

Numerical Study on Crude Oil Pool Fire Behavior in an Enclosure



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Abstract This paper analyzes the experimental results on crude oil pool fire obtained in an enclosure fire experiment, by using FDS software. Experiment is conducted in an enclosure of volume 64 m^3 . A cylinder pan of diameter 0.5 m is used to burn jatropa oil fuel. Fire dynamics simulator (FDS) is used to perform the numerical simulations in which heat release rate of jatropa oil measured using the mass loss method was inputted. Simulation results show that calculated temperatures are in good agreement with the experimental findings. Overall, simulation using FDS provides an effective way to study the burning behavior of crude oil pool fire.

Keywords Jatropa oil · Enclosure fire · Heat release rate · Fire dynamics simulator

1 Introduction

With the widespread use of biodiesel, it becomes necessary to consider the various safety aspects regarding its storage and transportation. Experimental investigation and numerical analysis are the two methods to study the behavior of enclosure fire. In a full-scale fire investigation, focus is on the reproduction of the scenario of real fire, and this requires lot of budget and space for carrying out the experiments. Also, as the experiments are limited, it is difficult to extend the tests or to point out the main conclusions from the limited number of experiments. However, data of the

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full-scale experiments can be compared with the available correlation and numerical simulations results to validate the model.

A number of experimental and numerical investigations in fire dynamics have been carried on petroleum fuels by many researchers using CFD tool packages such as JASMINE, FLUENT, SOFIE, and FDS [1–8]. Among the various software available, fire dynamics simulator (FDS) is widely used for fire modeling studies. FDS solves numerically a large eddy simulation form of Navier–Stokes equation for low speed flows, with an emphasis on smoke and heat transport from fires. Many researchers have used FDS for simulating pool fire experiments. LES simulations of buoyant flows with a Smagorinsky turbulence model showed that three-dimensional computational with large grid volumes perform better than the two-dimensional counterparts [1]. Simulation of large-scale pool fire using FDS shows that the results match well with experimental findings of Ryder et al. [2]. A review of modeling challenges done by Trouve and Wang [6] for LES treatment of enclosure fires showed that simulations of the enclosure fire require many physical sub-models to describe a range of multi-physics phenomenon occurring in fire. FireFOAM has been used to model purely buoyant fire plumes with different heat release rates. The simulations results were compared with McCaffrey’s experiments, and it showed good agreements with experimental results of Wang et al. [8]. Recently, Paudel and Hostikka [9] studied the model uncertainty propagation in compartment fire and reported that the uncertainty in the heat flux measurement is a measure component of overall uncertainty.

The present paper reports validation of experimental results of Chaudhary et al. [10] by using FDS software. Additional results are presented in terms of smoke layer height and hot gas layer temperature at a depth of 0.5 m below ceiling. The heat release rate measured using mass loss method was inputted into FDS for performing simulation. Simulation results also shows the effectiveness of simulation technique in real fire scenario.

2 Experimental Study

Chaudhary et al. [10] conducted experiments in an enclosure of dimension 4 m × 4 m × 4 m, as shown in Fig. 1. Fire is produced by burning of jatropha oil in pan diameter of 0.5 m. Natural ventilation is provided by an opening on front wall of enclosure. Initial fuel quantity is 10.095 kg, and fuel is filled in the pan up to a height of 0.045 m. The fuel is heated by using an oil heating assembly. Fuel pan assembly is kept on weighing platform to record the fuel consumption rate. Heat release rate is determined using mass loss method. Temperature is measured at location of ceiling, corner and centerline of door opening. Figure 2 shows the positions of the thermocouples at 0.5 m below ceiling.

