Studies on a fire retardant coating on Expanded polystyrene under-deck roof

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Dedicated to my Parents

Smt. Mythili Venugopalan

&

Late. Shri. Venugopalan

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Abstract

This thesis is concerned with basic studies on a suitable coating that enables protection of the existing Expanded Polystyrene (EPS or Thermocole) under-deck roofing during occurrence of fire. The coated EPS is also tested for its performance towards fire using enclosure fire studies in small and large size rooms. The objective of this work originates from an examination of fire accidents involving the use of expanded polystyrene under-deck roofs leading to loss of life and loss of property in public places like hotels and shopping places.

The aim is to evolve a strategy to protect existing EPS-based roofing systems at an affordable low cost. The technique involves thin coating of gypsum / plaster of paris (PoP) over low (~45) GSM paper, by a process that helps prevention of the dripping during fire event, thus improving fire safety. Several methods of coating gypsum PoP over EPS were also tried to optimize the layer loading of protective coating to the EPS board with improved aesthetics.

Initial trials with a coating layer of ~ 1 to 1.5 mm gypsum PoP reinforced with a porous paper found to hold the kerosene pool fire ignition source with a predetermined power of range 25 to 35kW for a period of about 30 minutes in 1m^3 cubical room while under identical conditions the uncoated roofing got burnt in less than 80s.

Fire studies carried out in a large room size of dimension 8.5 m × 5 m × 2.5 m with coated EPS roofing using centrally located pool fires of different power levels ranging from 100 kW to 320 kW. Response of coated EPS to room ignition sources at various strengths and chosen scales of fire power are determined with an emphasis to egress time. The maximum power the coated roof could take up is found to be with a centrally located pool fire with a power of ~320 kW for a period ~ 3 minutes. Smoke layer height is found to get stabilized to a level of about 1.4 m from the floor for the pool fires ranging up to 320 kW for the experimental room with a vertical door opening of 1 m (W) × 2 m (H).

Computational studies are conducted to predict the temperature profiles and heat flux at different locations of the enclosures, both on 1 m^3 cubical room as well as the large sized room. These were conducted using Fire Dynamic Simulator (FDS), a widely used Computational Fluid Dynamics (CFD) based open /free software tool available from National Institute of Standards and Technology (NIST) website. The predicted results were compared with that of experimental results that show reasonable comparison. When the comparisons are considered not satisfactory, explanations are attempted.

The present studies bring out that gypsum coating on existing uncoated EPS-roof is possible and to ensure egress time of 3 minutes in case of fire, the maximum possible fire power in a given size room is also determined using the data from the cases studied. It is also inferred that a fire study conducted in this manner could provide valuable information in terms of life safety, equipment safety and protection of valuable items that were accommodated in a given enclosure. Further it can also help in designing the fire protection systems accordingly.

This thesis comprises of seven chapters. Chapter 1 introduces various types of materials including EPS and method of roof insulation that are in practice. Types of EPS, their properties and behavior towards fire, applicable codes and standards related to EPS, existing fire protection techniques and the need for fire protection of existing EPS under deck roofings are discussed. Experiments conducted by various authors using pool fires to check the fire performance of EPS and their validation through simulations are discussed. Chapter 2 is on the market survey, existing usage of EPS, preliminary studies of the locally purchased materials. Importance of fire protection and opportunity for fire proof coating of the existing roofs with EPS false ceiling tiles are discussed. Chapter 3 discusses in detail about Tools and Techniques that are employed in the studies. Chapter 4 is about the experimental studies that are conducted in $1m^3$ cubical room. Results of coated and uncoated EPS roofings are discussed. Chapter 5 discusses the experimental studies that are conducted in the large scale room with a view to understand the coated EPS roofing's performance to fire of large scale. Effect of location of ignition source with respect to the door opening on air entrainment, gas layer temperature and velocities at door way, smoke layer height were determined giving emphasis to safe egress timings. Chapter 6 details on the fire simulations carried using the fire dynamic simulator and comparison of the results obtained with that of the experimental data. Chapter 7 gives an overview of the work, the advantages of the fire proof coating for existing EPS roofing and limitations.

Nomenclature

List of Symbols

ε	emissivity
δ	Thickness, m
v	Velocity, mean velocity, m/s
ρ_0, ρ_∞	Ambient gas density
℃	Degree centigrade
ΔP	Pressure difference , Pa
ΔT	Temperature difference, °C
$\dot{Q}$	Fire power , fire heat release rate
c_p	Heat capacity at constant pressure
D^*	Characteristic fire diameter
g	Acceleration due to gravity , m²/s
H	Room height, m
H_p	Target height from floor, m
Hz	Hertz (frequency unit)
k	Thermal conductivity, W / m.K
K	Kelvin
k_f	Fire location factor, m
F_e	Fire elevation, m
kW	Kilo watt
LC	Least count
Pa	Pascals
P_f	Final pressure, Pa
P_i	Initial pressure, Pa
Q_f	Fire power , fire heat release rate
r	Radial distance, m

t	Time, seconds or minutes
$T\infty$	Ambient temperature, °C
T_{amb}	Ambient temperature, °C
TC	Thermocouple (Type – K)
T_f	Fuel temperature, °C
T_g	Gas phase temperature, °C
T_{pl}	Plume temperature, °C
T_s	Surface temperature, °C
T_w	Wall temperature, °C
u	u-velocity, m/s, velocity component x-direction
v	Velocity component, y- direction, m/s
W	watt
w	Velocity component, z- direction
Z_i	Neutral plane height i^{th} level, m

List of abbreviations

ASTM	American Society for Testing and Methods
BIS	Bureau of Indian standards
C	Circular
CBRI	Central Building Research Institute, Roorkee (India)
CFD	Computational fluid dynamics
CFL	Compact fluorescent lamp
Cr.	Corner location
Daq	Data acquisition system
DNS	Direct numerical simulations
EPS	Expanded poly styrene (thermocole)
EUMEPS	European Manufacturers of EPS
F	fuel

FDS	Fire Dynamics Simulator
FR	Fire retarded
GSM	Grams per square meter
IS	Indian standard
ISO	International organization for standardization
LES	Large eddy simulations
LPG	Liquid Petroleum gas
MLR	Mass loss rate (g/s or kg/s)
NFPA	National fire protection association
n-H	Normal Heptane
NIST	National Institute of standards and technology
PoP	Plaster of Paris
RBI	Reserve Bank of India
S	Square
SE	Self-extinguishing
SMEP	Smoke movement evaluation programme
SPIV	Stereoscopic particle image velocimetry
TPD	Tons per day
UL	Underwriters Laboratories

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Chapter 1

Introduction and Literature Survey

1.1. Introduction

Under-deck roofing or false ceiling was originally developed to conceal underside of floor above and to offer acoustic balance and control in a room. It was invented by Donald A Brown of West Lake, Ohio (see Intnet1, 2013). The space above the false ceiling, called the plenum space is often used as a space for ventilation systems, requiring only enclosed ducts that deliver fresh air into the room below. Return air enters the ceiling space through open grills across the ceiling. Further, it is also used to hide the electrical wiring that run above the false ceiling to meet the changing needs of the office space. In addition, the under-deck roofing also helps in energy saving, reducing heat transferred through ceilings by roof insulation.

In India, a variety of materials are put to use for roof insulation purpose like expanded polystyrene (EPS) or thermocole boards, plywood boards, mineral fibre boards, fibre glass etc. History of usage of EPS for the purpose of roof insulation in India goes back to 1960s and the Indian standard, EPS for thermal insulation IS: 4671 was actually introduced in the year 1968. This standard still prevails with reaffirmation in the year 2004. The size of the board used is generally 1 m × 0.5 m, 0.61 m × 0.61 m, or 0.6 m × 0.6 m with thickness ranging from 8 mm to 50 mm or as per customer's requirement. The Indian standard recognizes two types of EPS for insulation purpose namely Self-extinguishing (with fire retardant) and Non-self-extinguishing (without fire retardant) types. In addition to this, part 4 of National Building Code of India, NBC 2005 prescribes requirements for interior surface finishing material in which material put to use for covering wall, ceiling materials need to be classified according to IS: 12777:1989, Indian standard for Fire Safety- flame spread of products – method for classification.

Thermal properties of EPS make it more suitable for cyclic temperature variations and hence are preferred for the purpose of thermal insulation. Being a closed cell light weight material produced from polystyrene, EPS gains its exceptional insulating properties from the stabilized air trapped within its structure which enables it to provide long term performance in low temperature applications.

Concerns arise due to some of the recent fire accidents, although the reports mention the reason for the fire accidents in most cases as electrical short-circuits; the involvement of materials to cause the spread of fire could not be ignored. Table 1.1 contains a list of fire accidents that have taken place in shops, malls, and banks, which are linked to EPS.

Table 1.1 Information on publicly reported fire accidents in recent times

Date	Details of the Accidents
June12, 2012	Fire due to thermocole in Jeedimetla unit of Hyderabad resulted in property loss in lakhs (Intnet4, 2012)
Sep. 26, 2011	A major fire broke out at research and development facility of a pharmaceutical company in Sholinganallur, Tamilnadu (Intnet5, 2011)
June 02, 2011	Fire in a three storied textile show room, Belgaum, resulting in five deaths.(Intnet6, 2011)
Mar 17, 2011	Fire in SBI Branch, Kolhapur leading to loss of documents (Intnet7, 2011)
Feb 26, 2011	Major fire in Canara Bank Branch, Mandipet leading destroying of electronic gadgets and furniture (Intnet8, 2011)
Sep 06, 2010	Fire destroys computer shop at OTC road, Nagarthpet, Bangalore leading to goods loss of Rs. 25 million (Intnet9, 2010)
Mar 13, 2010	Fire broke out in thermocole factory leading to loss of property of worth Rs. 50 million (Intnet10, 2010)
Feb 23, 2010	Fire in Carlton towers, killing Nine and injuring 68 people (Intnet11, 2010)
Dec 09, 2009	Fire broke out in basement of Hotel Capitol, Bangalore (Intnet12, 2009)
Nov. 07, 2009	Fire in a factory at Sancoale due to thermocole led to a loss of property worth Rs. 60 lakhs (Intnet13, 2009)
Oct 07, 2009	Fire in a mall at MG Road, Bangalore (Intnet14, 2009)
May 22, 2008	Fire in a Mall, Vashi, Navi Mumbai. (Intnet15, 2008)

Many such fire accidents indicate the need for the fire proof materials in place. The false ceilings and the wall linings should be fire-proofed as they hide adhoc electrical wiring and eventually become source for fire spread at the instance of electrical short-circuit. Codes and Standards at national and international levels like Part 4 of NBC 2005 of India, Approved Document B of UK and International Fire Code of USA have separate clauses for interior surface finishes that provides guidelines on the requirement of classification of these materials and respective method of safe applications inside different type of occupancies. More details on EPS properties and behavior, operating safety codes on interior surface products, type of usage in practice, the need for protection and subsequent evaluation by appropriate method in this regard is discussed in the following sections.

1.2. Literature survey

Literature survey is presented under four headings namely, (a) survey on behavior and properties of EPS, (b) operating safety codes for interior surface products, guidelines / fire protection techniques available in literature for EPS usage, (c) enclosed pool fire tests, and (d) review on FDS validation of enclosed pool fire tests.

1.2.1 Survey on behavior / properties of EPS

Collier and Baker (2013) have worked on the influence of construction detailing on the fire performance of polystyrene insulated panels. They quantify the fire performance of polystyrene insulated panel consisting of an EPS core material sandwiched between light gauge metal skins. The paper also discusses the thermal properties of EPS. EPS is resistant to a temperature of 90°C for short duration, and 80 °C for long term exposure. Above this temperature EPS will soften until ~150 °C where it will begin to shrink and return to the density of the base material. Subject to continued heating EPS will melt and form gases above 200 °C which will undergo piloted ignition at ~ 360 °C – 380 °C and auto-ignite above ~ 500 °C. Fire performance experiments on Panels with regular and FR EPS showed beneficial results with FREPS. Preliminary experimental studies conducted with locally purchased EPS thermocole also gave identical results and these are covered in the following chapter 2.

Suman and Srivatsava (2009) in their work on Influence of thermal insulation on conductive heat transfer through roof ceiling construction emphasize the importance of roof insulation to reduce incoming heat flux, since major heat transfer (> 60%) occurs through roof in composite climate. Their study compares the performance of thermal insulation of roofing system with expanded polystyrene (EPS) and fiberglass (FG) with conventional roof having no insulation as reference. Ceiling temperature of untreated roof was found higher than all other treated roof. They have also found out under identical conditions that rooms with EPS experiences 1.5°C less room temperature than that of Fiber glass material.

Singh et al (2006) have conducted a study using thermocole and recommend the usage of thermocole for the purpose. Table 1.2 drawn from their work compares the thermal resistance of various insulating materials. A combination of 38 mm thick thermocole is combined with 6 mm thick plywood is hanged to the roof by means of hooks. This system is found to improve occupant comfort during summer as well as winter seasons.

Table 1.2 Comparison of various thermal insulating materials *(Singh et al, 2006)*

S.No.	Insulation Materials		Thickness mm	Thermal Resistance $m^2.K/W$
1	Flexible (mineral wool, glass fibre)	Low density	140	2.83
		Medium density	140	3.3
		High density	140	3.93
2	Loose fill	Glass fibre	100	2.00
		Mineral fibre	100	2.30
		Cellulose fibre	100	2.50
3	Spray	Polyurethane	100	4.1
		Isocyanurate	100	3.4
		Cellulose fibre	100	2.4

Papadopoulos (2005) in his paper on state of art in thermal insulation and aims for future developments refer to insulation materials as a key tool in designing and constructing energy thrifty building. The author classifies the insulation material into inorganic, organic, combined, new technology materials.

Table 1.3 Thermal insulation properties *(Papadopoulos et al., 2005)*

Parameter	Glass wool		Stone Wool		Extruded polystyrene		Expanded Polystyrene		Poly-urethane foam	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Density (kg / m^3)	13	100	30	180	20	80	8	50	30	80
Thermal conductivity (W / m K)	0.03	0.045	0.033	0.045	0.025	0.035	0.029	0.041	0.02	0.027
Temperature Application (°C)	-100	500	-100	750	-60	75	-80	80	-50	120
Reaction to Fire Class	A1	A2	A1	A2	B1	B2	B1	B2	B1	B2

Table 1.3 shows the comparison of various insulation materials in line with their thermal properties. It can be noted that EPS has the least density and the corresponding thermal conductivity is close to other members. The paper also details about the composition and process of EPS as being made up of 1.5 to 2% of polymerized polystyrol and air 98 to 98.5%, while pentane is used as propellant gas in the expansion process. HBCD (hexa-bromo-cyclo-dodecane) is used as a fire retardant in EPS at a level of 0.5 to 0.7 %. Thermal properties of EPS found to be *between those of organic and inorganic insulation materials*.

Yucel et al (2003) discuss the thermal insulation properties of expanded polystyrene as construction and insulating material; the usage ratio of EPS in construction is found to be 15% due to its relatively light weight and high insulation property. EPS is affected by changes in the composition of the materials in the cells. The thermal conductivity varies according to the production density which normally varies from 10 – 100 kg/m^3. Generally, densities of 10 – 30 kg/m^3 are used in construction. Experimental results indicate that thermal conductivity decreases with increase in density and is valid till to an optimum value. Figure1.1 shows experiments carried for densities up to 50 kg/m^3 because of the fact that, decrease in the amount of total voids in EPS will increase in compactness leading to increase in thermal conductivity.

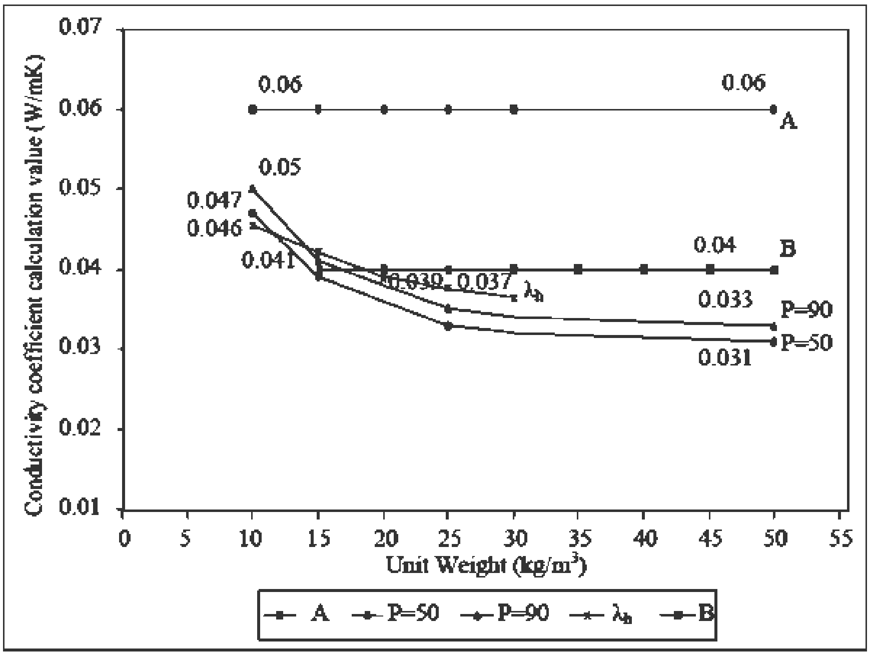


Fig. 1.1 Plot of thermal conductivity of EPS vs. density (kg/m3) *Yucel et al (2003)*

Rossi et al (2001) worked on characterization of smoke in EPS combustion, with and without fire retardants (FR) in cone calorimeter at 35kW/m^2 irradiance level. HBCD (Hexa-bromo-cyclo-dodecane) is used as FR additive for EPS. The presence of fire retardant modifies the combustion characteristics of EPS and the composition of smoke. Ignition is delayed by about 67% (from 47 s to 75 s at35 kW/m^2). Similarly, the release or appearance of smoke, CO_2 production although delayed, is not significantly affected by the presence of FR additive. Composition and morphology of smoke particles remain unaffected as per SEM (scanning electron micrograph). From the data shown in Table 1.4 on the concentration of major gaseous combustion products in the case of EPS without FR and with FR additive, it is observed that the addition of FR reduced styrene concentration and increased production of phenol, α-methyl styrene, and benzaldehyde with no significant effect on smoke formation.

Table 1.4 Major gaseous products of combustion EPS and FREPS *(Rossi et al, 2001)*

Name	EPS without FR (w/w)	EPS with FR (w/w)
Styrene	22.1 %	14.5 %
α-methyl styrene	1.0%	5.1%
1,3-diphenyl-propane	0.3%	1.9%
Propenylbenzene	2.4%	2.3%
Naphthalene	4.3%	4.6%
Anthracene	0.5%	1.0%
Phenol	1.3%	5.1%
Benzaldehyde	2.9%	1.6%

From the above references, it is inferred that while EPS usage in construction is encouraging with growing awareness of energy saving by the industry, the fire behavior of EPS points to the need for fire proofing of the material. Replacement of the board by furnishing a new one may not be cost effective in all occasions; instead, a cost effective fire proof coating should be conceived. The next section presents the requirements of existing codes of various countries for the application of interior surface products.

1.2.2 Operating Safety Codes for interior surface products

Codes operating in three countries, namely, UK, the USA and India are outlined here; the reason is that the codes currently operating in India has its origins in that of UK and has some influence from that of the USA.

UK:

The Building Regulations 2006 edition Fire Safety Approved Document B (BR, 2010) incorporating 2007, 2010 and 2013 amendments is the recent document to be enforced from

April 2013. Section B2.v of the code describes classification of fire performance and the classifications of 0,1,2,3 based on tests in BS 476 Fire tests on building materials namely,

Part 6: Method of test for fire propagation for products

Part 7: Method of test to determine the classification of surface spread of flame of products

Part 4: Non combustibility test for materials

Part 11: Method for assessing the heat emission from building products

While part 6 and 7 guides to assess materials of classes 1, 2 and 3, class 0 is assessed by Part 4 and part 11 tests.

For European countries, classifications for interior surface products are specified in BS EN 13501-1:2007, Fire classification of construction products and building elements, part-1 – classification using data from reaction to fire tests. The classification is for all products excluding flooring and is A1, A2, B, C, D, E and F (A1 being highest rating and F being the lowest) based on a combination of four test methods namely

BS EN ISO 1182:2002- Non combustibility test

BS EN ISO 1716:2002 – Determination of the gross calorific value

BS EN 13823: 2002 – Building products excluding flooring exposed to the thermal attack by the single burning item

BS EN ISO 11925:2002 – Ignitability when subjected to direct impingent of flame

For suspended ceilings Table 10 of the code provides the guidelines details of which are mentioned in the following Table 1.5

Table 1.5 Classifications of linings as per Table 10 of approved document B

Location	National Class (British)	European Class
Small rooms of area not more than: a. 4 m^2 in residential accommodation b. 30 m^2 in non- residential accommodation	3	D-s3, d2
Other rooms (including garages) Circulation spaces within dwellings	1	C-s3, d2
Other circulation spaces, including the common areas of block of flats	0	B-s3, d2

Note: "s3, d2" means there is no limit set for smoke production and/or flaming droplets / particles.

USA:

In USA building codes are developed by not to profit organizations and are adapted by the states. The codes are referred to as model codes and the major model code adapted is the International Building Code (IBC) comprising International Commercial / Residential Code (ICC / IRC), International Fire Codes (IFC, 2006), electrical and plumbing codes, mechanical codes developed by International Code Council. According to section 803 of IFC, interior finish, decorative materials and furnishings should be grouped in accordance with ASTM E 84, (identical to UL 723, Steiner Tunnel test) Standard Test Method for Surface Burning Characteristics of Building Materials or NFPA 286 (identical to ISO 9705) Standard Methods of fire tests for evaluating contribution of wall and ceiling interior finish to room fire growth. Following Table 1.6 provides a glimpse of these two methods of classifications with respect to interior products.

Table 1.6 ASTM E 84 and NFPA 286 requirements for interior products

Classification as per ASTM E 84	Acceptance criteria as per NFPA 286
Class A : flame spread index 0-25; smoke developed index 0-450	40 kW exposure for 5 minutes: flames shall not spread to the ceiling
Class B: flame spread index 26-75; smoke developed index 0-450	160 kW exposure for 15 minutes: 1. flame shall not spread to the outer extremity of the sample or any wall or ceiling 2. flash over, as defined in NFPA 286 shall not occur
Class C: flame spread index 76-200; smoke developed index 0-450	During entire test : smoke released shall not exceed 1000 m^2

India:

Section 3.4.15 of Part 4 of NBC 2005, specifies the need for treatment of the material of combustible nature with fire retardant and the treated product should be put to use as per section 3.4.15.3.

According to section 3.4.15.1, the interior finishing materials that are used in buildings should not generate smoke or fumes. Their susceptibility to fire is determined in terms of rate of flame spread. Section 3.4.15.2 classifies the surfacing material in to four different classes based on the flame spread rate.

Class 1 – surfaces of very low flame spread

Class 2 – surfaces of low flame spread

Class 3 – surfaces of medium flame spread

Class 4 - surfaces of rapid flame spread

Section 3.4.15.3 specifies the way in which these various classes of materials should be adapted in building construction as shown in the following Table 1.7.

Table 1.7 Usage of interior finish materials in building construction

Class	Usage
Class -1	May be used in any situation
Class -2	May be used in any situation, except on walls, facade of the building, staircase and corridors
Class -3	May be used only in living rooms and bed rooms (but not in rooms on the roof) and only as a lining to solid walls and partitions; not on staircases or corridors or facade of the building

Note: paneling shall be permitted in a limited area but shall not be permitted in a vestibule.

Section 3.4.15.4 specifies that the materials of Class – 4 as above, shall be put to use as ceiling lining with due fire retarding treatment provided the ceiling is atleast 2.4 m high from the top surface of the floor below. The treated material should meet the requirement of Class – 3 above (See Table 1.7).

The test method recommended by the standard with regard to classifications as above is the IS: 12777:1989 Fire Safety – Flame Spread of Products – Method for classification. In this method flame spread, one of the factors which contributes to the fire growth is determined and according to this standard test results relate only to the behavior of tested specimens of the product under the particular conditions of the test and are not intended to be the sole criterion for assessing the potential fire hazard of the product in one.

The standards mentioned in this section above help in qualitatively classifying the materials to be put into use for specific purpose. The results of these tests do not necessarily reflect the actual fire performance of the product in the real fire scenario. A product that passes a standard test can fail in the real fire situation or vice versa because the flow conditions to which the product is exposed in practice is vastly different from that of the test and research study correlating the results from the standard test to a real fire situation is seldom available. Testing the products' performance in terms of minimum time to egress would thus help in quantifying the fire performance of the product under development. This is one of the reasons that the work aimed at in this thesis uses a testing procedure through which the actual fire performance of the product is rated in terms of available time to egress and the maximum threshold of fire the product can hold.

1.2.3 Guidelines available in literature for EPS usage

A recent released report by Central Building Research Institute (see Intnet3, 2011) presents a method of roof insulation to homes where in EPS sheets of 1 m × 0.5 m × 0.05 m size and density 18 kg/m3 is fixed directly on to the ceiling using bitumen primer. A 19 mm wire mesh is fixed below the EPS sheets and tied to the roof by means of GI wire. This is then coated with PoP over EPS sheets. These methods are shown to be successful but not cost effective in case of existing EPS false ceilings. The coating technique should either involve carrying out the job either at the customer place or it can be taken for coating at the service providers' place.

Nelligan (2006) in his work provides guidelines for the use of expanded foam polystyrene panel system in industrial buildings so as to minimize the fire risk. The work discusses the types of EPS, their manufacturing process, and properties and behavior to fire and provides guidelines for safe usage of panel systems making note of various fire accidents that had occurred in New Zealand and also mention passivation of line trusses with gypsum plaster board.

Table 1.8 Toxic releases of EPS and natural materials during fire
(*Source: EUMEPS, 2004*)

Type of test piece	**Constituents of the fire gases**	**Fire gas composition in ppm at a test temperature**			
		300°C	**400°C**	**500°C**	**600°C**
Standard EPS	CO	50*	200*	400*	1000**
	Styrene monomer	200	300	500	50
	Other aromatics	Traces	10	30	10
	Hydrogen bromide	0	0	0	0
Flame retardant EPS	CO	10*	50*	500*	1000**
	Styrene monomer	50	100	500	50
	Other aromatics	Traces	20	20	10
	Hydrogen bromide	10	15	13	11
Pine wood	CO	400*	6000**	12000**	15000**
	Aromatics	-	-	-	300
Insulating soft board	CO	14000**	24000**	59000**	69000**
	Aromatics	traces	300	300	1000
Expanded Cork	CO	1000*	3000**	15000**	29000**
	Aromatics	traces	200	1000	1000

Note: Test conditions as specified in DIN 53 436, air supply 100 LPH
Specimen size (mm): 300 × 15× 10; * - smoldering fire; ** - flame fire; - Not measured

European Manufacturers of EPS, EUMEPS (See Intnet2, 2004) have quantified the fire performance of EPS when used as insulation materials in buildings. They have considered aspects of fire performance of EPS in terms of heat release, flame spread, smoke production and toxicity and its contribution to the propagation of fire. Performance of fire retardant additives is also evaluated. Their study has shown that burning behavior depends on the surrounding conditions as well the inherent properties of EPS. Addition of fire retardant to the cellular material can vary the inherent property. EUMEPS recommends introduction of a facing material or complete encapsulation. Further, they describe the behavior with temperature increase; if the EPS is exposed to a temperature above 100 °C, the material begins to soften, contract and melt finally. It is indicated that the material ignites above a temperature of 350 °C. EPS – SE grade (Self-extinguishing) which contains a fire retardant additive will burn if exposed to ignition sources of heat fluxes in the range of 50kW/m^2. Flaming ignition did not occurred for fluxes in the range 20kW/m^2. EPS produces a heavy, dense, black smoke in proportion to the mass consumed by fire. It appears that smoke released from EPS is equally or less toxic than those released from the natural products as shown in the Table 1.8. It should be noted that EUMEPS regulations strongly recommend that EPS should be used with a proper protective system.

D'Souza (1981), studied on the flammability of common interior linings when used as protective finishes for EPS. The experiment consisted of a modified corner wall test conforming to ULC-S127-1978 in which the material is lined on all surfaces of the room interior and are exposed to natural gas fire of 33 kW power using 220 mm Ø burner located at wall corner of 1.2 m cubical room. Results indicate that usage of 12.7 mm gypsum board as protective lining for EPS is advantageous compared to other alternatives such as wood, plywood, fibre glass. This method is not a cost effective one for the existing roof with EPS.

