Simulation of Fire Dynamics and Firefighting System for a Full-Scale Passenger Rolling Stock

Ramy E. Shaltout and Mohamed A. Ismail

Abstract The secure travel and the safety of passengers are the utmost priority for transportation authorities all over the world. The fire safety in railway rolling stocks has gained significant importance in recent years. The study of fire dynamics including the fire growth and spreading, allows the development of fire protection techniques and passenger evacuation scenarios. Understanding fire development in train carriages is limited as few experimental investigations have been conducted on full-scale fire dynamic measurements of entire passenger coaches. This paper represents a comprehensive account of the computational fluid dynamics model used for the simulation of the fire dynamics in full scale rolling stock vehicle. Full-scale heat release rate (HRR) measurements were carried out for the entire vehicle as well as temperature distribution for various fire compartment scenarios. The model was tested and the simulation results were verified against those presented in experimental research developments in the literature.

1 Introduction

Fire dynamics simulations are important because of their influence on the assessment of the thermal effects and threats on the design of evacuation procedures and plans, structural damage, and eventually the design of fire protection systems. Investigating fire development inside a rail vehicle aims to reduce the risk to passengers inside the vehicle as well as the users of the infrastructure. It permits the prediction of smoke

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and toxic hazards that might disturb the evacuation process of the passengers and the vehicle crew (GM/GN 2630 2013).

Numerical simulations using computational fluid dynamics (CFD) techniques have been used for the prediction of fire developments in train carriages (Zhang et al. 2017; Guillaume et al. 2014). The use of numerical simulation techniques in modelling fire development is a complex interdisciplinary topic. CFD models can be used in scenarios validated by experimental results or in qualitative studies (Guillaume et al. 2014; Li and Ingason 2016). However, by increasing the complexity in the railway tunnel and train designs, the use of CFD simulation is increased to predict the fire growth and smoke hazards for different simulation scenarios. Chiam (2005), presented a CFD model for predicting the HRR peak value for emergency tunnel ventilation systems. Chaim extended his study to include 13 fire scenarios using Fire Dynamics Simulator (FDS) to simulate the smoke spread and fire growth for a metro carriage in an underground subway tunnel. It was concluded that there is a significant need to enhance the modelling and simulation procedures used for the prediction of fire hazards for passenger trains, especially for scenarios where the carriage had stalled in a subway tunnel. Full-scale experimental studies were recommended by Chaim to validate the obtained simulation results.

Few experimental research activities have been conducted for investigating full-scale fire dynamic measurements of an entire passenger coach. This shortage in experimental investigations, has a significant impact on studying fire developments in train carriages and its impact on the vehicles' sustainability and reliability (Matsika 2018). The limitations in experimental research in such a field has influenced the understanding of fire behaviour, the economic impact, and implications for vehicle safety in terms of both manufacturing and material testing costs. It is worth mentioning that a number of tests were carried out in RSSB commissioned research projects such as T843 and T1012 (Tooley 2011; Rail Safety and Standards Board Ltd. 2014), for testing of the main elements of rolling stock interiors compared to both the British and European testing rules. These projects explored the weaknesses and strengths of the new standard EN45545 and identify the influence of the British industry in shifting from British standards such as RGS GM/RT2130 and BS 6853 (BS 6853 1999; GM/RT2130 2010).

An experimental study was carried out by White (White 2010), to investigate and analyse fire development in Australian metropolitan passenger trains. To estimate the Heat Release Rate (HRR) for a full-scale passenger train, the conservation of energy model was used based on experimental observation and measurements. The research also evaluated the existing methods used for fire estimations applied to passenger rolling stocks. Li et al. (Li et al. 2014; Li and Ingason 2016), experimentally investigated fire development in three series of train carriages. The fire tests were carried out for train carriages including a 1:10 model, a 1:3 model and a 1:1 full scale tunnel test. It was noticed that fire development was similar for the three test models. The HRR was also investigated for the three models of the train carriages. It was observed that the maximum HRR is dependent on the type of fuel, the train carriage configuration, material characteristics and the ventilation conditions. An overview

of the experimental tests carried out on a full-scale passenger trains was presented by Li, Y. Z see (Li and Ingason 2016).

Fire performance characteristics of passenger train materials were investigated by Peacock et al. (2001). A cone Calorimeter tests were used to predict the smoke and HRR characteristics for the materials used in US passenger cars including the seats and interior panels. Afterwards, a full-scale test was carried out in a complete train car incorporating the tested components. The final results have been used in the fire safety requirements as well as providing a profitable way for designers and car builders to evaluate materials used in manufacturing passenger rail cars.

A comprehensive investigation of the dynamics of design fire in trains was presented in Hjohlman et al. (2009). A full-scale test was carried out on a complete passenger rail car to investigate the flashover design fire and its influence on the vehicle materials and design. Small scale tests were performed for the vehicle materials. The results of these tests were used as an input for the Fire dynamics Simulator (FDS) software. This was used to investigate the design fire for the tested sections. These do not vary greatly from the tested configuration for material selection and vehicle geometry. A good correlation was obtained between the simulation results using FDS and the full-scale experiment. It was noted that the results obtained from FDS model was significantly affected by the grid size.

The importance of designing fire protection systems and firefighting solutions has greatly increased for both existing and newly designed trains. Due to the safety measures presented by safety standard boards around the world and the European TSI (TSI LOC&PAS 2014), it is necessary to install, test and analyze the performance of fire protection systems. To compensate for the lack of existing standards and guidelines concerning the fire safety in passenger vehicles, a series of guidelines (ARGE) (ARGE Guideline 2012a, b, c) was introduced to evaluate the system performance and to define the necessary measures for the firefighting systems.

