

# AN EXPERIMENTAL STUDY ON CRIB FIRES IN A CLOSED COMPARTMENT

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*An experimental investigation on burning behavior of fire in closed compartments is presented. Fire experiments were performed in a closed compartment of interior dimensions  $4 \times 4 \times 4$  m (length  $\times$  width  $\times$  height) with ply board cribs as fire source. The parameters including the gas temperature, mass loss rate, heat flux, flame temperature and compartment pressure were measured during the experiments. Experimental results indicated that the providing sudden ventilation to the closed compartment had great influence on the behavior of fire. The mass loss rate of the burning crib increased by 150 % due to sudden ventilation which results in the increase in heat release rate by 198 kW. From the perspective of total heat flux, compartment pressure and gas temperatures closed compartment with sudden ventilation were more hazardous.*

*Key words: compartment fire, heat flux, gas temperature, flame temperature, compartment pressure*

## 1. Introduction

The closed compartment fire has always been a significant area of research. Ship cabin fire, closed-door electric cabinets in nuclear power plants, engine rooms in industries are some example of closed compartment fire, which is very destructive in nature causing huge loss of property as well as life. In closed compartment fires it is important to understand the burning behavior of fuel and the thermal load distribution within the compartment. Many researchers have studied the burning behavior of fuel in the closed compartment [1-3]. A significant work has been done by Zukoski [4] on the phenomenon of filling of smoke in a close compartment. Zukoski [4] performed the theoretical analysis and explained the smoke filling phenomena in the closed compartment and suggested that for the elevated fire the time required to fill the compartment with combustion products was greater than that of fire located on the floor. Nikitin [5], based on the thermal theory of the initiation of flaming combustion explained the self-extinction phenomenon of pool fires within a closed enclosure. On the other hand, Beyler [6] modeled the extinction theory for closed compartment fire. He found that the extinction time of fire can be modeled by predicting the time required for oxygen concentration to reach the Limiting Oxygen Index (LOI). Bailey *et al.* [7] carried out several fire tests in a large-scale pressurizable chamber with methanol as a fire source to study the effect of pressure and oxygen concentration on methanol pool fire. The mass burning rate of the fuel was found to be decreased linearly with the concentration of oxygen depletion from a volume fraction of 21% to 13.5%. Moreover, the fire extinguish when the concentration of oxygen reached 12%. Zhang *et al.* [8] investigated fires in closed compartment and measured different parameters such as mass burning rate, gas temperature distribution, oxygen concentration and light extinction coefficient. Analyzing the experimental data it was found that the interface of the stratification was the surface of the fuel level. Quintiere [9] theoretically examined the extinction of diffusion flames and found that the extinction of

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flame also depends on the gas temperature and heat flux to the fuel surface apart from limiting oxygen concentration. Zhang *et al.* [10] performed fire experiments in two different sizes of the compartments to investigate the smoke filling in closed compartments with elevated fire sources. Analyzing the experimental results it was found that the interface of the stratification was the fuel surface level for both the compartments. Utiskul *et al.* [11] investigated the behavior of heptanes pool fire in a 40 cm cubic compartment having vent at the ceiling and at the floor. A theory based on a critical flame temperature showed that self extinction of fire depends on oxygen concentration as well as heating. Zhang *et al.* [12] carried out several experiments in compartment having volume of 17.55 m<sup>3</sup> and 0.75 m<sup>3</sup> to study the self-extinction time of pool fire in closed compartments. Based on the experimental results it was found that the fire self extinction time was proportional to compartment volume but on the other hand fire self-extinction time was inversely proportional to the area of the pool. The self-extinction phenomena occurred at the time when the oxygen mole fraction in the flame reaches to a level of 10.7-15.3 %. Chow [13-14] performed several numerical simulation on closed chamber fires and suggested that the input heat release rate to Fire Dynamic Simulator is a key point. Hu [15] conducted several fire experiments to investigate the compartment gas temperature distribution during smoke filling process. Analyzing the experimental results it was found that the compartment gas temperature profile at the moment of self-extinction fit the Boltzmann distribution. However, the present study focuses on the effect of sudden ventilation on gas temperature, heat flux, compartment pressure, flame temperature and mass loss rate. Effect of sudden ventilation when provided on closed compartment needed to provide more attention, since effect of varying ventilation rate in a compartment with fire is observed comprehensively. Compartment fire and its radiation effect in the compartment has become an important aspect for fire researchers for estimating temperature and heating of compartment itself. Various parameters of compartment fire like gas temperature, mass loss rate, fire spread and flame temperature have been focused in lots of researches during past decades. For fire researchers and investigator it is very important to assess the distribution of heat flux within the compartment. During fire in a compartment the fire plumes tends to move towards the ceiling and with time as the fire growth the hot gas layer grows thicker resulting in the formation of two zone layer. Therefore, due to hot gases the heat flux is made of both radiation and convection on the upper zone. For fire safety design concerning construction design, the building code it is very essential to emphasize the distribution of heat flux on walls, floor and ceiling. The magnitude of heat fluxes strongly depends on the dimension of the compartment, size of fire and the ventilation within the compartment. Tofilo *et al.* [16] measured the total heat flux on side walls using industrial methylated spirits (IMS) as fuel. IMS was burned in three square pans of dimension 0.2 × 0.2 m, 0.25 × 0.25 m and 0.3 × 0.3 m. Author found that the heat flux is directly proportional to gas temperature if the radiation emitted from the fire is not significant. Lee *et al.* [17] measured gas temperature and heat flux in various enclosure geometries. Empirical relations between heat flux and gas temperature has been developed from the experiments. Ohlemiller *et al.* [18] used two square propane burners in the corner of enclosure having lining material with heat release rate varied from 30 to 150 kW. Four Schmidt-Boelter heat flux gauges were used to record the heat flux incident on the wall. Lattimer [19] performed experiments using 0.17 m square propane gas burner and line burner in ISO 9705 room with heat release ranging from 25 kW to 300 kW and measured total heat flux incident on the combustible and noncombustible boundaries. Xu *et al.* [20] carried out fire test with wood cribs within compartment having dimensions of 1.4 × 1 × 0.2 m (length × width × height). Two Schmidt-Bolter total heat flux gauges were installed to record the thermal distribution in an enclosure.

