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Enhancement of fire safety of existing false roofing systems – a new approach

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Abstract— **This paper is concerned with enhancing fire safety of existing expanded polystyrene (EPS) based false roofing. A number of shops and offices built over a time have false roofing made of very light EPS panels within a metal framework. This is generally done to improve thermal insulation in addition to visual aesthetics for commercial purposes by covering overhead electrical wiring that has come up arbitrarily after construction. Fire accidents in a few places led to the present investigation on introducing a low cost in-situ fire-safety enhancement process. Experiments in 1m^{3}cubic and 5 m × 8.5 m × 2.4 m rooms with low density EPS panels much like in practice were conducted at various power levels ranging from 25 to 315 kW, with gypsum coating of 2 mm over the panels only as well as over the metal framework. Two safety features considered were 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 the existing EPS roofing systems.**

Keywords— **burn rate, coating techniques, egress, false ceiling, fire studies, smoke.**

I. INTRODUCTION

While formal requirements of fire safety are present in all nations, the degree of awareness and enforcement is vastly different in different countries essentially due to differing economic levels of all infrastructures. In particular, small commercial establishments procure and use materials that do not measure up to standards. Expanded polystyrene (EPS) boards used for false roofing belong to this category.

Quite often, the false ceilings become an add-on to the establishment and the addition is performed without a consideration of the overall safety plan. Specifically, mineral boards are recommended for use. In some instances, when EPS is used, the recommendation is to use material with densities between 15 to 35 kg/m^3 [1] as these are also available in the market. However, EPS boards at densities of 7 to 9 kg/m^3 that are lower in cost by 25 to 30 % are the ones that are often used with the fitment at heights between 2 to 2.4 m from floor. The usage of the floor space gets altered over time and in several instances, has been found to be covered with cooking fires as a part of low cost food service system. Such places have serious fire hazard issues about which the current owners of the space may be completely unaware. Even if awareness is brought in, the differences in cost that could be substantial will drive them to continue to use the space without concern. A survey was conducted over a number of establishments in and around mega cities as well as peri-urban locations to determine the extent of use of EPS boards. What became clear is that with corporate culture driven establishments the awareness has led to the use of mineral boards that are least fire sensitive in the creation of future infrastructures. However, those outfits created earlier have been allowed to continue with the use of low density EPS fittings. It is this profile of usage that led to a thinking of a strategy for enhancing the fire safety of existing buildings with EPS false roofing. An examination of literature showed that while much work is available on the behaviour of EPS itself, its use is limited to that of sandwich construction with its core made of EPS boards to help thermal insulation [2, 3]. In these applications exposure of EPS to harsh thermal conditions or of fire occurs very much later in a fire scenario and the results of such a study are not particularly relevant to the current study.

Work on enhancing safety of EPS roofing material has been addressed by the Central Building Research Institute (2011)[4] and their strategy is to surround the EPS boards with wire mesh and then coat it with gypsum and fix it directly on to the bare ceiling of the room. While the idea is proposed, details of how much to be loaded and what the consequences are have been left uninvestigated.

The present work is aimed at evaluating coatings of gypsum alone on EPS boards, first, evaluating the physical integrity and life aspects since this approach offers for the most economical solution and then the thermal performance. The EPS boards with different densities procured from the market are characterized using radiant heat flux of ~ 20 kW/m^2, to ascertain the known behaviour of these boards and their use in 1 m ×1 m × 1 m (high) room and a 5 m × 8.5 m × 2.4 m (high) room both with one door, in terms of the fire performance evaluated using pool fires of 25 to 400 kW with thermocouple data from several stations including those on either side of the roof. The difference between uncoated and gypsum coated roof has been elucidated and subsequently, the time taken for safe egress from such a room examined based on the limit caused by smoke filling in the compartment. The integrity of the roof is also examined for the entire duration of the experiment. The key findings are (a) that the metal frames should be coated in addition to the boards, for this alone ensures integrity of the roof in fire situations, (b) the safe operating time for egress as a function of the power of the fire and (c) a number of subsidiary features of significance some of which that conform to earlier understanding.

