The

Dissertation report

on

EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS OF POOL FIRE IN A COMPARTMENT

by

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Master of technology

In

Thermal Engineering

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CANDIDATE’S DECLARATION

I hereby declare that the work carried out in this seminar titled “**EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS OF POOL FIRE IN A COMPARTMENT”** is presented on behalf of partial fulfillment of the requirement for the award of the degree of **Master of Technology** with specialization in **Thermal Engineering** submitted to the department of **Mechanical & Industrial Engineering, Indian Institute of Technology Roorkee, India**, under the supervision and guidance of **Dr. Akhilesh Gupta** and **Dr. Ravi Kumar** (Professors MIED, IIT Roorkee, India).

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

DATE – 25 June 2019	**RAVI SHANKAR PANDAY**
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CERTIFICATION

This is to certify that the above statement made by candidate is correct to the best of my knowledge and belief.

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ABSTRACT

Burning behavior of any fuel is very important parameter for the fire hazard assessment in any industry or home. Study of burning behavior of fuel will help to understand the behavior of fire in different condition.

An experimental set-up is designed and fabricated in fire research laboratory to investigate and analysis of burning characteristics of different kind of solid as well as liquid fuel. Experiments are carried out in a compartment of dimension of 4× 4× 4 and having a door of 2×1. In fire compartment fuel is burnt in small as well as large scale and energy analysis is carried out. Different burning characteristics of fuel like Heat release rate, study of combustion products concentration like O_2, CO_2 are measured by gas analyzer and temperature, heat flux reaching at various locations are measured by thermocouples and heat flux sensors respectively. The result which we are going to get after experiment will help in to control the fire hazard.

In this thesis the experiment has been done on solid fuel involving mango wood crib of stick size of 50 cm length and 5×5 cross section.

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CHAPTER 1 INTRODUCTION

1.1 GENERAL

Physical experiments are necessary to understand the fire dynamics and its applications. For the last few decades efforts have been made consistently to investigate the basic phenomena involved in fire and the possible variables to develop engineering approach accordingly to predict the course of fire and response of fire safety measures to fire. The study of basic mechanism of fire growth, fire spread and flashover are the main objective here. The fire model can be a physical model or a mathematical model According to The American Society of Testing and Materials (ASTM E 603-77). A rapid development in theoretical modelling of fire has been simulated with the evolution of modern computing systems. The fundamental principles of conservation of mass, momentum and energy based mathematical fire models are quite general in nature. Once we validate mathematical fire models with experiments then it can be used to predict the complete fire environment in economic manner as well as in less time. Further we can classify mathematical models in two probabilistic and deterministic models. But probabilistic models are difficult to use because it is difficult to obtain the reliable value of probability. Deterministic models are preferred as it can predict the behavior of fire if we have defined the environment. The benefit of mathematical fire model is that it can predict the hazardous condition of fire and suggest the preventive measures well in advance. On the other hand Physical models are experimental models created to study and investigate the different variables and parameter involved in enclosure. Physical models may be same or may be scaled version of original fire conditions like reduced scale and full scale. Physical models or experimental models are can create the same condition which we are going to face in a accidental fire conditions. The data which are produced in experimental models are applicable in particular condition hence can not be generalized. We prefer reduced scale physical models due to its low cost of experimentation and better control on experiments. We need physical models to evaluate the applicability of mathematical models. It is important to validate the mathematical models with the large number of experiment results which are generated from physical models. Figure 1.1 will give us idea about different models we can take to investigate the fire development in an enclosure which are mostly used in fire safety area.

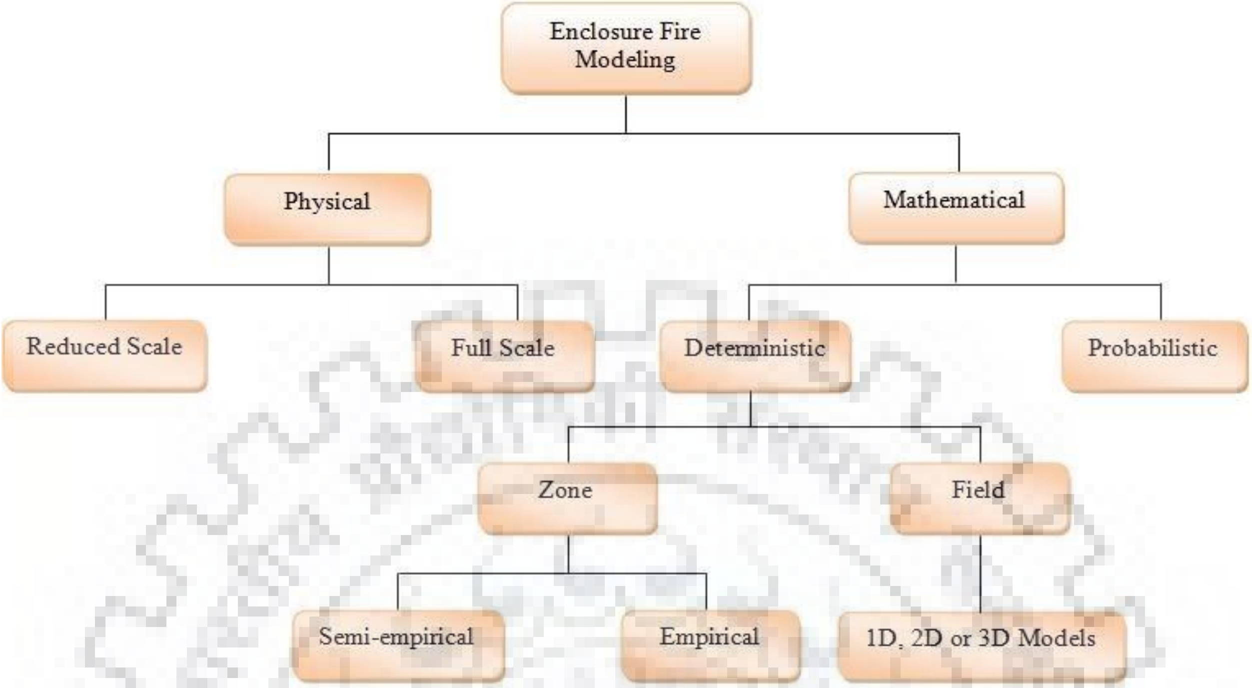

Fig 1.1 (Different fire modelling)

“Fire is a physical and chemical phenomenon that is strongly interactive by nature. The interactions between the flame, its fuel and surrounding can be strongly nonlinear and quantitative estimation of the process involved is often complex”. The enclosure fire mainly involves mass fluxes and heat fluxes to and from the flame and surroundings.

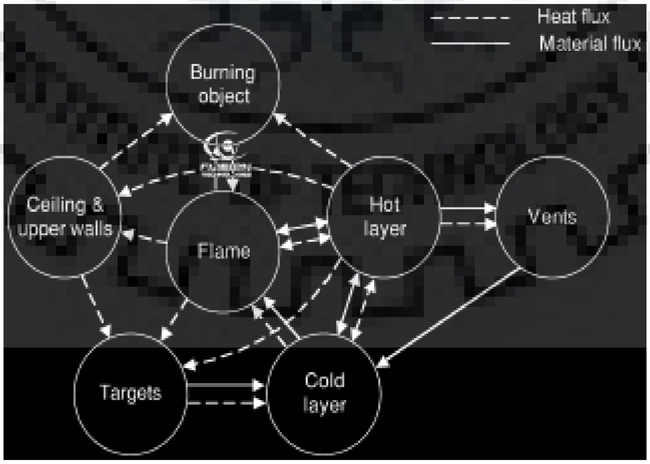

Fig 1.2(Heat and mass fluxes occurring in enclosure fire)

1.2 BACKGROUND

A compartment fire is a fire which is confined in a space or a room in a building where the supply of ambient air and the condition inside the room is controlled by the ventilation provided to the fire. Over past decades several experiments have been performed to analyze the fire dynamics of compartment fire. The fire source that are commonly used are wood crib due to their easily availability and low cost. Ingberg (1928). Kawagoe (1958) performed many fire experiments in reduced as well as full scale enclosure for wood crib fire specially for fuel load and fire severity.

Theoretical relationships between burning rate and ventilation have been found also. He additionally discovered that the burning rate isn't just reliant on the ventilation, yet in addition a component of ventilation height also. In view of various exploratory information the absolute first theoretical model was created by Kawagoe and Sekine (1963, 1964) for post-flashover fires which allowed the assurance of compartment gas layer temperature from the fire load, ventilation factor, and thermal qualities of the compartment limits. Magnusson and Thelandersson (1970) proposed an improved model which permitted evaluating the fire development, ignition characteristic and temperature of compartment using cellulous fuel at various ventilation.

1.3 ORAGNISATION OF THESIS

The Thesis consists of five chapters which includes following topics.

Brief introduction of fire dynamics of compartment fire, computation fluid dynamics and present research work objective comes under chapter 1.

Detailed literature review of theory of compartment fire and fire dynamics are given in chapter 2. Historical prospect of compartment fire is presented.

Experimental facility present in fire research laboratory are presented in chapter 3. Detailed configuration and set up are discussed. Principles on which different facilities are working are discussed in details. Instrumentations installed to measure many parameters such as fuel mass loss rate, compartment gas temperature, vertical flame temperature, heat flux, concentration of CO ,O_2, and CO_2, compartment differential pressure, and outgoing gas temperature are presented.

Detailed configuration and set up are discussed in chapter 4.

Detailed discussion of experimental results are presented in chapter 5. Many parameters such as burning characteristic of wood crib, ventilation effect on burning behavior and compartment environment. Energy balance investigation of compartment.

Chapter 6 focuses on conclusion of report and summarizes the major findings of experiments. Scope of future work is provided too.


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1.4TERMINOLOGY

1.4.1 Backdraft : Large amount of unburned gases are produced with limited ventilation. Introducing a opening suddenly will lead to mixing of incoming air with these and creates some combustible mixture. Any ignition source will ignite this mixture resulting in very rapid fire burning.

1.4.2 Flashover : Flashover is “A rapid transition to a state of total surface involvement in a fire of combustible material within enclosure”. It is a demarcation point between pre flashover and post flashover fire.

1.4.3 Fuel controlled fire : After ignition during initial fire growth stage fire is said to be fuel controlled because there is sufficient oxygen available for combustion. In later stages also fire can be fuel controlled.

1.4.3 Fully developed fire : Fully developed fire is the stage of fire in which entire fuel is participating in fire after flashover.

1.4.4 Ventilation controlled fire : After sometime fire may become ventilation controlled fire because there is not sufficient amount of oxygen present to combust most of the fuel. In this condition heat release rate is calculated based on the amount of oxygen which entered in enclosure through openings.

CHAPTER 2 LITERATURE REVIEW

2.1 BASICS OF COMPARTMENT FIRE

Fires which occurs in confined spaces like rooms in buildings, vessels in transportation ships, planes, compartment of trains etc. Development of fires in such geometries depends on fuel load, compartment geometry, sources of ignition and ventilations. Therefore the development of fire can be classified in various stages.

2.1.1 Stages of compartment fire :

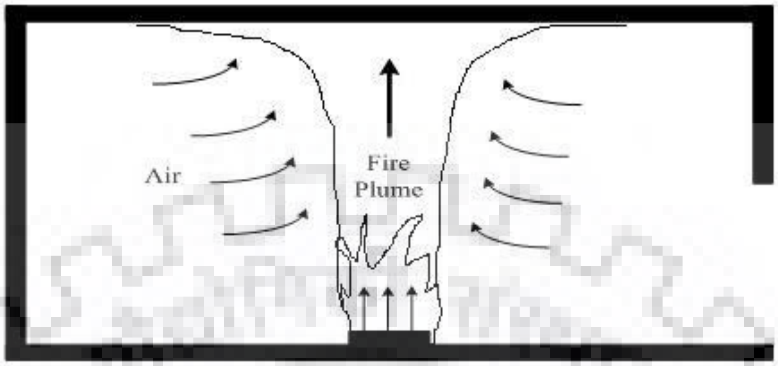
Followings are the stages in fundamental development of compartment fire (Walton and Thomas, 1995)

Ignition : Ignition which is exothermic reaction can occur either spontaneously or through piloted ignition. Configuration and characteristics of fire are the main factor on which development of fire depends after ignition. Adjacent fuel surface gets heated by radiant heat flux once the fuel gets ignited and thus pyrolysis proceeds.

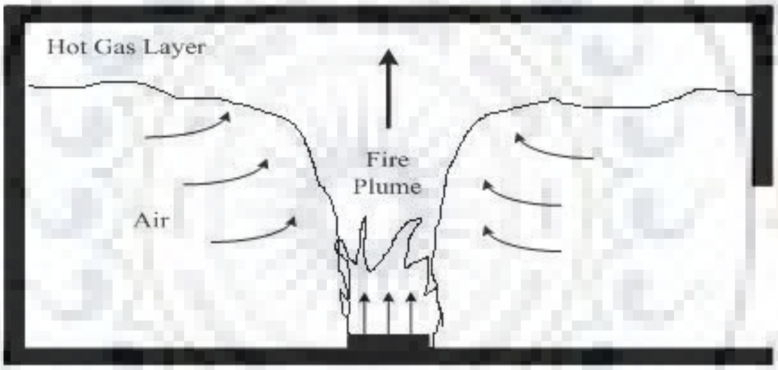
Growth : Type of combustion, enclosure geometry, fuel and oxygen supply are the main contributors in fire growth. It is difficult to predict fire growth phases because the availability of fresh air is required sufficiently. The best period to control or extinguish the fire in enclosure is growth phase. As the fire develops it produces fire products and the energy release rate increases constantly as the burning rate increases. According to Heskestad (2001),”The growth phase of fire is generalized as a t-squared fire, which is considered that the heat release rate of the fire (HRR) increases with the square of the time” as given below

$$Q = \alpha t^2 \tag{2.1}$$

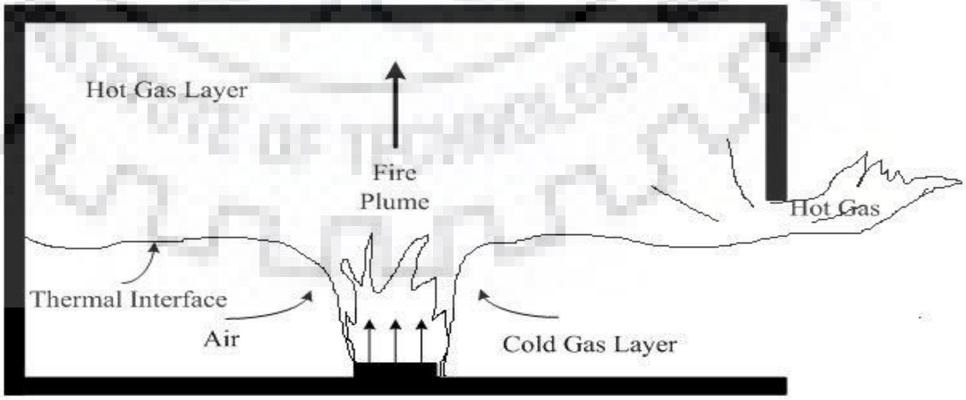
where α is the growth rate coefficient (kW/s^{2}), t is time (s) and $\dot{Q}$ is the heat release rate(kW



a. Initial stage



b. Growth stage



c. Fully developed stage

Figure 2.1 compartment fire development stages

Flashover: Sudden transition between growth phase and fully developed phase is known as flashover. The definition of flashover is “the transition from a localized fire to the general configuration within the compartment when all fuel surface are burning” (Drysdale, 1985).

Fully developed: After flashover period there comes fully developed phase in which gas temperature in the compartment and heat release rate is maximum.

