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Estimations of heat release rate curve of railcar fire †

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Abstract

This paper presents curve estimations of the heat release rate of an intercity railcar fire. Three different estimation approaches were used, which were compared with a full-scale fire test of the car. Two of these approaches were based on the assumption of a specific burning rate of materials with the heat release rate per unit area and burning area decision. The curve of the heat release rate of an actual railcar fire was measured by using the ignition scenario in EN 45545-1. In the fire test, the surface temperature of every part of the interior was measured by using the burning area decision for summation method estimation. The third approach used combustion and reaction heat to analyze microscopic-material pyrolysis. The pyrolysis model requires more sophisticated material property inputs to achieve the same degree of curve accuracy. The differences and similarities between the experimental fire curves and estimations were analyzed.

Keywords: Burning area-based summation; Fire dynamic simulation; Full-scale fire test; Railcar fire; Heat release rate

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1. Introduction

The representative heat release rate (HRR) fire curve for every type of railcar must be derived for fire risk assessment in the safety design of tunnels and underground stations [1]. However, an actual fire test of a full-scale railcar requires a huge facility and tremendous cost, which makes the test highly infeasible. Thus, much effort has been made to derive fire curves by simulations of computational fluid dynamics (CFD) [2, 3]. A fire dynamics simulator (FDS) developed by the National Institute of Standards and Technology (NIST) in the United States is the most popular tool among fire protection engineers. Two different approaches can be used in an FDS for HRR estimation. Another fire curve estimation approach is supported by summation methodology based on experimental data and burning areas. This study compares the HRR fire curves derived through simulations and analytical methods with the results of a full-scale fire test of a Korean intercity railcar.

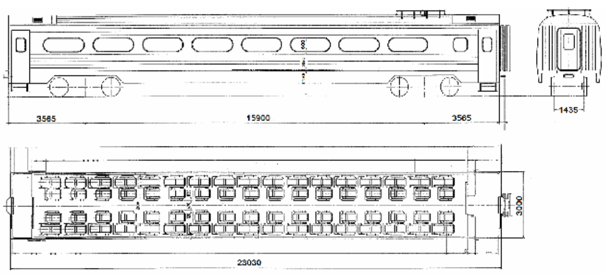

Fig. 1. Design of tested railcar.

2. HRR curve from full-scale fire test

2.1 Railcar descriptions

A full-scale fire test of a Korean railcar was carried out in the tunnel test facility of Carleton university in December 2010. The railcar was 3 m wide, 3.4 m high, and 23 m long, and was equipped with 68 passenger seats. Fig. 1 shows the railcar design. The interior materials used for the railcar included polyester fiber-reinforced plastic (FRP) wall panels, polyvinyl chloride (PVC) floor covering, glass fiber insulation, urethane foam (seats), and polyester fiber (seat covers). The details of these and of other materials are summarized in Table 1. Eighteen panes of tempered double-pane window glass

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Table 1. HRRPUA and fire load of interior materials.

Interior	Material	HRR [MJ/m^2]	Applied area [m^2]	Fire load [MJ]
Wall panel	FRP	58.5	63.5	3714.75
	PE foam	88	63.5	5588
Ceiling panel	MPAL	10	54.24	542.4
Coving and lack	MPAL	10	34.74	347.4
Floor center	PVC	50.2	18.08	907.62
	Adhesive	12.7	18.08	229.62
	plywood	85.3	18.08	1542.22
	PE foam	88	18.08	1591.04
Floor side	PVC	22.2	45.2	1003.44
	Adhesive	12.7	45.2	574.04
	plywood	85.3	45.2	3855.56
	PE foam	88	45.2	3977.6
Partition	MPAL	10	75.68	756.8
Seat base	PE moquette	6.1	32	195.2
	PU foam	88	32	5256.53
Seat back	PE moquette	6.1	40.32	245.95
	PU foam	88	40.32	9461.76
Foot rest	ABS plastic	113	9.6	1084.8
Seat arm	Integral skin foam	152.6	6.08	927.81
Seat back panel	ABS plastic	113	17.6	1988.8
Seat side cover	ABS plastic	113	12.16	1374.08
Seat leg rest	PE moquette	6.1	8.32	50.752
	PU foam	88	8.32	1366.7
Total				46,583

were set in both sides of the vehicle. The car also had two mid-gate doors between the passenger quarters and service areas, one door at each end of the car, and four side doors for passenger entry and exit.

