

# Fire Testing and Study of Liquid Pool Fire in Multiple Compartments



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**Abstract** Many experimental/numerical studies on single compartment or single room fires have been reported in the literature but few studies are available for multiple compartments. There is a need for fire studies in multiple compartments as it may help in predicting fire impact in buildup environments with multiple compartments. In the present work, fire experiments were conducted in a real life two-storey compartmentalized concrete building. Aviation Turbine Fuel (ATF) was used as the liquid fuel to generate pool fire. The work, focused on the thermal hydraulic aspects like heat distribution to the corresponding walls, temperature near walls, vertical distribution of temperature close to fire and comparison of heat-flux and temperature at specified locations in the interconnected rooms. The study elucidates the impact of ventilation on various thermal and hydraulic aspects of fire.

**Keywords** Multi-compartment · Pool fire · Thermal-hydraulics · Wall heat flux

## 1 Introduction

The loss of lives and property damage because of fire accidents will always remain a subject of global concern and scientific research, whether it is a fire accident in a building, in an office or in a nuclear power plant. The degree of concern increases with the importance of that building: for example, fire in a nuclear plant is more of a concern than fire in a commercial building because the former causes loss of life and property as well as long-term environmental impact on its surroundings. This motivation for fire research has varied vastly from investigating fire scenarios to

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understanding the production of toxic species and behavior of fire and heat spreading during building fires. Studying compartment fires is a part of that motivation where researchers are more interested to study the fire behavior and its effect in a confined enclosure, which replicates an actual fire scenario in a building. The behavior of fires in building structures with interconnected multiple compartments often differs in fundamental ways from fires in a single confined space. Such fires have been poorly explored so far. The work by Luo and Beck is one of those few previous studies which were performed in a multi-room environment [1]. The current work adds to this literature.

Room fire or compartment fire is treated as enclosure fire. As defined by Karlsson [2], enclosure fire is the fire in a confined space, which is controlled by confined space for air availability and thermal environment; and this affects the burning rate, growth and life period of fire. So, while designing the fire safety models; fire growth, temperature, heat and duration required for fire control are some of the aspects that always need to be considered [2]. Materials used in building construction and plastic materials used in building interiors are some other factors that should not be overlooked [3].

Life Period of fires in compartment start with growth phase followed by fully developed fire during development phase and then burns out with decay phase [4]. Fire ignited in development phase grows in size from a small to large fire; if it is not suppressed it grows to its maximum size which depends on the amount of fuel supply and amount of oxygen available [5–11]. The development of fire depends on: (a) size and shape of compartment [10], (b) amount of fuel supply [10], (c) amount and availability of other combustible material around fire (which feeds the fire and causes it to grow), (d) provision and amount of ventilation in the compartment that regulates the air flow which can influence the thermal energy distribution [12, 13] and (e) type of building construction materials used [2]. Fire development phase goes through flashover transition, which requires major attention because it is the phase where fire can be suppressed before it affects the safety of human life and structure [5]. After flashover, when fire becomes fully developed, heat energy released in the enclosure is at its greatest and sometimes it is limited because of unavailability of sufficient oxygen. In case of insufficient oxygen, the fire becomes oxygen starved and starts to decay.

In compartment fires with growth of fire, heat transfer occurs by the process of radiation, convection and conduction but it is usually dominated by radiation [2]. The soot is the carrier of heat because the soot particles produced by combustion radiate the heat energy in all direction. Ventilation plays an important role in fire sustenance as the lack of oxygen can lead to burnout; on the other hand, it generates the path for smoke and soot to travel from one compartment to another. In buildings, doors and windows are generally used to provide natural ventilation and they become the passage for air entrainment to enclosures. The limited supply of oxygen in a closed enclosure creates chances of generation of the carbon mono-oxide (CO) gas if any oxygen hungry equipment is running nearby [8].

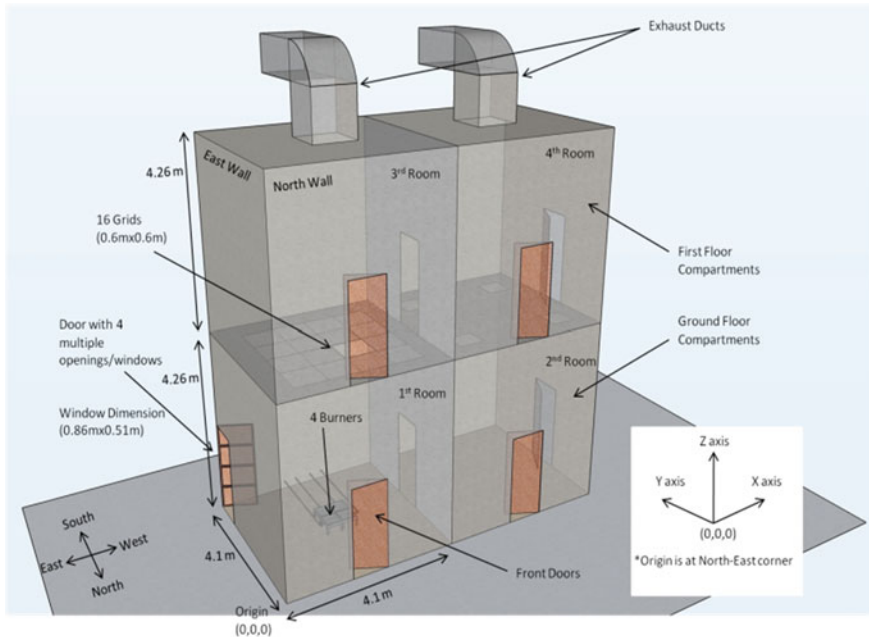
Heat flow, convection, combustion, radiation, soot generation and burnout phenomenon are also the part of prediction for evaluation and generation of a fire

