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Investigation of Flame and Soot Propagation in Non-Air Conditioned Railway Locomotives

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Abstract—Propagation of fire through a non-air conditioned railway compartment is studied by virtue of numerical simulations. Simultaneous computational fire dynamics equations, such as Navier-Stokes, lumped species continuity, overall mass and energy conservation, and heat transfer are solved using finite volume based (for radiation) and finite difference based (for all other equations) solver, Fire Dynamics Simulator (FDS). A single coupe with an eight berth occupancy is used to establish the numerical model, followed by the selection of a three coupe system as the fundamental unit of the locomotive compartment. Heat Release Rate Per Unit Area (HRRPUA) of the initial fire is varied to consider a wide range of compartmental fires. Parameters, such as air inlet velocity relative to the locomotive at the windows, the level of interaction with the ambiance and closure of middle berth are studied through a wide range of numerical simulations. Almost all the loss of lives and properties due to fire breakout can be attributed to the direct or indirect exposure to flames or to the inhalation of toxic gases and resultant suffocation due to smoke and soot. Therefore, the temporal stature of fire and smoke are reported for each of the considered cases which can be used in the present or extended form to develop guidelines to be followed in case of a fire breakout.

Keywords—Fire dynamics, flame propagation, locomotive fire, soot flow pattern.

I. Introduction

FIRE dynamics and propagation study are important and reckon attention due to the role they play for taking proper measures at the time of fire breakout. Since the introduction of high speed travel methods, fire has been one of major culprit for loss of lives and properties. Being one of the largest rail network in the world, Indian Railway shares a major crunch of these fire accidents. It is difficult to ascertain the exact reason of fire in a train after the disaster has occurred. But short circuits and pantry always pose a major risk. Pantry has potential sources of fire like stoves and contains combustible materials like gas cylinder, cardboard storage boxes among others, which are easy to catch fire. Similarly once the fire has initiated, it spreads through the length of the coach. Due to high relative speed of wind coming into the train, non-air conditioned coaches are the most affected and encounter maximum number of casualties. It is necessary to study the dynamic behavior of flame and smoke in case of such hazards, so that we can prepare for and minimize the loss of lives and properties it causes.

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It was in 1982 that Markatos et al. [1] argued the increasing importance of numerical simulations in the study of fire dynamics. In order to dodge the use of huge financial and human resources, researchers usually rely on scaled physical model with questionable similarity, and on real life experiences. However, with ever increasing computational power. it is now possible to use numerical simulations to investigate the fire breakout situations without incurring huge costs. Compartmental fires have been studied extensively over the years to develop building designs and evacuation strategies ([2], [3]). Fire in train coaches is a special case of compartmental fires that has the potential to cause inevitable damages once it spreads owing to large population and low free space density [4]. Estimation of temperature distribution and air flow velocities given by Enbaya et al. [5] show promising trends justifying the use of computational fluid and fire dynamics as an effective tool in order to analyze railway compartment fires and develop safe and reliable safety systems for such applications. In 2011, Chow et al. [6] 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 has been shown that the smoke flow is more threatening than the actual flame. In his PhD work, White [7] studied the fire development scenarios in terms of heat release rate *vs* time curves. Ignition of upper walls and ceiling lining are found to be critical for fire spread. Significant spread of flames results in flash-over conditions. Roh et al. [8] discussed the evacuation requirement time along with the travel speed of individuals as a function of population density. Based on the measurements complementing the heat release rate, a system approach to the typical passenger train fire scenario is analyzed by Peacock et al. [9] in order to explore the advantages and disadvantages of the current method employed for fire performance of rail transportation and suggested exhaustive fire endurance tests to be conducted for the materials used in trains. However, the effects of change in speed and direction of air flow through the windows are unexplored along with the effects of degree of interaction of the computational domain with the ambient surrounding. Combustible and thermodynamic properties of material used in the railway locomotive are not properly cataloged. Since, the materials pertain a major contribution to the fire dynamics study, the analysis have been found to be off by some factor. Further, the literature lacks in any case specific to the Indian Railways' locomotives which holds one of the biggest shares of global railway locomotion.

For this study, extensive surveys are conducted to determine the materials used in different components of the railway compartment. Exhaustive measurements are carried out to regenerate the exact dimensions of the domain to be studied. It has been observed that the materials of the berths and advertisement boards are not made up of fire-proof materials, but are composed of fiberglass, carbonated vinyl and polyethylene, posing a serious threat at the time of fire breakout. No adequate smoke control measures are currently in place in the coaches. Soot flow pattern studied in this investigation can be used to install adequate measures for smoke control as it has been observed that smoke is as injurious as flame, if not more. In the next section, domain description is illustrated followed by results from our finding. Employed numerical methodology can be found in Appendix IV-A.

II. Domain Description

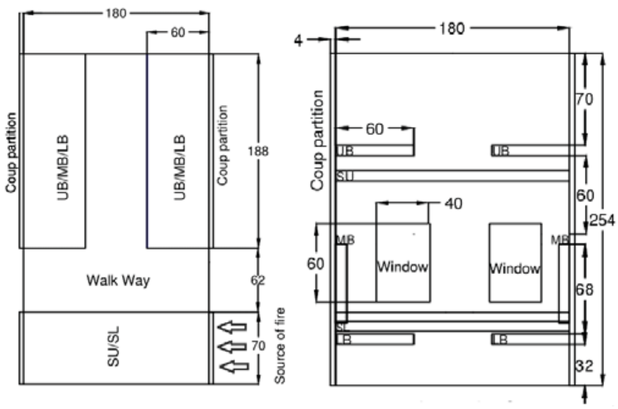

Fig. 1 Schematic representation of a coupe (all dimensions are in cm)

Realistic measurements of a locomotive coupe in Indian Railway are taken as inputs for the three dimensional mesh geometry of numerical simulations. Schematic of the domain for a coupe is shown in Fig. 1 along with all the functionalities and dimensions. A single coupe (180 cm x 320 cm x 254 cm) has 8 sleeping arrangements (two upper berths (UB), two middle berths (MB), two lower berths (LB) and one side upper berth (SU) and side lower berth (SL)) with 4 windows in the side walls and two openings for walkway. To account for the ambiance, an offset of 50 cm is provided all around the compartment. Coupe partition wall is considered to be constructed by layered material having 2 cm steel sheet sandwiched with wooden frames on both sides. Floor of the coupe is made of steel block over which wooden frame and PVC floorings are layered. Ceiling of the domain is considered to be a steel block with wooden frame and PVC furnishing on the inner side. Side walls of the coupe are made of steel block with wooden frame and plywood covering on the inner side. All the sleeping berths are considered to be having steel construction with fabric and foam layering for comfort. Fig. 2 illustrates the fire dynamic simulator (FDS) model of the single coupe.