As stated earlier in the section 1.2 of this thesis NBC 2005 requires the material used for interior ceilings should be classified as per IS: 12777: 1989. Further ISO 9705, 1993, a Full Scale Room Test is found to be global standard for evaluating fire growth potential of interior surface finishing materials. Apart from this, studies have been conducted by the research community (see section 1.2.1 & 1.2.4) to evaluate the fire performance of floor / wall lining or roofing materials. It is therefore necessary to conduct experiments that are most suitable to the conditions of its usage, towards evaluating the materials performance to real fire situations.

Considerable work has been carried out by researchers with rooms of varying sizes with different power levels and these are discussed in the next section.

1.2.4 Literature on enclosed pool fire studies

Poulsen and Jomaas (2012) carried an experimental study on the burning behavior of pool fires with n-heptane as fuel under free burn and room burn conditions. The objective of the study is to investigate the impact of thermal feedback on the HRR of an object with a fixed area of burning in a room in comparison with results from free burn experiments. The experiment was conducted in ISO 9705 room (Fig. 1.2) of 3.6 m × 2.4 m × 2.4 m dimension and the inner side of the room was furnished with lining materials lining-1 and lining-2 with thermal inertia 0.0036 and 0.09 kW^2s/m^4K^2 respectively. Individual experiments were carried to study the influence of these materials on thermal feedback with heptane pools of varying pan sizes viz. 0.35 m, 0.50 m and 0.70 m having a lip height of 0.152 m, 0.2 m and 0.2 m respectively. The pool sizes were chosen so that the calculated flame heights are below and above the ceiling. The pans were located centrally and studies were conducted individually for free burn, wall lining 1 and 2 inside the compartment.

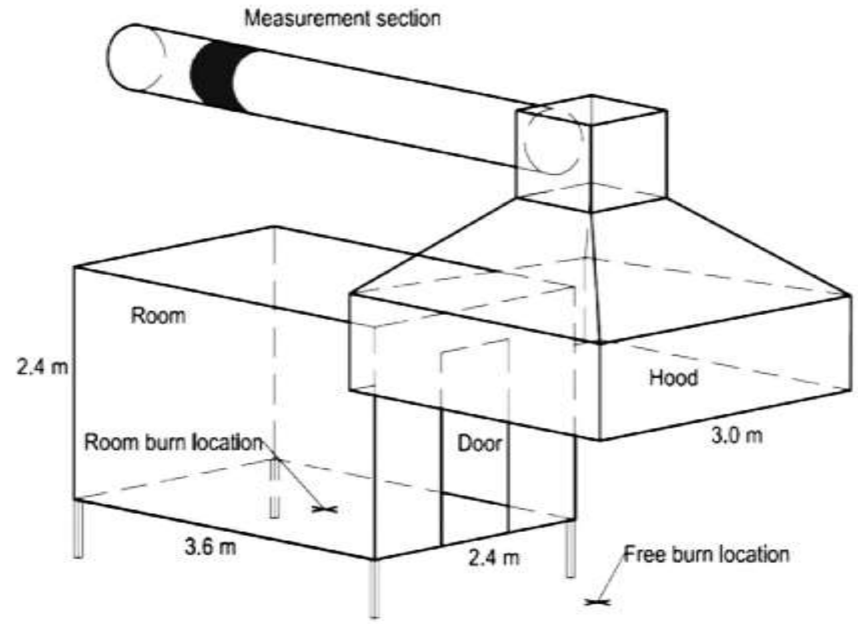


Fig. 1.2 Experimental set up as per ISO 9705 (*Poulsen and Jomaas, 2012)*

Results indicate that the burn rate and thus HRR of the pools in the case of confined and unconfined studies vary significantly to a level of 66 to 130% for 0.7 m diameter pools while in the case of 0.5 m diameter pool there is only slight difference increase up to 20% with lining-1. With lining-2 which has relatively higher thermal inertia compared to lining-1, not much difference is found in both the cases of 0.5 and 0.7 m pools, while in the case of 0.35 m both

HRRs of lining-1 and lining -2 were found to be lower than that of the free burn. Thus the effect of enclosure and linings were found to be significant only with a higher power like 0.7 m pool where the flame height is such that it impinged on the surface of the ceiling shortly after the ignition. Experiments conducted in a similar manner with centrally located fire inside an 8.5 m × 5 m × 2.4 m room also gave identical results in that no effect of thermal feedback observed in the HRRs with centrally located pool fires of the range 100 kW, where the flame height is found to be ~1.5 m.

Gupta et al (2012) report the experimental results performed in a 1m^{3}cubical chamber, on the suppression of n-heptane pool fires, using water mist. The experiment uses pool fire created using two circular diameter 100 mm (C100), 125 mm (C125) and one square pool of size 150 mm x 150 mm (S150), all with a depth of 50 mm, located at corner of the room leaving a space about 200 mm from the wall. Burn rate and HRR were studied by maintaining a fuel depth of 35 mm and a free board of 15 mm, fuel quantity being 50 ml (C100 & C125) and 100ml (S150). Mass of the fuel was recorded manually during burning using dynamic weighing counter at 5 s intervals. HRR calculated was plotted with time and average HRR during the steady state was estimated to be 5, 6.2 and 12.5 kW for the pools. Characteristics of the pool fire with respect to the size and quantity of the fuel are tabulated below in the Table 1.9. It is observed that steady state burning is achieved in 20 s in all the cases and the duration of steady burning was 130 s in the case of circular pools and 100 s in the case of S150, dropping thereafter. Total burn duration was found to be 390 s, 280 s and 200 s respectively for C100, C125 and S150.

Table 1.9 Effects of pool parameters on HRR

Author	**Pan Size (mm)**	**Fuel**	**Fuel Qty. (ml)**	**Fuel level (mm)**	**Water level (mm)**	**Lip height (mm)**	**Pool location**	**HRR kW**
Gupta et al (2012)	Ø 100	n-H	50	35	0	15	Cr.	5.0
	Ø 125	n-H	50	35	0	15	Cr.	6.2
	S 150	n-H	100	35	0	15	Cr.	12.5
Kang et al (2010)	Ø 100	n-H	100	13	0	27	**	4.3
	Ø 140	n-H	200	13	0	27	**	11.9
	Ø 200	n-H	408	13	0	27	**	25.0
	Ø 300	n-H	918	13	0	27	**	68.9

S- Square; n-H – n-heptane; Cr. –corner; ** – not indicated

Kang et al (2010) have performed experimental studies on burning rate of small scale heptane pool fires. Experiment consisted of pans of dia. 0.1 m, 0.14 m, 0.20 m, and 0.30 m with 0.04 m height and wall thickness 0.003 m, initial fuel thickness 0.013 m of n-heptane. Flame height, burning rate, real time fuel and wall temperature profiles have been measured. From the burn rates of individual pools the respective powers are calculated to be 4.3 kW, 11.9 kW, 25.0 kW and 68.9 kW for the pans of dia. 0.1 m, 0.14 m, 0.20 m, and 0.30 m respectively. These are shown in Table1.8 which highlights the effect of various parameters on the burn rate of the pool.

Hamins et al (2008) has provided data from a large scale fire test conducted in a 7.04 m (W) × 21.66 m (L) × 3.82 m (H) with a doorway of 2.0 m (W) × 2.0 m (H). It consisted of centrally located hydrocarbon spray fire of 1MW power positioned in the room for over ½ hr. Vertical temperature profiles, heat flux to compartment surfaces, velocity and temperature at compartment door and total heat release rate data are presented. From data (between pan and wall opposite to door) it is evident that thermal discontinuity (neutral layer) stabilizes at about 1.5 m height from the floor after about 200 seconds. Cold layer temperature attains a temperature of 60°C in 200 seconds which then gradually increase to 80°C in about 1200s. Hot gas layer temperatures are in the range of 150 - 220 °C. Weighted average temperature at 320 mm below the ceiling quickly rose to 250°C in 400s and stabilized with a very gradual increase to 280°C in 1200 s. Measured velocities at the door, coming into the room was recorded at 1.5 m/s (30 s time average data) and upper most profiles measured velocities of 1 m/s leaving out of the room, during the fire. Neutral plane in the door way varied from 1m to 1.4 m above floor during steady burning period.

Johnsson et al (2007) worked on reduced scale compartment fire experiments, which include local measurements of temperature and species composition. 17 experiments with 56 different combinations of fuel, HRR and door configurations were carried. The internal dimensions of the 2/5 scale ISO 9705 room used in the experiments were measured as 0.95 m (W) × 0.98 m (H) × 1.42 m (D) with doorway geometry 0.81 m × 0.48 m located centrally and horizontally on the 0.95 m wall. The experiments provided a comprehensive and quantitative assessment of major and minor carbonaceous gaseous species and soot at two locations in the upper layer of fires. The paper discusses the distinctions between fires with different fuels in terms of temperatures, heat fluxes and CO concentrations and about the differences regarding half-width and full-width door way experiments. Only a portion of the experimental results are highlighted in the paper and it states that the soot producing fires of heptane, toluene and polystyrene generated hotter temperatures than the cleaner fires of alcohols and natural gas at the same HRR. Experiments conducted with heptane with varying HRR 150, 245, 340 kW, using 0.25 m × 0.25 m pan, gave an average temperature of 700 °C, 850 °C and 1100 °C at rear gas sampling location when keeping the door vent fully open and HRR 140, 220 kW gave temperatures of 750 °C and >1200 °C when keeping the door vent narrow (0.81 m × 0.24 m). It is found that the transition to ventilation – limited burning occurred at a much lower HRR, narrow vent configuration than for a full doorway configuration as result of reduced O_2 (from 9% to 2%) and increased CO (from 0.5% to 1%) concentrations. Further oxygen concentrations depleted for fires larger than 280 kW. The measured door way velocities were in the range of -7 m/s (flowing out) and +1.5 m/s (flowing in to the enclosure).

Jeong and Ryou (2002) have carried out an investigation on fire induced smoke movement in room fire with various pool locations. The aim of the study is to examine the wall effect on smoke movement and flame structure in three dimensional room fires towards validation of a self-developed Smoke Movement Evaluation Program (SMEP) model. The experiment consisted of 10 mm thick acryl and asbestos plate enclosure with dimensions 1.8 m × 1.8 m × 1.38 m (H) with a door opening of 1.18 m (H) × 0.48 m. Pool fires of methanol were used with three different sizes of square pan viz. 0.15 m × 0.15 m, 0.25 m × 0.25 m and 0.39 m × 0.39 m dimensions with 0.07 m depth and power levels of 7.6 kW, 21.2 kW, 51.7 kW respectively. Results of the experiment indicate that as the fire strength becomes larger for fire source located at the centre, air mass flow rate in the door, average hot layer temperature, flame angle and mean flame height increase but the doorway neutral plane height decreases. On the other hand, as the wall effect becomes larger in room fires, the hot layer temperature, mean flame height and doorway neutral plane height increase. With corner fire although the temperature near ceiling is found to be higher than that of the central fire, it takes longer for smoke to fill the top region and with egress point of view such as the smoke filling time and early spread of plume in room space, the results of the center fire are more critical compared to the wall and corner fire. The work presented in this thesis also considers this point and experiments are carried using centrally located pan fire.

Quintiere et al (1981) in their work on the effect of room openings on fire plume entrainment, uses the experimental results in a room of size 2.8 m × 2.8 m × 2.13 m and with methane as fire source supplied through a 0.3 m diameter centrally located diffusion flame burner flush mounted to the floor has studied evaluation of insitu entrainment characteristics, at two different power levels 62.9 kW and 158 kW. Vent configurations of varying door openings 4/3, 1, 1/3 and 2/3 of 0.98 m × 1.83 m and full, 2/3, 1/3 top and 1/3 bottom window configurations chosen. Temperatures were measured inside the room with a vertical array of aspirated thermocouples mounted near the room corner and centerline of door opening. It is seen that the plume orientation, gas temperatures as well the neutral plane height varied with differing vent configurations in both power levels. Also the neutral plane height (Z_i) from the floor decreased with increase in vent opening area as well the air entrainment rate decreased as the neutral plane grew downwards. Temperatures increased with height up to the neutral plane height and also increased with reduction in vent area. Not much variations observed in neutral plane height with increase of power. Table 1.10 details on this.

Table 1.10 Effect of door openings on neutral plane height and gas layer temperatures (*Quintiere et al, 1981)*

		62.9 kW				**158 kW**			
Door / window	**Area m²**	**Z_i (m) ± 0.1**	**m_a kg/s**	**Neutral plane temp °C**	**Roof Temp °C**	**Z_i, (m)** ± 0.15	**m_a kg/s**	**Neutral plane Temp, °C**	**Temp roof °C**
4/3 door	2.39	1.11	0.66	90	85	0.99	0.93	167	163
3/3 door	1.79	0.97	0.56	100	95	0.99	0.71	194	184
1/3 door	0.89	0.80	0.45	110	105	0.80	0.53	229	227
2/3 door	0.44	0.51	0.26	144	140	0.57	0.25	301	299

McCaffrey and Rackett (1977) studied the static pressure measurements of enclosure fires. Pressure measurements for both full and scale model rooms have been presented and are compared with hydraulics – orifice model for fire induced flow into and out of enclosures. A comparison on FDS results with this model will be presented later in the chapter 6 of this thesis. The authors present some measurements of vertical distribution of both ΔP and ΔP as a function of temperatures for a given height, in full scale and scale model enclosure burns. This is intended to facilitate validation of flow portion of enclosure models incorporating hydraulic scheme and assessing the enclosure modeling in terms of plume entrainment which determines the height of the thermal discontinuity.

Fire source being a movable gas burner with a power of 140kW for full scale room test and a combination of three Meker burners (spelt as meeker) power of which is not mentioned in the paper (a Meker burner provides uniform heat of ~3.5 kW) were used. Pressures were found to be measured with a variable capacitance electrical manometer calibrated against a micro manometer. Temperatures were measured using Type K thermocouple having 0.5mm bead thickness. The paper discusses the variation of pressure and temperature with the location of fire within the enclosure by locating a 140 kW power source at centre, corner, and middle of the rear wall and rear corner. It is found that the upper gas temperature is significantly hotter for the corner location of the burner as compared to the centre. Further the thermal discontinuity and predicted neutral height will also be higher for the corner configuration. Reason for this has been explained considering the plume entrainment as the centre burner is able to entrain more cold air and yields cooler upper gas temperature than the corner burner location. The authors also present the effect of fire size with varying power source of 62, 140, 340, 459 kW leading to higher temperatures and larger pressure differential with increase of power of fire source.

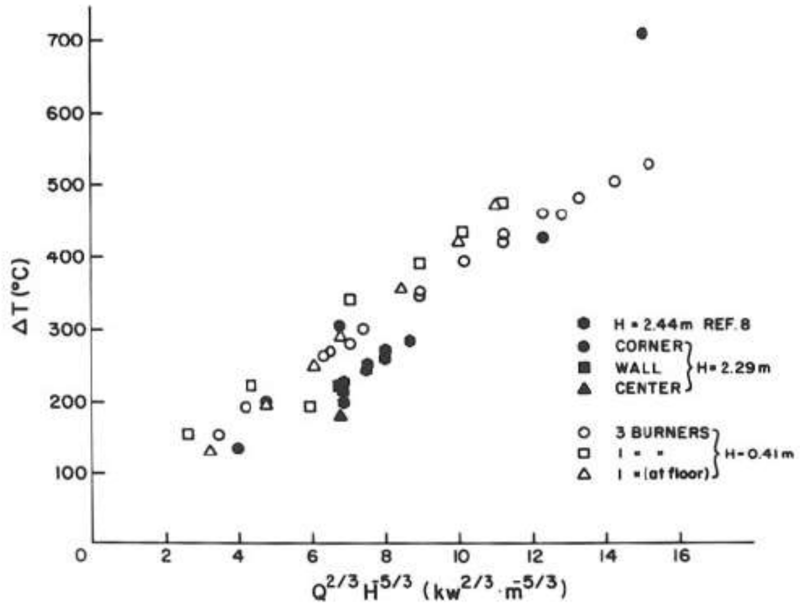


Fig. 1.3 Upper gas temperature as a function of fire and compartment size
(*McCaffrey and Rackett, 1977)*

Fig.1.3 shows the plot of upper gas temperature as a function of fire and compartment size which the authors explain using Heskestad correlation which gives the temperature rise for an isolated ceiling as

$$\frac{\Delta T}{Q^{2/3}H^{-5/3}}\left(\frac{c_p^2\rho_0^2 g}{T_0}\right)^{1/3} = f\left(\frac{r}{H}\right) \qquad \text{….. (1.1)}$$

r is the radial distance away from the axis of the plume, $Q$is the power*,* H room height, c_p specific heat capacity of the gas, ρ_0 ambient gas density, $g$acceleration due to gravity 9.8 m/s^2.

From the plot (Fig 1.3) it is implied that a slope of line through the full scale data yields $\frac{\Delta T}{Q^{2/3}H^{-5/3}} = 34 \pm 5K/kW^{2/3}m^{-5/3}$, $\left(\frac{c_p^2\rho_0^2 g}{T_0}\right)^{1/3}$ = 0.38 and $f = 13$.The value of f is found to remain constant when most of scatters were within ± 15 % . Based on this, for the room under consideration having dimensions 8.5 m (L) × 5 m (W) × 2.3 m (H), it is found that $f\left(\frac{r}{H}\right)$ is 9.32 thus ΔT is $9.32 \times Q^{0.666}$.This implies for a power (Q) of 250 kW, a rise in temperature (ΔT) by 368 K, i.e., a temperature of 668 K be expected inside the room.

Utiskul et al (2005) studied the compartment fire phenomena under limited ventilation. Regime of limited ventilation examined to study the effect of extinction and influence of oxygen concentration. Experiment was conducted in a 40 cm cubical room built out of 25 mm thick *Type- M*, *Kaowool*, with wall-vent arrangement located at top and bottom heights of 1-3 cm, having equal vent area varying from 0.02 to 2.4 m^2. Fire source consisted of *Pyrex glass* pan with dia.65, 95, 120 and 190 mm, with heptane as fuel. Measurements on pressure, mass loss, temperature, heat flux, gas mole fraction (O_2, CO, CO_2) were made. The results are indicative of thermal and vitiation effects. Further influence of compartment radiation feedback on the evaporation rate is stronger in the case of small scale tests shown. This emphasizes on the need for interpretation of large increased burn rates in the case of small scale studies when we extend small scale studies results to material performance in the real fire scenario.

Bryant (2009) has compared gas velocity measurements on a full-scale enclosure containing a natural gas fire. Two independent techniques, *Stereoscopic Particle Image Velocimetry* (SPIV) and *Bi-directional Impact Pressure* probes were utilized. The experiments were performed in ISO 9705 room, dimensions being 3.6 m × 2.4 m × 2.4 m, with a door opening of 0.8 m × 2 m (H). The depth of the doorway was 0.3 m which was larger than usual, resulting in a door jamb that extended beyond the exterior frame work of the enclosure. The source of fire is a centrally located burner of 0.305 m × 0.305 m size that can be operated with varying power levels ranging from 32 to 511 kW by regulating the supply of natural gas to it. Gas velocities inferred from the bidirectional probe measurements were consistently greater than SPIV measurements in a region of the flow between the flow and floor interface.

ISO 9705, Fire tests—full-scale room test for surface products is an international standard available to the fire research community towards evaluating the fire performance of the surface / lining materials as it has an advantage in simulating and comparing the results. Non ISO room experiments are also carried as part of establishing / understanding the fire performance of materials to real fire scenarios. Table 1.11 summarizes pools of varying sizes characteristic of a source fire with different power levels kept at different locations of the room have been used in the experiments. It can be seen that there exists a relation between the size of the room and fire power used in the studies and this needs to be investigated and understood.

Table 1.11 Fire source to different size of enclosures used by different authors

Ref.	Enclosure Details							Pool Details					Standard
	Size, m L	 W	 H	Vol. m^3	Door Size, m W	 H	Area m^2	Size mm	F	HRR kW	Flux kW/ m^2	Location	
Poulsen & Jomaas (2012)	3.6	2.4	2.4	21	0.8	2	1.6	Ø 350 Ø 500 Ø 700	H	248 389 780	2578 1982 2028	C	ISO Room
Gupta et al (2012)	1.0	1.0	1.0	1	Exhaust Ø 0.025		5×10^{-4}	Ø 100 Ø 125 Sq 150	H	5 6 12	637 488 533	C	Non ISO Room
Hamins et al (2008)	21.7	7.0	3.8	582	2.0	2.0	4	1000 × 2000	H	1000	500	C	Non ISO Room
Johnson et al (2011)	1.4	0.95	0.98	1.3	0.5	0.8	0.4	Sq 250	H	150 245 340	2400 3920 5440	C	2/5 of ISO Room
Bryant (2009)	3.6	2.4	2.4	21	0.8	2	1.6	Sq 305	N G	34 to 511	365 to 5493	C	ISO Room
Jeong & Ryou (2002)	1.8	1.8	1.4	4.5	0.48	1.2	0.57	Sq 150 Sq 250 Sq 390	M	8 21 52	356 336 341	C	Non ISO Room
McCaffrey& Rackett (1977)	3.0	3.0	2.3	21	1.93	0.73	1.41	- - - -	G	62 140 340 459	- - - -	C Cr. WC	Non ISO Room
	0.39	0.29	0.41	0.05	0.37	0.11	0.04	-	G	~10	-	C	

Note: F-Fuel; G - Gasoline; H - heptane; M - methanol; NG - Natural Gas; C- centre; Cr. -Corner; WC-wall centre.

Figure 1.4 shows individual plots of height and volume of the room versus fire size used by different authors in their studies [McCaffrey and Rackett (1977), Hamins et al (2008), Bryant (2009), Johnson et al (2011), Gupta et al(2012), and Poulsen and Jomaas, (2012)]. There is a trend of agreement of roof height to the ignition source while in the case of volume it is not so. Fire size of the range 30 kW to 800 kW is found used in the ISO 9705 room tests. In the case of non-ISO rooms power level of 200 kW to 500 kW with the exception of Hamins et al (2008) where 1MW fire is used. The size of pool or the types of fuel is varied depending on the geometry of the room chosen by the researcher to simulate a real fire scenario. This involves studying various parameters like centerline temperatures just above the pool, corner, roof and wall temperatures with time.

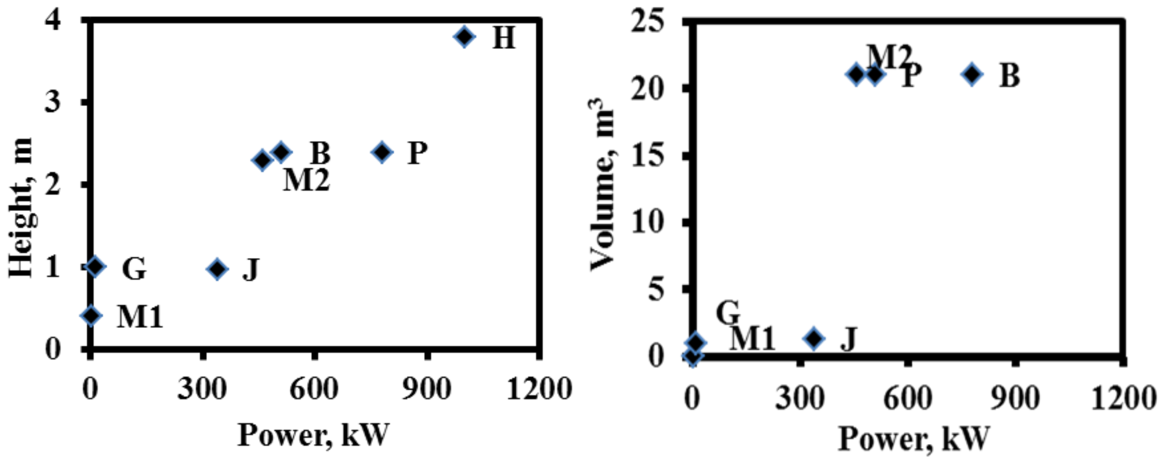


Fig. 1.4 Plots of height vs. power (Top) and volume vs. power (Bottom) of fire source in rooms used by various authors *[M1,2-McCaffrey and Rackett(1977), H-Hamins et al (2008), B-Bryant (2009), J-Johnson et al(2011),G- Gupta et al(2012), and P-Poulsen and Jomaas, (2012)]*

Studies on the formation of smoke and smoke layer depth are performed as smoke obscuration and the toxic nature of smoke lead to loss of life in most of the fire accidents. The structure of fire and movement of smoke differs with the location of fire and constituents of the enclosure. Also, ventilation effects have been studied aimed at understanding the impact on structural elements due to the variations in ventilation conditions. How much of power would an enclosure hold needs to be determined before conducting pool fire experiments within enclosure, in other words, this requires choosing an appropriate fire source depending on the geometry of the room under consideration. CFD tools such as Fire Dynamic Simulator (FDS) helps in choosing the appropriate size of fire and location with respect to the experimental condition. Following section details on prediction capabilities of FDS.

1.2.5 *Review on FDS validation of enclosed pool fire tests*

There is a good resource material in the book by Yeoh and Yuen (2009) that describes the foundations of computational approaches to fire studies. Important aspects of field modeling approach like validation and verification are discussed. Field modeling of the fire dynamics comprises mainly of two components, (i) the CFD methodology which provides the basic transport mechanisms for mass, momentum, and energy (including heat transfer due to conduction convection and radiation), (ii) fire model which contains the detailed specification of the fire description such as combustion, non-luminous and luminous radiation, soot production, and solid pyrolysis. It is emphasized thus for an acceptable use of the field model, it calls for a good CFD computer code, a good fire model, and ultimately the knowledge as well as proficient use of the CFD-based fire model.

Xiao (2012) has made comparisons of numerical and experimental results of fire induced door way flows compares the real scale experimental data with numerical calculation using FDS 5 for two cases viz., with and without sprinkler activation. Neutral plane, Mass flow rates in doorway, gas concentrations in the room and temperature distribution are the key parameters chosen for comparison using three different fire sizes of 45 kW, 75 kW and 100 kW, from premix propane–air burner of size 0.46 m^2. The test compartment dimensions considered was 9.75 m × 4.88 m × 2.44 m (H) with a door way opening of 1.04 m × 2.24 m (H) dimensions.

Table 1.12 Ceiling temperature comparison with different fire sizes *(Xiao, 2012)*

Temperature °C, Locations	**45 kW**			**75 kW**			**100 kW**		
	Exp.	**Num.**	**Var. %**	**Exp.**	**Num.**	**Var. %**	**Exp.**	**Num.**	**Var. %**
2.44 m, 1.22 m	70.8	70.8	0	102.9	98.8	4	117.6	112.8	4
2.44 m, 3.66 m	68.2	65.7	4	101.5	91.4	10	114.8	105.3	8
4.88 m , 2.44m	64.6	62.1	4	95	86.1	9	107.1	98.7	8
7.33 m, 1.22 m	63.5	57.1	10	92.5	79.6	14	104.9	90.9	13
7.33 m, 3.66 m	60.6	57.5	5	89.3	79.6	11	101.2	91	10

Results and summary (See Table 1.12) show that FDS calculations provide results that agree reasonably with the experimental data. It is also observed that FDS 5 numerical calculations of doorway temperature are less than those of measured in experiment. Mass flow rate showed zigzag patterns in contrast to the experiment and ceiling temperature were found under predicted. Neutral plane height of the experiment remained stable at 1.3 m.

Chen et al (2011) studied the rate of gas temperature rise in enclosure fires. The study comprises measurement of hot gas temperature inside a compartment of dimension 0.6 m (L) × 0.3 m (W) × 0.36 m (H) with a door opening of 0.22 m × 0.28 m, at every 5s and uses the same to investigate the correlation of peak hot gas temperature with 1st and 2nd order gradients of fire growth. The ignition source was PMMA square slabs of thickness 0.015 m and area 0.032 m^2.

It is found that the average rate of temperature rise increases with the peak hot gas layer temperature and the change agrees well with the equation,

$$\left(\frac{dT_g}{dt}\right) = 0.076e^{0.00283T_{peak}} \quad \text{…. (1.2)}$$

The correlation between the peak rate of temperature rise displayed during the fire growth and the peak temperature eventually achieved is

$$\left(\frac{dT_g}{dt}\right)_{peak} = 0.076e^{0.00283T_{gpeak}} \quad \text{…. (1.3)}$$

The correlation invokes the possibility of temperature rise data to predict the subsequent peak hazards.

Delichatsios (2009) has presented a correlation for predicting enclosure gas temperature based on the energy balance for adiabatic conditions, an estimate of heat flux imposed on the enclosure boundary and the transient thermal response of the boundary. The new correlation predictions are found to be comparable with that of the experimental results and also with the popular MQH (*McCaffrey, Quintiere and Harkleroad)* correlation. The experimental set-up consisted of 1/3rd of ISO room size (0.8 m × 1.2 m × 0.8 m H) with ignition source of Industrial methylated spirit with composition being ethanol 91%, methanol 4%, impurities and water 5%, in three different pan sizes 0.2 m × 0.2 m, 0.25 m × 0.25 m, 0.3 m × 0.3 m, for six different cases of openings Op1 to Op6. Comparison of the results shows that the new correlation is able to predict with a % error range of -10 to 25 against MQH correlation to -4 to 55.The details are tabulated in the Table 1.13.

