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Numerical Simulations of Fire in Typical Air Conditioned Railway Coach

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Abstract—Railways in India remain primary mode of transport having one of the largest networks in the world and catering to billions of transits yearly. Catastrophic economic damage and loss to life is encountered over the past few decades due to fire to locomotives. Study of fire dynamics and fire propagation plays an important role in evacuation planning and reducing losses. Simulation based study of propagation of fire and soot inside an air conditioned coach of Indian locomotive is done in this paper. Finite difference based solver, Fire Dynamic Simulator (FDS) version 6 has been used for analysis. A single air conditioned 3 tier coupe closed to ambient surroundings by glass windows having occupancy for 8 people is the basic unit of the domain. A system of three such coupes combined is taken to be fundamental unit for the entire study to resemble effect to an entire coach. Analysis of flame and soot contours and concentrations is done corresponding to variations in heat release rate per unit volume (HRRPUA) of fire source, variations in conditioned air velocity being circulated inside coupes by vents and an alternate fire initiation and propagation mechanism via ducts. Quantitative results of fractional area in top and front view of the three coupes under fire and smoke are obtained using MATLAB (IMT). Present simulations and its findings will be useful for organizations like Commission of Railway Safety and others in designing and implementing safety and evacuation measures.

Keywords—Air-conditioned coaches, fire propagation, flame contour, soot flow, train fire.

I. INTRODUCTION

WITH a population of over a billion, the preferred mode of transport is railways in India. Indian railways support over 8 billion journeys a year and has one of the widest network. With such high reliance on a particular mode of transport, safety is an important issue. Even with the current safety measures in place, occurrence of train fires is high. With varying combustible material carried by passengers and high crowd density inside locomotives, fires causing fatalities [1] are also frequent. Large number of such fires occur in air conditioned bogies of Indian railways ([2] and [3]).

In 1982, Markatos et al. [4] emphasized importance of using numerical simulations in the study of fire dynamics. It helps to avoid huge financial and human resources incurred in scaled experiments with questionable similarity with real life fires. Equipped with high computational power, simulations can be used to analyze real life fire scenarios without incurring much cost. Therefore, such studies, in the context of Indian locomotives, help to understand fire and smoke behavior in case of fires. Various real life factors affecting fires like velocity of inlet air velocity from windows, presence of combustible material and others can be modelled and studied. Such investigation helps in fire preparedness and ensuring safety measures by designated authorities. Fire in trains is a special case of compartmental fire with potential of high damage due to large population low free density [5].

The problem of railway system fires can be divided into railway vehicles, stations and tunnels. Train fires have been quiet exhaustively studied for the past decade. Examples of such efforts are study of numerical simulations for a typical train fire in China by Chow et al. in 2011 [6]. A full scaled fire experiment of a typical Australian passenger train was done to study developed fires in ambient conditions by White [7]. Similarly full scale burning tests were carried on trains in Europe in tunnels to study fire size and safety [8]. Studies pertaining to fire to railway locomotives in the US were done by Peacock et al. [9]. Similar such efforts were carried out jointly by nine European countries in the last decade of twentieth century to investigate and suggestive preventive measures to fire in tunnels [10]. Study showing promising trends justifying the use of CFD as an effective tool to study and analyze compartmental railway fires and design systems accordingly was done by Enbaya et al. [11]. Even though studies in this field have been ongoing for a decade now, specific India-focused analysis of trains has not been done. With such a wide network of railways, such investigation becomes of prime importance which is yet to be explored. Literature lacks any specific case pertaining to Indian Railways. Hence, extensive surveys to determine the materials used in different components of the compartment were conducted. Exhaustive measurements to regenerate the exact dimensions of the computational domain to be studied were done. Effect of air supply by duct in an air conditioned coach and possible variations in its operating conditions is yet another topic of exploration done in this paper.

