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The effect of embedded objects on pool fire burning behavior

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ABSTRACT

This study analyzes the influence of a thermally conductive object on the burning behavior of a hexane pool fire using a validated numerical model. The thermally conductive object comprises of a thin aluminum cylinder located at the center, exposed to the fire, and also immersed in the liquid pool. The physical process of the heat transfer by the flame to the cylinder and cylinder to the liquid pool is investigated using two segments: a one-dimensional model that solves the transient heat transfer in the cylinder and a transient two-dimensional scalar transport equation that solves the temperature field inside the fuel region. Different cylindrical geometries varying from 9 cm to 16 cm in height was considered in the numerical study. Experimental measurements of the temperature field and mass burning rate agree reasonably well with the predictions made by the numerical model. A parametric study of the influence of the cylinder length in the flame shows that the burning rate of the pool fire increases up to 4 times because of heat transfer from the cylinder to the liquid fuel via nucleate boiling and film boiling on the surface of the immersed portion of the cylinder. Applications of the study towards improvements in the design of burners for "skim and burn" disposal of oil spills at sea, and portable or fixed incinerators for rapid disposal of hazardous liquid waste are discussed.

1. Introduction

From 1989, since the Exxon Valdez Oil spill, in Alaska's Prince William Sound, to the worst spill in US history in 2010 by BP in the Gulf of Mexico, the fundamental problem of fast clean up of an oil spill continues to be unresolved. It has been well understood (and applied by the US Coast Guard) that *in situ* burning (ISB) or setting fire to the slick in place can cleanup 90% of the oil [1,2]. However, fundamental knowledge gaps in the application of this technique remain. This is evidenced by only 10.5 million off the 207 million gallons of oil being cleaned up by *in situ* burning using 411 burn operations during the BP Deepwater Horizon Oil Spill. One of the main problems associated with fast clean up by burning the oil slick [3], is the heat transfer from the flames back to the oil slick. In a typical ISB operation most of the heat generated by the burning process is lost to the ambient by buoyancy induced convection (thermal plume) and radiation [4]. Only a small amount of the heat is used for the vaporization and combustion of the fuel [5]. In order to enhance the burning rate of a pool fire, the heat losses have to be minimized and more heat should be directed back to the fuel. A recent experimental study [6] showed that a thermally conductive object (thin aluminum cylinder) located at the center, exposed to the fire, and also immersed in the liquid pool can significantly enhance the burning rate of a pool fire. While, several studies have investigated the effect of metal objects immersed in the flame [7–11], in these studies, the metal objects were only immersed inside the flame. But, when the metal object is in contact with both the flame and the liquid, a heat feedback loop is generated enabling increased heat transfer from the flame to the fuel surface. The experimental results showed that the metal object inside the liquid and the flame zone promoted higher mass loss rate of the liquid fuel. Nucleate boiling was the main reason of significantly enhanced fuel evaporation rate in the case of immersed metal object. Since the heat is conducted from the flame zone to fuel zone, the embedded object surface temperature can reach above the fuel saturation point. Further, the temperature difference between embedded object and the liquid around can affect the nucleate boiling and the evaporation of the fuel [12–14]. Nucleate boiling is a very complex physical phenomena that is not well understood yet [15]. However, there are available mathematical and experimental relationships between heat flux from a hot surface into the liquid with the temperature difference between the hot metal surface and the liquid saturation point [16–18].

The focus of the current work is systematically exploring the controlling parameters of the heat feedback and its coupled relationship with the fuel vaporization. The study develops a phenomenological computational model to predict the mass loss rate

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Nomenclature

H_f	flame height [m]
CV	control volume
T	temperature [K]
L_{vap}	latent heat of vaporization [J kg^{-1}]
D	pool diameter [m]
$\dot{q}''$	heat flux [W m^{-2}]
h	convection heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
$\dot{m}$	mass loss rate [g s^{-1}]
c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
ρ	density [kg m^{-3}]
ΔH_c	heat of combustion [J kg^{-1}]
ΔH_{vap}	heat of vaporization [J kg^{-1}]
a_1, a_2 *and* a_3	slopes
b_1, b_2 *and* b_3	constants
p	perimeter of the embedded object [m]
A	area [m^2]
L_H	heater length [m]
L_c	collector length [m]
N_x, N_y and N_z	number of grids in x, y, and z directions respectively
Nu	Nusselt number
Pr	Prandtl number
Gr	Grashof number
Bi	Biot number
g	gravity constant [m s^{-2}]
υ	kinematic viscosity [m^{-2} s]
β	volumetric expansion coefficient [K^{-1}]
ε	emissivity
σ	Stefan Boltzmann constant [W m^{-2} K^{-4}]