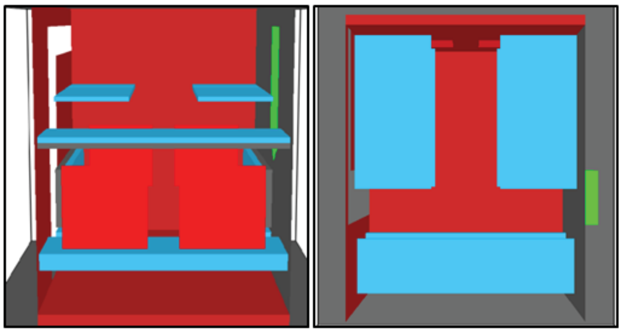

Fig. 2 Plan and elevation of the working domain

Table I presents all properties of the materials used in the current study. Fire is assumed to be entering from the right entry of the walkway (ignition is happening somewhere in neighboring coupe) with HRRPUA of 10000 kW/m^2 (for single coupe case). At the beginning, air speed and smoke concentration in the domain are both set to 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. Grid Independence Analysis is conducted to establish the optimum cell size as 0.06 m as described in Appendix IV-B.

TABLE I
Details of Materials Used - k, c, T_b and H_c Represent Thermal Conductivity, Specific Heat, Ignition Temperature and Heat of Combustion Respectively

Material	Density (kg/m^3)	k (kJ/m^2K)	c $(kJ/kg.K)$	T_b (^0C)	H_c (kJ/kg)
Fabric [3]	100	0.1	1	370	15000
Foam [3]	40	0.05	1	370	33280
Plywood [10]	545	0.12	1.215	-	-
Steel [3]	7850	45.8	0.46	-	-
PVC [3]	1300	0.17	1.2	-	-
Wood [10]	489	0.14	1.38	400	14500

III. Results and Discussions

Numerical simulations are carried out for single and three coupe domains, followed by variation of HRRPUA to cover a wide range of cases. Further, a three coupe case with 1000 kW/m^2 is used for parametric variation study in velocity (magnitude and direction) of air flow inside the coupe through windows. Next the dependence of characteristics of fire and soot on the degree of interaction of the coupe with the outside ambiance is established. At last, opening of middle main berths is considered and results are compared with one where they were closed. Ultimately, qualitative analysis is conducted to examine the spatial fraction of domain under the grab of fire.

A. Single Coupe of Railway Locomotive

All 4 windows of coupe are kept open to observe flame and soot release from windows. Results from the numerical simulation show propagation of fire and smoke inside the coupe with time. Fire propagation is seen in color variations of orange and yellow whereas black represents smoke Fig. 3 shows temporal variation of fire propagation and smoke flow

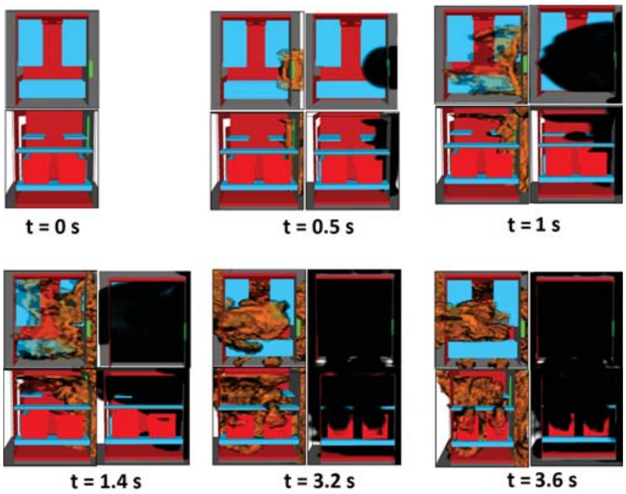

Fig. 3 Flame and soot propagation contour in single coupe domain

patterns in both plan and elevation view. Initially (till t = 0.8 s), both fire and smoke spread inside the coupe without any restriction and form a hemispherical shape under its grab. Soon the effect of different functionalities like berth and wall comes into picture. Both flame and smoke propagation halt after reaching the obstruction. Propagation of fire and smoke plumes are primarily seen as to moving horizontally along the ceiling and along the top surface of the compartments made by berths (e.g. compartment between top and middle berth). It is observed so because of buoyancy forces due to which hot gases in the fire 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, also known as the ceiling jet effect.

At t = 1 s, both flame and smoke touches the wall opposite to the fire initiation spot and start to fill the volume of the coupe by propagating in other directions. At 1.4 s, flame and smoke initiate to come out of coupe through the window. With passage of time, fire extinguishes (at t = 3.2 s) even though other items in the coupe continue to burn and generate smoke. Around 3.6 s, fabric and foam over the berths start to burn away and whole volume of the coupe comes under the grab of smoke making it impossible for life to survive inside. From the smoke and fire contours, volumetric filling rates for both flame and smoke increase with time up to the moment when fire extinguishes. But after that fire strength starts to reduce and smoke takes major detrimental role for hazards to life.