model. During comparison between computational results and available experimental results, thermal radiation and soot radiation are two of the significant factors that play important role in accurate prediction of fire scenarios [14]. Smoke flow and temperature distribution during ventilation-controlled fire in compartments are dependent on ambient wind flow direction and speed. During fire incidents in tall buildings, ambient wind blow/flow affects smoke dispersion and fire dynamics. Ambient wind entering the compartment has two different effects: it supplies fresh air for entrainment, which provides more oxygen to promote fire growth, and because of entrainment of air, it promotes cooling process through convective heat transfer [15]. Many works available in literature are proof of how experimental and simulated results were used for confident predictions of firefighting by creating real life fire conditions. The real scale fire studies help fire fighters to understand the phenomenon of fire growth and smoke filling in multiple compartments [16, 17]. There are many experimental studies; in which full-scale fires in real scale rooms were studied, which replicates real life fire scenarios like in an office fire [18] or a storehouse fire [19]. These studies tell us that these types of full-scale experimental studies also help to modify fire safety policies and regulations. Full-scale experimental studies on single enclosures fires are also conducted in different weather conditions as per the geographical location of the building [17]. Work by Byström et al. [17] is an example of experimental studies where the fire studies were done at very low ambient temperature in a real scale building where horizontal and vertical compartmentalization were present.

With the goal to improve our understanding of fire and plume dynamics in multiple compartments, a research program was initiated for the study of associated thermal hydraulic aspects in multiple compartments, for a controlled fire burning in one compartment. A two-storey building with four full-scale rooms (interconnected multiple compartments) was used for a range of experiments. The heat and smoke transport to multiple compartments was studied with detailed measurements of heat-flux on boundaries, temperatures at different points, measurement of velocity and pressure of fire plume entraining through an opening at the ceiling, soot concentration and detailed measurement of increment in level of carbonaceous gases with depletion of Oxygen.

## 2 Description of the Facility and Instrumentation

At IIT Kanpur, an extensive fire testing facility, the first of its kind in India, has been developed to study single or multi-compartment fire scenarios and understand various aspects of fire dynamics, propagation and control. The state of the art instrumentation available in the facility is being used for fundamental and applied studies involving fire, combustion and fire safety issues. We have used two liquid fuels to generate two different types of pool fires, Aviation Turbine Fuel (ATF) and n-heptane. However, only the results pertaining to oil (ATF) fire is presented in this paper. The details of other experiments can be found in [20]. Figure 1 represents the state-of-the-art fire facility being used for the study of compartment fires, which contains four real



**Fig. 1** Schematic of multi-compartment of fire testing facility at IITK

scale rooms in a two-story building. The figure shows all of the four compartments (/rooms), in which first and second rooms are on ground floor while third and fourth are above them. All the rooms have same dimensions. All rooms have an inspection door opening ( $0.86 \times 2.06$  m) on their North sidewall. The first compartment has multiple windows on its East-wall at its Southeast corner, which is built by dividing a door into four equal parts. Dimension of each window is  $0.84 \times 0.51$  m (L  $\times$  H). The adjacent compartments are interconnected through a middle door between them. The ceilings of the two top compartments are connected with an exhaust duct. Many slots are present at different locations in all of the rooms for positioning the sensors.

In the test reported here, free ventilation was maintained in the compartments. In this phase, all the 4 rooms in the facility were used for study; the first room where fires were ignited is the most important room for this study as this room has most of the sensors. The other rooms also have the sensors which were used to compare the data collected from fire room with other inter-connected rooms as the adjacent compartments are affected and influenced by the thermal-hydraulic affects due to room fire.

Measurement of the heat flux on the walls was one of our main goal. Therefore, we have installed different types of heat flux sensors on the walls of the room at multiple locations. There are 5 types of heat flux sensors mainly used for this study. The HFP01 is a wall mounting round plate type sensor that measures the conductive heat flux over the wall. The SBG01 is Schmidt-Boelter heat flux meter to study the

**Table 1** Location and Coordinates of heat flux sensors

Heat flux sensor				
No.	Sensor name	Room <sup>a</sup>	Location	Coordinates <sup>b</sup> (x, y, z)
1	SBG01	Fire room	Ceiling-center	1.98, 2.05, 4.2
2	SBG01		Floor	1.2, 1.54, 0.38
3	HF03	Fire room	South wall	2.06, 4.09, 1.34
4	HF03		North wall	2.63, 0, 1.35
5	RC01	Fire room	East wall	0, 2.03, 2.72
6	RC01	Side room (/Top room)	West wall	R-2 (4.09+4.01, 2.54, 2.71) R-3 (0, 2.54, 4.26+2.71)
7	HFP01	Fire room	East wall, E8	0, 3.78, 2.46
8	HFP01	Fire room	East wall-center	0, 2.03, 2.1
9	HFP01		South wall-center	2.06, 4.09, 2.25
10	HFP01		North wall-center	1.93, 0, 2.22
11	HFP01		West wall-center	4, 2.04, 2.34
12	HFP01		Side room	East wall-center
13	HFP01	Side room	West wall-center	4.09+4.01, 2.0, 2.32
14	HFP01	Top room	East wall-center	0, 2.11, 4.2+2.29

<sup>a</sup>For convenience room-1 is named as fire-room. Room-2 is named as side-room and room-3 is named as top-room

<sup>b</sup>Origin of the coordinate system is the North-East corner of the fire room

fire and fire resistance and HF03 is a portable high range heat flux sensor. The RC01 is a square plate radiation-convection heat flux sensor. Details of the locations of the heat flux sensors are provided in Table 1.

In two-zone fire models, generally a room is divided into two different zones, the upper zone and the lower zone. The upper zone is the hotter region affected by hot air floating beneath the ceiling while the lower zone is colder and heavier. Upon heating, the air from the lower zone moves towards the upper zone establishing a convection current. We have divided the room in two zones to study the distinctive behavior of each. The wall sensors (HFP01) are mounted at the center of the walls to measure the heat flux at the center point of zone boundaries. A set of HF03 sensors was mounted in the lower zone of north and south walls of the fire-room. Two SBG01 were mounted near the pool for fire monitoring, one was mounted on a frame kept near the pool facing upward and another one hanging from the ceiling center facing downward. Two RC01 or rad-con sensors were mounted at the upper zone of the east wall of fire-room and west wall of side-room to measure heat flux by radiation and convection on compartment boundaries.