From the above analysis, to the author's knowledge, less comprehensive and precise study has been done on ply board crib fire in closed compartment. The present work focuses on the burning behavior of cribs in a closed compartment, since it is the most commonly found fuel source for fires in

modern buildings, ship cabins, etc. During the experiments, various parameters like mass loss rate, gas temperature, heat flux, wall temperature, compartment pressure were measured with time lapse. In addition, the effect was also examined when sudden ventilation was supplied to the closed compartment.

## 2. Experimental set-up

The experimental compartment has been set up in Fire Research Laboratory at Indian Institute of Technology, Roorkee to study data from large scale fire tests. The internal dimension of the compartment is  $4 \times 4 \times 4$  m, walls of which are made up of normal bricks with plaster of cement and sand mortar of 3 cm on both sides, and ceiling is made up of RCC concrete 0.15 m thick. In the center of front wall there is a 1 m wide and 2 m high door opening. The schematic diagram of experimental compartment is shown in fig. 1. The cribs made up of ply board sticks were used as fire source. Sticks were  $50 \times 7.5 \times 1.8$  cm (length  $\times$  width  $\times$  thickness) in dimensions. The crib contains 20 layers, and each layer contains 4 ply board sticks. The heat of combustion of the plywood is 16.5 MJ/kg. The average weight and the average density of the sticks are 0.305 Kg and  $451 \text{ Kg/m}^3$  respectively. All tests were carried out under ambient temperature  $23 \pm 1^\circ\text{C}$  and  $65 \pm 5$  % humidity. The crib was ignited by mixture of cotton (30 g) and diesel (50 ml) which was placed at the centre underneath of the crib. The parameters of crib and experimental conditions are listed in tab.1. A digital load cell, manufactured by Vishay Nobel having a load capacity of 300 kg with least count of 5 mg is used to measure the mass loss rate, of the burning ply board cribs. Mass loss rate, heat flux, vertical gas layer temperature, flame temperature, compartment pressure were studied under two conditions:

- Compartment door closed during entire experiment of burning crib.
- Compartment door opened at 2400 s from the ignition time providing sudden ventilation to the burning crib.

**Table 1. Experimental and crib details**

Experiment label	Location	Initial mass [Kg]	Ventilation	S [cm]	$L - B - T$ [cm]	H [cm]	N	n
Test-1	Center	24.575	Closed	6.6	50-7.5-1.8	36	20	4
Test-2	Center	24.550	Ventilated at 2400 s					

To measure the total heat flux reaching at various locations such as floor, walls and ceiling, nineteen Schmidt-Boelter water cooled heat flux sensors (from Hukseflux thermal sensors), labeled as HF1 to HF19 were used. All heat flux sensors had field view of  $180^\circ$  and emissivity of greater than 0.95. The sensors labeled as HF1, HF2, HF3, HF4 and HF5 were placed on the ceiling facing vertically downward. The sensors labeled from HF6 to HF15 were placed on the wall facing the fire source and the sensors labeled as HF16, HF17, HF18 and HF19 were located on the floor facing vertically upward direction. The heat flux sensors, labeled as HF7, HF9, HF11, HF13 and HF15 which were placed at the upper portion of the compartment wall are referred as upper zone sensors in the

paper. While the sensors, labeled as HF6, HF8, HF10, HF12 and HF14 which were located at the lower portion of the compartment wall are referred as lower zone sensors.

The vertical gas layer temperature of the experimental compartment was measured by a thermocouple tree (TC) installed at the rear corner of the compartment. Twenty K-Type thermocouples of 1 mm diameter were installed with frequent vertical spacing of 0.20 m throughout the tree, the lowest thermocouple being placed at 0.05m above the compartment floor and the highest thermocouple at 3.85 m above the compartment floor. To avoid the radiation effect from the boundary layer i.e. compartments walls the thermocouples were placed 0.25 m off the side wall, 0.25 m from the rear wall of the compartment. All the thermocouples were protected with the shielding of stainless steel tubing of 5 mm diameter. To measure flame temperature, eight K-Type thermocouples were installed on thermocouple tree (TF) with spacing of 0.20 m each, the lowest being 0.20 m above the upper surface of the crib and the topmost thermocouple at 1.60 m from the upper surface of the crib.

