011). As the desired data was available in the report of Heskestad (2002) we have been able to use the model of (Babrauskas, 1983).

$$m = m_\infty \left(1 - exp^{-K\beta D}\right) \tag{1}$$

$$m_\infty = \frac{\sigma T_f^4}{\Delta H_V} \tag{2}$$

$$\Delta H_v = \left(87 \times T_1 \times \left(\frac{T_c - T}{T_c - T_1}\right)^{0.38}\right) \tag{3}$$

where

m is the burning rate (kg/m^{2}s).
m_∞ is the mass burning rate per unit area for a infinite pool fire (kg/m^{2}s).
D is the diameter of the pool (m).
k is an absorption extinction coefficient (m^{-1}).
β is a mean beam length corrector.

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