A PARAMETRIC STUDY OF A WATER MIST SYSTEM FOR FIRE SUPPRESSION IN A TRAIN COMPARTMENT

Yunlong Liu, Vivek Apte, Nathan White and David Yung
Fire Science and Technology Laboratory
CSIRO Manufacturing and Infrastructure Technology
PO Box 310 North Ryde, NSW 1670, Australia

ABSTRACT

This paper investigates the effects of varying the key water mist system parameters - the number and locations of nozzles, on the efficacy of fire suppression in a train compartment. This theoretical study uses Fire Dynamics Simulator (FDS) to model fire growth, as well as fire suppression with a sprinkler spray system.

We refer to a fire experiment, which was conducted on a furnished real-scale train carriage. The aim of the experiment was to study how a fire started by an act of arson at one end of the carriage would spread and grow along the carriage length. The experiment did not comprise fire suppression. During the experiment, the fire spread resulted in a flashover, involving all flammable materials fitted inside the carriage.

Four scenarios were modelled using FDS. The first scenario modelled the fire growth without suppression. The subsequent three scenarios were hypothetical, incorporating variations in the number and locations of the nozzles inside the experimental train carriage. The rate of water discharge per nozzle was assumed to be constant, and the total water application density was proportional to the number of nozzles deployed. The assumed water mist characteristics were based on a nozzle design currently available in the market.

FDS predictions show that the effectiveness of a water mist system is highly dependent on the number and the locations of the nozzles. It was found that the number of nozzles required to effectively suppress the fire could be reduced, if one of the nozzles was located closer to the ignition source.

This paper demonstrates how FDS can be used to investigate the effects of key water mist system parameters on the suppression efficiency. However, such model predictions would only serve as a basis for the design of a water mist system. A final engineered solution must incorporate real-scale suppression experiments to validate the efficacy of the water mist system to suppress a range of fires. FDS can serve as a valuable tool to conduct sensitivity analysis and to reduce the number of experiments required to achieve an engineered solution. FDS can thus be used to reduce the cost of designing a water mist system.

KEYWORDS: Water mist, parametric study, Train Fire, Fire suppression, CFD.

NOMENCLATURE

CFD = Computational Fluid Dynamics
FDS = Fire Dynamics Simulator
HRR = Heat Release Rate (MW or kW)
GRP = Glass Reinforced Polyester
NIST = National Institute of Standards and Technology

INTRODUCTION

Deploying an effective fire suppression system is an important aspect of the fire safety design of a train carriage. Constraints on the amount of water that can be stored on a train for a sprinkler system, and a ban on the use of ozone depleting Halon 1301 would make water mist an attractive alternative for fire control in trains.

Fire suppression by water mist involves several parallel complex processes. In comparison to a sprinkler spray, the smaller sized water mist droplets offer larger surface area for the same amount of water, allowing faster evaporation of the droplets, and more effective heat extraction from a fire. The mist vapour dilutes the concentration of oxygen as well as of the pyrolysis fuel vapour, thus slowing or arresting combustion. Water mist can also block the thermal radiation and pre-wet other combustibles in the neighbourhood to reduce their temperature and delay the ignition.

Liu et al [1,2] and Yao and Chow [3] have reviewed recent work on water mist fire suppression. Recent research papers on the applications of water mist include: suppression of a cooking oil fire [4], fire suppression in a small retail shop [5], fire suppression in a 500m^3 machinery space [6] with a fire size up to 2MW, fire protection of shipboard engine room with a fire size up to 6MW [7], and the control of a fire caused by a back-draft in a compartment [8]. Despite such research studies, and some general standards on water mist [9], explicit performance-based standards for designing water mist systems are not available. Water mist systems have to be engineered for specific applications, using credible scale suppression experiments.