The main objective of the presented work in this paper, is to study the development of fire dynamics in passenger trains in order to establish an efficient fire protection system for such important assets. A methodology was proposed in this research that incorporates a series of sprinklers distributed through the vehicle ceiling. 83% reduction in HRR was achieved when using water-spray with the fire, which gives more time to allow passengers safe evacuation.

2 Proposed Methodology

The computational models presented in this paper were built in the Fire Dynamic Simulation (FDS) package. Existing three different models used to simulate the solid fuel burning in the FDS software. The user should define the type of models used in the analysis according to the input parameters including the ignition source, material characteristics and the fire load. The first model used in the analysis is (HRRPUA). It simulates a gas burner with a determined Heat Release Rate Per Unite Area. The use of HRRPUA in FDS was validated by comparing the results with experimental tests

(Li et al. 2014; Ma and Quintiere 2003). The second model is the simple ignition model. In this model, when the material surface temperature reaches the ignition temperature then the ignition temperature is assigned to a combustible material. The third model is the Kinetic pyrolysis model (Li et al. 2014). In this model, the reaction is described by means of the kinetic parameters defined for the combustion of each material. The simple ignition model and the kinetic pyrolysis model are still under development and needs more verifications in case they are used to predict the fire development in different scenarios (Li et al. 2014). In this paper, HRRPUA is used in the analysis. The prescribed fire is defined throughout burning wood cribs in the right corner of the vehicle.

3   Computational Model Description

Modelling and simulation of fire development in train carriages can be used as a suitable alternative option for making possible design changes as well as investigating all parameters that could influence the fire dynamic behaviour. Small scale laboratory tests have been used by many authors as an input data to the CFD computational tools to model the fire development in passenger rolling stocks (White 2010; Li et al. 2014; Li and Ingason 2016; Lönnermark et al. 2017). These tests included for example, the Cone Calorimeter and Thermo-Gravimetric Analysis (TGA) tests. In this paper, Fire Dynamic Simulation (FDS) software has been used in modelling the fire development and smoke spread for a 1/3 train mock-up model and for a full-scale carriage respectively.

FDS software (McGrattan et al. 2013, 2015), is still widely used for simulating the design fire in train compartments which do not vary considerably from the tested configurations. The simplifications and assumptions in the FDS model are in the input parameters, especially for the combustion model and the combustible glazing and materials, which might lead to a lake of realistic design fires prediction (Guillaume et al. 2014; White 2010; Li and Ingason 2016). The obtained results from the FDS model built in this paper for the 1/3 train carriage, were compared to those obtained by Lönnermark et al. (2017), for the validation purposes of the model and the methodology used in the analysis. The model is then extended to include a full scale carriage.

3.1   Geometry Description

3.1.1   1/3 Train Carriage Mock-up

The preliminary analysis in this paper was carried out based on a model described by Lönnermark et al. (2017). A model with 6 m × 3 m × 2.4 m (L × W × H) dimension was defined for a 1/3 train carriage as shown by Fig. 1. To simulate the
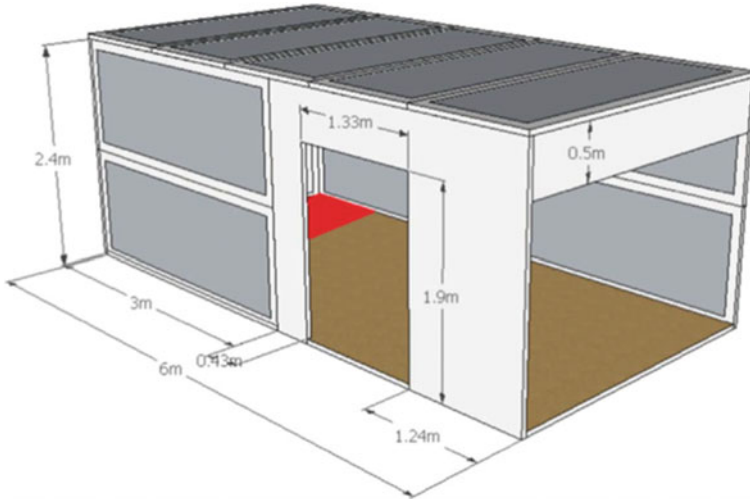
Fig. 1 1/3 train mock-up used in the experiment (Lönnermark et al. 2017)

smoke layer in the carriage, an edge was created with a height of 0.5 m. The fire source was placed at the corner of the model. The inner layers of the carriage ceiling, walls and linings were initially covered by noncombustible boards (Promatect H). For more details see (Lönnermark et al. 2017).

3.1.2 Full-Scale Train Carriage

In this paper, fire development in a full train carriage was investigated. The dimensions of the entire train carriage were 18 m × 3 m × 2.4 m in x-, y-, and z- direction respectively. The governing equations were approximated on a three-dimensional mesh with cubic elements (Fig. 2).

3.2 CFD Model and Parameters

3.2.1 1/3 Train Carriage Mock-up

K-type thermocouples have been used for the gas temperature measurements using 0.5 mm welded junction. In some positions, an 0.25 mm K-type thermocouple was placed to estimate the effect of radiation on the temperature measurement. The locations of the thermocouple are shown in Fig. 5. Thermocouples were located at different heights from vehicle ceilings. Some of them were placed 0.29 m below the ceiling while two others were sited at 0.05 m below the ceiling. A thermocouple tree was

placed in at various heights from the ceiling to determine the vertical temperature variation above the ignition source position (Fig. 3).

