Proceedings of the 12th International Fire Science & Engineering Conference, Interflam 2010, 5-7th July 2010, University of Nottingham, UK, **Volume 2, pp. 1725-1730. ISBN 978 0 9541216-6-2, 2010.**

SIMULATING A RAIL CAR FIRE USING A FLAME SPREAD MODEL

Xiaoqin Hu, Zhaozhi Wang, Fuchen Jia, Edwin R. Galea
Fire Safety Engineering Group, University of Greenwich, London SE10 9LS UK

ABSTRACT

In this paper, an enhanced flame spread model implemented in the SMARTFIRE CFD fire simulation software is used to simulate a rail car fire. The study focuses on three areas: demonstrating the shortcomings of the single criterion of surface ignition temperature in flame spread models; reproducing the rail car fire using the enhanced flame spread model and investigating the effects of configuration and burnable properties of interior materials on the fire development. The results show that the enhanced flame spread model is better able to reproduce the fire experiment results compared with flame spread models using the ignition temperature as the sole ignition criterion. The results also demonstrate that the configuration of the interior furniture and burnable properties of materials are important factors affecting the time to flashover.

INTRODUCTION

In flame spread models, the gasification process of solid material is usually handled in two ways, one is the prescribed fuel rate measured from small-scale experiments such as the cone calorimeter under various radiant heat fluxes; while the other is to use a fuel generation rate based on a measured heat of vaporization[1]. No matter which approach is adopted, ignition temperature is one of the most important model parameters in simulating the spread of fires on solid surfaces – determining which cell faces are considered to be ignited. Theoretically, the criterion of surface ignition temperature alone is sufficient for CFD fire simulations if computational meshes are reasonably fine. However, in practice, large-scale fire simulations usually make use of coarser meshes as the use of a fine mesh is often prohibitively expensive. As a result, the predicted fire development may not accurately follow that of the actual fire. Furthermore, it is often difficult to initially ignite the fire in CFD simulations using the single ignition criterion. To compensate for this deficiency an artificially large heat release rate (HRR) is often used to initially ignite the materials[2].

In this study, an enhanced flame spread model, which was first developed by Jia et al[3] and then successfully applied in simulations of a full-scale aircraft fire test and the mock-up of the Rhode Island nightclub fire[4,5], is used to simulate a rail car fire. This study focuses on three areas. The first is to reproduce the full-scale rail car fire test with the enhanced flame spread model. The second is to demonstrate the shortcomings of the single criterion of surface ignition temperature in flame spread models due to the use of an unpredictable HRR for the initial ignited area or burner. The third is to investigate the effects of configurations and burnable properties of interior materials on the fire development by repeating the simulation with changes of related parameters.

FIELD FIRE MODELS

In field modelling, the fluid is governed by a set of three-dimensional partial differential equations. The generalised governing equation for all variables is expressed as equation [1]

$$\frac{\partial \rho \Phi}{\partial t} + div(\rho \vec{U} \Phi) = div(\Gamma_{\Phi} \nabla \Phi) + S_{\Phi} \qquad [1]$$

Proceedings of the 12th International Fire Science & Engineering Conference, Interflam 2010, 5-7th July 2010, University of Nottingham, UK, **Volume 2, pp. 1725-1730. ISBN 978 0 9541216-6-2, 2010.**

where Φ represents the fluid vaiable; ρ and $\vec{U}$ are the local density and velocity vector; Γ_{Φ} is the effective exchange coefficient of Φ; S_{Φ} represents the source term for the corresponding variable Φ and time *t* is an independent vaiable. The SMARTFIRE V4.0[3-5] software is used to perform the fire simulations in this study. The CFD engine in SMARTFIRE has many physics features that are required for fire simulation, including a radiation model, a volumetric heat release model, a gaseous combustion model, smoke modelling and k-epsilon turbulence model.

The enhanced flame spread model[3-5] used in these simulations is briefly described. In this model, all combustible surfaces are assigned a face patch which is identified as a burnable material. At the end of each time step, conditions at a cell face of a burnable face patch are assessed to determine if one of the two ignition criteria is reached

A. the material surface temperature reaches its ignition temperature;
B. the pyrolysis front advances from an adjacent burning cell face to the cell face in question.