Combustible and thermodynamic properties of material used in the railway locomotive are not properly documented. They pertain a major contribution to the fire dynamics study and the flame spread depends on the materials inside the train compartment therefore the simulated results of fire and smoke layer would be different for different combustibles and off by some factor. It has been observed that the materials of the berths and the support on which they rest are not made up of fire-proof materials, rather are composed of fiberglass, carbonated vinyl and polyethylene, posing a serious threat at the time of fire breakout. No exhaust measures are present in the closed air conditioned coaches posing high risk to smoke during fire. Soot flow pattern study done in this investigation

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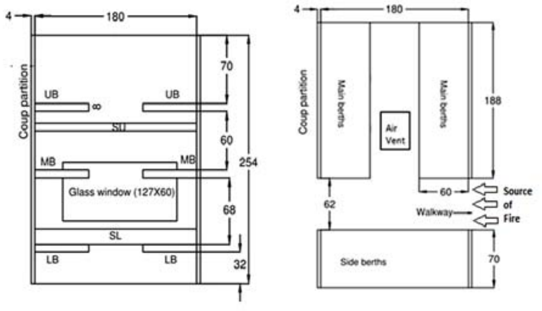
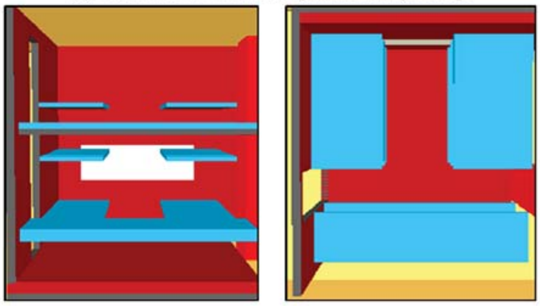


(a) Schematic elevation and plan of a single coupe



(b) Elevation and Plan of single coupe FDS model

Fig. 1 The working domain (single coupe)

can be useful to take safety measures as smoke and other toxic gases produced during fire are equally harmful as fire. Domain description is discussed in the next section followed by results from our finding. Volumetric filling of the domain by fire and smoke while fire propagation is approximated by areal analysis of top and front view. Employed numerical methodology can be found in Appendix A and corresponding grid independent study can be found in Appendix B.

II. DOMAIN DESCRIPTION

Measurements of air conditioned coupe were taken comparable to that of air conditioned locomotive of Indian Railways. Fig. 1 (a) shows schematic of top and front view for single coupe domain along with dimensions (in cm) and associated functionalities.

A single air conditioned coupe (180 cm X 320 cm X 254 cm) has 8 sleeping arrangements (2 upper, UB; 2 middle, MB;2 lower, LB; side upper, SU; side lower, SL) with 2 glass covered windows in the side walls and two openings for walkway. The entire domain is kept inside a box of dimension of 7 m x 4.6 m x 3.05 m. Coupe wall is considered to be constructed by layered material having steel sheet along with wooden frames sandwiched from both the sides. Floor of the coupe is made of steel block over which wooden frame and PVC flooring are layered. Ceiling of the domain is considered to be steel block with wooden frame and PVC furnishing in the inner side. Ceiling is made invisible in all the simulations for clarity. Side walls of the coupe are made of steel block with wooden frame and plywood covering in the inner side. All the sleeping berths are considered to be having steel construction with fabric and foam layering for comfort. All the berths are kept in open condition in all the simulations. FDS model of a single coupe is shown in Fig. 1 (b).

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 [12]	100	0.1	1	370	15000
Foam [12]	40	0.05	1	370	33280
Glass	2520	1	0.72	-	-
Plywood [14]	545	0.12	1.215	-	-
Steel [13]	7850	45.8	0.46	-	-
PVC [12]	1300	0.17	1.2	-	-
Wood [14]	489	0.14	1.38	400	14500

k, c, T_b and H_c represent Thermal conductivity, Specific heat, Ignition Temperature, Heat of combustion.

In the present simulation, material properties are taken as in Table I). These materials can be grouped into two types. First, for whose combustion a definite model or formula is available such as foam, fabric, wood and second, like PVC, plywood for whose combustion heat release rate data exist but no proper model has been developed ([12] and [13].

Fire initiation is considered from right entry of walkway (ignition is happening somewhere in neighboring coupe) with 10000 kW/m^2 heat release rate per unit area (HRRPUA). Ambient pressure and temperature is taken as 101.325 kPa and 25 ^0C. At t = 0, air speed is 0 m/s and smoke concentration in the domain is zero. The gaseous fuel used is $C_{6.3}H_{7.1}O_{2.1}N$. Results from numerical simulation show propagation of fire and smoke inside the coupe with time.