3.2.2 Full Scale Train Carriage

The total number of cells of the computational model of three dimensions was about 129,600 cells. A computational mesh of $180 \times 30 \times 24$ was used along the length, width, and height of the carriage. Mesh dependency test was carried out to identify the optimum grid size for the proposed computational domain. The cell size was selected based on the non- dimensional quantity $(D^*/\partial x)$ that defined the optimal number of computational cells spanning the characteristic fire diameter. Thus, the
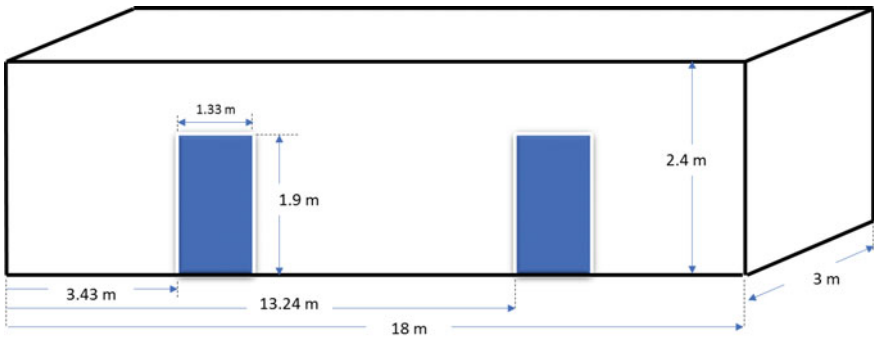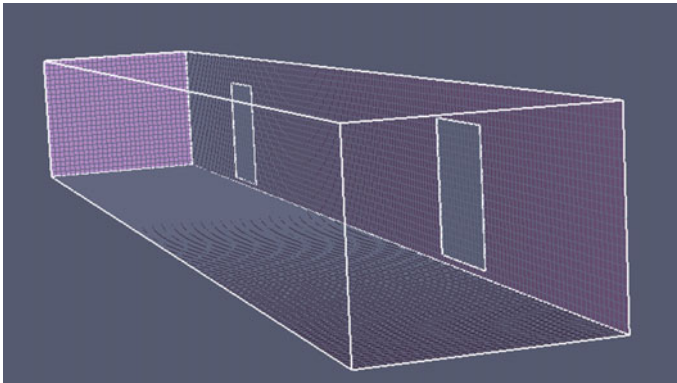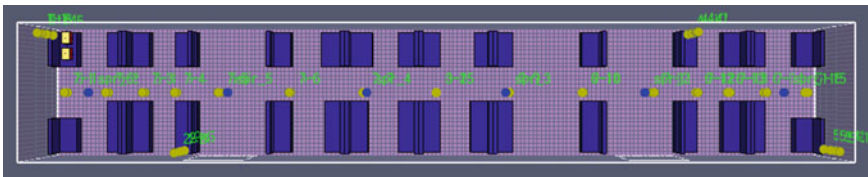

Fig. 2 Schematic diagram of the full train carriage used in the simulation

Fig. 3 Thermocouples distribution for FDS model of the 1/3 train carriage mock-up

Fig. 4 Computational model of full-scale carriage

Fig. 5 Thermocouples distribution along the full-scale train carriage

computational cells were almost cubic with dimensions of $0.1 \times 0.1 \times 0.1$ m³ as shown by Fig. 4.

Following the same procedure followed in the mock-up model, thermocouples were distributed along the full-scale carriage.

To determine the temperature distribution in the full-scale train carriage, 25 thermocouples were distributed according to the dimensions given in Table 1. 5 thermocouples trees were defined in the model. Each tree contains 5 thermocouples numbered as shown by Table 1 (Fig. 5).

Table 1 Thermocouple trees position and distribution along the full-scale carriage model	Thermocouples tree #	Thermocouple	Thermocouple tree position	
			X	Y
	1	T_{1-1}:T_{1-5}	0.3	2.7
	2	T_{2-1}:T_{2-5}	3.2	0.3
	3	T_{3-1}:T_{3-5}	9	1.5
	4	T_{4-1}:T_{4-5}	14.8	0.7
	5	T_{5-1}:T_{5-5}	17.3	0.3

In addition to the thermocouple trees defined in Table 1, a thermocouple tree contains 15 K-type thermocouple T_{6-1}:T_{6-15} was installed at the horizontal plane along the full train at a height of 0.5 m from the ceiling. This tree provides a temperature distribution for the smoke layer in the carriage. Another thermocouple tree T_{7-1}:T_{7-15} was fitted on a height of 0.29 below the carriage ceiling. A summary of the simulation parameters are included in Table 2.

4   Simulation Results

The simulation results are presented in the following section. A comparison has been made between the experimental results of the carriage mock-up presented by Lönnermark et al. 2017) and those obtained by the developed simulation model in this paper. The main objective of the comparison is to validate the computational model and the applied fire development criteria proposed in this paper. Subsequently, simulation results of a full-scale train carriage will be presented. Various fire development scenarios were also investigated. The HRRPUA used in the analysis of the full car varied from 400 to 8800 [kW/m^2] to simulate several fire ignition setups. Finally, simulation results of a 1/3 train mock-up model and full-scale train model incorporating a series of sprinklers, as a firefighting mechanism, were illustrated. A fire source in the corner of the vehicle was proposed with various heat release rates per unit area (HRRPUA) varying from 400 to 8,800 kW/m^2. The lower limit simulates a small fire source, while the upper limit of the HRRPUA simulates a very big fire source or terroristic attack. At this case, the total HRR reached 11,800 kW after 70 s and the maximum temperature reached to 1300 °C after 40 s. The design of the water-spray firefighting system was proposed in the presented paper. It was found that the maximum HRR reduces from 11,800 to 2000 kW (83% reduction) when using water spray with the fire and it was delayed 30 s more, which gives more time to allow passengers evacuation.