With improvement in our ability to model turbulence, combustion, radiation and buoyancy flow, Computational Fluid Dynamics (CFD) models are becoming valuable tools to assist with the design of water mist systems. Yang et al [10] have investigated the interaction of water mist and radiation. Downie and Polymeropoulos [11] have discussed the influence of water mist on buoyancy. Adiga [12] has investigated the influence of droplet size and water spray density on the suppression effectiveness of water mists, without considering the influence of radiation. Kuldeep et al [13] have presented a CFD study on the suppression of large compartment fires with water mist. CFD fire models SMARTFIRE [14] and FDS [15] incorporate the interaction of water spray and fire. Kim and Ryou [16] have validated the fire suppression sub-model of FDS against a fire test, with a median droplet size of 121 μm.

Lattimer and Beyler [17] have estimated the heat release rate (HRR) during post flashover fires inside railcars using a one-layer zone model. The predictions are not compared with experimental data.

Using FDS, the present paper models a fire experiment performed by CSIRO researchers [18-20] on a real-scale train carriage with doors and windows, and fitted with wall, ceiling and floor linings, and seats. The objective of the experiment was to study and measure how a fire started at one end of the carriage would spread along the length of the carriage. *The experiment did not involve fire suppression.* FDS is used to study the effects of the key parameters such as the number of water mist nozzles and their locations on the suppression efficiency.

PHYSICAL MODEL

The scenario studied assumes that the fire was started by an arsonist at one end of a train carriage using crumpled newspaper while the train had stopped at a station. Two doors on the platform side were fully open. As shown in Fig 1, door A is closer to the ignition source, and door B is far from the ignition source. The outdoor air temperature was 22ºC, and the wind-induced airflow into the carriage was negligible. The train remained stationary at the station after the fire was detected.

The experimental train carriage [20] was 23.05 m long x 2.75m wide x 2.5m high inside, with 32 seats, ignition source located at the corner of the end wall, as shown in Figure 1. The carriage had fourteen windows, 2m x 1.2m, which broke successively in the CSIRO test, as the windows were heated by the spreading fire to temperatures exceeding the critical glass breakage temperature [20, 21].

One kilogram of crumpled newspapers placed between the end wall of the carriage and the adjacent seat was used as an ignition source. Figure 2 shows the heat release rate profile from the ignition source measured separately in a furniture calorimeter using oxygen depletion calorimetry. The peak heat release rate is seen to be ~ 140kW. The main fuel inside the carriage that contributed to the heat release rate comprised of the crumpled newspaper used as the ignition source, seats with cushions, wall lining, ceiling lining and the flooring material including the carpets.

The seat cushions were primarily made of Polyurethane foam. The ceiling and the sidewalls above the windows were lined with 4 mm thick Glass Reinforced Polyester (GRP) sheets. The floor and the lower sidewalls below the windows were covered with carpets made of 5mm thick mottled pink nylon loop pile with a 3mm thick jute backing. Table 1 lists the physical properties of these materials. The fire properties of these materials – heat of combustion, heat of vaporisation, peak heat release rate, ignition temperature and thermal inertia are required as inputs to the FDS model to predict fire growth. Table 2 presents the fire properties of the above materials obtained from the literature, or measured and inferred from cone calorimeter tests conducted on the materials [18, 19]. Triplicate specimens of each material were tested in the cone calorimeter. Flooring materials were tested at an irradiance level of 25 kW/m^2. The seat material was tested at irradiance levels of 25 and 35 kW/m^2. Wall and ceiling linings were tested at irradiance levels of 35 and 50 kW/m^2. These levels are taken to be representative of radiant heat exposure for flooring and wall and ceiling linings in a real fire [20]. As seen in Table 2, the inputs to FDS include either peak HRR or H_v and ΔH_c.

