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Full Scale Experimental Studies on Liquid Fuel Fires in a Compartment

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ABSTRACT

The compartment fires have been studied through full-scale experiment, which were conducted in a compartment of size 4m x 4m x 4m with a door of size 2m (height) x 1m (width). Three experiments were performed with same size of fire using three different types of fuel. The fuel pan of 0.8 m diameter and 0.12 deep was placed in a center of compartment. The steady heat release rates measured were approx. 800 kW, 700 kW and 260 kW for Exp. 1, Exp. 2 and Exp. 3 respectively. The local and average hot gas temperatures were measured to observed severity of fuel types. The average hot gas temperature in Exp. 1, Exp. 2 and Exp. 3 were found 400 °C, 280 °C and 160 °C respectively. The mean flame height as obtained by image processing was compared with the predicted correlation for using three fuels. Experimental diesel flame height is found to be 79.5% and 73.5% underneath than the Heskestad and Thomas correlation respectively.

1. Introduction

Compartment fire study is affected by thermal and chemical condition. The design of fire protection system requires that the dynamic of fire inside the room to be clearly understood which requires measurement of burning rate, heat release rate, flame temperature, heat flux, compartment temperature etc. These characteristic depends upon fuel properties, fire size and compartment geometry. Babrauskas [1] estimated the burning rate in an open-atmosphere system can be estimated with a simple correlation that only requires the knowledge of fuel properties. Ohmiya et al. [2] conducted experiments on different fuel surface area and ventilation condition. Kumar and Naveen [3] conducted experiments in which three different fuel trays and two different fuels were adopted, with and without cross-ventilation, to study the effect of cross -ventilation on the burning rates and the temperature profiles at different location in the hot gas layer in the compartment. Tang et al. [4] investigated the impact on mean flame height and smoke temperature profile of the geometry of windows (opening factor) and heat release rate (HRR) based on a series of model-scale experiments.

Steckler et al. [5] studied the flow through induced by fire in a compartment, generated temperature and velocity in compartment under different ventilation condition, which are characterized the developing fire. Large-scale pool fire experiments performed by Koseki et al. [6] used different pool sizes, i.e. 5 m, 10 m and 20 m. They investigated fuel burning characteristics, i.e. burning rate, flame height and radiative loss fraction of the fuel on different pool sizes. Burning rate was found to be proportional to pan size and radiative loss fraction was found to decrease with pan size. Koseki and Yumoto [7] measured the air entrainment and found that for any pool sizes, maximum rate of air entrainment resulted at base of the flame. Munoz et al. [8] analyzed burning characteristic, i.e. burning rate, flame height, flame tilt and emissive power of flame. Thermal graphic camera (IR) was used to measure emissive power of luminous and non-luminous part of the flame. It was found that the energy distribution of luminous flame is independent on pan diameter and fuel type. Avinash et al. [9] has fire size of 0.6 m used with crude jatropha oil in same compartment with varying door opening conditions. They have concluded that fire remains over ventilated type even though door ventilation is ¼ th of the full door opening. Deepak et al. [10] full-scale experiments were performed in same compartment with diesel fuel pan 0.6m diameter for varying ventilation through door opening, in their maximum value have found at the ceiling is 13.6 kW/m^2 for 1/5 th of the full door opening and maximum heat release rate was found 564 kW for half door opening.

This present study is continuation of previous study to determine thermal behavior and flame height which is the major fire characteristics required to know the maximum hazard of elements placed inside the compartment. The knowledge about burning characteristic of diesel fuel inside the enclosure is scarce. The current study is part of a larger project aimed at better understanding compartment fire dynamics to facilitate model development.