Table 1.13 Percentage errors of heat flux from Delichatsios (D) and MQH models

Opening #	**Opening (W × H) (m^2)**	**Pan size (m^2) 0.2 × 0.2 MQH**	**D**	**0.25 × 0.25 MQH**	**D**	**0.3 × 0.3 MQH**	**D**
Op*1	0.27 × 0.67	-3.2	-6.5	3	0.2	23.4	12.3
Op2	0.13 × 0.67	5.3	2.6	15.9	15.1	25	25
Op3	0.67 × 0.67	24.4	6.4	45.2	25.9	27.7	11.3
Op4	0.27 × 0.67	8.9	-8.9	24.6	14.8	42.9	20
Op5	0.13 × 0.67	30	7.8	50.9	20.8	39.7	12.1
Op6	0.67 × 0.67	52.5	20	61.9	19.1	54.5	14.8

*Op – opening.

Merci and Vandevelde (2007) studied on natural roof ventilation in full scale enclosure fire tests in a small compartment. The aim of the study is to investigate the influence of different parameters on the average temperature rise in the hot upper layer as well as on the hot layer thickness and also to what extent the outcome of the design calculation methods mentioned as supported by experimental findings. The different parameters are

- Total roof opening area
- Fire source area
- Fire heat release rate

Large scale experiments are carried out in an enclosure of size 3 m × 3.6 m × 2.3 m, with different roof openings of size 1.45m × 1m, 0.75 m × 1m and 0.5 m × 1m and ignition source with different power levels 330 kW, 440 kW and 550 kW. Further it is observed that different manual calculation methods that are widely used for natural ventilation design compartments in the case of fire under predicts the hot layer thickness and the total smoke mass flow rate while the hot layer temperature is over estimated. These results need interpretation through numerical simulation using FDS.

Wen et al (2007) have worked on the validation of FDS for the prediction of medium scale pool fires. The study relates to an open methanol fire burning using a circular burner of 0.305 m diameter giving a constant total HRR of 24.6 kW. Sub-grid scale combustion model based on laminar flame let approach of Cook and Riley (1998) along with existing mixture fraction model used for simulation through FDS. Studies on computational domain and grid sensitivity conducted by setting the domain with dimensions 1.6 m × 1.6 m × 3.2 m (H) in a Cartesian coordinate and with three grid resolutions, coarse (64 × 64 × 96), medium (108 × 108 × 128), fine grid (128 × 128 × 144) showed that the prediction of mean temperature distributions with fine grid resolution have closest agreement to the experimental data. The paper also brings out the good agreement of the predictions on temperature and axial velocity characteristics of the two combustion models with the experimental data. Pulsating nature of air entrainment was demonstrated by air entrainment velocity fluctuations. The predicted variations in air entrainment at different heights seem to agree well with the published data and correlation. Limitation of the code in predicting puffing frequency is brought out. Capabilities of FDS to produce reliable predictions on temperature, velocities and other important parameters of medium scale pool fires are discussed. The paper also emphasizes the need for exploring radial velocity predictions and soot modeling in FDS.

1.3. Summary

A variety of materials are put to use for roof insulation purpose like expanded polystyrene (EPS) or thermocole boards, plywood boards, mineral fiber boards, fiber glass etc. An examination of the products sold in Indian market (based on the websites of the manufacturers) showed that manufacturing facilities were generally installed with a capacity of ~1.5 TPD.

Thermal properties of EPS make it more suitable for cyclic temperature variations and hence are preferred for the purpose of thermal insulation. Being a closed cell light weight material produced from polystyrene EPS gains its exceptional insulating properties from the stabilized air trapped within its structure which enables it to provide long term performance in low temperature applications. Concerns have arisen due to some of the recent fire accidents, although the reports mention the reason for the fire accidents in most cases as electrical short-circuits; the involvement of materials to the spread of fire cannot be ignored. The false ceilings and the wall linings should therefore be fire-proofed as they normally hide adhoc electrical wiring and eventually become source for fire spread at the instance of electrical short-circuit. Codes and Standards at national and international levels like Part 4 of NBC 2005, Approved Document B of UK and International Fire Code of USA have separate clauses for interior surface finishes which provides guidelines on the requirement of classification of these materials and respective method of safe applications inside different type of occupancies. EPS properties and behavior, operating safety codes on interior surface products, the current way of usage in practice, the need for protection and subsequent evaluation by appropriate method in this regard are discussed in detail.

Review of the EPS properties towards fire shows that the material is combustible, is resistant to a temperature of 90 °C for short duration, and 80 °C for long term exposure. Above this temperature EPS will soften until ~150 °C where it will begin to shrink and return to the density of the base material. Subject to continued heating EPS will melt and form gases above 200 °C which will undergo piloted ignition at ~ 360 °C – 380 °C and auto ignite above ~ 500 °C. Several incidents reflected in various news articles and reports of KSFES also had contribution of EPS to fire, which emphasized the need for fire proofing of the material. EUMEPS, the European manufacturers association for EPS and few papers on EPS properties (section 1.2.1) recommends the encapsulation of the material towards roofing purpose.

Pool fires are found employed for testing and qualification of ceiling and wall lining products within the enclosures. Standard related to this is ISO 9705 by International organization for standardization. Rooms of various dimensions ISO and Non-ISO were found to be employed with a variety of fuels in different pan sizes, of which heptane pool fires are found employed widely. While there is a trend of relation existing between heights of the room and power, relation of enclosure volume and power could not be traced. Ignition source with power levels of range 100 kW to 800 kW are found employed for the purpose.

Numerical simulations using FDS by various authors (section 1.2.3) reveal the strengths and capabilities of the FDS to predict HRR, temperature and velocity profiles inside enclosures of ISO and Non ISO dimensions. Comparison of the results with that of the experimental results show close agreement by choosing appropriate grid size of the domain. Reviewing of papers showed a mixed type of predictions both on higher and lower sides.

1.4. The current study

The various inputs from the literature survey conducted and the properties of the EPS brings about the need for protection of the material that are in existence and those which are being installed for the purpose. Even if the replacement of the existing EPS false roofing systems by other alternatives may appear as one solution, they may not be practical since affordability may become a limitation. A more acceptable affordable solution may be an in-situ gypsum-based thin layer fibrous paper reinforced coating. Further single side facing of the coating retains the water resistant property as well as the insulation property of the EPS material. The current study is concerned with the development and study of this coating technique and evaluating the performance of protection through enclosure fire studies. Enclosure fire studies are conducted with enclosures of two different sizes small and large with false roofing of both coated and uncoated EPS were experimented with pool fires of selected power levels to establish the safe usage of material. The experimental conditions are also simulated using CFD tools for comparison. Performance of the coated roofing is also evaluated in terms of available egress time using centrally located fires of varying powers. This led to a correlation for safe egress in terms of fire power for a given room size which would help taking appropriate preventive measures in terms of fire safety.

Chapter 2

Market survey and studies

2.1 Aim of the survey

The survey is concerned with gathering information about the various types of EPS that are available in the market, the option of varying sizes and their price range. It also includes the details of manufacturers available in the country and the total volume being manufactured by them. Special attention is given in collecting the information on the FR grade EPS otherwise referred as EPS – SE (self- extinguishing) grade. Survey also included the extent of usage of the material in the local places like banks, offices, hotels, malls, etc. Details and reports on internet survey and visit to local places are presented in the following sections.

2.2 Internet survey

A survey through internet showed numerous manufacturers of EPS in India including few multinational companies like BASF. The material is being catered to a variety of sectors that include white goods, FMCG (Fast Moving Consumer Goods), pharmaceuticals, agricultural products, the automobile industry, construction, electronics and fisheries. The manufacturing companies are generally installed with a capacity to process approximately 1 to 1.5 tons of EPS material per day. There are a few large scale manufacturers having their manufacturing facilities strategically located to meet the demand and supply. LG polymers India Private Limited, Vizag, Supreme petrochem limited, Chennai, Walambia Industries, Kamdar Plastics, Vrindavan Plastic Industries, Thermoshell, Mumbai are few leading companies involved in large scale production of EPS, 20,000 – 60,000 TPA.

2.3 Local market survey

Survey on EPS usage was conducted at various locations in Bangalore. The purpose was to locate buildings that are provided with EPS false roofing and collect information about the roof height. Malls, Offices, Banks and Hotels in some areas of Bangalore (Malleswaram and Jayanagar) were visited. A few old buildings in MG Road (Higginbotham's Book House) and Brigade Road (Hotel) were found to use EPS. A survey conducted at banks in Kanakapura, a town 34 km from Bangalore showed use of thermocole false roofing. Interacting with bank officials of a leading bank showed that about 70% of rural branches are facilitated with thermocole false ceiling. Further it is also observed that most of the commercial buildings have their false roofing at a height of 2.4 m.

2.3.1 *Purpose of survey*

- To hold discussions with the manufacturers and collect the information relate to their supply of EPS used for false roofing purpose
- To collect contact address of the customers who make false roofing with EPS
- To check with the existing level of demand of EPS for false roofing purpose
- To enquire about the existing prices at manufacturer's end

2.3.2 *EPS Manufacturers located at Peenya*

Following are the manufacturing facilities visited towards understanding the existing level of manufacturing and usage of EPS and Table 2.1 summarizes the details of the companies.

- Fortifori Plastic Private Limited, B-43, Peenya Industrial Area, Bangalore -560058
- A1Thermopack, NR Thiglarapalya, Bangalore -560058
- Elegance Group No.8, II Main, Balaji Nagar, Peenya II stage, Bangalore -560058
- Pragathi Hospitality, Abigere, Lakshmipura Road, Jalahalli West, Bangalore -560015

Table 2.1 Summary of companies visited in Bangalore

Company	Location	Sizes manufactured	Purposes utilized
Fortifori Plastics	Peenya	1 m × 0.5 m of thickness ranging from 10 mm to 100 mm 2' × 2' and 0.6 m × 0.6 m of thickness ranging from 8 mm to 50 mm (Non FR and FR grade as per customer requirement) EPE sheets	Construction, packing and false roofing systems false roofing systems for packing
A1 Thermo pack	Mahalaxmi lay out, Bangalore	1 m × 0.5 m of thickness ranging from 10 mm to 100 mm and dealers in cups and plates	Construction, packing and false roofing systems, food packaging
Pragathi hospitality	Jalahalli	1 m × 0.5 m of thickness ranging from 10 mm to 100 mm and dealers in cups and plates	Construction, packing and false roofing systems, Food packaging

It is observed that the capacities of these manufacturing facilities for the production of thermocole is 1-2 TPD and are found catering to construction and packaging industries.

Thermocole is produced in bulk form and is then finished to sheets of varying sizes as per customer's requirement. Further the densities of these materials sold in the market are in the range of 7 – 10 kg/m^3. Details related to analysis will be discussed in chapter 4.

2.3.3 List *of a few suppliers of EPS material within Bangalore territory*

- Kwality Products, K-20, FM Complex, Kumbarpet Main Road, SP Road – 560002
- M A Matheen&Bros,#106, N R Ravindra kalakshetra, J C Road, 560002.
- Quality Themopack & insulation Industries, #B-29, 30, KSSIDC Industrial Area, Mysore Road, Kumbalgodu -560074
- Rathnakar's Thermocole Designer, #76, Jayanagar Shopping Complex, Jayanagar 4thBlock,Bangalore -11
- Hindpac Industries – 138/1, K Daabbagere Cross, Machohalli, Sunkadakatte
- Some of the companies referred to their regular customers and out of them the following persons could be contacted and enquired about the existing level of usage of EPS. It is learnt that the majority of the product goes into the construction and packaging industries and the use of the material for the purpose of false ceiling is generally on customers demand.

2.3.4 Visit *to Banks*

The primary objective was to meet the Premises Manager and seek firsthand information related to usage of Thermocole (EPS) false roofing in banks.
Two of the branches Canara Bank Head Office, 112, J C Road, Bangalore – 560 002 and Circle Office, Canara Bank, Spencer's Towers, 86, M G Road, Bangalore, involved in purchase and facility arrangements to various branches across the state were visited and concerned authorities involved in facility arrangements were interacted.

It is learnt from the discussion that generally mineral fibre board is used for the purpose of false roofing. When asked about whether thermocole has been used it was indicated that the use of thermocole was stopped 10 years back as they had difficulty in fitting the modern CFL fittings and other appliances. However, it was indicated that there could be few branches with thermocole false roofing that were laid earlier. Further, as of now false roofing are provided to only those branches that seem to attract more business and the budget is based on the location of the site. This was done through the local carpenters close to the area. The cost for false roofing was indicated to be around Rs. $450/m^2$. It is understood from the discussion that an area of about 160 - 180 m^2 (excluding the area of strong room which is designed as per RBI's rule) have been dealt with and that premises of 70 rural branches will be under the control of these premises sections and is practically difficult for them to visit and meet the requirements and hence it is all done through the developed vendors who could also use EPS roofing for the purpose of false roofing. The visit has provided the information that there could be at least 20 percent of rural branches existing with thermocole false ceiling.

2.4 Summary

Local market survey conducted to know the extent of EPS material in construction and for the purpose of false ceiling indicated that the material is put into use for various purposes. EPS false ceiling that is being sold for the purpose of false roofing is generally found to have varying density ranges. This information is conformed through interaction with manufacturers and vendors as well as people in the construction field. Density of the material put for the purpose is generally found to be in the range of 7 - 10 kg/m^3, any other quality is sold only under the specification by the user material of self- extinguishing type is not readily available in the market but is made to order. Although the exact extent of usage of the material for the purpose of false roofing could not be traced, visit made to few places in Bangalore and in Tamilnadu indicated that there is considerable number of buildings with EPS as false roofing. Also interaction with bank officials and manufacturers indicate that the material is still put to use in rural places which could be around 20 percent. Further it is also observed that in most of the commercial locations the false roof height is found to be 2.4 m.

Chapter 3

Tools and techniques

3.1 *Introduction*

This chapter discusses about the various materials, experimental tools and techniques that are adapted during the course of the studies. Materials discussed include the various types of fuels that are used. Primary material EPS and materials used for coating EPS such as Gypsum PoP, porous paper, etc., and their qualities are given in brief. Details of the tools used for measurement of mass loss rate, temperature, gas velocity are presented. This includes the mechanism adapted to ignite the fuel through quenching of the fire at completion of the experiment.

A schematic representation Figure 3.1 of the experimental setup not to scale and an outline of the experimental procedure is presented to give an idea about the enclosure studies conducted. Various tools used to acquire data viz. thermocouple, data acquisition system, laptop, stop watch and digital camera are also discussed. A separate heading on the fuel pan used to carry out pool fire experiments at various power levels that characterizes the ignition source is given.

Various measurement techniques that are adapted such as measurement of burn rate, temperature measurements, smoke layer height measurements, door way velocity measurements are given in detail. Coating techniques that are possible and the respective quality outcomes are discussed to give an idea about how a particular coating technique is chosen amongst varying alternatives.

3.2 Materials

Expanded polystyrene (EPS) as described earlier comes in two varieties self- extinguishing and non- self- extinguishing grades. Non- self-extinguishing EPS that are readily available from the local market are procured and subjected to analysis. They are verified for dimensions, density and flammability using LPG torch. The tests were conducted to understand the fire behavior of the material. The EPS sheet was found not following the recommended specifications as per IS: 4671 (2004) bulk density of min. 15 kg/m^3 with a tolerance of 5% for the mentioned size. The material was found to be readily combustible and required protection from exposure to fire, if used for false roofing applications.

The material chosen for protecting the EPS board is Gypsum PoP or Plaster of Paris which is calcium sulfate hemihydrate, $CaSO_4 . \frac{1}{2}H_2O$. PoP is obtained by subjecting gypsum, calcium sulfate di-hydrate $CaSO_4.2H_2O$ to a temperature of about 160°C. It is a well-known construction material and has very good water absorption property and is widely used for plastering. The material comes in wide range of qualities. The quality chosen for the purpose of fire protection of EPS is micro fine quality which has particle size.

3.3 *Preliminary studies conducted on EPS*

Preliminary studies conducted on EPS boards / slabs used in the experiments are discussed in this section. Studies are conducted to check the water absorption property and thermal behavior of the material. Thermal behavior of the EPS material is studied by introducing cut samples of dimension 0.1 m by 0.05 m in size into a twin heater arrangement as shown in Figure 3.1.

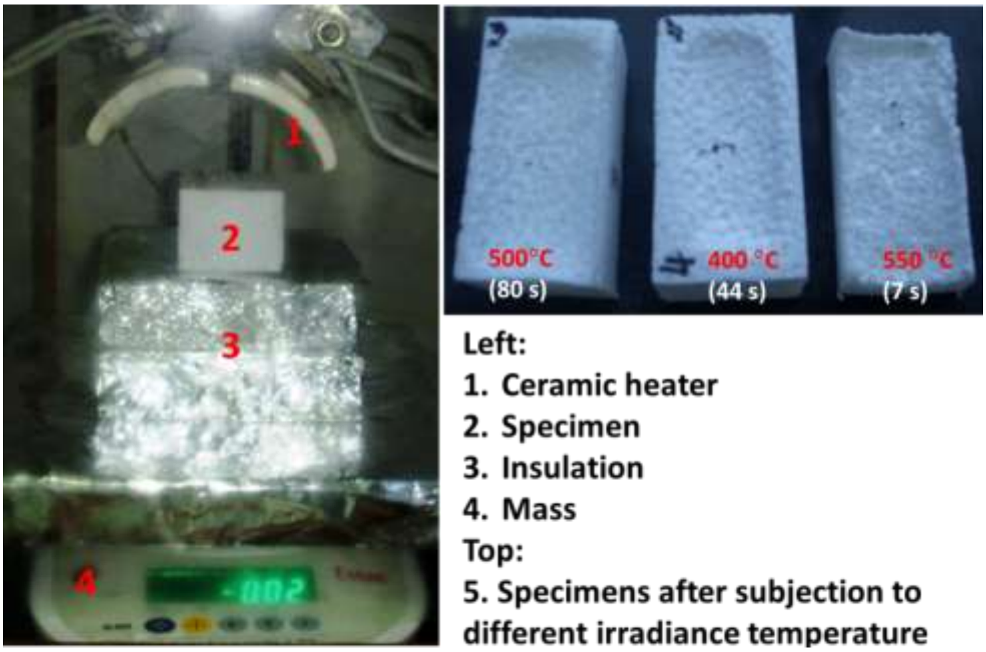


Fig. 3.1 Experimental set up to test EPS behavior to heat

The heater used is a ceramic heater of 1 kW capacity. The heater arrangement is found to give uniform heat flux of ~ 20 kWm^{-2} at a central location of 25 mm below the heater. Results of the studies are presented in the Table 3.1 along with selected images of the process taken from the full length videos of the process. It can be seen from the images of the specimens that the shrinkage has near to double when exposed to heater temperature of 550 °C within a short duration of ~ 7 s which is roughly one-fifth of the original specimen. A careful examination of the data and the videos of the process indicated that the mass loss less than 10 mg is very noisy.

Thus, the only important conclusion from the data is that the shrinkage alters the geometry very significantly and this occurs at a surface temperature of ~100°C and therefore, for safety considerations, this temperature should not be exceeded.

Water absorption property is checked by cutting a piece of 0.05 m by 0.05 m of the slab and dipping the same in to boiling water for a period of 5 minutes. Sample mass is noted prior and post to the experiment. A similar study is conducted by keeping the sample overnight in the cold water. It is observed that sample did not gain or lose mass in both the cases.

Table 3.1 Thermal behavior of EPS to radiant heat

#	$M_{initial}$ g	M_{final} g	Difference g	Loss %	Duration s	MLR g/s	T_{heater} °C
1	1.382	data not acquired					
2	1.3904	1.3614	0.029	2.09	446	0.0001	500
3	1.318	1.3104	0.0076	0.58	80	0.0001	500
4	1.3926	1.3888	0.0038	0.27	44	0.0001	400
5	1.3255	1.3161	0.0094	0.71	7	0.0013	550
6	1.3621	1.3603	0.0018	0.13	7.5	0.0002	250
7	1.35	1.3495	0.0005	0.04	6.4	0.0001	250
8	1.3353	1.3346	0.0007	0.05	7.6	0.0001	250
9	1.3725	1.372	0.0005	0.04	7.6	0.0001	254
10	1.3166	1.3077	0.0089	0.68	14.3	0.0006	255
11	1.4513	1.4468	0.0045	0.31	7.9	0.0006	252
12	1.3631	1.3607	0.0024	0.18	7.8	0.0003	240
13	1.3832	1.3777	0.0055	0.40	7.9	0.0007	240
14	1.4187	1.4114	0.0073	0.51	10.4	0.0007	241
15	1.3329	1.3287	0.0042	0.32	7.8	0.0005	242
16	1.3987	1.3945	0.0042	0.30	7.7	0.0005	242
17	1.434	1.429	0.005	0.35	8.5	0.0006	242
18	1.5107	1.506	0.0047	0.31	7.6	0.0006	241
19	1.4249	1.4184	0.0065	0.46	7.8	0.0008	240
20	1.3915	1.3847	0.0068	0.49	5.3	0.0013	241
21	1.435	1.429	0.006	0.42	5.3	0.0011	239
22	1.4739	1.4651	0.0088	0.60	5.5	0.0016	240
23	1.4027	1.399	0.0037	0.26	5.36	0.0007	240

3.3 Experimental Tools

3.3.1 *Weighing balance*

The balances that are used in the experiments are of digital electronic balances. Four different balances of different capacities were used of which three were directly involved in acquisition of data and one is used to measure out fuel of known quantity. The balances that were used in the experiment were calibrated with standard range of weight for the full scale range of operation before the conduction of the experiments.

Following are the specifications of the balances used in the experiments:

- Digital electronic balance, ESSAE – DS852, 3.1 kg ,0.2 g accuracy with in- built battery and RS 232 interface
- Digital electronic balance, ESSAE – DS 852 G precision balance, 600g capacity with accuracy 10 mg, with external battery and power supply and RS 232 interface.
- Digital electronic balance, custom made, 10 kg and 100 kg capacities
- Digital electronic balance, commercial purpose

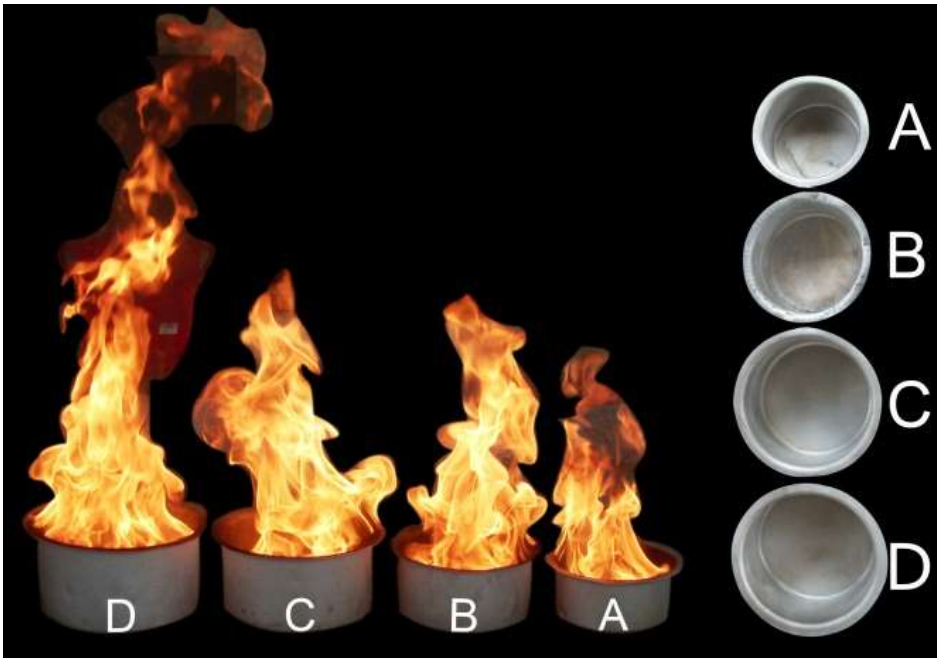


Fig. 3.2 Circular Pans used for the studies

3.3.2 Fuel pans

Both Square and Circular pans were used in the experiments. Fig. 3.2 shows the circular vessels marked A through D. Circular Pans were aluminum vessels having diameter 110 mm, 150 mm, 180 mm (A), 205 mm (B), 225 mm (C) and 240 mm (D). These were used to estimate the power levels required for $1m^3$ cubical experiments.

A set of square pans were made using mild steel sheet of 3mm thickness for different sizes with dimension of side being 0.21, 0.26, 0.3, 0.33 m to give power levels of approximately 50 kW, 100 kW, 150 kW and 200 kW. These were used in the large room experiments to evaluate the fire performance of the coating developed.

3.3.3 Ignition Torch

The torch used to ignite the fuel in Pan is simply a hand held wick torch, made by winding a small quantity of cotton waste wound on steel rod. This is dipped in fuel like n-heptane and then used for igniting the fuel in the pan during the large scale experiment.

3.3.4 Fire quenching approach

Two methods of quenching adapted during the experiments. During small scale experiment, a calcium silicate board 10mm thick with smooth surface is used to shut the pan and thus enable quenching. This enabled in saving the fuel and minimizes the time for quenching. Alternatively the large scale experiments required foam extinguishers to quench the fire. In both the cases fire quenching activity were carried with the help of professional fire fighters. Experiments are also conducted to the complete burn duration without quenching.

3.3.5 Thermocouples

A thermocouple tree is constructed with 1 mm bead type K thermocouple to obtain vertical, axial temperature profile of the pool fire during $1m^3$ room fire studies. A thermocouple tree constructed with 200 micron single strand Type K thermocouples, bare bead, used for measuring the temperature during large scale room fire experiments.

3.3.6 Data acquisition system (DAQ)

The data acquisition is carried out with the help of Measurement Computing MC personal DAQ -56series. This, with the combination of a laptop loaded with Lab view software formed the data acquisition system.

3.3.7 Digital stop watch

A digital stop watch, make supported the monitoring of the start and close of the experiment timings.

3.3.8 Anemometer

A digital anemometer (Fig.3.5) PROVA make, model AVM-03 with measurement range 0 -45 m/s accuracy ± 3% ± 0.2 is used to measure velocity.

3.3.9 Digital camera

Different digital cameras were used to capture real time picture and videos of the experiments. 8.1 mega pixels Nikon cool pixel, canon G10, 16.1 mega pixel Sony cameras.

3.5 Experimental set-up and technique

Experiments were conducted in $1m^3$ cubical room and in an 8.5 m × 5 m ×2.4 m large scale room. The $1m^3$ experimental room constructed with metallic angles fitted with GI sheet on all the sides leaving the front side open. Experiments involved the studies of the fire performance of Coated and uncoated EPS boards to a fire source of known power level. Centrally located pool fires with different power levels are used to study the fire performance. Power levels were studied by allowing the fuel to burn freely and measuring the burn rate and calculating for heat release rate. A thermocouple tree mounted with Type K thermocouples at specific locations served the purpose of Gas phase temperatures. Fuel Pan is kept over an insulated digital electronic balance connected to a data acquisition system which served the purpose of obtaining the mass loss data in the lap top.

3.6 Measurement techniques

Following are the details of different measurement techniques that are adapted to obtain reliable data during the experiments conducted.

3.6.1 Measurement of burn rate

Burn rate is an important parameter in enclosure fire studies. The value of burn rate is obtained by acquiring real time data of the mass loss rate of the fuel during burning. A previously calibrated digital electronic balance combined with a DAQ system served this purpose. Mass loss obtained in mV was converted to respective mass using the calibration factor and mass loss rate is obtained by plotting mass versus time. Mass loss rate thus obtained is nothing but burning rate of fuel.

3.6.2 Temperature measurements

Temperature measurements involved measurement of gas phase temperatures using type K thermocouples positioned at definite heights. Bare bead thermocouples were used. Further temperature measurements are also taken at top and bottom faces of the coated EPS board with bottom face being the coated one. Temperature measurements are taken to study the effect of changing the power levels at various locations which give an idea about how far the temperature the coated EPS board can hold.

3.6.3 Smoke layer height measurements

A vertical scale drawn to the full height with markings at 5" interval on the walls of the enclosure and at the door way exit served the purpose of measuring the smoke layer height. The measurement is supported by videos and photos of the experiment.

3.6.4 Door-way velocity measurements

Measurements of doorway velocities were carried out using an anemometer capable of measuring 0 to 45 m/s with least count of 0.1 m/s. Measurements were carried at different heights and were recorded periodically throughout the experiment manually. The measurement is carried essentially to know how mass flowing out and flowing in to the room through the door opening.