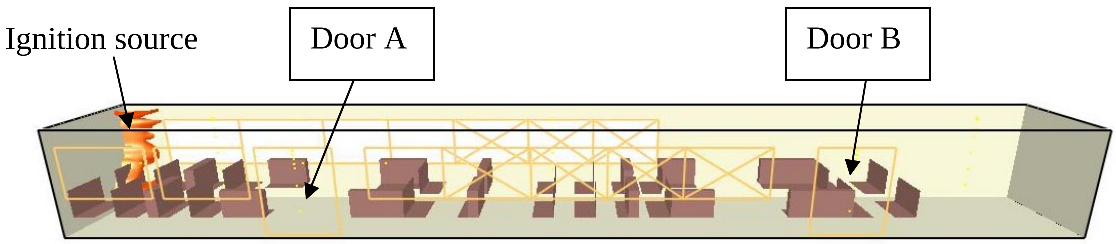

Figure 1: A schematic of experimental carriage and computational domain

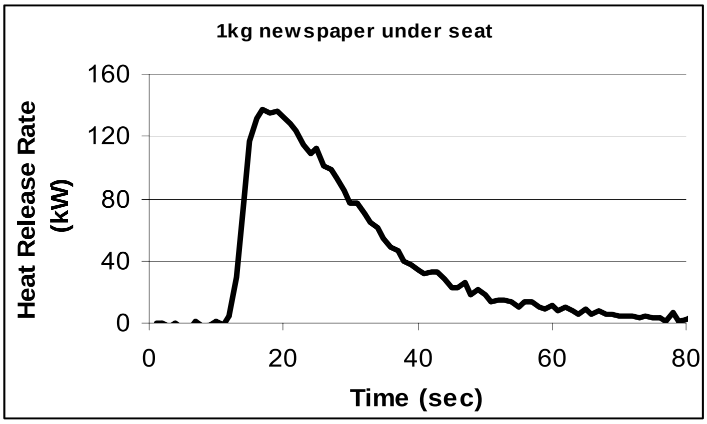

Figure 2: Fire ignition source Heat Release Rate from 1 kg crumpled newspaper, measured in a furniture calorimeter at CSIRO

The train carriage experiment [18-20] involved measurement of temperatures, heat fluxes, gas species measurements at a number of locations, and video records. The experiment did not comprise fire suppression using water mist. The ignition source used in this experiment resulted in fire growth along the carriage, culminating in a flashover involving all combustible materials in the carriage.

Table 1: Physical properties of the combustible materials in the carriage

No.	Description	Surface Area(m^2)	Thickness (m)	Density (kg/m^3)	Combustible Fraction	Combustible load (kg/m^2)
1	Seats	58	0.064m	137.3	0.190	1.67
2	Floor carpet	25.50	0.008m	519.6	0.595	2.47
3	Floor plywood	33.15	0.020m	580.0	0.200	2.32
4	Ceiling GRP	25.50	0.004m	1080.8	0.761	3.29
5	North Wall GRP	4.04	0.005m	1080.8	0.761	3.29

Table 2: Fire properties of combustible materials in the carriage

No.	Description	T_{ig} °C	Peak HRR kW/m^2	H_v kJ/kg	ΔH_c kJ/kg	K $w.m^{-1}K^{-1}$	C_p $J.kg^{-1}K^{-1}$
1	Seats	258	386	/	/	0.09	2.4
2	Floor carpet	294	270	/	/	0.16	3.0
3	Floor Plywood	300	/	5000	10800	0.12	1.2
4	Ceiling/wall GRP	409	386.6	/	/	0.19	1.4

T_{ig} - Ignition temperature; HRR - heat release rate; H_v - heat of vaporization; ΔH_c - Heat of combustion; k - thermal conductivity; C_p - Heat capacity

THEORETICAL MODEL

Next, we undertake an investigation on how a hypothetical water mist system installed in the above experimental train carriage scenario would suppress the fire. *No physical experiments were conducted using water mist.* Using FDS version 4 [15], we undertake a theoretical analysis of the effects of number and locations of water mist nozzles on the extent of fire suppression in the above train fire scenario.

For our analysis, we consider a commercially available water mist nozzle with specifications given in Table 3. The maximum coverage for this nozzle is 8m^2. The water mist system activates when the temperature close to the nozzle reaches 74°C. It is assumed that the nozzle pressure and the flow rate of water mist from the nozzle are constant. Thus, the water application density is proportional to the number of nozzles.