Table 1 also lists the total fire load calculated based on the area of each material used in the car. The total fire load of this railcar was 46.58 GJ, which would not be totally burned even in severe fire.

2.2 Fire scenario

A stair-type flame output with propane gas with a 0.7 m^2 square sand burner was used based on fire scenario EN 45545-1 (railway applications - fire protection of railway vehicles - part 1: general) (Annex A and Fig. 2). The burner was placed between the rear side seats (Fig. 6) to create a spreadable flame. The doors on both ends of the railcar were closed to prevent a blowing effect. However, the two side doors were opened to simulate emergency evacuation.

2.3 Test results

The test facility, which was uses the oxygen consumption method, measured the oxygen, carbon monoxide, and carbon dioxide concentrations to calculate the heat release rate (Eq. (1)) [4]. This test facility was designed to measure gas concentrations with a sophisticated sampling probe in the pathway of the combustion gas. The uncertainty of the test facility presented by the equipment operator ranged from 10% to 15% [5].

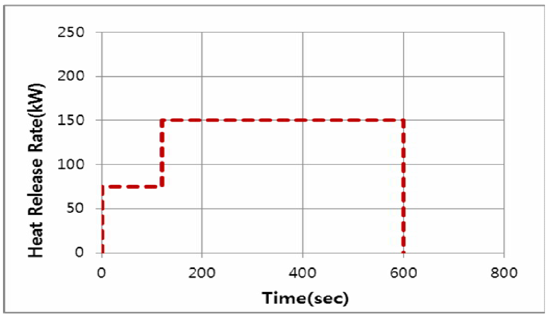

Fig. 2. Burner output scenario of EN 45545-1.

Fig. 3. 170 s after ignition (HRR: 1 MW).

Fig. 4. 1180 s after ignition (HRR: 32 MW).

$$\dot{Q} = \left[E_{O2} - (E_{CO} - E_{O_2}) \frac{(1-\phi)}{2\phi} \frac{X_{CO}^{Ae}}{X_{O_2}^{A0}} \right] \phi \frac{\dot{m}_e}{1+\varphi(\alpha-1)} \frac{M_{O_2}}{M_a} (1 - X_{H_2O}^{O}) X_{O_2}^{A0} \quad (1)$$

where

$$\phi = \frac{X_{O_2}^{A0}(1 - X_{CO_2}^{Ae} - X_{CO}^{Ae}) - X_{O_2}^{Ae}(1 - X_{CO_2}^{Ao})}{(1 - X_{O_2}^{Ae} - X_{CO_2}^{Ae} - X_{CO}^{Ae}) X_{O_2}^{A0}}$$

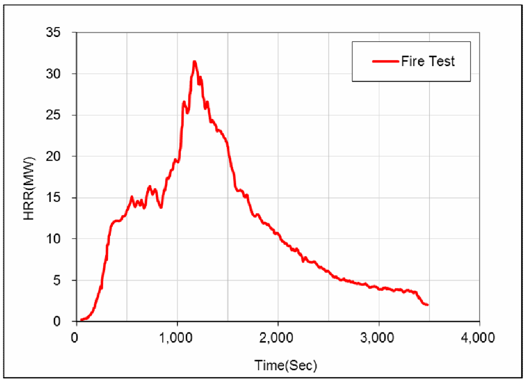

Fig. 5. HRR curve from the real-scale fire test.

$$X^{o}_{H_2O} = \frac{RH p_s(T_0)}{p_a} = \frac{RH}{p_a} EXP(23.2 - \frac{3816}{-46 + T_0})$$
$$\approx \frac{RH \times 2.5\text{kPa}}{101.5\text{kPa}} = 0.0123$$
$$M_a = M_{dry}(1 - X^0_{H_2O}) + M_{H_2O} X^0_{H_2O} .$$

Numerous thermocouples were installed on the interior and in the cabin to measure the surface temperature of the interior panels and the inner space of the cabin while the fire developed. Flame propagation was observed using six cameras. Flashover occurred at 170 s with the visible flame extending out of the enclosure with an HRR pass over 1 MW (Fig. 2) [6]. The widespread destruction of the windows followed the flashover, and the fire curve quickly shifted upward again to its peak level.