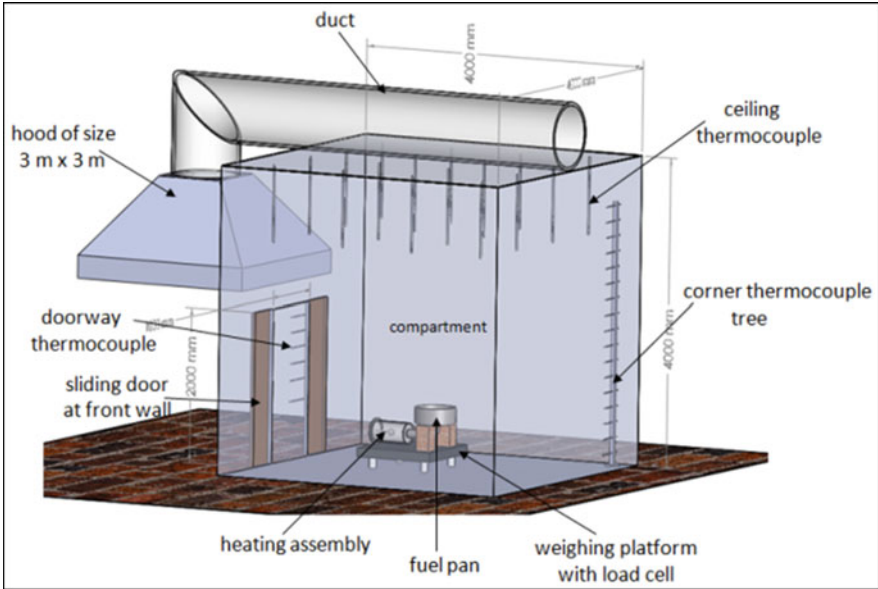


Fig. 1 Details of experimental test enclosure

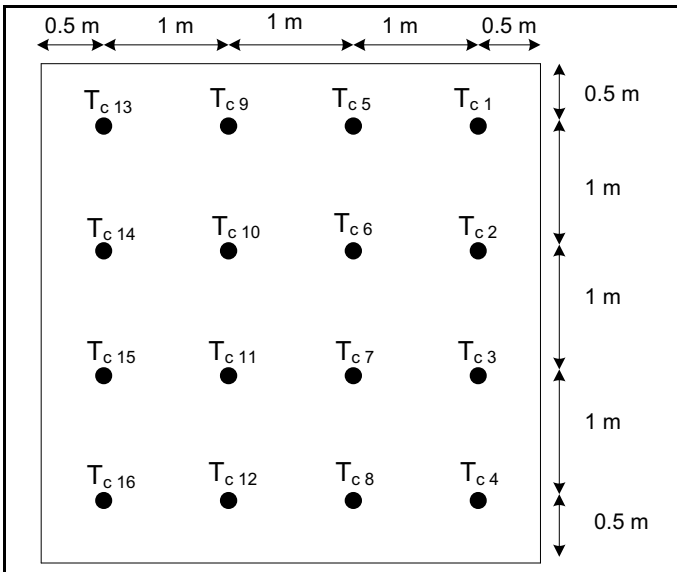


Fig. 2 Schematic showing positions of thermocouples at 0.5 m below the ceiling

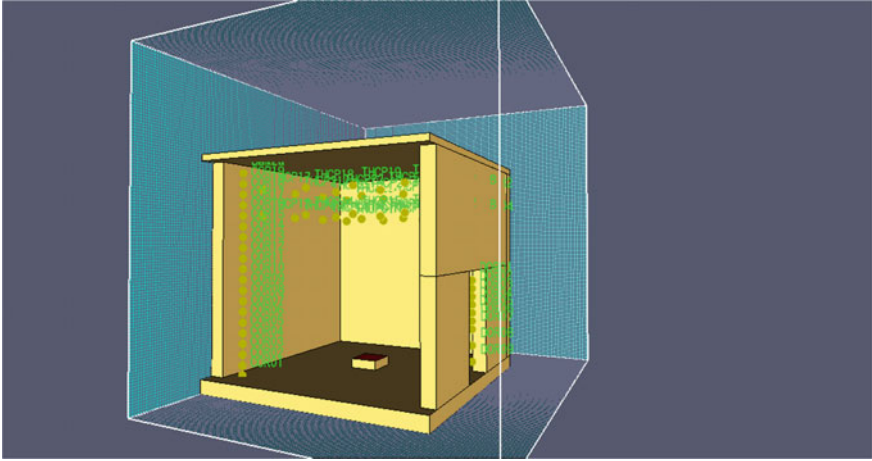


Fig. 3 FDS numerical model with 0.05 m grid size

3 Numerical Simulation

Fire dynamics simulator (FDS) version 6.2.0 is used for performing the simulation. The various models available are $k - \varepsilon$ model [11–13], large eddy simulation (LES) model [14–16] and direct numerical simulation (DNS) model [17]. In this paper, LES turbulence model is adopted.

