 SL, vol.7, no.3, pp.161-166, 2012

Application Study of Burning Area-Based Summation Method for Fire Curve Estimation

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Abstract: To estimate heat release rate (HRR) for a large structure with a full-scale fire test using the oxygen consumption method, a large calorimeter is used to inhale all combustion gas from combustibles. However, it is hard to inhale all combustion gas into the calorimeter completely. In this case, the summation method is effective because it estimates the HRR of the test subject by sum the HRR of small specimens. This study assumed the HRR fire curves of a simple single sheet material, a train seat assembly, and a room-scale train saloon mockup using a compensated burning area-based summation method, and then compared the results with the results of simple summation and fire tests to review the application of the method.

Keywords: heat release rate, burning area based summation method, ISO 9705 fire test

1 Introduction

To design the fire resistance and smoke control capacity properly in places with high risk of fire such as long tunnel or underground shopping area, there is a need to estimate the accurate potential fire size. Note, however, that the size estimation of a full-scale fire using an experiment is very expensive because of the large-scale test equipment needed. Therefore, the simple estimation method for full-scale fire curve using the result of small specimen has been researched for a long time Nowadays, fire modeling analysis using CFD model is frequently used with material properties [Chiam, B. H. (2005)]. This study introduced a summation method that estimates the full HRR curve using only HRR of each combustible specimen measured by cone calorimeter without large scale calorimeter. In this calculation, the areas of each materials used in an assembled product and evaluated ignition times of every divided area are needed. Tree cases of fire curve estimation will be compared to

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that of real fire tests to review the application probability of the burning area-based summation method.

2 HRR estimation for three fire tests

2.1 Outline of the burning area based summation method

The HRR generated from combustibles is calculated by multiplying the effective heat of combustion (ΔH_c) by the pyrolysis rate per unit area of combustibles ($\dot{m}''$) and the burning area (A) as shown in equation (1). It can be rearranged like equation (2) with $\dot{q}(t)$ taken from cone-calorimeter test which means the HRR of unit area of the material to the time variation. Therefore, if it is possible to calculate the burning area (Aij) over time using burning behavior analysis of full scale test case, burning area-based HRR estimation can be performed as in equation (3).

$$\dot{Q}(t) = \dot{m}''(t) A(t) \Delta H_c \tag{1}$$

$$\dot{q}(t) = \dot{m}''(t) \Delta H_c \tag{2}$$

$$\dot{Q}(t) = \sum_{i}^{m} \dot{q}(t) A_i(t) \tag{3}$$

This method is called by summation method because it sums the heat release rate of all interior materials. The first simple summation method consider just the total area of each materials [Duggan, Gary.J.(1997)]. So, this simple summation method can assume the fire curve empirically from the measured HRR of individual materials, but it also contains an irrational assumption, i.e., all materials in the vehicle burn simultaneously. The burning of combustible materials starts at different times based on the scenario of the fire's progress. In particular, in a long place such as a train, it is harder for all materials to be burned simultaneously. To correct it, Dowling, et al assumed that combustion progresses to the length of the vehicle at 10% per minute.[N.White, V.Dowling, J.Barnett(2005)] Note, however, that the actual fire does not progress at a certain ratio. To resolve this problem rationally, Lee et al suggested a flaming area-based HRR estimation method based on experimental fire behavior as a modified summation method as equation (5)[D.H Lee et al(2009)]

$$A(t) = \sum_{i}^{m} \sum_{j}^{t_j \le t} A_{ij}(t) \tag{4}$$

$$\dot{Q}(t) = \sum_{i}^{m} \sum_{j}^{t_j \le t} \dot{q}(t - t_j) \times A_{ij}(t) \tag{5}$$

In these equations, i mean the number of each material, and j is a subscript of time sequencing. For example, t_j is the time the fire is generated in Aij.

