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Study of Fire Propagation and Soot Flow in a Pantry Car of Railway Locomotive

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Abstract—Fire accidents in trains bring huge disaster to human life and property. Evacuation becomes a major challenge in such incidents owing to confined spaces, large passenger density and trains moving at high speeds. The pantry car in Indian Railways trains carry inflammable materials like cooking fuel and LPG and electrical fittings. The pantry car is therefore highly susceptible to fire accidents. Numerical simulations have been done in a pantry car of Indian locomotive train using computational fluid dynamics based software. Different scenarios of a fire outbreak have been explored by varying Heat Release Rate per Unit Area (HRRPUA) of the fire source, introduction of exhaust in the cooking area, and taking a case of an air conditioned pantry car. Temporal statures of flame and soot have been obtained for each scenario and differences have been studied and reported. Inputs from this study can be used to assess casualties in fire accidents in locomotive trains and development of smoke control/detection systems in Indian trains.

Keywords—Fire propagation, flame contour, pantry fire, soot flow.

I. INTRODUCTION

SERIOUS damage to the property of the Indian Railways and huge loss of human lives occur due to the fire incidents in trains. The casualties caused due to fire accidents in train are alarmingly high with little time for rescue and evacuation. The Indian Railways is one of the world's largest networks. According to the Annual Report of Indian Railways of 2014-15, IR carried 8.397 billion passengers annually or more than 23 million passengers a day [1]. A major portion of all the railway fire accidents across the world happen in India. The prevention of train fire is a serious concern for the Railways.

It is difficult to ascertain the exact reason of fire in a train after the disaster has occurred. However, short circuits and pantry pose a major risk. A pantry car of the Dibrugarh-New Delhi Rajdhani Express caught fire in 2013 [2]. A minor fire broke out inside the pantry car of the Bangalore-Hazrat Nizamuddin Rajdhani Express in 2009 [3]. In another case, fire broke out in pantry car of Rajdhani Express near Mughalsarai, India in 2009 [4]. Pantry has potential sources of fire like electrical and LPG fittings. It contains inflammable materials like cooking oil, cardboard storage boxes etc. which are easy to catch fire. Considering the susceptibility of pantry car to fire, it is necessary to assess the behavior of fire and smoke in the pantry car to reduce the hazard of fire accidents in locomotives. Currently, no smoke detection systems are installed in the Indian Railways trains. The inputs from this study can be helpful in development of smoke detection system design for Indian locomotive trains. Experimental fire behavior research projects on trains have been conducted. Full scale experiments were conducted in moving trains in the Fire Behavior on a Running Train Project (1974) of Japan National Railway [5]. Its objective was to verify the improvement of fire safety and understand post-flash over fire behavior on moving trains. Large-scale fire experiments have been conducted by the Commonwealth Scientific and Industrial Research Organization (CSIRO) [6] on current Australian passenger train interiors to understand factors affecting fire growth in trains. Due to high costs incurred in experimental fire analysis, numerical simulations gain importance. Markatos et al. [7] in 1982 argued the increasing importance of numerical simulations in the study of fire dynamics. Now with powerful computational resources, numerical simulations to analyze fire behavior help in reducing cost and resources. Numerical simulations are used extensively in research on compartmental fires. Numerical simulation studies have been done using on fire in a train coach, which forms a part of compartmental fires. Chow et al. [8] established a numerical model for a typical train fire in China. Velocity vectors and air flow patterns along with flame and smoke speed have been reported in the numerical simulations using Large Eddy Simulation (LES). It is shown that the smoke flow is more threatening than the actual flame. In 2013, Mo et al. [9] analyzed the accidental hazard of smoke in the confined spaces of a passenger train compartment. Effect of temperature and CO level are analyzed in different scenarios. While studies on compartmental fire propagation are found to be done for locomotive trains in Australia [6], China [8] and other countries [5], [10], studies on the train fire accidents in the Indian context are not found. Moreover, pantry car is a part of Indian trains and in many cases the reason for a fire outbreak. While there have been many studies on fire scenario in a passenger train coach, no study was found to deal with pantry/kitchen cars. Also, the literature lacks in properties of materials used in trains, which play a decisive role in the spread of flame. Materials properties of components of the train used in the simulations are enlisted in this study. The mathematical model for simulations is given in Appendix A. Dimensional measurement data from the pantry car of an express train of the Indian Railways are used to build the model. The domain of study is described in the next section.