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2. Methodology

A test facility as shown in figure 1a is developed in Mechanical and Industrial Engineering Department at the Indian Institute of Technology, Roorkee, India to perform full scale fire experiments. The compartment is of size 4 m × 4 m × 4 m having a door opening of size 2 m height and 1 m wide. Mild Steel fuel pan is of 0.8 m diameter and 0.10 m height. A constant 0.06 m height of fuel maintained above the pan bottom. The fuel supply system layout has been described in Sahu et al. [12]. The fuel pan is located at the center of compartment, and further we have provided constant supply of fuel upto 900 s to measure temperatures through thermocouple rack A, B, and C. The incident heat flux at ceiling center measured through SBG01 water cooled type heat flux sensor. The fuel pan is flushed after 900 s with the floor. Fig.1b shows Large-scale heat release calorimeter, which works on O_2 depletion method suggested by Huggett [11], is used to measure the heat release rate (HRR). The calorimeter hood of size 3.0 m x 3.0 m and 1 m height is mounted at door opening to collect the product gases. The exhaust duct is connected to hood plenum. The sample gas probe is used for collecting the gases for further analysis in gas analyzer. Figure 1c shows thermocouples T1.4 – T16.4 are located 1.0m below the ceiling while thermocouples T1.3 – T16.3 are located 0.5 m below the ceiling, T1.2 – T16.2 are just at the false ceiling and thermocouples T1.1 – T16.1are located between ceiling and false ceiling. The locations have been selected to find out the variation of temperatures within the gas layer.

Table 1: Details of experiments with fuel properties [15]

Exp.	Fuel	Heat of combustion (MJ/kg)	Latent heat of vaporization (kJ/kg)	Experimental fuel burning rate (g/s.m^2)
1	Diesel	43.50	228	22.98
2	Iso-Propanol	30.45	663	18.39
3	Methanol	19.94	1101	13.0

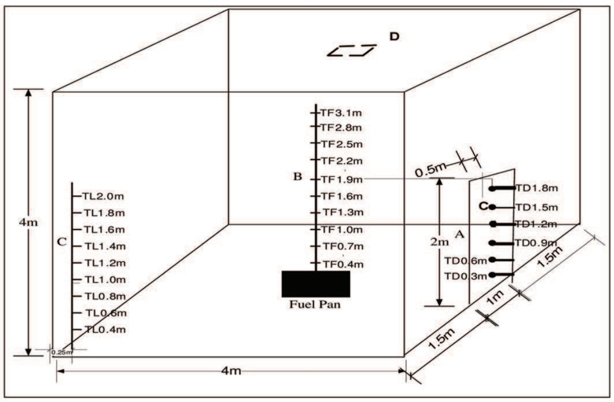


Fig.1a. Schematic of fire test compartment;

A: Thermocouple rake at centre of door opening; B: Thermocouple rake above the fuel pan surface C: Corner thermocouple rake; D: Heat flux sensor at ceiling center

Fig.1b. View of Large-scale heat release calorimeter

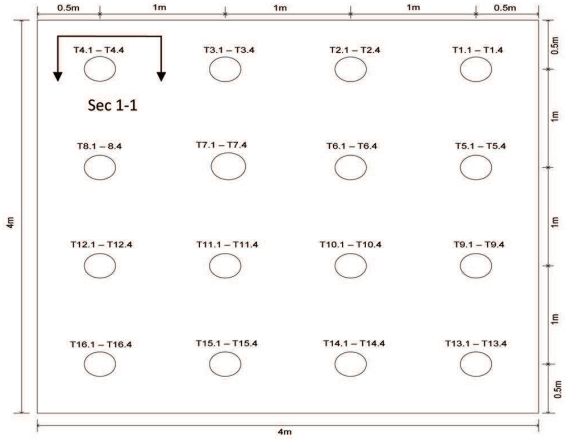
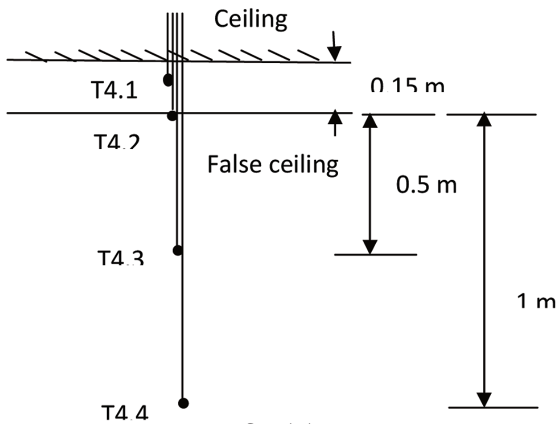


Fig.1c. Detailed locations of thermocouples installed under the ceiling in compartment



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Vertical positions of ceiling thermocouples

3.0 Results and Discussion

3.1 Heat release rate (HRR) and smoke production rate (SPR)

Fig. 2a shows the steady heat release rate is reached at 350 seconds in Exp.1 and 150 seconds in both Exp.2 and Exp.3 conditions. In a period of steady state, the average value of heat release rate is found to be 800 kW, 700 kW and 260 kW in Exp.1, Exp.2 and Exp.3 respectively. The properties of fuel used are given in Table 1. The heat of combustion of diesel fuel is higher than isopropanol and methanol, resulting that high heat release rate obtained in a diesel pool fire compared to isopropanol and methanol pool fire.