III. RESULTS AND DISCUSSIONS

Simulations with single coupe and three coupe domains of Indian air conditioned railway locomotive are done to investigate flame and soot propagation. HRRPUA of the fire source is varied to analyze the impact. Air conditioning is maintained inside the coupes by pumping conditioned air from vents present on the roof. Air velocity coming out of the vent is varied to analyze its effect on fire and soot spread. Alternate route of fire propagation is through ducts. Simulations are done to analyze effects to fire and soot propagation with and without restrictions of flow inside duct. Quantitative analysis of fraction of total area under fire or smoke of roof and intermediate section is performed using MATLAB image processing toolbox.

A. Single Coupe System

Fire ignition and growth occur almost simultaneously. Fully developed fire in the compartment can be observed from 1 s to 3 s. However, decay of fire starts from 3 s onwards because oxygen acts as a limiting agent as all ducts and vents are closed. Fire plume propagation is seen in color variations of orange and yellow whereas the black represents soot particle. Propagation of fire and smoke plume is primarily seen as to moving horizontally along the ceiling and along the top surface (apparent ceiling) of the compartments made by berths (e.g. compartment between top and middle berth). It is observed so because of buoyant forces due to which hot gases in the fire

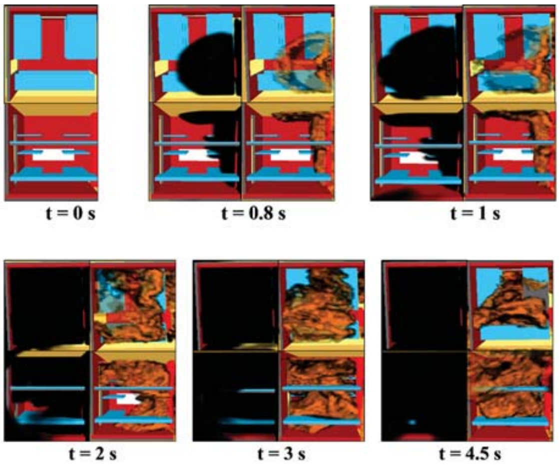


Fig. 2 Flame and soot propagation contour in a single coupe domain

plume ascend upwards and impinge on the ceiling. The ceiling surface restricts the upward flow, deflects them downwards, and makes them move horizontally to the other areas of the compartment. Fig. 2 shows the temporal variation of flame and smoke flow in the domain. Semicircular spread of fire and soot plume is seen for the first 0.8 s. However, interactions with obstacles and with ignition of several objects the shape and spread gets randomized. The speed of propagation of soot is observed to be greater than that of fire, it is because of density difference between the both. Fire has taken 1 s to reach the end of first coupe and soot propagation has taken 0.9 s for the same. Combustion of the seats is seen starting from 4 s onwards.

B. Three Coupe System

The current compartmental fire study is of three air conditioned coupes of railway locomotive of Indian Railways. It is taken to be the basic unit for further studies. The soot propagates in an accelerated fashion takes 0.9 s to reach the end of first coupe, 0.6 s to travel the second and 0.4 s to travel the third. This phenomenon is observed due to increase in formation rate of soot over time. As no ducts or window is open to provide fresh oxygen, it acts as limiting agent producing excess soot. At the end of first coupe, the soot plume has to travel through walkway. Due to constant volumetric flow but substantial reduction in the entry area, plume which had been traveling horizontally along the ceiling transcends downwards randomizing the semicircular propagation along ceiling. Fire propagation takes 1.1 s to travel through the first coupe, 0.5 s for the second and 1 s for the third. It can be well understood taking into account limiting oxygen and soot filled coupes by the end of 2 s. For the first coupe, fire fully develops at 1.8 s and starts decaying by end of third second. The burning of berths start from 2 s onwards. In the second and third coupes, fully developed fire is successively smaller (in area and flame) than the first. It is shown in Fig. 12. 3 s onwards incomplete combustion starts and hence the blackness in flames. Fire from the source gets extinguished at around 3.5 s due to lack of oxygen making the fire triangle incomplete. Berths of second coupe start burning by 4 s and that of third by 6.5 s. Approximately around 13 s, fire dies off entirely in the first coupe due to exhaustion of all the combustible materials available. Temporal enhancement of flame and smoke is illustrated in Fig. 3.