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II. DOMAIN DESCRIPTION

A schematic layout of the pantry car is given in Fig. 1. The store 1, 2 and 3 are meant for storing edible items like beverages, vegetables and LPG cylinders respectively. Fold-able storage racks and berths are attached to the wall on the passage side which are shown in Fig. 3.

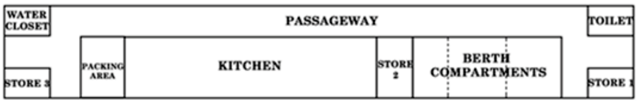


Fig. 1 Schematic layout of the pantry

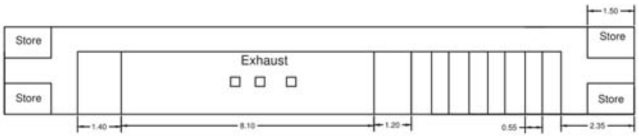


Fig. 2 Schematic layout of the pantry

The berth compartment consists of two compartments with two berths each and a third compartment with a single berth. The packaging area contains a deep fridge, two wooden tables and a refrigerator. The top view dimensions of the pantry are shown in Fig. 2.

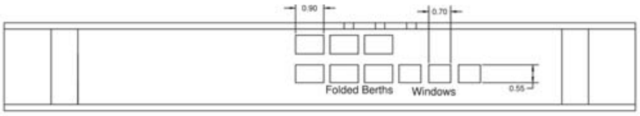


Fig. 3 Schematic layout of the pantry

The front view of wall on the stove side is given in Fig. 4. The three windows in the berth compartments are shown. The kitchen area has five windows and two openings for exhaust which are shown in Fig. 4. Fig. 3 shows the dimensions of the wall on the side of the passageway. The passageway has three windows. There are six folded berths attached to the wall of the passageway which could be opened at night for sleeping. An extension of 0.2 m in domain is given on each side to observe the flow of flame and soot out of the windows, doors and exhaust vents into the ambient atmosphere.

TABLE I
DETAILS OF MATERIALS USED

Material	Density (kg/m^3)	k (kJ/m^2K)	c $(kJ/kg.K)$	T_b (^0C)	H_c (kJ/kg)
Fabric [11]	100	0.1	1	370	15000
Foam [11]	40	0.05	1	370	33280
Plywood [12]	545	0.12	1.215	-	-
Steel [11]	7850	45.8	0.46	-	-
PVC [11]	1300	0.17	1.2	-	-
Wood [12]	489	0.14	1.38	400	14500

K, c, T_b and H_c represent Thermal conductivity, Specific heat, Ignition Temperature and Heat of combustion respectively

The material used for walls, floor and roof is layered steel and wood. A layer of PVC which is a fire retardant material is spread over the floor. The material properties are enlisted in Table I.

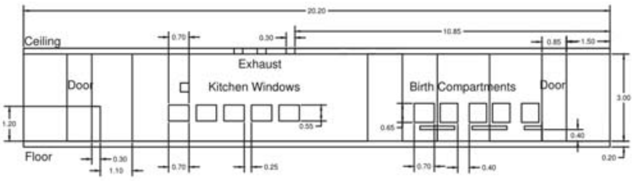
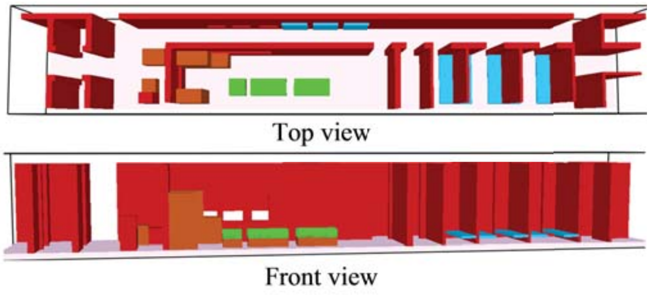