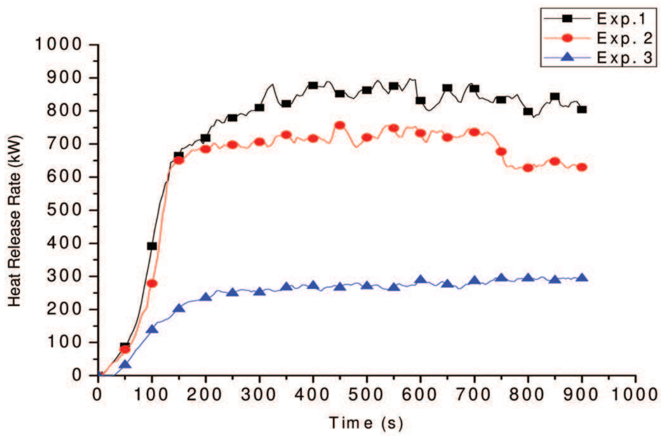

Fig. 2a: Variation of heat release rate with time under different fuel fire condition

Fig. 2b shows the smoke production rate under different fuel fires. The light obscuration system is used for measurement of smoke production rate to determine the properties of burning fuel in terms of smoky or non smoky fuel. In present study the smoke concentration is determined by the extinction concentration using helium-neon laser system. An optical system installed at the duct for the measurement of light obscuration across the centerline of the exhaust duct. The smoke production rate is found to be higher in diesel, a characteristic of sooty fuel and smoke production rate is found to be least in methanol fire, showing the nature of fuel as a clean fuel or non-sooty fuel.

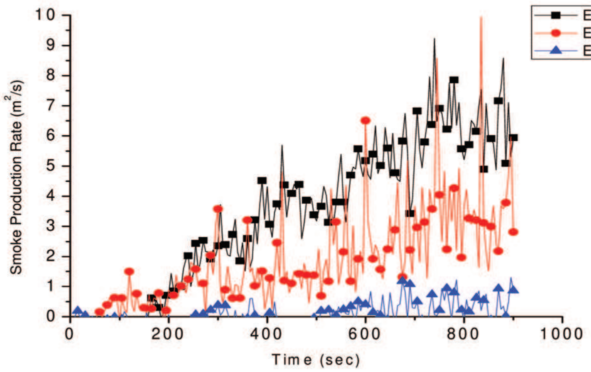

Fig. 2b: Variation of smoke production rate with time under different fuel fire condition

Extinction coefficient is determined from given below equation (1)

$$K = \frac{1}{L_p} \ln\left(\frac{I_0}{I}\right) \qquad (1)$$

Where I_0 is the light intensity in smoke free environment, I is smoke intensity in presence of smoke, L_p is path length (m).

Rate of smoke production (m^2/s) is given as:

$$RSP = \dot{V}_S \times K \qquad (2)$$

Where V_s is volumetric flow rate of smoke in exhaust duct and given by following equation (3)

$$\dot{V}_S = \frac{\dot{V}_{298} T}{298} \qquad (3)$$

3.2 Ceiling heat flux

The variation of ceiling heat flux with time under different fuel fire is shown in Fig. 3. The maximum heat flux is achieved at the ceiling due to direct impact of hot gases. The profile of ceiling heat flux is found to be similar in Exp.1 and Exp.2, because of the development of heat release rate is almost similar in both experimental conditions.