The peak HRR was 32 MW at 1180 s (Fig. 3), and the total heat release from this fire curve was calculated as 38.6 GJ by taking the area under the fire curve.

3. HRR Estimations

3.1 Calculation from burning area observations

Lee et al. (2009) reported that the HRR of a fire can be calculated based on the surface burning area, which was experimentally obtained [7]. Based on this method, the HRR at any time can be calculated by the product of the HRR per unit area (HRRPUA) and the burning area at that time step. The burning area of an interior can be determined by actual measurements during a fire test. This methodology refined the summation method as Eq. (2):

$$\dot{Q}(t) = \sum_{i}^{m} \sum_{j}^{t \le t_j} \dot{q}(t - t_j) \times A_{ij}(t) \tag{2}$$

where

$\dot{q}(t)$ is the HRRPUA

i is the interior number

m is the total number of interiors

j is the time step

$A_{ij}(t)$ is the burning area of i at j .

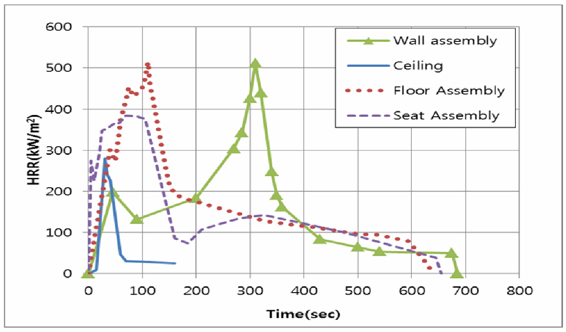

Fig. 6. HRRPUA of interior surfaces.

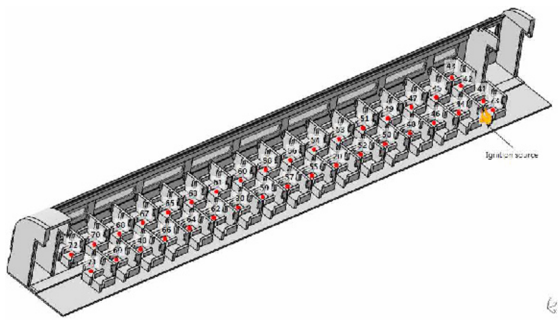

Fig. 7. Ignition burner and temperature measuring points for seats.

The HRRPUA method requires the HRRPUA curve of each flammable material. The HRRPUA curve of each surface was evaluated using a cone calorimeter based on ISO 5660-1 (reaction-to-fire tests - heat release, smoke production and mass loss rate - part 1: heat release rate). Given that the HRRPUA model does not allow multi-layers, every surface should be assembled as in Fig. 6.

All interior surfaces were divided into appropriate sizes, which were considered as simultaneous burning areas, to determine the total burning area. Approximately 100 K-type thermocouples were fitted on each division of the seats, wall, ceiling, and floor. The thermocouple points for the seats are shown in Fig. 7.

A drastic surge of surface temperature from a thermocouple was considered as an occurrence of ignition in that area. Every numbered line in Fig. 8 matches with the thermocouple number in Fig. 7, and shows the different ignition times of the seats.

The HRR curve of the railcar was determined using the burning area-based calculation method (Fig. 9). The peak HRR was 50.5 MW at 1211 s, and the total heat release from this fire curve was 34.7 GJ.