For the corrected summation method, now it will be better to call burning area instead flaming area, it is also hard to reflect the effects of the ventilation structure because it still relies on the test result of specimens. In addition, the evaluation of oils at the bottom of the floor or core materials in the structure may be omitted because of the difficulty of extracting specimens. It is also difficult to evaluate the burning area in a complex structure or with burning core materials. This study reviewed the range of deviation calculated by the burning area-based HRR estimation model with simple flat tests free from the aforesaid problems as well as complex combustion tests for the train's interior materials HRR estimation model. Each test was conducted within ISO 9705 room corner test equipment.

2.2 Application to the surface fire with cardboard

The first application case was the cardboard installed at the end of the room corner equipment as shown in Fig. 1. It was burned with 100kW Heptane pool. The cardboard had density of 0.178 g/cm^3, burned after 5 seconds when exposed to 50kW radiation using cone calorimeter, and showed maximum HRR of 190kW/m^2 after 9 seconds at that specimen test. Tab. 1 shows the time step and burning area calculation from video analysis of the test.

Table 1: Burning area observation for the cardboard fire test

Time step [i] [sec]	Left panel fire[m^2]			Center panel fire[m^2]			Right panel fire[m^2]			Total area [Aij]
	Width	Height	Area	Width	Height	Area	Width	Height	Area	
t_1=45	0.5	0.5	0.069							0.069
t_2=50	0.5	0.2	0.028							0.028
t_3=55	0.2	0.7	0.039							0.039
t_4=60	0.2	0.5	0.028							0.028
t_5=65	0.7	0.2	0.039							0.039
t_6=70	1	0.4	0.110	0.5	0.3	0.041				0.152
t_7=75	1	0.2	0.055	0.5	0.4	0.055				0.110
t_8=80	1	0.2	0.055	0.7	0.4	0.077				0.132
t_9=85	1	0.2	0.055	1	0.2	0.055				0.110
From t_1=90 to t_{27}=180 step is abbreviated										
t_{28}=190			0.00	0.2	0.8	0.044	0.1	2	0.055	0.099
t_{29}=200			0.00			0.00	0.1	2	0.055	0.055
t_{30}=220			0.00			0.00	0.1	0.5	0.014	0.014
Sum[m^2]			1.35			1.265			1.240	3.854

The measured peak HRR from the fire test is 433.2kW at 150 seconds, and that calculated by the burning area based summation method is 416.8kW at 166 seconds. The difference is about 3.8%. For the fire developing step, the estimated increasing ratio value is very similar to the test value; for the descent stage, however, it is a little slower than the real test case.