3.1 Computational Details

The calculation domain set was $7.46 \times 6 \times 6 \text{ m}^3$. Figure 3 shows the FDS model for grid size of 0.05 m. The thermocouple positions in FDS model are the same as in test enclosure. The fire is modeled as a horizontal rectangular surface. The experimental obtained heat release rate is inputted into FDS. Simulations were performed on a system having specifications of 6 GB RAM and Intel Pentium (R) 2.90 GHz.

3.2 Grid Resolution Analysis

Simulation results depend upon the grid size. Axially symmetric flames using FDS were simulated, and a characteristic length of around 0.05 was reported for best results by Ma and Quintiere [18]. A ratio D^*/Δ between 4 and 16 has been recommended to accurately resolve the fire events [19]. Equation (1) is used to determine the grid size, for the present study.

Table 1 Simulated domain with total number of cells for different mesh sizes

Mesh	Mesh size Δ (m)	Simulated domain $x \times y \times z$ (m ³)	Total number of cells
Coarse	0.12	$7.46 \times 6 \times 6$	138,240
Medium	0.05	$7.46 \times 6 \times 6$	2,343,750

$$D^* = \left(\frac{\dot{Q}}{\rho_{\infty} C_P T_{\infty} \sqrt{g}} \right)^{2/5} \quad (1)$$

Here D^* is characteristics fire size in m; \dot{Q} is fire power (heat release rate) in kW; C_P is air specific heat in kJ/kgK; ρ_{∞} is ambient air density in kg/m³; T_{∞} is ambient temperature in K; g is gravitational acceleration in m/s². The average heat release rate obtained in the jatropa oil pool fire is estimated to be 198.2 kW. So D^* is computed to be 0.495 for this fire size. Table 1 gives the value of mesh size considered in the simulation.

Two grid sizes of 0.12 and 0.05 m are chosen to verify the independence of FDS simulation results on the grid size. Comparison of FDS predication with experimental results is presented at some selected locations. Among simulation parameters, ambient temperature was set as 30 °C, ambient pressure 10⁵ Pa, relative humidity 54%, simulation time 2200 s, simulation type LES.

4 Results and Discussion

4.1 Heat Release Rate

Figure 4 represents the variation of mass loss rate and corresponding heat release rate. The heat release rate is calculated using Eq. (2).

$$\dot{Q} = \dot{m} \Delta H_c \chi \quad (2)$$

where \dot{m} is mass loss rate (kg/s), ΔH_c is heat of combustion (38,800 kJ/kg), combustion efficiency χ is assumed to be 0.85 [10].

After the ignition of jatropa oil fuel, heat release rate rises sharply to 180 kW at 500 s; this time period shows the growth phase. After that, fire behavior shows steady profile up to 1710s. Later heat release rate starts to decrease, pointing out the decay phase. The highest heat release rate achieved is 225.0 kW corresponding to 1480 s. The curve can be divided into four parts including (I) ignition; (II) growth; (III) steady profile; and (IV) decay. The experimentally obtained heat release rate is used as input to FDS for performing simulation.