Fig. 4 Schematic layout of the pantry

Fig. 5 shows top view and front view of the the pantry at t = 0 s in smokeview. Three stoves placed in the kitchen area are taken as the source of fire with HRRPUA value of 10000 kW/m^2. There are two shelves for storage purpose inside the kitchen. The door openings of all the compartments are depicted the smoke-view, Fig. 5. Two of the stoves have dimensions 0.6 m x 1.3 m x 0.3 m and one stove has dimensions 0.6 m x 0.6 m x 0.3 m. The gaseous fuel used is $C_{6.3}H_{7.1}O_{2.1}N$. Sanjay and Das [11] formulated a numerical model to simulate fire propagation in stationary enclosures and compartments. Same approach has been used in the present study and the domain is discretized into rectilinear grids with cubical cells with edge length 0.09 m each.


Top view

Front view

Fig. 5 Schematic layout of the pantry

III. RESULTS AND DISCUSSIONS

The pantry car of the Indian Railways is modeled in FDS. Simulations have been performed in a non-air conditioned pantry car to study the behavior of fire and soot propagation. No inventory items have been placed in this simulation. The effect of change in HRRPUA of the fire source is studied. Then simulations are done with provision of exhaust fans in the cooking area. An air conditioned model of the pantry is developed next and results of simulation have been analyzed.

A. *Non-AC Pantry Simulation*

Simulation is done on the non AC railway pantry car to determine fire and smoke spread patterns. The stoves inside kitchen are considered to be the source of fire with 10000 kW/m^2 of HRRPUA. All the windows and entry doors are kept open in this scenario. Fig. 6 shows the top and front view of fire and smoke of the pantry coach at different time steps of the simulation. Fire and smoke is seen to arise from the stoves in kitchen. The flow is obstructed by walls. Flame and smoke spread to the passageway through the kitchen door and towards the packing area through the window.