4.1   Test Characteristics

The experimental work presented in Lönnermark et al. (2017) included a total number of six tests. Three tests were selected for the validation purposes of the obtained results from the developed computational model in this paper. In Table 3, the maximum heat release rate and time to maximum for each of the selected tests are used in the comparison.

As it can be noticed in from the simulation results, the time to reach the maximum HRR in the simulation is quite similar to the time obtained from the experimental tests with a permissible computational variation.

Table 2 Simulation parameters for the 1/3rd train mock-up model and the complete carriage model

Model	Model dimension (L × W × H) m	Fire load	Fire source location	Variation of maximum HRRPA	Thermometer number-type	Simulation scenarios
1/3 train mock-up	6 × 3 × 2.4	Wood cribs	Left corner	360–3500 kW/m²	14 K-type	Without sprinklers
						With sprinklers
Full train carriage	18 × 3 × 2.4	– Wood cribs – Small bag	Left corner	400–8800 kW/m²	25 K-type	Without sprinklers
						With sprinklers

4.2 Mock-up Model Simulation Results

In this section, the simulation results for the 1/3 mock-up carriage is compared to the experimental data for the model validation. Three tests were compared but only test#1 (Lönnermark et al. 2017) will be discussed here. As shown in Fig. 6, the heat release rate peak for both simulation and experimental cases are identical. The heat release rate reaches a maximum of 355 kW after a time of 6:01 min for the simulation results. This was compared to the experimental data which has a maximum heat release rate of 360 kW after 6:12 min as shown in Table 3. The error in the maximum heat release rate between the simulation results and the experimental data was found to be 1.4% which is acceptable for model validation (Anderson and Wendt 1995). This small error might come from not accounting for all the actual materials of seats used in the real test. To get an overview of the quantity of the carriage material burned, the mass loss rate is plotted against the heat release rate for Test#1 as shown in Fig. 7. It is clear from that figure that mass loss rate is following the same trend as the heat release rate curve. The mass loss rate reaches a maximum of 0.92 kg/s at time of 6:00 min which is slightly before the maximum heat release rate. These phenomena are common in natural fires because mass is lost first in a fire followed by heat release (Drysdale 2011).

The temperature along the vertical plane directly above the fire source was measured by thermocouple tree#1, which contains 5 thermocouples. T_{1-1} is the nearest to the fire source and T_{1-5} is the furthest from the fire source and nearest to the ceiling. As illustrated in Fig. 8, all the thermocouples have the same trend which have peaks after 6:00 min from starting fire. This delay in temperature peaks comes from the time needed to get maximum heat release rate and transfer of this heat by diffusion and radiation. The maximum temperature decreases in the upward direction and going further from the fire source. Temperatures in tree#1 varies from T_{1-1} = 610 °C to T_{1-5} = 279 °C. At the time of maximum heat release rate (6:01 min), the temperature varies horizontally away from the fire source. At a height of 0.29 m below the ceiling, the temperature varies from 264 °C at 0.7 m horizontally from the fire source to 173 °C at the end of the carriage mock-up. It should be noted here that during test#1 no flashover occurs, and the fire does not move to the seat facing the fire source.

Test #	Maximum HRR (kW)		Time to max. HRR (min)	
	Exp.	Sim.	Exp.	Sim.
1	360	365	6:12	6:04
3	640	590	5:30	5:20
6	3500	3450	7:00	7:10

Table 3 Maximum HRR and time to reach it for simulation tests versus their corresponding experimental data from Lönnermark et al. (2017)
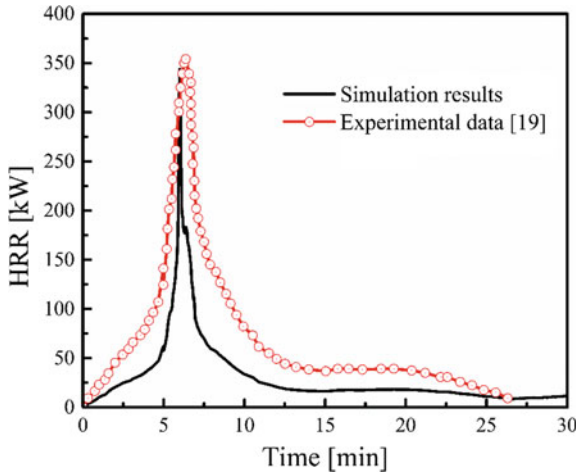
Fig. 6 Comparison between the obtained HRR from the FDS simulation results of and the experimental results for test #1 documented in Lönnermark et al. (2017)
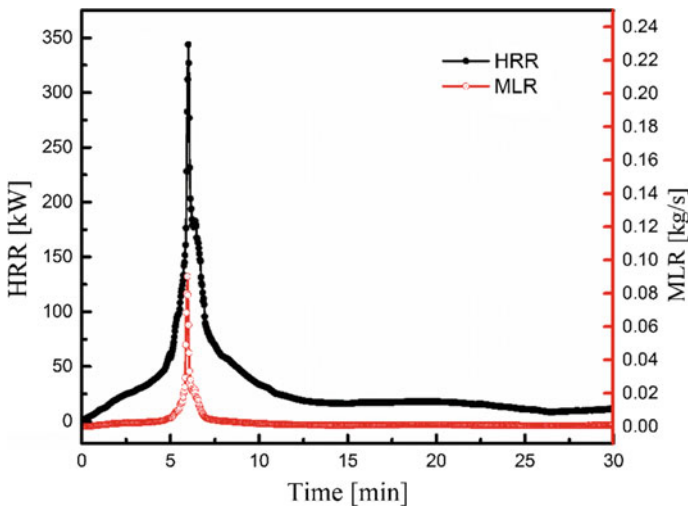