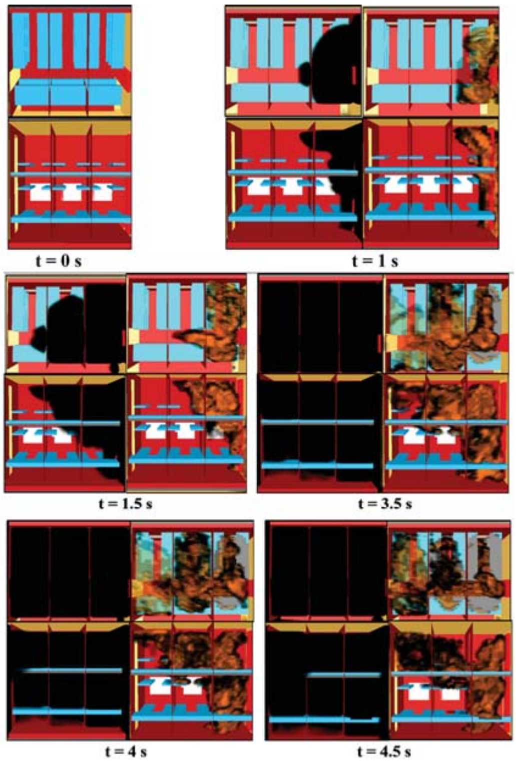
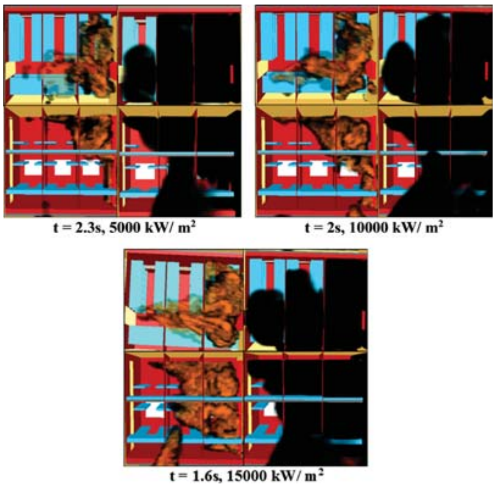


Fig. 3 Flame and soot propagation contour in a three coupe domain

C. Variations in HRRPUA of Initial Fire

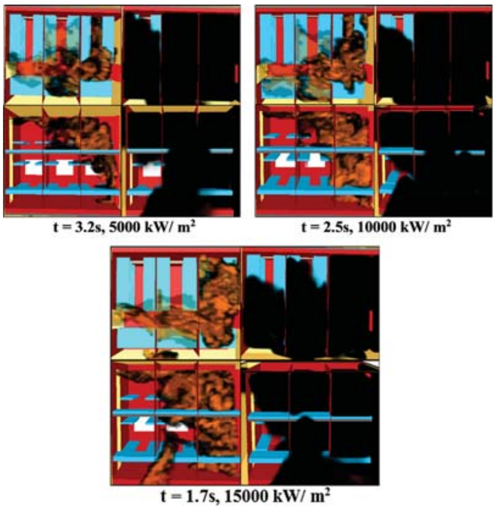
To study the effects of magnitude of fire on propagation, HRRPUA of the fire source are varied. All the other parameters (domain area, location of fire source, grid size etc.) are kept constant for the propagation study. Three representative cases are taken here, with values of HRRPUA as 5000 kW/m^2, 10000 kW/m^2 and 15000 kW/m^2 respectively. Soot flow is observed to propagate faster with increasing HRRPUA. It is found that it takes 2.3 s, 2 s and 1.6 s respectively in the first, second and third cases respectively as shown in Fig. 4.



t = 2.3s, 5000 kW/ m² t = 2s, 10000 kW/ m²

t = 1.6s, 15000 kW/ m²

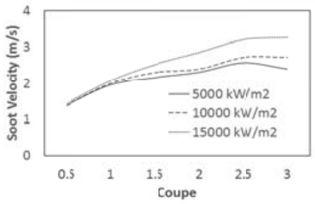
Fig. 4 Flame and soot pattern when smoke reaches farthest corner



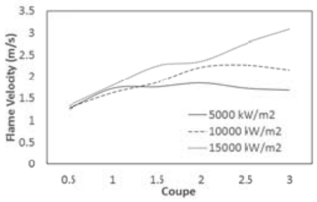
t = 3.2s, 5000 kW/ m² t = 2.5s, 10000 kW/ m²

t = 1.7s, 15000 kW/ m²

Fig. 5 Flame and soot pattern when fire reaches farthest corner



(a) Soot velocity with respect to distance travelled inside coupe



(b) Flame velocity with respect to distance travelled inside coupe

Fig. 6 Velocity variations of flame and soot with distance traveled inside coupe

Fig. 6 (a) illustrates the velocity of soot with respect to distance traveled inside the coupe. Similarly, Fig. 5 shows that the fire propagation in third case with maximum HRRPUA (1.7 s to reach last end of third coupe) is observed to be faster than second (2.5 s to reach last end of third coupe), which in turn is faster than first case (3.2 s to reach last end of third coupe).