B. *Three Coupe System in a Railway Locomotive Coach*

A typical non-air conditioned coach of Indian Railways contains nine coupes. However, comparison of numerical simulations of this system with a three coupe configuration shows no variation in terms of propagation of flame and smoke in first three coupes which are more critical for the fire breakout. Windows of all three coupes are considered open to observe flame and smoke release from them. Fire enters from the right of the domain. Results from numerical simulation show propagation of fire and smoke inside coupes with time. In Fig. 4 fire and smoke flow pattern in coupes at different time intervals are shown. Middle berths of all coupes are considered folded (not in use). As ambient conditions around provide sufficient oxygen initially, soot and fire propagate at same rate and enter the second coupe after 1 s. However due to absence of oxygen over time, soot propagates at faster rate than fire. Fire and smoke enter the second coupe through door and net. Due to constant volumetric flow but substantial reduction in entry area, the plume which had been traveling horizontally along the ceiling transcends downwards thereby randomizing the semicircular propagation along ceiling. Due to presence of net in non ac coaches which are given for ventilation purposes, fire propagates easily through them. In their absence fire would have less area to propagate and fire would have accumulated more in first coupe only. At t = 1.9 s fire crosses second coupe and enters in the last coupe. At t = 2.4 s smoke reaches the opposite wall of the fire initiation spot and flames take 2.6 s for the same and then start to fill the coupe by propagating in other directions. At 3.6 s, fire starts extinguishing due to lack of oxygen making the fire triangle incomplete and fabric and foam over the berths start to burn away. Also all of 3 coupes comes under the grab of fire and smoke after t = 3.6 s.

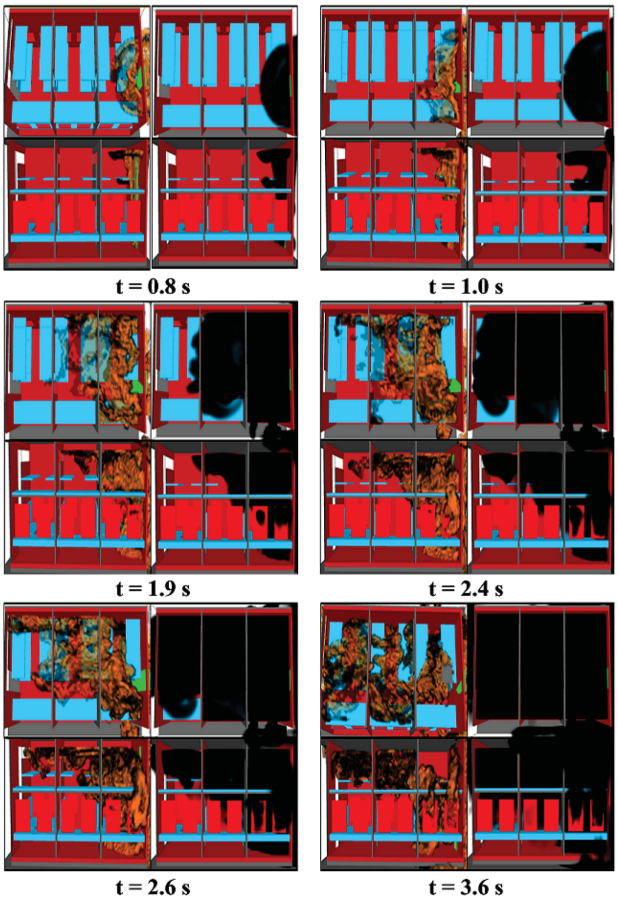

Fig. 4 Flame and soot propagation contour in three coupe domain

C. Variation in HRRPUA of Initialized Fire

In this case, effect of various HRRPUA is studied in three coupe domain. HRRPUA is used to control the burning rate of source. Even though there have been very little research available on passenger train fire, HRRPUA considered for this comparative study are 500, 1000 and 15000 kW/m^2 to visualize its effects on flame and soot propagation.

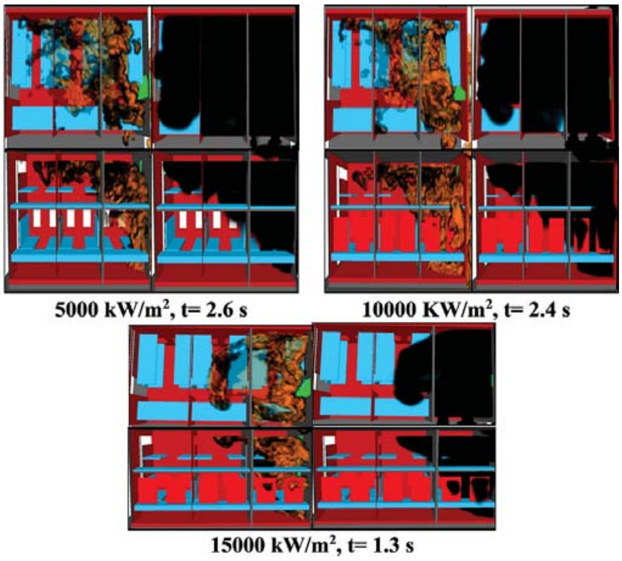

Fig. 5 Flame and soot pattern when smoke reaches the farthest corner

Train is considered stationary and there is no flow of air inside the train but windows are kept open and interacting with ambient condition. Since there is no entry of air inside the train, fire is extinguished in all three cases.