3.7 Coating Techniques and coating quality

A variety of possible coating techniques were identified and are verified for quality of finishing in terms of layer loading and surface uniformity. Layer loading is a parameter that indicates the amount of material loaded on to the board as coating for a given thickness. Surface uniformity is measured by measuring the thickness at various locations on the board.

3.7.1 Simple coating

Simple coating is the routine way of coating the material manually on to the EPS board using trowel. A small quantity of the gypsum pop material is taken and mixed with water to get a thin consistency (say 100 g of PoP in 150 ml of water) and mixed in a beaker. A porous paper of 45 to 60 GSM is taken and laid on to the wet board with primary coating avoiding any shrink. The PoP mix is *poured quickly on to the board with constant spreading using the trowel.* This gave a rough finish which was smoothened by scrubbing after drying the board.

3.7.2 Frame Cast Coating

A frame suitable to hold the EPS board is made using aluminium box channels. The board is then held tight inside the frame. A small quantity of the gypsum pop is prepared and porous paper of 45 to 60 GSM is taken and laid on to the wet board as above and the PoP mix is *poured quickly on to the board with constant shaking*.

3.7.3 Roller coating

This method is similar to the simple manual coating mentioned above in that a cylindrical sponge roller used in painting is used for applying PoP mix. *Uniform layer coating could not be achieved as the sponge gets dried up fast and required cleaning*. This led to loss of coating material.

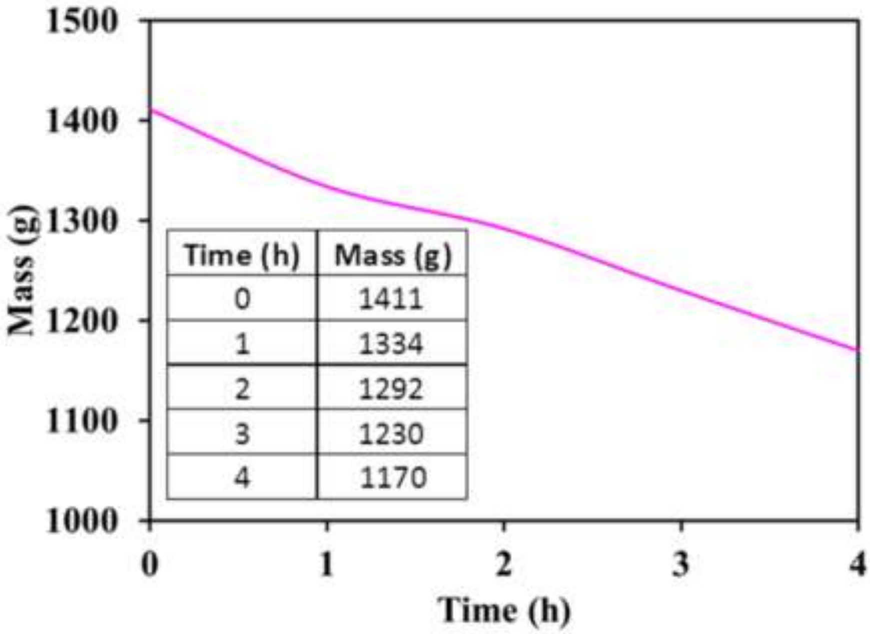
3.7.4 Spray coating

It is perhaps the simplest of the techniques for in-situ operations. Method is similar to the above in that a manual spray pump is used. Uniform coating could be achieved yet material loss is high compared to the earlier ones as the hard PoP material settles at the bottom of the holding tank. This method can be further explored to minimize the loss in handling.

3.8 Preliminary studies on EPS boards

Coated boards were studied after coating for uniformity of the coating by visual observation as well as by mass. Few boards picked at random were checked for uniform showed that mass vary by ± 5g. Further coated boards were verified for rate of drying and the gypsum drying rate is found to be at an average rate of 60 g per day for the first four days. After four days the mass found to be remaining stable to ± 1g. Figure 3.3 shows the plot of mass vs. time of gypsum drying.

Average density of EPS boards used is found to be ~ 9 kg/m^3 and this after coating found to have a density of ~ 49kg/m^3 after cutting to the required dimension of the frame which is 0.6 m by 0.6 m from 0.61 m by 0.61 m with density ~ 61 kg/m^3. Thus over all layer loading for a 0.002 m thick gypsum reinforced with paper increase by ~7 times the original mass of EPS board.



Time (h)	Mass (g)
0	1411
1	1334
2	1292
3	1230
4	1170

Fig. 3.3 Coated EPS board drying rate

3.9 Summary

This section introduced all the necessary tools and techniques adapted in the experiments. Various parametric measurement techniques adapted to measure burn rate of pool fire, roof temperature, gas phase temperature, door way velocities, smoke layer height were discussed. Also studies related to the basic materials such as EPS and gypsum was discussed. It is learnt from these studies that shrinkage of EPS material upon heating with heater temperature of ~ 500°C has less impact over the mass loss rate for short durations and this is due to the removal of air from the puffed material. Once the material has shrunk it started losing mass upon melting. Physical examination of surface temperatures during shrinkage using type K thermocouple showed indicated a temperature in the range of ~150°C while EPS begins to shrink at a temperature of ~100°C.

Four types of coating techniques adapted for coating the gypsum over EPS board are explained and out of the four frame cast coating found to be the better option for the coating purpose considering the cost, time and better utilization of the coating material. Studies on the coated

EPS boards showed that the density increase by 7 folds and the initial rate of drying of coated boards is found to be at a rate of ~ 60 g.

Chapter 4

$1m^3$ cubical room studies

4.1 Aim of the study

The study is focused towards improving the fire performance of the EPS boards that are available from the local market and are being or already been put to use for the purpose of false ceiling. These studies are intended to provide basic information related to the behavior of EPS to a fire of known power level and which can be applied to large room studies. Experiments were conducted with the EPS boards that were purchased from the local market in the $1m^3$ cubical room for both before coating and after coating towards aiding in comparison.

4.2 Experimental set-up

A test room of $1m^3$ size is constructed using slotted angles of 39 mm × 2 mm and is covered on three sides by a thin GI sheet (120 g/m^2) excluding the floor and front side open for access as shown in Figure 4.1. Top is covered using EPS sheet. Studies are conducted with kerosene, heptane and kerosene/ heptane mixtures as fuel.

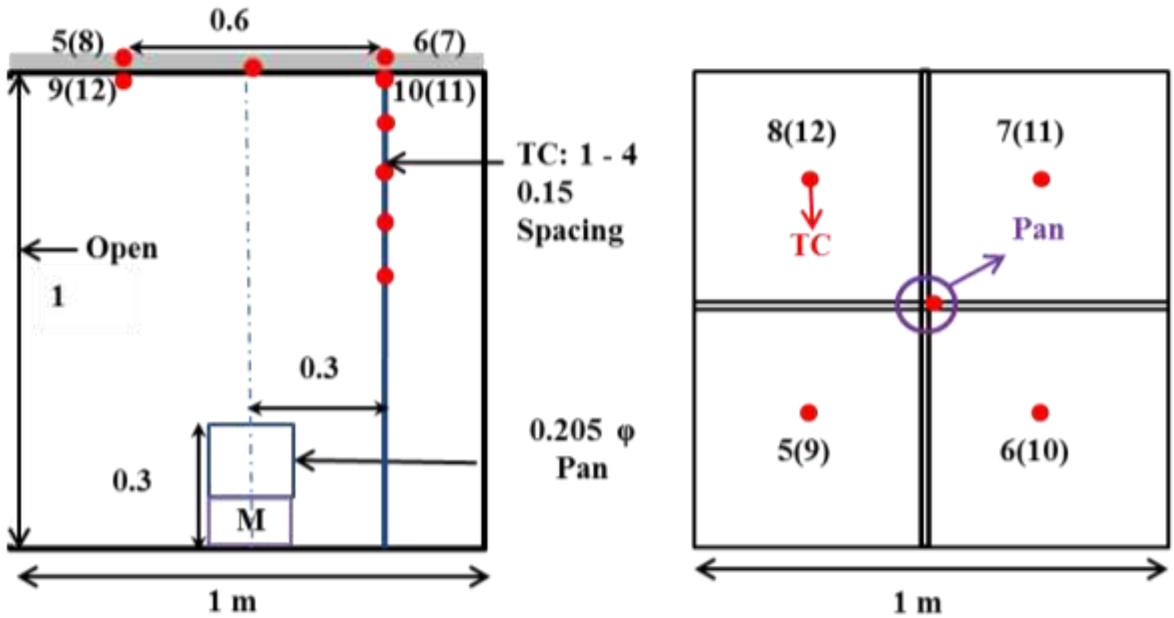


Fig. 4.1 Schematic representation of the experimental arrangement

Approximate size of fire base required for obtaining a temperature of about 150°C in the vicinity of a 1m high ceiling is determined for a flame elevation of about 2 times the fire base using

Alpert correlation. Based on this, pool diameters of 181, 205, 225 and 240 mm dia. are chosen for study. Real time mass data is acquired to evaluate burn rate using digital balance (ESSAE, 0.2 g least count, 3100 g range) connected to data acquisition system (IOTech, Personal Daq 56, 80 Hz, 10 μV least count) to acquire mV data calibrated for mass. A thermocouple tree with 1 mm bead size type K thermocouple is used to obtain vertical, axial temperature profile of the pool fire. Tests are video graphed for analysis. Experiments are conducted to test both the uncoated and coated EPS boards for the fire performance in 1m³ room maintaining the nominal atmospheric conditions. Roof constituted of two equal boards of size 1 m × 0.5 m × 0.04 m with EPS boards are mounted without the metal support frame work normally seen in false roofs. Experiments are also conducted with square roof frame work of 0.6 m ×0.6 m dimension towards meeting the optional requirements of the customer. While doing so care was taken to protect the metal to EPS slab contact through appropriate insulation as initial experiments indicated the necessity for this protection.

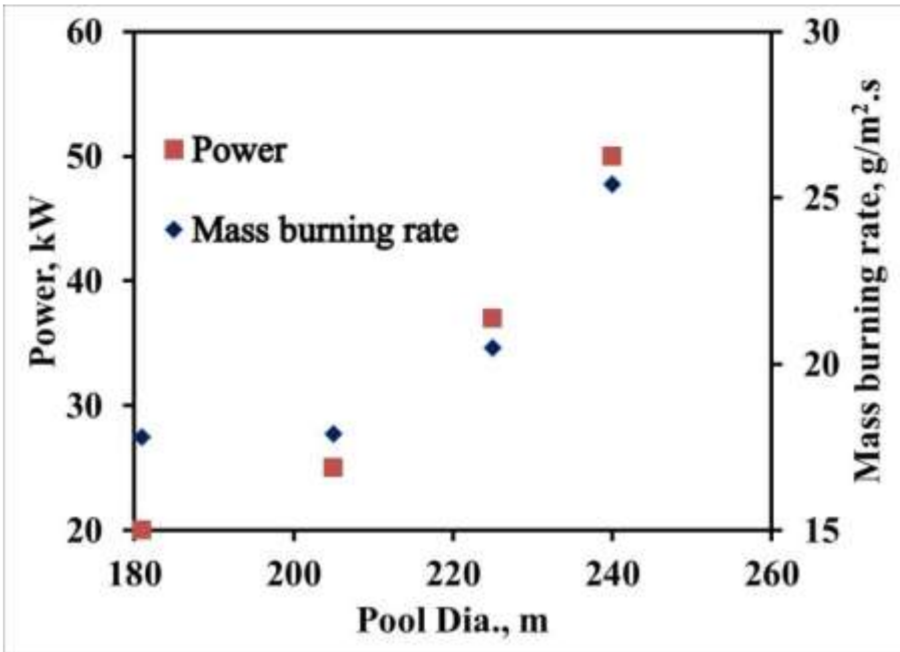


Fig. 4.2 Burn rate of kerosene pools vs. pool dia.

4.3 Characterization of the ignition source

Density and boiling point of kerosene used is determined to be 0.81 g/ml and 165°C respectively. Figure 4.2 graphical representation of linear burning rate and power level versus pool dia. Obtained linear burn rate data is in the burn rate range indicated in burn rate range for kerosene pool fires (Babruskas, 1983).

4.4 Fire studies

Experiments are conducted to test for the fire performance both the uncoated and coated EPS boards of two different size options that were found common in market inside $1m^3$ room maintaining the nominal atmospheric conditions. Experiments conducted at the initial phase were conducted using boards of equal sizes 1 m × 0.5 m × 0.04 m. Subsequent studies in the later stage were conducted using 0.6 m × 0.6 m × 0.04 m EPS slabs as frame work of this kind are also found in the market.

Table 4.1 Power levels and predicted (Alpert correlation) plume temperatures

Sl. No.	Pool dia. mm	Area cm^2	Fuel mass loss g/s	Linear burn rate cm/min	Mass burn rate $g/m^2.s$	Power level kW	Predicted plume temp. °C
1	181	257	0.47	0.14	14	20	434
2	205	330	0.61	0.14	15	25	515
3	225	415	0.95	0.17	19	41	682
4	240	452	1.20	0.20	21	52	792

Table 4.1 shows the power levels and predicted plume temperature from Alpert correlation (Quintiere, 2006) given below.

$$T_{pl} = T_{amb} + 16.9\left[\frac{(k_f \cdot Q_f)^{\frac{2}{3}}}{(H_p - F_e)^{\frac{5}{3}}}\right] \ldots\ldots\ldots (4.1)$$

T_{pl} is plume temperature (°C), T_{amb} is ambient temperature (°C), k_f fire location factor (m), Q_f fire heat release rate (kW), F_e Fire elevation (m), H_p target height measured from floor (m). The experiments were conducted in two modes, keeping the ignition source at centre and at the corner of the room.

A kerosene pool fire of 205 mm diameter with average power level of 25 kW is chosen for establishing the fire performance of EPS coating. Experiments are conducted with ignition source at centre and at the corner of the room with an objective of determining the effect of fire on uncoated and gypsum coated EPS. With uncoated EPS roof, the duration for roof failure and floor condition at roof failure are recorded. With coated EPS, gas phase temperatures and fire sustenance duration are recorded. Figure 4.3 shows typical mass and temperature histories recorded at 5 vertical locations during experimentation.

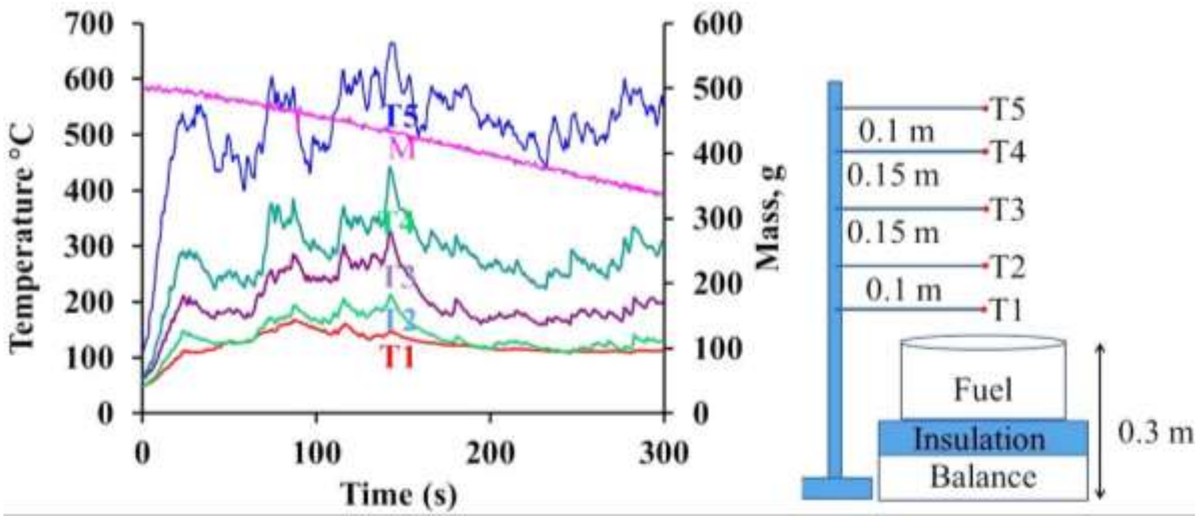


Fig. 4.3 205 mm φ Pool fire temperature and mass profile; Right: TC tree

Experiments in a larger room with regular false roof with metal support frame work to hold the coated EPS boards of 0.6 m × 0.6 m × 0.04 m, positioned at 2.4 m height revealed that it could withstand 300 kW for about 4 minutes. Details of this experiment will be discussed in the following chapter though an important observation is highlighted here. It is observed after 4 minutes that the central region of coated EPS board is intact but edges of board in contact with metal support framework have failed. Upon reviewing the failure of the roof, it is understood that higher heating rate of unprotected metal framework would have contributed to the failure of the roof. This led to the requirement of insulating the metal also from fire onslaught.

Experiments were conducted by coating the frames and comparing the same with uncoated frames for temperature rise under a common external radiant heat source of 1000 W. Figure 4.4 shows the experimental set up used for this purpose. Two identical rods from the existing frame support for EPS roofing taken of which one is coated with gypsum PoP, by dissolving 50 g PoP in 100 ml of water. The thickness of coating is about 2 mm. Both coated and uncoated frame rods were tested together subjecting to radiation, the radiating heater was maintained at a temperature of 200°C. The rods were supported between three identical insulating boards made of fibre glass wool and were centrally (to the rod as well to the radiating heater) mounted with single strand 250 microns type K thermocouple at the back and were held intact using metal paste. Further, these were also covered by the supporting boards. The frame face facing the heater is coated and the uncoated face of the rod held between the insulating boards. Results indicated after 100s, the uncoated rod temperature over took the temperature of coated frame which increased with a ΔT of up to 16°C (at a rate of ~ 0.03°C per s), as the temperature of uncoated rod reached 100°C in 670 s.

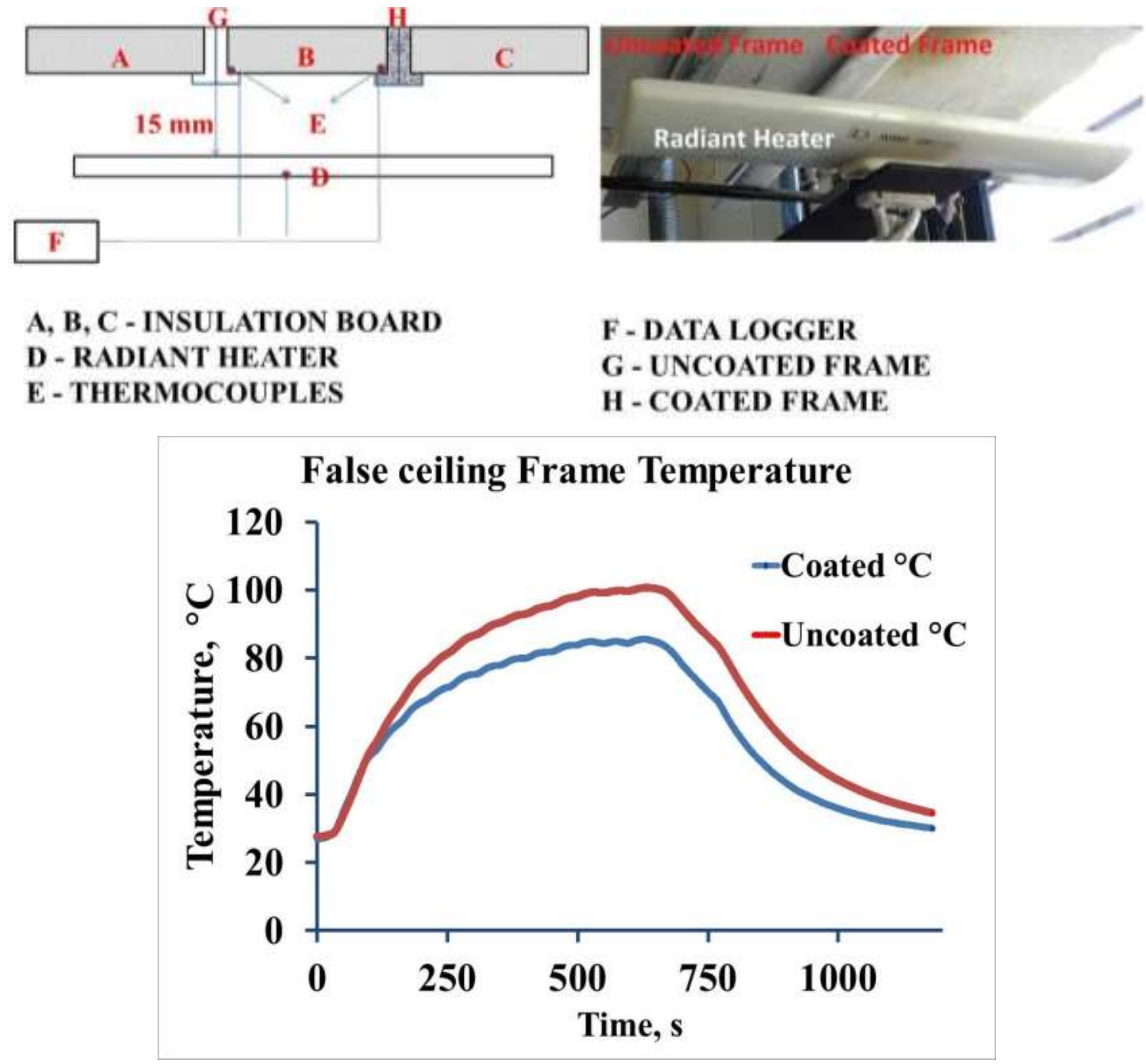


Fig. 4.4 Radiant heat exposure of uncoated and coated metal frame
Top: Experimental Scheme, Inset: Photo, Bottom: Plot

Experimentation inside 1m^3 cubical room with protective EPS coating on metal gave encouraging results favoring the strategy. The study has been conducted with a 205 mm diameter pool fire using 55% kerosene + heptane pool fire. Figure 4.5 shows fuel mass and power histories for this pool fire. It can be seen that about 10 minutes are required to reach steady burn rate in all the cases. First minute average power is about 55% of full power. From the testing carried out for over 15 minutes without failure at the metal-board interface at 36 kW nominal power it is evident that coating metal with a layer of gypsum can protect EPS board from failure due to heat transfer through metal pathway. Studies with higher power (50 kW) indicate that coated roof can withstand nominal power of about 50 kW for a maximum of 3 minutes in 1 m^3 configuration.

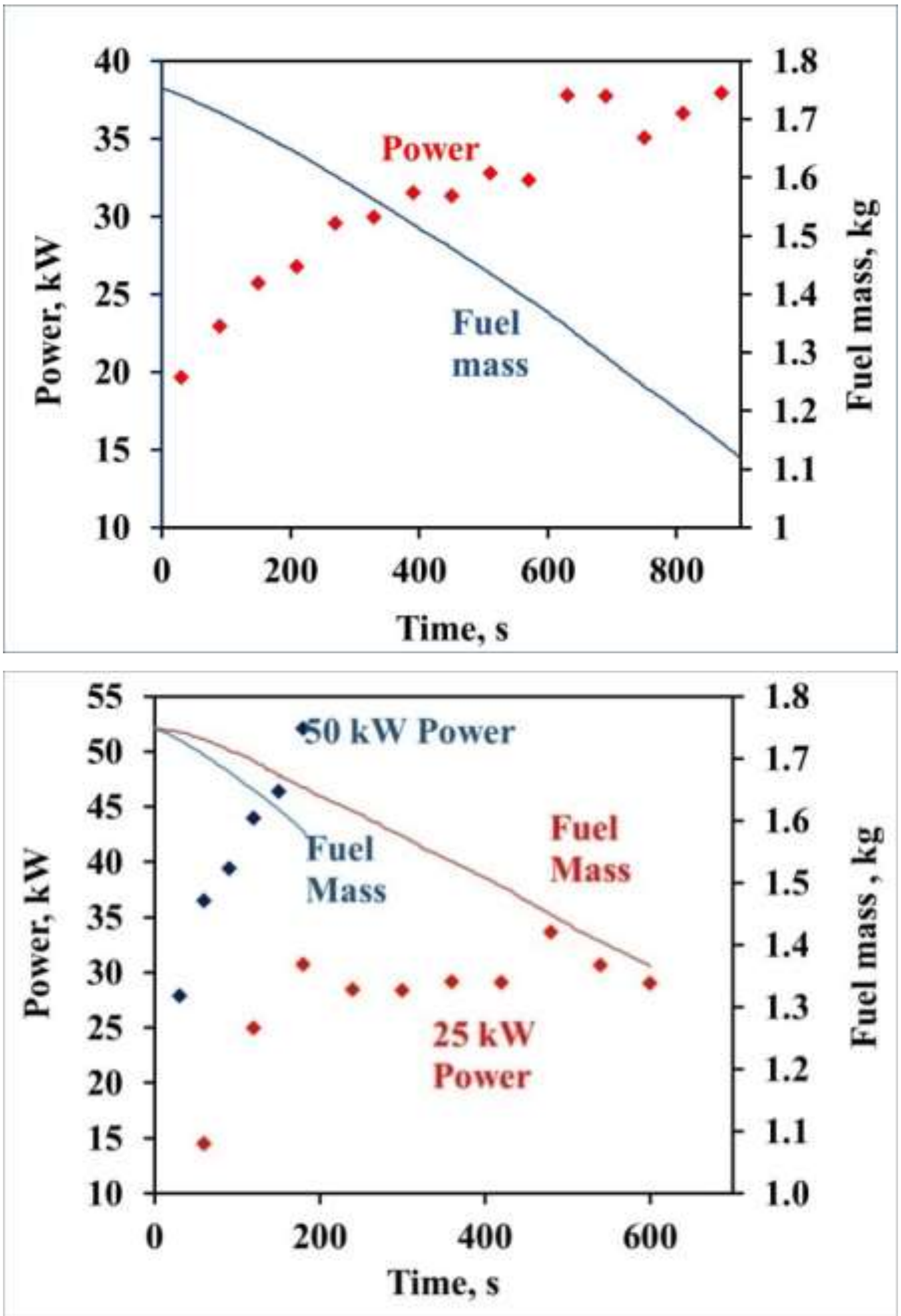


Fig. 4.5 Fuel mass and power histories of pool fires
Top: 36 kW; Bottom: 25 & 50 kW

4.5 Results and Discussion

Roofing is tested in 1 m^3 room with centre and corner fires. In both cases, the uncoated EPS started to vaporize creating holes of 0.05 m at 18 s which increased to a bigger size up to a diameter of about 0.4 m. The volume loss rate as observed from video is approximately to be at a rate of 0.01% per second. The coated EPS did not experience any volume loss till the end of the experiment, about 30 minutes from the start of ignition. Figure 4.6 shows the condition of the floor after experiment with the EPS uncoated boards at centre and corner locations. Dark regions were traced from images of actual experiment. It is seen that about 35% floor area is compromised in both corner and centre cases of test while coated EPS shows extended safety.

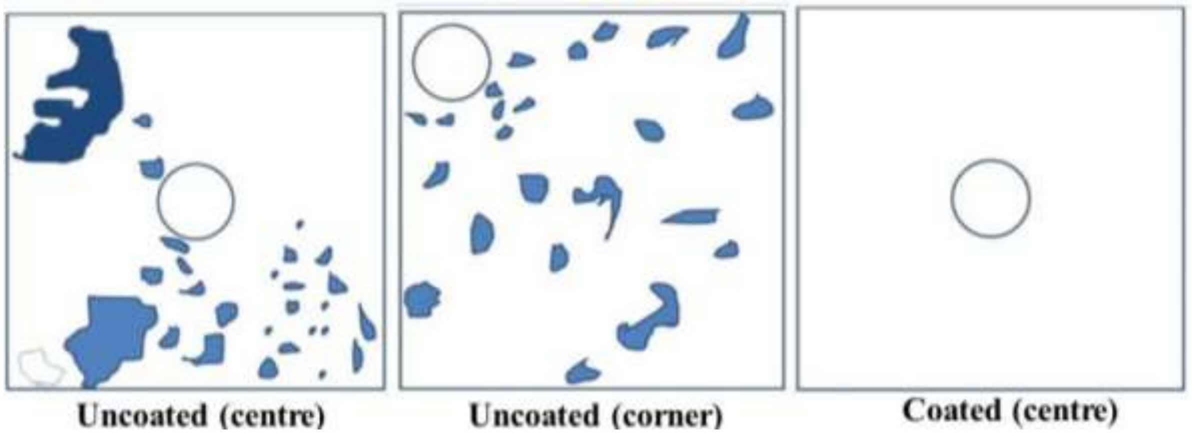


Fig. 4.6 Schematic of floor after tests (dark regions show dripped material)

Further recent experiments inside 1 m^3 room with EPS roof has sustained a maximum of 50 kW nominal power fire for 3 minutes, while it is capable of sustaining 25 kW for over 30 minutes. It is important to note that available safe egress time is also just 3 minutes during full scale fire incidents. Metal support frame work is coated to prevent premature failure of roof due to alternate thermal pathways. This technique has succeeded in preventing edge failures of EPS roof slabs.

a. Uncoated EPS **b. Coated EPS** **c. Coated EPS**

Fig. 4.7 Images of EPS boards before and after pool fire tests and c/s of EPS

Figure 4.7 shows comparisons of EPS surface conditions. The conditions (temperature and velocities) existing in tested configuration in the region just below the EPS surface is comparable to actual situations. Figure 4.7-c shows a section view of coating.