The velocity of flame with respect to distance traveled inside coupe is calculated and plotted as shown in Fig. 6 (b). These observations can be attributed to the fact that maximum HRRPUA implies high strength of fire which engulfs more combustibles in a given duration of time. Moreover, the burning away of combustible materials (berths) in first coupe starts at 1.75 s in the third case, at 2.4 s in second case and at 2.7 s in the first case. However, in second and third coupe burning starts nearly at the same time for all the cases (slightly late for the first case). It is because of different distances from the fire source. With time, fire gets extinguished due to insufficient fresh oxygen inside the domain. Oxygen in the first case lasts longer than others owing to least HRRPUA.

D. *Variations in Air Velocity through Vents*

Fig. 7 contains the schematic of the present group of simulations in which the variation of inlet conditioned air velocity from vents is stimulated to observe fire and soot propagation.

According to guidelines of Indian Railway, maximum air flow velocity from ducts is to be 3 m/s [15]. For study purpose,, four variations in velocity (1 m/s, 2 m/s, 3 m/s and 4 m/s) are observed. Fire propagation in all the four cases gradually decreases in speed. It takes 2.1 s for fire to reach the third coupe for first case whereas for the fourth case it takes 2.7 s. For the intermediate cases, a gradual variation is seen. Burning away of combustible materials inside the first coupe is seen 2.6 s onwards for first case whereas for the fourth case, it is 2.1 s onwards.

Similarly, in the third coupe it is observed at 6.3 s for first case and at 7 s for the fourth. Fig. 9 shows fire propagation inside the three coupes for all the four cases. Moreover, Fig. 10 (a) illustrates the time taken for flame propagation inside the coupe with varying vent velocity.

Soot propagation in all the four cases is observed to be same. It reaches to end of the domain by 2 s. And all the three coupes get entirely filled by soot by 6 s. Fig. 8 shows soot propagation inside three coupes for the four cases. Further, Fig. 10 (b) demonstrates the time taken by smoke to propagate inside the coupes. Comparing above results with a case when no air is circulated from vents, results are nearly the same. We can therefore safely conclude that variations in air velocity from ducts would not make much of a difference in case of conflagrations or even flashy fires.

E. *Effects Due to Inclusion of Duct*

Current comparison is of propagation of fire and smoke when the fire spread is inside both coupe and duct: case (i) versus that only in a coupe: case (ii). For case (i), volume flow of air inside duct is taken as per standard railway guidelines (air velocity of 3 m/s, standard cross-sectional area) [15] and fire propagating inside the duct and spreading into coupes via vents. It is also made that no fresh circulation of air is available by closing the circulation system. Case (ii) occurs when the duct pipeline is artificially shut down (artificial mechanical arrangement) and fire spread inside it is not allowed. Fire spread is therefore considered via a single vent. In case (i), fire source is inside duct, oxygen requirement for combustion is met only by oxygen available in the duct pipe, which is low. As no new oxygen is available, the fire source dies off at 2.5 seconds whereas in the other case as lot of oxygen is available in the first coupe, flame is active till 6.5 seconds.

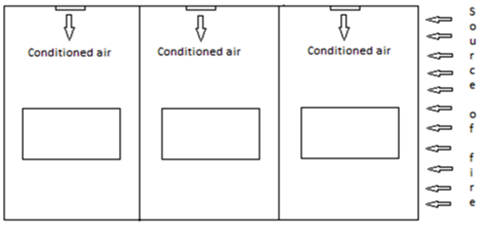


Fig. 7 Directions of conditioned air flow and fire into three coupe domain

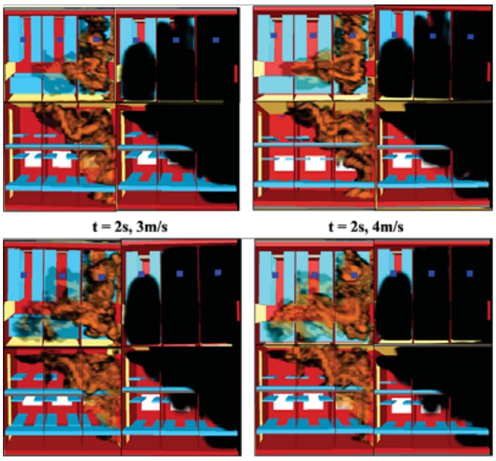

t = 2s, 3m/s
t = 2s, 4m/s
t = 2s, 1m/s
t = 2s, 2m/s

Fig. 8 Flame and soot contour with variations in vent velocity when smoke reaches the furthest corner