**Table 2** Location and coordinates of thermocouples

	Room	Location of thermocouple	Coordinates (x, y, z)
1	Fire room	East-wall	0, 2.03, 2.72
2	Side room/top room	West-wall East-wall	R-2 (4.09+4.01, 2.54, 2.71) R-3 (0, 2.54, 4.26+2.71)
3	Fire room	Pole, P4 (4.13 m above)	2.0, 2.70, 4.14
4	Fire room	Pole, P3 (3.13 m above)	2.0, 2.70, 3.14
5	Fire room	Pole, P2 (2.13 m above)	2.0, 2.70, 2.14
6	Fire room	Pole, P1 (1.13 m above)	2.0, 2.70, 1.14
7	Top room	center of room (2.13 m above floor)	2.0, 2.10, 4.26+2.14
8	Side room	center of room (2.13 m above floor)	4.09+2.0, 2.1, 2.14
9	Fire room	East-South corner @E8, above windows	0, 3.82, 2.46
10	Outside the fire room	S1 (2.13 m above floor)	Behind the south wall at South-East corner
11	Fire room	South-West corner @S4	4.08, 3.50, 1.40
12	Fire room	West-wall, within wall above door	4.09, 2.0, 2.13

Table 2 shows the list of the thermocouples with their location and coordinates. K type thermocouples of 3 mm thickness were used at different places to record the temperature variation at respective points with respect to time and with respect to the fire growth. A vertical pole was installed at the center of the fire-room (near the pool) into which 4 thermocouples were mounted to measure the temperature variation of the fire plume rising upward. The 1st thermocouple was 1.13 m above the ground, the 2nd, 3rd and 4th thermocouple were at 2.13, 3.13 and 4.13 m above the ground. Two thermocouples were hung from the ceiling at a height of 2.13 m above floor at the center of side-room and top-room. This arrangement allowed us to compare the temperature variation in all 3 rooms at the same point.

An NDIR based gas analyser that can measure NO, CO, CO<sub>2</sub>, CH<sub>4</sub> and O<sub>2</sub> gases was installed outside of fire-room. The emission gas probe was kept at the north-east corner of the fire room 0.5 m above the ground. Output results from analyser were displayed on analyser's display panel and output current in mA was acquired via the data acquisition module. A 5-hole probe was used to measure the pressure and velocity profiles at the ceiling opening of 0.5 × 0.5 m between room 1 (ground floor)

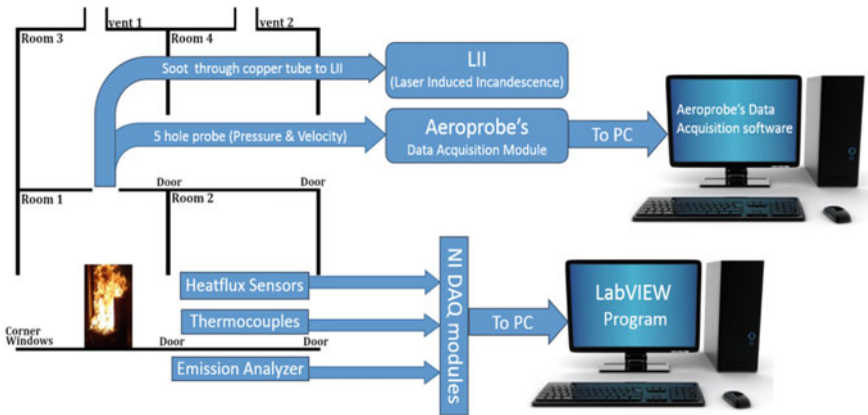


Fig. 2 Schematic of experimental setup

and 3 (first floor) at the centre of the ceiling at different points on a grid. The pressure data for a probe was acquired using a 36-port pressure scanner.

Various data acquisition modules were used to acquire analog outputs from these sensors, which were in physical units, using LabVIEW software for further processing. Further details of the measurements and instrumentation can be found in [20]. A schematic of the experimental setup is presented and an image of the pool fire is shown in Fig. 2.

### 3 Results and Discussion

In the series of liquid fires, the first test involved the study of small oil pool fire. For this test ATF (aviation turbine fuel) was used as the combustible liquid fuel. We name this as oil fire because ATF is used as aviation oil and is similar to kerosene oil used in industries and households. A small cylindrical vessel of 0.32 m diameter was kept at a height of 0.35 m above the ground on a stand. Initially, the pool was partially filled with water, and then ATF was poured to fill the vessel. All the windows and front door were kept open to support free ventilation during fire. The fire was ignited using a small cardboard paper dipped in ATF and placed over the surface of the liquid; as the paper cardboard ignited it heated up the rest of fuel over the surface and the fire spread over the surface. The estimated heat release rate [4] from this fire was 200 kW. Test conditions are tabulated in Table 3.

Different measurements, e.g., heat flux, temperature, etc. were taken at different locations and the results are discussed in this section. First, we will discuss the heat flux variations at different locations. Figure 3a shows the heat flux measured at the ceiling and the floor level. This plot shows that the maximum heat flux measured at the ceiling was 1.06 kW/m<sup>2</sup> at 420 s while that at the floor was 0.6 kW/m<sup>2</sup> at 430 s.