Besides the ignition temperature and flame spread rates, the density, thickness, conductivity, specific heat, and HRR (kW/m^2) from cone calorimeter experiments are also required as model inputs. Once a cell face is ignited, it starts to release a certain amount of fuel according to the time dependent burning rate (kg/m^2s) for this material. Unlike in FDS simulations[6], the flame spread rate is the only additional parameter in this enhanced flame spread model. As discussed previously, the criterion of surface ignition temperature alone is sufficient to simulate fire spread along combustible solid surfaces. In practice however, within CFD fire simulations ignition of a solid surface can be strongly mesh dependent making it generally impractical to perform reliable simulations. In the case of wind opposed flame spread, extremely fine meshes in areas of flame fronts are required to accurately predict fire spread. It is very likely that, with coarse meshes, no fire spread is predicted at all. As fire is normally a large scale phenomenon, it is prohibitively expensive and impractical to use extremely fine meshes in fire simulations. In addition to this dilemma, it is impossible to know in advance at the mesh generation stage what fire conditions (wind assisted or opposed) are likely to occur at a given point. Therefore, as a practical engineering method, flame spread rate, which is measurable from experiments, is introduced alongside surface ignition temperature in the enhanced model presented in this paper.

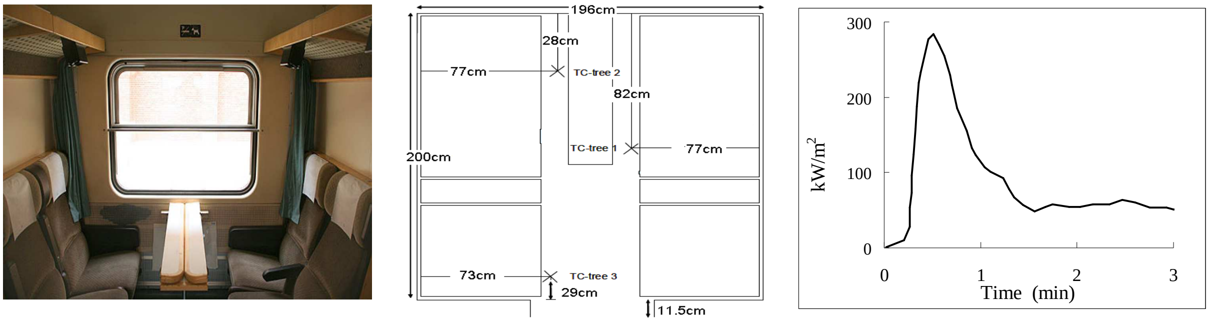
In this study, the original flame spread model[3-5] is further refined to minimise the mesh dependence of the simulation results. This is achieved by dividing each solid surface cell (or 'original face cell'), into a number of sub-cells. The ignition criterion B, which was applied to the 'original face cell', will be adopted for each sub-cell in this paper. Once a sub-cell face is ignited, it starts to release a certain amount of fuel according to its area. The released fuel from this sub-cell contributes to the control volume adjacent to the 'original face cell'. The current implementation method for the flame spread model equivalently utilise very fine meshes for the flame to spread based on the flame spread rate without any increase in the number of the control volumes in the computational domain. The additional computational cost due to refining the surface cells is negligible compared with typical CFD runtimes.

FIRE AND SIMULATIONS

SP Technical Research Institute of Sweden conducted a fire experiment within a rail car compartment[6] (see Figure 1 (a)), with dimensions and locations of three thermocouple trees shown in Figure 1(b). A burner with a HRR of 7 kW was applied to the seat in one of the rear corners for 76 seconds. The properties of burnable materials are listed in Table 1. Additional information concerning the experimental facilities was kindly provided by Ms Maria Hjohlman, one of the authors of the SP report[6]. As reviewed in the SP report[6], the heat fluxes received by the seats and walls in the test fires are around $35kW/m^2$ and $50\ kW/m^2$ respectively. Therefore, the cone calorimeter HRR data for these materials under corresponding heat fluxes are used in these simulations. For example, Figure 1(c) shows the cone calorimeter HRR data for the seats. The flame spread rates for the seats were

Proceedings of the 12th International Fire Science & Engineering Conference, Interflam 2010, 5-7th July 2010, University of Nottingham, UK, **Volume 2, pp. 1725-1730. ISBN 978 0 9541216-6-2, 2010.**

estimated from separate tests[6]. Other materials are expected to be ignited mainly by the ignition criterion A after the fire is well established and a conservative value of 0.001 m/s is therefore assumed here for their flame spread rate. The eddy dissipation combustion model (EDM)[7] is used to simulate the burning of the combustible gases released from the ignited materials, with an effective heat of combustion of 17.5 MJ/kg for polyurethane foam ($C_1H_{1.7}O_{0.3}N_{0.007}$)[5]. The multi-ray radiation model with 48 rays is used to represent thermal radiation. An unstructured mesh is applied to represent the complex rail car geometry (Figure 2). A mesh size of around 0.06 m is adopted in all simulations based on mesh sensitivity study as seen in Figure 3, in which the solid squares represent the actual measured data before 190 seconds while the empty squares are estimations after this time[6].