Decay : When fully developed phase occurred then after that decay phase comes in which heat release rate and gas temperature in the compartment will be in declining phase as the fuel has been consumed. The reason of decay phase can be suppression, scarcity of oxygen and combustible material consumption.

2.1.2 Factors influencing fire development in a compartment :

The major factors which influences the development of fire in a compartment are briefly as follows

Fuel supply: Fuel supply is one of the major factors involve in development of a fire. In modern building fires combustible materials are mainly solid like furniture and fittings, cellulous, surface lining etc. Liquid fuel as well as gaseous fuel can be found in different industrial applications. The fuel packaging that is the distance between near by fire source and type of fuel affects the growth of fire.

Compartment geometry: The fire growth is also affected by the shape and size of compartment. As the flames develops and reaches the roof of compartment and spread out under the roof of compartment results in upper hot gas layer formation. As the temperature of upper gas layer increases it radiates more heat to lower cold gas temperature resulting in increase burning rate of fuel. The temperature of ceiling, walls have significant impact on fire development because same fire source in a small compartment will increase the temperature of walls very rapidly compare to large enclosure and large compartment will have slow fire growth.

Ventilation: The sufficient level of oxygen is very important for continuous growth of fire. In small enclosure as the fire develops the available oxygen is consumed and until there is intake of fresh oxygen from outside is present the self extinguishment phenomenon takes place or continue to occur at slow rate. In general there is sufficient leakage in any compartment for the entry of fresh air around vents. The geometry and position of ventilation are very important in compartment fires. If there is a condition of over ventilation in fire then the fire spread is less because entry of excessive air causes cooling of fire plume.

Location of fire: Fire growth rate depends largely on location of fire too. The growth and burning phenomenon of fire which is located at center of compartment is different than the fire located in corners of the compartment. Center located fire has better entrainment of air than corner fires because in corner fires the air flow is restricted by the surrounding walls.

Construction materials: Construction materials of compartment also have great impact on development of fire as depending of thermal properties of material different material response differently for same fire source. Like Gypsum and calcium silicate have large heat absorbing capacity so absorb large amount of heat before being heated up results in lower gas temperature in compartment. On the other hand materials like steel heat rapidly and transfers heat to fuel source resulting in high burning rate.

2.2 COMPARTMENT GAS TEMPERATURE :

Several correlations have been proposed to calculate the compartment gas temperature by many researchers. Some of them are discussed here –

McCaffrey et al. (1981):

Applying the basic law of conservation of energy on the upper hot gases layer within the compartment volume at a uniform temperature and the equation is as follows

$$\dot{Q} = \dot{m}_g c_p (T_g - T_a) + q_{loss} \tag{2.2}$$

where, Q is the total heat release of the fire (kW), $\dot{m}_g$ is the mass flow rate of hot gases out through the compartment opening (kg/s), c_p is the specific heat capacity of the gas (kJ/Kg.K), $T_g$is the upper hot gas layer temperature (K), $T_a$is the ambient air temperature (K) and q_{loss} is the heat transfer from the upper hot gas layer temperature in form of radiation and convection (kW).

In the Equation (2.2), the left hand side is the total heat released rate of the fire and on the right hand side, it is the sum of net heat loss through the compartment opening and the net radiative and convective heat transfer from the upper hot gas layer to the compartment boundaries. The radiative and convective heat transfer to the boundaries is approximately equal to the rate of heat loss from the compartment boundaries to the ambient in form of conduction and is expressed as follows

$$q_{loss} = h_k A_T (T_g - T_a) \tag{2.3}$$

where, h_k is the effective heat transfer coefficient (kW/m.K) and A_T is the total surface area the compartment boundaries (m^2).

From Equations (2.2) and (2.3) the non dimensional temperature rise can be written as in form of two dimensionless terms:

$$\frac{\Delta T_g}{T_a} = \frac{\dot{Q}}{\dot{m}_g c_p T_a + h_k A_T T_a} = \frac{\dot{Q}/(c_p T_a \dot{m}_g)}{1 + h_k A_T/(c_p \dot{m}_g)} \tag{2.4}$$

where, ΔT_g is the rise in the upper hot gas layer temperature $(T_g - T_a)$ (K).

The fire experiments were performed under different opening geometries, which includes height of the compartment varies in the range of 0.3 m to 2.7 m and the compartment floor area ranging from 0.14 m^2 to 12.0 m^2. The constant $2/3$ is the ratio of the heat release rate of the fire to the heat transferred through convection and the constant $-1/3$ represents the ratio of the total heat loss and heat loss through convection. Based on several compartment fire experiments for both transient fires and steady-state fires involving wooden cribs, cellulosic materials and several hydrocarbon fuels, the constants 480, 2⁄3 and −1⁄3 were derived. The Equation 2.4 can also be:

$$\Delta T_g = 480\left(\frac{\dot{Q}}{\sqrt{g}c_p\rho_a T_a A_o\sqrt{H_o}}\right)^{2/3}\left(\frac{h_k A_T}{\sqrt{g}c_p\rho_a A_o\sqrt{H_o}}\right)^{-1/3} \tag{2.5}$$

where, A_o is the area of compartment opening (m^2) and H_o is the height of compartment opening (m). By substituting the values of ambient conditions of g = 9.8 m/s^2, c_p = 1.05 kJ/kg.K, ρ_a = 1.2 kg/m^3 and T_a = 295 K into Equation 2.5 its becomes

$$\Delta T_g = 6.85\left(\frac{\dot{Q}^2}{A_o\sqrt{H_o}h_k A_T}\right)^{1/3} \tag{2.6}$$

The heat transfer coefficient h_k is a function of thermal characteristics of the compartment boundaries and is determined as follows

$$h_k = \frac{\kappa}{\delta} \quad \text{for} \quad t > t_p \tag{2.7}$$

$$h_k = \left(\frac{\kappa\rho c_p}{\delta}\right)^{1/2} \quad \text{for} \quad t \leq t_p \tag{2.8}$$

Where t is exposure time(s) and t_p is penetration time(s). Thermal penetration time is the minimum amount of time required for a thermal pulse to Penetrate the boundaries. It is determined by treating the boundaries as semi-infinite solid wall. The dimensionless time parameter, i.e. Fourier number for semi-infinite solids may be taken as follow

$$\frac{\alpha t_p}{\delta^2} = \frac{1}{2} \tag{2.9}$$

Where α is thermal diffusivity thus,

$$t_p = \left(\frac{\rho c_p}{\kappa}\right)\left(\frac{\delta}{2}\right)^2 \tag{2.10}$$

The correlation given by McCaffrey et al. (1981) was validated by Delichatsios et al. (2009). The correlation for determining upper hot gas layer temperatures has several limitations which are as follows:

1. The correlation is valid for determining compartment hot gas layer temperatures up to 600^{o}C.
2. It cannot be applied for large scale compartment fires which involve rapid fire growth and also the phenomenon of fire growth has occurred before the combustion materials have exited the enclosure.
3. The heat release rate of the fire, $\dot{Q}$ is to be determined from the experimental data from empirical correlations.
4. The correlation is valid for centrally placed fires. The effects of combustible wall linings and large ventilation openings were not considered.

Foote et al. (1986) :

They introduced correlation for determining the compartment gas temperature for forced ventilation fires using basic correlation of McCaffrey et al. (1981). The correlation was derived from Equation (2.11) in which the expression for mass flow rate across compartment opening was excluded

$$\frac{\Delta T_g}{T_a} = 0.63\left(\frac{\dot{Q}}{\dot{m}_g c_p T_g}\right)^{0.72}\left(\frac{h_k A_T}{\dot{m}_g c_p}\right)^{-0.36} \qquad (2.11)$$

The constants 0.63, 0.72 and -0.36 are derived from fire experiments performed under well-ventilated compartment having dimension of 6 m length, 4 m width and 4.5 m height with ventilation rates in the range of 110 to 325 g/s. The hot gases and the combustion products are exhausted through a duct of 0.4225 m^2 located at a height of 3.6 m above the compartment floor and a opening of 0.06 m^2 was located for the inlet of ambient air. A centrally located methane burner was used as fire source and generated HRR in the range of 150 to 490 kW resulted in the upper gas layer temperature of 100 to 300 ^{o}C.

Mowrer and Williamson (1987) :

They modified the correlation proposed by McCaffrey et al. (1981) to predict the upper hot gas layer temperature for fires placed near the walls and in corners. Because of the fires at corners and along the walls, the rate of entrainment is restricted causing higher temperatures than that of prediction from McCaffrey, Quintiere, and Harkleroad (MQH) correlations which are applicable to fires placed at the center of the compartment. Analyzing the experimental data collected for a wide range of HRR in the standard room fire test compartment ASTM standard E 603-77 (1985), it was found that the predicted temperature difference by the M-Q-H formula should be multiplied by a factor of 1.7 for fires located at the corners and by a factor of 1.3 for fires located near against the walls. The usefulness of the modifications has been confirmed by performing fire experiments in an enclosure having dimensions of 2.44 m length, 3.66 m width and 2.44 m height having a door opening of size 2.03 m high and 0.76 m wide. The fire was generated using 0.3 m^2 propane burner located at a height of 0.3 m above the floor. It was observed that the predictions of modified correlation were in better agreement than that of M- Q-H correlation.

Deal and beyler (1990) :

They correlated several existing empirical expressions for determining compartment gas temperature with fire experimental data base derived from over 250 compartment fire experiments and found that compartment with single opening well-ventilated fires, the correlation proposed by McCaffrey et al. (1981) gives better results for predicting gas temperatures. Further, based on simple energy balance a correlation (Equation 2.12) was proposed for forced ventilation compartment fires where the ventilation rate

$$Q = \dot{m}_g c_p (T_g - T_a) + h_k A_T (T_g - T_a) \tag{2.12}$$

The rearrangement of Equation (2.12) in terms of upper gas layer temperature rise ΔT_g (K) yields

$$\Delta T_g = \frac{\dot{Q}}{\dot{m}_g c_p + h_k A_T} \tag{2.13}$$

A new correlation was developed for determining effective heat transfer coefficients:

$$h_k = 0.4max\left(\sqrt{\frac{k\rho c}{t}}, \frac{k}{\delta}\right) \tag{2.14}$$

2.3 CRIB FIRE EXPERIMENT :

Wood cribs are commonly used fire source to generate experimental fires either independently or for the ignition of other combustible fuels. Wood cribs fire has a phenomenal quality to duplicate itself in various burning conditions and it is a good source of fire which has good repeatability. Wood and cellulose materials are now a day widely used for furniture in modern buildings, offices and households. The burning behavior of the wood cribs is closer to the real fire development in compartment as compare to other combustible materials. The free burning of wood cribs was first reported by Folk (1937). The research of Folk (1937) focused at quantifying the effectiveness of different means for extinguishment of fires. Several fire experiments were performed using cross piles of wood sticks to study the different means of fire extinguishments. The crib was formed by air-dried fir sticks of uniform geometry and was ignited using a small pan of gasoline place underneath of the cribs.

Analyzing the results of experiments performed with varying the orientation and number of the sticks it was concluded that the better reproducibility of burning cross piles of wood sticks can be achieved by maintaining the constant density and moisture content of sticks for each experiment. Alignment of successive layers of sticks perpendicular to the other layers, repeatable orientation of the pile and maximum access of fire extinguishing agent to the surface of the wood piles can be achieved. The arrangement of piles of wood sticks made by Folk (1937) latter known as wood cribs. Prior to performing fire experiments to investigate extinguishment phenomena of wood cribs, transient mass loss of burning wood cribs data were collected by visual observation of an weight scale. The mass loss rate curve was also determined using the transient mass loss data which are presented in Figure 2.2

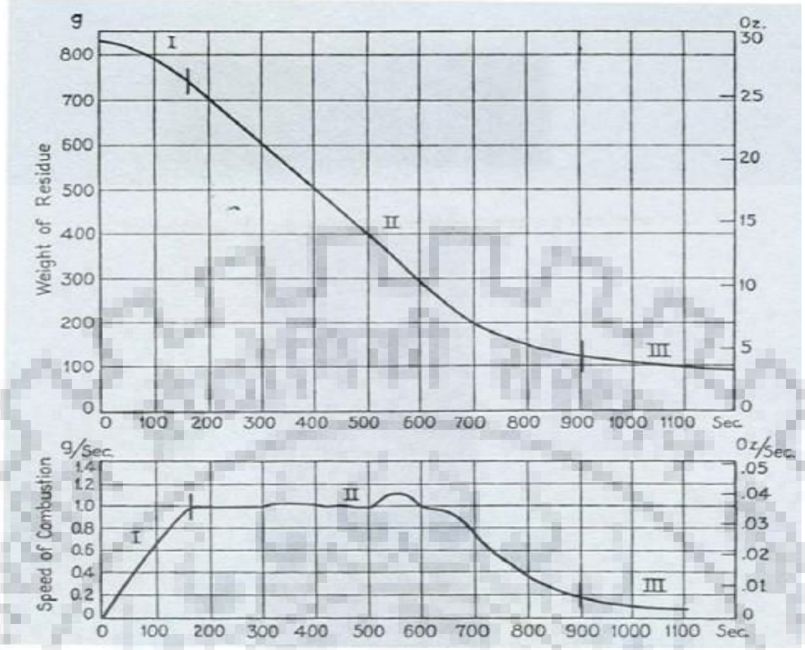


Figure 2.2 Transient Mass loss and mass loss rate curve (Folk, 1937)

Visualizing the mass loss curve of the burning wood cribs Folk categorized the curve into three stages. The ignition of the wood crib was identified as the initial stage. The second stage is that at which the mass loss rate of the burning crib is relatively constant and is identified as steady state burning stage followed by the final stage. At the final stage, the fire starts decaying and referring to the crib fires; it is commonly known as smoldering stage. During the steady state burning stage a short-lived peak is described as the period at which an optimal mixture of air and fuel for combustion is achieved.

2.4 MASS LOSS RATE :

The modeling of mass loss rate is an important parameter to be studied for compartment fire.

Ventilation controlled : Kawagoe and Sekine (1963), conducted several experiments within the compartment varying the ventilation size to measure the mass loss rate of the wood cribs and found that the mass loss rate was directly proportional to the shape and size of the vent, and introduced a term called ventilation parameter $A_0\sqrt{H_0}$. From the experimental data, the constant of proportionality was found to be 0.092 kg/s/m$^{2.5}$ and 5.5 kg/min/m$^{2.5}$ and given in Equations (2.15) and (2.16) respectively.

$$\dot{m}_f = 0.09A_o\sqrt{H_o} \quad \text{kg/s} \tag{2.15}$$

or

$$\dot{m}_f = 5.5A_o\sqrt{H_o} \quad \text{kg/min} \tag{2.16}$$

These Equations have been widely cited and frequently used to measure the mass loss rate of wood cribs when burn in ventilation controlled compartment (Harmathy, 1972 and Drysdale, 1985). Thomas and Heselden (1972) and Thomas (1974) found that the numerical constant between vent parameter $A_0\sqrt{H_0}$ and mass loss rate lies in a good range only for limited range of values of vent parameter. The entertainment of mass flow rate of air into the compartment strongly controls the burning rate of the fuel. However, for compartment having large opening area a period will occur when the burning rate of the fuel subsequently becomes independent of the shape and size of the vent opening. Law (1983) introduced the enclosure aspect ratio- height to width ratio and total surface area of the compartment, D/W and A_T linked with $A_0\sqrt{H_0}$ and mass loss rate of fuel surface area of the Law (1983) linked the vent parameter, mass loss rate of fuel, $\dot{m}_f$ gave a correlation know as law correlation:

$$\dot{m}_f = 0.18A_o\sqrt{H_o}\left(\frac{W}{D}\right)^{0.5}\left(1 - e^{-0.036\left(\frac{A_T - A_o}{A_o\sqrt{H_o}}\right)}\right) \tag{2.17}$$

Porosity Controlled:

Extensive work has been done for analyzing the burning rate of wood crib. Notable research which includes that of Gross (1962) who used same species of wood (douglas fir) for majority of his experiments in an effort to keep the density of the sticks as constant as possible. In order to maintain the content of moisture, prior to experiments the sticks were maintained at 23^0C and 50% humidity until the moisture percentage reached to 9.2%. Square cross section stick having its length equal to 10 times its thickness was used. Further for his crib arrangement he gave the following nomenclature which has been widely used was $l - b - n - N$, where l is the length of the stick, b is the cross section of the stick, n is the number of sticks per layer, and N is the number of layers. A schematic of the gross experimental arrangement is shown in Figure 2.3.