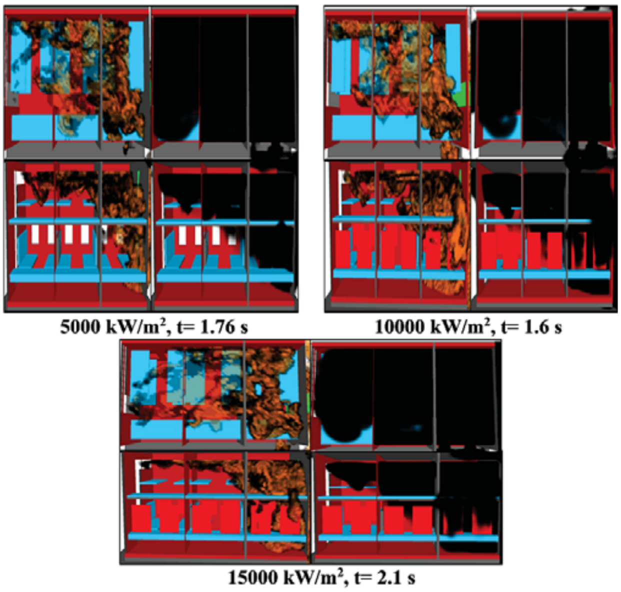

Fig. 6 Flame and soot pattern when flame reaches the farthest corner

Main causes of spread of fire are found to be the interior materials as seats, flooring and wood. Causalities occur mainly due to inhalation of toxic smoke and there is no adequate smoke control system. Comparing speed of flow of soot and flame propagation, at the end of 2.74 s, 2.6 s and 2.1 s fire reaches at the completion of the third coupe for 5000, 1000 and 15000 kW/m^2 respectively. Fig. 5 shows the snapshot of fire and smoke at timestamps where smoke reaches the farthest corner. Smoke took 2.6 s, 2.4 s and 2.1 s. to cross the third coupe for 500, 1000 and 15000 kW/m^2 respectively. Fig. 6 shows plan and elevation of fire and smoke when fire crosses the third coupe. Thus fire and soot propagate at faster rate at higher HRRPUA and thus results in more damage. Fire extinguishes at different times in different cases owing to the variation in the initial strength of fire. In case of 5000 kW/m^2, fire extinguishes after 4 s while it took only 3 s in case of 15000 kW/m^2. Seats of upper berth starts burning into ash in the first coupe at the onset of 2.6 s in case of 5000 and 10000 kW/m^2. In case of 15000 kW/m^2 combustion starts after 2 s only.

D. Variation in Magnitude of Inlet Air Velocity through Windows

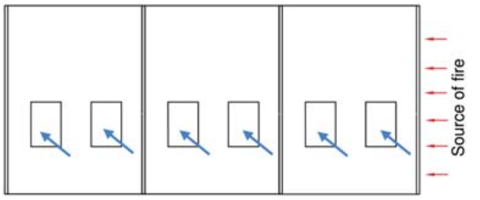

Fig. 7 Entry of air through windows along the direction of fire

Changes in fire and soot propagation with velocity of air through the windows in three non AC coupes of Indian Railways are observed. Magnitude of velocity considered for this study are (a) 0 km/h (b) 60 km/h (c) 80 km/h and (d) 100 km/h.

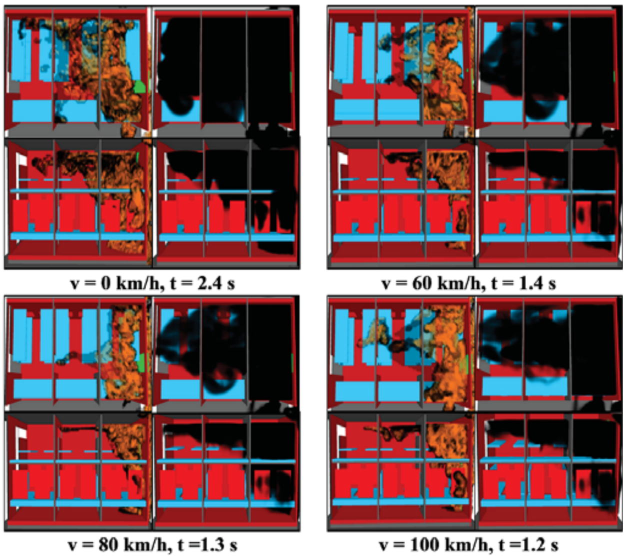

Fig. 8 Flame and smoke pattern when smoke reaches farthest corner

Direction of velocity is kept constant at 45 degrees inwards and along the direction of fire with the wall. Fig. 7 shows relative direction of entry of air through the windows. Since windows are open and air flux is pushed through all windows, providing sufficient oxygen for fire and soot to propagate. Thus, proper combustion takes place. In case of 0 km/h. fire extinguishes after 4.2 s due to unavailability of sufficient oxygen which is not true for other cases where sufficient oxygen is available due to air influx. Comparing timing of soot when it crosses last coupe for rate of soot propagation is shown in Fig. 8. Fire and smoke propagates at same rate till the end of first coupe for all velocities.

