Experimental Investigation on Large Scale Diesel Pool Fire in a Vertically Ventilated Compartment

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Abstract: An experiment was performed for pool diameter 1 m located at the center of a compartment which has a size of 4 m x 4 m x 4 m (l x w x h). The door size was 2 m x 1 m (Height x Width) which was fully open during the experiment. The purpose of experiment was to obtain a data of burning characteristic of diesel fuel within the compartment. The large scale heat release calorimeter measure the heat release rate (HRR) and concentration of O2, CO2 & CO. The thermocouple arrays are installed at different places to measure the ceiling temperatures; centerline temperatures above the pool, doorway temperatures. The maximum HRR has found 1 MW and during steady period average hot gas layer temperature reaches to 400 °C. The average mass burning rate was maintained to 0.037 kg/m²s, which was compared with other previous conducted experiments for diesel pool fire.

1. Introduction
The idea of fuel burning behavior in compartment fire is very important for making judgment on fire scenarios. This gives information for putting controlling mechanism of particular fire. How much personnel and equipment may be required from a particular distance that is decided by burning phenomena happening inside the enclosure Croce et al.[1].

Compartment fire may be of two types, first one is fuel control fire and another is ventilation control fire. Earlier study has done for giving the mass burning rate in small scale compartment pool fire. The Joulian [2], Steinhaus et al. [3] and Hu [4] described methods for finding burning characteristics of pool fire. The large scale pool fire results are not clear to understand full scale compartment pool fire burning [3]. Mass burning rate is gives heat release rate proportionally with some time lag up to end of the burning. Babrauskas [5] has shown influence of convective and radiative heat transfer rate with the range of small to large scale pool fire. He has given useful information of laminar and turbulent flame with respect to size of pool fire. Blinov and Khudyakov [6] found that burning rate decreases for increases pan diameter up to 0.15 m and burning rate increases after increasing fuel pan diameter up to certain range after that burning rate becomes constant. Variables like atmospheric conditions and fuel pan lip height also having influence on the mass burning rates.

Hiroshi et al. [7] noted mass loss rate decreasing continuously with decreasing height of fuel layer inside the fuel pan. Therefore, thin layer of fuel burning rate becomes unsteady and mass burning rate founded in a decreasing order. Hamins [9] determined mass burning by applying energy balance on the upper fuel surface. He has found that radiative heat feedback influences more to mass loss rate.
From this literature review, it appears that large pool sizes are not used in earlier study for confined and ventilated compartment with commonly used diesel fuel. In this work heat release rate, heat flux and temperature estimation have determined within the large pool diameter fire inside the compartment. The heat flux sensors have fixed at different location of compartment wall, ceiling and floor.

2. Methodology

2.1 Experimental description

Figure 1 shows the experimental facility which was constructed in Mechanical and Industrial Engineering Department at the Indian Institute of Technology, Roorkee, India to carry out full scale fire experiments. The compartment is made of dimension 4 m x 4 m in plan and 4 m in height having a door opening of 2 m x 1 m (H x W). Wall thickness of room was 0.27 m. The walls are constructed by normal bricks and plastered in the proportion of 1:6 (cement-sand). The 0.02 m thick plastered have been applied to provide finishing of wall surfaces. Ceiling of the compartment was made of RCC (1:2:4) and roof thickness was kept 0.14 m. The false ceiling was designed to protect the ceiling due to effect of higher thermal load while elevating a fire source inside the compartment. The false ceiling shown in figure 2 was 0.15 m below from the ceiling and 0.025 m thick calcium silicate board was used as false ceiling material. The bulk density and thermal conductivity of calcium silicate board was 860 kg/m³ and 0.24 W/(mK). The properties of compartment surfaces are given in Table 1.

![Figure 1. Schematic of fire test compartment with fuel pan.](image)

A: Thermocouple rake at centre of door opening; B: Thermocouple rake above the fuel pan surface
C: Corner thermocouple rake.
Figure 2. View of false ceiling inside the compartment.

Figure 3. View of Large-scale heat release calorimeter.