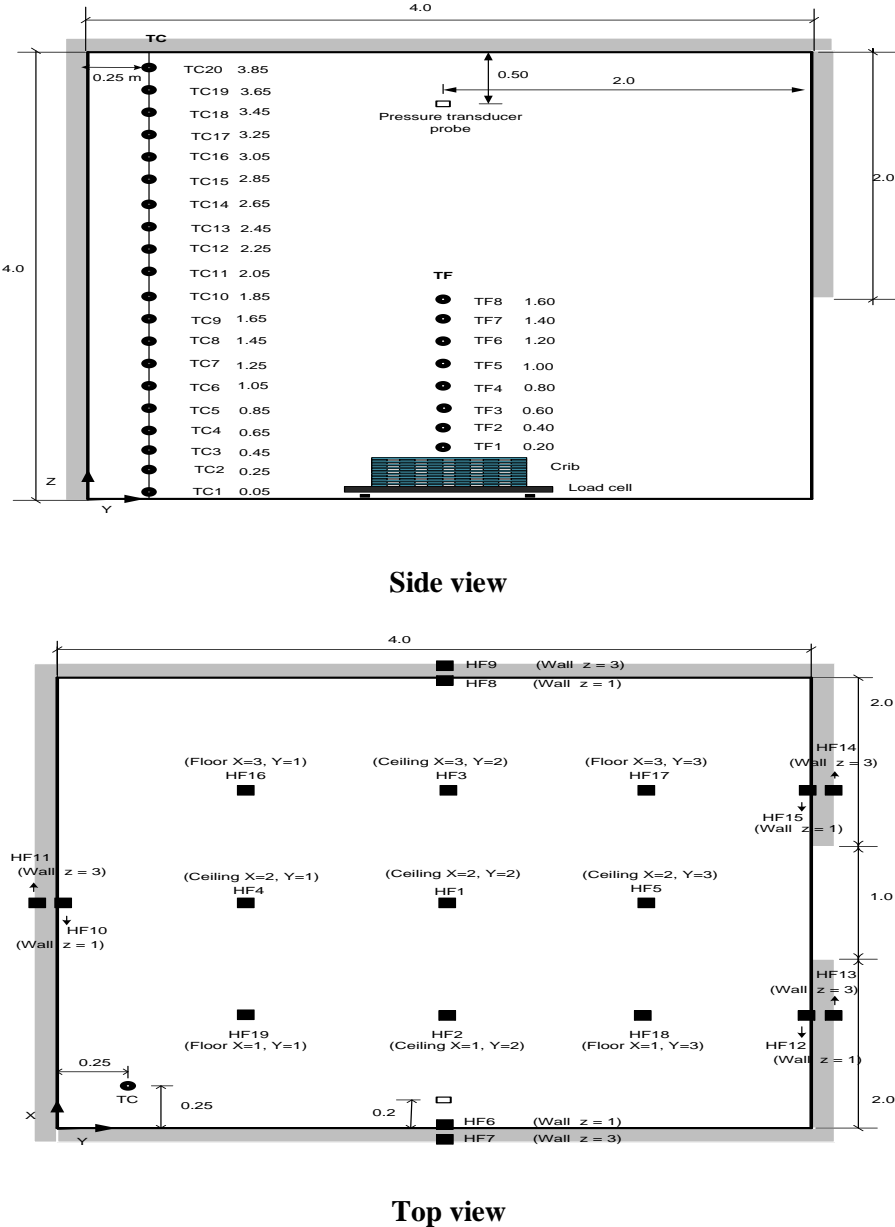


Figure 1. Schematic of experimental compartment. (All dimensions are in m)

In order to measure the compartment pressure, the pressure difference between the compartment and ambient atmosphere i.e. outside the compartment was measured. The pressure transducer (Setra Model-264) was used to measure the differential pressure. The high side of the pressure transducer was placed inside the experimental compartment. Whereas the low side was open to the ambient outside the compartment. The location of heat flux sensors, pressure transducer and temperature sensors installed in the experimental compartment are shown in fig. 1.

All heat flux sensors, pressure transducer and temperature sensors were connected to a data acquisition system from National Instruments. Lab VIEW version 10.0 was installed to acquire, display and save data from the acquisition system. Data were logged at 0.5 Hz with 2 samples per second.

### 3. Result and discussion

The experiments have been conducted in compartment of dimensions (4 m × 4 m × 4 m) to study the burning behavior of ply board cribs, under two conditions i.e. in test-1 door of compartment was kept closed throughout the experiment, while in test-2 door was opened at 2400 s to observe the effect of sudden ventilation on various parameters in compartment fire.