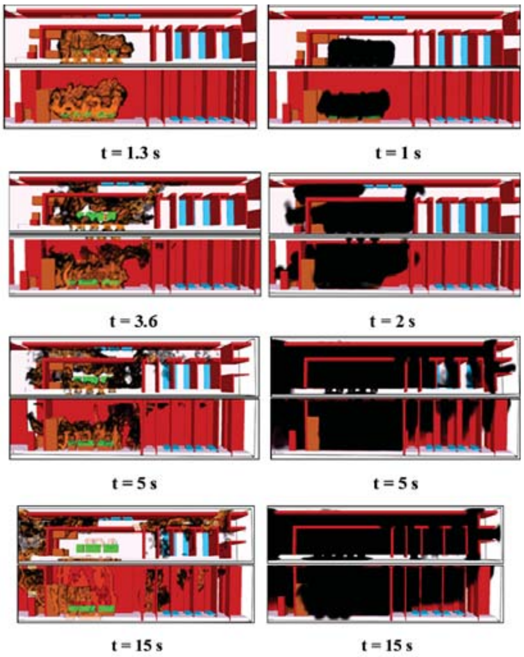

t = 1.3 s t = 1 s
t = 3.6 t = 2 s
t = 5 s t = 5 s
t = 15 s t = 15 s

Fig. 6 Flame and soot propagation contour for 10000 kW/m^2 fire source

Fire and smoke rise and reach the roof of the kitchen in 1.8 s and 1.6 s respectively. Ceiling jet effect can be observed as they are deflected back down by the roof of the pantry coaches and propagate to other parts along the ceiling increasing the downwards grab. From the roof, smoke takes 6 s to spread upto 1.8 m (height of an average human being) height measured from the floor. At 3.6 s and 2 s, the kitchen area is covered by fire and smoke respectively. Owing to differences in densities, smoke travels at a faster rate. We notice that the grab of fire and smoke is more towards the ceiling due to buoyancy effects. It could thus be concluded that flammable inventory should not be stored on high shelves. To understand the physical phenomenon better, flame and soot propagation have been quantified. To achieve this, fractional area of top view and front view engulfed under fire and smoke with respect to time is calculated. Fractional area vs time graphs have been plotted for the obtained data. MATLAB Image Processing Toolkit (IPT) is used for this purpose employing an in-house post-processing code. The top view graph (Fig. 7) of fractional area under grab of smoke initially increases linearly when smoke spreads from the kitchen to other parts. It asymptotically tends to a constant value of 1 after 5.5 s when it spread across the roof to all the parts of the coach. A same trend is observed for front view. It tends to a value between 0.8 and 0.9. Because of buoyancy smoke travels along the ceiling through the pantry so the top view is entirely blocked by soot which translates downwards with the passage of time. However, smoke finds outlet through doors and windows into the atmosphere therefore the entire height of the coup is never covered by soot. The area under grab of fire also shows an increasing trend as fire spread across the coach. A series of maxima and minima are observed because with time, some new parts catch flame while fire extinguishes on some parts which have already been burnt away or where localized burning is no more possible due to lack of oxygen.

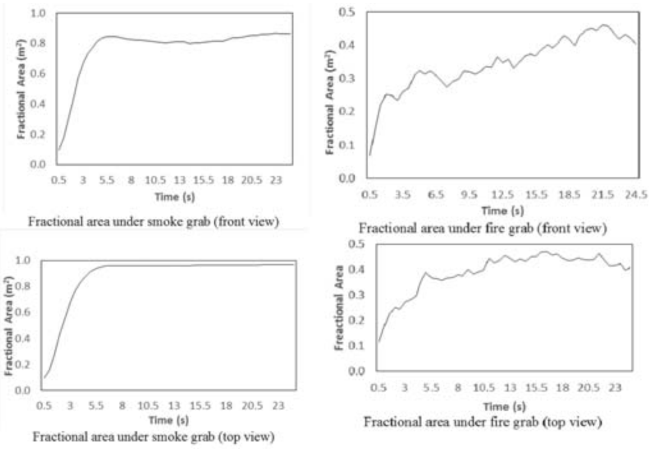

Fractional area under smoke grab (front view)
Fractional area under fire grab (front view)
Fractional area under smoke grab (top view)
Fractional area under fire grab (top view)

Fig. 7 Plots of fractional area under the grab of fire and smoke for top view and front view

B. Variation in HRRPUA

The initial Heat Release Rate in case of a fire scenario is quite uncertain but it plays a crucial role in determining the extent of damage afterwards. The HRRPUA values of the fire source are varied to take into account a wide range of possibilities of fire outbreaks. Simulations are carried out at the following values of HRRPUA of fire source (cooking stoves) - 5000 kW/m^2, 10000 kW/m^2 and 15000 kW/m^2.

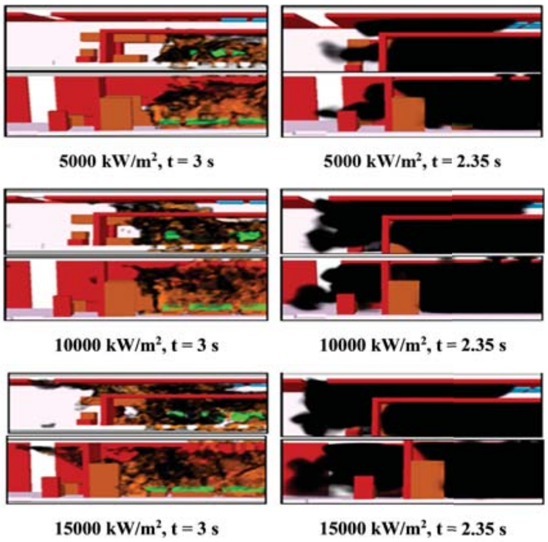
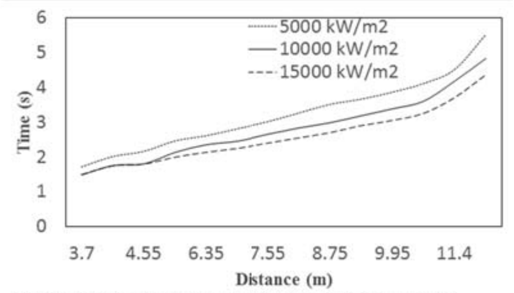
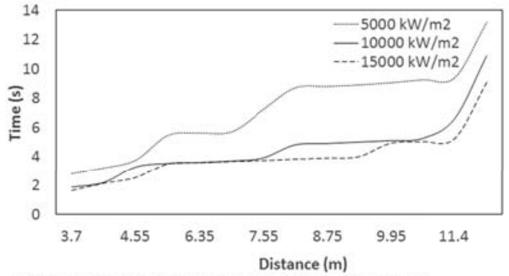