Subscripts

g	gas
o	object
$cond$	conduction
$conv$	convection
rad	radiation
os	object surface
l	liquid
f	flame
F	fuel
∞	ambient
sat	saturation
R	region

of pool fire with immersed thermally conductive objects. The model is validated using experimental data [6] and good agreement is observed enabling a parametric study on the primary controlling parameters associated with enhancement of the burning rate because of an immersed object.

2. Problem description

A schematic of the problem studied is shown in Fig. 1. The geometry of the pool fire with an immersed thermally conductive object is divided into two control volumes. Control volume 1 (CV1) depicts the domain for immersed thermally conductive object. The CV1 can be further divided into two parts; the portion of the object exposed to the flame and hot gases (collector) and the part surrounded by the fuel (heater). As the fuel burns, the "collector" absorbs heat from the flame and transmits it to the heater which dissipates the heat to the fuel. The control volume 2 (CV2) shows the domain for the fuel. The assumptions made in the development of the model are; (1) the immersed object is assumed to be cylindrical in geometry. (2) The density, specific heat and the thermal conductivity of the fuel are kept constant during the transient simulation. (3) The convection inside the fuel and in-depth radiation are neglected.

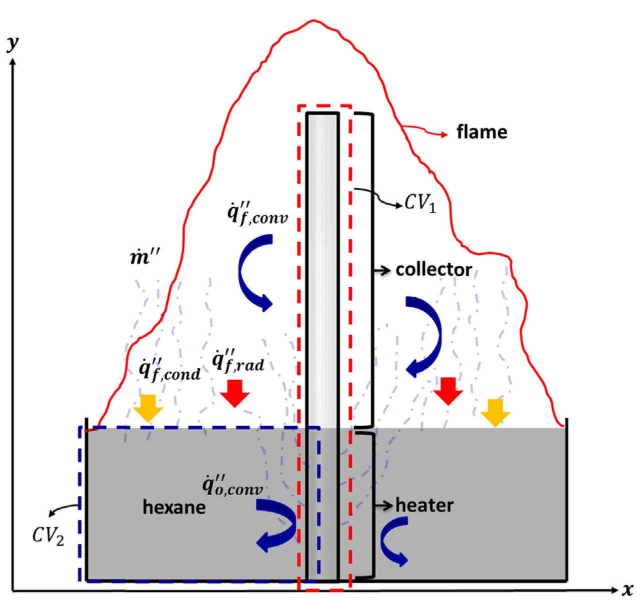

Fig. 1. Schematic of the pool fire, with thermally conductive metal rod, having a liquid and a solid computational domain. (The dashed line in represents the mass evaporation which occurs on the surface of the pool fire because of the heat flux from the flame and also around the embedded object because of the nucleate and film boiling).

A hexane pool with a diameter of 10 cm with an immersed object, an aluminum cylinder of 1 cm diameter, is considered in the present study. The fuel and dimensions are based on a series of well-controlled experiments performed in [6] and provide a benchmark for validating the numerical model developed in the current study. The physical properties of the fuel and the embedded object used in the simulations are given in Table 1. These physical parameters are taken at a temperature of 298 K and a pressure of 1 atm. The geometric details of the test cases selected for the simulations are listed in Table 2.

2.1. Modeling of flame temperature

The basis of enhancement of mass loss rate is the heat flux from the flame into the collector. The estimation of the heat flux

Table 1
The thermo-physical properties of the fuel and the metal rod.

Properties	Units	Hexane	Aluminum
Density	kg m^{-3}	654.8	2700
Specific heat	J kg^{-1} K^{-1}	2260	910
Saturation temperature	K	341	–
Thermal conductivity	W m^{-1} K^{-1}	0.124	237
Emissivity	–	0.2	0.02
Stefan-Boltzmann constant	W m^{-2} K^{-4}	5.67E–08	–
Heat of evaporation	kJ kg^{-1}	355	–
Vapor thermal conductivity	W m^{-1} K^{-1}	0.0234	–