II. PRELIMINARY STUDIES

Two varieties of EPS – normal variety and fire retardant variety are procured. The density of the varieties is 7 ± 1 kg/m3. The difference between the two is that the fire retardant variety has a special compound, namely, hexa-bromo-cyclo-dodecane introduced into it. The primary effect of this compound is that for temperatures beyond 100°C, the material opens up and shrinks. When the temperature goes beyond 350°C, the material ignites and flame around the dense droplets causes occasional drop of hot polymeric liquid drops on to the floor. The FR variety has a delayed ignition by 30 s at a flux of 35 kW/m^2. These features were confirmed from preliminary experiments. Further, the release of smoke and CO_2 production although delayed, is not significantly affected by the presence of FR additive [5]. Though the composition of the gases is different, there is not much of difference in toxicity between the two.

Next, several techniques of coating the boards with gypsum are attempted.

a. Manual coating is attempted using a trowel to make the coating uniform. Typically 1 kg of gypsum powder is mixed with 1.5 litres of water to a very thin consistency. A porous paper of 45 to 60 GSM is taken and laid on to the wet board with primary coating avoiding any shrink. The gypsum liquid mix is poured on to the board with constant spreading using the trowel. This gave a rough finish which is smoothened by scrubbing after drying the board.

b. A frame suitable to hold the EPS board is made using aluminum box channels. The board is then held tight inside the frame and the process noted above is repeated.

c. A cylindrical sponge roller is used for applying gypsum mix. Uniform layer coating is not achieved as the sponge dried up fast and required cleaning. This led to loss of coating material and hence is abandoned.

d. A spray gun is used to coat the boards and this process is found to lead to uniform coating even though material loss is higher compared to the manual process. This technique could be used in field situations due to convenience it affords in the process.

The boards are then open-air-dried for over 100 hours to get well prepared boards for use as roofing material. These are fitted on to the metal framework for room-fire experiments. It is also needed that the frames be coated with gypsum to eliminate the heat transfer from the hot metal causing serious thermal problems as was evident in the first test on the large room. All subsequent 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.

III. FIRE TESTS

A cubical 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 galvanized iron (GI) sheet (120 g/m^2) excluding the floor and front side open for access as shown in Figure 1.