#### 3.1. Mass loss rate and weight loss

The growth of burning is an important parameter to design the crib fire. The burning of crib is categorized into three regimes: 1) growth period, 2) steady period and 3) decay period. After the ignition, the burning rate of the crib increases in the initial period until it reaches the steady burning stage. The growth of ply board crib is determined by exponential fitting method. Hence, the mass loss rate is fitted against the time for both the tests and is described in tab. 2 and fig 2 respectively.

$$m = Ae^{\alpha(t-t_0)} \quad (1)$$

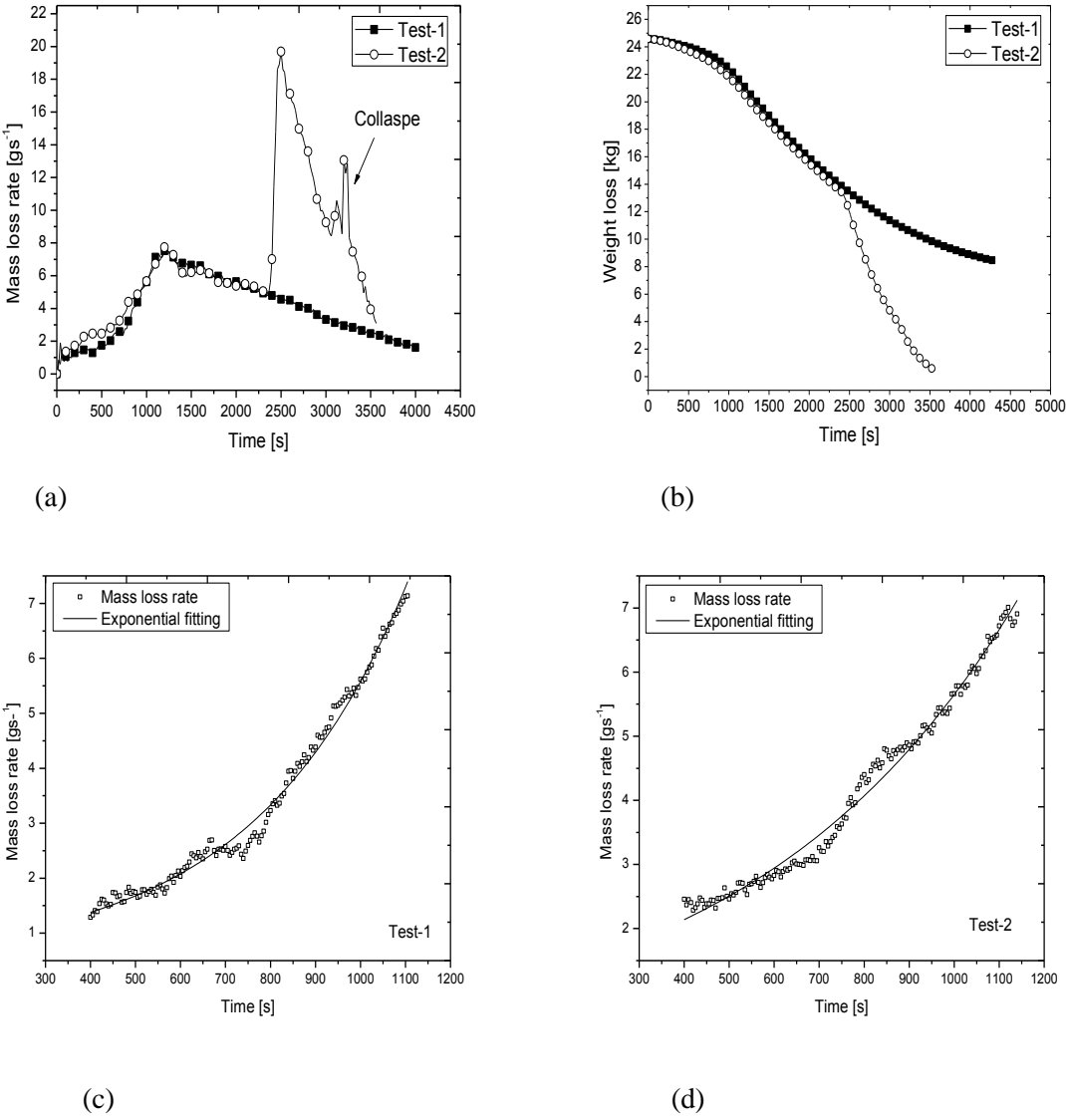
Where  $m$  is the mass loss rate, [ $gs^{-1}$ ] is,  $\alpha$  is the growth coefficient for exponential fire growth model, [ $s^{-1}$ ],  $t$  the time after ignition, [ $s$ ],  $t_0$  is the time for beginning of fire, [ $s$ ] and  $A$  is the constant parameter.