Fig. 4.8 Coloured coated false ceiling tiles

Studies are also conducted to *improve on aesthetics* using few aqueous based colors purchased from local market, refer Figure 4.8. These colors are added during the making of gypsum aggregate for coating the board. About 10 drops (~ 3 ml) of the color were found sufficient to make two boards of 1 m × 0.5 m that is 3 ml per square meter of coating and the cost of 100 ml bottle is around Rs.16. This would lead to marginal increase in the making cost by about fifty paise.

4.6 *Summary*

This study has been concerned with an approach to improve the fire performance of commercially available EPS that has actually been already used in buildings. Experiments with coating thin layer of about 1 mm thick reinforced gypsum improves fire safety substantially in existing rooms with EPS insulation by retaining its integrity for over 30 minutes to a pool fire exposure having overall power of ~25 kW. This is found to be a fairly good performance upon considering the requirements of NBC. Studies conducted in large scale room would help in strengthening these aspects of fire safety. Further addition of suitable coloring material to the coating aggregate found to help in making the tiles with better aesthetics. The increase in cost required to improve on aesthetics is found only marginal.

Chapter 5

Large scale room studies

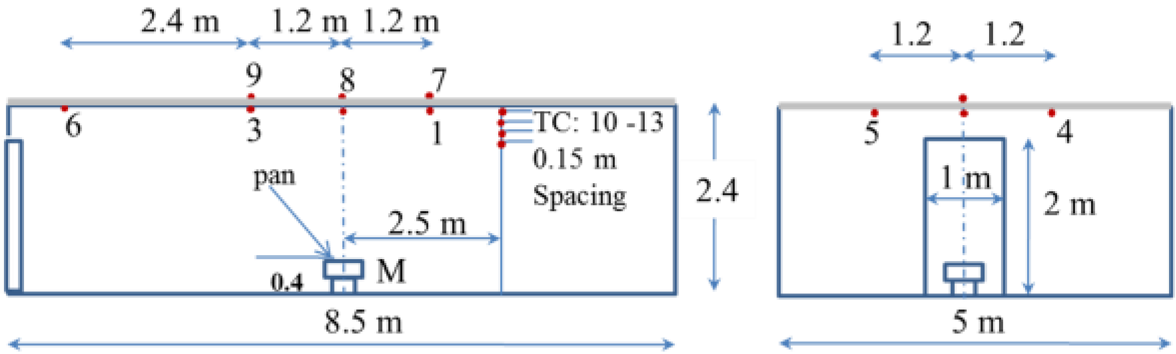
5.1 Objective

The objective of this large scale room studies is to understand the fire performance scenario of the coated EPS false roofing to a quasi-real fire situation. It should be noted that the purpose of fire protection coating avoids advanced fire situation and at worst, deal with fire during its incipient stages. The protective coating should be able to face initial stages of fire and provide sufficient egress time. Considering these requirements a room of moderate size is chosen to evaluate the performance of the coating. Critical parameters such as heat flux to the roof, gas layer temperature, smoke layer height, door way velocities are studied. Experiments are conducted with centrally located pool fires of different power levels and results are evaluated in terms of maximum power level that the roof can hold and provide time to egress as applicable to local fire codes and standards.

5.2 Experimental set-up

The experimental set-up consists of an enclosure size of 8.5 m long, 5 m wide and 2.4 m height. The size of the room is chosen after considering the various experiments conducted by different authors in ISO rooms and Non-ISO rooms, presented in the Table 1.11 where in most studies consisted of roof height close to 2.4 m while the rest of the dimensions vary widely. It is thought that the results obtained through the studies conducted in this kind of enclosure would be of useful to the fire situations faced by different class of occupancies such as banks, class rooms, book shops, library area, hotels or retail shops where false ceilings are generally noticed.

The false ceiling roof of the room is constructed with metallic frames holding the coated EPS boards of size 0.6 m × 0.6 m. The schematic diagram of the experimental room is shown in the figure 5.1. The room consisted of a single door opening of 1m wide and 2 m height located centrally on width of the room. A centrally located square pan of appropriate size to hold the fuel / fuel mixture served the purpose of fire source. Square pans of different sizes with side dimensions 210, 260, 300, 360, and 480 mm were evaluated for power in open environment before putting into use. Thermocouples, bare bead type K ~400 micron size made using ~200 micron single strand wire, mounted on the boards of the false ceiling at strategic locations on both top and bottom sides of the board served the purpose of measuring roof temperature.



Data	Sensor	Acquisition
1-9	400 µm bead - K type thermocouples	Daq56
TC 10-13	400 µm bead - K type thermocouples	Equinox
M	Mass Data	Daq56

Fig. 5.1 Schematic of the Large Room Enclosure fire study

Experimental mass measurement inside enclosure are conducted using LOAD MASTER make load cell model BB-100 of capacity 10 kg with 1g LC and 100 kg capacity with 10 g LC and connecting them to LOAD MASTER load indicator Model LI 455 to read. An IOTECH Personal Daq 56, (80 Hz, 10 µV LC) having 10 analog data acquisition channels is coupled to lap top to acquire mass and roof temperature data. A bare bead Type K single strand 200 micron thickness thermocouple tree located at about 2.5 m distance from the centre of the pool served the purpose of measuring the gas layer temperatures at different vertical locations with spacing of 0.15 m starting from 0.04 m below the roof. A data logger EQUINOX with 4 channels is used to measure vertical temperature. A vertical scale painted at the rear side wall with a least count of 5"served the purpose of measuring the smoke layer height at various time intervals during the experiment. The smoke layer height is also tracked through videos taken. Schematic representation of the experimental set up covering the details as above is presented in the Figure 5.1.

5.2 Characterization of the ignition source

The ignition source is characterized to ascertain the power levels for the enclosure experiment. Pools of varying sizes circular as well as square types with different fuel combination of heptane and kerosene are studied to achieve the desired power level before conducting the fire study. The studies were focused entirely towards fire holding capacity of the false ceiling fitted with 0.6 m × 0.6 m boards of EPS coated with gypsum PoP reinforced with porous paper. The experiments are conducted in an open enclosure and the power levels are obtained by acquiring real time mass data of the fuel burnt using digital balance (ESSAE , DS-451HP, 5 g LC, 0-60 kg range) connected to data acquisition system (IOTech Personal Daq 56, 80 Hz, 10 μV LC) to acquire mV data calibrated for mass loss. The data thus obtained are compared with the burn rate from earlier experiments carried out by different authors, details of which are consolidated in Table 5.2. Table 5.1 below details the data obtained for various fuel mixtures in different square pans. S100 means square pan with side length equal to 100 mm, this notation is followed for the different pan sizes mentioned in the Table 5.1

Table 5.1 Fire tests conducted on 5 m x 8.5 m x 2.4 m (high) room

Pan size	Area	Fuel	Amount	F-burn rate	Q	P	T_{peak}	T_g
m × m	m^2		kg/kg*	g/s	kW	S	°C	°C
0.48 × 0.48	0.231	mix	13.6/11.5**	7.05	315	248	270	200
0.26 × 0.26	0.068	C_7H_{16}	1.4/11.5	2.11	94	675	130	120
0.21 × 0.21	0.044	C_7H_{16}	0.9/7.4	1.15	51	732	NA	104
0.21 × 0.21	0.044	C_7H_{16}	0.9/7.4	1.35	60	659	115	114
0.26 × 0.26	0.068	C_7H_{16}	1.2/11.5	2.41	107	487	160	142
0.30 × 0.30	0.090	C_7H_{16}	2.1/15.1	3.86	171	548	220	189

Mix: 45 % n-Heptane in Kerosene; * kg fuel/kg water (water layer thickness 169 mm);
** Water layer thickness 50 mm; F-fuel; P-period;

Figure 5.2 shows the plot obtained using the data from Table 5.1 along with the data from Bing Chen (2011) et al, Kang (2010) et al, and Chih-hung (2010) et al, it is observed that the burn rates of n-heptane pools are on the higher side. The variations in power level observed in these experiments is attributed to many factors that influence burn rate such as rim effect, wall effect, cooling by water, etc., and have already been discussed by several authors beginning with Babruskas (1983) . Hence the presently measured data form the basis of calculations presented herein.

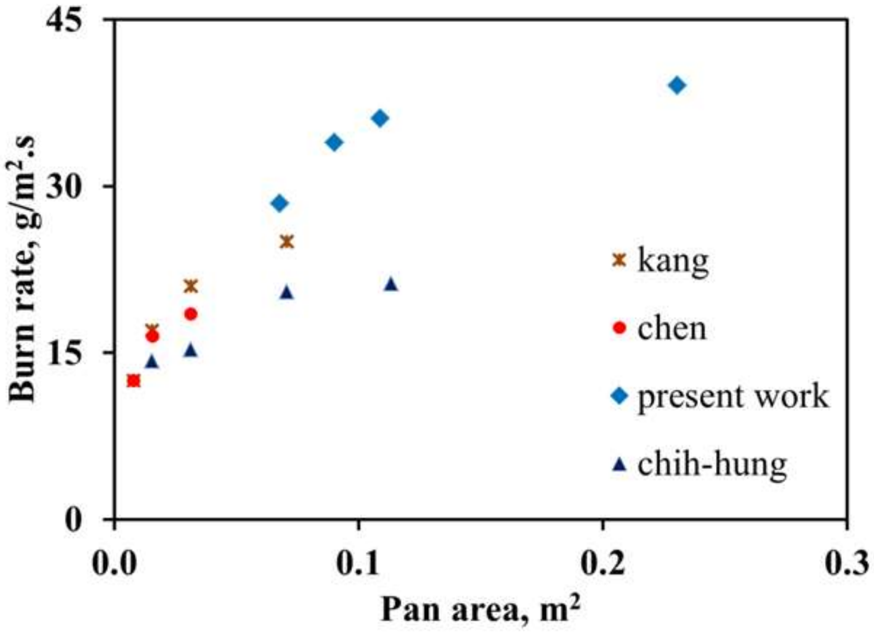


Fig. 5.2 Burning rate per unit area versus pan area

Fig. 5.3 Experimental arrangement inside large room
A-Pan; B-Vertical scale; C- Thermocouple tree; D- Coated Roof

5.3 Fire Studies

Experiments conducted in the large room enclosure consisted of the arrangement as given in the Figure 5.3. Only coated boards were tested considering the safety issues. The room consisted of roofing made of coated GI frame of 0.6 m × 0.6 m size on to which coated EPS boards were held intact. Vertical scale marked at three different locations using red colored paint on to the walls of the room served the purpose of smoke layer measurements. This again is traced from the videos. Temperature at the roof was measured using single strand with 200 micron thickness thermocouples mounted at strategic locations. A thermocouple tree with bare bead Type K single strand with 200 micron thickness located at different heights served the purpose of measuring the gas layer temperatures at the respective positions.

Experiments are carried using different fire power levels ranging from 50 kW to 315 kW. The first experiment consisted of centrally located pool fire of ~315 kW. Fuel chosen was a mixture of 55% kerosene in n-heptane with fuel quantity of 18L. The quantity of fuel is calculated based on individual burn rates of kerosene and n-heptane and is ensured to support experiment for a period of 30 minutes plus 5 minutes extra. The details are presented below in the Table 5.2.

Table 5.2 Details of Expt. #1

Description	**Details**
Pan Size	0.48 m × 0.48 m × 0.2 m
Fuel	55% kerosene in n-heptane
Fuel Quantity	18 L (13.59 kg)
Water Quantity	11.5 kg
Fuel depth	0.083 m
Free board	0.067 m
Fuel temperature	28 °C
Fuel mass burnt	1.748 kg
Burn duration	248 s
Burn rate	7.05 g/s
Power	315 kW

Ignition was started at time t = 0 s and the fire got stabilized in about 10 s with a pulsating frequency of 2.24 Hz as observed through video the theoretically calculated value being 2.26 Hz. The fire was quenched at t = 257 s which took a period of 31s. *The fire was quenched as coating of one of the board lost its integrity.* No spread of fire observed across the roofing and total duration of the study is found to be 248 s. A video coverage using Canon 100 camera gave input to the smoke layer height with time. Smoke layer developed downwards and reached a height of 1.65 m in 33 seconds and got stabilized at 1.27 m from floor in about 92 seconds. This resulted in a smoke formation rate of 1.22 cm/s and a smoke volume fraction of 0.47.Overall power of the pool fire as calculated from the differential mass is found to be 315 kW details of which are given below. Figure 5.4 shows the room with a centrally located pool fire of 315 kW capacity during the beginning, at stable smoke layer formation and roof conditions after the experiment was stopped.

Fig. 5.4 Large room fire study (Expt. #1): (a) beginning (at 4s) of the experiment; (b) at 33 s of the experiment (c) roof condition after 257 s

Figure 5.5 (a, b & c) shows the plot of temperature measurements at various locations on the coated roof. Details of the locations are presented in the Figure 5.3. The temperature at the roof top found to stabilize at 50°C and the peak temperature is found at the central location with a maximum of ~ 160 °C indicating that the roof conditions are safe. The circled portion in the Figure 5.5 (a) is because the experiment was stopped at 257 s by manual quenching due to failing of one of the board around the central region of the enclosure refer Figure 5.4 (c). The sudden shoot up of temperature in all the plots as represented inside the circled portion is due to the disturbance of the fuel layer which got rapidly transferred to combustion zone resulting in a glowing fire as a result of manual quenching using foam extinguisher. Further, the board at the central location surprisingly found less affected compared to the surrounding locations. Upon observing it was noticed that the supporting frame also contributes to the heat transfer to the coated boards and that the uncoated sides gets affected because of this. In summary, the coated boards could withstand for a period of 248 seconds ~ 4 minutes which is in excess to the time egress requirements of the national building code. The mass loss data in the present experiments was obtained by considering the initial and final mass of the fuel and the total duration the experiment run. This was found match the free burn rate data obtained separately.

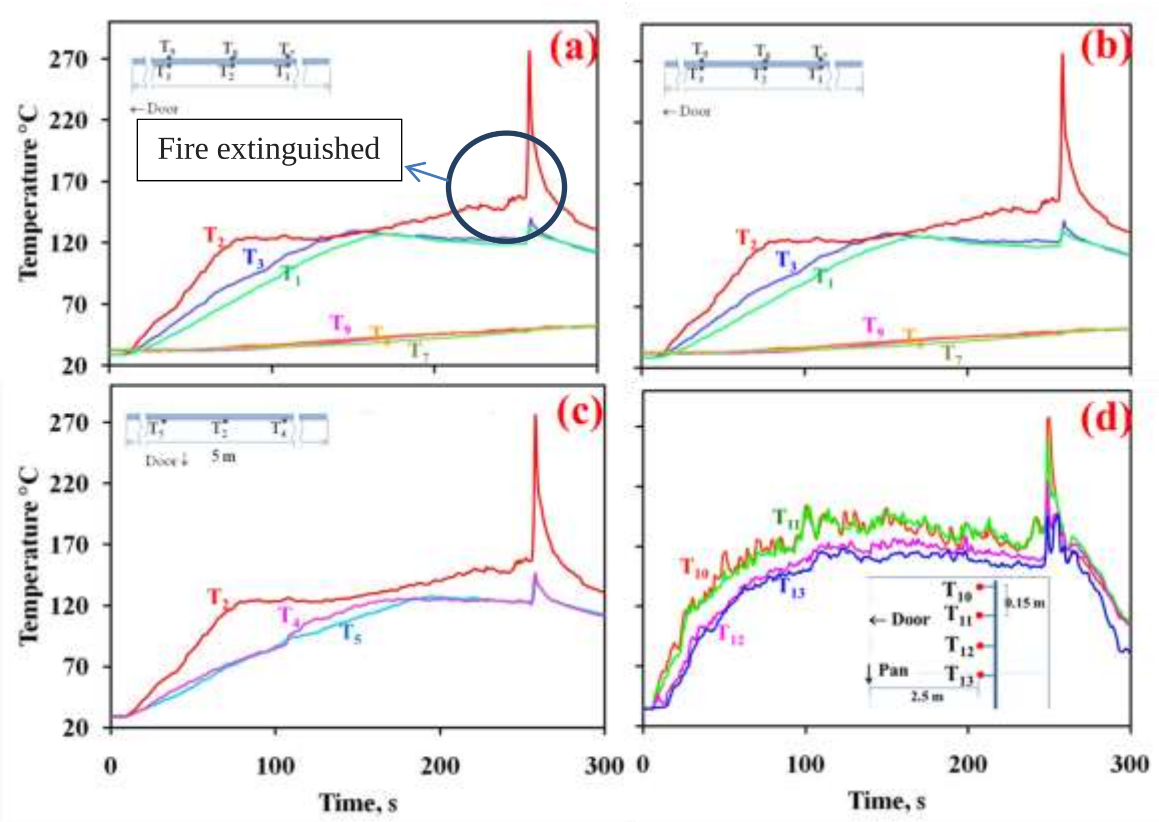


Fig. 5.5 Temperature measurements of the enclosure Expt. #1: (a) Roof temperature above the pool (b) Roof temperature across the room length (c) Roof temperature across room width and (d) Gas phase temperature measurements at a location 2.5 m from edge of the pan towards rear side wall

Figure 5.5 (d) details the gas phase temperature at vertical locations and at a distance ~2.5 m away from the pan centre. The thermocouple locations are detailed in the Figure 5.3. It is observed that the gas phase temperatures above the thermal interface are in the range of 150°C to 200°C for a period of about 200s. This again indicates the boundary conditions to the roof are at safe levels to meet the criteria of NBC.

The second experiment was run with relatively much lower power of ~ 100 kW in S260 mm Ø pan with n-heptane as fuel. Additional protection to the roof was given through appropriate coating of the metal frames with gypsum PoP as this is found to be beneficial from the initial radiant exposure experiments and 1 m^3 cubical room experiments as described earlier in the previous chapter. Details of this experiment are presented in the following Table 5.3.

Table 5.3 Details of Expt. #2

Description	Details
Pan Size	0.26 m × 0.26 m × 0.2 m
Fuel	n-heptane
Fuel Quantity	2 L (1.4 kg)
Water Quantity	11.5 kg (0.165 m)
Fuel depth	0.032 m
Free board	0.006 m
Fuel temperature	28 °C
Fuel mass burnt	1.4 kg
Burn duration	675 s
Burn rate	2.074 g/s
Power	92.5 kW

The fuel quantity taken is ensured to give a steady burning duration of about 10 minutes. The experiment could be successfully run for the entire period of 675 s when the fuel is completely burned off. Overall power of the pool found to be 92.5 kW, while the peak power went up to 110 kW. Velocity measurements to and fro the enclosure were measured using anemometer and the smoke layer were also recorded using video. Only the velocity of gases leaving the system could be measured. Velocity of gases leaving the room is found to be in the range of 0.4 to 0.7 m/s and the velocity found to build up with the increase in burn rate and found to be stable at 0.5 m/s in about 3 minutes which then increased to a maximum of 0.7 m/s in 8 minutes. Details of the measurements are presented in the Table 5.4. These measurements were made at a location ~ 1m below the roof and at the door exit. Temperatures of the gases leaving the enclosure are found to be in the range of 100 to 120°C at the door exit as measured by hand held thermometer. Smoke layer height is found to be stable at a height 1.37 m from the floor in 3 minutes as seen from the video.

Table 5.4 Velocity of gases leaving the room

Time, min	1	2	3	4	5	6	7	8
Velocity m/s	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.7

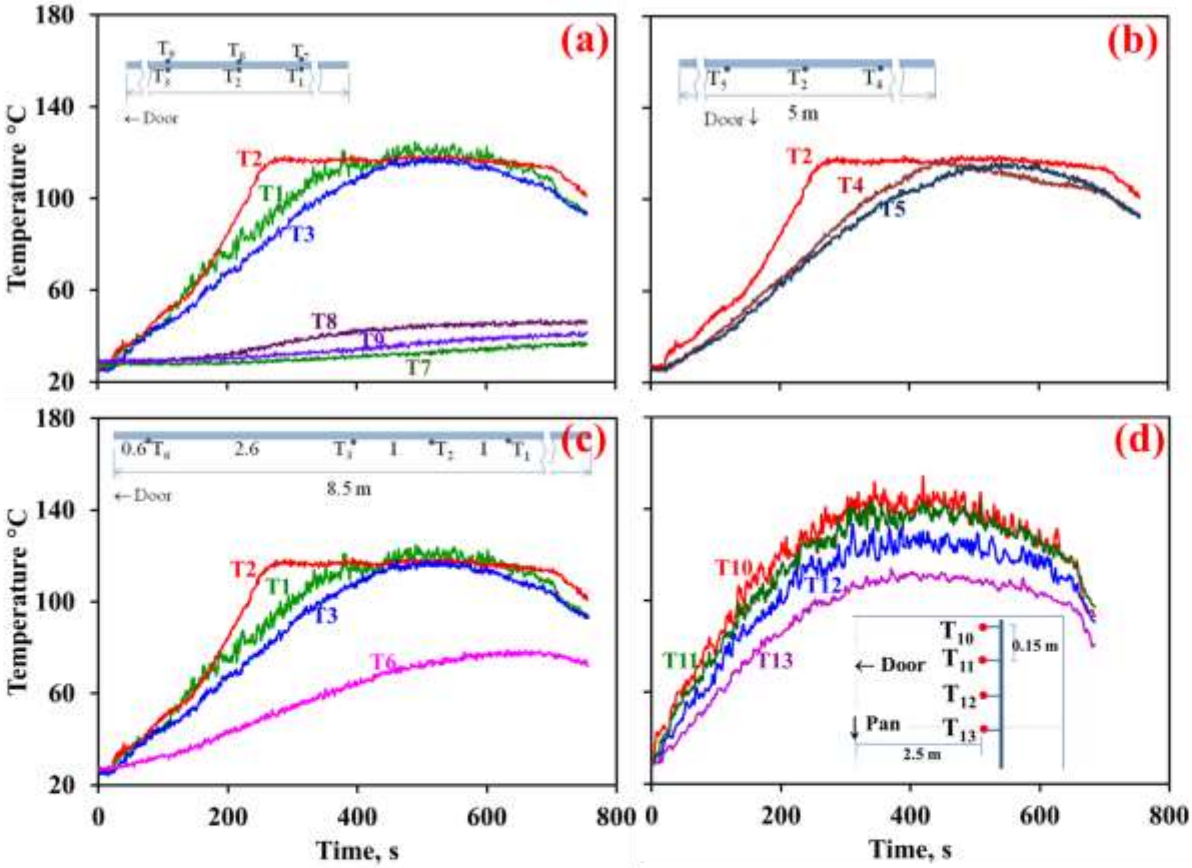


Fig. 5.6 Temperature measurements of the enclosure Expt. #2: (a) Roof temperature above the pool (b) Roof temperature across the room width (c) Roof temperature across room length and (d) Gas phase temperature measurements at a location 2.5 m from edge of the pan towards rear side wall

Measurement of temperatures at the roof was carried like in the previous experiment at different locations and these are shown in Figure 5.6 (a, b, c). Average temperatures around the central area of the coated roof bottom found to be ~120 °C. This temperature is attained in about 200 s and found to be stable for a period of 500 s, there after it started decreasing as the flame height decreased due to cooling effect caused by the water layer with decreasing fuel layer thickness. Roof top around the central area found to attain a temperature to a maximum of 45°C which is well within the requirement of safe usage of EPS. Gas phase measurements at a location 2.5 m from the pool fire inside the enclosure as shown as per the experimental scheme are presented in the Figure 5.6 (d). Peak temperature recorded at 40 mm below roof (T1) is 150°C.

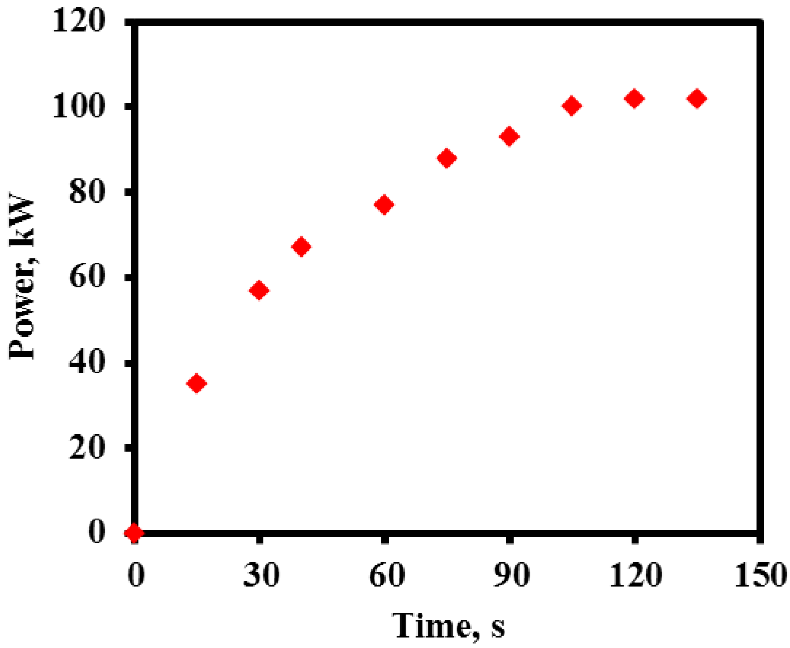


Fig. 5.7 S- 260 mm Ø heptane pool power history

Experiment #2 with S260 mm Ø heptane pool fire is conducted for a period of 675 s and during this period the peak power is found to get established between 200 s to 500 s. Periodic averaging of burn rate gave an idea of power levels attained at different progressing intervals wherein the initial power was found to be 43 kW which rose up to ~90 kW in about 4 mins and a peak power ~103 kW as in Figure 5.7.

Table 5.5 Details of third set of heptane pool fire experiments

Expt. #	Pan	Area m^2	period s	Q kW	Q_{peak} kW	PPD s	T_{peak} °C	T_g °C
3.1	S210	0.0441	732	51	55	100	*	104
3.2	S210	0.0441	659	60	69	110	115	114
3.3	S260	0.0676	487	107	116	60	160	142
3.4	S300	0.09	548	171	178	60	220	189

*Data not acquired; PPD – peak power duration

Experiment # 3 consisted of a set of four consecutive experiments using square pans of sizes S210 mm (50 kW), S300 mm (150 kW) and S260 mm (100 kW) heptane pool fires conducted inside the large room enclosure. All the experiments were conducted maintaining a uniform level of liquid layer inside the pan such that 165 mm of water, 44.5 mm of n-heptane and 6 mm free board. Temperature and smoke layer heights were measured like in earlier experiments. Earlier a set of twenty five boards which were identified weak due to the previous experiments were replaced with new boards and were fixed to the frame and left in place for over a month before conducting the new set of pool fire experiments. The details of these experiments are tabulated in Table 5.5. Door way velocities of gases leaving the room were found to be in the range of 0.5 m/s to 1.5 m/s.