Fig. 7 Simulation results of heat release rate (HRR) and mass loss rate (MLR) for test#1
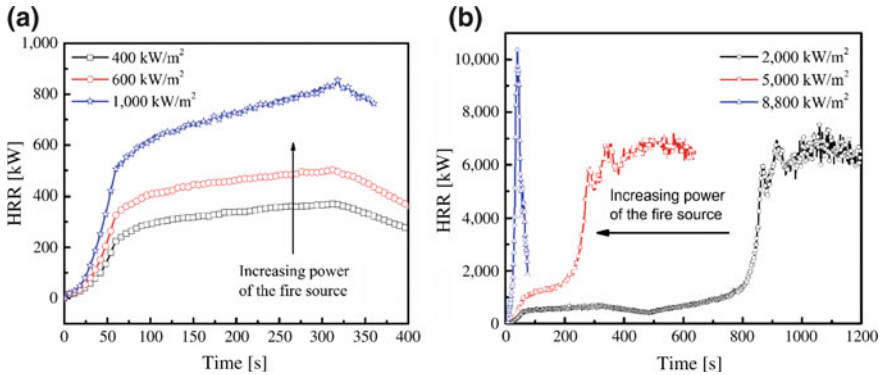
4.3 Full-Scale Carriage Simulation Results

After verification of the model against the 1/3 carriage mock-up, the model was expanded to include the full-scale carriage as shown in Fig. 5. In this section, the fire source with various heat release rate per unit area (HRRPUA) will be used. The position of the fire source is fixed at the left corner of the carriage above the seat that lies under the thermocouple tree #1, Fig. 5. The fire source will vary from

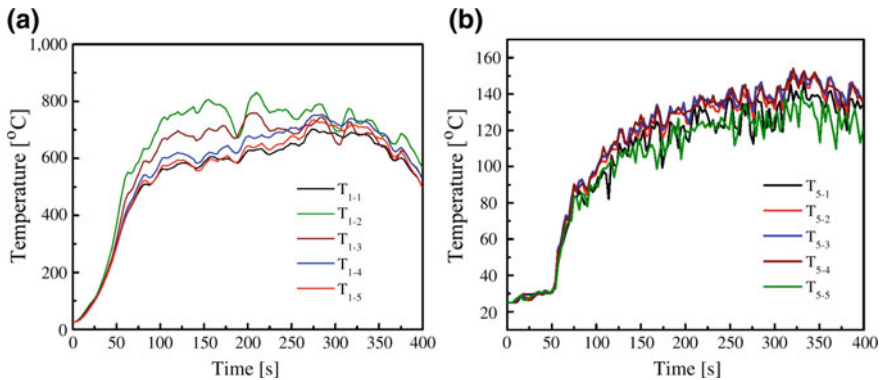**Fig. 8** Temperature distribution of the thermocouple tree # 1, test 1
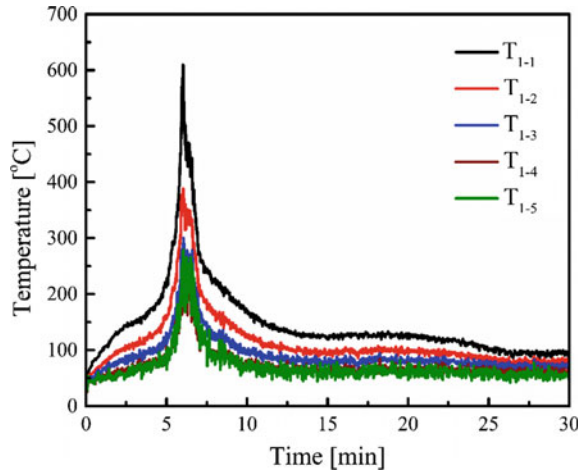
burning a small bag (HRRPUA = 400 kW/m^2) to simulating a larger source of fire (HRRPUA = 8,800 kW/m^2) (e.g. Arson or terroristic attacks). Figure 9 illustrates the total heat release rates (HRR) produced from burning the carriage using various fire loads. When the HRRPUA of the fire source increases, the total HRR produced from the carriage increases, especially from the low fire powers, because more seats are exposed to burn according to heat radiated from a larger fire source. It can be concluded from Fig. 9a, that there is no flash over for the low fire loads (HRRPU from 400 to 1000 kW/m^2) and the HRR did not go high beyond 800 kW for the whole vehicle. The radiated heat from the fire source is not enough to ignite any of the neighbouring seats (Quintiere 2006). For the higher fire loads (HRRPU from 2000 to 8800 kW/m^2) flash over occurs and the carriage burned with HRR exceeding 6000 kW for the three cases. The time needed to reach the maximum HRR decreases by increasing the fire source power, as shown in Fig. 9b. The HRR reached its maximum after 800 s when the fire load is 2000 kW/m^2 whereas, it needs only 70 s for the largest fire load (8800 kW/m^2). At this large fire source, the full carriage takes only 90 s to be fully burned simulating a terroristic attack with maximum HRR exceeding 10,000 kW.