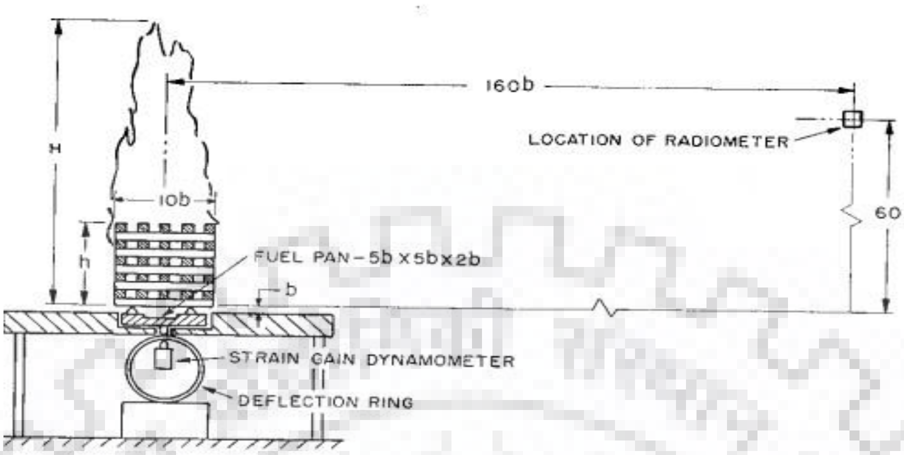


Figure 2.3 Gross experimental arrangement (Gross, 1962)

The crib was ignited by heptane which was placed in a square metal pan placed below the crib. The fuel pan was smaller than the cross section area than the crib and distance between fuel pan and the crib was maintained by the distance equal to that of stick thickness. He noted that type of the fuel which was used as initial ignition of the crib least affect the burning of the crib only the quantity of the fuel affects the initial burning of the crib. Similar to the finding of Folk's he also identified the three stage of burning. From the series of experimental data he concluded that the internal air flow within the wood crib was due to an empirical parameter, φ which is defined as the porosity factor of the crib. To determine the porosity of the crib, he derived the total exposed surface area of the crib (A_s) and the total cross-section area of the vertical crib shafts(A_v).

$$A_s = 2nb^2[N(2L-n)+n] \tag{2.18}$$

$$A_v = b^2(10-n)^2 \tag{2.19}$$

$$\varphi = N^{0.5}b^{1.1}\frac{A_v}{A_s} \tag{2.20}$$

With less crib porosity the peak mass loss rate was decreased due to insufficient air flow through the vertical shafts of the crib. The test data from Gross (1962) experiments and Flok (1937) are showed in Figure 2.4.

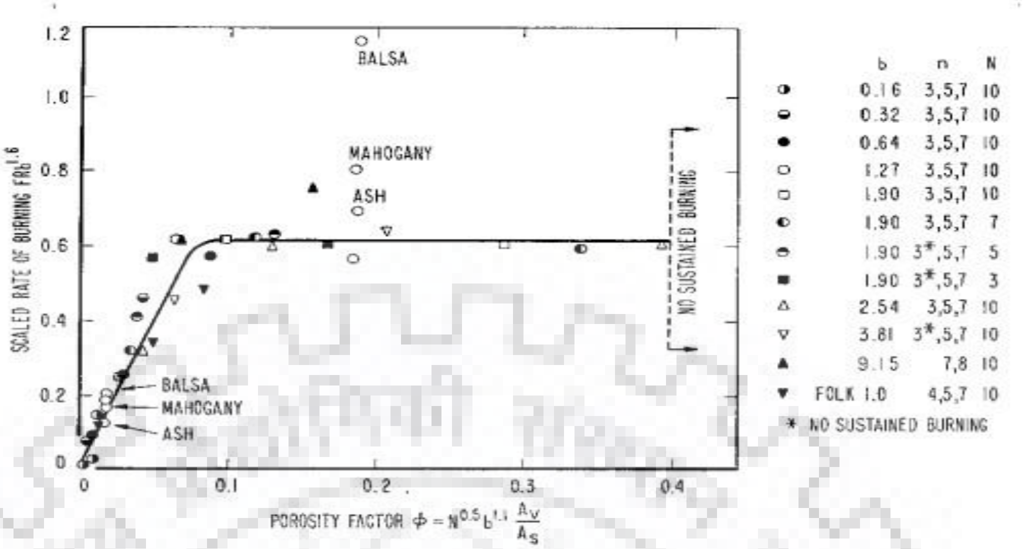


Figure 2.4 Crib porosity effect on scaled crib burning rate (Gross, 1962)

From the above figure three regions of combustion are identified. For the first region when the crib is burned with low porosity the combustion of crib is diffusion limited. The second region the crib porosity becomes independent of the burning rate and for the third region when the porosity is further increased a point reaches when the sticks burn individual and become incapable of burning as a unit.

Fuel Surface Controlled:

Not all post-flashover fires are ventilation-controlled. The rate of burning may sometimes be controlled by the surface area of the fuel, especially in large, well ventilated rooms containing fuel items which have a limited area of combustible surfaces. In this case, the rate of burning will be similar to that which would occur for the fuel item burning in the open air, with enhancement from radiant feedback from the hot upper layer of gases or hot wall and ceiling surfaces. Depending on the fuel location, most fires become fuel-controlled in the decay period when the exposed surface area of the fuel decreases and the thicker items of fuel continue to burn (Babrauskas, 1995).

2.5 COMPARTMENT FIE EXPERIMENTS:

A number of compartment fire experiments have been conducted by different investigators. Some of the investigators are discussed below

Steckler et al.(1982):

The research of Steckler et al. (1982) is considered as a benchmark in the field of compartment fire. They were the very first investigators to successfully measure the gas velocities and flow field induced by fire in a compartment having vertical openings and is considered most authentic. The experiments were performed in an enclosure of size 2.80 m × 2.80 m in plan and

2.18 m in height. The boundaries of the compartment were 0.1 m thick and insulated with a ceramic fiber insulation board. The steady state fire was produced by a diffusion burner of 0.3 m diameter fuelled with high grade methane. A total of fifty five fire experiments were conducted with ten different configuration of vent opening. The compartment gas temperature and doorway velocity were measured. Nineteen aspirated thermocouples were located in the front corner of the compartment with vertical spacing of 0.114 m each. Adjustable bi- directional probes and thermocouples were placed at the door opening to record the gas velocities and gas temperatures. A basic sketch of Steckler et al. (1982) experimental compartment is shown in Figure 2.5.

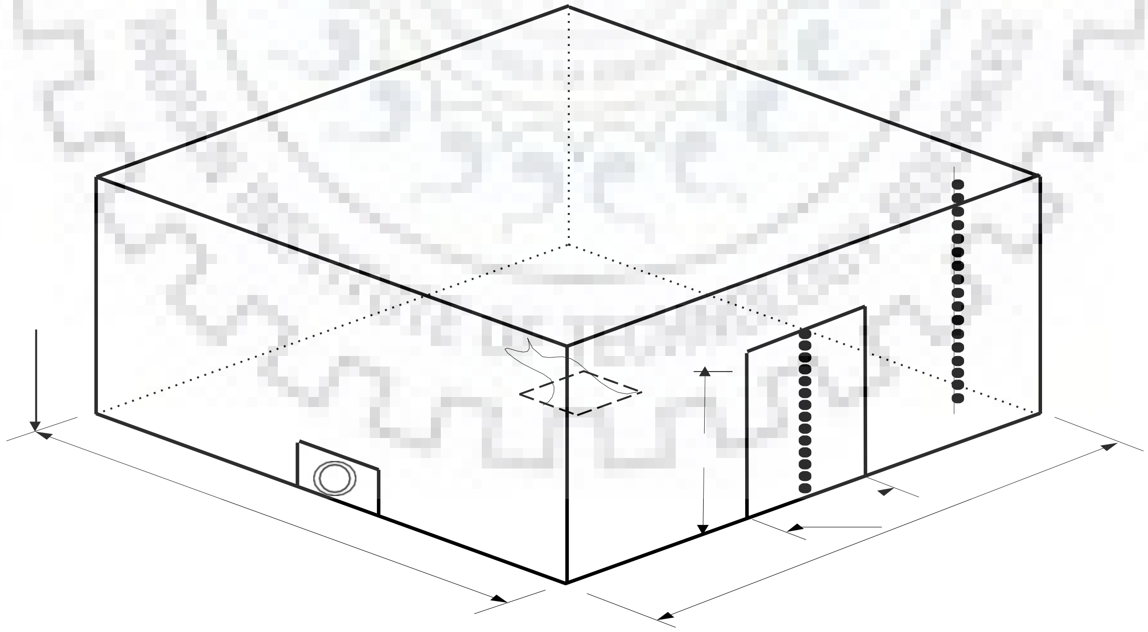


Figure 2.5 Sketch of Steckler et al. (1982) experimental compartment

Based on the fire experiments results the major conclusions drawn are as follows

1. The mass flow rate of the hot gases across the compartment opening is the highest for centrally placed fire sources followed by fire location at against back wall and at the corner of the compartment.
2. On comparing experimental data with correlation proposed by Zukoski et al. (1981) and McCaffrey (1979) of entrainment into fire plumes it was found that the model of Zukoski et al. 1981 serve as a useful reference to the in-situ fire entrainment rates.
3. The average outflow coefficient for all the fire experiments was 0.73.

Thomas et al. (2007):

Thomas et al. (2007) conducted fire tests in compartment constructed as specified in ISO 9705. The compartment was ventilated with a door opening of 0.8 m wide and 2.0 m high located at one of the compartment walls. The compartment boundaries, ceiling and walls were made up of 0.25 thick fire resistance gypsum board which serves as an insulator. The compartment floor was constructed with 0.012 m thick millboard covered with two layers of cement board. The fire was generated using mixture of ethanol 97% and water 3% and was burned in steel trays of size 0.81 × 0.70 × 0.05 m^3. Three different locations i.e. center of the compartment, against back wall of the compartment and near the door opening of the compartment were selected for the fire experiments. Instrumentations were made to measure the gas temperature and radiative heat flux. Two thermocouple arrays consisting of seven K type thermocouples each were situated at the center of the compartment and at the distance of 0.3 m inside the compartment from the door opening. Two Gardon-type heat flux gauges were installed at the centerline of the floor at 1.0 m away from the door opening and from the back wall. Following conclusions were drawn from the fire experiments.

1. The heat release rate obtained experimentally using oxygen calorimetry method should be used wisely for estimating the likely heat release rate of fires in a compartment since the HRR may vary with the position of the fire source in the compartment
2. The maximum heat release rate obtained with different locations of fire source is observed to be near door opening followed by back of the wall and at the center of the compartment in a descending order.

3. The heat flux can be as high as 30 kW/m^2 at back side of the compartment and 12 kW/m^2 at the front
4. The maximum gas temperatures have no significant difference and are almost equal when the fire source is place at the front and back of the compartment. Both of these maximum gas temperatures were substantially higher than those measured when the fire source was located at the center of the compartment.

Xu et al.(2007) :

The fire experiments were performed in a ISO 9705 specified compartment. Some fire experiments were also conducted outside the compartment under the exhaust hood of size 3.0 m by 3.0 m. The dimension of the compartment is 3.6 m length, 2.4 m width and 2.4 m height with a single door opening of dimension 2.0 m height and 0.8 m width. Wood cribs made up of radiant pine sticks were used to create fire and were ignited using 0.5 liter methylated spirits. Fire experiments under the hood were performed with nominal peak HRR of 0.5, 1.0, and 1.5 MW, respectively. Experiments conducted inside the compartment have nominal peak HRR of 0.15, 0.25, 0.5 and 1.0 MW, respectively. The heat release rate is determined using oxygen depletion method. Several measurements, such as gas temperature, heat flux, and oxygen concentration were made both inside and outside the compartment. Xu et al. (2007) mainly focused on the heat flux distribution and intensified inside and outside of the compartment. Analyzing the experimental results following conclusions were made

1. The measured heat flux at the wall near to the door opening was higher than that of the back wall since amount of hot gases accumulated at the back portion is less.
2. The heat flux measured at the compartment floor was almost similar, however the heat flux located at the back side of the floor posses slightly more since the flame gets tilted towards back due to the entrainment of the free air from the door opening
3. The heat flux measured at the ceiling of the compartment was the highest due to the direct impingement of flame and heat transfer from the ceiling jet.
4. The increase of total heat flux in almost all positions on the wall changed evenly with the increase of heat release rate.

CLOSED COMPARTMENT EXPERIMENTS :

Compartment with no ventilation is termed as closed compartment. Several fire experiments have been conducted to investigate the fires in closed compartment. Some investigators are discussed below

Zhang et al. (2013) :

They conducted fire experiments in closed compartments with interior geometries of 3.0 m × 3.0 m × 1.95 m and 1.0 m × 1.0 m × 0.75 m (L × W × H). The compartment walls were constructed with rock wool and the ceiling and floor were constructed with 5mm thick steel. A circular diameter of 300 mm pan filled with n-heptane (C_7H_{16}) was used as fire sources. In case of compartment A the experiments was performed with different elevations of fire source, 0.08 m, 0.115 m, 0.22 m, 0.275 m, 0.3 m, 0.375 m, 0.48 m, 0.595 m, 0.695 m, 0.865 m, 1.045 m, 1,16 m and 1.30 m from the bottom surface of the fuel pan to the floor. In case of compartment B the fuel pan was elevated at a height of 0.08 m, 0.10 m, 0.20 m, 0.30 m, 0.40 m and 0.50 m from the bottom surface of the fuel pan to the floor. Instrumentations were installed to measure the movement of hot gas layer, oxygen concentrations, and smoke density. Following findings were reported by the authors

1. Due to the elevation of fire source a distinct smoke filling phenomenon was observed. The smoke layer height was descended to the fire source level and did not descend further at the center of the compartment but continued the filling process by the wall jets.
2. The thermal layer of discontinuity was found to be at the surface of the fire source for both the compartments.
3. The visualization experiments showed that the wall jets penetrated the interface and traveled along the wall. Then, the smoke accumulated at the floor and rose from the center of the floor. With the continued burning of the fuel, increasingly more smoke traveled along the wall by wall jets and rose in the lower layer until the smoke filled the lower layer.
4. The concentration of the oxygen measured at different height of the compartment varied with the elevation of the fire source.

RESEARCH FOCUS AND SCOPE :

The investigation of compartment flames has turned into a significant territory of research for flame specialists and firemen, and a few flame models have been created to comprehend the major systems of flame development and to survey fire risk. In the present research work, an exertion has been made to create trial information on compartment fire with solid fuels as fire sources. The exploration destinations of the present work are given as follows:

1. Plan, manufacture and authorizing of fire test facility.
2. Investigation of burning behaviour of large scale wood cribs with cone calorimeter.
3. Effect of Sudden Ventilation in a Compartment Involving Crib Fire.
4. Examinations on the Effect Ventilation on Fire Development and Compartment Environment.
5. Investigation of Energy Balance in a Compartment Involving Crib Fire.
6. Calculation of different parameters at different positions of compartment like heat flux temperature concentration of O_2, CO and CO_2 etc.