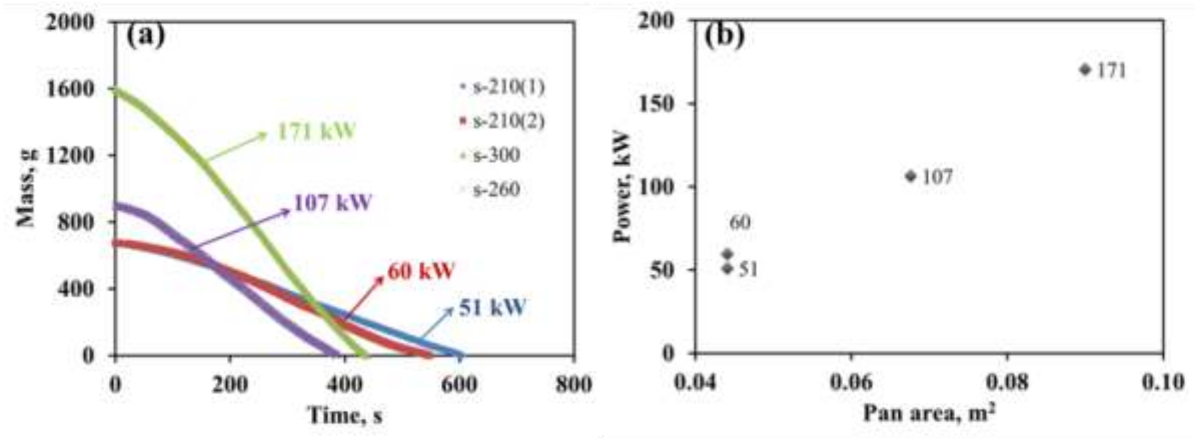


Fig. 5.8 (a) Burn rates of heptane pools of S210 mm,S-260 mm and S-300 mm (b) power vs. pan area

In Figure 5.8 is presented the burn rates and the plot of power versus pan area details of which are shown in Table 5.5. It can be observed that the overall burn rates were found to be 51kW, 60 kW, 107 kW and 171 kW for the three different sizes. Expt. 3.2 is a repeat experiment of the 3.1 since roof temperature data could not be acquired properly due to power related issues. An increase in the burn rate of the the repeat experiment by ~ 15% of the experiment 3.1 is observed indicating the contribution of increased initial room temperatures following the first experiment. Following this sufficient gap to achieve ambient room condtions were given for the subsequent experiments. This could be observed from the Figure 5.8 (b) showing plot of power versus pan area in which the powers increase linearly with the increase in size of the pan. Table 5.5 also presents the peak heat release rate for the different pan sizes which also show a similar trend. The peak temperature attained at the central location above the pool on the roof of the enclosure and the time to reach this peak temperature are plotted against power inFigure 5.9. It can be observed from the plot that these increase linearly with power. Furthermore it can also be seen from the plot that the peak temperature attained by the central roof top are 38 °C, 44 °C and 46 °C corresponding to central roof bottom temperatures 115 °C, 160 °C and 220 °C right above the pool consequent upon the overall thermal conductivity of the coated material and the convective heat flux received by the material during these experiments. The roof top temperature in all the experiments is much less than 80 °C which is more crucial for the EPS material begins to soften once past this temperature. As long as the roof top temperature is held within this, the roof is under safe condition.

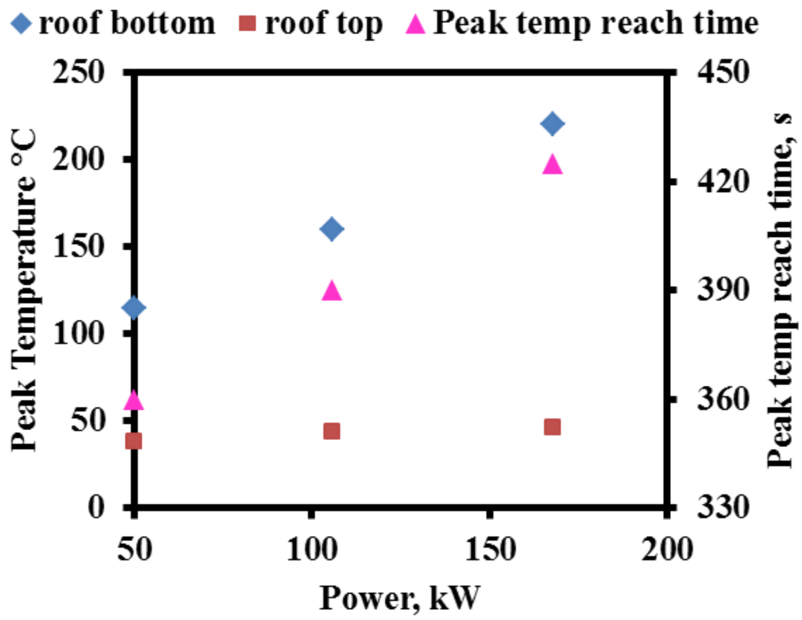


Fig. 5.9 Time to reach peak temperature at roof top and bottom for 50, 106, 168 kW heptane pool fires inside the enclosure

Table 5.6 Thermal profile at roof (1 m radius)

Pan mm	Q_c kW	$\dot{q}_c''$ kW/m^2	k at roof W/m.K	T_s-T_a K	T_b-T_t K
S210	51	1.8	1.11	348	340
S260	107	3.2	1.67	383	354
S300	171	4.9	1.99	433	376
S480	315	7.9	2.55	473	403

Table 5.6 consolidates the thermal profile of the roof obtained during the experiments. The details of these results are presented in the plots Figures 5.10 and 5.11 through which average temperature difference across roof along the central locations of 1m radius above the pool and temperature difference of the inner roof surface in other words roof bottom with respect to ambient temperature are obtained. Convective heat flux received at the roof bottom for a radius of 1 m is calculated using the suggested formula of Veldman et al (See Quintiere 2006).

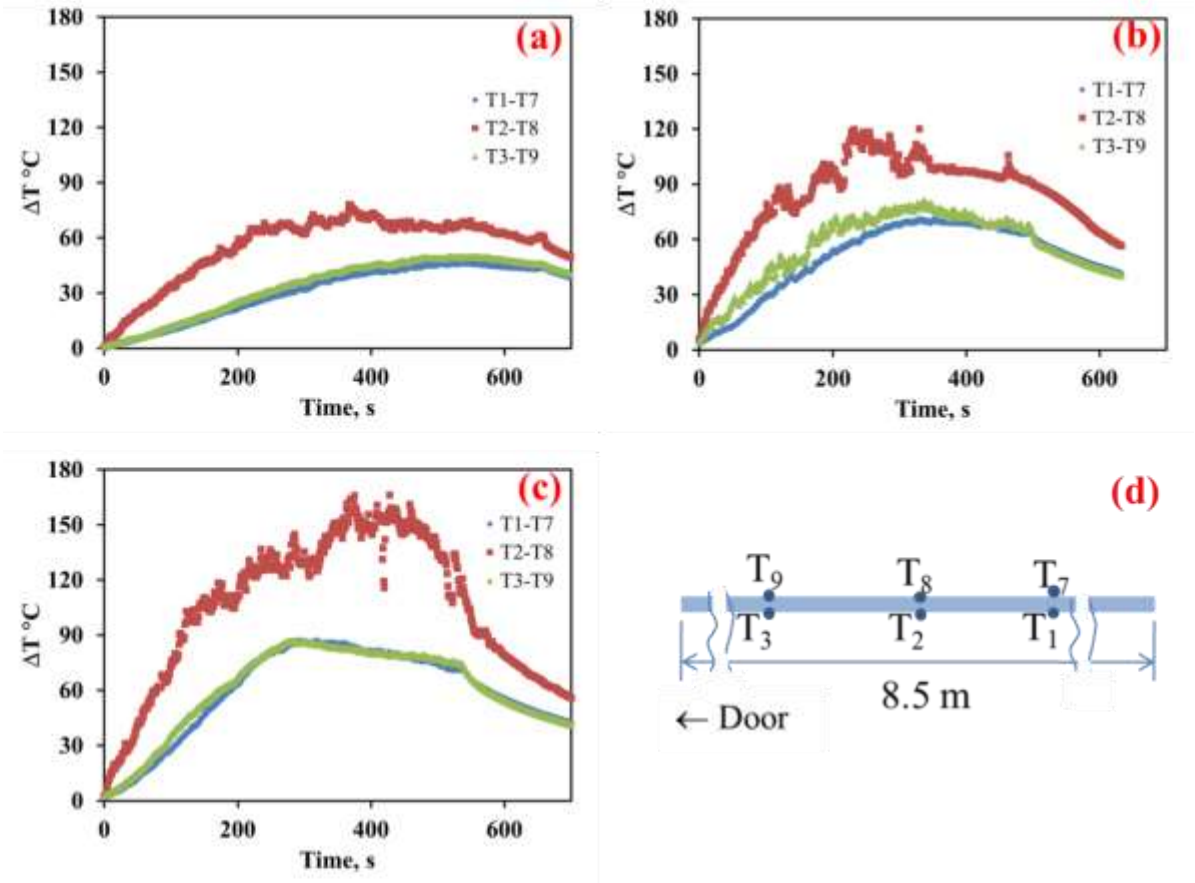


Fig. 5.10 ΔT across roof at location centrally above (a) 51 (b) 107 (c) 171 kW heptane pool fires; (d) Thermocouple locations

Using the convective heat flux and the temperature difference at roof in the Fourier law of conduction thermal conductivity of the roof material for different power levels is obtained. It should be noted that in the plots mentioned above only steady burning period of the experiments are considered where in the data is found to be stable and uniform except in the case of S480 (315 kW) pool size last 100 s before extinguishing is considered due to discontinuation of the experiment.

It is also observed that the temperature differences with respect to ambient temperature and that of temperature difference across roof material vary by ~15% with the increase of power level inside the enclosure and hence the conductivity of the material is also showing the increasing trend with respect to increasing power levels and thus temperature. With this it is found that these values exhibit power-law dependency.

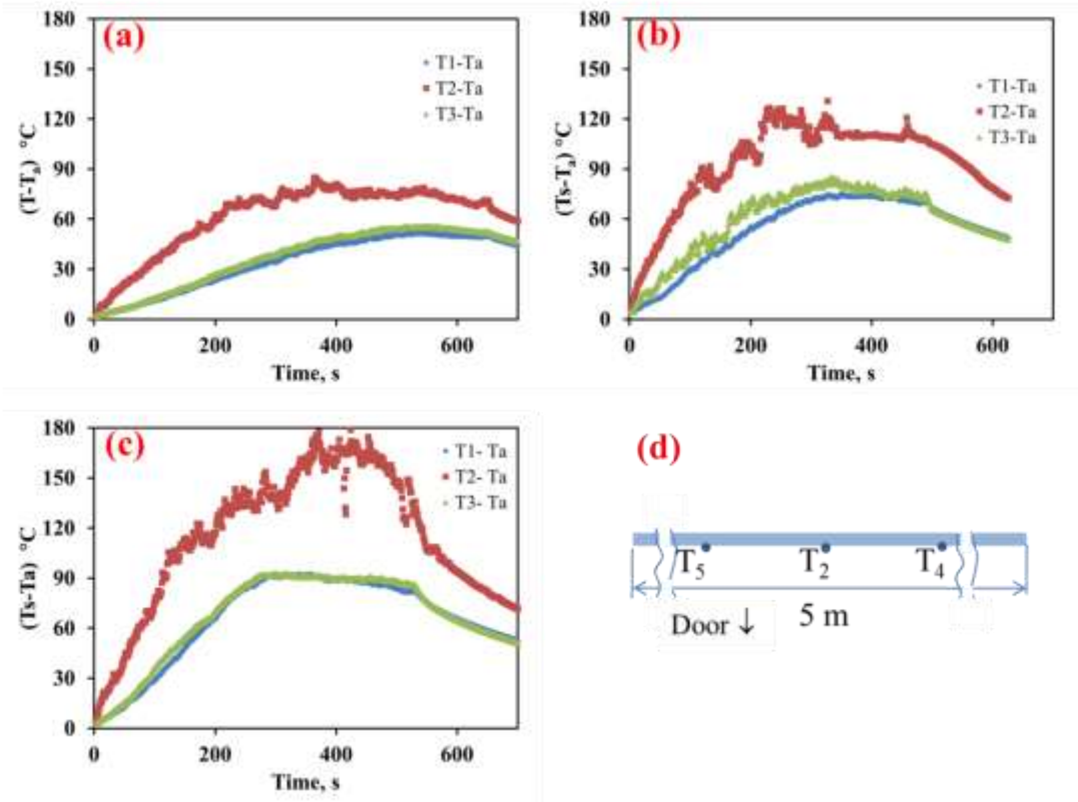


Fig. 5.11 ΔT (roof bottom – ambient temperature) at location centrally above (a) 50, (b) 100, (c) 150 kW heptane pool fires, (d) Thermocouple locations

Table 5.7 Smoke layer height from floor with time

Time	Smoke layer height from floor, m			
min.	51 kW	60 kW(R)	107 kW	171 kW
0	2.40	2.40	2.40	2.40
1	2.40	2.40	2.40	2.40
2	1.63	1.63	1.63	1.63
3	1.50	1.63	1.50	1.38
4	1.50	1.50	1.38	1.25
5	1.38	1.38	1.38	1.38
6	1.38	1.38	1.38	1.38
7	1.38	1.38	1.38	1.38
8	1.38	1.38	1.38	1.38
9	1.38	1.38	stop	1.38
10	1.38	1.38		stop
11	1.38	1.38		
12	1.50	stop		
13	stop			

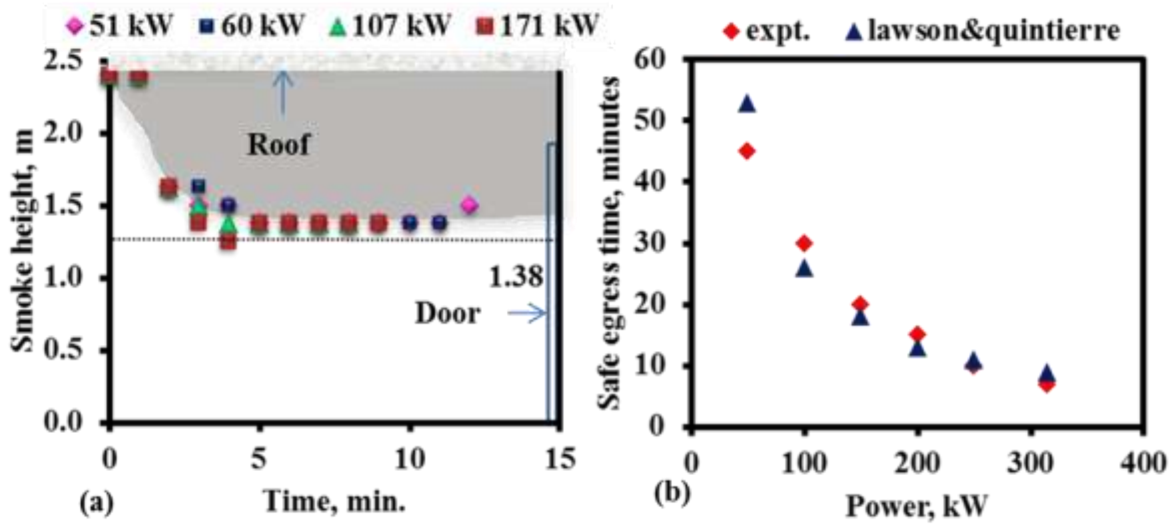


Fig. 5. 12(a) Smoke height versus time
(b) Safe egress time available for various power levels

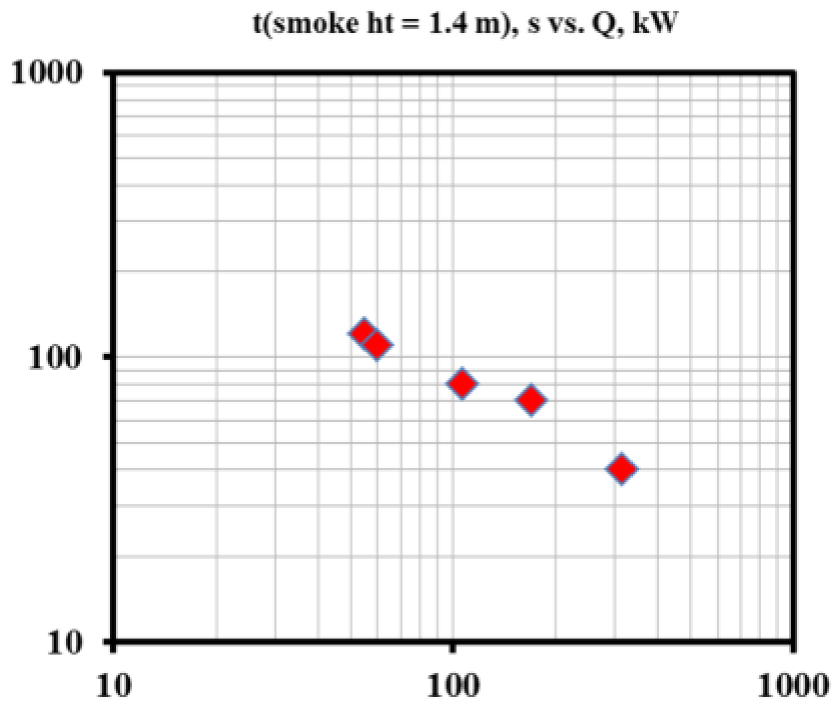


Fig. 5. 13 Safe egress time vs. Power level

Figure 5.12a shows the smoke layer height variation with time in minutes from the floor level as detailed in Table 5.7. It can be seen that smoke layer height stabilizes at 1.38 m from the floor in about 5 minutes. Figure 5.12b is the plot of power versus egress time presented based on the experimental results observed and compared with the theoretical results. It can be seen that the experimental results are in close comparison with that of theoretical results. It is found that the coated roof has sufficient capacity to hold the fire when the fire power is in controllable range. Studies have shown that a fire power of 400 kW can be approachable with PPEs and portable extinguishers. Smooth human egress is also possible as obscuration due to smoke layer is within safe limits (>1.2 m).

Figure 5.13 presents the power log plot of safe egress time to power level. The key finding is that this time varies as $Q^{-0.63}$. Doubling the power level does not have halving influence. The reduction in safe egress time is much higher (15 % more than halving effect).

5.4 Results and Discussion

Initial experiment with S480 mm Ø pool fire of n-heptane kerosene mixture revealed that the roof could withstand ~300 kW for about 4 minutes. Smoke layer stabilized at a height of 1.3 m from floor level after a minute and a half (1.1 m down from roof as in Figure5.3) giving a smooth egress clearance of 1.3 m. The failure of roof at 250 s occurred due to higher heating rate of unprotected metal framework during experimentation. This was confirmed after critically examining the physical condition of the roof of the enclosure post experiment (Figure5.6). Interestingly the central roof element survived but edges of roof element in contact with metal support framework failed. This led to the requirement of insulating the metal also from fire onslaught. Experimentation at $1m^3$ size with gypsum PoP insulation to metal frame along with coated EPS roof also confirmed that insulation to the frame is necessary in addition to the fire protection of the EPS tile. Details of this have been covered earlier in chapter 4.

Subsequent experiments conducted with 100 kW using S260 mm diameter pan gave encouraging results. While doing so it is observed that these experimental results can be of much useful to decide on the power level that a particular roofing of this kind can hold and provide safe egress to the occupants. Time to safe egress in occupancy could be easily arrived by plotting power versus available egress time. Egress time for the large room found to vary with power as $Q^{-0.63}$.

A set of four experiments with different power levels conducted show that the roof is able to hold a power of more than 170 kW (recorded during the experiment with S300 mm pan using heptane as fuel for about 9 minutes. It should be noted that the coated EPS roof is able to hold varying powers of the range up to 315 kW. Further one advantage is that the roof top temperature from the central location found well within safe limits < 50 °C. In all with the third set of experiments the roof could bear the fire load of 50 to 170 kW range for more than 30 minutes. This raises a question if this improved roof condition will also be able to bear fire load more than 400 kW for more than 3 minutes.

5.5 Summary

Experiments have been carried out in the large enclosure using 315 kW power heptane kerosene fuel mixtures and these have indicated that the roof can with stand the power for a period of 4 minutes which is more than safe egress time requirement of 3 minutes as per NBC. Further it is also observed that the safety to the coating is also compromised due to the thermal conduction of the frame to the EPS board indicating the requirement of an appropriate coating or insulation of the frame towards improving on the fire safety. This is verified by carrying out relative experiments with coated and uncoated frames results of which showed progressive results with the coated frames. Also subsequent experiments carried with lesser powers indicated the roofing could hold safely for a period of about 15 to 30 minutes leading to safe egress opportunity.

Chapter 6

Computational Studies

6.1 Aim of the study

Computational studies are intended to numerically estimate the desired parameters by making use of appropriate software tools. The results of the numerical studies can become input to real scale experiments. This helps in unraveling aero-thermal behavior inside the working space under fire conditions that will ultimately help design. Section 1.2.5 describes the earlier work on the use of computational tools to understand enclosure fires. The aim of the present study is to compare the experimental results with that of the theoretical (FDS) results and present the extent of agreement between the two. Computations are carried out in two different domains $1m^3$ cubical and a large size domain with dimensions 8.5 m × 5 m × 2.5 m (H) and are compared with experimental results obtained with similar dimensions which will be discussed in detail in the following sections.

6.2 The Computational details

The present computations are carried out in FDS 5.5. Fire Dynamics Simulator (FDS, Version 5.5), a Large Eddy Simulation (LES) / Direct Numerical Simulation (DNS) based CFD tool for computation of unsteady flows, available from NIST web site, is used to carry out simulations (the latest version FDS 6.1 was released only recently much after the present work was completed). FDS solves numerically a form of the Navier-Stokes equations including energy and exothermic chemistry appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Gray gas model is used to solve radiation transport equation with 104 angles in the present set of simulations. Also, radiation solver is updated every 3 time steps with 5 angles skipped every update. Mixture fraction model is used for combustion.

Fuel release is modeled using the parameter, heat release rate per unit area (HRRPUA) based on experimentally measured fuel flux varying with time. The default value of initial time step, ΔT is $5(dxdydz)^{1/3} / (gH)^{1/2}$ s, where dx, dy, and dz are the dimensions of the smallest mesh cell, H is the height of the computational domain, and g is the acceleration of gravity. During calculations time step is set automatically by dividing the size of a mesh cell by the characteristic velocity of the flow. An i7 series HP Server with 16 GB ram is used for calculations.

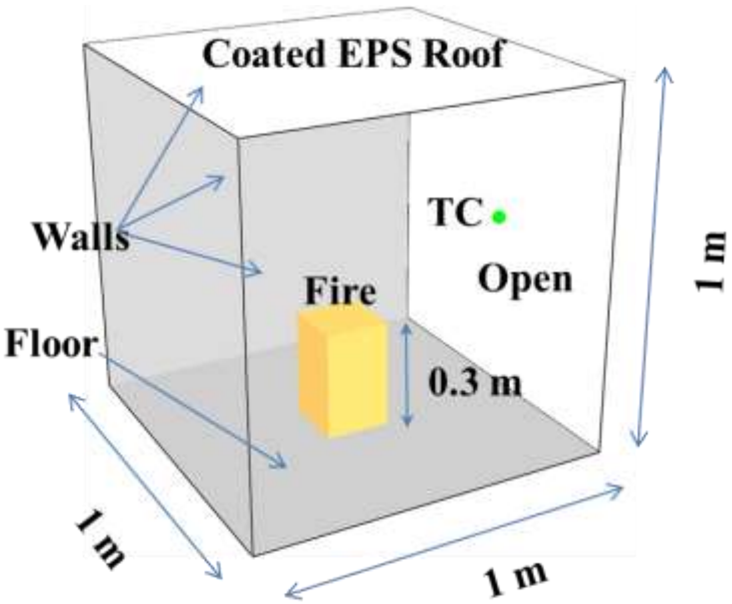


Fig. 6.1 FDS model for Pool fire simulation

6.3 Experimental domain for 1m^3 cubical room

Figure 6.1 shows FDS model of 1 m^{3}cubical room. Multi-grid structure with 1.4 million grid points with a resolution of 5 mm in the flame zone is used for calculations. The choice of this mesh size is based on preliminary trials among 3 different mesh sizes 10 mm, 8 mm and 5 mm of which 5 mm is found to give more sharp results. Different set of calculations are carried for duration ranging from 100 s to 200 s burn time. Fire boundary is simulated as heat release rate per unit area from equivalent square surface of the circular pool of 205 mm diameter and this amount to 181 mm. Appropriate specifications of the materials, EPS and the gypsum coating were given through FDS input file. A peak heat release rate per unit area (HRRPUA) of 757 kW/m^2 is used as fire boundary condition located at 0.3 m above the floor. Heat release rate (HRR) is increased in proportion to experimentally measured one-minute average fire power. Slice files output were sought at various planes of the domain viz., x=0, y=0 and z=0.4, z=0.6, z=0.8, z=0.9 and z=1.0. A device file introduced at 0.5 m location gave the temperature status of the opening at x maximum. Walls and floor were specified inert. The simulation time is found to be at a rate of ~12 s in 24 hours.

6.4 FDS studies carried in 1m³ geometry

Studies using FDS are carried out in 1m^{3}cubical geometry with different grid sizes to understand the grid independent level of the calculations. According to FDS user guide mesh resolution can be chosen using a non-dimensional expression $D^*/\ \delta x$, where D^* is characteristic fire diameter given by

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5}$$

and δx is the nominal size of the mesh cell. It is recommended that finer the grid size better is the resolution of the calculation. To verify this, calculations are carried using 10 mm, 8 mm and 5 mm grid sizes at the same conditions. Outputs are sought for various parameters along horizontal and vertical directions along xz plane of which, mean temperature, pressure and velocity along central vertical distance of the fire region averaged over 50 s are presented in Fig.6.2 a-c.

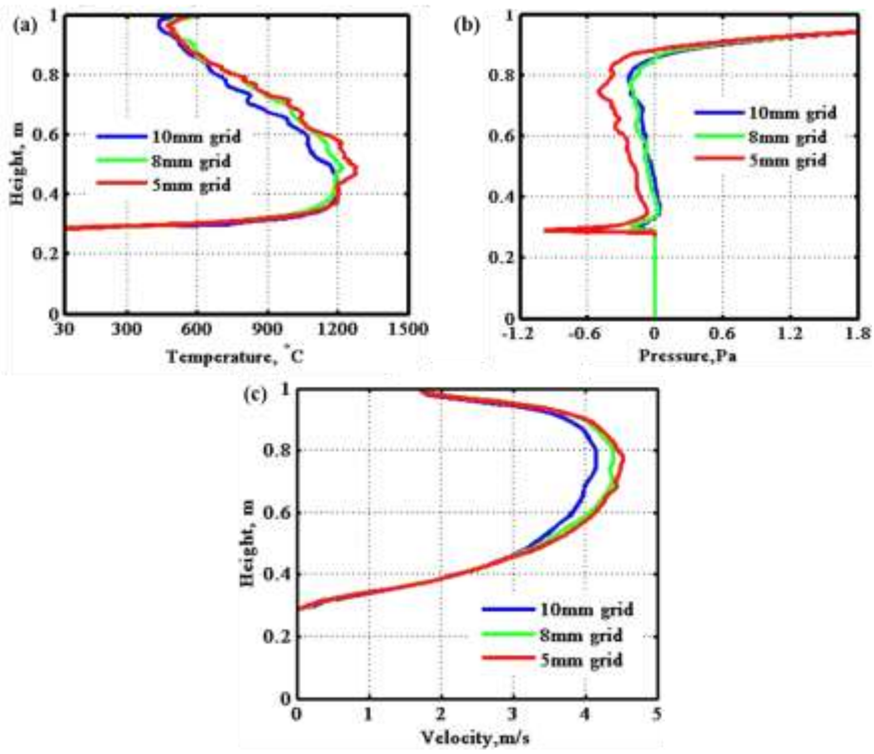


Fig. 6.2 FDS results with different grids – (a) temperature (b) pressure (c) velocity

It can be seen from the Figure 6.2 (a-c) that the comparison is (a) reasonable with regard to temperature and velocity and (b) tolerable for pressure. The key problem with pressure is that the values are very small and hence small errors seem significant. While calculations can be considered acceptable even at a grid size of 8 mm, results presented here are corresponding to 5 mm grid as these computational results are available and are considered acceptable.

6.5 Results and Discussion – 1 m^3 geometry

For making realistic FDS calculations, the power increment is provided in a manner identical to that in experiments. Figure 6.3(a) shows the experimental power history of 25 kW pool fire which is used in FDS simulation. Powers of the pool fires were calculated from burn rate averaged over one minute and fuel energy content of 43.2 MJ/kg for kerosene and 44.6 MJ/kg for heptane. One can notice that there is a slower increase in the power for a period of 60 s before stabilization is achieved in these cases.