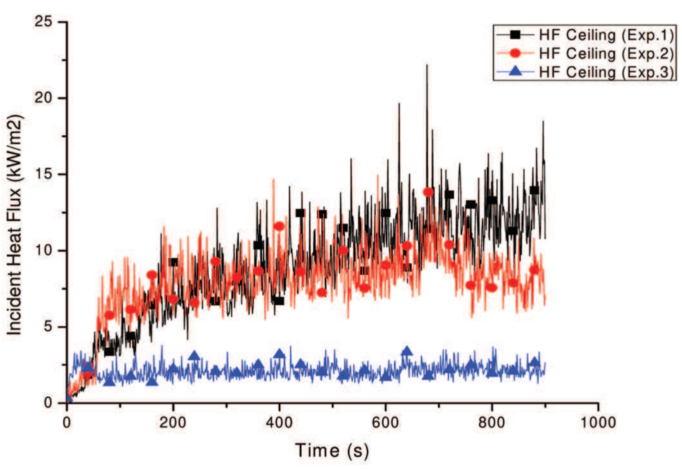

Fig. 3: Incident heat flux variation with time at ceiling surfaces under different fuel conditions

3.3 Temperature variations within the compartment

Fig. 4a, Fig. 4b and Fig. 4c shows the variations of temperatures with height for different location of compartment surface at time 5 min. 10 min. and 15 min. The temperature distribution at respective surfaces of compartment in Exp.1 and Exp.2 is found to be similar, which shows similarity with the heat release rate profile. In case of methanol fire (Exp.3) temperatures are found to be lower than the diesel (Exp.1) and isopropanol (Exp.2) fire.

The compartment fire is divided into two distinct zones i.e. one is cold zone and another is hot upper zone. The cold air enters into the compartment from lower half portion of the dooway opening and hot exhaust gases out through the upper half of the doorway opening. The intermittent region between two zone is called thermal discontinuity at the doorway opening.

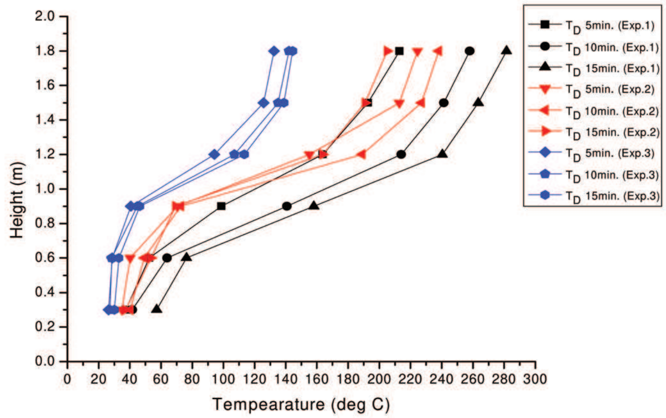

Fig. 4a: Variation of doorway temperature with door height at different time interval under different fuel conditions

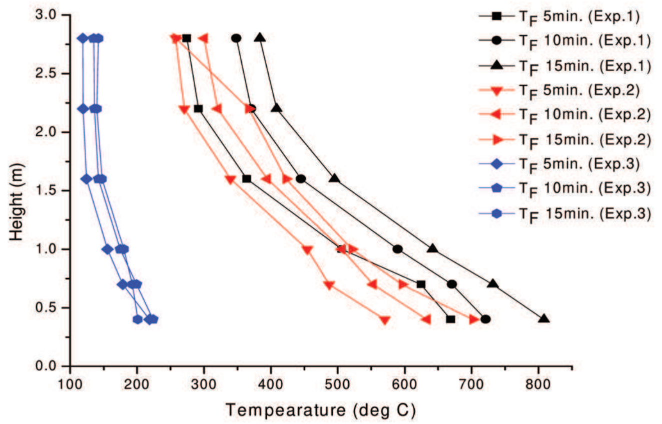

Fig. 4b: Variation of temperature with height above the pool surface at different time interval under different fuel conditions

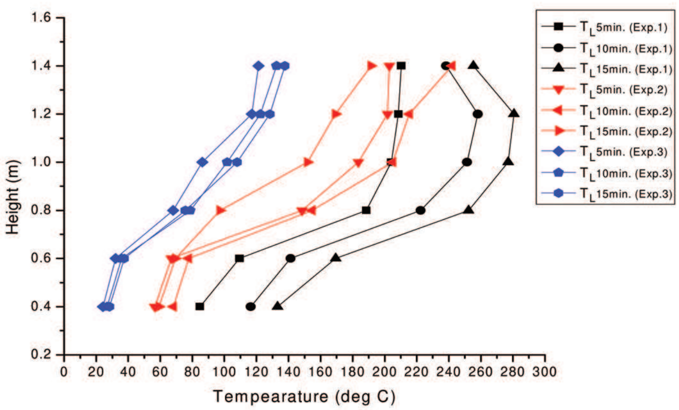

Fig. 4c: Comparison of corner rack temperature with at different height of compartment under different fuel conditions