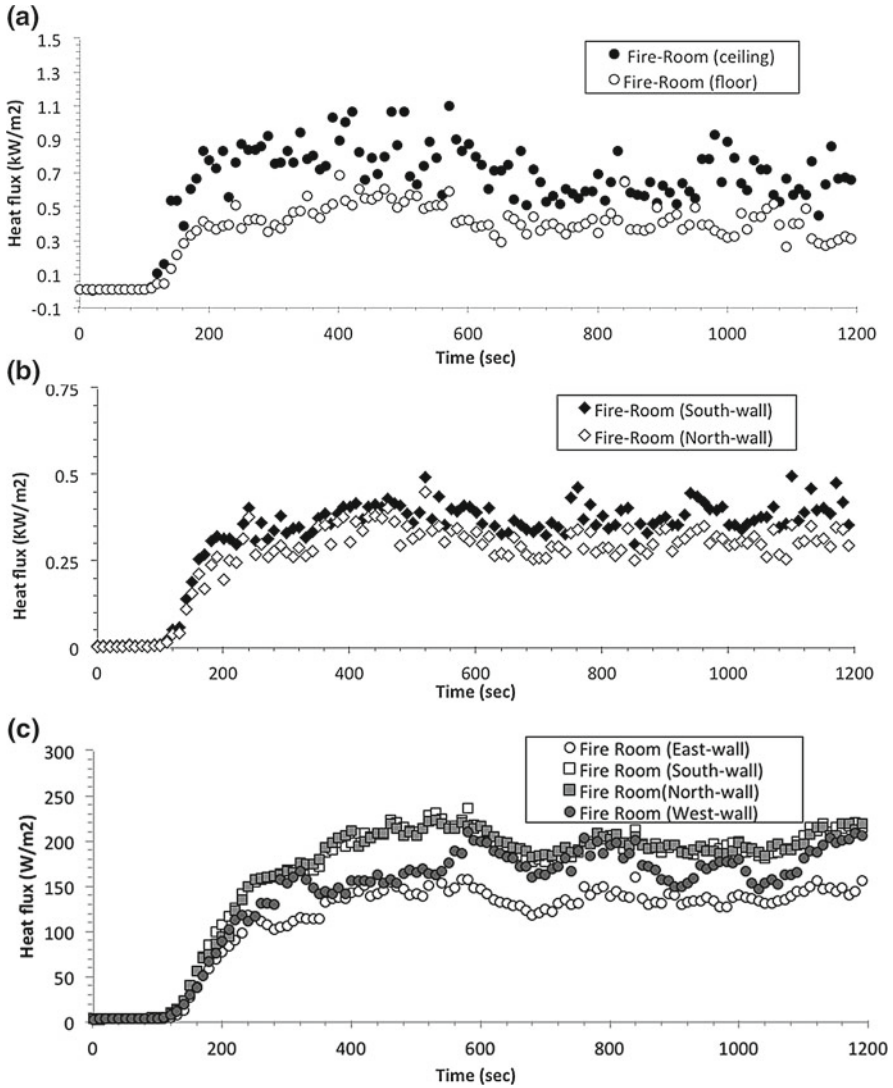
**Table 3** Details of the test

Test conditions	
Fire type	Pool fire
Fuel type	ATF (Aviation turbine fuel)
Fuel burner type	Small cylindrical vessel of diameter 0.32 m
Windows/opening condition	All windows open
Door opening condition	All doors open
Ventilation condition	Free ventilation (ambient temperature 23 °C)
Test duration	1200 s
Data rate (of processed results)	1 data per 10 s

The fact that the heat flux measured at the ceiling is almost double that at the floor suggests the well-known dominance of buoyant convection in free burning pool fires. After reaching the maximum, the heat flux started to decline at both the locations which suggests that fire stabilized and then started to decay at a very slow rate after 420 s. Due to the excess amount of fuel, the fire did not extinguish till 1200 s which was the specified time for the data acquisition. The opening in the ceiling ensures that there is no accumulation of heat close to the ceiling. The measured heat flux close to the ceiling exhibits a low frequency fluctuation due to the “Puffing” of burned products out of the ceiling opening. Inherent buoyancy driven fluctuation of the flame also contribute to this fluctuation in the heat flux.

Figure 3b shows the heat flux measured on the two opposite walls (north and south wall) of fire room, which lies in the lower zone of the fire plume. At 460 s, the maximum heat flux measured on north was 0.4 kW/m<sup>2</sup> while that on south wall was 0.42 kW/m<sup>2</sup>. Due to the symmetry of the room, both the sensors received almost the same amount of heat flux. Figure 3c shows the heat flux at the center of the east, south, north and west walls of fire room. The maximum heat flux measured on the north, south and east walls at 520 s were 221.3, 229 and 151 W/m<sup>2</sup>, respectively. Whereas that at the West wall was 209 W/m<sup>2</sup> at 580 s. The north wall, having the open door and hence source of combustion air, has received higher heat flux compared to others. On the other hand, the east wall did not have any ventilation opening, resulting in lower heat flux due to the lower concentration of combustion oxygen in that side of the room. The similarities in values are mainly because of the geometric symmetry and differences are due to the presence of openings, which affects the hot air distribution in the compartment. The fire seeks a source of oxygen to sustain itself and hence tilts towards the door or window, resulting in higher heat fluxes closer to the openings and lower fluxes away from the openings. Figure 3d shows the heat flux measured at the center of walls of 3 rooms; i.e., the east wall of fire room, west and east wall of side room and east wall of top room. The maximum heat flux was measured on the fire room’s east wall (163 W/m<sup>2</sup> at 530 s). On the side room’s east wall, the heat flux was 19.5 W/m<sup>2</sup> at 760 s, on top room’s east wall the heat flux was 98.6 W/m<sup>2</sup> at 610 s and on side room’s west wall was 18 W/m<sup>2</sup>. Thus, it can be





**Fig. 3** a Total heat-flux on floor (close to fire) and at ceiling (above the fire) in fire-room. b Total heat-flux on lower zone of two opposite side of boundary walls (North wall and South wall) of fire room. c Comparison between heat fluxes at center point of all 4 walls (North, South, East and West wall) in fire room. d Comparison between heat flux at centre point on boundary walls of three interconnected rooms (fire room, side room and top room). e Convective heat-flux at upper zone of end boundaries of fire-room and side-room. f Total heat-flux at upper zone of end boundaries of fire-room and side-room. g Convective heat transfer coefficient “h” at upper zone of boundary wall of fire-room