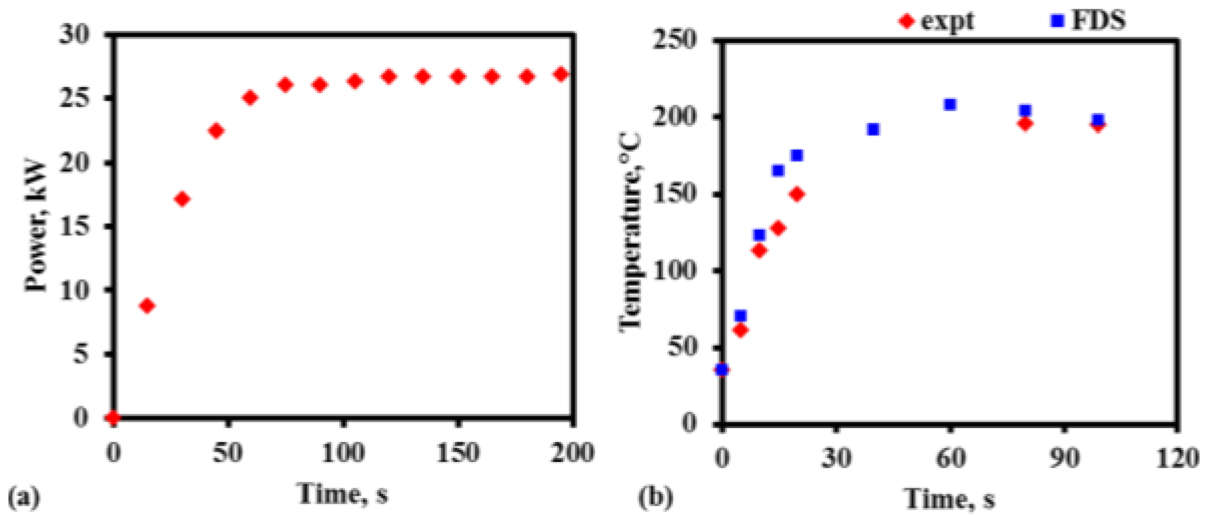
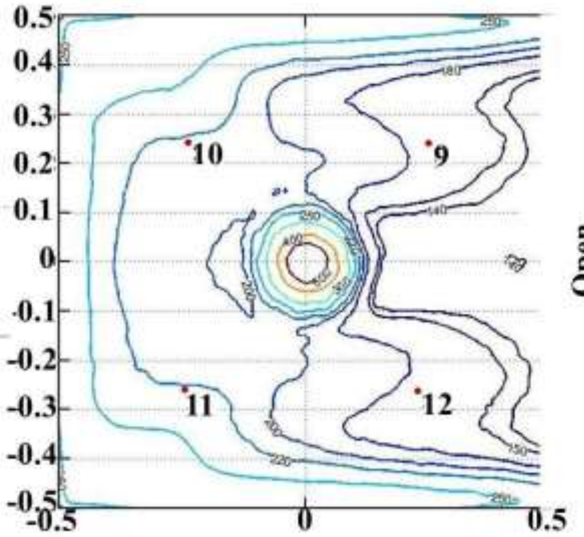


Fig. 6.3 (a) Experimental power history of 25 kW
(b) Gas phase temperature history at location T1

Figure 6.3(b) details the experimental and FDS outputs of pool fires with 25 kW power level at a location T1, 0.1 m below roof and Figure 6.4 indicates the temperature contours at the roof and measured temperatures at the specified locations on the roof. Comparison of these results indicates a close agreement. Similar good comparisons were also obtained for gas temperatures at other locations (they are not presented here).



Measured Values	
Position	T °C
9	140
10	220
11	250
12	180

Fig. 6.4 Temperature contours of the roof (100 s) and experimental data at 12th min.

Figure 6.5 shows time averaged exit velocities at the open face of the room with a power of 25 kW nominal. Inset to figure is the photographic image taken during 25 kW experiment. FDS correctly predicts the neutral layer (zero velocity) to exist below smoke layer of thickness 140-160 mm as can be seen from velocity plots. Positive velocity (XMAX=Open, See Appendix – I, FDS input file) is indicative of outward high velocity hot gases.

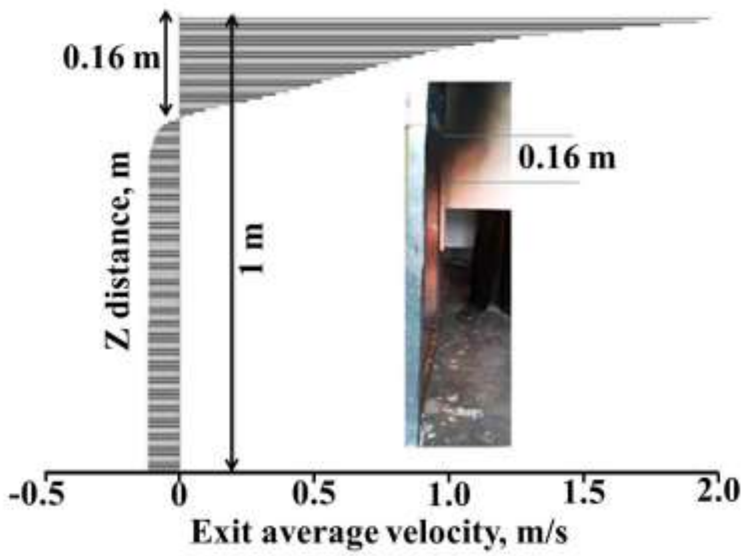


Fig. 6.5 FDS average velocity and steady smoke height (Inset: experiment image)

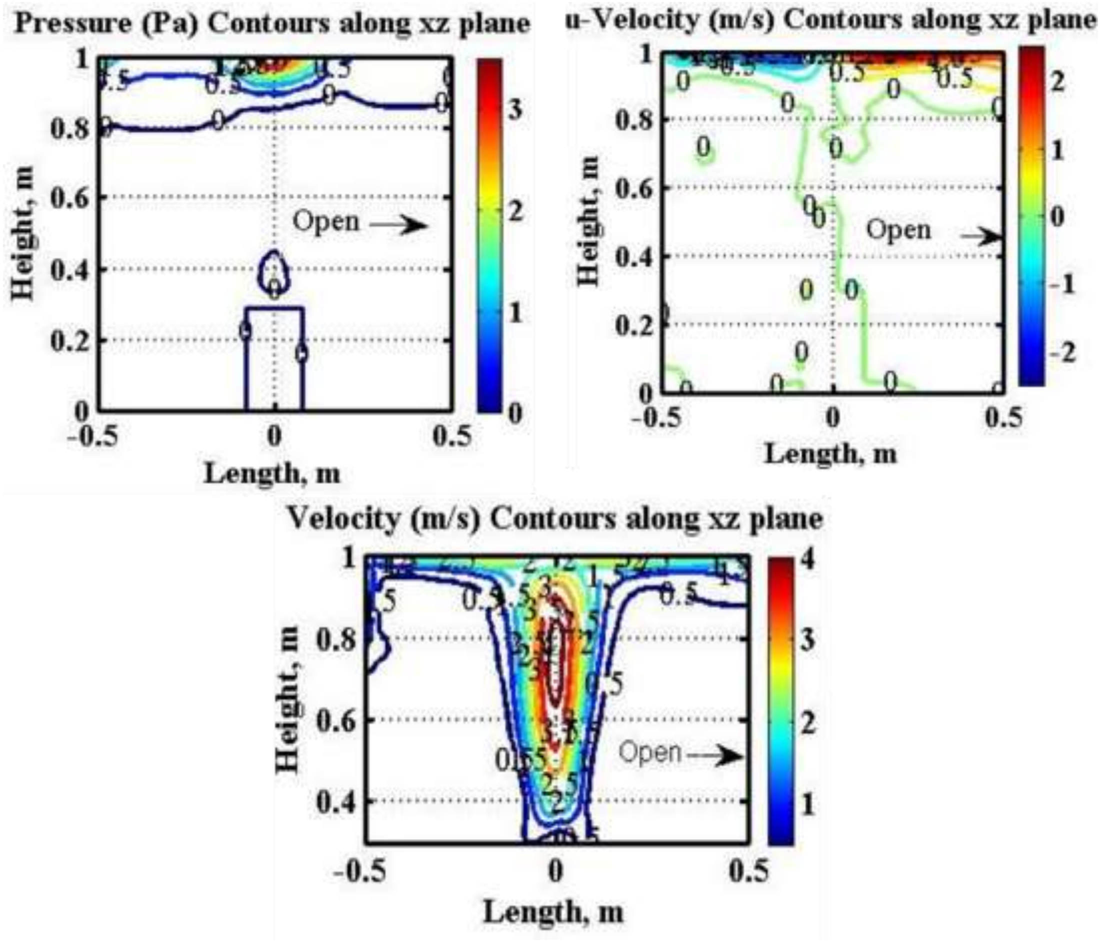


Fig. 6.6 Pressure and velocity contours (150 s avg.) along XZ plane (a) Pressure (b) Horizontal velocity (c) Mean velocity

Figure 6.6 (a-c) shows the pressure and velocity contours for 1 m^3 cubical room simulation averaged for a period of 150 s along xz- plane (length of the room) where x- max is open. It can be seen that the pressure below the neutral plane (0.16 to 0.2 m below the roof) is zero and negative velocities as seen in Figure 6.6 b is because of the flow towards wall along –x direction, ignoring the sign we get uniform velocity in both the direction (typical to centrally located fire) and this can be seen from Figure 6.6 c. Since the cubical room is fully open at x-max the layer formation is much restricted close to the roof (up to 0.2 m below roof).

It should be noted here that the domain in the case of large room is constructed locating the door at x-min, therefore the flow direction will be in the –x directions and therefore the values are seen with negative sign. Ignoring the sign we get actual velocities of the hot gases flowing out of the room.

6.6 Experimental Domain set-up for large size room

Experimental domain of the large room measuring 8.5 m (L) × 5 m (W) × 2.5 m (H) in dimensions used for the simulation is shown in the Figure 6.7. Extra region in front of the door is simulated to ensure boundary conditions at the door are appropriate. FDS studies are carried out using large room domain to determine the pool fire power that could give a hot gas temperature to a maximum of about 225 °C close to roof as hot gases at this temperature is detrimental to EPS surface.

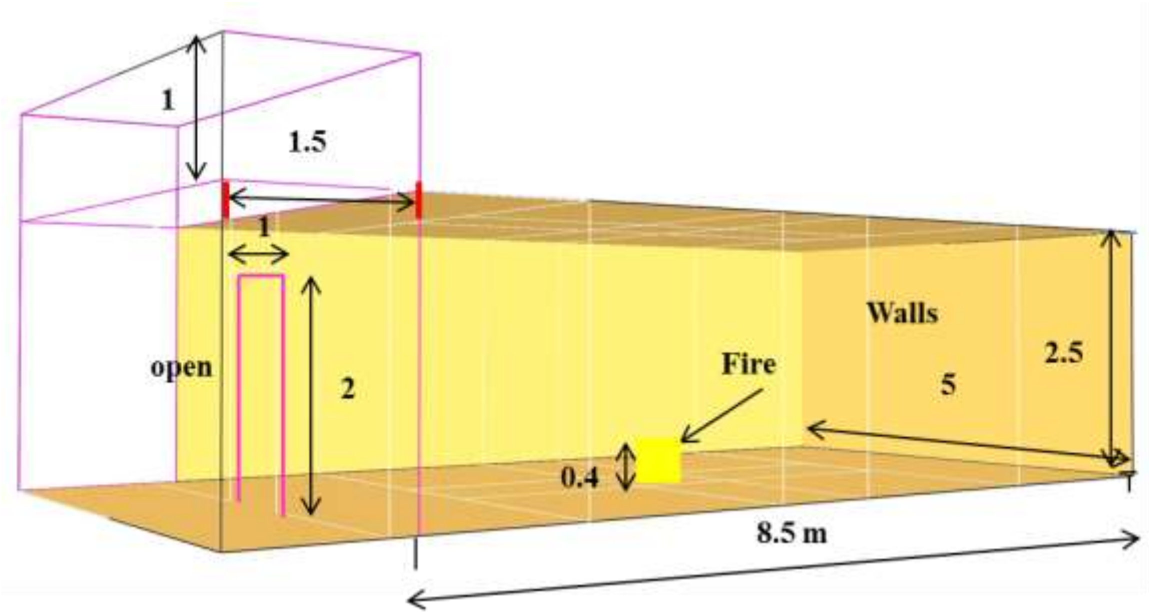


Fig. 6.7 FDS domain of 96 m³ room for computations

A multi grid structure with 8.75 million grid points is used. Central fire region of 1 m × 1m area are discretized with 10 mm mesh and rest of the domain with 20 mm mesh. An i7 series HP Server with 16 GB ram is used for calculations with a simulation time of ~ 2.8 s in a clock time of 24 hours. Roof and wall surfaces are treated to match the real experimental conditions through the input parameters. Roof parameter consisted of inner boundary surface of 2 mm thick gypsum followed by 40 mm thick EPS. Fire is simulated with appropriate choice of heat release rate per unit area and is carried out with different power levels 100 kW, 150 kW, 250 and 300 kW. FDS outputs were sought for the parameters like temperature, velocity, pressure, mixture fraction and soot fraction in the form of slice file out puts. Roof conditions are monitored by acquiring data at the roof boundary through profile files. Flux at the boundary is monitored by means of Gauge heat flux and a device point served the purpose of tracing mass flow in and out of the compartment. Two calculations are carried out, one by varying HRRPUA for 150, 250 and 300 kW in a sequential pattern and the second by ramping up the power periodically to a peak power of 100 kW. Results of the first calculation will be presented first followed by the second one in the following section.

6.7 Results and discussion - large room geometry

The first set of computations involved a centrally located fire boundary with a surface geometry to match 0.48 m × 0.48 m pool. Fire boundary is treated suitably with HRRPUA for different power levels 150 kW for a period of 100 s followed by 250 kW for 50 s and 300 kW 30 s respectively (See Figure 6.6). HRRPUA is changed by stepping the power level sequentially. Comparisons are carried with corresponding experimental results and studied.

6.7.1 *g-phase temperature profiles – Large room computation #1*

The slice file corresponding to the thermocouple tree location as per the experimental scheme is chosen at the plane for x = 2.5. It should be recalled that the experimental thermocouple tree location at 2.5 m from the centre of the pool (See Figure 5.1). The experimental data from four locations T10 –T13 from the bottom of the roof during the experiment #1 conducted with 315 kW pool fire are compared with respective nodes from FDS out with time average of 5 s. It is emphasized here that the input to the FDS simulation during the first computation is treated with varying HRRPUA corresponding to power levels of 160 kW, 250 kW and 300 kW at 100 s, 150 s and 180 s.

It can be seen from Figure 6.8 that up to 150 s the FDS predictions are on the lower side and there after increases corresponding to a power of 300 kW and this goes above the experimental results. This is due that the peak power during the experiments is reached at a later stage compared to the FDS predictions and in the comparison above the results at the first 50 s matches closely with the temperature data of 160 kW peak power and there after the experimental power keep on rising to a power corresponding to 250 kW, the drift seen in the comparison is due to the change in power to 250 kW in FDS input is given only at 100 s. Past 100 s it can be seen there is tendency of FDS results to match to that of experiment and this shoots up beyond experiment when the peak power is reached. Yet this comparison leads to understanding two key points that (i) the burn rate in actual burning scenario of pool fires come across atleast three distinct stages prior to reaching of peak power level (duration of which is dependent on burning area and the fuel) and (ii) the tendency of over- prediction of FDS results to that of experimental results is due to the reason that FDS reaches the peak power level much earlier and this calls for the need to treat the FDS input appropriately to match the experimental power. These requirements are attempted in subsequent computations at lower power levels both in the case of $1m^3$ cubical room (presented in the earlier sections) and in the large scale room.

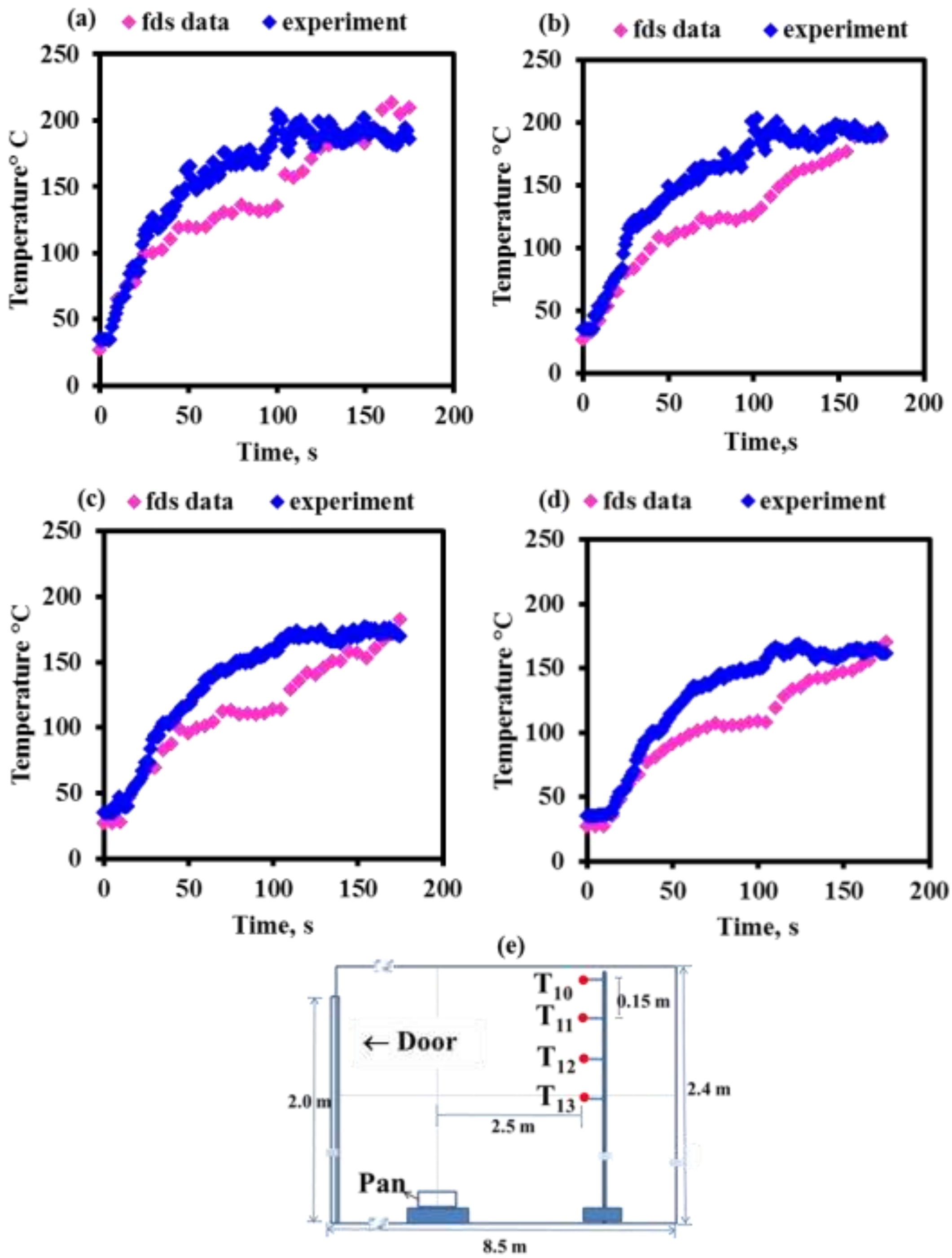


Fig. 6.8 Comparisons of first set of FDS computations with experiment #1 for temperature profiles at locations below roof: (a) T10 at 40 mm (b) T11 at 190 mm (c) T12 at 340 mm and (d) T13 at 490 mm

6.7.2 *Large room computation #2*

Further to the understanding of the requirement of stage wise approach to the burn rate in FDS it is decided to make use of ramping utility in FDS to carry out this task. Accordingly a second set of computations are attempted in which power levels are chosen at a lower HRRPUA corresponding to 100 kW. This has reason due to the learning gained from the large scale experiment #1 with 315 kW, it is decided to carry out the experiments with power much lower than that such as a power level of 100 kW are so.

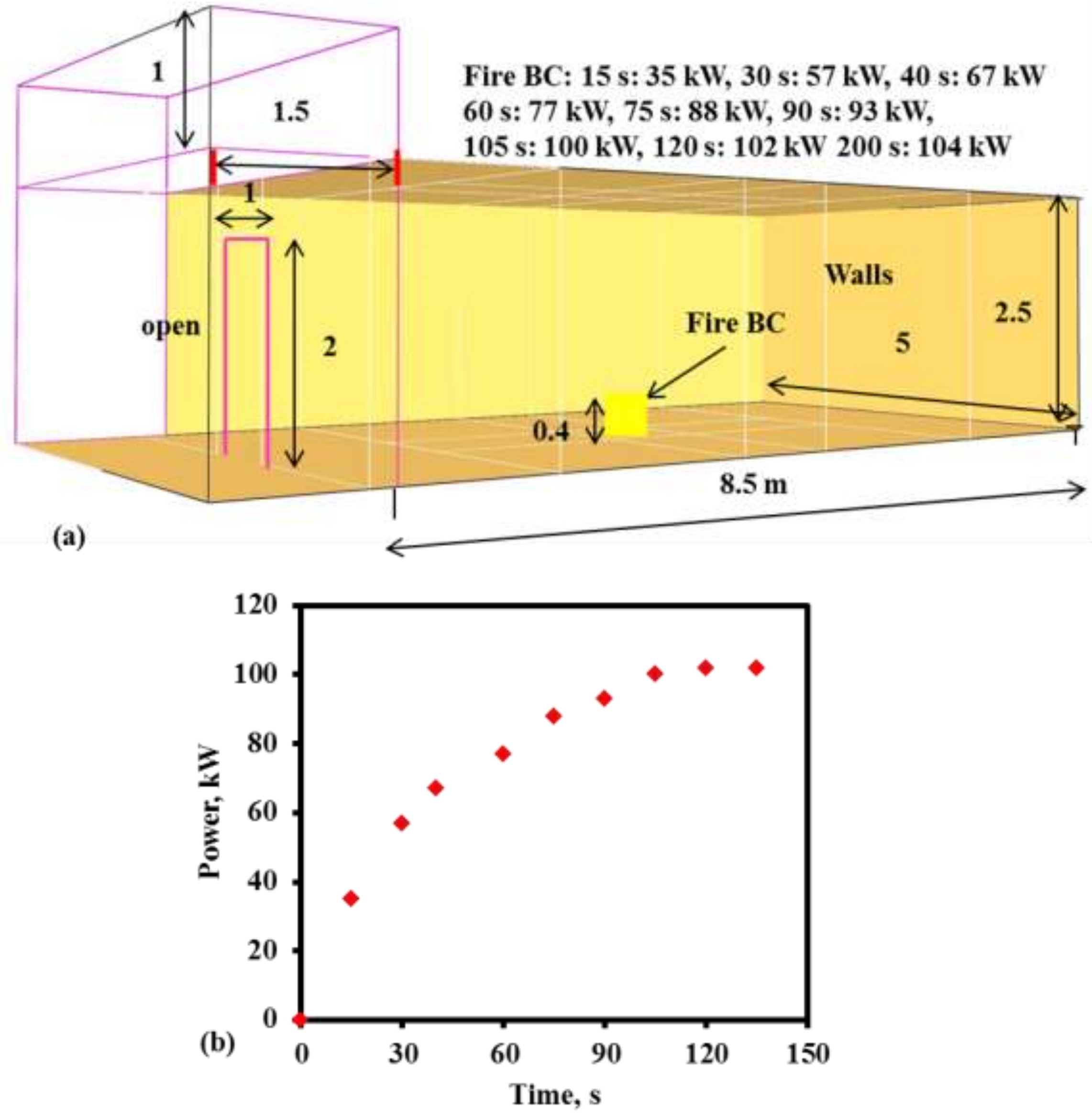


Fig. 6.9 Large room computational domain and the experimental power history given as input to the fire boundary condition

The FDS computational domain and the fire boundary conditions based on the experimental power history of 100 kW is shown in Figure 6.9. The input file corresponding to the computations is set out in the Appendix -II. It can be seen that the powers are ramped using the ramping utility to match the experimental power history and the results are compared at different times. Fire boundary conditions are from experimentally measured data.

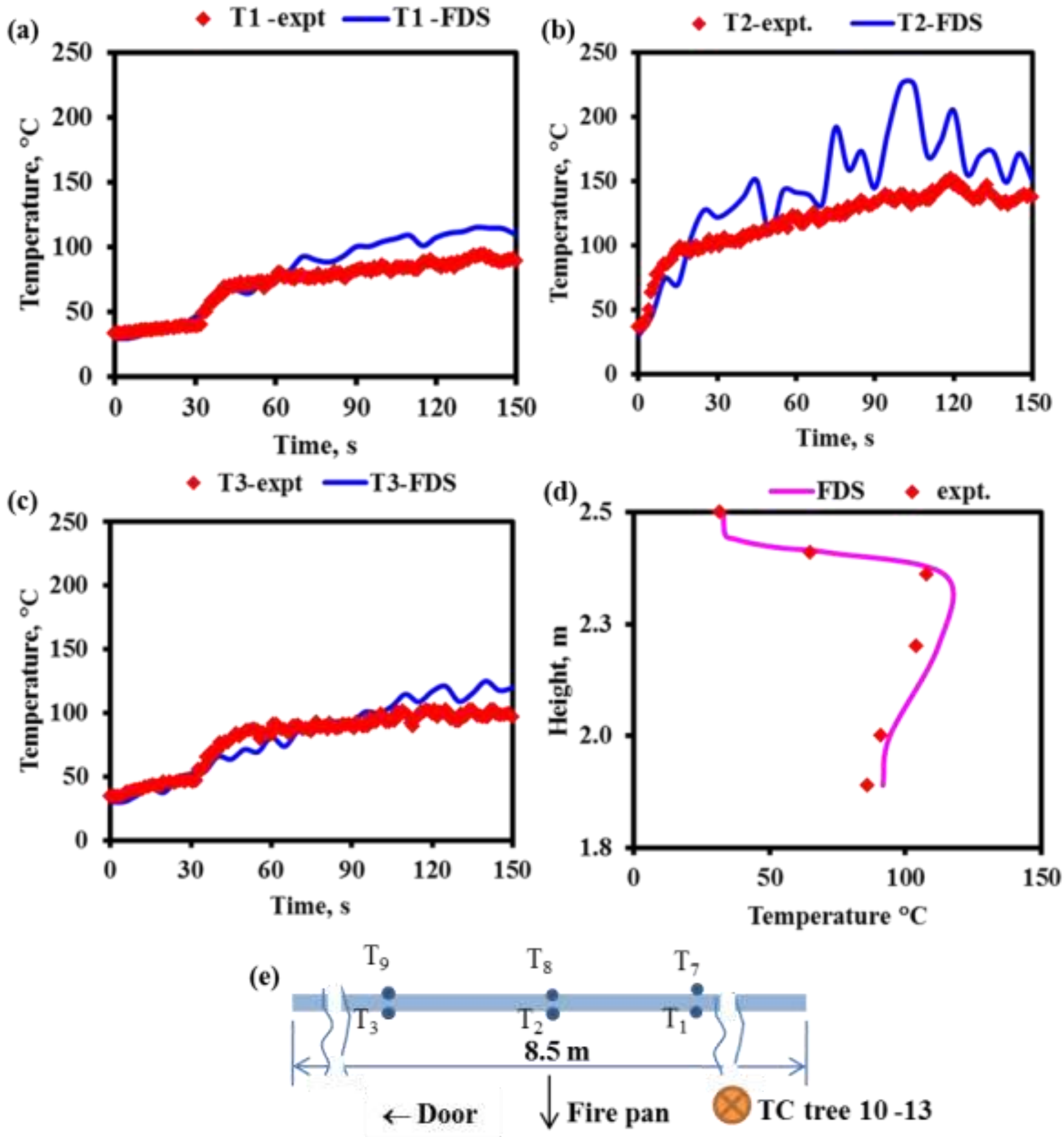


Fig. 6.10 Comparison of temperature profiles at roof with FDS results: (a&c) Temperature profile at 1.2 m radial distances T_1 and T_3 from centre of the pool; (b) at central location (T_2) experiment and FDS; (d) Comparison of temperature profile gas and condensed phase at 2.5m from centre of the pool; (e) Thermocouple locations

6.7.3 Comparisons of FDS results with experimental results (100 kW)

FDS computations carried out with the above said approach are compared for g-phase and c-phase temperature profiles with that of the experimental one. Experimental results with S-260 mm pan giving 100 kW power with n-heptane are considered for comparison. Figure 6.10 (a – c) shows the comparison of temperature profiles of the roof at and adjacent to the central location above the pool and Figure 6.10(d) is the comparison of g- phase and c-phase temperature profiles at a horizontal location 2.5 m from the centre of the pool. The locations are condensed in to the Figure 6.10(e) (also See Figure 5.1).

It should be recalled here that earlier comparisons shown in Figure 6.8 of gas phase temperatures at wall locations indicated higher values than that of the experiments while there is a good agreement with the temperature measurements at thermocouple locations of the tree. This could possibly be due to conduction losses through the bare bead thermocouples mounted on to the board. This is confirmed by checking the response time of the thermocouple in accordance with a standard method, EGOLF agreement 2008. (For details refer to Appendix – III).

The temperature data so corrected are set out in Figure 6.10 (a-c) above. It can be seen that the temperature data comparison is fair; it is felt that perhaps, the response calibration needed further improvement at larger times. The broad behavior is also seen for the remaining temperature data. Further average temperature across the roof material and the gas phase temperatures at thermocouple tree locations (See Figure 6.10 e) are also compared as in Figure 6.10 d that shows the comparison between experiments and FDS predictions are good.