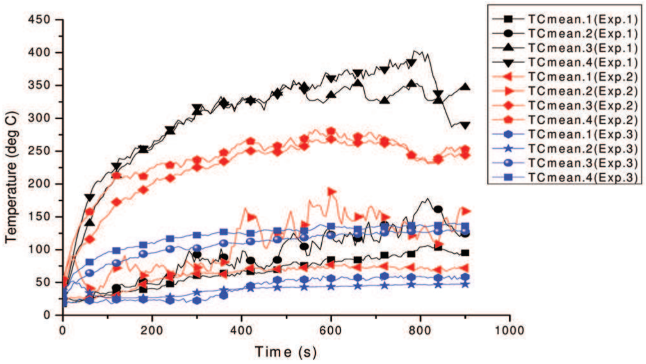

Fig. 4d: Variation of mean ceiling temperature with time under different fuel conditions

3.4 Flame height

Fig. 5 (a)-(c) shows the instant capture of flame for different experimental conditions. During experiments, burning behaviour is recorded with the digital camera of Fujifilm make (model-HS50EXR) at a frame rate of 35 fps and resolution of 640 x 580. The images at 900 s has extracted from video clip of steady burning duration. We have used MATLAB software for further image processing of extracted image. Extracted image is converted in MATLAB Figure file and at this stage, size of each image is noted down in terms of pixel. The fuel pan diameter is known of 0.8 m, the same distance inside the image is recorded in terms of pixel. Ratio of these term gives scaling factor. Previously calculated pixel size of each image is multiplied with this scaling factor to calculate the height of luminous flame for each experiments.

Fig. 5: Luminous flame height at time of 900 s

Experimental flame height was also compared with the flame height correlations developed by Heskestad [13], as shown in Eq. (4).

$$L = -1.02D + 0.235(\dot{Q}^{2/5}) \quad (4)$$

Where, L is flame height (m), D is pool diameter (m) and Q is heat release rate (kW).

Thomas [14] provided highly simplified dimensionless analysis to relate maximum flame height to mass burning rate. Equation (5) shows correlation to measure flame height:

$$L/D = 42\left[\dot{m}''/\rho_\infty (gD)^{0.5}\right]^{0.61} \quad (5)$$

where m'' : mass burning rate (kg/m^{2}s); ρ_α : density of surrounding air (kg/m^3), g: acceleration due to gravity (m/s^2).

Experimental flame height is determined by analysis of video recording and MATLAB software, as mentioned earlier. Table 2 summarizes comparison of experimentally obtained flame height with the values obtained from the Heskestad correlation and Thomas correlation. It was found that experimental flame height for methanol pool fire is near the predictions of Heskestad correlation and Thomas correlation. The diesel fuel is highly sootiness in nature so that some portion of diesel fire flame is invisible and obscured within the soot. In this study only non-obscured flame has measured.

Table 2: Comparison of experimental flame height with the value obtained by correlation

Flame height (m)			
Experiment	Experimental	Heskestad correlation	Thomas correlation
Diesel	0.53*	2.59	2.0
Iso-propanol	1.56	2.42	1.75
Methanol	1.48	1.35	1.41

* Luminous flame height

4. Conclusion

The present work is focused to investigate the behavior of liquid pool fire in a large scale compartment. It is observed that the fuel properties (heat of combustion, burning rate, sootiness etc.) have most important role in the growth of compartment fire. The maximum mass burning rate is proportional to the ratio of heat of combustion to heat of vaporization. The ratio is highest in diesel fuel, thereby resulting in highest burning rate compared to isopropanol and methanol fuel fires. The thermal discontinuity between hot and cold zone is found to be approximately 0.8 m above the floor in all three experiments based on corner temperature measurement. The doorway temperature profile is distinguished into two zones, i.e. cold zone and hot zone. Similarly thermal discontinuity occurs at door approximately height of 1.2 m above the floor in all fuel experiments. At the door thermal discontinuity is higher than the room due to influence of inflow air through the half bottom of the door. The experimental flame height is less than the flame height obtained from correlation because the fire is underventilated compartment fire, and correlations have been free burn fire condition. The ceiling effect and fuel sootiness is also responsible for much reducing flame height in case of diesel fuel compare than alcohol fuel.

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