Variations of flame color can be understood by the above fact too. Accordingly, soot formation is more in case (i) than in case (ii). Comparing timings of soot and flame propagation in both cases, we find that at the end of 2 s, in case (i) soot and fire spread is in all the 3 coupes while in case (ii), its only in the first. It spreads gradually in the latter case and at the end of 7 s, similar conditions of soot is observed for both the cases only in the first coupe. In the latter case, second and third coupes are in better conditions of visibility and damage due to fire. The situation becomes nearly the same in both the cases by 13 s because fire source in both cases has died off and spread is purely by burning of combustible materials. Turning into ash of combustible materials in the first coupe starts at the onset of 8 s and by 9.5 s in second and third coupe. Whereas it is at the onset of 8.5 s for the first coupe, 13 s for the second and fire is extinguished before loss due to turning into ash in the third coupe in the latter case.

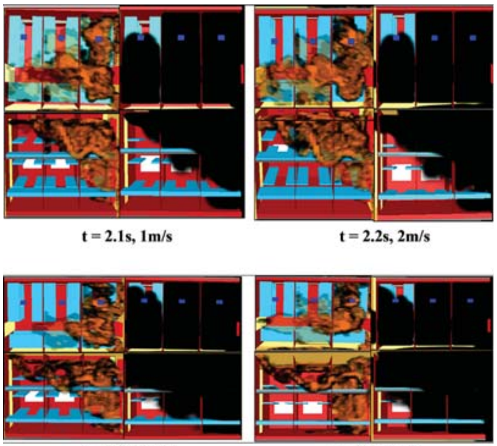
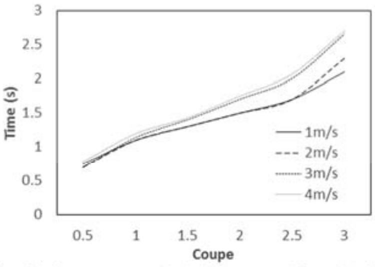
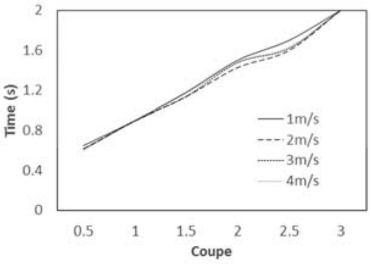

t = 2.1s, 1m/s
t = 2.2s, 2m/s
t = 2.5s, 3m/s
t = 2.6s, 4m/s

Fig. 9 Flame and soot contour with variations in vent velocity when fire reaches the furthest corner



(a) Time taken for flame propagation inside coupe with varying duct air velocity

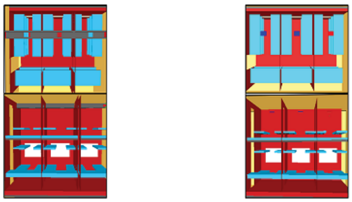


(b) Time taken for smoke propagation inside coupe with varying duct air velocity

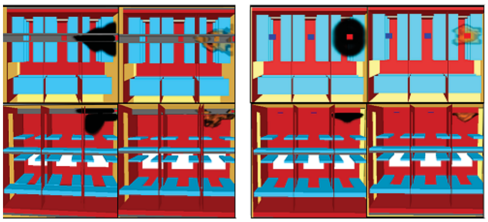
Fig. 10 Time taken for flame and soot propagation with distance traveled inside coupe

F. Quantitative Analysis

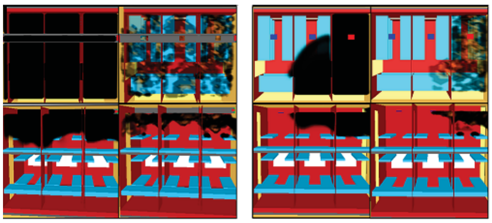
Quantifying the fire and soot propagation proves important to better understand the physical phenomenon. To achieve this fractional area of top view and front view, engulfed under fire and smoke with respect to time is calculated. The same is plotted in fractional area *vs* time graphs. It has been done using MATLAB Image Processing Toolkit (IPT).