**Table 2. Summary of exponential fitting**

Experiment label	Exponential fitting ( $m = Ae^{\alpha(t-t_0)}$ )				
	$\alpha$	Std. error of $\alpha$	A	Std. error of A	$R^2$
Test-1	0.002	0.000025	0.4604	0.0111	0.9886
Test-2	0.0018	0.000017	1.1053	0.0172	0.9866

Figure 2 illustrates the mass loss rate and weight loss of ply board cribs versus time in the compartment. The variation of mass loss rate was consistent with that of fuel weight loss. Oxidising environment of compartment in initial stage of burning led to rapid growth of fire. The peak mass loss rate and heat release rate of the burning crib for the test-1 was as high as 7.9 g/s and 130.35 kW at

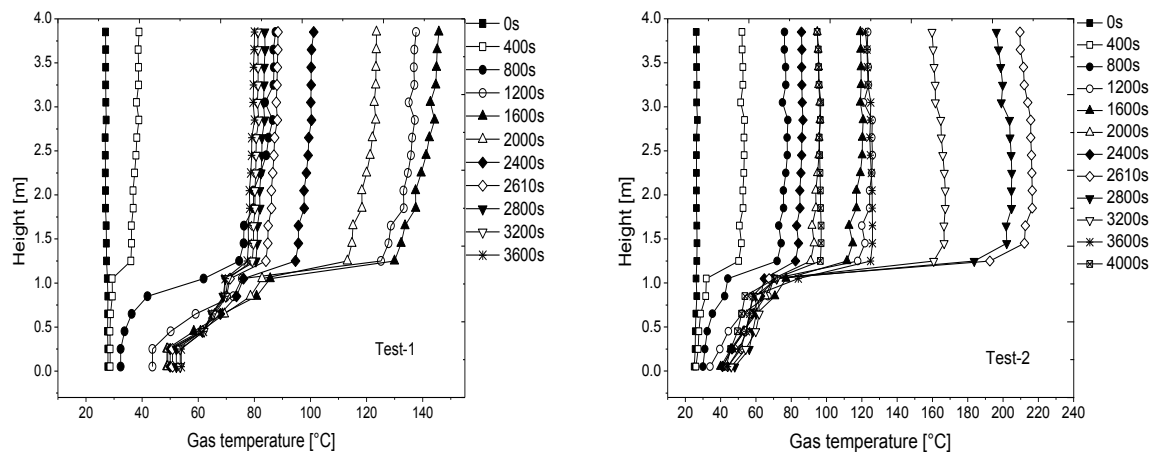
1300 s. However, after achieving the peak, decreasing oxygen concentration in the compartment led to slow combustion of fuel with a linear decay period. Similar trend was seen in test-2, until the compartment was ventilated at 2400 s, which had a great impact on the burning rate of crib. The peak mass loss rate and heat release rate achieved in test-2 before providing ventilation was as high as 8 g/s and 132 kW which was almost similar to test-1. After 90 s from the opening of door there was an exponential increase in mass loss rate which recorded to about 20 g/s at 2600s. The heat release rate was 330 kW at 2600 s. The crib collapsed at 3250 s in test-2, which was not observed in test-1. One interesting fact was noticed for crib fire was that the self extinction phenomenon did not occur, instead, cribs continued to smolder for both the tests. Weight loss was uniform in test-1 where mass of fuel reduced from 24.575 kg to 9.75 kg i.e. to 39.6 % of initial mass till 3600 s, unlike test-2 which had shown similar trend till 2400 s, but a swift decline thereafter left only 1.2% of cribs i.e. 0.3 kg remnants in the form of ash and charcoal, by the end of 3600 s.



**Figure 2. Variation of mass loss rate and weight loss curve versus time (a) Mass loss rate, (b) weight loss rate, (c) exponential fitting test-1 and (d) exponential fitting test-2)**

### 3.2. Vertical gas layer temperature

The vertical gas layer temperature was measured by twenty thermocouples placed at rear corner of the compartment. Figure 3 shows the vertical gas layer temperature profile for various time intervals. It can be seen that the gas temperature for test-1 increases with time and the maximum temperature was as high as 130 °C. The maximum gas temperature measured for test-2 was 220 °C at 2610 s, which was due to the fact that when the sudden ventilation was provided at closed compartment the fresh air injected tends to increase the combustion efficiency. Figure 3 also presents a typical two layer phenomena of the compartment fire. The interface between hot and cold gas layers lies at 1.05 m above the floor for test-2 whereas for tes-1 the interface layer was 0.45 m above floor. In both the tests, upper layer temperature rises sharply with lapse of time, while variation of temperature in lower gas layer is less conspicuous with time, which is due to the reason that the hot gas loses some momentum and thermal energy to roof on collision with it, and by formation of wall jet, moves downward along the compartment wall towards lower layer. Hence, the temperature in the lower layer was relatively on the lower side as compared to that of the upper layer.