Using FDS, we simulate four scenarios as shown in Table 4. The first scenario refers to the actual train fire experiment without suppression. Scenarios 2, 3 and 4 study the effects of different nozzle configurations on the fire. Two parameters controlling the water mist delivery are analysed – the number of nozzles, and the positions of the nozzles in the train carriage.

Figures 3a, 3b and 3c show the nozzles arrangements in scenarios 2, 3 and 4.

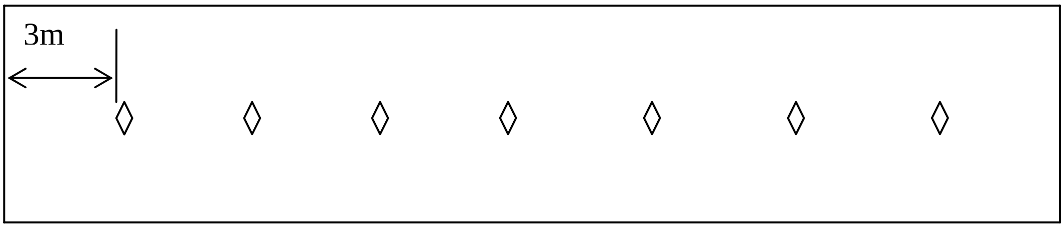

Figure 3a: A plan view of the nozzles arrangement in scenario 2

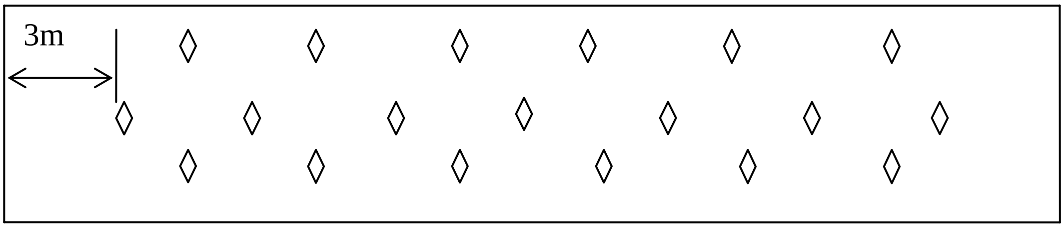

Figure 3b: A plan view of the nozzles arrangement in scenario 3

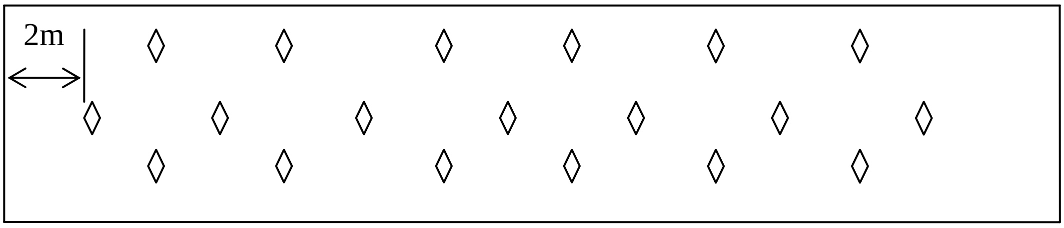

Figure 3c: A plan view of the nozzles arrangement in scenario 4

In scenario 2, (Fig. 3a), seven nozzles were installed 0.1m below the ceiling surface along the longitudinal centreline of the carriage. The first nozzle was 3m from the centre of the ignition source, and the successive nozzles were placed 3m apart.

Scenario 3 (Fig. 3b) had a total of 19 nozzles of which seven were deployed along the centreline of the ceiling as in scenario 2. Another 12 nozzles were located, six on each side of the centreline nozzles.

In scenario 4 (Fig. 3c), the nozzle arrangement was the same as in scenario 3, except that the first nozzle was located 2 m from the centre of the ignition source.