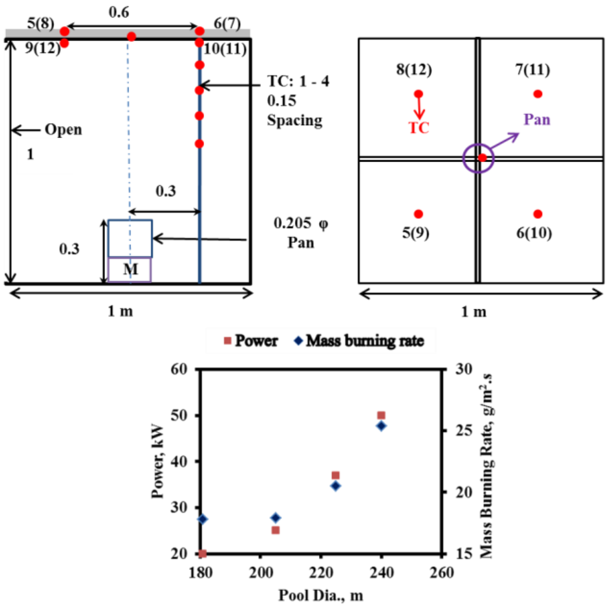


Figure 1. Room configuration & power histories of pool fires used in fire tests

Top is covered using EPS sheet under test. In the first study EPS sheets of 0.5 m × 1 m and 40 mm thick are used held over 2mm thick Aluminium T-section (25 mm × 25 mm) for support. Studies are conducted with kerosene, heptane and kerosene/heptane mixtures as fuel. Several tests were conducted to obtain the burn rate and the power of the fires using pool diameters of 181, 205, 225 and 240 mm dia. Fire experiments are conducted with 205 mm dia. pool fire using 55% kerosene and 45% heptane. Roofing showed that 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 coated EPS did not experience any volume loss till the end of the experiment, about 30 minutes from the start of ignition. Figure 2 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. The coated roof remained intact for 30 minutes at 25 kW, for 15 minutes at 36 kW and for 3 minutes at 50 kW. If it is taken that 3 minutes is the available egress time, 50 kW will be the peak power level for this room size. Since the room is very small indeed, egress may not be the issue. It is the integrity of the roof and all that the room contains that is important. In this experiment, the central metal support seemed to be intact and did not affect the fire performance, as in cases described later.

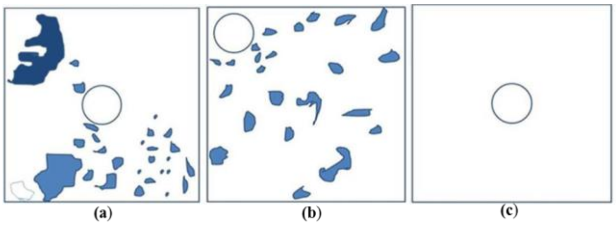


Figure 2. Schematic of floor after tests (dripped materials are darkened) with (a & b) uncoated roof, (c) coated roof. Circle represents the position of the fire pan.

Figure 3a-d shows comparisons of EPS surface conditions. It can be seen clearly that while the uncoated board has failed with a large melt, the coated board has stood the fire for 30 minutes. Figure 3 e shows a section view of coating. While these experiments provided encouraging results, it is thought essential that a large size room be considered for tests since most situations would involve large spaces.

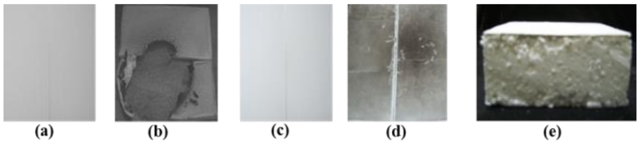
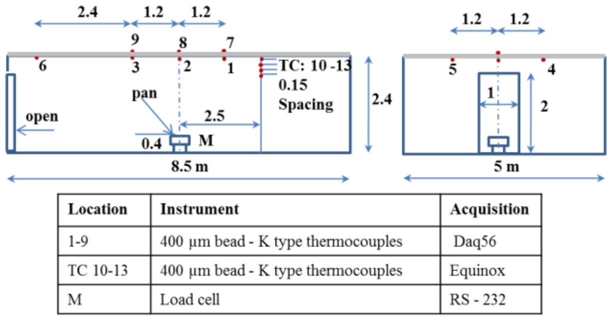


Figure 3. EPS boards before and after 30 min pool fire & c/s of EPS: (a & b) uncoated; (c & d) coated; (e) section view of coated board

IV. LARGE ROOM STUDIES

An examination of the working spaces of the establishments visited during the survey showed that the roof height is about 2.4 m but the rest of the dimensions varied widely. It was thought that using a larger space than what is recommended for enclosure fire studies in ISO 9705 room [6], 3.6 m (L) × 2.4 m (W) × 2.4 m (H)) would add value to the test results. Based on these considerations, enclosure size chosen was of 8.5 m length, 5 m width and 2.4 m height.

The false ceiling roof of the room is constructed with thin (1 mm) GI 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 4. The room has a single opening of 1 m width and 2 m height door located centrally on width of the room. A centrally located square pan of appropriate size to hold the fuel served the purpose of fire. Square pans of different sizes with side dimensions 210, 260, 300, 360, and 480 mm are evaluated for power in open environment before putting them into use into the room. The pan fires used in the tests are separately tested for the burn rate features. Pools of varying sizes circular as well as square types with heptane in most cases except one in which required power was achieved with the available pan by using a 55 % kerosene - heptane mix.