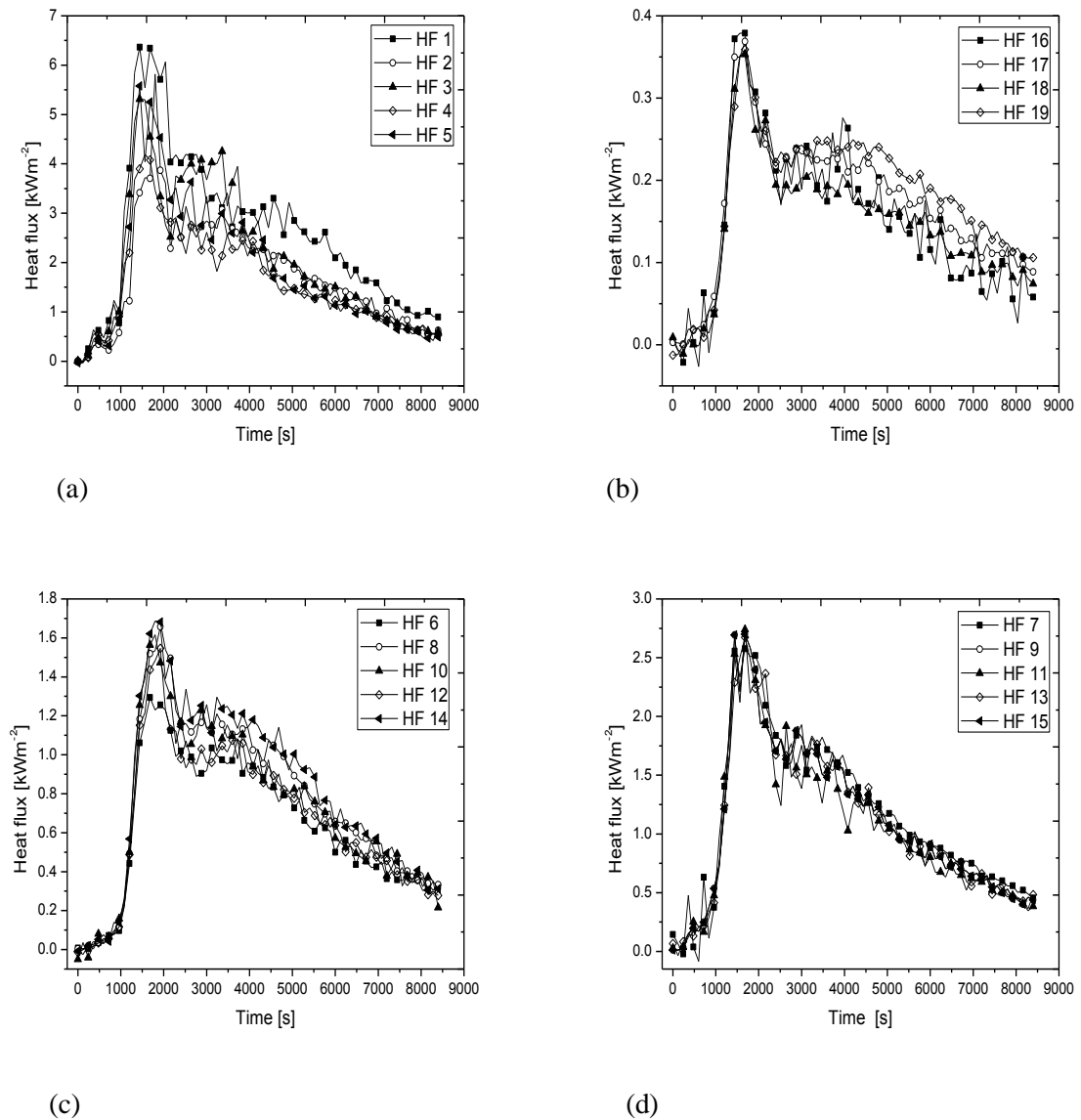
**Figure 3. Vertical distribution of gas temperature in the compartment**

### 3.3. Heat flux

Heat flux variation during compartment fire has been also studied for both tests. Heat flux was measured at ceiling, floor, upper zone and lower zone of walls by heat flux sensors, details of which has been discussed in the experimental setup section. Figure 4 illustrates the variation of heat flux at various locations in the compartment for test-1. The maximum heat flux measured in the compartment was 6.4 kW/m<sup>2</sup> at HF1, which was located on the ceiling at a point just above the fire source. Whereas the maximum heat flux recorded on the floor, upper zone sensors, and lower zone sensors were 0.38, 2.8 and 1.7 kW/m<sup>2</sup> respectively. The heat flux measured at upper zone sensors are comparatively on higher side than that of lower zone sensors which was due to the fact that the sensors located at the lower zone were dominated by radiation only whereas, the upper zone sensors were dominated by both radiation as well as convection. As the gas temperature at upper layer was significantly high than lower layer which can be seen in fig. 3.

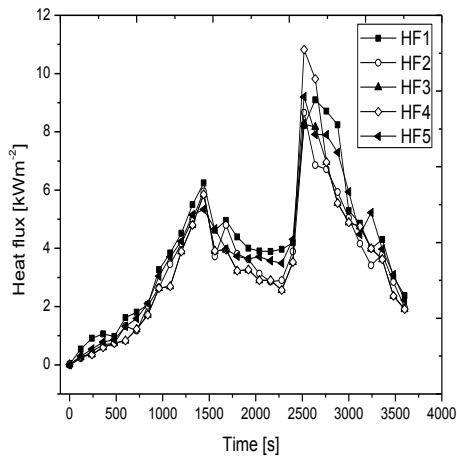
The variation of heat flux with time during sudden ventilation at 2400 s in test-2 has been presented in fig. 5, where two peaks can be seen in graph. The maximum heat flux recorded for ceiling, floor, upper zone sensors and lower zone sensors till 2400 s were 6.2, 0.4, 2.8 and 1.65