Figure 6.11 (a) shows the plot of pressure profiles in Pascal (Pa) across different heights at a plane located 1.75 m distance from door plotted at 10 s intervals up to 150 s. Fire is located at 2.5 m behind this plane. This increases with time due to the upper region continuing to be occupied by hot gases displacing the colder air to move out. The slight pressure drop at around 1.3 to 1.5 m height is due to the air entrainment by the pool fire and subsequent cooling of hot gases at that layer. Positive pressure as shown by Figure 6.11 (b) pressure contours at height of 1.2 m from floor inside the room indicates that all the air required for combustion is drawn from within the room. There is a net flow of gases from the farthest end of the room through the fire towards the exit. This is further established by the data on the horizontal velocity (u-velocity) from the FDS results.

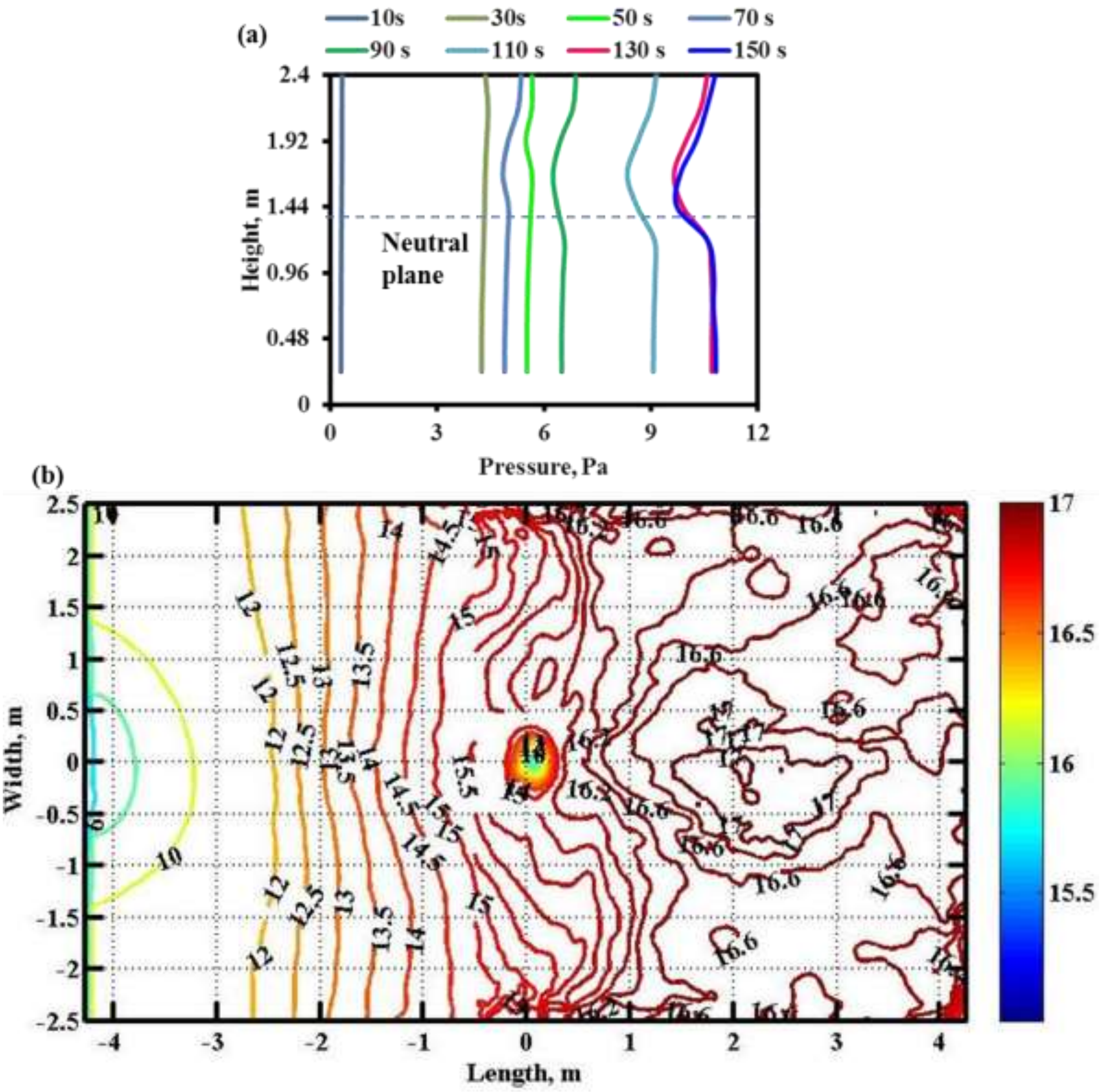


Fig. 6. 11 FDS results of static pressure profiles in Pa (above the ambient pressure): (a) along width of the room at a location 1.75 m from the door; (b) at plane across 1.2 m height

Figure 6.12 shows a contour plot of horizontal velocities across plane 1.2 m above floor, obtained from FDS calculations with a power level of 100 kW. It can be seen that velocity of gases leaving the room is 0.05 m/s (negative sign indicates that gases leaving the room). It should be noted that the flow in these simulations are in the –x direction as the door is located at x-min in contrast to 1m^3 cubical room experimental simulations the velocity signs are positive as the flow direction is towards x-direction and the x-max is open. The air inside the room of large room of 96 m^3 is roughly 96 kg and the air needed for combustion is estimated at 30 to 35 kg in most experiments conducted. This is less than the available quantity and thus no air is needed to be drawn from outside to burn the fuel. Perhaps, if the burning continues for much longer, there could be reversal of this trend. The formation of smoke layer provides enough pressure on the lower layers to allow the burning fuel to draw the air. It appears that the neutral plane for 100 kW stabilizes at around 1.4 m from the floor. Recalling Figure 5.13 (a), it can be seen that the smoke layer height as measured during the experiment with 100 kW power fire also stabilizes to a height of 1.38 m.

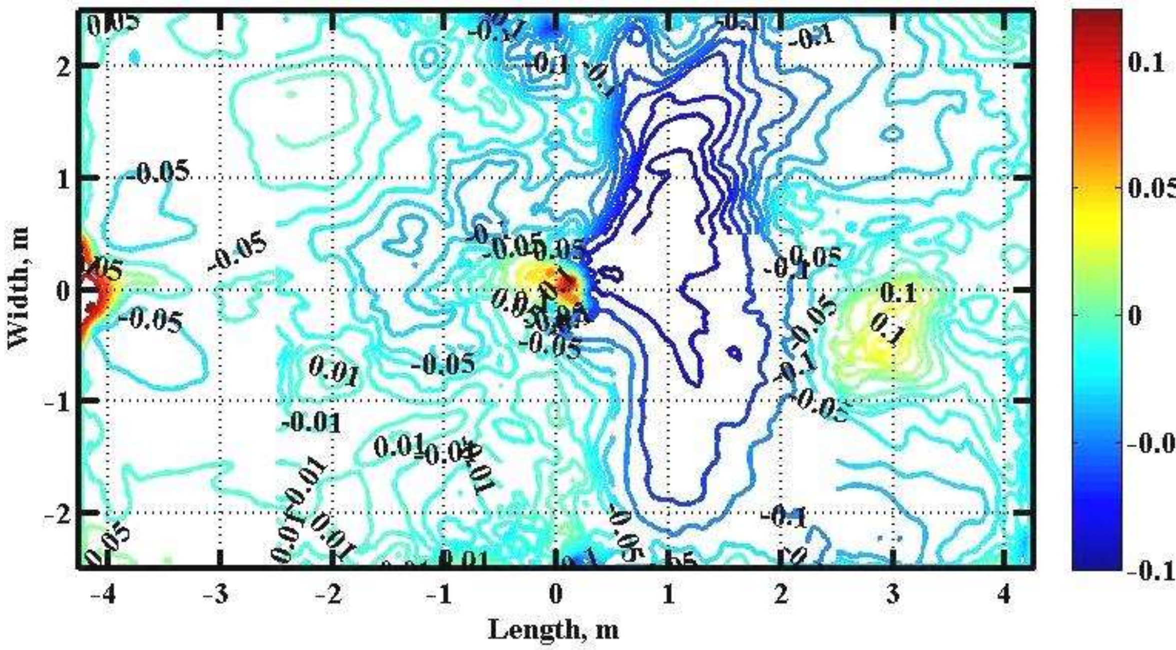


Fig. 6. 12 Contours of horizontal velocities (m/s) across 1.2 m height

6.8 Summary

CFD based computations using FDS in LES mode are studied and discussed in detail for both $1m^3$ cubical room as well as large scale room. It is made clear that FDS gives fair predictions provided the inputs are treated appropriately to match the real fire scenario. FDS does not account for early stages in fire and therefore to be treated suitably in the input file. It should be noted here that the duration of these stages vary with size of the size of the pool and type of fuel and the relation between the two needs to be explored further. With this learning and upon increasing the power level in a stage wise manner based on the experimental power history fair comparisons of gas temperatures and roof temperatures are obtained with FDS computations.

An interesting aspect uncovered in this study is that for a room of 96 m^3 and a power level of 100 kW the air needed for combustion is drawn from inside and therefore air was not drawn from outside. It is recognized that this will last for duration of time when the air supply for combustion within the room reduces substantially.

Chapter 7

Overview

This thesis is concerned with enhancing fire safety of existing structures with false roofing. A number of shops and offices built over a time have false roofing made of very light expanded polystyrene (EPS) panels within a metal framework. This is done to enhance the visual aesthetics for commercial purposes and also cover overhead electrical wiring that may have come up arbitrarily after construction. The outcome of the local survey conducted on EPS usage and the fire accidents in a few places led to the present investigation on introducing a low cost *in-situ* fire-safety enhancement process.

7.1 On the coating of EPS board

Several techniques of coating the boards with gypsum are attempted.

Amongst many techniques attempted one in which a spray gun used to coat the boards was found to lead to uniform coating even though material loss was higher compared to the manual process. It is inferred that this technique could be used in field situations. All tests are conducted by coating the metal frames with gypsum material to the same level of thickness as the boards (2 ± 0.2 mm). After mounting, thermocouples (0.2 mm wire thickness and 0.4 mm bead size) are fixed carefully so that they are flush with the surface. Any coating on the beads is subsequently scraped to make their original condition is brought back.

7.2 *On the results of the studies conducted*

Experiments in $1m^3$ cubic and 5 m × 8.5 m × 2.4 m rooms with low density EPS panels much like in practice are conducted at various power levels, 25kW for the small room and 50 to 315 kW for the larger room with gypsum coating of 2 mm over the panels only as well as over the metal framework. Two safety features considered are egress time and smoke level, the former being well recognized with a 180 s value set and the latter to determine if the height available for egress is adequate for escape. Two results of significance from this study are (i) the gypsum coating remains stable for very long times and at the time of fire allows conditions that maintains the integrity of the roof for power levels lower than a value (315 kW for the larger roof) and (ii) a safe-egress time vs. power level plot that enables determining a safe design power level for a given roofing system.

7.3 *Advantages and Limitations*

This approach is ideal to those places that are constructed with false roofing with EPS boards. This method offers additional protection to the EPS boards while retaining its primary insulation benefits to support cyclic/seasonal temperature variations.

Based on the results of the experiments conducted in this work and the outcome of the field survey establish the advantages of gypsum coating to EPS board over the rest of its siblings in the market to provide a low cost fire-safe roof for establishments that have already adopted EPS roofing. Thus the main advantage is that the owners of the buildings are encouraged to ensure fire safety at an affordable cost.

Further the new occupancies that are coming up with such EPS roofing can also adapt a similar protection. In such cases two options are available that the coating can be made *in-situ* or it can be pre-treated, tested, certified and given. This will also ensure in introducing appropriate active fire protection systems to the location as the owners are informed with available egress time and safe operation limits of the kind of enclosure put to use.

This approach is expected to provide better roof insulation compared to the corresponding alternatives that are available in the market. The only limitation of this approach is that the operations require clearing of occupancy for a short period till the job is completed in contrast to the ready- to-replace boards.

7.4 Scope for further research

So far the results of the fire studies conducted with varying power levels of range 50 to 300 kW in a large size room of dimensions 8.5 m × 5 m × 2.4 m indicate that the coated EPS roof can provide safe egress time of about 10 min even at a fire power of 300 kW. These studies are conducted with single point fire location at a specific power level. Further studies of interest would be multi point varying fire power options that might yield better results to further the improvement of the coating idea adapted in this method. Also further experiments with relatively higher power would yield results related to behavior of the roof to Flash over situations.

Studies also need to be conducted towards comparison of other similar false roofing materials that are in practice to understand the level of available fire safety with these materials.

Computational simulations adapted in this work are restricted to single point fire source with maximum HRR up to 300 kW only. FDS studies conducted with multi point varying power situations for similar kind of enclosure can further the research.

In some areas where specific operations are conducted like microbiological lab, the method needs to be verified for ambient air contamination before choosing the option of coating. Possibilities treating the coating material with anti-microbial activity are available but the extent of their active life is not studied. In such cases the effect of ingredients added to the coating material to fire will be required to be studied.

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Appendix -I

FDS input file – 1m^3 cubical room

```
1m^3 room simulation 205mm dia heptane pool

16th december 2013

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&TIME T_END=200, DT=1e-3, WALL_INCREMENT = 1 /


&DUMP DT_RESTART=1, DT_PL3D=10000000. /  No Plot3D output

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  EMISSIVITY = 0.9

  DENSITY = 7850.

  CONDUCTIVITY = 45.8

  SPECIFIC_HEAT = 0.46/


&MATL ID='EPS'

  EMISSIVITY = 0.7

  DENSITY = 11.

  CONDUCTIVITY = 0.08

  SPECIFIC_HEAT = 1.5/

&SURF ID = 'STEEL_SHEET', MATL_ID='STEEL', COLOR='SILVER',THICKNESS =
0.01/

&SURF ID = 'EPS_SHEET', MATL_ID='EPS', COLOR='WHITE',STRETCH_FACTOR = 1.

      CELL_SIZE_FACTOR = 0.25,THICKNESS = 0.04/


&MISC RESTART=.FALSE.,SURF_DEFAULT = 'STEEL_SHEET'/


&REAC ID = 'HEPTANE'

SOOT_YIELD = 0.01

C = 7.

H = 16.

HEAT_OF_COMBUSTION = 44600.

IDEAL = .TRUE.,HRRPUV_AVERAGE=1e+10 /


&RADI RADIATIVE_FRACTION=0/
```

```
&SURF ID='FIRE',HRRPUA=802.4, RAMP_Q='fireramp'/
&RAMP ID='fireramp', T= 0.0, F=0.0 /
&RAMP ID='fireramp', T= 15.0, F=0.3334 / 8kW
&RAMP ID='fireramp', T= 30.0, F=0.6477 /16 kW
&RAMP ID='fireramp', T= 45.0, F=0.8484 / 19.8
&RAMP ID='fireramp', T= 60.0, F=0.9242/22.8
&RAMP ID='fireramp', T= 105.0, F=1.0 /
&RAMP ID='fireramp', T= 200.0, F=1.0 /

&OBST XB=-0.0908,0.0908,-0.0908,0.0908,0.0,0.3, SURF_IDs =
'FIRE','INERT','INERT'/ fire pan

&VENT MB='XMAX', SURF_ID='OPEN' /
&OBST XB= -0.5, 0.5, -0.5, 0.5, 1.0, 1.0, SURF_ID='EPS_SHEET'/

Output

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&SLCF PBY=0.0, QUANTITY='PRESSURE' /
&SLCF PBY=0.0, QUANTITY='MIXTURE FRACTION' /
&SLCF PBY=0.0, QUANTITY='SOOT VOLUME FRACTION'/

&SLCF PBX=0.0, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBX=0.0, QUANTITY='VELOCITY' /
&SLCF PBX=0.0, QUANTITY='PRESSURE' /
&SLCF PBX=0.0, QUANTITY='MIXTURE FRACTION' /
&SLCF PBX=0.0, QUANTITY='SOOT VOLUME FRACTION'/

&SLCF PBX=-0.3, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBX=-0.3, QUANTITY='VELOCITY' /
&SLCF PBX=-0.3, QUANTITY='PRESSURE' /
&SLCF PBX=-0.3, QUANTITY='MIXTURE FRACTION' /
&SLCF PBX=-0.3, QUANTITY='SOOT VOLUME FRACTION'/
```

```
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&SLCF PBZ=0.4, QUANTITY='PRESSURE' /
&SLCF PBZ=0.4, QUANTITY='MIXTURE FRACTION' /
&SLCF PBZ=0.4, QUANTITY='SOOT VOLUME FRACTION'/

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&SLCF PBZ=0.8, QUANTITY='PRESSURE' /
&SLCF PBZ=0.8, QUANTITY='MIXTURE FRACTION' /
&SLCF PBZ=0.8, QUANTITY='SOOT VOLUME FRACTION'/

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&SLCF PBZ=1.0, QUANTITY='VELOCITY' /
&SLCF PBZ=1.0, QUANTITY='PRESSURE' /
&SLCF PBZ=1.0, QUANTITY='MIXTURE FRACTION' /
&SLCF PBZ=1.0, QUANTITY='SOOT VOLUME FRACTION'/

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&PROF XYZ = 0.3,0.3,1.0, IOR=-3, QUANTITY = 'TEMPERATURE' /
&PROF XYZ = -0.3,-0.3,1.0, IOR=-3, QUANTITY ='TEMPERATURE'/

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&BNDF QUANTITY='CONVECTIVE HEAT FLUX'/
&BNDF QUANTITY='RADIATIVE HEAT FLUX'/

&DEVC XB = 0.5,0.5,-0.5,0.5,0,1, QUANTITY=   'MASS FLOW +', ID='mass1' /
&DEVC XB = 0.5,0.5,-0.5,0.5,0,1, QUANTITY=   'MASS FLOW -', ID='mass2' /

&TAIL /
```

Appendix-II

FDS input file (100 kW) – large room

```
EPS Room Simulations

29th January 2014

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&TIME T_END=200, DT=0.5e-3, LOCK_TIME_STEP=.FALSE.,WALL_INCREMENT=1/

&DUMP DT_RESTART=1, DT_PL3D=10000000., NFRAMES=10000/ No Plot3D output

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&MESH ID='mesh3', IJK=50,100,125, XB=-0.5,0.5,-2.5,-0.5,0,2.5/0.625 M

&MESH ID='mesh4', IJK=50,100,125, XB=-2.5,-0.5,-0.5,0.5,0,2.5/0.625 M

&MESH ID='mesh5', IJK=50,100,125, XB=0.5,2.5,-0.5,0.5,0,2.5/0.625 M

&MESH ID='mesh6', IJK=50,50,125, XB=-2.5,-0.5,0.5,2.5,0,2.5/0.3125 M

&MESH ID='mesh7', IJK=50,50,125, XB=0.5,2.5,0.5,2.5,0,2.5/0.3125 M

&MESH ID='mesh8', IJK=50,50,125, XB=-2.5,-0.5,-2.5,-0.5,0,2.5/0.3125 M

&MESH ID='mesh9', IJK=50,50,125, XB=0.5,2.5,-2.5,-0.5,0,2.5/0.3125 M

&MESH ID='mesh10', IJK=50,125,125, XB=2.5,4.25,-2.5,2.5,0,2.5/0.7815 M

&MESH ID='mesh11', IJK=100,125,125, XB=-5.5,-2.5,-2.5,2.5,0,2.5/1.5625 M

&MESH ID='mesh12', IJK=50, 125,75, XB=-5.5,-4.0,-2.5,2.5,2.5,3.5/ 0.1875 M


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   DENSITY = 7850.

   CONDUCTIVITY = 45.8

   SPECIFIC_HEAT = 0.46/


&MATL ID='EPS'

   EMISSIVITY = 0.7

   DENSITY = 7.0

   CONDUCTIVITY = 0.08

   SPECIFIC_HEAT = 1.5/


&MATL ID='CERAMIC_BOARD'

   EMISSIVITY = 0.7
```

```
  DENSITY = 350.

  CONDUCTIVITY = 0.08

  SPECIFIC_HEAT = 1.5/


&MATL ID='GYPSUM'

  EMISSIVITY = 0.7

  DENSITY = 350.

  CONDUCTIVITY = 0.08

  SPECIFIC_HEAT = 1.5/


&SURF ID = 'STEEL_SHEET', MATL_ID='STEEL', COLOR='SILVER',THICKNESS =
0.01/

&SURF ID = 'EPS_SHEET', MATL_ID='EPS', COLOR='WHITE',THICKNESS = 0.05,
TMP_INNER=25.0, STRETCH_FACTOR=1., CELL_SIZE_FACTOR=0.5/

&SURF ID = 'CERAMIC_SHEET', MATL_ID='CERAMIC_BOARD',
COLOR='WHITE',THICKNESS = 0.05,TMP_INNER=30.0, STRETCH_FACTOR=1.,
CELL_SIZE_FACTOR=0.5/


&SURF ID = 'GYPSUM_COATED_EPS'

COLOR = 'WHITE'

BACKING = 'EXPOSED'

MATL_ID(1:2,1) = 'GYPSUM','EPS'

THICKNESS(1:2) = 0.002,0.05,

TMP_INNER=25.0, STRETCH_FACTOR=1., CELL_SIZE_FACTOR=0.05/


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&REAC ID = 'HEPTANE'

SOOT_YIELD = 0.01

C = 7.

H = 16.

HEAT_OF_COMBUSTION = 44600.

HRRPUV_AVERAGE=1e+10 /


&RADI RADIATIVE_FRACTION=0/


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```

```
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&RAMP ID='fireramp', T= 30.0, F=0.5513 / 57kw
&RAMP ID='fireramp', T= 45.0, F=0.6484 / 67kW
&RAMP ID='fireramp', T= 60.0, F=0.7454/  77kW
&RAMP ID='fireramp', T= 75.0, F=0.8453 / 88kw
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&RAMP ID='fireramp', T= 135.0, F=0.9827 / 102kw
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'FIRE','INERT','INERT'/ fire pan


ROOM
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&OBST XB= -5.5, 4.25, -2.5, 2.5, 0, 0, SURF_ID='CERAMIC_SHEET'/
&OBST XB= -4.25, -4.25, -2.5, 2.5, 0, 2.5, SURF_ID='CERAMIC_SHEET'/
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&OBST XB= -4.25, 4.25, -2.5, -2.5, 0, 2.5, SURF_ID='CERAMIC_SHEET'/
&OBST XB= -4.25, 4.25,  2.5, 2.5, 0, 2.5, SURF_ID='CERAMIC_SHEET'/


DOOR
&HOLE XB= -4.3,-4.2,-0.5,0.5,0,2/


OPENINGS
&VENT XB= -5.5,-4.0, -2.5, 2.5, 3.5, 3.5, SURF_ID='OPEN'/
&VENT XB= -5.5,-5.5, -2.5, 2.5, 0, 3.5, SURF_ID='OPEN'/
&VENT XB= -4.0,-4.0, -2.5, 2.5, 2.5, 3.5, SURF_ID='OPEN'/
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&VENT XB= -5.5, -4.0, -2.5,-2.5, 2.5, 3.5, SURF_ID='OPEN'/
&VENT XB= -5.5, -4.0,  2.5, 2.5, 2.5, 3.5, SURF_ID='OPEN'/
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&SLCF PBY=0.0, QUANTITY='SOOT VOLUME FRACTION'/

&SLCF PBY=1.2, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY=1.2, QUANTITY='VELOCITY' /
&SLCF PBY=1.2, QUANTITY='PRESSURE' /
&SLCF PBY=1.2, QUANTITY='MIXTURE FRACTION' /
&SLCF PBY=1.2, QUANTITY='SOOT VOLUME FRACTION'/

&SLCF PBY=2.5, QUANTITY='TEMPERATURE', VECTOR=.TRUE. /
&SLCF PBY=2.5, QUANTITY='VELOCITY' /
&SLCF PBY=2.5, QUANTITY='PRESSURE' /
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Appendix –III

A.3.1 Determination of Response time of Thermocouples

In the large scale experiments discussed in the Chapter 6 earlier initial comparison of gas phase temperatures at wall locations indicated higher values than that of the experiments while there is a good agreement with the temperature measurements at thermocouple locations of the tree. This has been found to be due to conduction losses through the bare bead thermocouples mounted on to the board. This is confirmed by checking the response time of the thermocouple in accordance with a standard method, EGOLF agreement 2008.

A.3.2 Principle of the method as per EGOLF 2008

A test thermocouple is inserted into a preheated furnace or other acceptable heating device, set at a temperature of 750°C. The test thermocouple is allowed to equilibrate to that temperature. The test thermocouple is then quickly removed from the furnace and placed in still air at a temperature of 20°C, where it cools. The temperature indicated by the test thermocouple is recorded as it cools. The time taken to fall from a temperature of 700°C to a defined critical temperature is taken as the measured response time of the test thermocouple.

A.3.3 Experimental arrangement and procedure adapted

Using this principle a similar method is adapted and experiments are conducted in a tubular furnace with digital temperature controllers and provisions to acquire temperature data from the samples are used. Two types of thermocouples are used a bare bead 200 μm dia Type – K thermocouple and a thermocouple made out of 30 μm thick copper foil mounted with Type – K thermocouple wire of 200 μm (that is used in the experiments). The bare ends of the thermocouple wire pair is flattened to 100 μm and mounted on to the100 mm^2 copper foil held in place with the help of Kapton tape (a special adhesive tape that is used in high temperature operations and measurements up to 300 °C).

Figure A-1 (a, b) shows foil mounted thermocouple, a flattened Type K thermocouple (100 μm) mounted on to the copper foil of 30 μm thick with the help of Kapton tape, a thermally stable tape and a bare bead thermocouple mounted on to the coated EPS board of (0.1 m ×0.1 m size) with 3 mm projection from the board surface identical to the large room experiments and the tubular furnace used for the test for non-combustibility. The thermocouple mounted board is kept over this tubular furnace maintained at constant temperature of ~200 °C and observed for temperature response. Results indicated that the response time of the foil mounted thermocouple is found to be 46 s which is more than three times less than that of bare bead TC with a response time of 150 s. This means the temperature sensing is delayed by 100 s as compared to the foil thermocouple. This lead to temperature differences between the two. The difference in temperature is arrived for every time instant from the data acquired during this study and is added as correction to the experimental temperature data from the enclosure experiments.

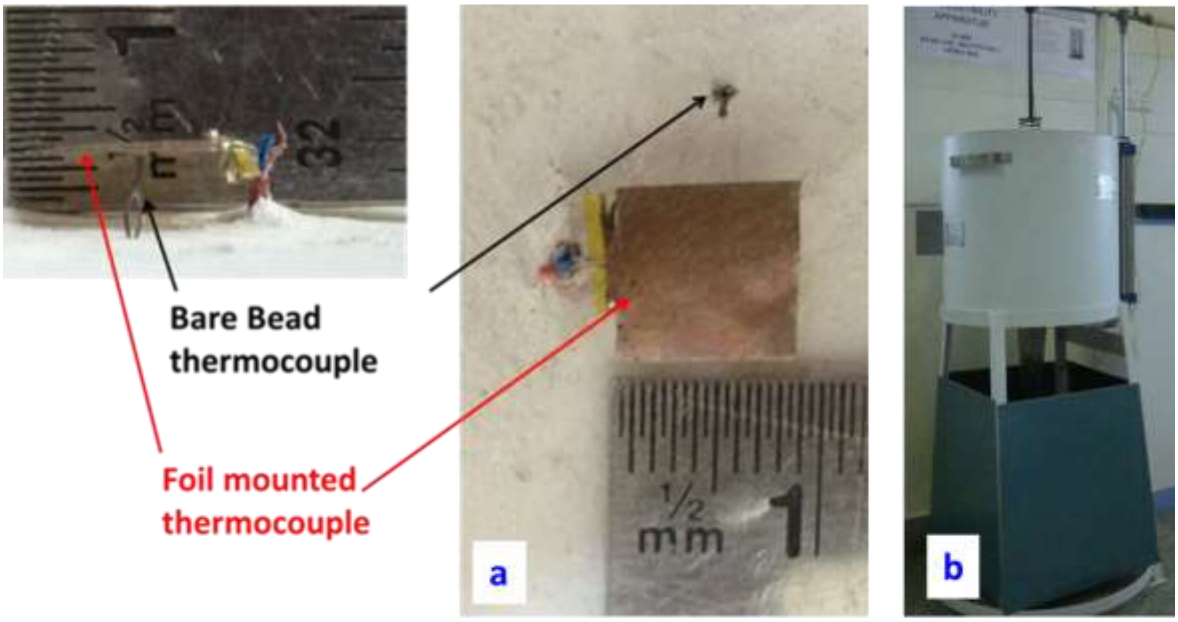

Fig. A-1 (a) Bare bead and foil mounted Thermocouple arrangement to compare response time (b) Tubular Furnace