CHAPTER 3 EXPERIMENTAL SET-UP

3.1 EXPERIMENTAL SET-UP

3.1.1 Experimental compartment

The trial compartment was build at Fire Research Laboratory in Indian Institute of Technology Roorkee to produce information from large scale fire test. The inner component of test compartment was 4 m length by 4 m width by 4 m height. In the focal point of the front wall there is an entryway opening of measurement 1 m width by 2 m stature. The sliding entryway was introduced at the entryway opening to change the ventilation in the compartment. The test compartment walls were comprised of standard clay blocks of measurement 22.5 × 11 × 5.5 cm^3 and a layer of concrete and sand blend (1:6) of thickness 3 cm was connected on the two sides of the compartment divider to give wrapping up. The roof was comprised of Reinforced Concrete Cement (RCC) [cement: sand: concrete:: 1:2:4]. The floor of the compartment was produced using the standard flame block. A square window fitted with imperviousness to fire glass was set in one of the compartment dividers abutting to the entryway to watch the conduct of flame inside the compartment. A hood of 3m by 3m was introduced pretty much the entryway opening of the compartment so as to gather the burning gases turning out from the compartment during flame tests. The hood was bolstered with 4 column situated at corner of the hood. A total outline of compartment and hood game plan is appeared in Figure 3.1. The trial compartment was housed in a greater square shed of 8 m × 8 m × 9 m. The shed had two moving shades of 3.0 m width and 3.6 m high. One moving screen was situated before the compartment entryway to ensure the free development of air to the compartment. Another shade was fixed on the contrary divider which stays shut through the tests.

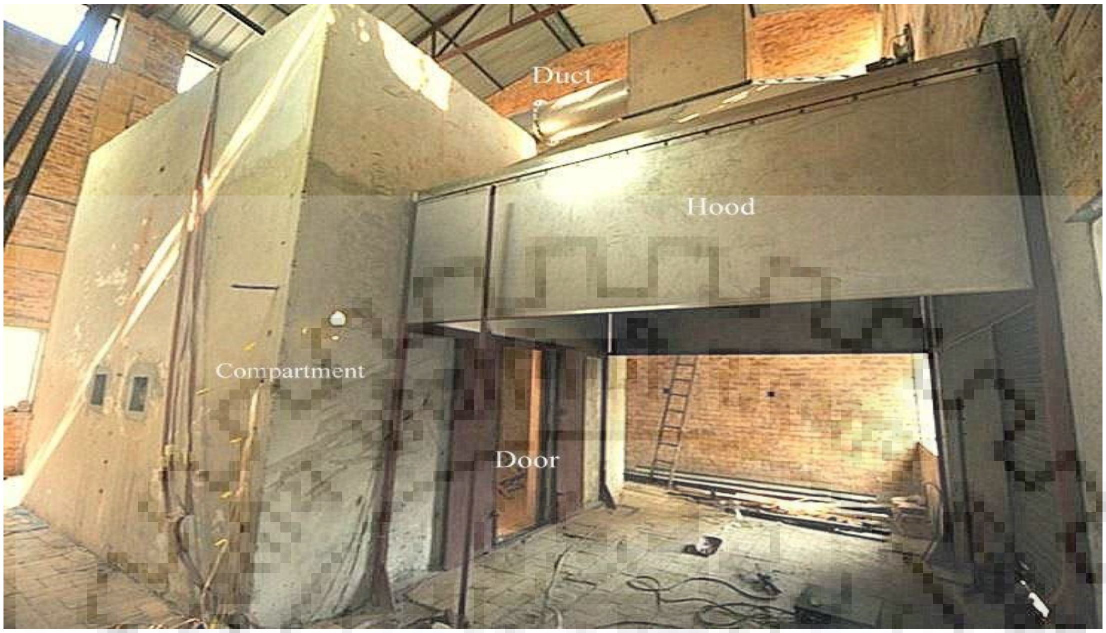


Figure 3.1 Experimental fire compartment

3.1.2 Fire source :

In the current experiments performed the wood crib has been used as a fire source with different ventilation conditions for four experiments respectively. The ventilation was controlled by the door in front wall by sliding the door. In experiment 1st the door is fully open , in experiment 2nd the door is 75% open , in 3rd experiment the door is 50% open and in the 4th experiment the door is only 25% open.

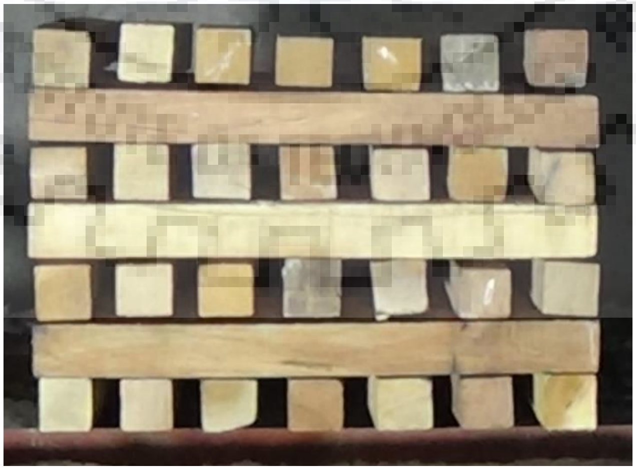


Figure 3.2 Wood crib used in experiments

Wood crib is made up of wood sticks of length 50 cm and square cross section of size 5 cm. Before this experiments have been done but on different size sticks and wood crib.

3.1.3 Procedure :

Before performing fire experiments the moisture content of wood cribs is measured . The cribs are appropriately organized on the burning platform with respect to the experiment we are going to perform. The door opening is also adjusted before experiment according to the ventilation we want to provide. A fix amount of cotton and diesel mixture is prepared to start the ignition of crib. The water storage tank is checked and filled with distilled water which is used to cool the heat sensors which is very necessary. Pumps must be on to circulate the water for cooling sensors. The data logging system and calorimeter all is started before 5 min of experiments and digital load cell is also calibrated for actual weight of crib. To get the exact value of difference in pressure each probes should be cleaned using vacuum cleaner. Each time filters and derlite must be changed before performing experiment.

3.2 ISTRUMENTATION :

While performing experiment, for measurement of different parameter like temperature and heat flux different type of sensor is used

3.2.1 Thermocouples :

Various thermocouples are used for measurement of temperature at different-different locations. Thermocouples works on the principle of **Seebeck effect** which states that when two different metals wires are joined together at two junction and if they are different temperature then an emf will be generated within the circuit and it is the function of temperature difference of two junctions and due to this emf, current will flow within the circuit and output can be measured in the form of voltage. In our experiment “K type chromellalumel" thermocouple of different thickness is used. The range of these thermocouples are form -200℃ to 1350℃ with an accuracy of $\pm 0.75\%$. For extending the length of thermocouple double core Teflon insulated compensating cables are used.

Total 111 thermocouples are In our experiment out of which 64 thermocouples are used in ceilings, 18 thermocouples in a vertical line are above the flame, 20 thermocouples are used at the corner of the left wall and 9 thermocouples are used in the doorway to measure the temperature of exhaust gases which further used in measuring the velocity of exhaust gases.

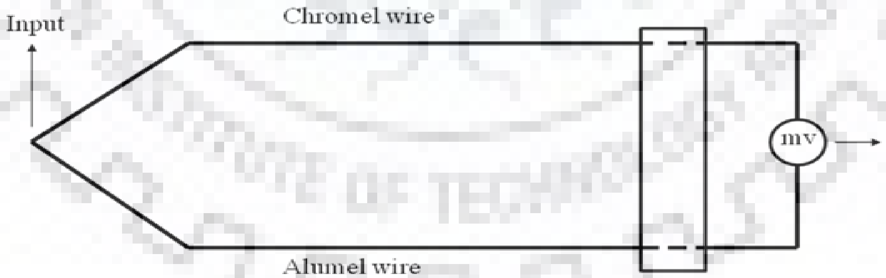


Figure 3.3 Thermocouple schematic diagram

3.2.2 Heat sensor :

The total heat flux reaching at compartment boundaries, viz., ceiling, floor, and walls, was measured with the help of Schmidt–Boelter heat flux sensors manufactured from Hukesflux

Thermal Sensors providing a level of confidence of 95%. A total of nineteen heat flux sensors (Model SBG01) were installed at various locations within the compartment boundaries which gives the output in the form of voltage. The capacity of these sensors are is 20 kW/m^2, 50kW/$m^2$and 100kW/m^2. These sensors are water cooled sensors for which two pipe are attached at the port, one for cold water and other for hot water coming out from sensor, provided in the sensor through which distilled water flows. A pump arrangements is also made for supply of water.

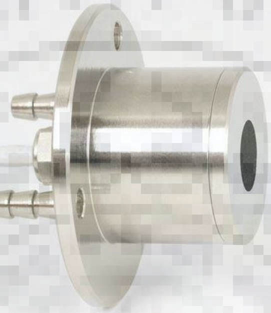


Figure 3.4 Heat flux sensor

3.2.3 Velocity measurement :

For the measurement of velocity and flow rate of hot exhaust gases coming out from the fire compartment bi-directional velocity probes are used. The bi-directional probes were made up of stainless steel having dimensions 2.5m in length and diameter of each tube is 5 mm and dimensions of probe is 15 mm in diameter and 30 mm in length and fabricated as detailed in Macaffrey and Hesketad (1976). It works with an accuracy of ±5%.

Generally, the measurement of velocity in fluid flow is done by the standard Pitot – static tube due to its accurate velocity measurement. However, in case of fire experiments in compartment, the standard Pitot-static tube not preferred because of its sensing holes and low impact and it measures velocity in any single direction. Since, in compartment fire soot is a primary concern as it can cause blockage on the Pitot – static tube, which could possibly results in measurement error

Figure 3.5 velocity probe

3.2.4 Differential pressure transducer :

Differential pressure transducer is a device which converts pressure into electrical analog signal which is linearly dependent with pressure. It consist an elastic material which get deformed under pressure and an electric device which convert those pressure into electrical signal and results in terms of mA. This electrical signal generate because of the change in resistance. In our experiment, we use setra, model 264 differential pressure having a differential pressure range of 0 -50 pa with the accuracy of $\pm 1\%$ full scale.

The other end of bi-directional probe is connected to a differential pressure transducer through pipe and the length of the pipe should be as small as possible to reduce the pressure loss in pipe. The differential pressure, Δp, determined across each bi-directional probe and doorway gas temperature measured at the corresponding bi-directional probe location were used

$$\upsilon = \frac{1}{k}\sqrt{\frac{2\times\Delta p}{\rho}} \quad \text{where } \rho = \frac{352.8}{T} \tag{3.1}$$

where ρ is calculated from ideal gas equation by using doorway temperature and absolute temperature. k is constant taken as 1.08.

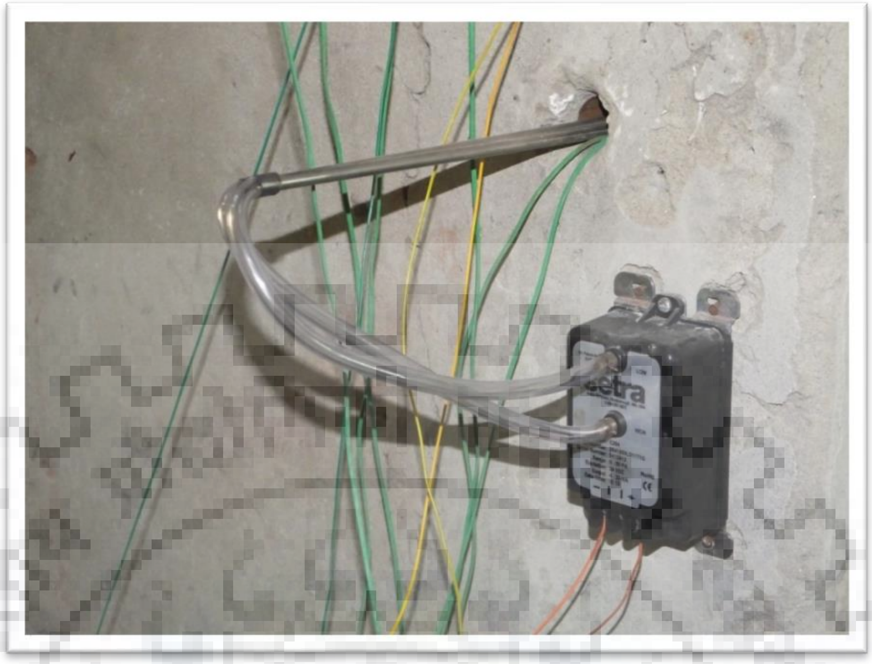


Figure 3.6 Differential pressure transducer

3.2.5 Digital load cell :

Digital load cell is a weight measuring device. It is used to measure the mass of the crib with respect to time. We are using digital load cell manufactured by Vishay Noble having load capacity 300kg and least count of 5 gram. For measurement, we have to connect digital load cell with computer which stores the data in every 5 seconds

Figure 3.7 Digital load cell and load indicator

3.2.6 Data Acquisition system :

Two data acquisition system were used for the recording the data coming from experiments One of them from national instruments NI PXLe-1062Q, which has four Four NITB-4353 DAQ module each having 32 channels for recording the temperature and heat flux and other form data Taker Model CEM20 which has 2 module each having 20 channel and in each channel we can get maximum 3 outputs.

In our setup, all the heat flux sensor 7 differential pressure transducer and 47 thermocouples are connected to NI system and 64 some of temperature and 6 differential pressure transducer is connected with DT system.

Figure 3.8 (NI PXLe-1062Q NI DAQ SYSTEM)

Figure 3.9 Data taker CEM 20

3.2.7 Combustion gas analyzer :

For the measurement of heat release rate two methods are used

1. weight loss method
2. oxygen consumption method

For the measurement of heat release rate in oxygen consumption calorimetry, a gas analyzer is required. A gas analyzer tells about the oxygen concentration of combustion gases. For the measurement of oxygen concentration a " Servomax 4100 "gas analyzer is used. It works on magneto-dynamic paramagnetic technology which provide percentage level of oxygen present with an accuracy of ±0.02.

Figure 3.10 Gas analyzer set-up

CHAPTER 4 EXPERIMENTAL LAY-OUT

Before doing the experiment, we have to fix the locations of velocity probes thermocouples and heat sensors means how they are installed and at what positions they are installed because according to this we can understand the condition of compartment.

4.1 Thermocouples :

64 thermocouples are installed on ceiling. 18 above flame. 20 left corner wall and 9 in doorway.