(a) (b) (c)

Figure 1. (a) Interior and (b) top view of the compartment; (c) Cone calorimeter HRR data for seats

Table 1. Material properties

		Seat	Metal laminate	HPL Laminate	PVC carpet	Table
Thickness (m)		0.05	0.02	0.02	0.002	0.03
Density (kg/m^3)		77	648	548	1400	616
Conductivity (W/mK)		0.015	1.07	0.11	0.25	0.11
Specific Heat (J/kg)		1200	2500	2500	1500	2500
Ignition temperature (^{O}C)		346	607	526	278	433
Flame spread rate (m/s)	**upward**	0.005	0.001	0.001	0.001	0.001
	lateral	0.0025	0.001	0.001	0.001	0.001
	downward	0.001	0.001	0.001	0.001	0.001

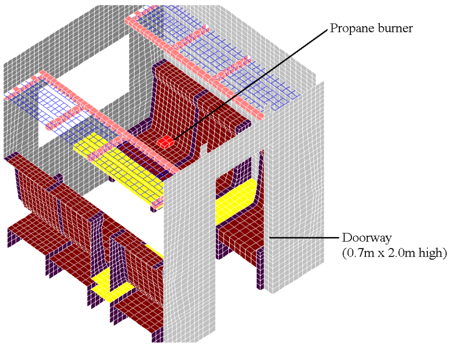


Figure 2 Setup with mesh size of around 0.06 m

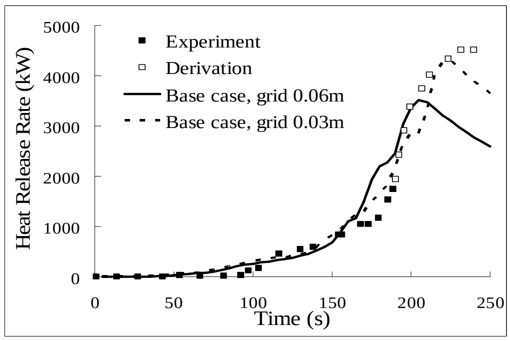


Figure 3 HRRs for Base Case

A total of eight scenarios are investigated in this study. They are

Base Case: the rail car fire experiment with holes in the luggage racks and actual material properties.

Case 1: the same as Base Case but the flame spread rate for seat is increased by 10%.

Case 2: the same as Base Case but the flame spread rate for seat is decreased by 10%.

Case 3: the same as Base Case but the luggage racks are non-combustible.

Case 4: the same as Base Case but the holes in the luggage racks are not included in the model.

Case 5: the same as Base Case but the luggage racks are non-combustible and without holes.

Case 6: the same as Base Case but the ignition criterion B is inactive. The HRR from the burner for the initial burning area is the same as that in the experiment.

Case 7: the same as Case 6 but a large HRR of 1500 kW/m^2, which was used in the investigation of the nightclub fire[2], is applied for the burner.

The setup of the Base Case is the same as in the fire test. Cases 1-5 involve variations in material properties and furniture configuration. These cases make use of the enhanced flame spread model. In contrast, Cases 6 and 7 and the work in[6] utilise the surface ignition temperature as the sole ignition criterion. These simulations make use of various initial HRRs as the ignition source.

RESULTS AND DISCUSSIONS

Firstly, the simulation results from the Base Case are compared with the experimental observations namely, the measured HRR and temperatures. The predictions in the Base Case with the enhanced flame spread model and the material properties provided in the SP report[6] are in good agreement with the observed fire dynamics in the experiment. For example, in Figure 4a we see the entire seat on which the fire is initiated and part of the neighbouring seat are involved in the fire at 132 seconds and in Figure 4b we see that the model predictions are in good agreement.

(a) (b)

Figure 4 (a) Observed fire development and (b) predicted burning locations at 132s.

Flashover is a critical factor affecting passengers' survivability in rail cars. The ability to accurately predict the onset of flashover is therefore one of the key requirements for fire models. The definition of flashover for enclosure fires is generally accepted as occurring when the upper layer gas temperature exceeds 600^{O}C[8]. In the experimental analysis, the onset of flashover was defined as occurring when the HRR begins to rapidly escalate[6]. For the purpose of convenient comparisons among all scenarios, the measured HRR value of 1.17 MW at the reported onset of time to flashover (180 seconds) is regarded as a criterion for flashover in this study. With this criterion, the predicted time to flashover in the Base Case is 165 seconds (Figure 3), which is only 15 seconds or 8.3% sooner than the observed time.