$\text{kW/m}^2$  respectively, nearly same as test-1. After opening of door, abrupt increase in the heat flux was recorded, owing to increased rate of combustion of crib, on ventilation of compartment. Unlike test-1 the maximum heat flux recorded in the compartment was  $11.2 \text{ kW/m}^2$  at HF4, while at the floor it was about  $1.3 \text{ kW/m}^2$ . The heat flux recorded at HF16 and HF19 were slightly higher than that of HF17 and HF18 although they were located on floor. This was due to the fact that the flame gets tilted towards the back on account of the sudden entrance of fresh air into the compartment. Similar reason was responsible for the higher heat flux at HF11 and HF10.

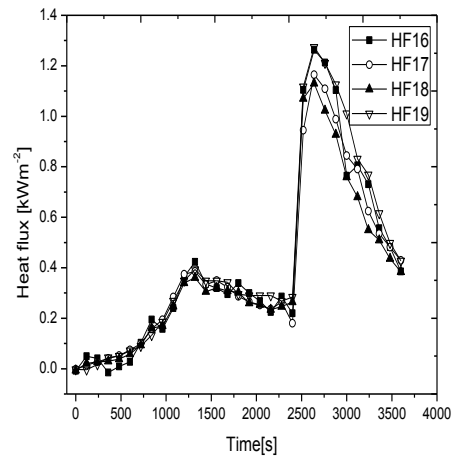


**Figure 4. Variation of heat flux versus time for test-1 (a) ceiling, (b) floor, (c) lower zone and (d) upper zone**

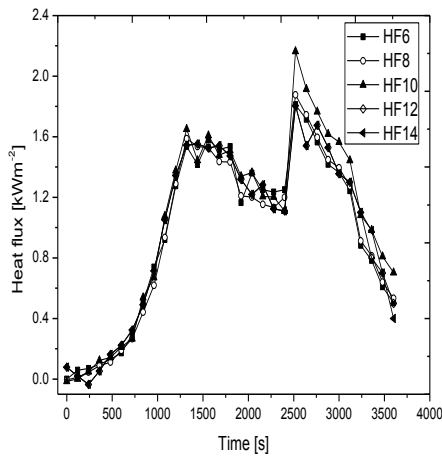




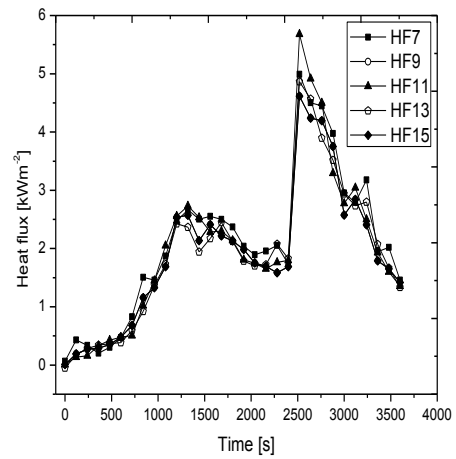
(a)



(b)



(c)

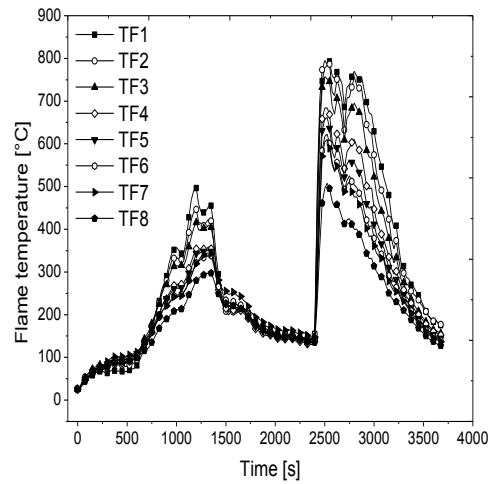


(d)

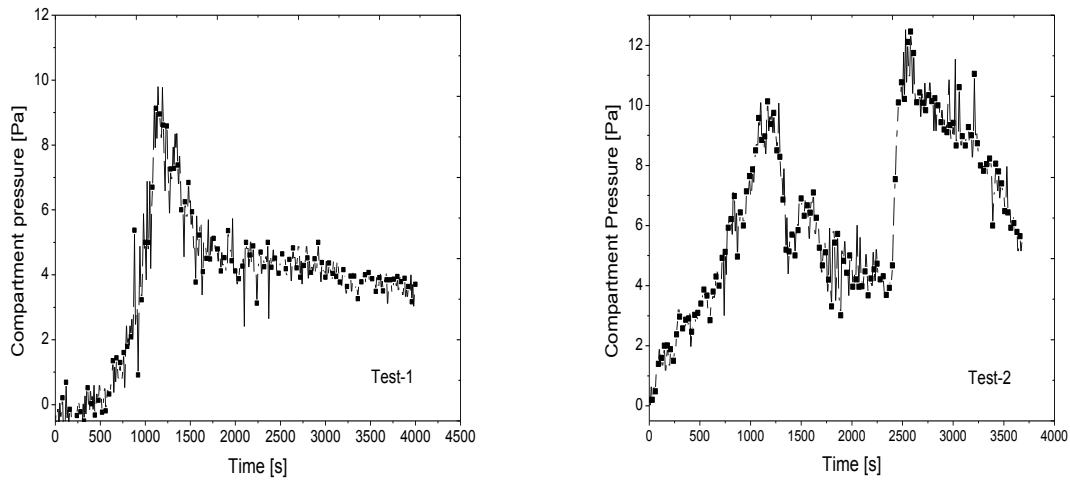
**Figure 5. Variation of heat flux versus time for test-2 (a) ceiling, (b) floor, (c) lower zone and (d) upper zone**