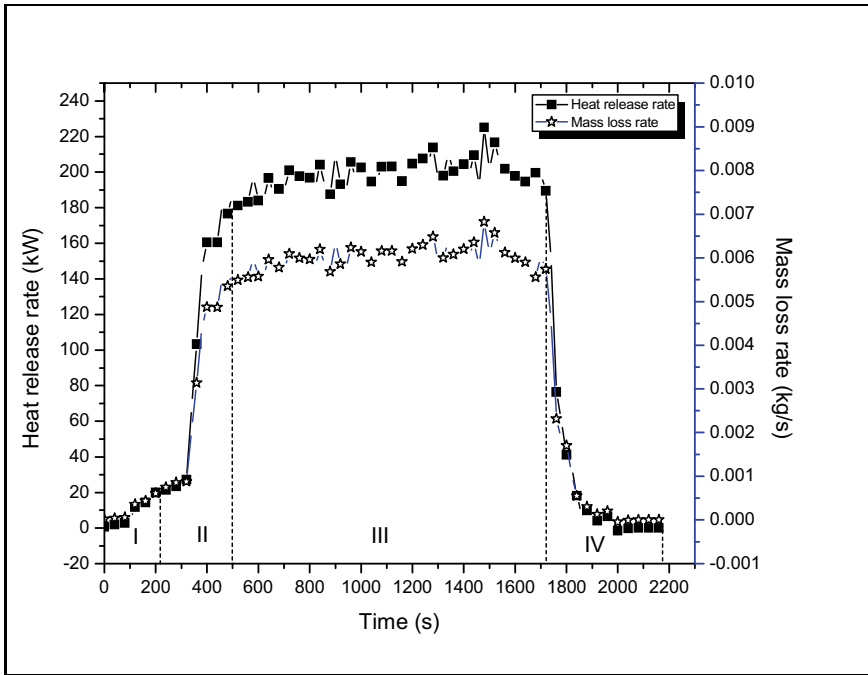


Fig. 4 Mass loss rate and heat release rate variations with time for pool size of 0.5 m

4.2 Hot Gas Layer Temperature

Figure 5 shows the comparison between the temperature under the ceiling (hot gas layer temperature) for T_{C1} and T_{C3} from the experimental and FDS results. During the phases (I) and (II), FDS results are very close to measured value. Hot gas layer temperature during experiment was 180–185 °C. Experimental results are higher than the FDS results just before the start of decay phase, maximum percentage deviation 20%. During the decay phase, FDS results drops down more than experimental results. The results verify that the hot layer temperature in the fire enclosure can be simulated very well by FDS.

4.3 Doorway Temperature

Figure 6 shows the temperature at center of the door for experimental as well as simulation. Both types of flows exist at the door: outward and inward. Above the neutral plane height, hot gases generated in the enclosure leave the enclosure, while to sustain the combustion, fresh air enters from below the neutral plane. From Fig. 6, it could be seen that simulation results matched well with experimental results.