5000 kW/m², t = 3 s 5000 kW/m², t = 2.35 s
10000 kW/m², t = 3 s 10000 kW/m², t = 2.35 s
15000 kW/m², t = 3 s 15000 kW/m², t = 2.35 s

Fig. 8 Flame and soot propagation contour with variation in HRRPUA of fire source



(a) Time taken for soot propagation inside pantry with variation in HRRPUA of fire source



(b) Time taken for flame propagation inside pantry with variation in HRRPUA of fire source

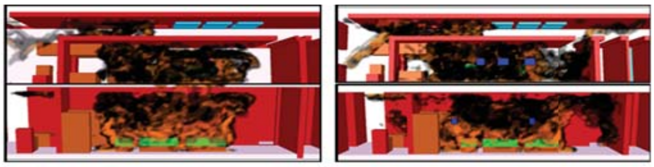
Fig. 9 Plots to compare the time enhancement of flame and soot towards right for different values of HRRPUA

TABLE II
TIME TAKEN BY FIRE AND SMOKE TO REACH THE GATE FARTHEST FROM THE FIRE INITIATION SPOT

HRRPUA (kW/m^2)	Time taken by fire to reach right entry door (s)	Time taken by smoke to reach right entry door (s)
5000	9.26	4.1
10000	5.03	3.6
15000	5.25	3.25

Fig. 8 shows the top and front view for fire and soot of the left exit gate near packaging area at different HRRPUA values after 3 s and 2.35 s of simulation progress respectively. It is observed that after 3 s of simulation, fire in the case of 5000 kW/m^2 HRRPUA spread inside the kitchen area only. In the case of 10000 kW/m^2 HRRPUA fire reaches the passageway after 3 s. Whereas in the case of 15000 kW/m^2 HRRPUA, after 5 s fire covers a major portion of the passageway. It is reaching the packing area through the window. It is also observed to reach the exit gate in this time. Fire reaches the left exit gate after 6.80 s, 2.60 s and 2.25 s for 5000 kW/m^2, 10000 kW/m^2, 15000 kW/m^2 respectively. The soot propagation is observed for the three cases of HRRPUA variation at 2.35 s. In the first case (5000 kW/m^2) soot enters the packaging area. In the second case (10000 kW/m^2) soot reaches the exit door. In the third case (15000 kW/m^2) soot completely covers the exit door and packing area. The figure clearly depicts that the grab of both fire as well as soot increases with an increase in the HRRPUA value of the fire source. Fire reaches the left exit gate after 6.80 s, 2.60 s and 2.25 s for 5000 kW/m^2, 10000 kW/m^2, 15000 kW/m^2 respectively. For different HRRPUA values of the source, time taken by fire and smoke to traverse the length of the pantry is plotted against distance from the fire source in the right hand direction. This is depicted in Fig. 9. It is observed that fire takes 13.2 s, 10.9 s and 9.1 s and smoke takes 5.5 s, 4.83 s and 4.35 s to reach the farthermost end of the pantry for 5000, 1000 and 15000 kW/m^2 respectively. This is depicted in Table II.