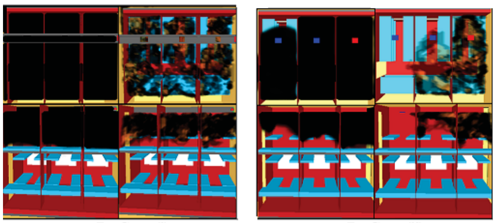
t = 0s, Case (i) **t = 0s, Case (ii)**



t = 1s, Case (i) **t = 1s, Case (ii)**



t = 4.5s, Case (i) **t = 4.5s, Case (ii)**

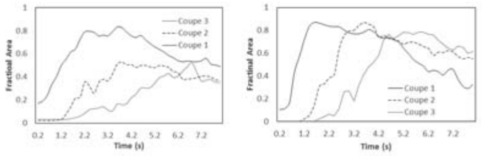


t =7s, Case (i) **t = 7s, Case (ii)**

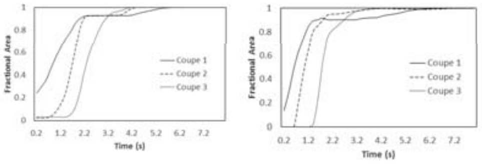
Fig. 11 Flame and soot contour with and without fire propagation inside duct

Analysis of fraction of area under fire and smoke of individual coupes in a three coupe domain is done and represented in Fig. 12. Fire initiates in walkway adjoining coupe 1 and propagates thereafter to the second and third coupes. Maxima of area under fire in both the views are seen accordingly. Due to depletion of oxygen, burning flame dies explaining descend in the curves. However, due to insufficient ventilation, soot concentration increases rapidly and completely fills the domain at 5.5 s. As no fresh supply of air is available inside, soot concentration remains same.

Effect of HRRPUA is studied. The three variations studied are with HRRPUA values of 5000 kW/m^2, 10000 kW/m^2 and 15000 kW/m^2. Shift in peaks for fractional area under fire in top view are in line with rates of oxygen consumption, death of fire flames and eventual reduction in area under fire. Similarly, in a confined space, with high HRRPUA, soot concentration increases, represented by the least time taken to completely fill the domain (fractional area = 1). Analysis of fractional area under fire and smoke with varying HRRPUA in a three coupe domain is shown in Fig. 13.

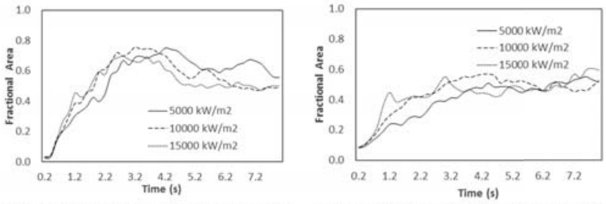


(a) Coupe wise fractional area under fire (top view) **(b) Coupe wise fractional area under fire (front view)**

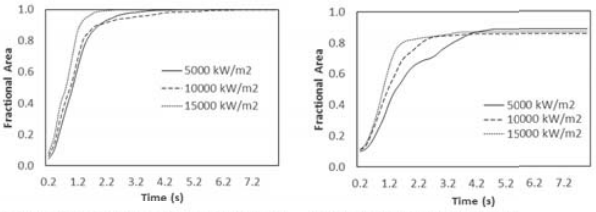


(c) Coupe wise fractional area under smoke (top view) **(d) Coupe wise fractional area under smoke (front view)**

Fig. 12 Fractional area versus time graphs for fire and smoke propagation in a three coupe domain



(a) Fractional area of domain under fire with varying HRRPUA (top view) **(b) Fractional area of domain under fire with varying HRRPUA (front view)**



(c) Fractional area of domain under smoke with varying HRRPUA (top view) **(d) Fractional area of domain under smoke with varying HRRPUA (front view)**

Fig. 13 Fractional area *vs* time graphs for fire and smoke propagation with varying HRRPUA in a three coupe domain

IV. CONCLUSIONS

In this paper, fire in a typical air conditioned railway compartment of Indian locomotive is simulated using FDS. As flame spread depends on the materials inside the train compartment, simulated results of fire and smoke would be different for different combustibles. It is observed that with increase in HRRPUA, fire and soot propagates rapidly. Closing of duct mechanically gives more time for evacuation. Changing air velocity of duct does not have impact on fire and soot spread. Results indicate that serious consequences would result in train compartment fire due to the small enclosed space. Appropriate fire suppression and smoke exhaust systems should be provided to reduce the indoor temperature and keep the smoke layer high.