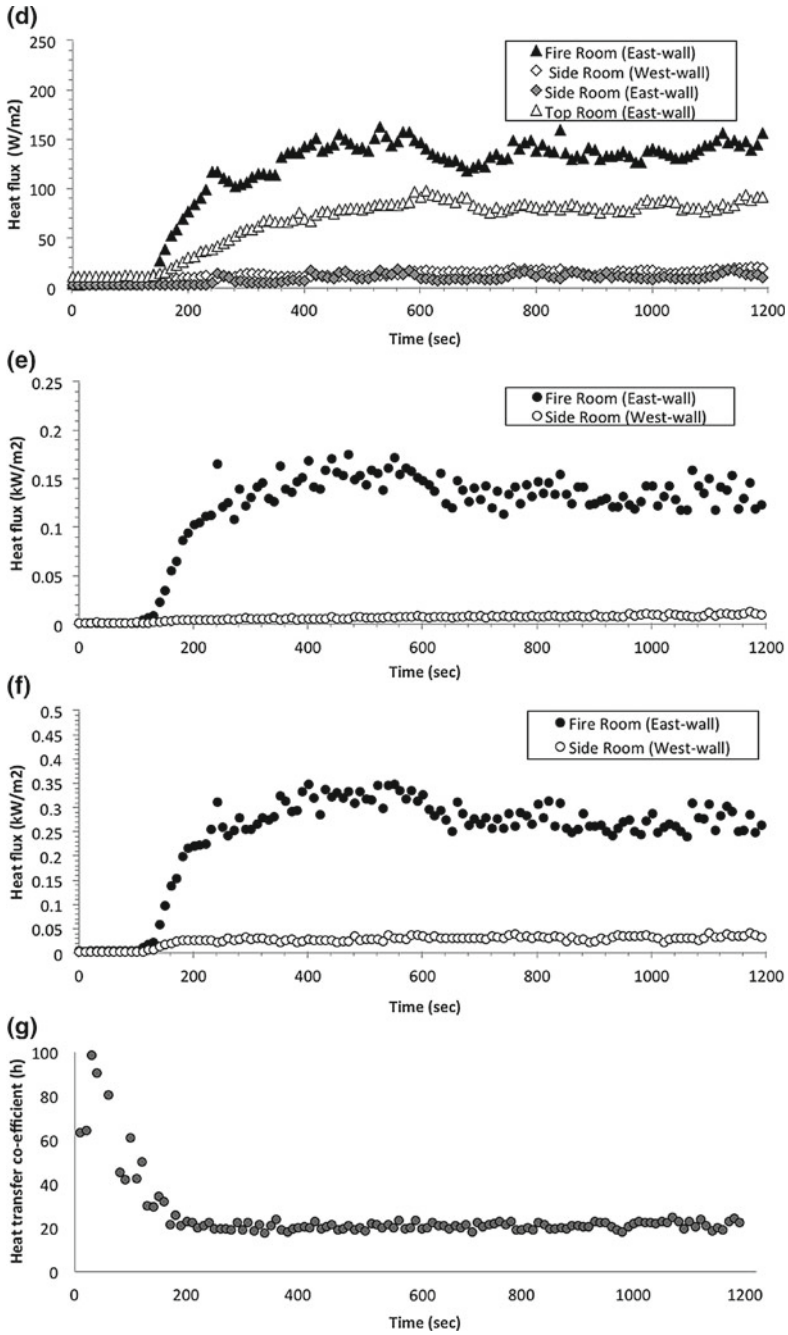


Fig. 3 (continued)

concluded that the fire room walls received the highest amount of heat flux followed by the top room and then the side room suggesting once again the dominance of buoyancy driven upward convection of heat. The west wall of the side room or the other end boundary of the lower compartment has received the least heat flux among all, which is justified because of its location. Figure 3e shows the convective heat flux measured on the east wall of the fire room and west wall of the side room. The maximum heat flux received by east wall of fire room was  $0.175 \text{ kW/m}^2$  at 470 s while on the west wall of the side room, the heat flux was only  $0.0137 \text{ kW/m}^2$ . This is much lower than the value on the same wall in the side of the fire room. The heat flux from the fire room to the side room is primarily conductive and hence the convective heat flux in the side room is very low even though there was an opening between the two rooms. Figure 3f shows the total heat flux measured at the same location as mentioned above in Fig. 3e. The maximum heat flux received by east wall of the fire room was  $0.34 \text{ kW/m}^2$  at 400 s and on the west wall of the side room, the heat flux was  $0.04 \text{ kW/m}^2$  at 760 s. The side room is not expected to receive any radiative heat flux. Therefore, since the maximum convective heat flux was  $0.0137 \text{ kW/m}^2$ , the conductive heat flux through the wall is  $0.0263 \text{ kW/m}^2$ , i.e. more than double the convective heat flux. Figure 3g shows the convective heat transfer coefficient or “h” in the upper zone of the boundary wall (east wall) of fire room. The coefficient starts with a relatively high value at the beginning but decreases rapidly during the fire growth stage stabilizing thereafter to a constant value of about  $20 \text{ W/m}^2 \text{ K}$ .

Figure 4a shows the temperature variation of fire plume rising upward in vertical direction plotted using data from four thermocouples, which were mounted on a vertical pole at every 1-m interval starting from 1.13 m. The maximum temperature recorded was  $41.3 \text{ }^\circ\text{C}$  at 1.13 m,  $56.4 \text{ }^\circ\text{C}$  at 2.13 m,  $56.6 \text{ }^\circ\text{C}$  at 3.13 and  $60.4 \text{ }^\circ\text{C}$  at 4.13 m. This shows that with increase in height the temperature of the plume is increasing, as is common in buoyancy driven fires. Figure 4b shows the comparison between 3 thermocouples at 2.13 m above floor level placed in 3 different rooms. The highest temperature was measured in the fire room at  $41.3 \text{ }^\circ\text{C}$ , the next highest temperature was measured in the top room at  $37.6$  and the temperature measured in side room was  $24.18 \text{ }^\circ\text{C}$ , reached after a time delay of 1180 s due to the low rates of heat transfer or heat flux as discussed in Fig. 3. Fire plume affects fire room the most whereas after striking the ceiling it entrains into the top compartment (or room) and very small amount of hot air enters the side room from the upper zone and from the lower zone (doors and windows) cold air entrains into the fire room to sustain the fire. Figure 4c shows the temperature variation of air close to the walls. The temperature comparison between the upper zone (above the doorway on East wall) and the lower zone (on South-West corner) of the fire-room shows that the maximum temperature recorded in the upper zone of the east wall was  $49.7 \text{ }^\circ\text{C}$  while that measured on the south wall was only  $28.7 \text{ }^\circ\text{C}$ . The temperature increase in the upper zone of the east wall is higher than the growth in lower zone of south wall. Figure 4d shows the temperature variation between the end boundaries of the two rooms (east wall of fire room and top room). The highest temperature measured in fire room was  $45.4 \text{ }^\circ\text{C}$  and in the side room was  $25.8 \text{ }^\circ\text{C}$ , which is also reached at a much later time. The difference in temperature and the time is quite obvious, as the temperature growth