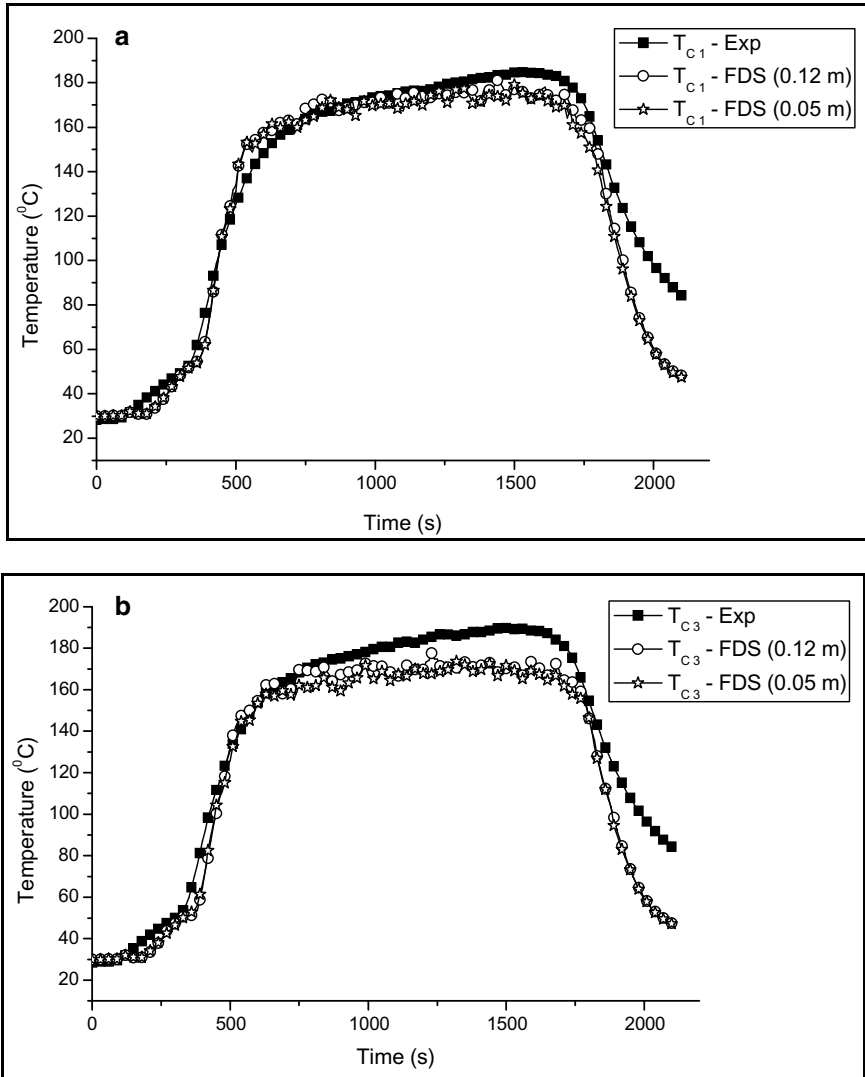


Fig. 5 a Comparison of hot gas layer temperature T_{c1} for experimental and numerical study. b Comparison of hot gas layer temperature T_{c3} for experimental and numerical study

4.4 Smoke Layer Height

Two methods have been used to calculate the smoke layer height, i.e., by analyzing the vertical temperature profile and by visual analysis. Visual analysis refers to the analysis of video recording which was done with Fujifilm HS50EXR digital camera during the whole duration of the experiment.