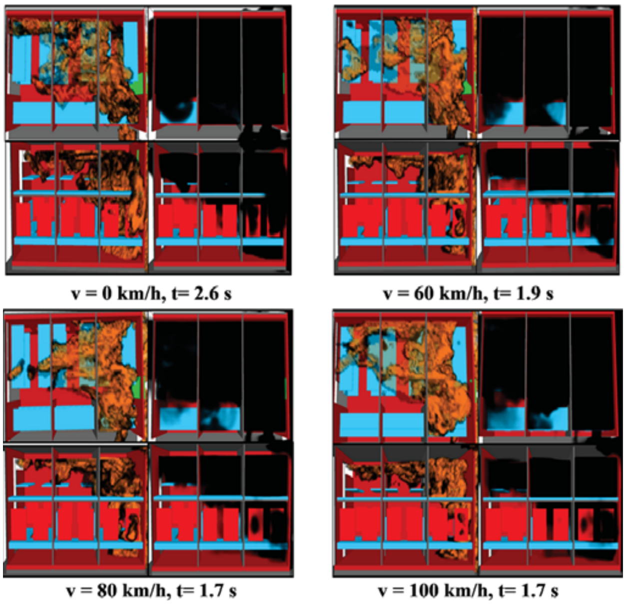

Fig. 9 Flame and smoke pattern when flame reaches farthest corner

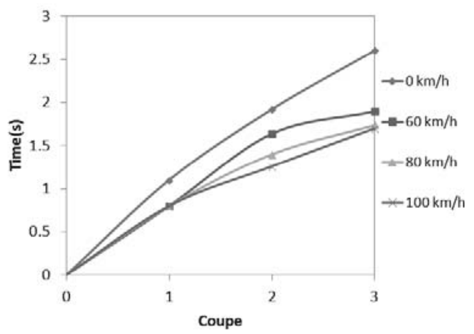

Fig. 10 Time required for fire to cross coupes at different velocities

Smoke crosses last coupe in 1.9 s, 1.4 s, 1.3 s and 1.2 s for 0, 60, 80, 100 km/h and fire took 2.6 s, 1.9 s, 1.7 s and 1.7 s for the same which is shown in Fig. 9. This phenomenon is observed due to increase in formation rate of soot and propagation of fire due to air velocity. Propagation rate of fire and smoke increase as magnitude of velocity of air increases in the direction of fire. Combustion rate of berths is faster in case of higher velocity. In case of 0 km/h seats of upper berth starts burning at around 2.7 s while it took only 2.05 s in case of 60 km/h. As magnitude of velocity increases more fire is generated and creates more damage. For ex: in case of 60 km/h, it took only 6 s to burn both upper berth of first coupe and only 4.5 s in case of 100 km/h. Flame color is more yellow and dark as magnitude of velocity increases. In case of 0 km/h flame is observed to have some black color as well, due to incomplete combustion in absence of air. Figs. 10 and 11 compares rate of flame and soot propagation which shows time comparison to cross coupes in case of different velocities.

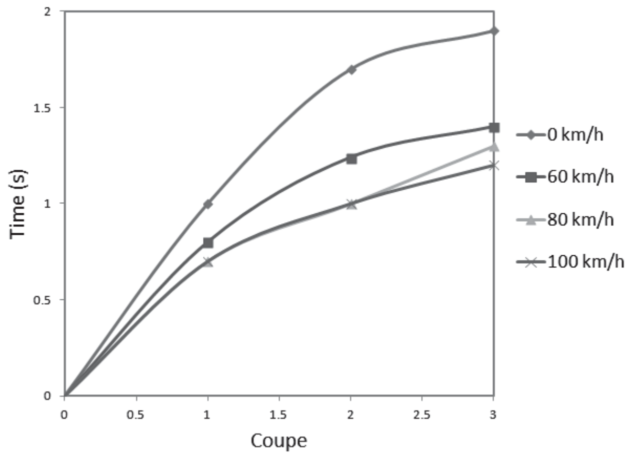

Fig. 11 Time required for flame to cross coupes at different velocities

E. Variation in Direction of Inlet Air Velocity through Windows

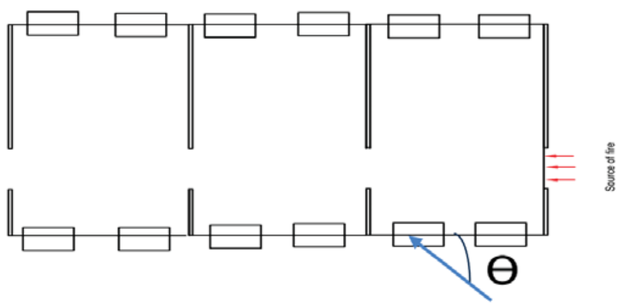

Fig. 12 Domain description with direction of inlet air through windows

In this case, the effect of velocity angle of inlet air (Θ) with the wall through the windows on fire and soot propagation is studied. In this case magnitude of velocity is kept constant at 80 km/h. Angles considered are (a) 20 (b) 45 (c) 50 (d) 60 degrees inwards and in direction of fire. Fig. 12 shows relative direction of entry of air through windows inside the domain. All windows are open and air is allowed to enter, providing sufficient oxygen for fire and soot to propagate. Velocity of air has two components: inwards and along the direction of fire propagation. The component inwards provide air for combustion and component along the direction of fire increase the rate of propagation.

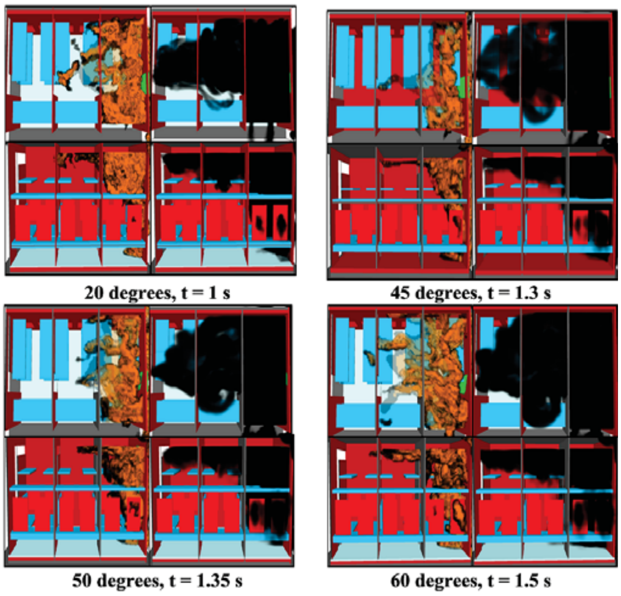

Fig. 13 Flame and smoke pattern when smoke reaches farthest corner

As angle increases inward component increases and the one along the direction of fire decreases. Since magnitude of velocity along the flame propagation decreases with increase in angle, rate of flame and soot propagation also decreases. This can also be analyzed by comparing the time it took for flame and smoke to reach the farthest corner in each case which is shown in Figs. 13 and 14 respectively.