on the boundary of the fire room will be faster compared to side room, due to larger heat fluxes in the fire-room. The hot air travelling from one end of the fire room to other end of the side room will take some time and meanwhile it will keep losing the heat to the surrounding. Thus, the temperature at the end boundary of side room is not affected much by presence of fire.

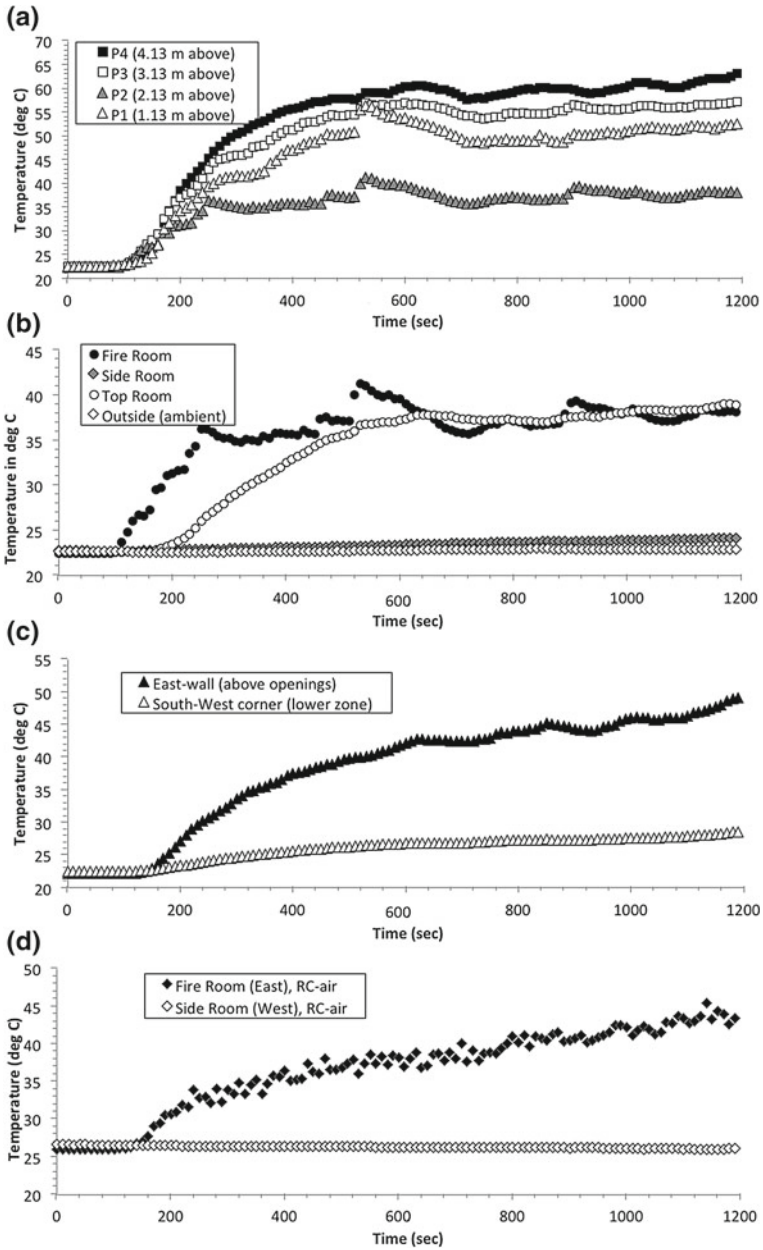
The measured data shows a rapid increase in wall heat flux followed by a gradual drift during the fire development and sustenance stage as seen in Fig. 3. However, the fire affects only the fire room and the top rooms, with almost no impact in the side room suggesting the dominance of buoyancy in fire propagation.

Figures 5a–c show the plots obtained from emission measurements. The average value of CO during peak period of fire was 0, CO<sub>2</sub> was 0.2 vol.% and O<sub>2</sub> decreased by 0.3 vol.%. The case being with free ventilation is expected to have minimal variation in emission parameters with almost complete combustion of the fuel vapour resulting in the absence of CO. Figures 6a–c show the velocity and pressure of fire plume entraining the top compartment. The maximum velocity of plume measured was 2.76 m/s. The maximum dynamic pressure measured was 13 Pa at 210 s. The higher values of axial velocity (Fig. 6a) as compared to other velocity components confirms the fact that the fire is primarily buoyancy driven and hence the side rooms are not affected by the fire plume as has been discussed earlier. The fluctuation of the velocity data with time suggests “puffing” of the burned products out of the fire room at a low frequency of about 0.05 Hz.