To show the effect of the fire source on the carriage, it is better to discuss the temperature behavior along the vehicle. Figure 10 illustrates the vertical variation of temperature at various positions for the lowest fire load (400 kW/m^2). The vertical thermocouple Tree# 1, located directly above the fire source, shows that temperature decreases going higher above the fire source with large differences in temperature between different positions. The temperature has a value of 800 °C above the fire source and decreases to 540 °C at 0.29 m below the ceiling, Fig. 10a. Going away from the fire source at the location of thermocouple Tree# 5, the vertical variation of temperature is very small which indicates the homogenous distribution of temperature at this position as shown in Fig. 10b. Figure 11 illustrates the horizontal distribution of temperature along different planes, at 0.29 and 1.0 m from the ceiling,

**Fig. 9** Comparison between the obtained HRR from the FDS simulation results of a full-scale carriage

Fig. 10 Temperature distribution at vertical planes for 400 kW/m^2 fire source; **a** tree 1 above the fire source and **b** tree 5 at the far end of the carriage and opposite to fire source

for the case with smallest fire load (400 kW/m^2). For the two planes, temperatures at T_{1-3} and T_{1-5} are much higher than all other thermocouples, evidence of no burning of the carriage. The heat from the fire source does not raise the temperature in positions away from it, indicating no flash over.

Figure 12 illustrates the vertical temperature distribution at different positions for the case with maximum fire load (8800 kW/m^2) of the full carriage. In this case, all the thermocouples in Tree# 1 read almost the same temperature with a maximum value of 1150 °C at the time of maximum HRR. Very high HRR due to rapid burning of the full carriage, indicates the temperature is homogenous vertically but has lower values going away from the fire source. For the thermocouple Tree# 5, the temperature rise is delayed more than Tree# 1 because of the time needed for the HRR to reach the other end of the vehicle.
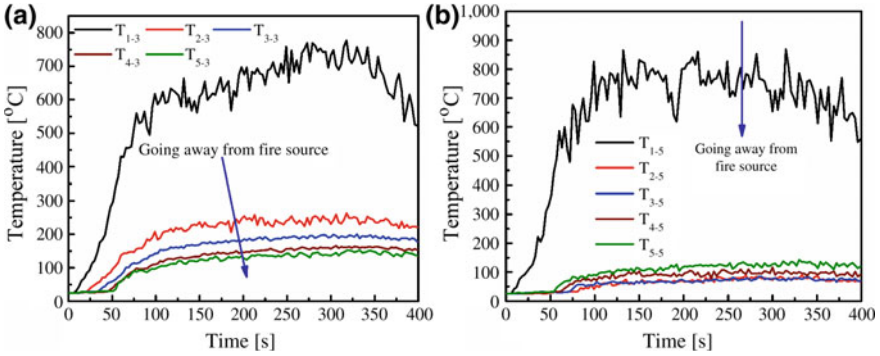
Fig. 11 Temperature distribution at different horizontal planes across the carriage for 400 kW/m^2 fire source at heights of 0.29 and 1.0 m below the ceiling for **a** and **b**, respectively
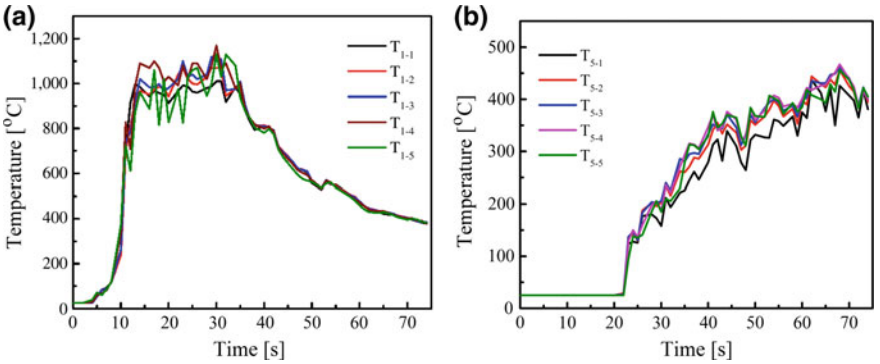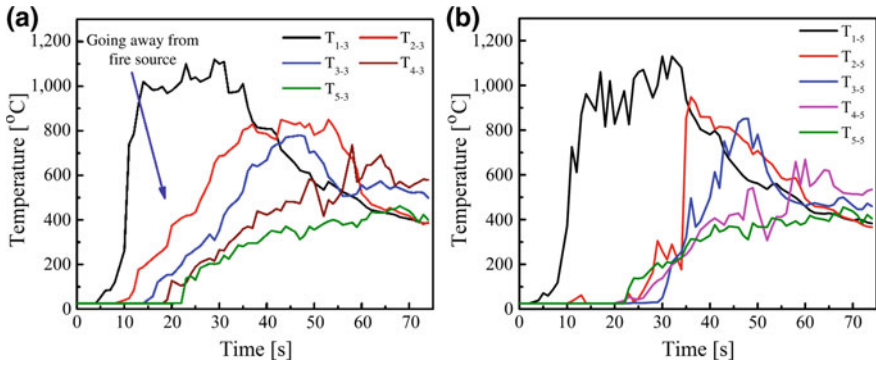

Fig. 12 Temperature distribution at different vertical planes for 8800 kW/m^2 fire source; tree 1 above the fire source and tree 5 at the far-end of the carriage and opposite to fire source

Figure 13 shows the horizontal temperature distribution across the full carriage for the highest fire load (8800 kW/m^2). In the first 30 s, the nearest thermocouples to the fire source (T_{1-3} and T_{1-5}) have a higher reading than other ones, but after 30 s the temperature is almost homogenous as the heat is transferred from the fire source to the different positions in the carriage.