3.2 FDS model calculations

In using the CFD code application for the HRR estimation,

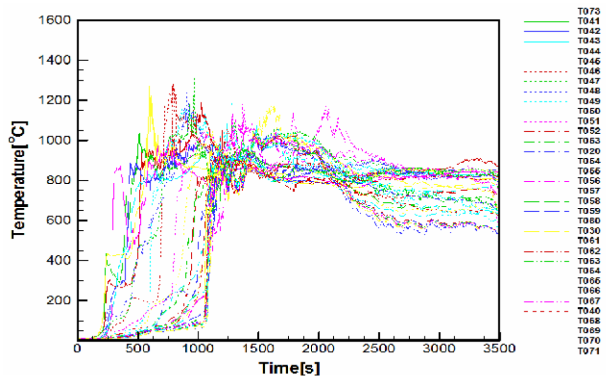

Fig. 8. Surface temperatures of seats.

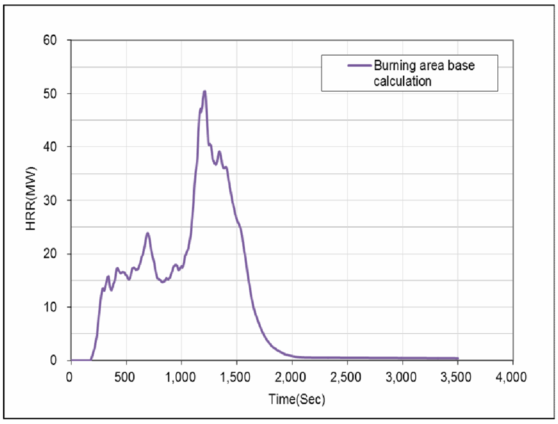

Fig. 9. Fire curve estimation from burning area-based calculation.

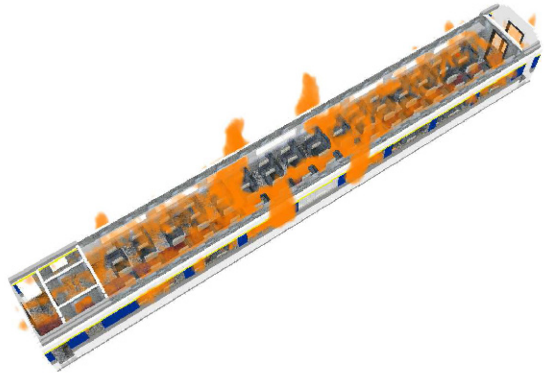

Fig. 10. Fully developed fire in HRRPUA model simulation.

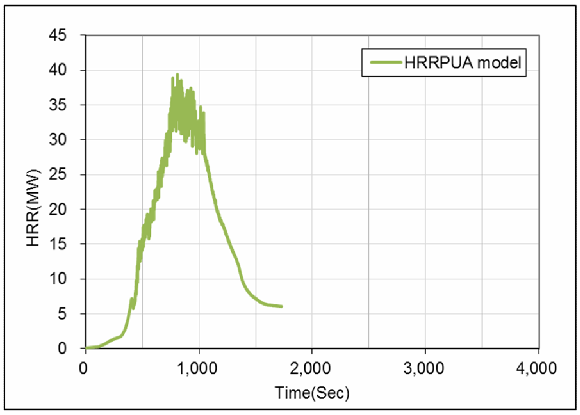

Fig. 11. Fire curve estimation by the HRRPUA method.

FDS 5.3 was used for the simulation. FDS uses a hydrodynamic model that includes large eddy simulation turbulence and accounts for radiation heat transfer with the finite volume method. FDS also uses the mixture fraction combustion model. The main governing equations of FDS are Eqs. (3)-(7). These equations are explained in detail in Ref. [4].