Table-3: Specifications of the water mist nozzle

Item	Additional description	Specifications
Median droplet diameter		100micron
Orifice diameter		15mm
Operating pressure		11.6bar
Flow rate		11.73litre per minute
K-factor		3.5 litre/bar$^{1/2}$
Spray pattern		Hollow cone
Spray angle	Outer	75
	Inner	55
Spray velocity		10 m/s
Activation temperature		74 deg C
RTI, Reaction time		0

Table-4: Fire and suppression scenarios analysed

Scenario	Nozzle locations	Number of Nozzles Activated	Water Application Density (mm/min)	Maximum Water Consumption (m^3)
1	No nozzles	0	0.0	0.0
2	See Fig. 3a	7	1.4	1.8
3	See Fig. 3b	12	2.4	3.2
4	See Fig. 3c	3	0.6	0.8

The computational domain was 23.05m x 2.75m x 2.5m covering the full carriage volume. The mesh size was 0.240m x 0.086m x 0.078m along the length, width and the height of the carriage respectively, yielding 96 x 32 x 32 cells. Turbulence is modelled using large eddy simulation (LES) and thermal radiation is modelled using the finite volume method [15]. The interaction between the water mist and the indoor gas is modelled by Eularian-Lagrangian method [15].

Material property data in Tables 2 and 3 are provided as inputs to FDS. For predicting the fire growth in the train carriage, either the peak heat release rate or the heat of combustion and the heat of vaporisation data for each material are required. Ignition of a combustible surface is assumed to occur when the surface reaches the ignition temperature given in Table 2. The heat release rate from the surface is computed from the peak heat release rate data measured in the cone calorimeter.

RESULTS AND DISCUSSIONS

FDS predictions of scenarios 1 – 4 are discussed in this section. Table 4 and Figures 3a, 3b and 3c give details on the nozzle configurations, number of the nozzles activated, the water application densities and the maximum water consumption in the scenarios studied.

Figure 4 shows FDS prediction of unsuppressed fire in scenario 1 at 3 min from ignition. The prediction assumes that the entire carriage length is furnished with seats. Figure 5 shows the fire growth observed at flashover in the actual experiment, where the carriage was furnished with seats only up to half the carriage length measured from the ignition end. Despite this difference in the fuel load assumption, it is reasonable to compare Figs. 4 and 5 because the fire at this stage had spread only up to half way along the carriage length. FDS predictions of smoke emerging from the doors A and B (Fig. 4) compare favourably with the observed extension of flames outside the doors during the experiment (Fig. 5). .

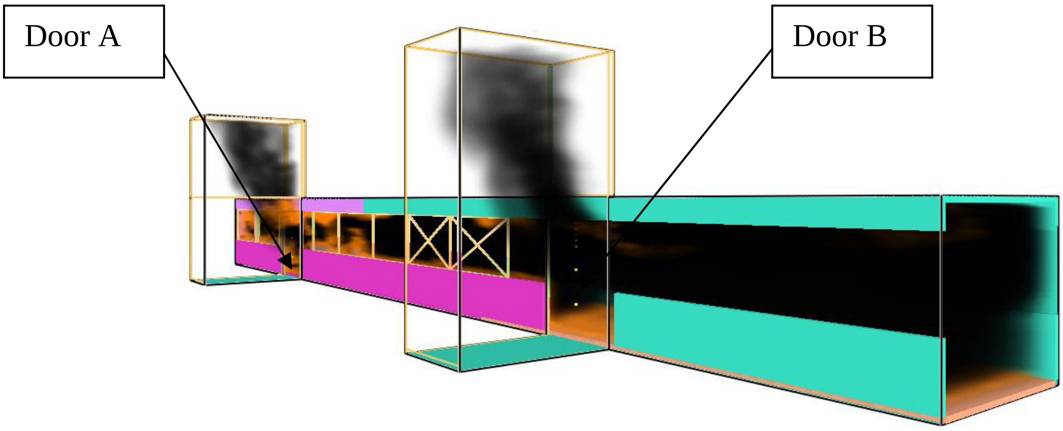

Figure 4: CFD simulated train fire without suppression

Figure 5: CSIRO train fire experiment

Figure 6a shows FDS prediction of fire growth in scenario 1, corresponding to the peak heat release rate. Figures 6b-6d show FDS predictions of the effect of water mist on the fire growth for scenarios 2- 4. Figs. 6b – 6d correspond to the time when the maximum number of water mist nozzles were triggered as predicted by FDS. The regions in Figs. 6a – 6d represent mixture fraction contours showing the presence of flames. Experimental data is approximated by for scenario 1. Scenarios 2, 3 and 4 are hypothetical, with only FDS predictions available for an analysis.