APPENDIX A
NUMERICAL MODEL

The overall continuity equation can be represented as given in (1), where the source term, $\dot{m}_b'''$ accounts for the addition of mass from the evaporating droplets or other sub-grid scale particles such as fuel sprays and sprinklers.

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

A form of Navier-Stokes equation appropriate for thermally driven flows with low mac number and an emphasis on smoke and heat transport due to fire has been considered in this model. A typical momentum transport equation has been given in (2):

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

$\vec{F}$ represents the net force per unit mass, including body forces and surface forces whereas $H\left(\frac{|\vec{u}|^2}{2} + \frac{\tilde{p}}{\rho}\right)$ denotes the net stagnation enthalpy per unit mass featuring the perturbation pressure, $\tilde{p}$. Equation (3) is the representative of the energy conservation scheme employed in this investigation and (4) shows the equation of state featuring the background pressure:

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

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

In order to solve these equations, an open source Computational Fire Dynamics code, Fire Dynamics Simulator (FDS), developed by National Institute of Standards and Technology (NIST) lab has been used. Finite Difference Methodology has been employed to estimate the partial derivatives as encountered in the transport and conservation equation of mass, momentum and energy. Further, the radiation effects have been incorporated using the Finite Volume technique. Simultaneous coupled solution of (1)-(4) leads to calculation of properties like velocity vector field, pressure and temperature. Temporal marching adopts a second order accurate explicit corrector-predictor scheme [16]. These solutions are updated on a three dimensional rectilinear grid.

APPENDIX B
GRID INDEPENDENCE STUDY

Entire domain of study is divided into cuboid shaped grids. To get the approximate grid size, the characteristic diameter of fire is calculated using (5) [17]:

$$D^* = \left[\frac{\dot{Q}}{\rho_\infty C_p T_\infty \sqrt{g}}\right]^{\frac{2}{5}} \tag{5}$$

Grid sizes depend on what is to be achieved. In our case, the results obtained should be impervious to the grid size taken. Mesh sensitivity study was done to achieve the discussed desired grid sizes. Start of the study was done taking fine mesh size. The quantity $\frac{\delta x}{L}$ denotes sensitivity of mesh sizes. It was varied, corresponding grid sizes obtained and so was the heat release rate (HRR) with respect to time. The obtained data was plotted in each case as shown in Fig. 14. Variation of $\frac{\delta x}{L}$ was done from 0. 007 to 0.017. Where δx denotes minimum mesh/grid size in all the three xyz coordinate system and L denotes maximum domain length of all the three directions.

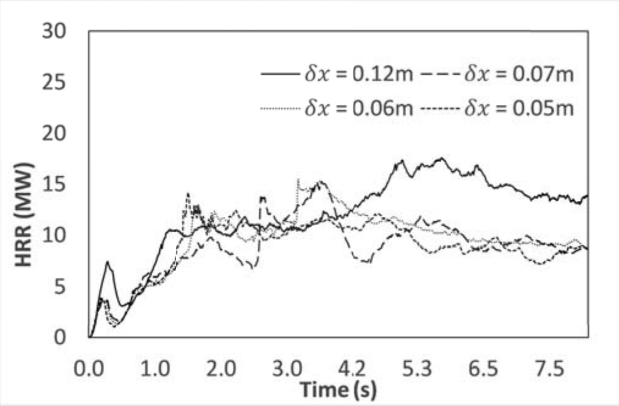


Fig. 14 Comparison of Grids using HRR

Heat release rate (HRR) due to fire is plotted against time for four number of representative grids with cell size of y and z direction being 0.051 m, 0.061 m, 0.076 m and 0.12 m. It is observed that the cell sizes attain saturation after 4 s. It is found that average difference between saturation values of HRR for grid size 0.061 m and 0.12 m is 30% whereas that between 0.051 m, 0.061 m and 0.076 m is 8%. Thus for all the simulations done, value of δx is taken to be 0.06.

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