Mass transport

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho U = \dot{m}''' . \quad (3)$$

Species transport

$$\frac{\partial (\rho Y_\alpha)}{\partial t} + \nabla \cdot \rho Y_\alpha U = \nabla \cdot \rho D_\alpha \nabla Y_\alpha + \dot{m}_\alpha''' + \dot{m}_{b,\alpha}''' . \quad (4)$$

Momentum transport

$$\frac{\partial (\rho U_\alpha)}{\partial t} + \nabla \cdot \rho U U + \nabla p = \rho g + f_b + \nabla \cdot \tau_{ij} . \quad (5)$$

Energy transport

$$\frac{\partial (\rho h_s)}{\partial t} + \nabla \cdot \rho h_s U = \frac{Dp}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla \dot{q}''' + \varepsilon . \quad (6)$$

Equation of state

$$p = \frac{\rho R T}{\overline{W}} . \quad (7)$$

The analytical space domain was set to be 5 m wide, 5 m high, and 32 m long. Thus, this adequate longitudinal space ensures that flame radiation and smoke are adequately reflected in the calculation. The grid size was set to 0.1 m to satisfy Eq. (8), in which the characteristic fire diameter is defined by Eq. (9).

$$\left(\frac{D^*}{\delta x} \right) \approx 10 \quad (8)$$

$$D^* = \left(\frac{\dot{Q}}{\rho_0 T_0 C_{p0} \sqrt{g}} \right)^{\frac{2}{5}} . \quad (9)$$

3.2.1 Estimation with HRRPUA method

The use of the HRRPUA model in FDS is principally same as in the burning area-based calculation method (section 3.1). The FDS program enables this process in a microscopic level within the specified grid size. The HRRPUA curves in Fig. 6 were inputted for the interior surfaces for the railcar fire simu-

Table 2. Material properties for HRRPUA model simulation.

Interior structure	Wall assembly	Floor assembly	Ceiling	Seat assembly
Material	FRP + PE foam	PVC + plywood + PU	MPAL	Polyester moquette + PU + steel
Thickness (m)	0.035	0.058	0.002	0.036
ρ (kg/m³)	183.4	270	2787	412.9
Cp (kJ/kgK)	1.904	1.67	0.9	0.98
k (W/mK)	0.0198	0.0309	204	0.0197
Ignition temperature (°C)	454	487	475	496

lation. However, instead of observing surface temperature by using thermocouples and video cameras, the ignition temperature of each material determines material ignition. Therefore, the reliability of the ignition temperature is essential to this estimation. We carefully tested the ignition temperatures based on ISO 871 (plastics - determination of ignition temperature by using a hot-air furnace).

Other material properties, such as thermal conductivity, specific heat, and density, are necessary to calculate for the variation in surface temperature in the railcar model. Table 2 lists the material properties for this simulation. The windows were set to break out at 600°C for increased ventilation during fire development.

The results of the HRRPUA model simulation are shown in Figs. 10 and 11. The peak HRR was 39.4 MW at 809 s, and the total heat release from this fire curve was 25.5 GJ.

3.2.2 Estimation via the pyrolysis method

Deriving the fire curve based on the thermal pyrolysis model requires the effective heat of combustion from the interior materials and physical values, as shown in Table 3. Test equipment, such as a thermo-gravimetric analyzer and a differential scanning calorimeter, were used to obtain the physical values of each material. The fire curve was predicted by applying a thermal decomposition model to the same scenario and fire source.

Although the thermal pyrolysis model uses a microscopic approach and maintains microscopic rigor, it holds that any microscopic error is cumulative. The prediction results are shown in Fig. 12. The peak HRR was 20.1 MW at 1268 s, and the total heat release from this fire curve was 34.8 GJ.

4. Discussion

The peak HRR with the HRRPUA model in FDS simulation was more consistent with the actual fire. However, the total heat release with the pyrolysis model was more consistent. Flashover time, peak HRR time, and total heat release with the burning area-based calculation method were better than those obtained from other methods. Table 4 summarizes the results of the three different approaches for the HRR curve estimation of intercity railcar fire.

Table 3. Material properties for pyrolysis model analysis.