C. *Introduction of Exhaust Fans in Exhaust Vents*

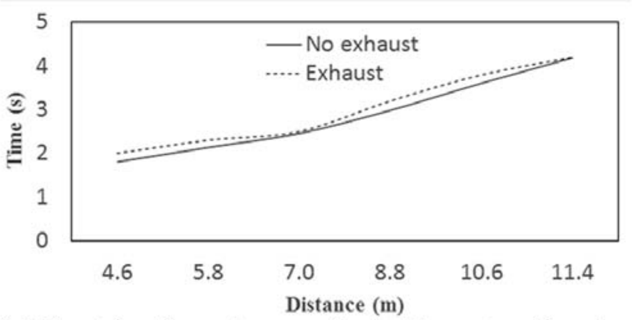


No exhaust, t = 2.8 s **With exhaust, t = 2.8 s**

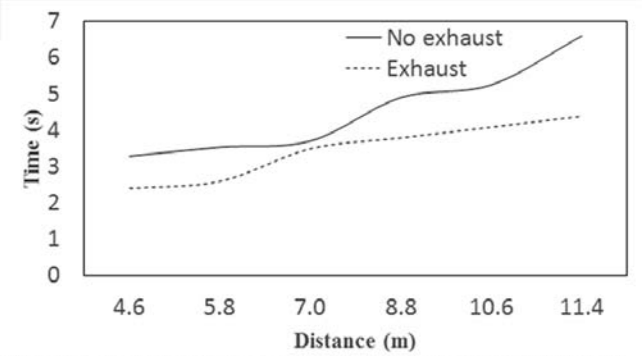
No exhaust, t = 1.7 s **With exhaust, t = 1.7 s**

Fig. 10 Contours for flame and soot for cases with and without exhaust

The simulation is performed to study the effect of exhaust fan in the cooking area. The HRRPUA of the source (cooking stoves) is kept constant at 10000 kW/m^2. Three exhaust vents are put on the ceiling measuring 0.3 m x 0.3 m and separated by a distance of 1 m and 0.8 m respectively between their centers. Two exhaust vents are put on the vertical wall behind the stoves at a height of 1.85 m measuring 0.3 m x 0.3 m and separated by a distance of 2.85 m. Air is drawn out of the domain at a velocity of 1 m/s through the exhaust vents. The top and front view of the kitchen area have been shown in Fig. 10 at 2.8 s and 1.7 s for fire and smoke respectively. The simulations show that with the introduction of exhaust fan there is an increase in the rate with which fire traverses through the coach. It takes 4.1 s and 5.25 s for fire to reach the farthest exit gate with and without provision of exhaust vents at 10000 kW/m^2 HRRPUA of fire source (Table III). The time required for flame propagation is plotted against distance from the source of fire in right hand direction in figure 11 for pantry without exhaust and with exhaust. The exhaust vents draw the air out from inside the pantry. This causes the fire to spread away from the source. Hence the rate of flame propagation is observed to increase with the introduction of exhaust. On the other hand, the smoke spread rate is observed to slow down with the introduction of exhaust fan. Smoke removal from the pantry, facilitated by exhaust fans, results in delay in spread of smoke. It takes 3.8 s (5.03 s without exhaust) for smoke to reach the farthest exit gate with the provision of exhaust vents at 10000 kW/m^2 HRRPUA of fire source. Time for flame and soot propagation is plotted against distance from the fire source in the right direction.