Table 1. Details of thermal properties of diesel and compartment surfaces [11]

| Material                  | Thermal Conductivity (W/mK) | Specific heat (J/kg K) | Thickness (m) |
|---------------------------|-----------------------------|------------------------|---------------|
| Mild Steel (fuel pan)     | 45                          | 460                    | 0.003         |
| Brick                     | 0.69                        | 840                    | 0.23          |
| Concrete                  | 0.8-1.4                     | 880                    | 0.14          |
| Diesel fuel in pan        | 0.15                        | 1750                   | 0.03          |
| Cement Plaster            | 1.208                       | 0.9719                 | 0.02          |

A large-scale cone calorimeter supplied by the Fire Testing Technology (FTT), UK was used to measure the heat release rate. The large-scale cone calorimeter has gives HRR reading based on oxygen consumption theory [10]. The based on a propagation of uncertainty analysis total expanded relative uncertainty of the heat release rate was ±14% reported. The cone calorimeter exhaust hood of size 3.0 m x 3.0 m in plan and 1 m in height was mounted at door opening to accumulate the product gases. Fig. 3 shows the exhaust duct connection to hood plenum and size of duct was 0.40 m diameter and 6 m length. Servomex 4100 Gas analyzer unit was inbuilt with cone calorimeter to display measurements of O₂, CO₂ and CO concentration in exhaust gases flowing through duct.

The compartment temperatures were measured through three thermocouple tree as shown in figure 1. Type-K thermocouples with bead diameter 1.0±0.25 mm were used in thermocouple trees. The thermocouples were having an expanded uncertainty of ±2.0 °C. Door centerline temperatures were recorded by thermocouple tree-A, where the thermocouple started from 0.3 m above the compartment floor. The measurements of temperature distribution above the pool center were done by the thermocouples tree-B. The compartment temperatures along the height in z-axis were measured by thermocouple tree-C which was located at the corner of west and north wall at a distance 0.25 m far from both sides. The temperatures obtained through this corner temperature tree were useful in finding demarcation between hot layer and cold layer zone.

Temperatures were continuously measured at the upper layer in the compartment. Total 64 numbers K-type thermocouples with a bead diameter of 0.5 mm ± 0.125 mm were installed at different depth from top surface such as 1.0 m below the false ceiling (∆TC₂), 0.5 m below the fall ceiling (∆TC₃), just at false ceiling (∆TC₁) and between ceiling and false ceiling (∆TC₂). As shown in
figure 4 the thermocouples T1.4 – T16.4 were located 1.0 m below the ceiling while thermocouples T1.3 – T16.3 were located 0.5 m below the ceiling, T1.2 – T16.2 were just at the false ceiling and thermocouples T1.1 – T16.1 were located between ceiling and fall ceiling. The locations have been selected to find out the variation of temperatures within the gas layer.

![Figure 4. Detailed locations of thermocouples installed under the ceiling in compartment.](image)

The arrangement of water-cooled Schmidt-Boelter, SBG01 heat flux sensors, which measures total heat flux (convective and radiative) at various surfaces of compartment i.e. ceiling, walls, and floor. A total 19 nos. heat flux sensors installed inside the compartment in which 4 nos. at floor, 5 nos. at false ceiling, 4 nos. at front wall and each 2 nos. in back wall and both sides wall. Heat flux sensor was a factory calibrated relative to a working standard ISO 14934, and uncertainty estimated to be ±6%, based on standard uncertainty multiplied by coverage factor of k = 2.

2.2 Fuel Delivery System
A fuel supply system has prepared for continuous supply of fuel within the completion of fire burning. One weighing unit has established at outside the compartment to measure fuel reduction with time, through that mass loss rate obtained Sahu et al.[11]. The fuel supply rate is maintained as per 3 cm height of fuel level consistently available inside the fuel pan.

3. Results and Discussion
The heat release rate (HRR) is attributed with mass burning rate of fuel per unit pool surface area. Figure 5 shows the variation of HRR with time. Ignition start is followed by growth stage where HRR reaches to greatest. Afterwards fire becomes under steady period with full spreads of fire over the entire pool surface. The fuel temperature becomes quickly maximum so that boiling temperature reaches at the fuel surface. Second stage is reaching to a particular value of HRR for very small period. After 300 s heat release rate is increases to second area of stability. The fuel properties are mainly responsible for these phenomena. Diesel fuel is non-standard fuel and their property is different basis of location. The mass loss rate is increased suddenly to a peak value due to
An supplementary quantity of fuel is at a vaporizing temperature. We stopped fuel supply manually at 600s, and then HRR becomes decreases up to continue burning of fuel. The end stage is decay period where HRR declines to minimum values.