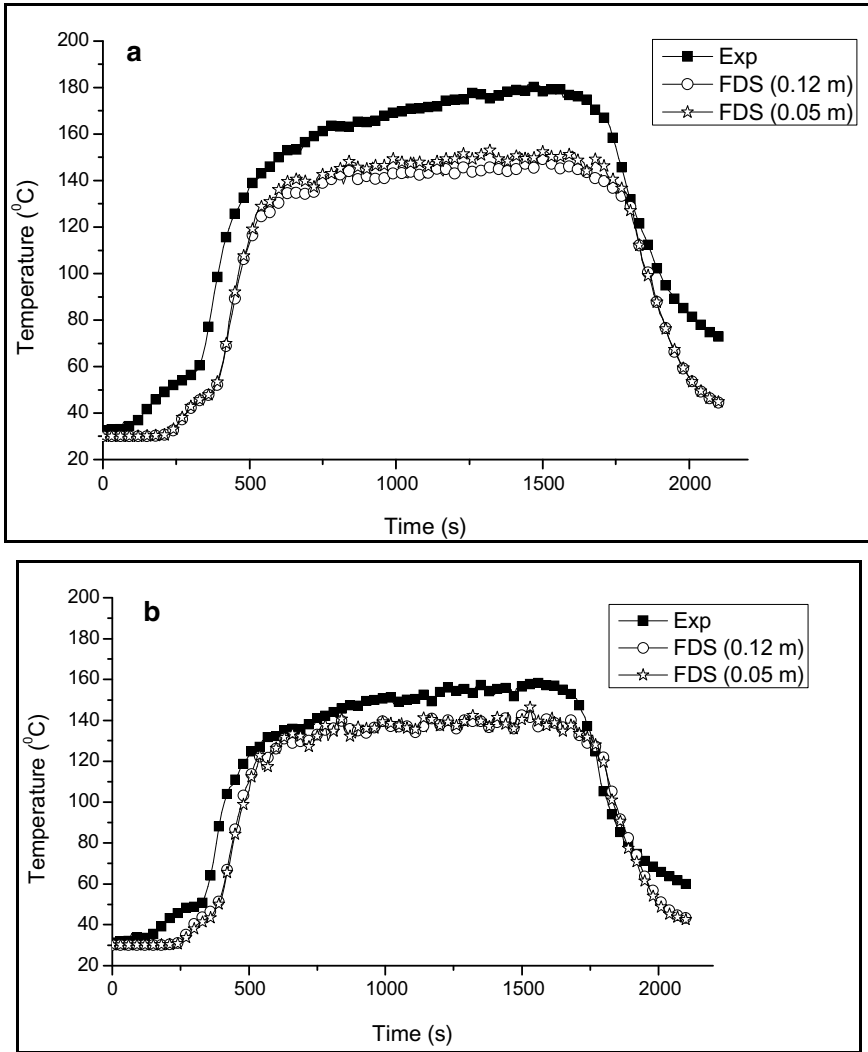


Fig. 6 **a** Comparison of temperature for door height 1.8 m. **b** Comparison of temperature for door height 1.5 m

Determination of smoke layer height is based on the studies presented in the work [20, 21]. The smoke layer height (shown in Fig. 7) is not same during experiment and in simulation results. Experimentally determined smoke layer height is approximately at 1.1–1.2 m while FDS predicted at grid size of 0.05 m lies at 1 m; but at grid size of 0.12 m, smoke layer height lies at 0.7–0.8 m. After height of 1.2 m, predicted temperature at both grid sizes does not change much and matched with the experimental findings (Fig. 5). Thus, in the upper zone of enclosure, changing the

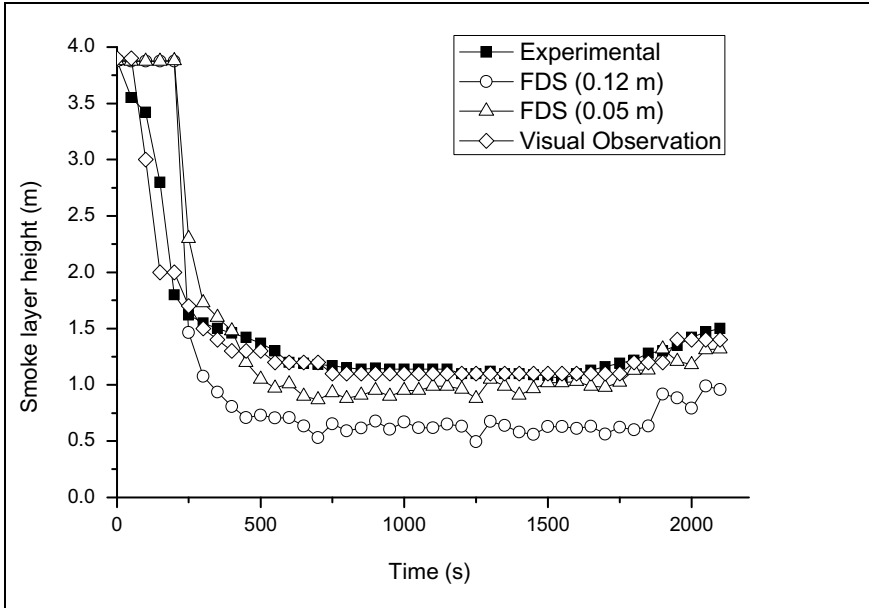


Fig. 7 Smoke layer height for the experiment and simulation results

grid size does not show much effect; but in the lower zone, better agreement is found between the experimental values and FDS results at medium grid size of 0.05 m.

5 Conclusions

In this paper, an attempt has been made to validate the experimental results of 0.5 m jatropa oil pool fire with simulation results using FDS. Simulation results matched well with experimental findings in upper region of the enclosure. Changing the grid size from 0.12 to 0.05 m does not have any significant impact on simulation results in upper region, while in lower region of the enclosure, better simulation results are obtained at grid size of 0.05 m.

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