4.4 Simulations Incorporating Firefighting System

To face the fire generated in the carriage, automatic water sprinkler systems are proposed. Based on fire standards (Lataille 2002; Puchovsky 1999), the Pendent sprinkler type with activation temperature of 79 °C and particle velocity of 5 m/s is suggested. Three automatic sprinklers are fixed in the 1/3 mock-up at a height

Fig. 13 Temperature distribution at different horizontal planes across the carriage for 8800 kW/m² fire source
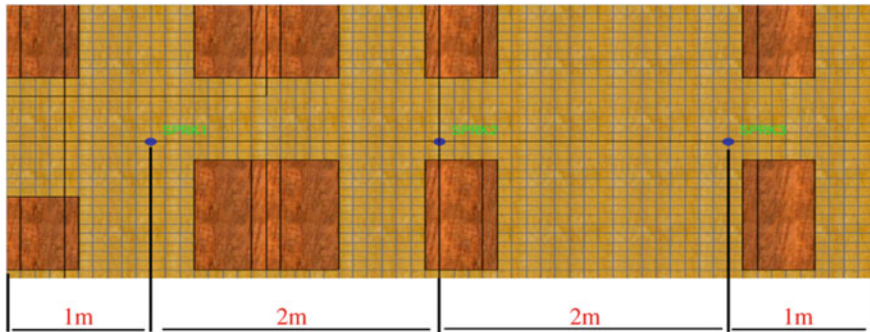

**Fig. 14** Sprinklers distribution along the 1/3 mock-up

of 2.35 m from the carriage floor with water flow rate of 200 L/min, as shown in Fig. 14. To study the effect of the water sprinkler on fire HRR and temperature inside the 1/3 mock-up, test #6 documented in Lönnermark et al. (2017) is simulated using sprinklers and compared to the original case without using sprinklers. It is clear from Fig. 15 that water sprinklers reduce the maximum HRR by 74.8% from 3500 to 880 kW. The temperatures also decrease from 950 to 90 °C as shown in Fig. 16. The huge reduction in HRR and temperature provides positive advantages for evacuating passengers inside the vehicle in case of any fire accident.

The temperature distribution along the horizontal plane (0.29 m below the ceiling) across the mock-up is shown in Fig. 17. Without sprinklers, the temperature has the value of 950 °C and decreases away from the fire source with a value of 550 °C at the end of the mock-up (5 m away from fire source). After using water sprinklers, the temperature reduces to a homogenous temperature of 90 °C along the mock-up.

Figure 18 shows the effect of water flow rate of the automatic sprinkler on the HRR produced from the 1/3 mock-up. Without any water sprinklers, the maximum HRR was 3500 kW. When water was used with a flow rate of 100 L/min, the reduction
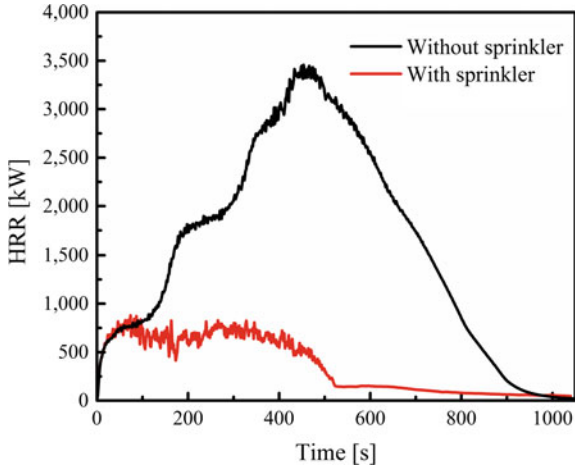
Fig. 15 Comparison between the obtained HRR from the FDS simulation results with and without sprinklers for test# 6 documented in Lönnermark et al. (2017)
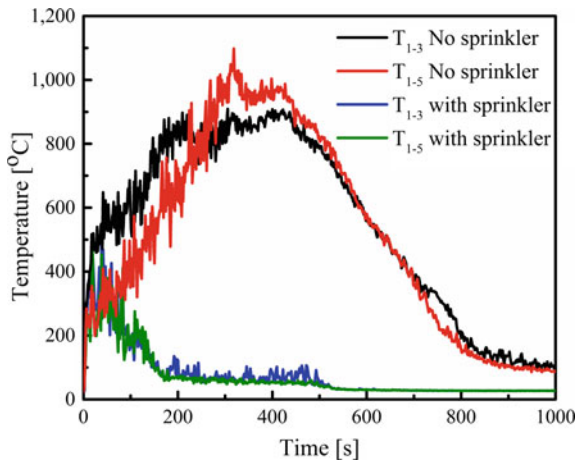

Fig. 16 Some temperature distributions in the 1/3 mock-up with and without sprinklers

in HRR was 69% and going further to 74.8% with flow rate of 200 L/min. For the maximum water flow rate of 300 L/min, the reduction in HRR reached 77%. It is clear from this figure that increasing the water flow rate further after 200 L/min will reduce the maximum HRR with small percentages, so it is recommended not to go beyond 200 L/min of water flow rate.

The sprinkler model is expanded to cover the full-scale carriage, as shown in Fig. 19. The first sprinkler is fixed at a position of 1.0 m from the start of the carriage with 2.0 m between each of the two sprinklers. Like the 1/3 mock-up, 9 sprinklers are fixed at a height of 2.35 m from the carriage floor with water flow rate of 200 L/min.