Interior structure	Wall panel	Floor covering	Ceiling panel	Seat		
				Cover	Cushion	Back panel
Material	FRP	PVC	MPAL	Polyester moquette	PU fFoam	ABS plastic
Thickness (m)	0.005	0.006	0.002	0.005	0.03	0.004
ρ (kg/m³)	1164	721	2787	157	116	905
Cp (kJ/kgK)	1.84	1.5	0.9	1.3	2.45	1.2
k (W/mK)	0.406	0.315	204	0.058	0.017	0.282
Heat of comb. (kJ/kg)	12,554	18,415	15,030	10,226	28,783	32,506
N_fuel	0.8	0.63	0.16	0.76	0.88	0.96
N_ residue	0.2	0.37	0.84	0.24	0.12	0.04
Heat of reac. (kJ/kg)	1,390	900	1,000	3,000	1,500	3,000
Pre-exp. factor	8.96E+03	3.36E+03	3.00E+12	5.93E+08	3.19E+15	1.93E+17
Activation E (kJ/kmol)	78983	66512	185000	149652	224478	249420

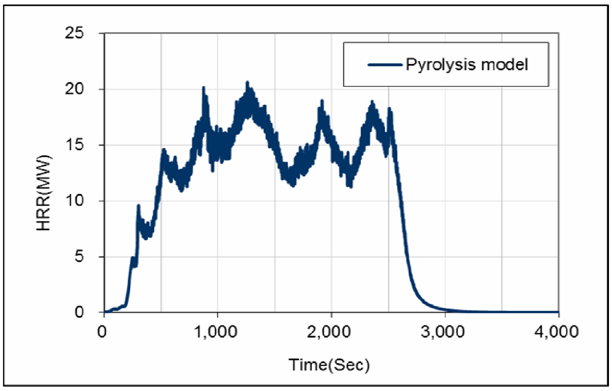

Fig. 12. Fire curve estimation via the pyrolysis method.

Estimations by the burning area-based calculation method from actual measurements were closest to the test curve for the developing stage, whereas those based on the FDS models showed somewhat greater differences from the actual measurements. The pyrolysis model could not produce a sharp increase such as in the actual fire curve. Every model calculation showed numerous differences for the stage after the peak HRR level. These model calculations did not reflect the decay of the fire curve in the declining stage because of the combustion of core materials in actual fire given that they only considered surface combustions.

Table 4. Results of three approaches.

	HRRPUA model	Pyrolysis model	Burning area-based calculation	Fire test
1 MW flash-over time (s)	204	195	192	173
Peak HRR (MW)	39.4	20.1	50.5	32.0
Peak HRR time (s)	809	1268	1211	1180
Total heat release (GJ)	25.5	34.8	34.7	38.6

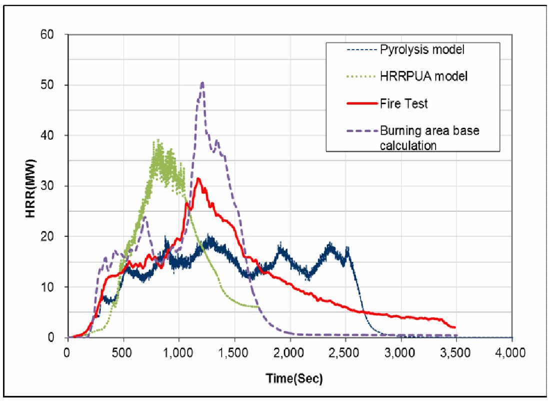

Fig. 13. Fire curves from models and actual fire test.

5. Conclusion

This study compares fire curves derived through experiment and model calculations. The physical properties of combustible materials determined the reliability of the results of FDS simulations. The burning area-based calculation method was more consistent with the real fire curve compared with other approaches. All estimations had limitations in reproducing core material combustion. These experimental results and estimations are expected to contribute to the development of a simpler method for curve estimation of railcar fires without expensive fire tests.

Acknowledgments

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Nomenclature

C_p : Specific heat
D^* : Characteristic fire diameter
k : Thermal conductivity
$\dot{m}$: Mass flow rate
M_a : Molecular weight of element *a*
p_i : Partial pressure of species *i*
$\dot{q}$: HRRPUA
$\dot{Q}$: HRR
RH : Relative humidity
T : Temperature
U : Fluid velocity
X_i : Molar fractions of species *i*
ρ : Density

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