Location	Instrument	Acquisition
1-9	400 µm bead - K type thermocouples	Daq56
TC 10-13	400 µm bead - K type thermocouples	Equinox
M	Load cell	RS - 232

Figure 4. Schematic of large room used for fire study of coated EPS roof

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 electronic balance (ESSAE, DS-451HP, 5 g least count (LC), 0-60 kg range) connected to RS 232 port for mass loss. The data thus obtained are compared with the burn rate obtained by different authors in their experiments [**Error! Reference source not found.-Error! Reference source not found.**] as in Figure 5.

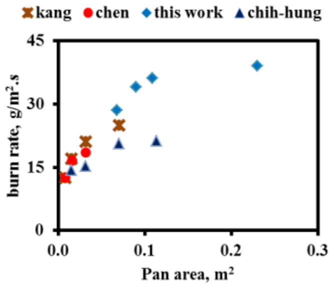


Figure 5. Plot of burning rate per unit area versus pan area

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 [**Error! Reference source not found.**-11]. In so far as the room fires are concerned, fuel mass data inside enclosure is obtained from "loadmaster" make load cell (BB-100, capacity 10 kg with 1 g LC and 100 kg capacity with 10 g LC and connecting them to "load master" load indicator Model LI 455 to read and the data acquired through RS 232 port connected to laptop. An IOTECH Personal Daq 56, (80 Hz, 10 µV LC) having 10 analog data acquisition channels is coupled to laptop to acquire roof temperature data. Bare bead Type K 400 µm wire dia. thermocouples served the purpose of temperature measurements at roof. The locations of the thermocouples are indicated in Figure 4. Measurements made with a bare thermocouple bead set into the EPS roof so as to project into the gas phase by 3 mm was calibrated for its response using tubular furnace maintained at specific temperatures up to 200°C. This response was factored into the measured data to obtain the temperature data for comparison with predictions.

Figure 6. Photograph of test area and flame ~33 s into the test: A-Pan; B-Vertical scale; C- Thermocouple tree; D- Coated Roof

A bare bead Type K 400 µm bead 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 0.1 m 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. Photographic image of the experimental set up covering the details as above is presented in the Figure 6.

Six representative experiments of the several conducted are reported here. The details of the experiments are set out in Table I.

TABLE I
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**	**SH**
m × m	**m^2**		**kg/kg***	**g/s**	**kW**	**S**	**°C**	**°C**	**m**
0.48 × 0.48	0.231	mix	13.6/ 11.5**	7.05	315	248	270	200	1.3
0.26 × 0.26	0.068	C_7H_{16}	1.4/11.5	2.11	94	675	130	120	1.4
0.21 × 0.21	0.044	C_7H_{16}	0.9/7.4	1.15	51	732	NA	104	1.5
0.21 × 0.21	0.044	C_7H_{16}	0.9/7.4	1.35	60	659	115	114	1.5
0.26 × 0.26	0.068	C_7H_{16}	1.2/11.5	2.41	107	487	160	142	1.4
0.30 × 0.30	0.090	C_7H_{16}	2.1/15.1	3.86	171	548	220	189	1.4

Mix: 45 % n-Heptane in Kerosene; * kg fuel/kg water (water layer thickness 169 mm); ** water layer thickness 50 mm; F-fuel; P-period; SH – Smoke layer height from floor

Figure 7. The failed coated board ~257 s from ignition

The first experiment is conducted to examine the limit of the operation at 315 kW. The fire stabilized in about 10 s from ignition and it was quenched at 257 s. The fire was quenched as the coating of one of the board lost its integrity. No spread of fire is observed across the roofing and total duration of the study is found to be 248 s. A video recording 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 s. An analysis of the failure mode showed that it had got initiated because of the heat transfer from the metal frames holding the panels. The heat was so excessive that local shrinkage caused the board to fall off (See Figure 7). Of course, there were cracks of the gypsum coating at other locations, but nothing so serious as to make the structure breakdown.