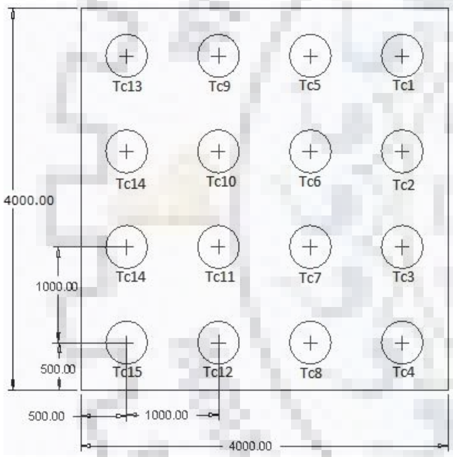


Figure 4.1 Ceiling thermocouples

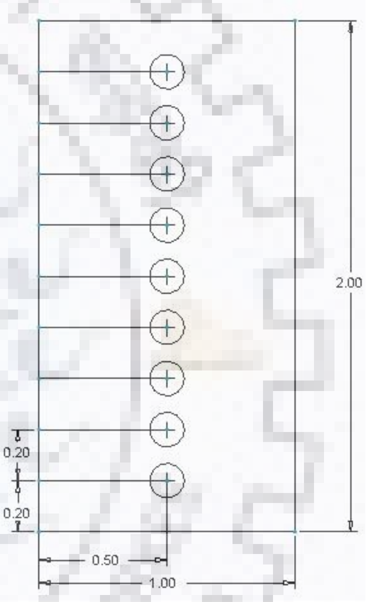


Figure 4.2 Doorway thermocouples

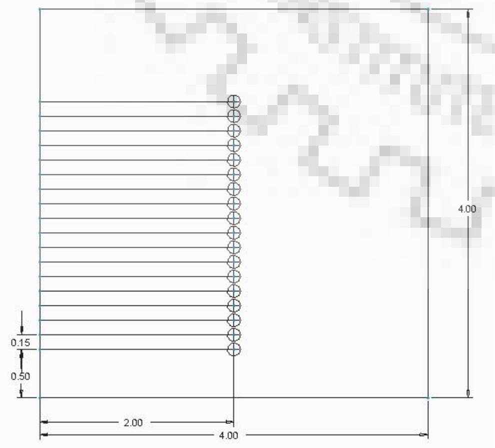


Figure 4.3 Flame thermocouples

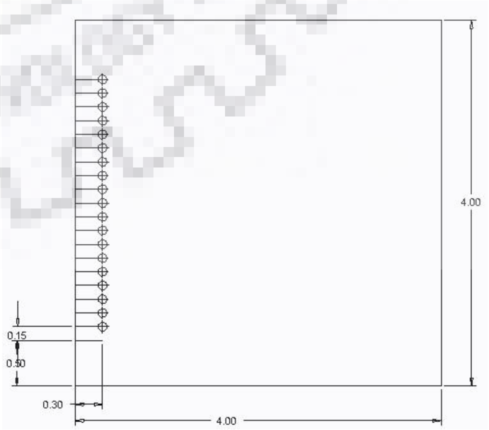


Figure 4.4 Wall corner thermocouples

4.2 Heat sensors :

There are 4 sensors on floor, 5 on ceiling, 4 on east wall and 2 each on west, south and north wall.

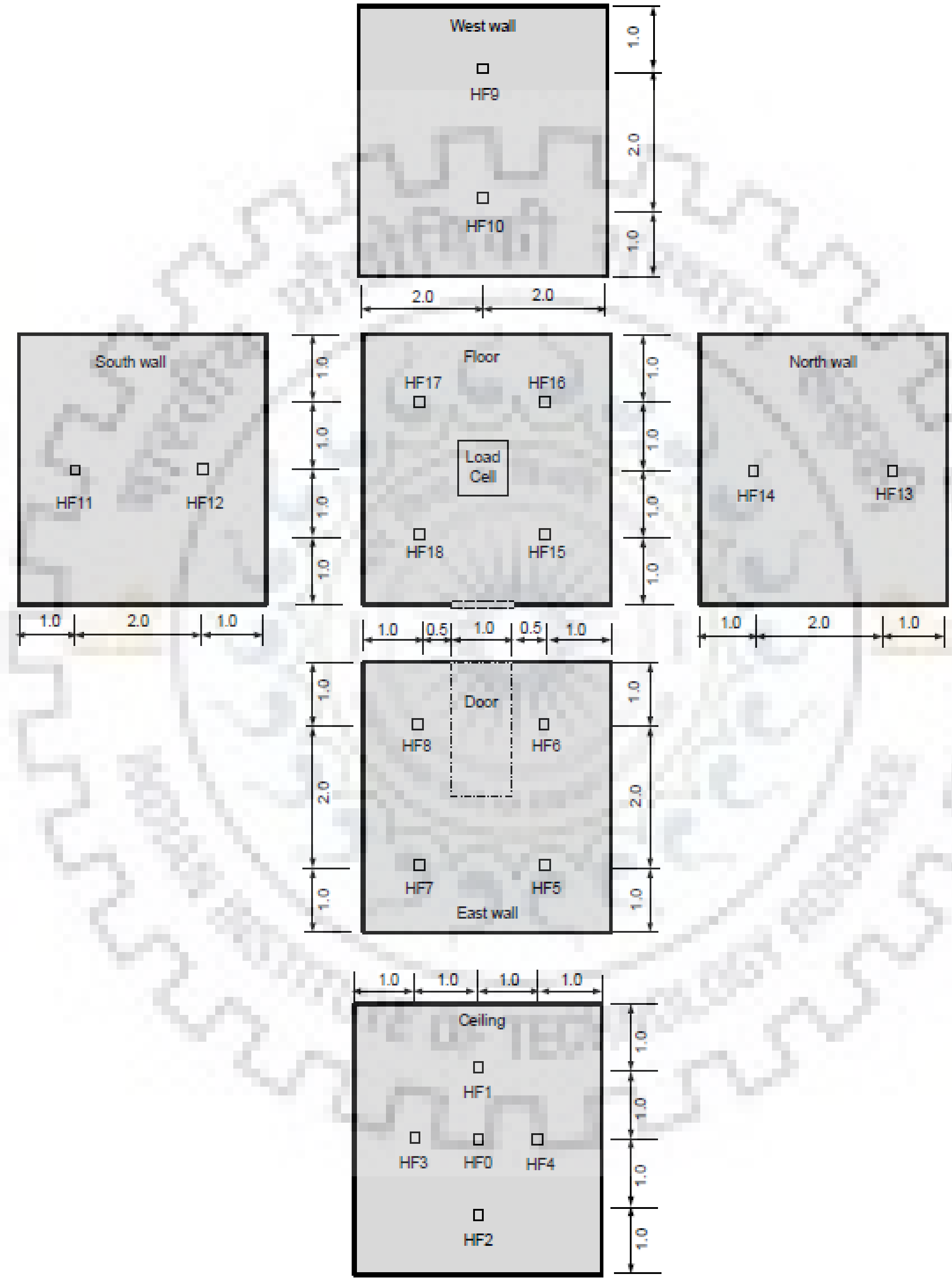


Figure 4.5 Heat flux sensors locations

4.3 Velocity probes :

There are 7 velocity probes are used just above the flame front and 6 velocity probes are used in doorway to find pressure difference of air between inside and outside of compartment.

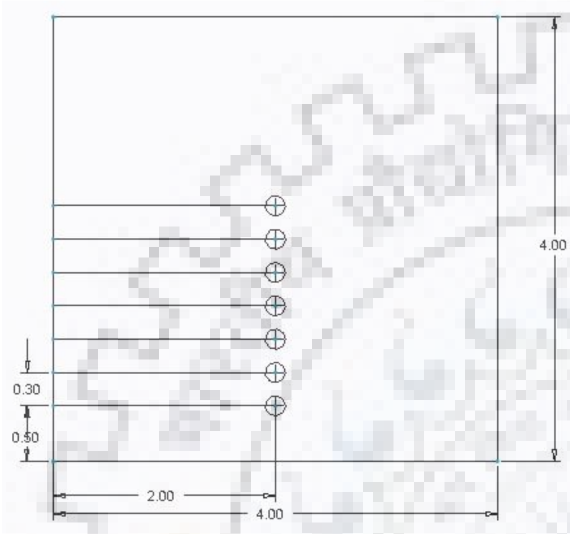


Figure 4.6 Flame velocity probe

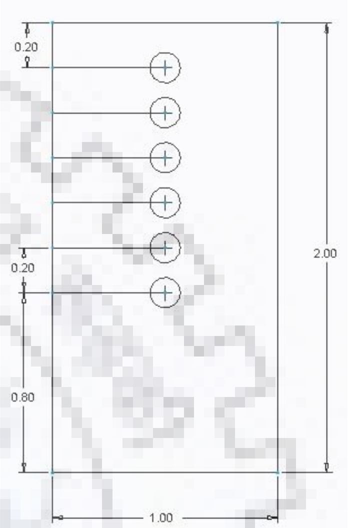


Figure 4.7 Doorway velocity probe

CHAPTER 5 RESULTS AND DISCUSSIONS

EXPERIMENTAL RESULTS :

5.1 Study of burning characteristics of large scale wood crib fire with cone calorimeter:

A series of four experiments has been performed with cone calorimeter to study the burning characteristics of wood crib fire on large scale. The dimension of sticks is constant for every experiment. The mass loss rate, heat release rate and species concentration were measured for each experiment. The experiments were performed using same sticks and crib but the ventilation is varied as follows

Experiment 1	The door is fully (100%) open
Experiment 2	The door is 75 % open
Experiment 3	The door is 50% open
Experiment 4	The door is 25% open

In all experiment mango sticks were used. In addition to mass loss rate and heat release rate different parameters like temperature, Heat flux, velocity at different locations were measured and analyzed for each case .

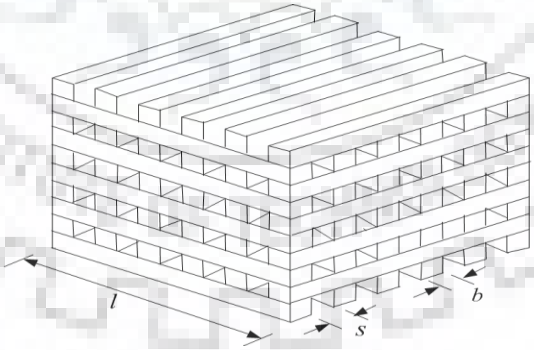


Figure 5.1 Crib schematic diagram

No. of sticks in one layer (N_s) = 7
No. of layers (N_L) = 7
Weight of wood sticks (W) = 39.5 kg
Fuel = Mango wood crib

$$s = \frac{l - N_S * b}{N_S - 1} = 2.5$$

$$A_C = 2N_S N_L (wh + hl + wl) - 2(N_L - 1)(N_S w)^2 = 36750 \text{ m}^2$$

$$A_v = ((N_S - 1)s)^2 = 225 \text{ m}^2$$

$$\Phi = N_L^{0.5} * b^{1.1} * \frac{A_v}{A_s} = 0.095 \text{ (porosity)}$$

$$Moisture\ content = \frac{Actual\ weight - dry\ weight}{actual\ weight} = \frac{80.612 - 76.5815}{80.612} * 100 = 5\%$$

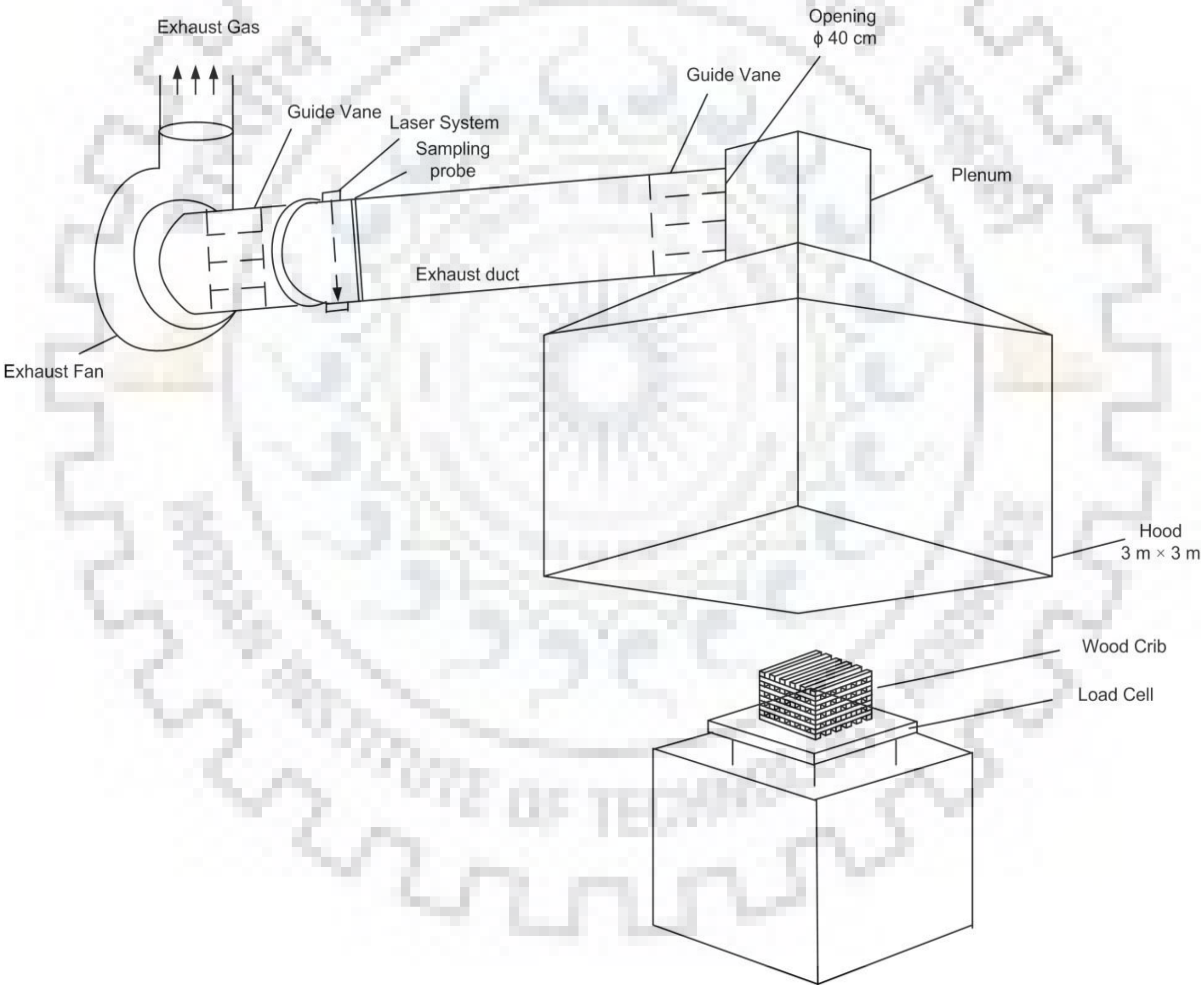
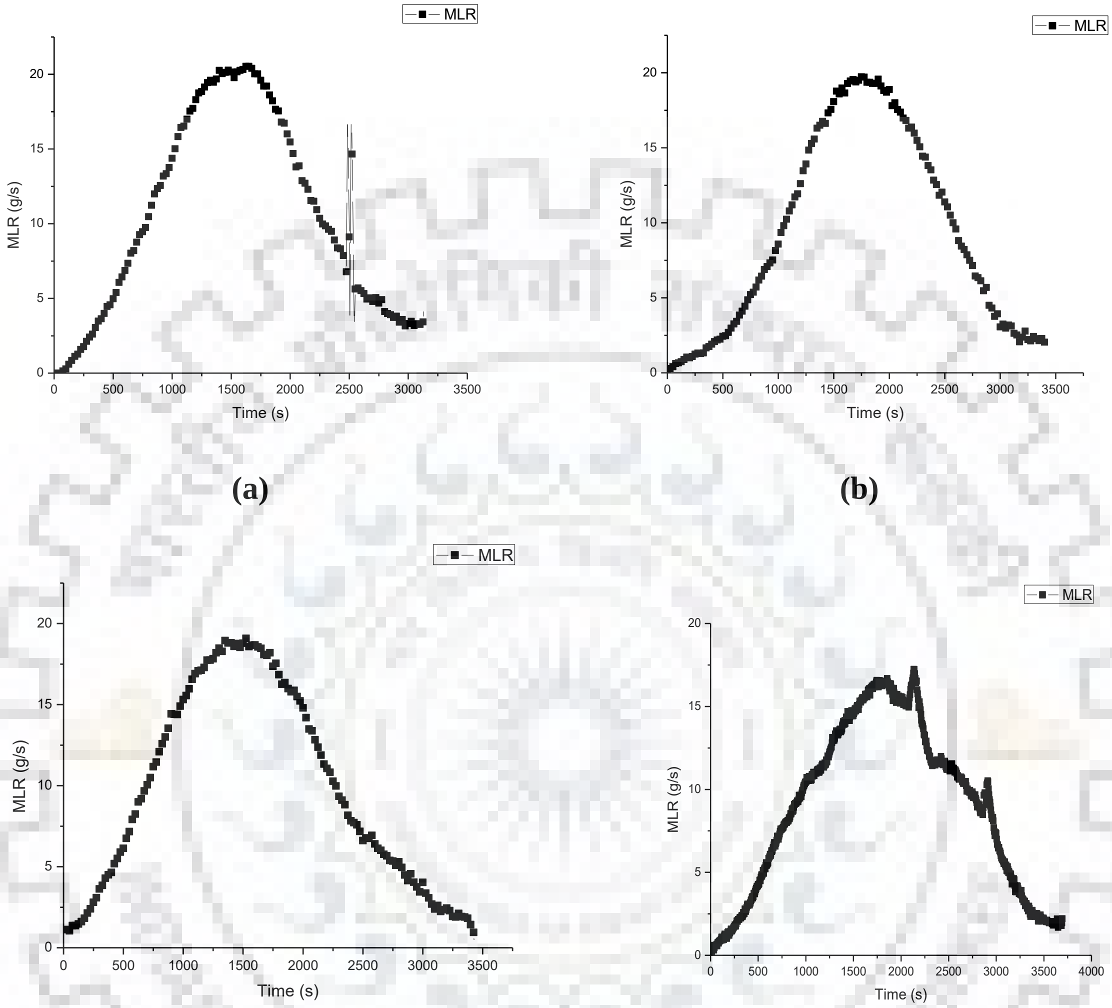