Figure 7 compares FDS predicted peak heat release rates for all the scenarios. Clearly, the predicted peak heat release rapidly decreases from scenario 1 to scenario 4. Figures 8-10 compare FDS predicted peak temperature at Door A, Door B and at 1m from the ignition source respectively. Temperatures at these locations decrease from scenario 1 to scenario 4.

In scenario 1 (Fig 4 and Fig 6a) FDS predicted the onset of flashover around 190s from ignition with flames extending from the doors. This compares favourably with the measured flashover time of 140s from ignition in the train fire experiment [20]. All the seats, carpets and ceiling materials were involved in the fire.

In scenario 2 (Fig. 6b), FDS predicted activation of all the nozzles within 540s of ignition. The flames first spread to the ceiling. The radiant feedback from the ceiling then ignited some seats and the carpet near the ignition source, generating a peak temperature of about 1100°C at a distance of 2m from the ignition source at 330s from ignition. The seats and the floor carpet beyond a distance of 15m from the ignition source did not ignite. The fire size was much smaller than that in scenario 1 without fire suppression, as demonstrated in Fig. 7.

In scenario 3 more nozzles were available, producing a higher water application density than in scenario 2. A total of 12 nozzles were activated, with the first one triggering at 140s and the last one triggering at 480s from ignition. For scenario 3, the flame spread was predicted (Fig. 6c) up to halfway along the carriage ceiling, with some seats near the ignition source igniting and no ignition of the floor carpet. There was no ignition of any seat or lining materials beyond a distance of 15m from the ignition source.

In scenario 4 (Fig. 6d), the fire was extinguished within 5 minutes from ignition. Only the first three nozzles where triggered during 120 to 150s since ignition. No fire spread was predicted on the linings, and the fire spread was limited to the region in the vicinity of the ignition source. The fire was effectively suppressed to a level, which could not have propagated along the carriage. A peak gas temperature of 180°C was predicted near the fire source at 130s. Compared to scenario 3, the first nozzle in scenario 4 was located closer to the ignition source, improving the activation time and the water mist coverage over the ignition area. Thus, despite the same number of nozzles and the water application density, fire suppression was faster in scenario 4 than in scenario 3 due to the closeness of the first nozzle to the ignition source in scenario 4. Scenarios 3 and 4 demonstrate the importance of nozzle location on fire suppression.

Figure 7 shows that if the train fire is not suppressed (scenario 1), the peak fire size can be very high. Deployment of a water mist system (scenarios 2, 3 and 4) can substantially reduce the heat release rate, depending on the numbers and the locations of the nozzles. In scenario 2 the peak fire size is predicted to be one third that of the unsuppressed fire. Further suppression is predicted for scenarios 3 and 4.

Figures 8-10 show that if the train fire is not controlled, the temperature inside the passenger carriage and at the train door can be as high as about 1200°C. If the water mist system is properly implemented, these temperatures can be significantly reduced. In Scenario 4, where the fire was predicted as effectively suppressed, the peak temperature was predicted to be only 180°C.