Two lessons learnt from this experiment are (a) the roofing system can stand more than 3 minutes, perhaps even more than about 4 minutes when the experiment is shutdown. The smoke layer of 1.27 m above the floor level would allow escape of people out of the door with some difficulty assuming smoke is the only cause of the limitation for escape and (b) the metal frames must be protected through coating to maintain the integrity of the roof. Subsequent to this, tests were conducted at lower power levels to examine the relationship between the integrity of the roof and safe operating times as a function of power level. The broad results are set out in Table 1.

One of the features that directly affect the performance is the temperatures attained on both the sides of the roof. The data of Table 1 are set out in Figure 8.

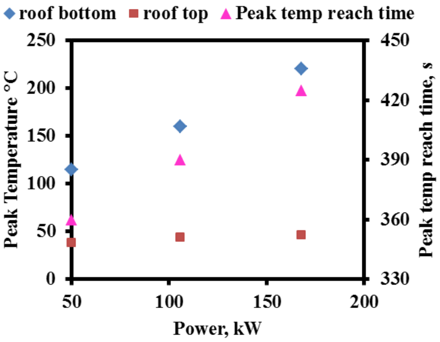


Figure 8. Peak roof temperatures and time taken to reach peak values

Though the bottom peak roof temperature increases with power, the top roof temperature increases only marginally – because of the low thermal diffusivity of the EPS (3.5 to 4 mm^2/s). The time taken to reach these conditions varies between 6 to 7 minutes, values much larger than the standard egress time of 3 minutes.

The smoke level from the floor as measured from the videos is presented in Figure 9a. The time taken to cover the roof area with smoke and bring down the accessible height (1.4 m) for egress is about 5 minutes. In 3 minutes the height of the smoke is about 1.5 m. Both these features are considered safe from the point of fire-safety design. Figure 9b is the plot of safe egress time available for different power levels of experiment and theory by Lawson and Quintiere [12].

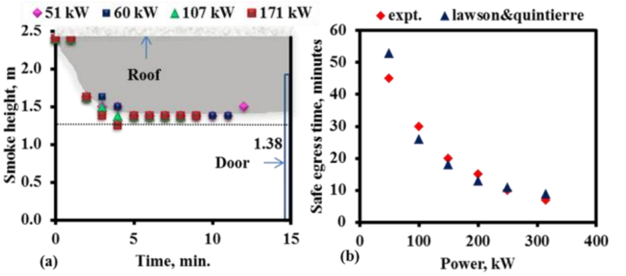


Figure 9. (a) Smoke height versus time (b) Safe egress time available for various power levels

V. COMPUTATIONAL STUDIES

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 [13] for computation of unsteady flows, available from NIST web site, is used to carry out simulations. FDS solves numerically a form of the Navier-Stokes equations 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 modelled 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 DT 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.

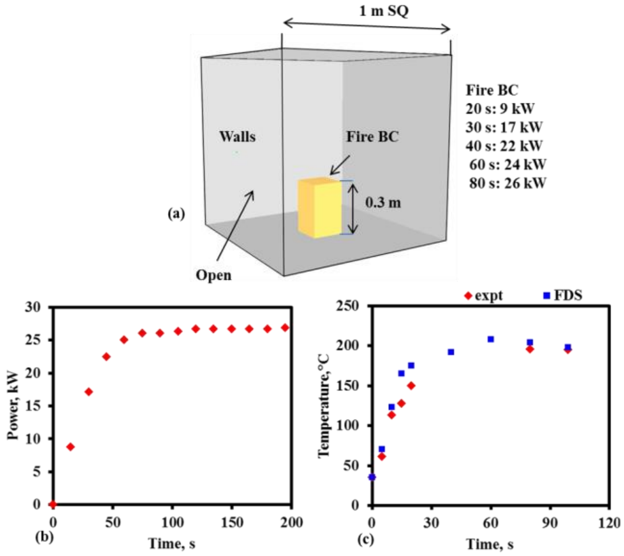


Figure 10. 1m3 cubic room computations (a) Boundary conditions (b) Experimental power history (c) g-phase temperature history at T1

Two FDS calculations carried out to investigate velocity and temperature fields in 1 m^3 cubic room and 5 m × 8.5 m × 2.4 m high (96 m^3) rooms will be presented here. Figure 10a shows the boundary conditions employed to model 1 m3 room. Results from a 5 mm uniform mesh size are reported. Figure 10b shows the power versus time from experiments which is used to set the fire power conditions for calculation. Figure 10c shows comparison of experimental results of the gas phase temperature 40 mm below the roof of 1 m3 room with that of FDS predictions. It can be seen that equilibrium values are well predicted.