The measured and predicted Base Case temperatures at 2.3 m and 1.0 m above the floor for thermocouple tree 3 are depicted in Figure 5. The measured temperatures at 2.3 m high gradually increase to 153 ^{O}C at 85 seconds, and then rapidly increased to 661 ^{O}C at 123 seconds followed by a quasi-steady state until 180 seconds. The predicted temperatures at this height essentially follow the measured trends. However, the curve of the predictions is shifted to left by approximately 30 seconds. The measured temperatures at 1.0 m high increase slowly to 138 ^{O}C at 176 seconds followed by a rapid increase due to the occurrence of flashover. The simulation has successfully reproduced the sudden change of the measured temperatures at this position.

Secondly, the predicted fire development in the Base Case with the enhanced flame spread model is compared with the predictions for the cases using the surface temperature as the sole ignition criterion (Cases 6, 7 and the work in[6]). The predicted HRRs for all scenarios and the results from[6] are depicted in Figure 6 while the times to flashover are compared in Table 2. In Case 6 in which the burner HRR and the time to remove the burner are the same as in the experiment, the fire self extinguishes after the removal of the burner within 76 seconds. To ignite the fire, an artificially large HRR of 1500 kW/m^2 (as used in[2]) is used as the ignition source (Case 7). This results in a predicted time to flashover of 46 seconds, which is much earlier than the 180 seconds observed in the experiment. In Case 7 (as in[2]), an additional unpredictable parameter is introduced into the model - an artificial initial HRR to start the combustion process. The simulations presented in[6] also made use of the sole ignition criterion. In spite of that it successfully started the fire and predicted the occurrence of flashover however, its predicted temperatures at 2.3 m above the floor for thermocouple tree 3 between 80 and 160 seconds are much lower than found in the experimental data (see Figure 5). It also failed to reproduce the gradual increase of HRR during this period of time (see Figure 6). All these indicate that the fire development be not correctly predicted. Cases 6, 7 and the work in[6] demonstrate that using the ignition temperature as the sole ignition criterion may not be adequate to correctly predict fire development.

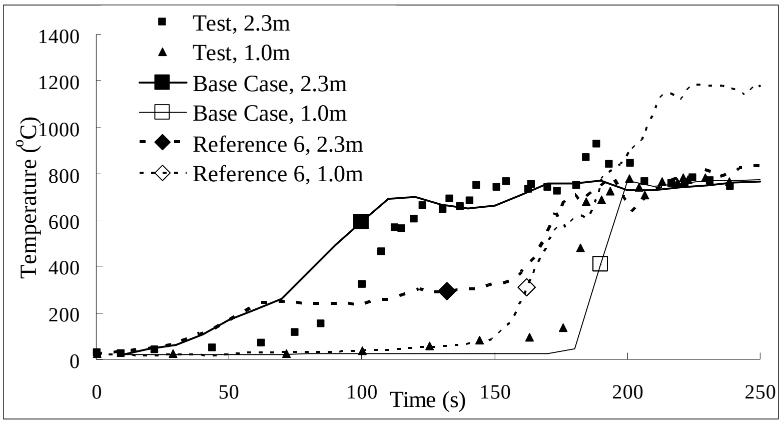


Figure 5 Measured and predicted temperatures at thermocouple tree 3.

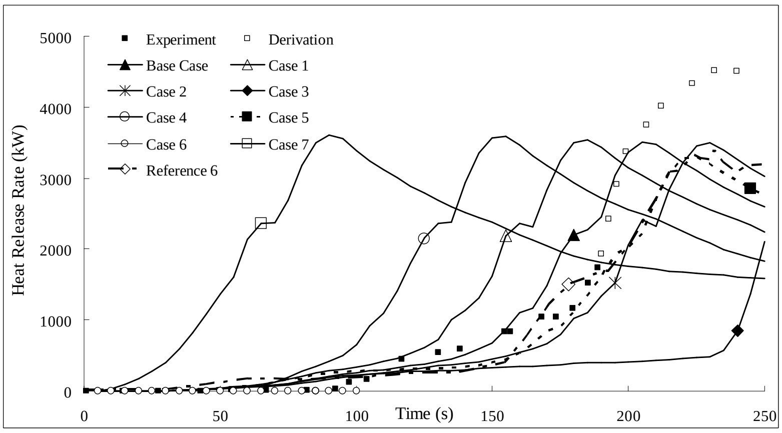


Figure 6 HRRs generated in different cases.