**Figure 5.** Variation of HRR and O₂, CO and CO₂ with time

**Figure 6.** Centerline flame temperature above the pool.

Figure 6 shows temperature variations above the fuel pan at different position. The ‘Y’ is vertical position of thermocouples above the fuel pan and ‘D’ is the diameter of fuel pan. The temperature is maximum at 0.5 m above from the fuel pan bottom surface. The temperature is near about constant in continuous flame zone. It has also observed that the temperature is decreasing towards upside of thermocouples above the fuel pan. The average upper layer temperature has reaches to 400 °C which may cause damage of RCC ceiling, so that provision of false ceiling made to save ceiling from higher thermal load. Figure 7 illustrates, ΔTC₄ and ΔTC₅ are almost same i.e. below the false ceiling temperature is uniform across the upper hot gas layer. False ceiling prevents to ceiling by 50% of thermal load.

**Figure 7.** Variation of hot gas layer temperature at position different of thermocouples.

**Figure 8.** Corner vertical temperature variation with time.
Compartment fire divided into two zones based on the vertical temperature values which have shown in figure 8, one is cold zone and another is hot zone. As the vertical position of thermocouple increases, the temperature value also increases. The demarcation has found between two zones 0.4 m from the bottom surface. The influence of radiative heat transfer by flame has not calculated here for corner vertical temperature values, so that temperatures at cold zone side getting more than actual values. Figure 9 shows that incident heat flux along with compartment height linearly increasing; since fire source is placed on centered and heat energy direct impinge on the ceiling so that incident heat flux is higher for ceiling surface. From figure 10 the demarcation between hot and cold zones found 0.6-0.9 m that is little bit higher than the compartment inner side. This is happening at the door of compartment, there are flows occurred in two directions and consisting differential pressure across the vertical plane.

**Figure 9.** Variation of incident average heat flux with time.

**Figure 10.** Doorway centerline temperature variations with door height of compartment.

**Figure 11.** Comparison of burning rate of diesel pool fire.
Figure 11 shows comparison of time averaged mass burning rate with before conducted test data for diesel pool fire. The trend has shown mass burning rate is increases with increasing pool diameter. However, difference has obtained for [13] and [14] at 0.6 m pool diameter, in [14] fuel level was not maintained so that fuel level was decreasing with time upto fuel extinction period. And in [13] fuel level was maintained through external fuel supply system.

Thomas [16] provided simple correlation of flame height based on mass burning rate and pool diameter at particular conditions. Below equation gives flame height (m):

\[ L/D = 42 \left[ \frac{\dot{m}^*}{\rho_\infty (gD)^{0.5}} \right]^{0.61} \]  

where \( \dot{m}^* \): mass burning rate (kg/m²s), \( \rho_\infty \): density of surrounding air (kg/m³), \( g \): acceleration due to gravity (m/s²). After putting all values in Equation (1), the maximum flame height is found to be 2.6 m. Zukoski et al. [17] given approximate flame height based on temperature of flame above centerline of pool, they have expected temperature region of 500-600 °C shows average flame height of respected pool fire. The flashover of fire occur at 500-600 °C, where flame may comes out to outside through windows or door [18]. So from figure 5, pool fire centerline temperature data, the average flame height can be taken as 1.9 m.

4. Conclusion

The experimental study conducted inside a compartment of 64 m³ to find a thermal environment and mass burning rate of 1 m diameter diesel pool fire. The diesel fuel is largely used hydrocarbon fuel because it’s higher calorific value, easily availability and higher flash point. It’s mainly used in large scale industries and generator for electricity backup in major places. The knowledge about burning characteristic of diesel fuel inside the enclosure is scare. Mass loss rate of diesel fuel maintains a constant rate of 0.029 kg/s through fuel supply system to know HRR inside the compartment. HRR is found to be 1 MW which comes under large scale fire behavior. Maximum average hot layer temperature is found to be 400°C. The average incident heat flux obtained at ceiling is14 kW/m². Upper half door temperature is found to be 350 °C which may create difficulties to approached fire. The data generated can be used for validation purpose and to design fire protection system.

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