For large room geometry (see Figure 4) 1 m × 1m area of fire in central region are discretized with 10 mm mesh. Rest of the domain has 20 mm size mesh. Figure 11 shows the boundary conditions employed. Extra region in front of the door is simulated to ensure boundary conditions at the door are appropriate. Fire boundary conditions are from experimentally measured data. 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 is inferred 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 [14].

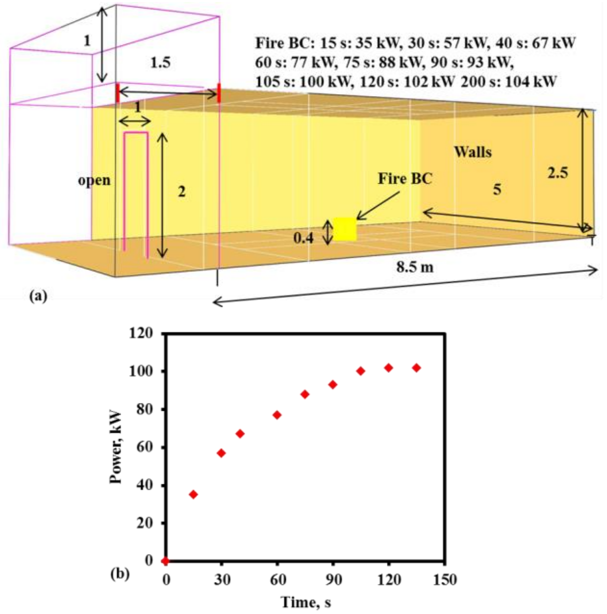


Figure 11. 96 m3 room boundary conditions for the computations and the experimental power history

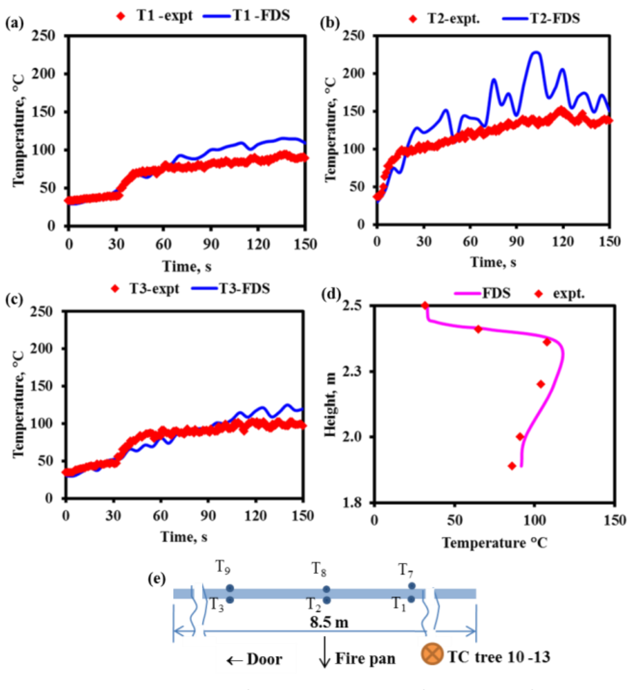


Figure 12. Comparison of temperature profiles at roof with FDS results: (a & c) Temperature profile at 1.2 m radial distances T1 and T3 from centre of the pool; (b) at central location (T2) experiment and FDS; (d) Comparison of temperature profile gas and condensed phase at 2.5m from centre of the pool; (e) Thermocouple locations (more details Figure 4)

The temperature data so corrected are set out in Figure 12 a, b, c for 100 kW fire power at 1.2 m radial distance from the center of the pool and the central locations. 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 12e) are also compared as in Figure 12d that shows the comparison between experiments and FDS predictions are good.