Table 2. Predicted times to flashover (seconds)

Exp.	**Enhanced flame spread model**						**Ignition temperature alone**		
	Base Case	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Work in [6]**
180	165	142	188	243	112	180	Extinguish at 76s	46	167

Thirdly, the effects of material properties and rail car configuration on the predicted time to flashover are analysed. To investigate the influence of flame spread rate in the enhanced flame spread model, 10% changes in the flame spread rate are made for the seats in Case 1 and 2. This change in flame spread rate causes the flashover to occur 23 seconds or 13.9% sooner or later than that in Base Case. In these cases, the times to flashover appear to be only moderately sensitive to the flame spread rate.

In the Base Case, the material properties for the luggage racks are those of wood as the majority of the racks are made from wood. In addition, the racks are perforated with a number of holes as seen in Figure 1(a) and these are represented within the model. Cases 3-5 are used to investigate the effects of the configuration and burnable properties of the racks on the fire development. Compared with the prediction in the Base Case, the non-combustible racks delay the flashover time by 78 seconds or 47.3% to 243s (Case 3). The racks without holes decrease the time to flashover by 53 seconds or 32.1% to 112 seconds (Case 4). The reason for this significant difference is that the accumulated hot gases under the racks speed up the ignition of the racks. In addition, radiation from the accumulated hot gases facilitates flame spread to other materials such as the seats. Thus the configuration of the rack is an important factor in determining the time to flashover. In Case 5 we have combined the effects of Case 3 and 4, and so we find the time to flashover is between that of Case 3 and 4 i.e. 180 seconds, a delay of 8.3% compared with the Base Case. It is clear that the combustible properties and configuration of the luggage racks are important factors in determining time to flashover.

CONCLUSIONS

This paper has examined the capabilities of an enhanced flame spread model by comparing model predictions with experimental data derived from a rail car fire experiment. The enhanced flame spread model utilises two ignition criteria – ignition temperature and flame spread rate - compared to the standard single ignition criterion model which only makes use of ignition temperature. As part of this study, the effect of car configuration and solid fuel material properties on fire development was also studied. The main findings of this work include:

- The enhanced flame spread model is better able to reproduce the fire dynamics, HRRs and temperature profiles measured in the rail car fire experiment than the standard flame spread model.
- Within the rail car simulations, the time to flashover is not strongly sensitive to the flame spread rate for the seat materials;
- Among all the factors investigated in this study, the time to flashover is most sensitive to the material properties and the configuration of the luggage racks.

ACKNOWLEDGMENTS

Ms Hu would like to thank FSEG of the University of Greenwich for their financial support through the PhD Bursary Programme. The authors would like to thank Ms Maria Hjohlman of SP Technical Research Institute of Sweden for kindly providing unpublished details regarding the fire experiment used in this study.

REFERENCES

1. McGrattan, K., ed., Fire Dynamics Simulator (Version 4), Technical Reference Guide, NIST SP 1018, NIST, Gaithersburg, MD, September 2004.
2. Grosshandler W., Bryner N., Madrzykowski D. And Kuntz K., Report of the technical investigation of the station nightclub fire, NIST NCSTAR 2: Vol. I-II, NIST, Gaitherburg, MD, USA, 2005.
3. Jia F., Patel M.K., Galea E.R., Grandison A. and Ewer J., CFD Fire Simulation of the Swissair Flight 111 In-flight Fire – Part II: Fire Spread within the Simulated Area, The Aeronautical Journal of the Royal Aeronautical Society, pp. 303, May 2006.
4. Wang Z., Galea E.R., Jia F., A computational study of the characteristics of aircraft post-crash fires. Proc Int Aircraft Fire & Cabin Safety Conf, Oct 29 – Nov 1, 2007, Atlantic City USA.
5. Galea E. R., Wang Z., Veeraswamy A., Jia F., Lawrence P. J. and Ewer J., Coupled fire/evacuation analysis of station nightclub fire, Proc of 9th IAFSS Symp, Sep. 21-26, 2008, Karlsruhe, Germany, pp 465-476.
6. Hjohlman M., Försth M., Axelsson J., Design fire for a train compartment, SP Report 2009:08; Fire Technology, SP Technical Research Institute of Sweden.
7. Magnussen B. F. and Hjertager B. H., On mathematical modelling of turbulent combustion with special embassies on soot formation and combustion, *16th Symp. (Int.) on Combustion*, the Combustion Institute, 1977.
8. Drysdale Dougal, An introduction to fire dynamics, Chichester, Wiley, 1985.