Fig. 17 Temperature distribution along the horizontal plane (0.29 m below the ceiling) across the 1/3 mock-up with and without sprinklers
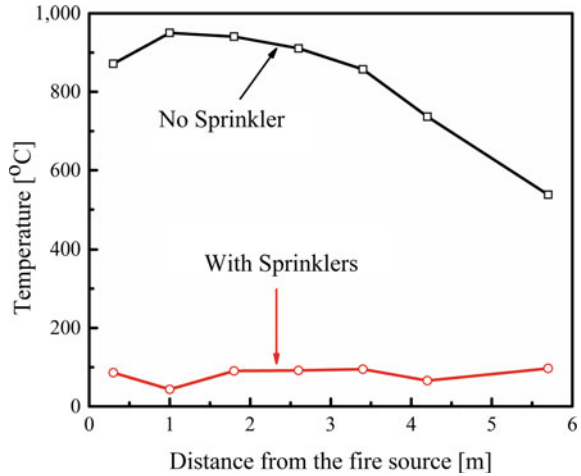
Fig. 18 Effect of sprinkler's water flow rate on the maximum heat release rate produced from fire in mock-up
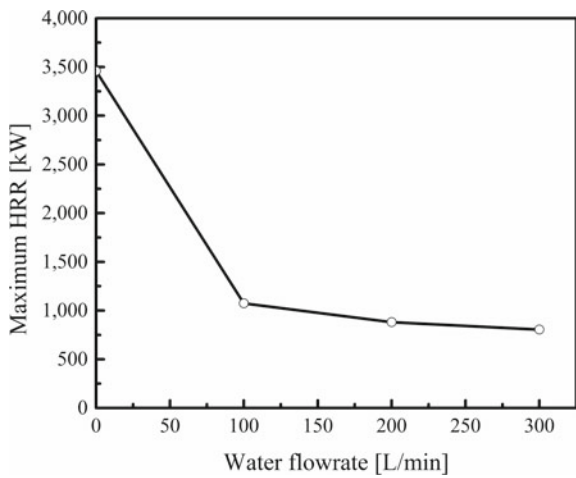
The highest HRR case (8800 kW/m^2) is modeled with the sprinkler in the full-scale carriage and the comparison with sprinkler is shown in Fig. 20. The water sprinklers reduce the maximum HRR from 10,366 to 2013 kW with a reduction percentage of 80.6% which saves the carriage from burning and gives enough time for passengers to escape in case of fire. It can be concluded that the water sprinkler system is very efficient in suppressing fire inside the train coach.
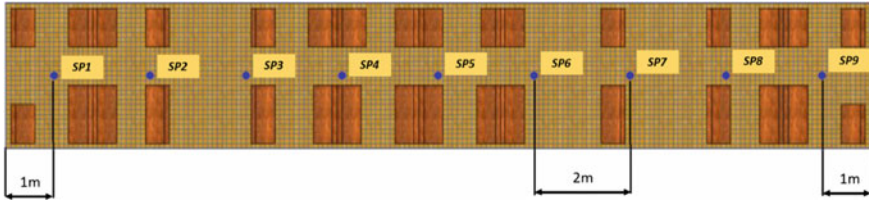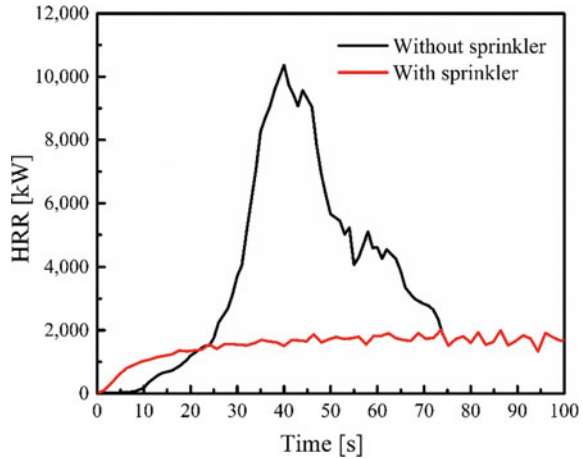
Fig. 19 Sprinklers distribution along the full-scale train carriage

Fig. 20 Comparison between the obtained HRR from the FDS simulation results with and without sprinklers for full-scale carriage with HRRPUA = 8800 kW/m^2

5 Conclusions

To evaluate fire safety criterion, it is important to initially identify the controlling parameters of the fire spread and development process. A crucial part in fire dynamic analysis is the measurement of the maximum HRR which will describes how fast the process is in reaching a fully developed fire in a train compartment. In this paper, a comparison has been made between the experimental results for a small-scale train coach and those obtained from the CFD model proposed in the presented work. The main objective of the comparison is to check the validity of the obtained results and to assess the reliability of the model to be used in the analysis of fire dynamics in train cars with different fire scenarios.

By varying the fire loads HRRPU from 400 to 1000 kW/m^2, no flash over was detected as the radiated heat from the fire source was insufficient to ignite any of the neighbouring seats from the fire source located on the left corner seat. But, in case the fire loads increased from 2000 to 8800 kW/m^2, the HRR in that case exceeded the 6000 kW and flash over was detected.

For the purposes of protecting rail assets, this paper investigated a fire protection system. It was found that the maximum HRR was achieved by 80.6%, by incorporating a water fire interaction mechanism using distributed sprinklers in the full train.

In this way the system delayed the complete burning of the full carriage and gives enough time for passengers to escape in case of fire accidents.

From the quality of the results obtained in the analysis of the fire development in a full train carriage, it can be concluded that the simulation model presented is reliable and efficient. It can be used in the fire dynamic analysis of different scenarios. Further work is still needed to study the impact of changing the fire source position in the train carriage and its influence on the fire and smoke spread as well as flashover in the whole carriage. In addition, investigating the effect of changing the sprinkler distribution and water mist flow on the fire and smoke development speed is required.

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