Figure 13a 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.

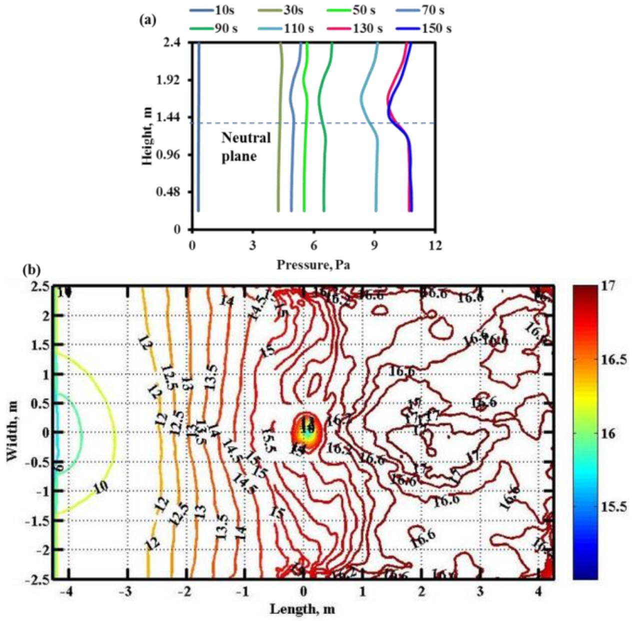


Figure 13. FDS results of static pressure profiles in Pa (above the ambient pressure): (a) along width of the room at a location 1.75 m from the door; (b) at plane across 1.2 m height

Positive pressure as shown by Figure 13b pressure contours at height of 1.2 m from floor inside the room indicates that all of 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.

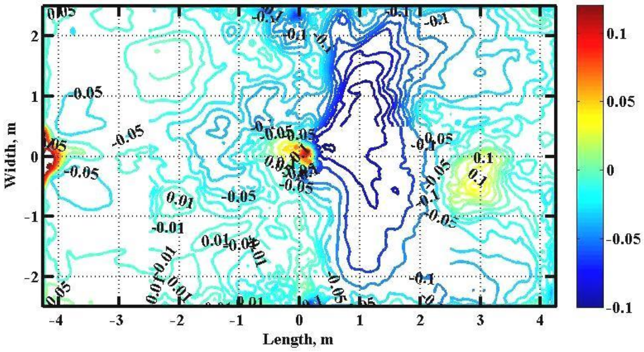


Figure 14. Contours of horizontal velocities in m/s across 1.2 m height above the floor

Figure 14 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). The air inside the room is 96 kg and the air needed for combustion is estimated at 30 to 35 kg in most experiments conducted. Thus no air is needed to be drawn from outside to burn the fuel. 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 9a, 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.

VI. CONCLUSIONS

This paper is concerned with enhancement of fire safety of existing EPS roofing. A gypsum based coating of 2mm thick has been developed and fire studies are conducted to understand the performance of the coating to fire. Also field survey has established such coating will provide a low cost fire-safe roof for establishments that have already adopted EPS roofing. Coating is tested in 1 m^3 cubic room. The study was then extended to 8.5 m × 5 m × 2.4 m room at several fire power levels. Results indicate coated EPS provides greater fire safety.

An important conclusion from this study is that all metal frames supporting the EPS boards also should be coated with gypsum to retard heat transfer and protect sides of the EPS boards.

Measurements of temperatures and smoke levels are made in large room built for study. Fair comparisons of gas temperatures and roof temperatures are obtained with FDS computations. An interesting aspect uncovered in this study is that 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.

Fire studies in 5 m × 8.5 m × 2.4 m high (96 m^3) room have indicated coated EPS roof can provide safe egress time of about 10 min even at a fire power of 300 kW.

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