Figure 5.2 Experimental arrangement schematic diagram

5.2 Mass loss rate :



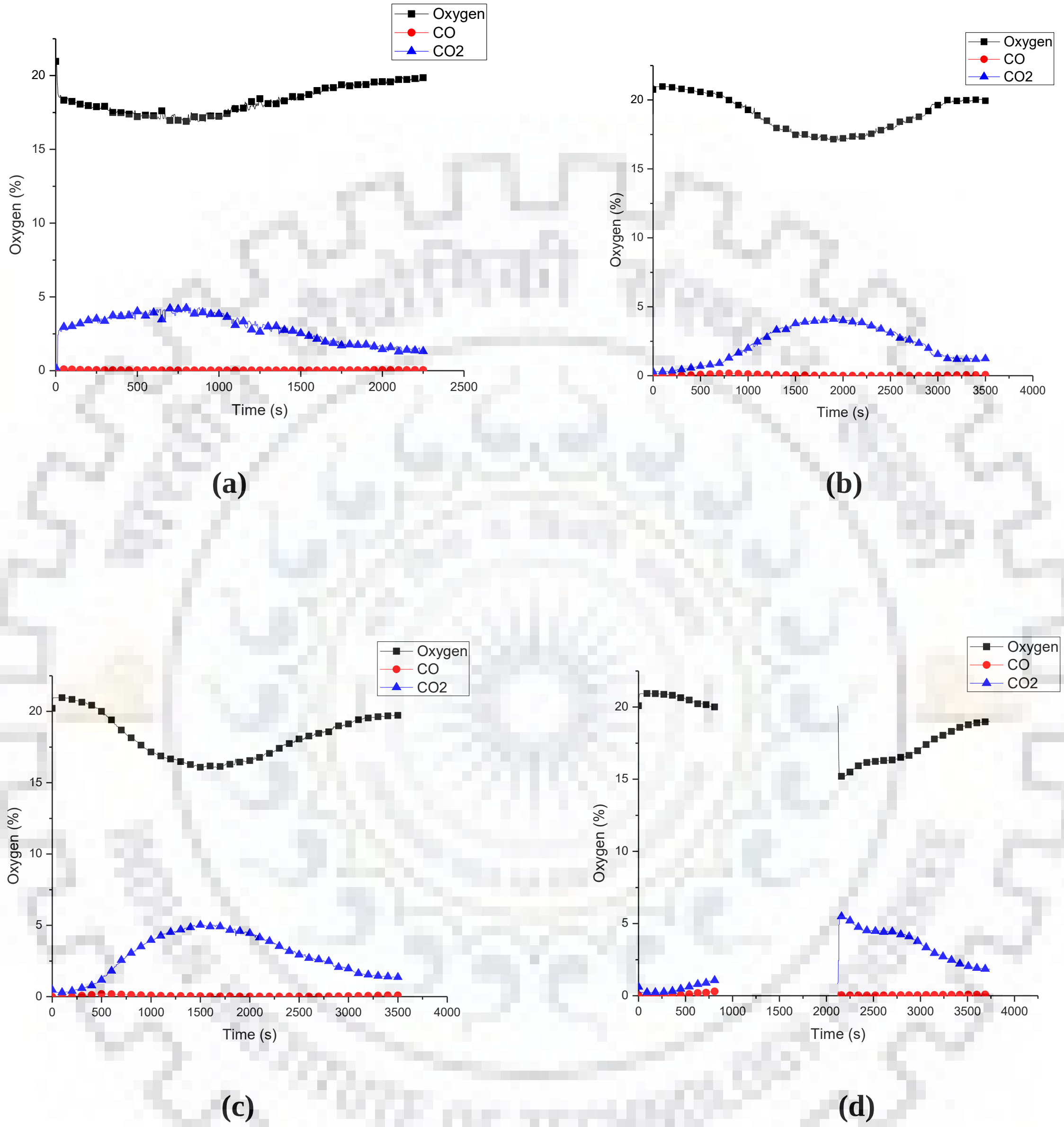
(a) (b)

(c) (d)

Figure 5.3 Mass loss rate in test 1, 2, 3, and 4

Mass loss rate is the rate at which mass of wood crib is decreasing or we can say mass of crib burning in the process of sustaining the fire. From the figure 5.3 we can see impact of ventilation on mass loss rate when door was fully open it is maximum but as the ventilation area is decreasing its value is also decreasing. It is maximum in fully open condition and minimum in condition when door is only 25% open.

5.3 Oxygen, Carbon monoxide and carbon dioxide :



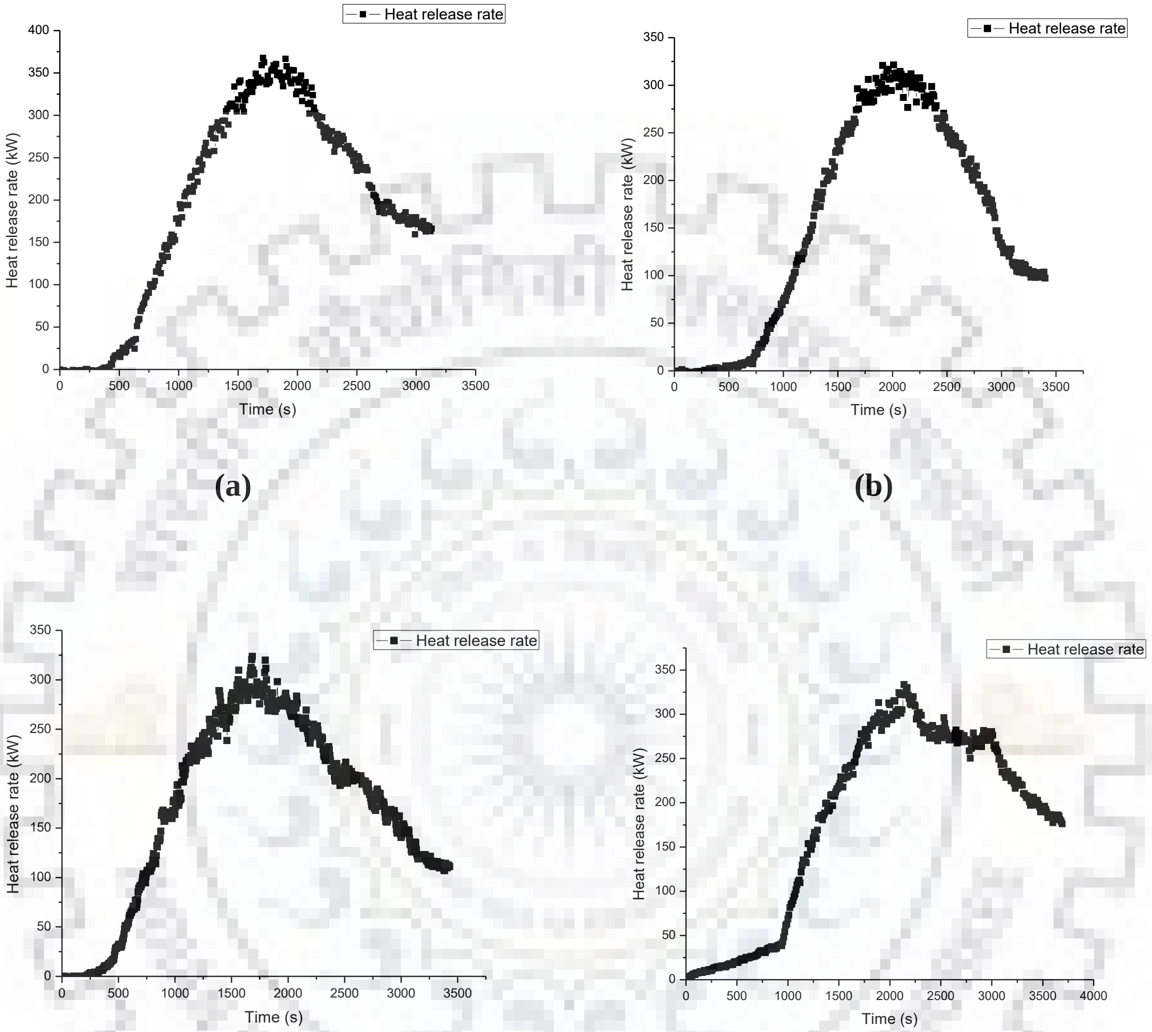
(a) (b)

(c) (d)

Figure 5.4 Concentration of O_2, CO_2, CO in upper layer of compartment

From the figure 5.4 we can observe the variation in concentration of O_2, CO_2, and CO. From figure a, b, c, d we can see when the door is fully open the concentration of O_2 decreases very rapidly and early goes to minimum point and then increases on the other hand concentration of CO_2 also increases then goes to maximum and then falls downwards.

5.4 Heat release rate :



(a)

(b)

(c)

(d)

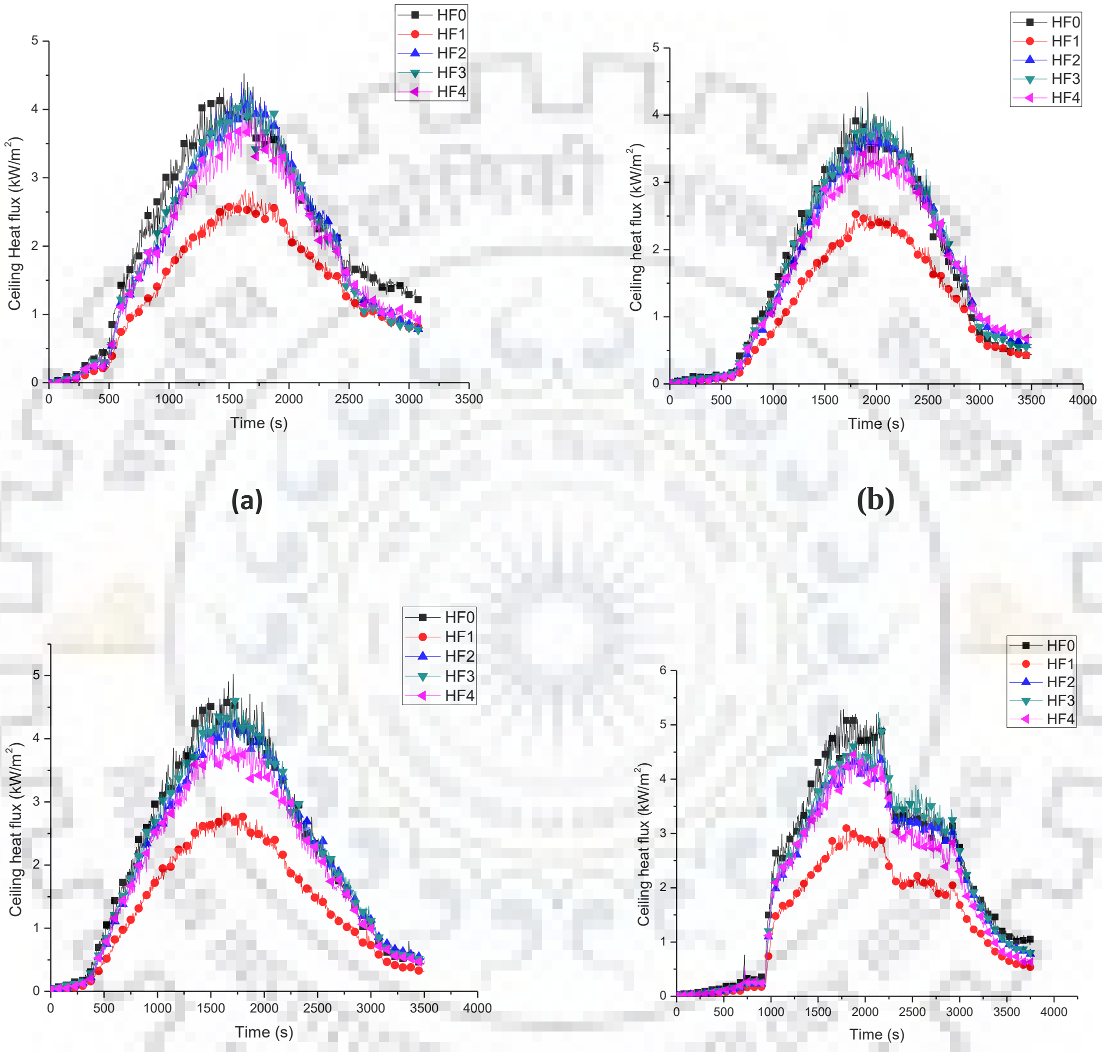
Figure 5.5 Heat release rate in experiment 1, 2, 3 and 4.

As we can see the heat release rate is decreasing as the ventilation area is becoming small this is due to shortage of oxygen in the compartment environment.