Figure 6a: FDS predicted fire growth– no suppression, 560s from ignition (scenario 1)

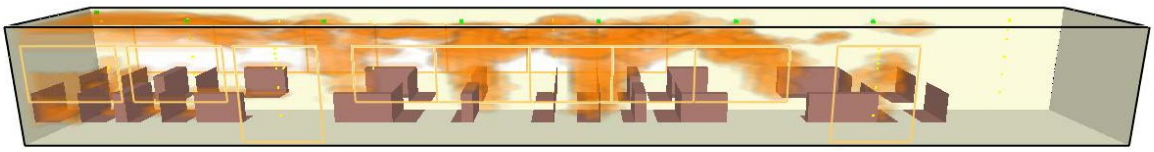

Figure 6b: FDS predicted fire suppression, 540s from ignition (scenario 2)

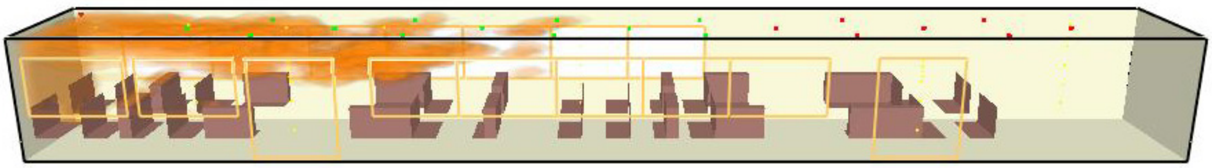

Figure 6c: FDS predicted fire suppression, 480s from ignition (scenario 3)

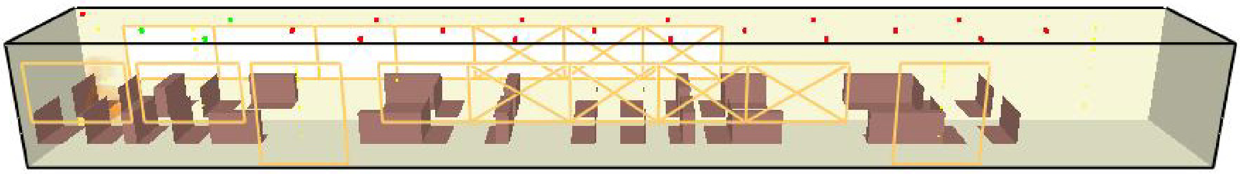

Figure 6d: FDS predicted fire suppression, 150s from ignition (scenario 4)

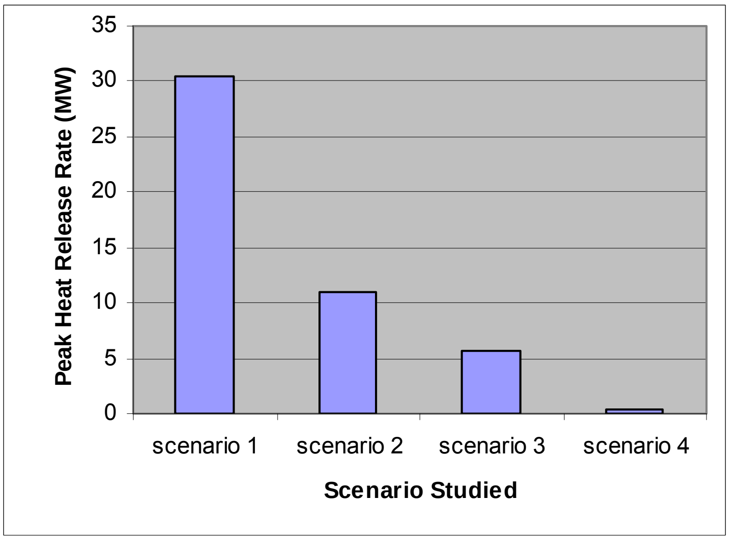

Figure 7: FDS predicted peak fire size for scenarios 1 - 4.