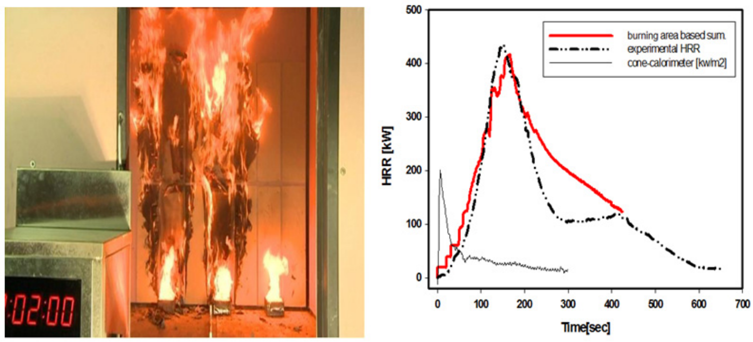

Figure 1: Cardboard fire test and HRR estimation

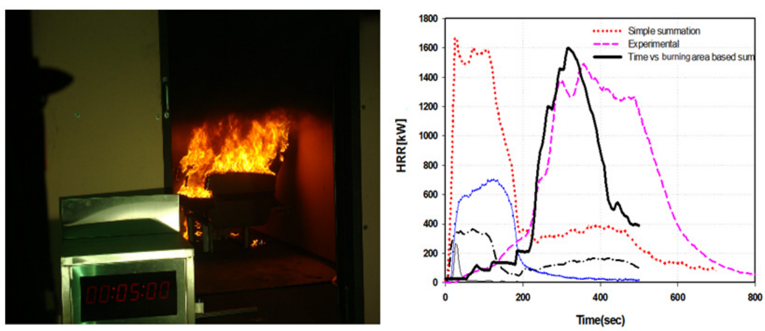

Figure 2: Seat fire test and HRR estimation

2.3 Application to the seat assembly of train

The second model of application was the seat assembly of intercity passenger train installed in the room corner as shown in Fig. 2. It was burned with 200kW Heptane pool. The seat consists of back and armrests made of polyester moquette, polyurethane cushion, and ABS resin frame body. The maximum HRR was 1.49MW at 317sec. HRR calculated by the burning area-based method was

1.54MW at 310 seconds or 3.3% higher. HRR calculated by the simple summation method was 1.672MW at 25 seconds. The test value and results of the simple summation method and the burning area-based summation method are indicated together to find out the improvement. Burning area was analyzed by videos in this case.

2.4 Application to the mockup test of the train saloon

Next application test was conducted for the train saloon mockup with complex structure and interior materials. The interior materials were collected from used trains. Two sets of seat made of polyester-reinforced plastic, polyester moquette and polyurethane cushion, polyvinyl chloride flooring materials, and polyethylene insulator were installed. The size of the 9705 room was 2.4m×3.6m×2.4m; therefore, the width of the train was reduced to match the test equipment. The ignition source was a step fire source in accordance with CEN/TS 45545-1. As shown in Fig. 3, the sand burner was located at the corner wall of the train saloon and lower front of the chair, exposed to 75kW for the first 2 minutes, and maintained as 150kW for 8 minutes. Though the test result provides information on the initial progress because sprinkler activated at 186 seconds due to the limit of test equipment, the fire showed rapid increasing curve after 120 seconds, and flashover of 2.2MW was determined. According to the research of Peacock(1945), radiation of 50kW was applied to wall and ceiling materials, and 25kW was applied to flooring materials at cone calorimeter specimen test. The burning area was analyzed by the videos and surface temperature measuring for the interior parts with thermocouples. The graph of advanced estimation method show the estimated heat release value 1.85MW which means 18% lower to the tested value at 186 seconds

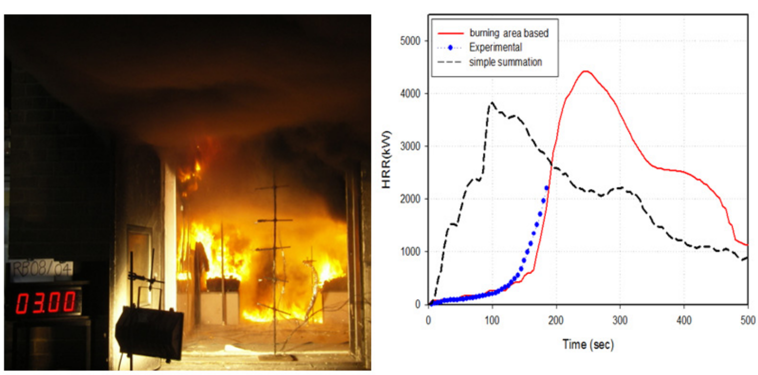

Figure 3: Train saloon mockup fire test and HRR estimation

3 Conclusions

Three surface fire tests and fire curve estimations with HRR summation method were carried out. The estimated HRR fire curve for cardboard, seat of train, and train saloon mockup interior material fire by the burning area-based summation method nearly matched the result of each fire test. For the peak HRR value, the estimated difference to the test results shows from 3.3 % to 18% along the test case. For cardboard fire case the estimation fire curve can't follow the test curve at decent stage. In the estimation of complex structures and materials such as mockup of the train interior materials was bigger owing to the difficulty in evaluating the burning area accurately and the limit of the summation method itself which is based on the HRR of the specimen test. Nonetheless, the burning area-based HRR estimation method can be considered as an effective method that can estimate fire curve only with the HRR data of specimens and video images of the test subject's fire without large test equipment.

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