5.5 Heat flux :

There are four different category of heat flux locations as follows

5.5.1 Ceiling heat flux :

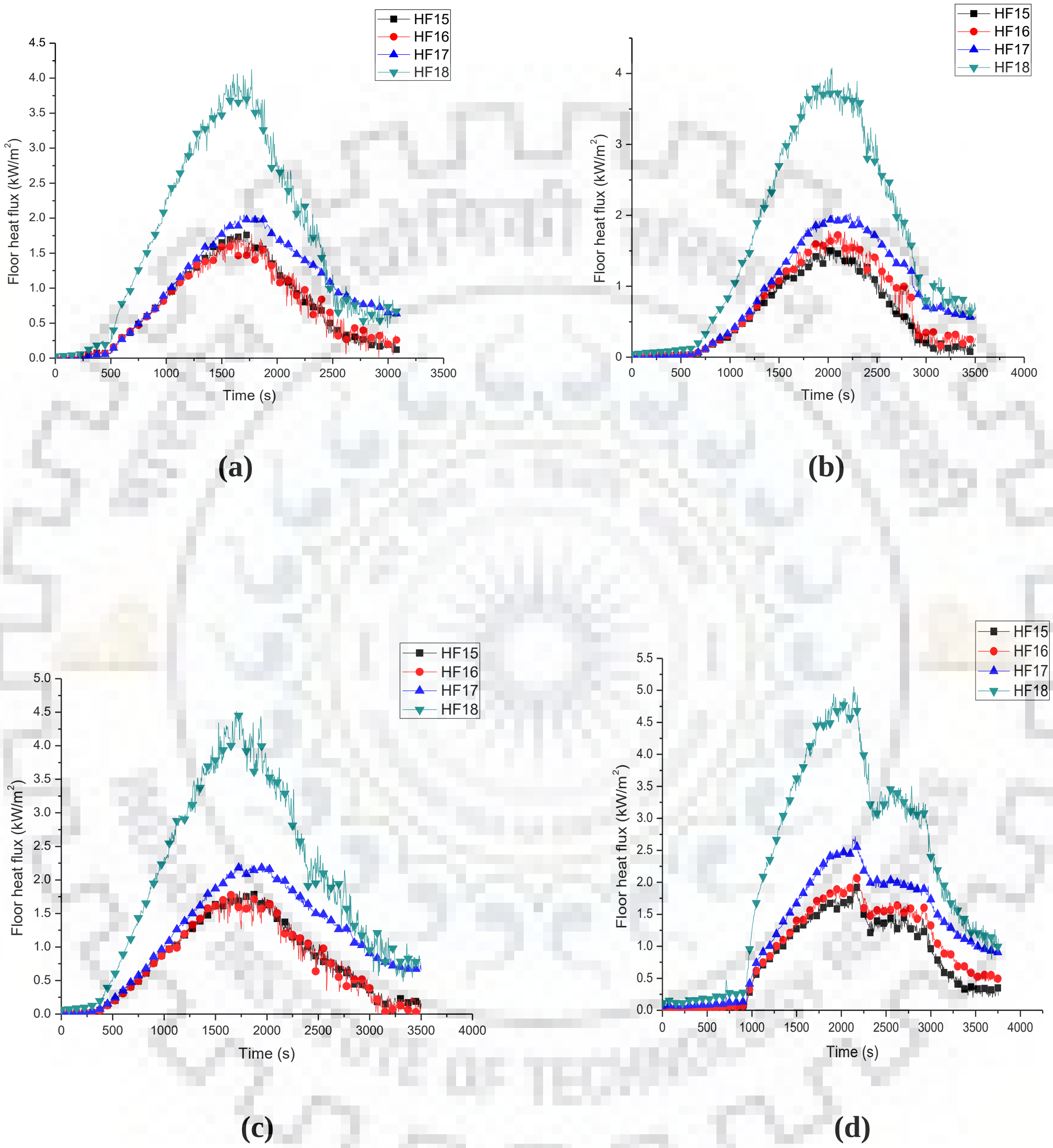


(a) (b)

(c) (d)

Figure 5.6 Ceiling heat flux for test 1, 2, 3 and 4.

5.5.2 Floor heat flux :



(a)

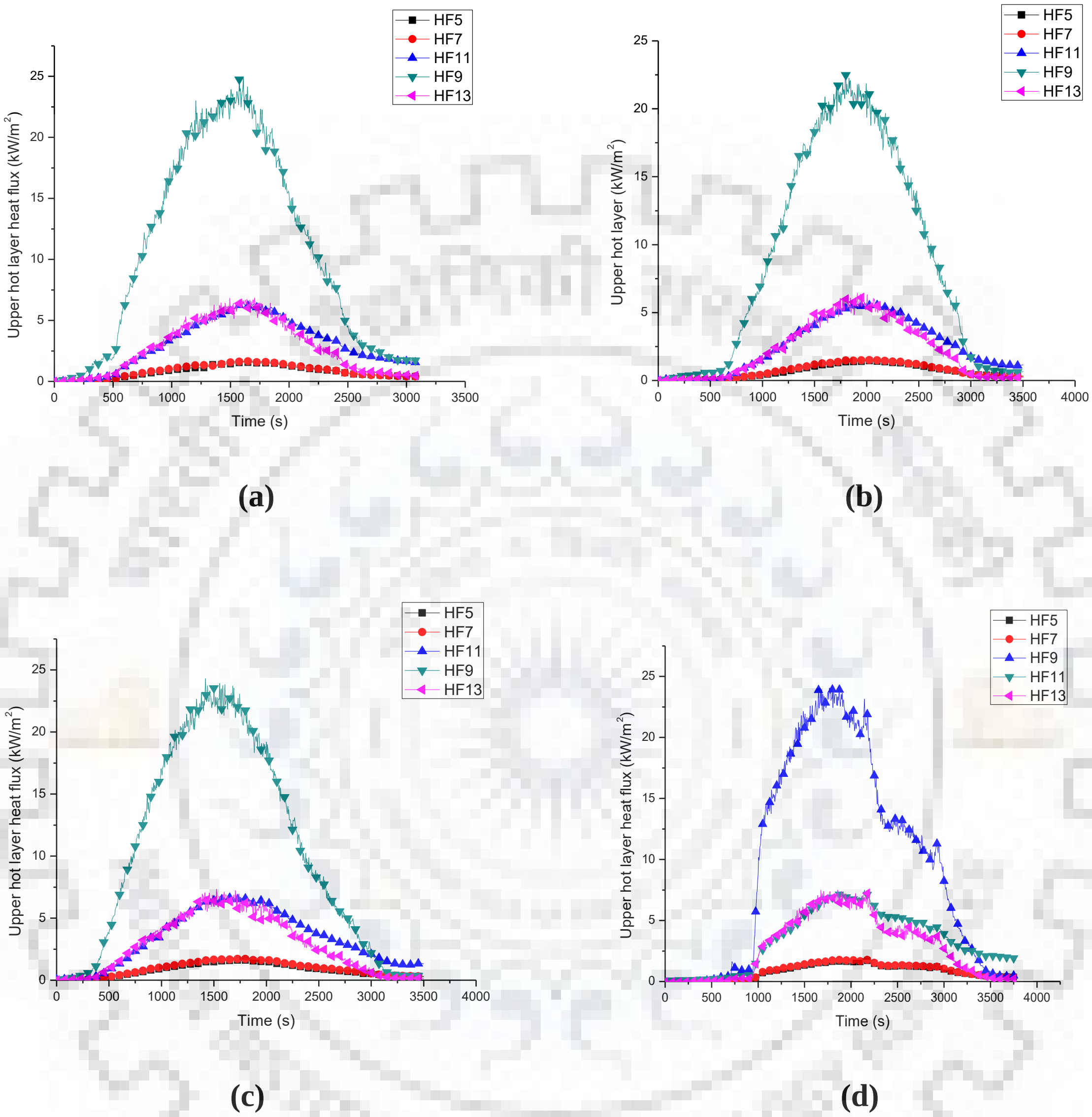
(b)

(c)

(d)

Figure 5.7 Floor heat flux variation in test 1, 2, 3 and 4.

5.5.3 Upper hot layer heat flux :



(a) (b)

(c) (d)

Figure 5.8 Upper hot layer heat flux variation for test 1, 2, 3 and 4.

5.5.4 Lower cold layer heat flux :

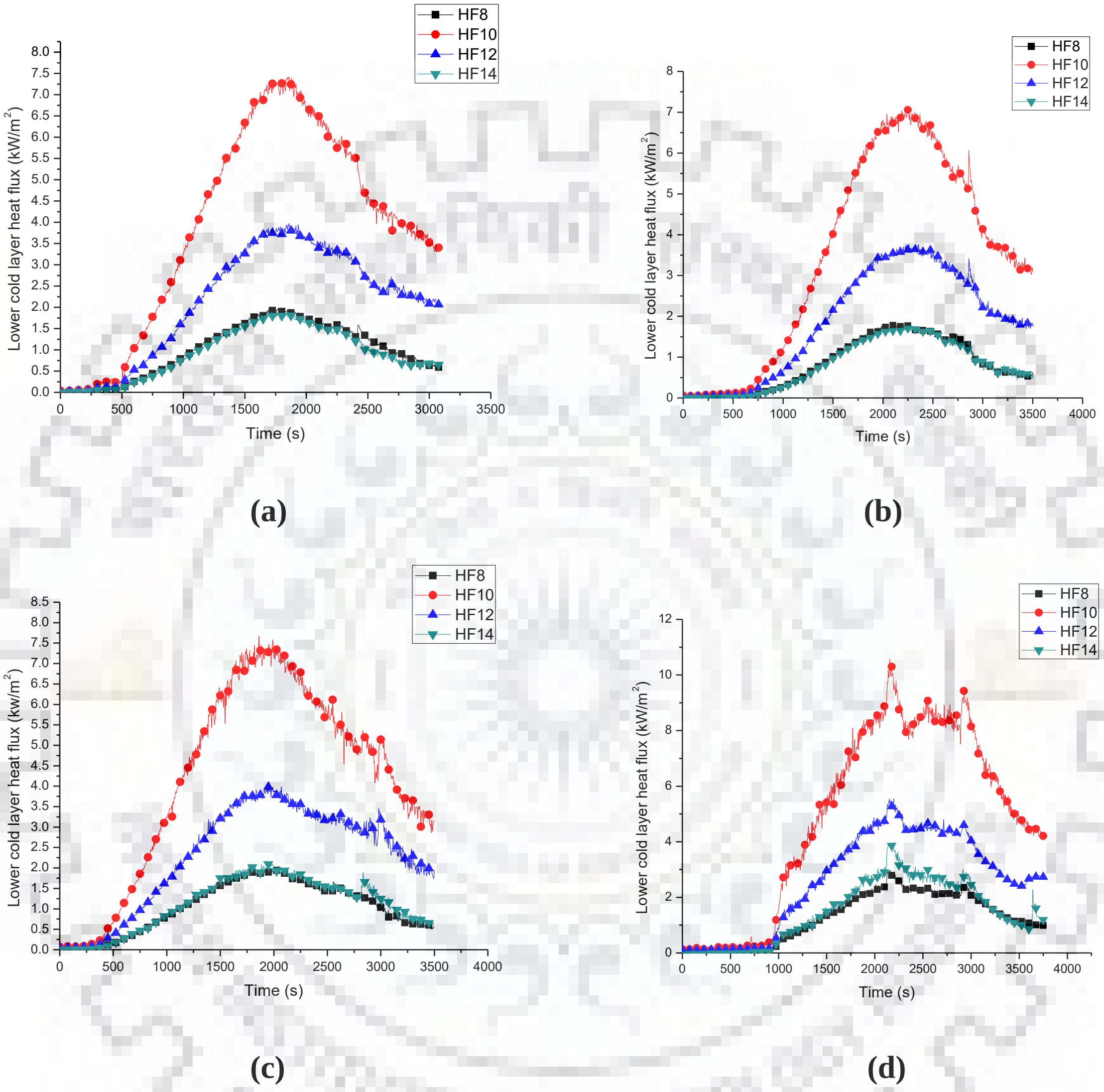
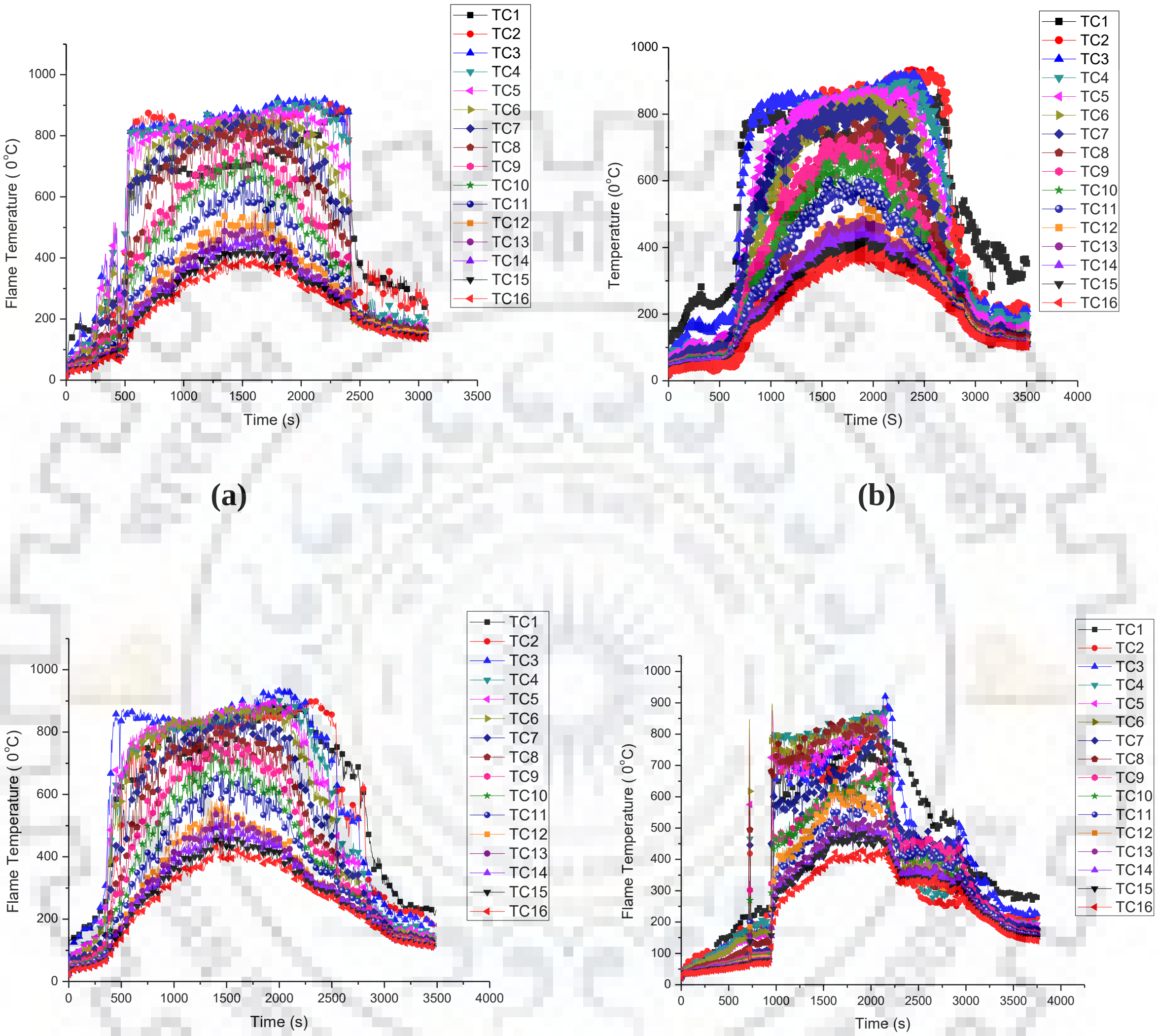


Figure 5.9 Lower cold layer heat flux variation for test 1, 2, 3 and 4.