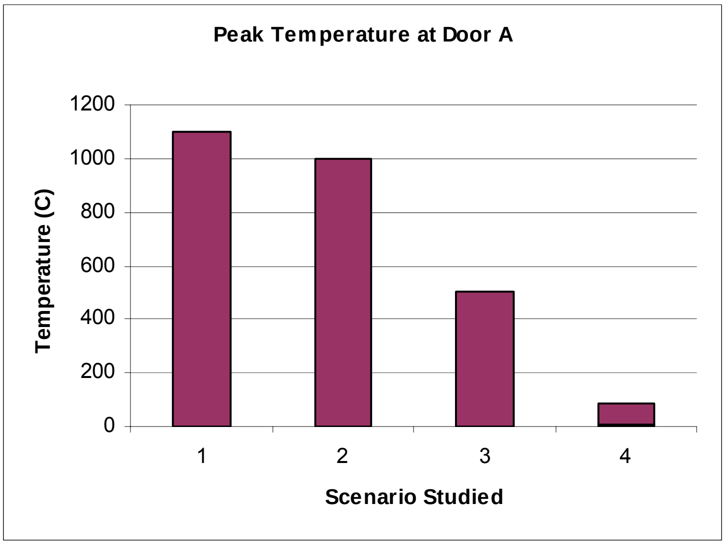

Figure 8: FDS predicted peak temperature at Door A for scenarios 1 - 4.

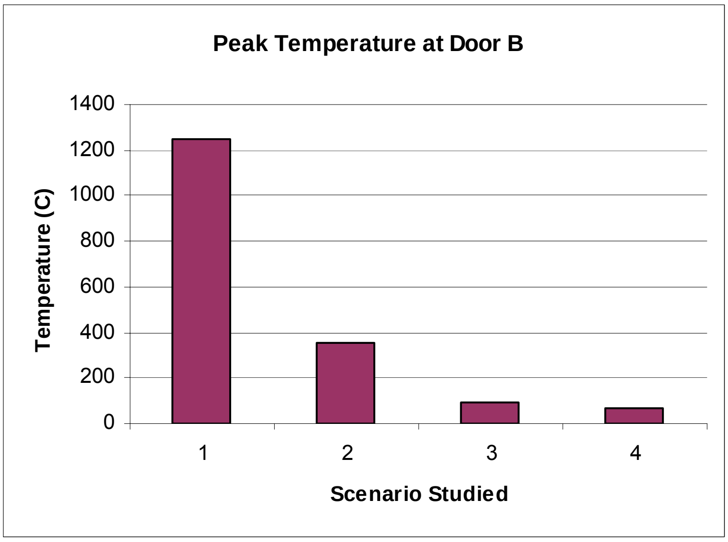

Figure 9: FDS predicted peak temperature at Door B for scenarios 1 - 4.

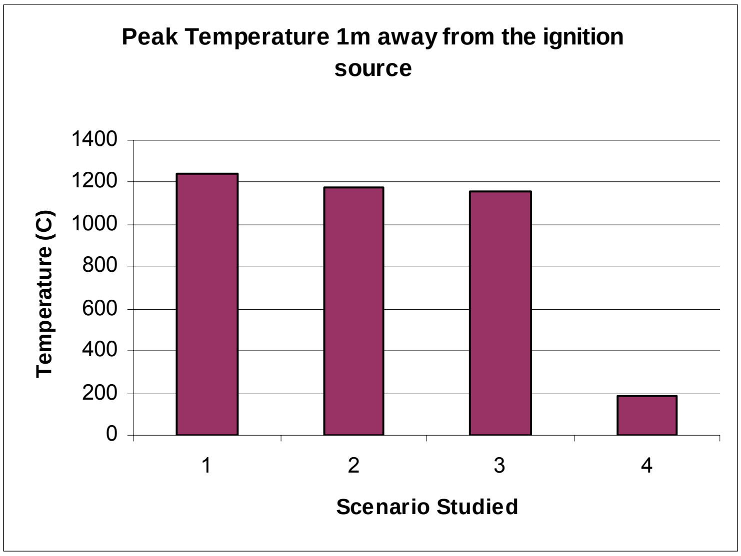

Figure 10: FDS predicted peak temperature inside train carriage 1m from the ignition source for scenarios 1 - 4.

CONLUSIONS

This paper demonstrates how FDS can be used to study the effects of key water mist system parameters such as the number and positions of nozzles on the extent of fire suppression. It is important to note here that such model predictions must be complimented by credible-scale suppression experiments to arrive at an engineered solution. FDS can be used as a valuable tool to conduct sensitivity analysis and to reduce the number of experiments required to achieve an engineered solution.

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