(a) Time taken for soot propagation inside pantry with and without exhaust



(b) Time taken for flame propagation inside pantry with and without exhaust

Fig. 11 Plots to compare the time enhancement of flame and soot towards right for the cases with and without exhaust

TABLE III
COMPARISON OF TIME TAKEN BY FIRE AND SOOT TO REACH THE FARTHEST END OF THE DOMAIN FOR SITUATIONS WITH AND WITHOUT EXHAUST

CASE	Time taken by fire to reach right entry door (s)	Time taken by smoke to reach right entry door (s)
With exhaust	4.1	3.8
Without exhaust	5.03	3.6

D. Air Conditioned Pantry

To study the behavior of fire and soot inside an air conditioned pantry coach, duct is modeled in the pantry and simulations are carried out. Ten outlet of 0.15 m X 0.30 m, separated by a distance of 1.85 m are located in the AC duct, across the length of the pantry. The doors and windows are considered closed in this case. Since the doors and windows are closed, there are no outlets for smoke. It is observed that smoke begins to spread out of the kitchen area after 1.5 sec and engulfs the entire pantry within the first 3.5 s of simulation. Suffocation due to inhalation of harmful gases and soot is the major reason of casualties in AC system. Smoke engulfs the entire coach and drastically brings down visibility. Fig. 12 shows top view and front view of the coach at various time steps for fire and smoke. Fire initiates from the kitchen stoves and covers the kitchen area in 1.4 s. It spreads out to other parts of the coach through the AC duct. It is observed that fire travels the whole length of the AC pantry within the first 5 s of simulation. But since the domain is closed, there is no supply of oxygen. The fire in the kitchen extinguishes completely at 6 s and moves to other areas (packaging area, passageway, berth compartments). The berths of the first, second and third compartment take 6.75 s, 9.2 s and 14.35 s respectively to completely burn away. The fire dies off completely at 15.2 s owing to no supply of oxygen.