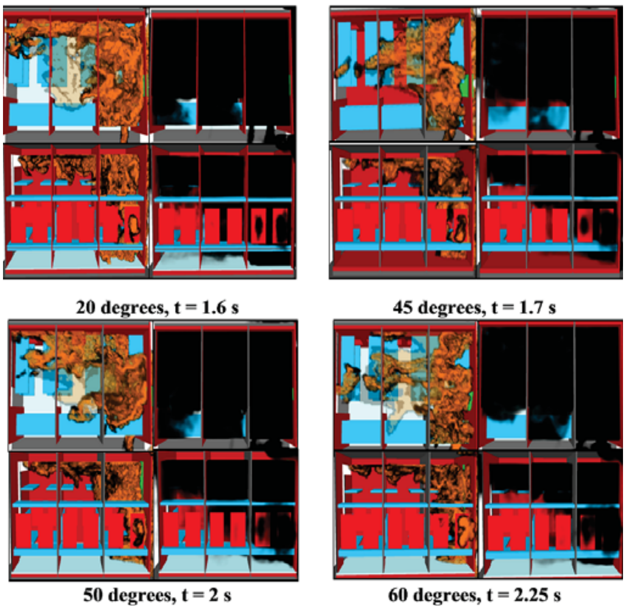

Fig. 14 Flame and smoke pattern when flame reaches farthest corner

Soot crosses last coupe in 1 s, 1.15 s, 1.3 s and 1.5 s for 20, 30, 45 and 60 degrees respectively and fire took 1.6 s, 1.73 s, 2 s and 2.25 s for the same. This phenomenon is observed mainly due to decrease in magnitude of velocity in direction of fire as angle increases. As magnitude of velocity inwards the coupe increases with increase in angle up to 90 degrees, it took more time for fire and soot to come out of windows and accumulated more in between. Table II shows the time instance at which flame and smoke reaches the farthest corner.

TABLE II
TIME WHEN FLAME AND SMOKE REACHES FARTHEST CORNER FOR DIFFERENT ANGLES

Angle in degrees	Time (s) when smoke reaches farthest corner	Time(s) when flame reaches farthest corner
20	1	1.6
30	1.3	1.7
45	1.35	2
60	1.5	2.25

F. Effect of Level of Interaction of Coupes with Ambiance

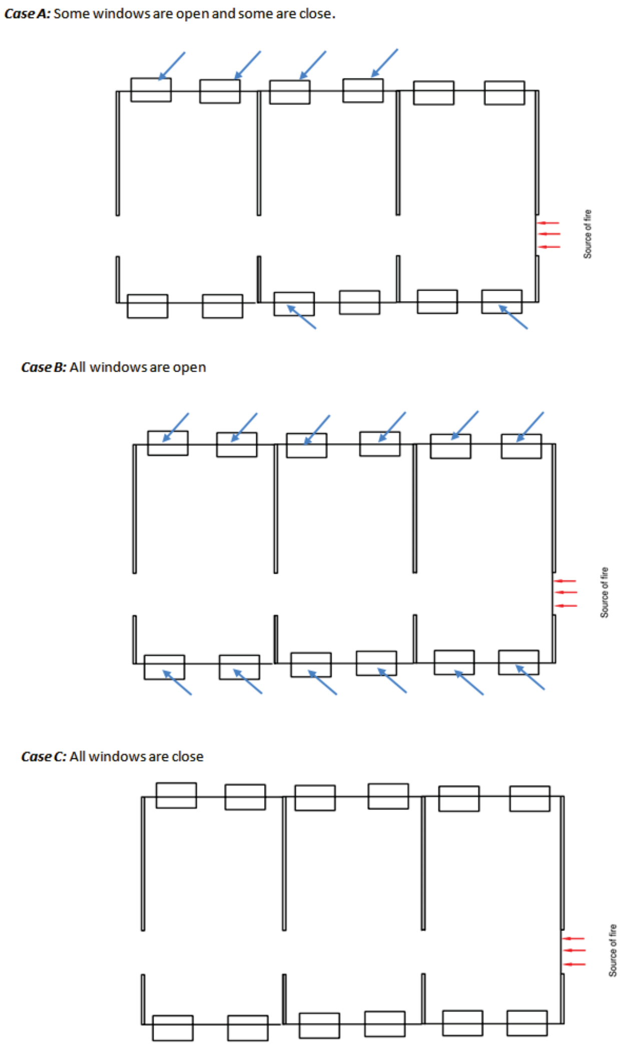

Fig. 15 Top view of domain showing interaction with ambiance in three cases

In this case, the soot and fire propagation inside the coupe are compared with the changing level of interaction of coupe and ambiance. For this study three cases are compared, in case (a) some of the windows are opened and some are closed, in

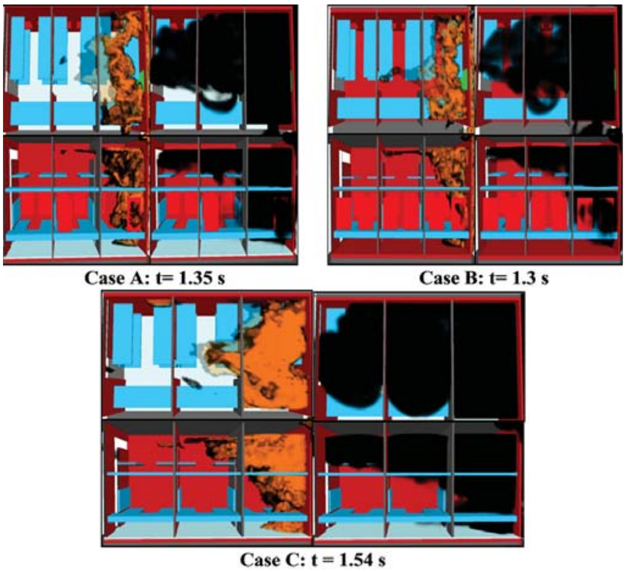

Fig. 16 Flame and smoke pattern when smoke reaches farthest corner

case (b) all the windows are opened and in case (c) all the windows are closed. Windows that are open have air influx at 80 km/h at an angle of 45 degrees with the wall. Fig. 15 depicts all three cases. Arrows in the figure shows the inlet of air through those windows, otherwise they are closed.