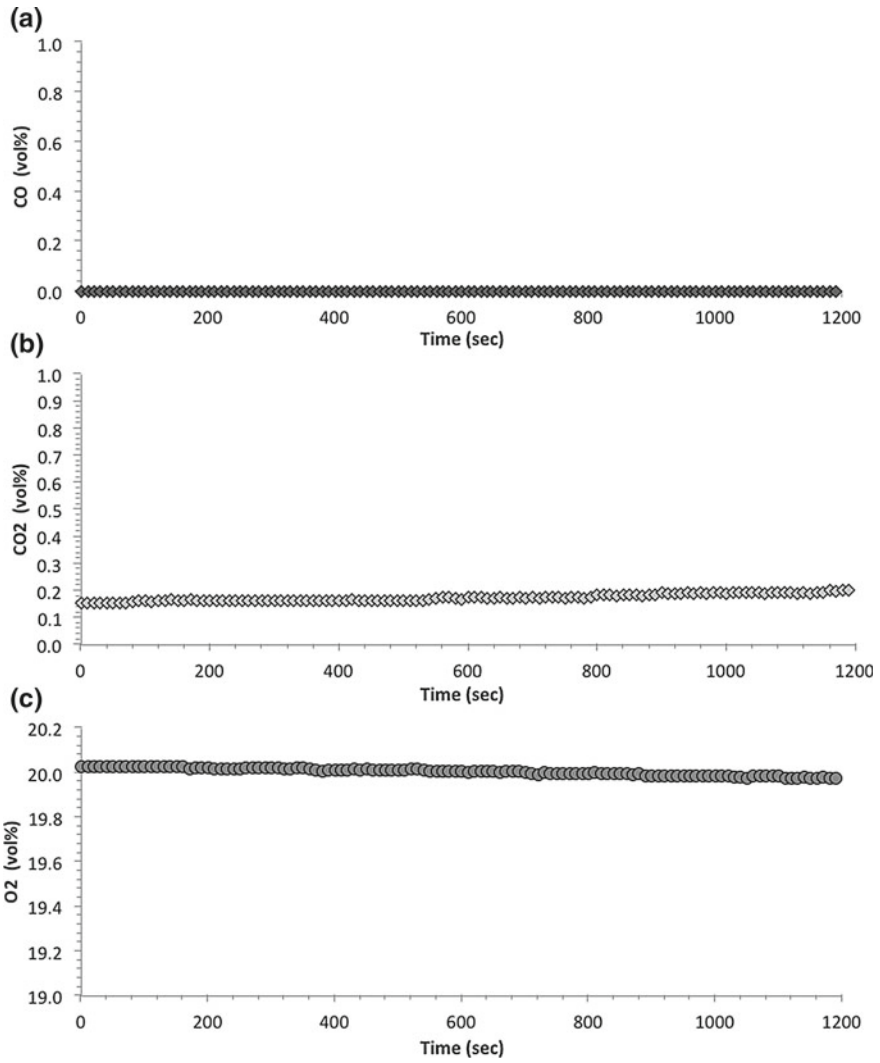
The data presented so far establishes the primacy of buoyancy in the thermal-hydraulic aspects of fire in a room. The side rooms are much safer as compared to the top rooms vis-à-vis the fire room. The emission parameters are well within the acceptable limits in case of well-ventilated fires and the wall heat fluxes are also not very large. Therefore, proper thermal stress management of the ceiling is expected to make a building fire safe. However, in order to study the impact of fire on walls, corner fires and the fires in the vicinity of the walls must also be studied. The present chapter provides an extensive data base of the designers to validate the fire safety codes.

## 4 Conclusions

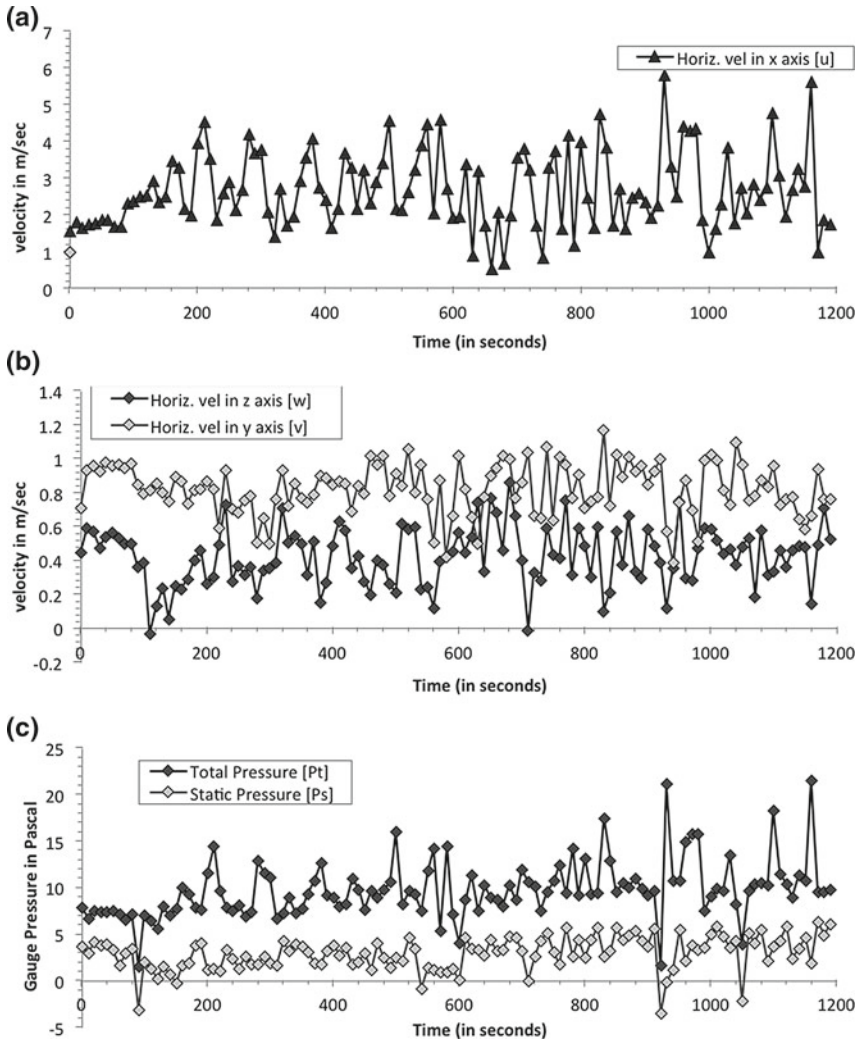
Detailed measurement of wall heat flux, temperature, pressure, velocity and emissions were carried out for a small pool fire of ATF in a multi-compartment fire facility under well-ventilated conditions. It was observed that the primary impact of the fire was in the fire room and in the room just above the burning fire suggesting the dominance of buoyancy on fire plume dynamics and growth. The fire had very minimal effect in the side rooms. The growth of the fire plume is accompanied by a rapid increase in wall heat flux and temperature in the fire room followed by a steady state. The data presented in this paper can be a good source for the validation of fire simulation codes.