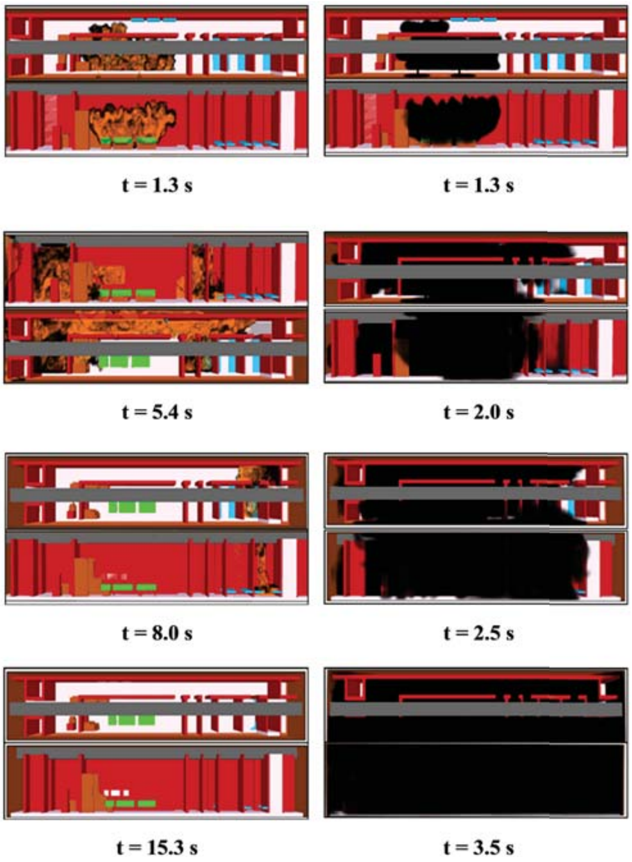


Fig. 12 Temporal variation of flame and smoke flow pattern across the domain

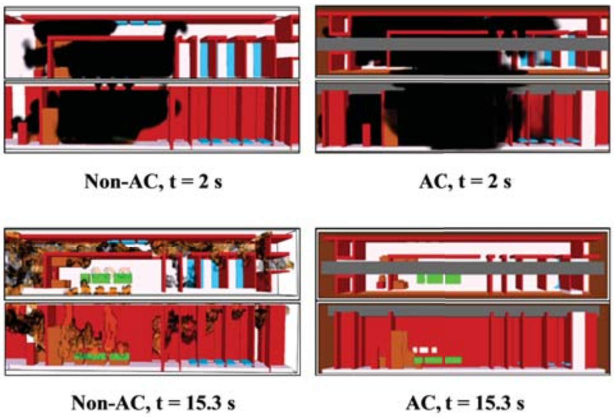
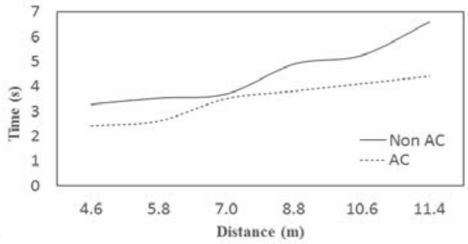
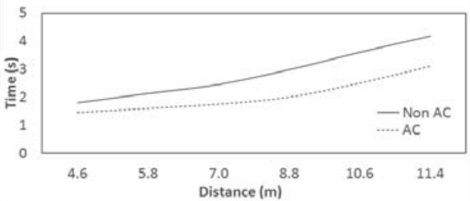


Fig. 13 Comparison between flame and soot flow contour for air conditioned and non-air conditioned pantry



(a) Time taken for flame propagation in AC and non AC pantry



(b) Time taken for soot propagation in AC and non AC pantry

Fig. 14 Plots to compare the time enhancement of flame and soot towards right for the cases with and without exhaust

Fig. 13 shows the difference in soot and fire propagation in AC and non AC pantry coach at 2 s and 15.2 s respectively. Time required for propagation of flame and smoke for AC and non-AC pantry have been compared at 10000 kW/m^2 HRRPUA value of fire source.

TABLE IV
TIME TO REACH FARTHEST EXIT FOR AC AND NON-AC

CASE	Time taken by fire to reach right entry door (s)	Time taken by smoke to reach right entry door (s)
With AC	3.55	2.5
Without AC	5.03	3.6

It can be clearly observed from Fig. 14 (a) that fire takes 3.55 s to reach the farthest exit gate in an air-conditioned pantry whereas the smoke takes 2.5 s to accomplish the same (Fig. 14 (b)). On comparison with a non air-conditioned pantry, it is found out that the both fire and soot take less time to traverse across the passage in case of fire breakout in an air-conditioned pantry. Table IV compares these values with that of non-air conditioned pantry car.

APPENDIX A
NUMERICAL MODEL

An open source Computational Fluid Dynamics (CFD) solver, Fire Dynamics Simulator (FDS) is used for simulations in the present paper. It is a fire driven fluid flow model, which solves Navier-Stokes equation, with approximations for low Mach thermally driven flows and an emphasis on smoke and heat transfer. The representative continuity equation solved in FDS is given in (1)

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{u}) = \dot{m}_b''' \tag{1}$$

Equation (2) gives the momentum transport equation used in FDS, where $\vec{F}$ represents the net force per unit mass, including body forces (gravity and drag) and surface forces (surface tension and viscous forces). $H = \frac{|\vec{u}|^2}{2} + \frac{\tilde{p}}{\rho}$ represents the net stagnation energy per unit mass. The energy conservation equation and equation of state solved in FDS are given in (3) and (4), respectively.

$$-\nabla^2(H) = \frac{\partial(\nabla \vec{u})}{\partial t} + \nabla(\vec{F}) \tag{2}$$

$$\frac{\partial(\rho h_s)}{\partial t} + \nabla(\rho h_s \vec{u}) = \frac{D\overline{P}}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla(\dot{q}'') \tag{3}$$

$$\overline{P} = \frac{\rho R T}{\overline{W}} \tag{4}$$

The source term, $\dot{q}'''$ is the heat released per unit volume due to chemical reaction and $\dot{q}_b'''$ is the rate of heat transfer to the sub grid scale droplets and particles.

Approximation of the partial derivatives in the mass, energy and momentum equation are done using Finite Difference technique. A three dimensional rectilinear grid is used to formulate the temporal advancement of the solution. Further, Finite Volume method is used to compute thermal radiation on the same rectilinear grid which is used for the flow solver [11]. An explicit second order predictor/corrector scheme is used to advance the variables involved. [13].

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