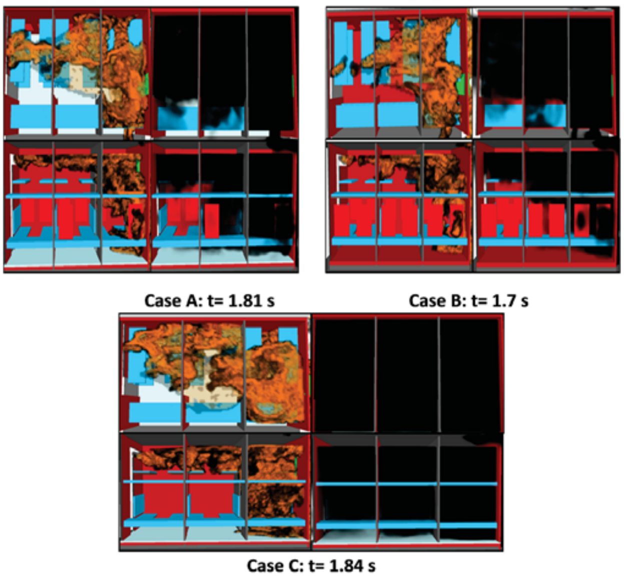

Fig. 17 Flame and smoke pattern when flame reaches farthest corner

In case (a) when some windows are open and in case (b) when all are open, oxygen requirement for combustion is met by fresh air entering the coupe through windows whereas in case (c) all the windows are close and no air is allowed to enter. As no fresh oxygen is available, the fire dies off at 3 s whereas in the other case as lot of oxygen is available in the first coupe resulting in an active flame. Variations of flame color can be understood by the above fact too. Accordingly soot formation is more in case (c) than in case (b) and case (a). Comparing timings of soot and flame propagation in all cases it is found that that the soot reaches the farthest corner in 1.35 s, 1.3 s and 1.54 s for case a, b and c respectively. Flame and soot pattern when smoke reaches the farthest corner is shown in Fig. 16. Fire took 1.81 s, 1.7 s and 1.84 s for crossing last coupe. This is depicted in Fig. 17. Thus windows can be closed in trains in order to control the rate of fire propagation but that can cause suffocation for passengers due to unavailability of oxygen. Turning into ash of combustible materials as seats of berth in the first coupe starts at the onset of 2.3 s, 2.5 s and 2.1 s for case a, b and c respectively. Rate of combustion is higher when air is allowed to enter in coupe providing enough oxygen for fire to propagate.

G. Effect of Opening of Middle Berth

In this case, Middle berth is opened which is closed till now in all above cases. During daytime, middle berths are considered folded and during night they are unfolded as people are sleeping over them. Velocity of air through the windows in three non AC coupes are considered to be 80 km/h. Direction is kept at 45 degrees inwards and along the direction of fire with the wall. As windows are open and air is allowed to enter, providing sufficient oxygen for fire and soot to propagate. Fire crosses last coupe in 1.7 s and 1.73 s for unfolded and folded respectively. Soot took 1.3 s and 1.2 s for the same. Not much considerable change in fire propagation is observed in two cases.

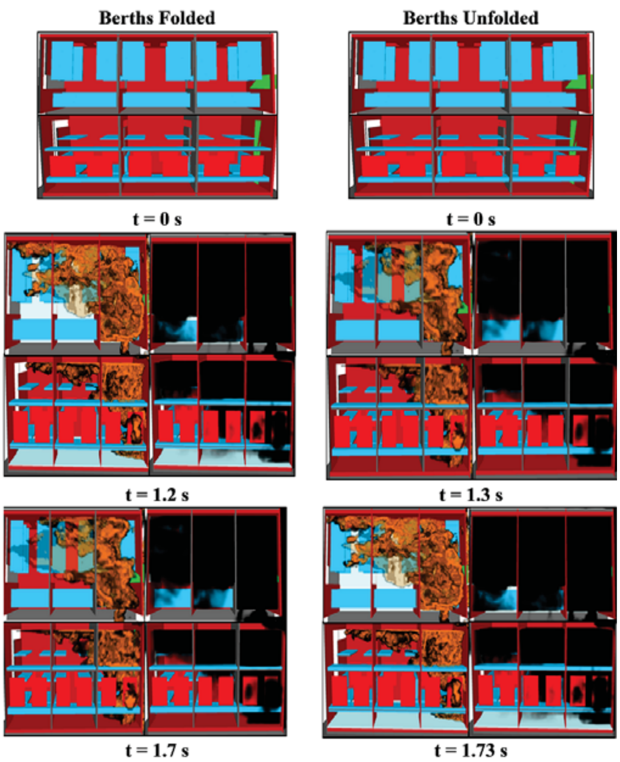

Fig. 18 Flame and soot pattern when fire is initiated, reaches the halfway and then crosses the last coupe.

H. Quantitative Analysis

In order to quantify results of fire and soot propagation, fractional area of top and front view surrounded by fire and smoke is plotted with respect to time. It is done using MATLAB Image Processing Toolkit (IPT).

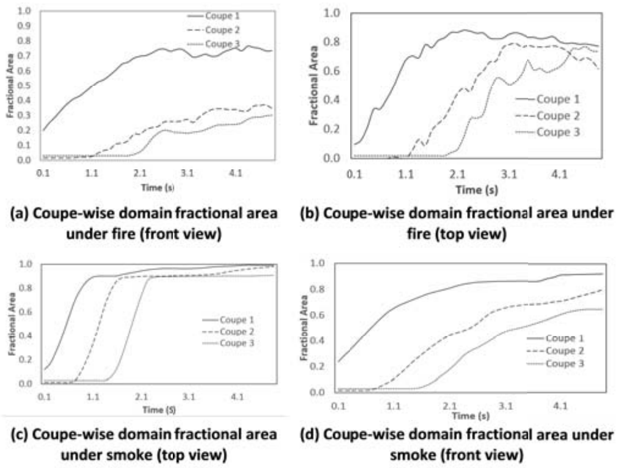

Fig. 19 Coupe-wise domain fractional area versus time.

Analysis of fraction of area under fire and smoke of individual coupes in a three coupe domain is done and represented in Fig. 19. Fire enters the domain through entry in coupe 1 and then propagates to the second and third coupes. Maximas of area under fire in both the views is seen accordingly.