### 3.4. Variation of flame temperature

The flame temperatures were measured with eight thermocouples located vertically above the fire source in a thermocouple tree as shown in fig.1, reading of which has been plotted in fig. 6 showing the vertical distribution of the flame temperature with different time intervals of test-2. The curve displays two peaks one at 1320 s and other at 2550 s after the ignition. Since the supply of fresh air in the compartment was restricted by keeping it closed, the maximum temperature of the flame achieved was 500 °C, which further declined with time. This was due to the formation of char formed due to incomplete combustion of plywood sticks in scarcity of air. The charring effect was sufficiently strong enough to decrease the heat release rate. On opening door at 2400 s, there was sudden increase in the flame, due to increase in combustion, resulting in peak flame temperature to 800 °C. Moreover, exhaustion of hot gas by sudden opening of door and inlet of fresh air in to the compartment held up the charring effect.



**Figure 6. Flame temperature versus time**



**Figure 7. Variation compartment pressure versus time**

### 3.5. Variation in compartment pressure

In a fire compartment, heating of air causes difference in pressure. Hot gases having lower density rise upwards in the fire compartment, which is known as thermal buoyancy, giving rise to an upper hot smoke gas layer and lower layer comprising mainly air, leading to pressure difference. Smoke escapes via openings located high up in the compartment, the same phenomenon was seen in test-2 where opening of door led to escape of hot air by upper portion of door and inflow of cool air by lower. Variation of compartment pressure is shown in fig.7. Like all other parameters, pressure also followed the same trend in test-1 and test-2. Pressure was recorded at its peak at 1200 s in both cases which was about 10 Pa, and then it gradually declined owing to slow burning process until 2400 s in test-2 where pressure raised to 12.5 Pa. This augmentation in pressure is due to the same fact that air inflow increased combustion. But discrepancy which can be observed in pressure variation is that rate of pressure increase was not that steep as other parameters, however, rate of combustion was higher

producing more hot gases, which surpassed its effect of escape after sudden ventilation, leading to rise in pressure.

#### 4. Conclusion

An experimental study on ply board crib fire in a closed compartment was conducted, under two conditions, first the compartment was kept close throughout the experiment, and the other, the door of compartment was opened at 2400 s. Heat flux sensors, thermocouples, pressure transducers were installed to study various parameters like compartment gas temperature, fuel mass loss rate, heat flux, flame temperature, compartment pressure. The study focused on the burning behavior of the ply board crib in closed compartment as well as the effect of sudden ventilation. Study has confirmed the effect of sudden ventilation on fire, tends to increase in mass loss rate by 150 % which results in increase in heat release rate by 198 kW. Moreover, the peak of total heat flux falling at the ceiling, floor, upper zone and lower zone of the compartment has the percentage difference of 57.5, 105, 70 and 28.5 % respectively. Mass loss Rate during fire achieved a peak and started declining until door was opened, where it not only increased manifold times, but also declined later sharply owing to complete burning up of fuel. The same was confirmed by weight loss curve, where complete combustion has left only 1.2 % of mass of cribs. Gas Temperature has invariably increased throughout the experiment, though the rate of increase was different in lower portion of compartment as compared to that of upper, attributable to gas buoyancy of hot air leading to accumulation of hot air towards ceiling. From the perspective of these parameters fire could be less hazardous and destructive when compartments are not ventilated all of a sudden. The data generated in the present study can be utilized for validation of the field model.

#### Acknowledgment

The present work is supported by the Bhabha Atomic Research Centre (BARC), Mumbai. The authors are indebted to Prof. Akhilesh Gupta, Prof. Surendra Kumar, Dr. Ashok Kumar Gupta, Prof. Shashi and Mr. Pawan Kumar Sharma for helpful discussion.

#### Nomenclature

$A$	- constant parameter.
$B$	- width of stick, [cm]
$H$	- height of the crib, [cm]
$L$	- length of stick, [cm]
$m$	- mass loss rate, [ $\text{g s}^{-1}$ ]
$N$	- number of layer, [-]
$n$	- number of sticks per layer, [-]
$R$	- correlation coefficient, [-]
$S$	- stick spacing, [cm]
$T$	- thickness of stick, [cm]
$t$	- time after ignition, [s]
$t_0$	- time for beginning of fire, [s]
$\alpha$	- growth coefficient for exponential fire growth model, [ $\text{s}^{-1}$ ]

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