5.6 Flame temperature :



(a) (b)

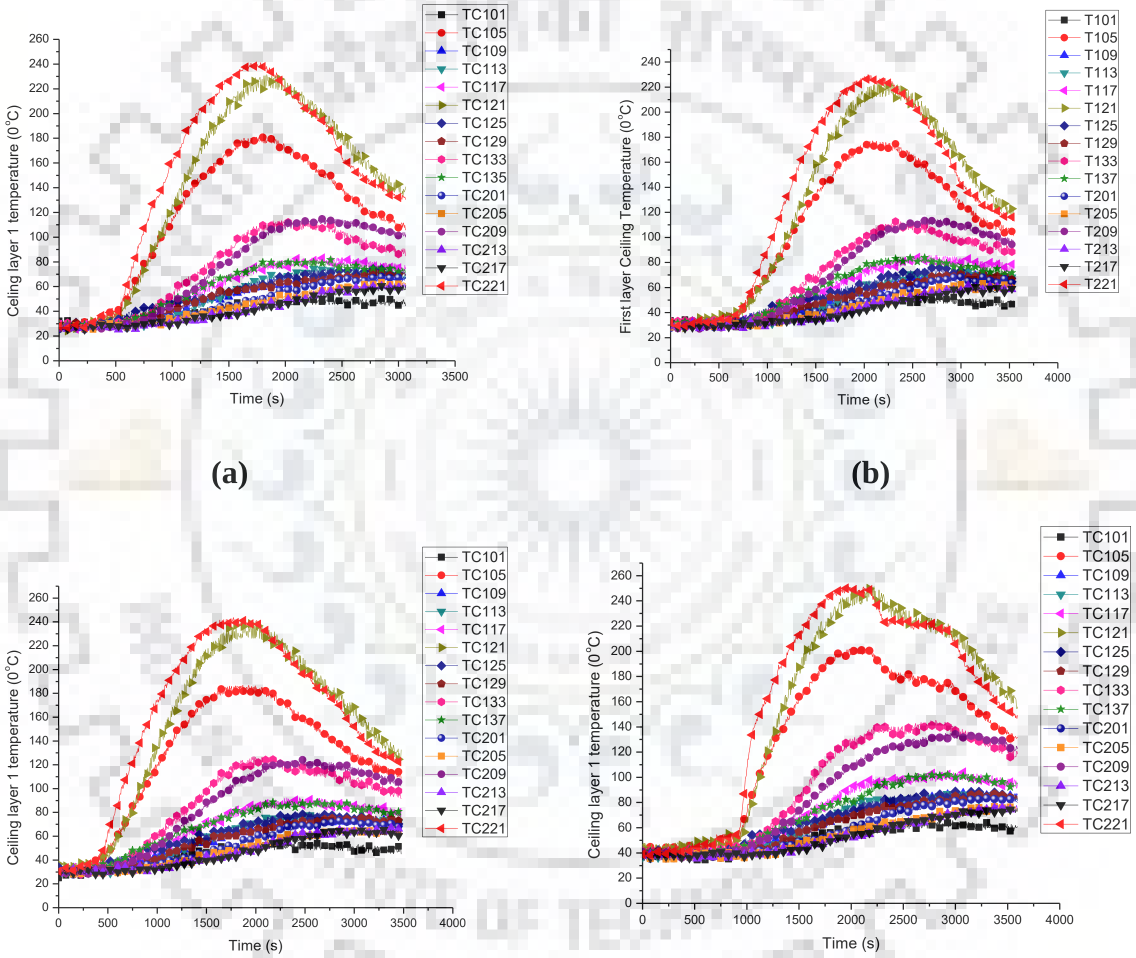
(c) (d)

Figure 5.10 Flame temperature variation for test 1, 2, 3 and 4.

5.7 Ceiling temperature :

Ceiling temperature has been characterized in 4 groups according to the distance of thermocouples from ceiling as layer 1, layer 2, layer 3 and layer 4.

5.7.1 Ceiling layer 1 temperature :



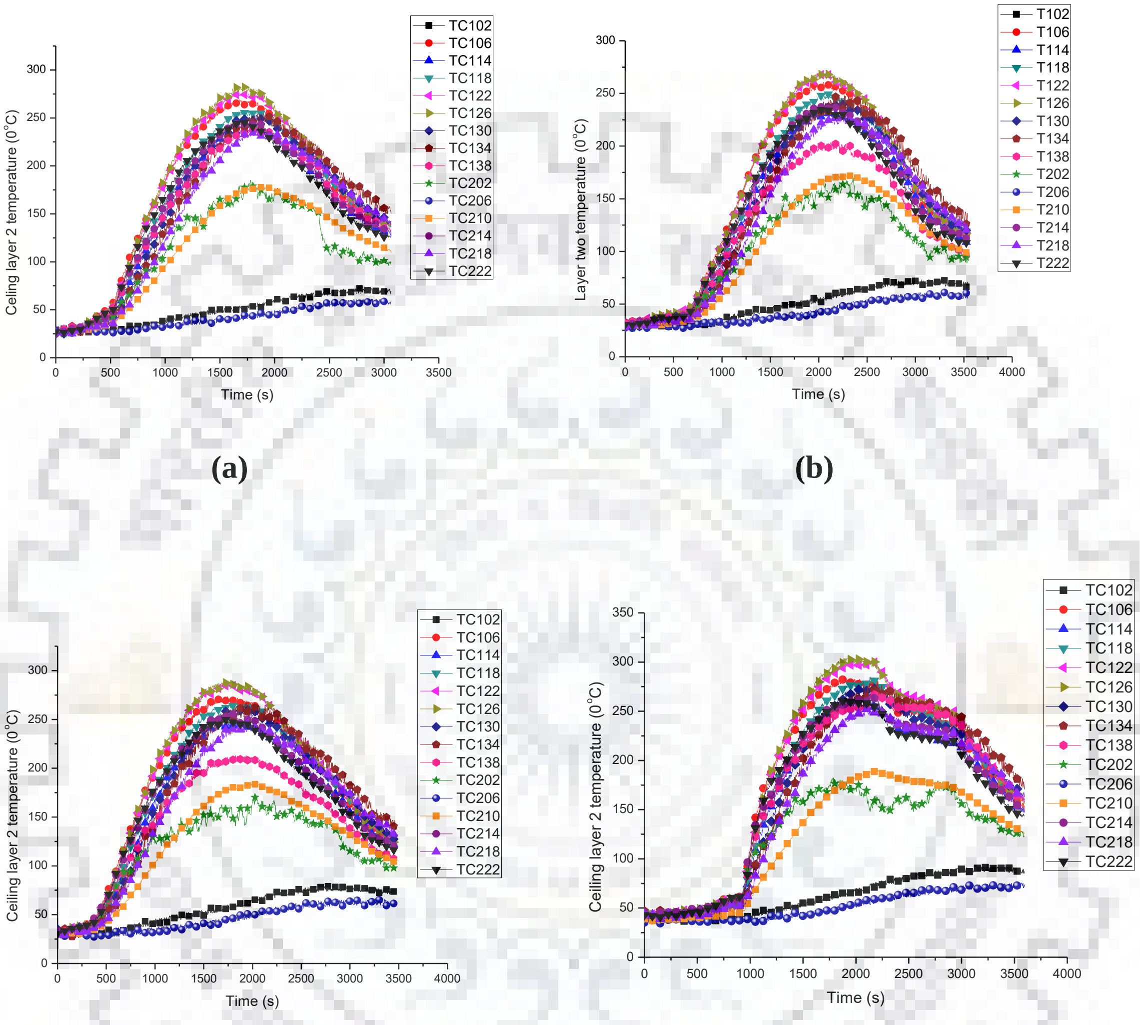
(a) (b)

(c) (d)

Figure 5.11 variation in layer 1 ceiling temperature (0.075 m from ceiling)

Ceiling layer 2 temperature :

Layer 2 thermocouples are installed on false ceiling which is 15 cm below the ceiling.



(a) (b)

(c) (d)

Figure 5.12 Temperature variation in layer 2 of ceiling

Ceiling layer 3 temperature :

Layer 3 thermocouples are installed 0.5 m below false ceiling means 0.65 m from ceiling.

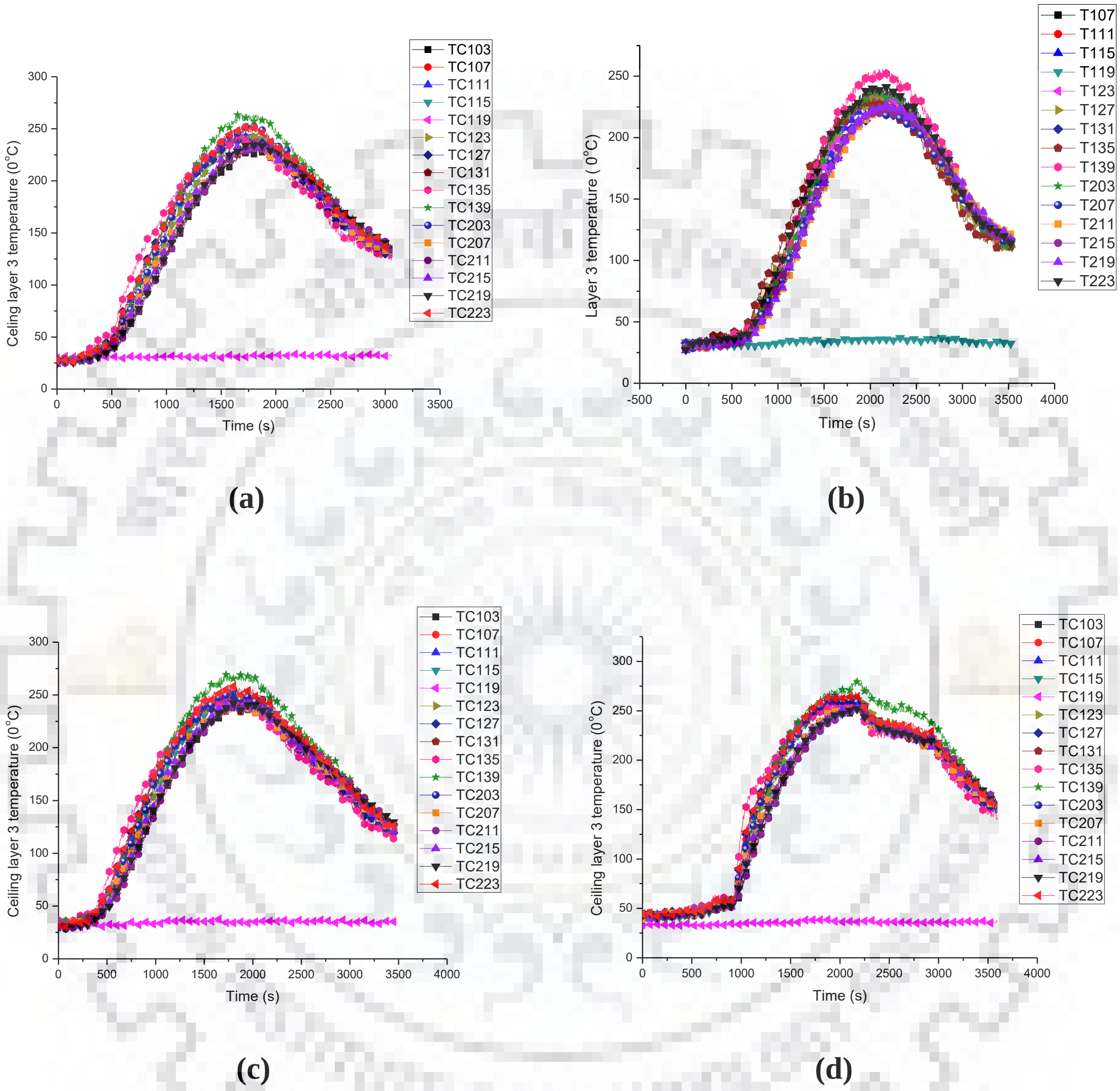
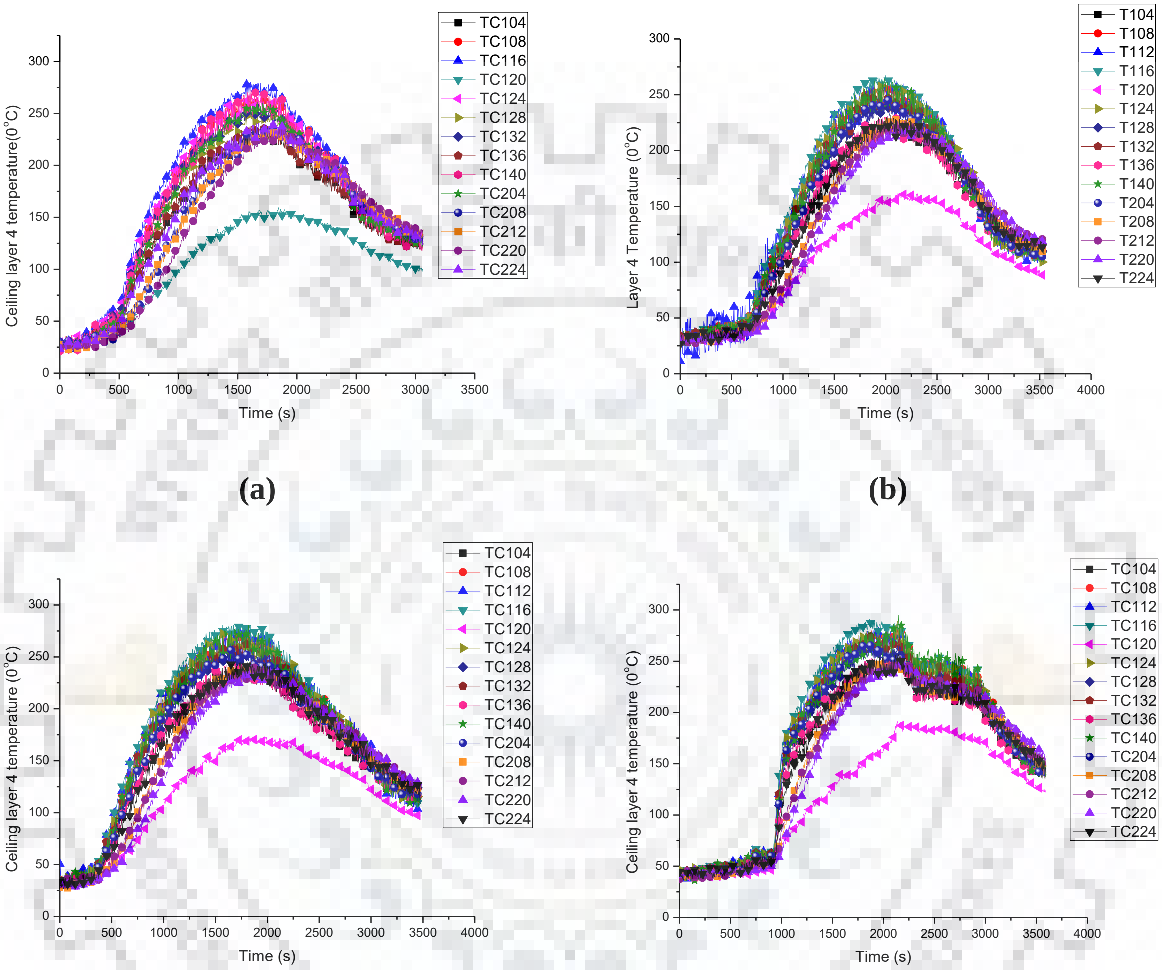


Figure 5.13 Variation in temperature of layer 3 of ceiling

Ceiling layer 4 temperature :

Layer 4 thermocouples are installed 1 m below the false ceiling and 1.15 m from ceiling.



(a)

(b)

(c)

(d)

Figure 5.14 Variation of temperature in layer 4 of ceiling

CHAPTER 6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion :

Mass loss rate has been greatly effected due to the ventilation variation by sliding the door. The maximum value of mass loss rate is very less effected but the rise duration has been significantly affected. As the ventilation has effect on the combustion of crib the temperature of hot gas layer decreases which results in formation of two zones. Ventilation also has the impact on the heat flux intensity and distribution . As the ventilation decreases the heat flux of ceiling, floor and upper zone of wall has invariably decreased but the heat flux at lower zone increased. The thermal layer height plays an important role in the distribution of heat flux in a compartment being ventilated variably.

6.2 recommendations for future work :

- Elevation of wood crib fire can be varied and the investigation can be done on behavior of fire and impact on compartment environment.
- Cross ventilation and forced ventilation can also be taken as a parameter and experiments can be performed to investigate the burning characteristic of crib.
- Water mist can also be employed to check the effect on burning characteristics of crib fire.
- Ventilation can be provided vertically and their effect can be observed.

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