**Fig. 4** a Temperature variation of fire plume rising upward in vertical direction above floor. b Comparison between temperatures at centre point of all three interconnected rooms. c Temperature variation closed to wall between upper zone (above doorway on East wall) and lower zone (on South-West corner) of fire-room. d Temperature variation between end boundaries of ground floor rooms (fire-room and side-room)



**Fig. 5** a CO concentration in vol.%. b CO<sub>2</sub> concentration in vol.%. c O<sub>2</sub> concentration in vol.%



**Fig. 6** a Axial velocity of the fire plume at the centre of the ceiling opening. b Planer velocities (along y and z) of the fire plume at the centre of the ceiling opening. c Gauge pressure measured at the centre of the ceiling opening

## References

- M. Luo, V. Beck, The fire environment in a multi-room building: comparison of predicted and experimental results. *Fire Saf. J.* **23**, 413–438 (1994). [https://doi.org/10.1016/0379-7112\(94\)90006-x](https://doi.org/10.1016/0379-7112(94)90006-x)
- B. Karlsson, J.G. Quintiere, *Enclosure Fire Dynamics* (CRC Press LLC, 1999), <http://dx.doi.org/10.1201/9781420050219>
- W.K. Chow, C.W. Leung, Necessity of testing fire behavior of plastic materials under flashover. *Polym. Testing* **25**, 853–858 (2006). <https://doi.org/10.1016/j.polymertesting.2006.03.012>
- D.D. Drysdale, *An Introduction to Fire Dynamics* (Wiley, 1985), <http://dx.doi.org/10.1002/9781119975465>
- V. Babrauskas, Free burning fires. *Fire Saf. J.* **11**, 33–51 (1986). [https://doi.org/10.1016/0379-7112\(86\)90051-2](https://doi.org/10.1016/0379-7112(86)90051-2)
- V. Novozhilov, Flashover control under fire suppression conditions. *Fire Saf. J.* **36**, 641–660 (2001). [https://doi.org/10.1016/s0379-7112\(01\)00019-4](https://doi.org/10.1016/s0379-7112(01)00019-4)
- F.W. Mowrer, Enclosure smoke filling revisited. *Fire Saf. J.* **33**, 93–114 (1999). [https://doi.org/10.1016/s0379-7112\(99\)00023-5](https://doi.org/10.1016/s0379-7112(99)00023-5)
- W.K. Chow, W.Y. Hung, On the fire safety for internal voids in highrise buildings. *Build. Environ.* **38**, 1317–1325 (2003). [https://doi.org/10.1016/s0360-1323\(03\)00114-8](https://doi.org/10.1016/s0360-1323(03)00114-8)
- N.P. Bryner, G.W. Mulholland, Smoke emission and burning rates for urban structures. *Atmos. Environ.* **25**, 2553–2562 (1991). [https://doi.org/10.1016/0960-1686\(91\)90172-4](https://doi.org/10.1016/0960-1686(91)90172-4)
- E.H. Yii, A.H. Buchanan, C.M. Fleischmann, Simulating the effects of fuel type and geometry on post-flashover fire temperatures. *Fire Saf. J.* **41**, 62–75 (2006). <https://doi.org/10.1016/j.firesaf.2005.09.001>
- V. Babrauskas, Heat of combustion and potential heat, in *Chapter 8, Heat Release in Fires, Elsevier Applied Science*, ed. by S. J. eds. (Grayson, NY, 1992), 207–223 pp
- K. Klobut, K. Sirien, Air flows measured in large openings in a horizontal partition. *Build. Environ.* **29**(3), 325–335 (1994). [https://doi.org/10.1016/0360-1323\(94\)90030-2](https://doi.org/10.1016/0360-1323(94)90030-2)
- P. Tuomaala, J. Rahola, Combined air flow and thermal simulation of buildings. *Build. Environ.* **30**(2), 255–265 (1995). [https://doi.org/10.1016/0360-1323\(94\)00044-s](https://doi.org/10.1016/0360-1323(94)00044-s)
- G.H. Yeoh, R.K.K. Yuen, S.C.P. Chueng, W.K. Kwok, On modeling combustion, radiation and soot processes in compartment fires. *Build. Environ.* **38**, 771–785 (2003). [https://doi.org/10.1016/s0360-1323\(03\)00022-2](https://doi.org/10.1016/s0360-1323(03)00022-2)
- H. Chen, N. Liu, W. Chow, Wind effects on smoke motion and temperature of ventilation-controlled fire in a two-vent compartment. *Build. Environ.* **44**, 2521–2526 (2009). <https://doi.org/10.1016/j.buildenv.2009.04.008>
- D. Mackay, T. Barber, G.H. Yeoh, Experimental and computational studies of compartment fire behavior training scenarios. *Build. Environ.* **45**, 2620–2628 (2010). <https://doi.org/10.1016/j.buildenv.2010.05.021>
- A. Byström, X. Cheng, U. Wickström, M. Veljkovic, Full-scale experimental and numerical studies on compartment fire under low ambient temperature. *Build. Environ.* **51**, 255–262 (2012). <https://doi.org/10.1016/j.buildenv.2011.11.010>
- C.J. Chen, W.D. Hsieh, W.C. Hu, C.M. Lai, T.H. Lin, Experimental investigation and numerical simulation of a furnished office fire. *Build. Environ.* **45**, 2735–2742 (2010). <https://doi.org/10.1016/j.buildenv.2010.06.003>
- P. Yang, X. Tan, W. Xin, Experimental study and numerical simulation for a storehouse fire accident. *Build. Environ.* **46**, 1445–1459 (2011). <https://doi.org/10.1016/j.buildenv.2011.01.012>
- P.K. Sharma, A. Raut, A. Kushari, *Study of Small Scale Room Fires, DAE/AE/20090034/2* (Department of Aerospace Engineering, IIT Kanpur, 2015)