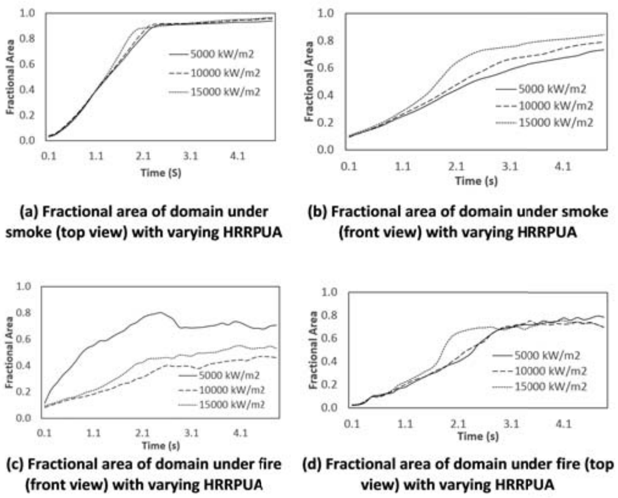

Fig. 20 Fractional area of domain versus time with varying HRRPUA .

Fractional area under fire and smoke increases up to extinguishing of fire. Front view and top view of fire saturates at around 0.8 for coupe 1. However fractional area of top view under fire reaches at 0.7 for coupe 2 and coupe 3 but only 0.3 in front view due to ceiling jet effect. However due to insufficient ventilation soot concentration increases rapidly and completely fills the domain at 5 s. Soot concentration remains almost same due to unavailability of fresh air. HRRPUA of initiation fire is varied to study its effect on fire and soot propagation. The variations studied are with HRRPUA values of 5000 kW/m^2, 10000 kW/m^2 and 15000 kW/m^2. Both flame and some propagate at higher rate with increase in HRRPUA. In a confined space, with high HRRPUA flame concentration increases, represented by the least time taken to fill the domain. Analysis of fractional area under fire and smoke with varying HRRPUA in a three coupe domain is shown in Fig. 20.

IV. Conclusion

Fire propagation and smoke flow patterns in non air conditioned compartment of railway locomotive is studied through numerical simulations using FDS. Numerical simulation is carried out for single coupe and three coupe system, which is considered as fundamental unit for further studies, with variations in HRRPUA of initiation fire, inlet velocity through windows, level of interaction with ambiance and closure of middle berth. Rate of propagation and properties of flame highly depends on these variations. Main reason of rapid fire spread is due to combustibles like seats, plywood, etc.

It is observed that flame and smoke increases with time up until it gets extinguished but after that smoke takes major detrimental role for hazards in life. With increase in heat release rate per unit volume, fire and soot propagates faster and creates more damage. As windows are open and inlet air is provided with velocity, evacuation time decreases with increase in magnitude of velocity along the direction of fire propagation. Coupes inside the domain interact with ambient through windows. Rate of combustion is higher when windows are open and air is allowed to enter in coupe providing enough oxygen for fire to propagate. Appropriate fire control systems and exhaust systems should be provided to control suffocation and temperature.

Appendix

A. Numerical Model

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

The simulations are done on an open source Computational Fluid Dynamics (CFD) solver, FDS developed by the National Institute of Standards and Technology (NIST), US. It is a large-eddy simulation (LES) code for low Mach thermally driven flows, with an emphasis on smoke and heat transport from fires. Equation 1 contains the continuity equation solved in FDS. Here, $\dot{m}_b^{'''}$ is the source term for addition of mass that are considered to occupy no volume and are generated from the evaporating droplets and other.

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

Domain consists of different materials with properties varying during the entire process of combustion. FDS uses the lumped species approach to tackle this. Products formed and air are considered as lumped species. Equation (2) is momentum conservation equation used in FDS where F represents the net force per unit mass, including body and surface forces ($H = \frac{|\vec{u}|^2}{2} + \frac{\tilde{p}}{\rho}$) represents the net stagnation energy per unit mass. Equations (3) and (4) represent energy conservation equation and equation of state respectively.

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

$$\overline{P} = \frac{\rho R T}{\overline{W}} \quad (4)$$

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.The partial derivatives in the equations for the mass, energy and momentum are approximated by finite differences and the solution is updated in time on a three-dimensional, rectilinear grid [11].

B. Grid Independence Study

Working domain simulated in FDS consist of cuboid shaped grids. The approximate cell size (δx), the characteristic diameter (D^*) of fire can be calculated using (5).

$$D^* = \left[\frac{\dot{Q}}{\rho_{\inf} C_p T_{\inf} \sqrt{g}}\right]^{\frac{2}{5}} \quad (5)$$

For reliable results, the value of $\frac{D^*}{\delta x}$ should lie between 4 and 16 [12]. Mesh size considered in this study is 6 cm. Therefore, grid independence study is carried out to justify the grid size and show that results obtained is independent of grid size. The formula gives very non conservative prediction and in this case HRR($\dot{Q}$) is time dependent. Study is started with fine mesh size. Mesh size is varied from 0.03 m to 0.15 m. Plots of heat release rate with time for domains with various representative cell size of 0.03 m, 0.04 m, 0.05 m, 0.06 m and 0.12 m is given in Fig. 21. It is observed that the average difference between the values of heat release rates for grids with cell sizes of 0.03 m and 0.06 m is 4.2% whereas the difference is 15.3% for grids with cell sizes of 0.12 m and 0.06 m. Thus grid size of 0.06 m seems more effective for further simulation and studies.

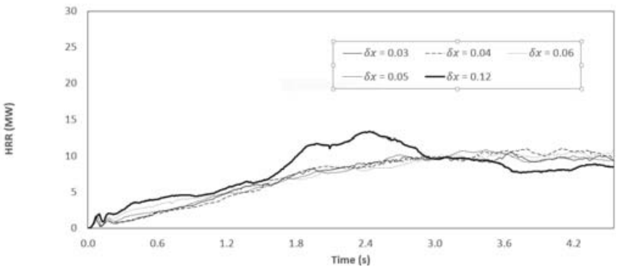

Fig. 21 Comparison of Grids using HRR

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