Quantitative Study on the Effect of Large Fire Thermal Radiation on Combustion Performance of Materials Used in Japanese Railway Rolling Stock

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In Japan, materials used in railway rolling stock are classified according to their behavior during Japanese standard fire tests for railway rolling stock materials in accordance with the relevant Ordinances. Fire test standards were established to contribute to rolling stock safety from fire. However, the thermal radiation cited in standard fire tests is relatively low and some criteria are only qualitative. A number of serious fires over the past few years demonstrated that some test conditions in the standard fire tests were underestimated. Consequently, this illustrated the importance of conducting a quantitative study to examine the effect of thermal radiation from large fires on the combustion performance of materials used in railway rolling stock. Cone calorimeter fire tests were therefore carried out to investigate the impact of large thermal radiation on a series of products used in rolling stock.

Keywords: railway fire, combustion performance, cone calorie meter fire test

1. Introduction

Materials used in Japanese railway rolling stock must satisfy requirements defined in Ordinances issued by the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Standard fire tests for railway rolling stock materials are also stipulated in MLIT Ordinance No. 151 [1].

Standard fire tests are performed with an alcohol lamp assuming a small fire such as cigarette fire. Materials are then graded based on the results of these standard tests and their behavior, according to four combustion classes: combustible, fire retardant, quasi-noncombustible, and noncombustible. Combustible materials cannot be used for railway rolling stock. For instance, fire retardant materials can be used as seat moquette or floor covering and noncombustible materials can be employed on walls and ceilings [2].

The standard fire tests are straight forward and quick. Nonetheless the thermal radiation value applied in these standard tests is relatively low and some criteria are only qualitative. Consequently, it was considered important to conduct a quantitative study on the effect of large fire thermal radiation on the combustion performance of materials used in railway rolling stock.

This study used a cone calorimeter (CCM fire test) to carry out the fire tests for large fire thermal radiation on materials used for rolling stock interiors [3]. The quantitative combustion performances of the products were evaluated. Test specimens were irradiated with varying heat fluxes during the CCM tests. The measured combustion performances and quantitative classifications according to the Japanese standard grades were also examined.

2. Effect of large fire radiation on the combustion performance of materials used in railway rolling stock

2.1 Features of CCM fire testing

CCM fire tests are used to quantitatively evaluate the heat release rate (HRR) and smoke production rate (S’’) of materials during combustion when irradiated with heat fluxes in a cone-shaped heater (Fig.1). Specifications for CCM appear in ISO 5660, and it is used as one of the main pieces of equipment for the fire testing of railway rolling stock materials outside Japan. CCM fire tests were introduced into Japanese standards for fire testing in 2004, following a recast of tests after the fire on the Daegu subway (Korea) in 2003. Since then, CCM fire testing has been used to test the ceiling materials used in passenger cars on subways and bullet trains, etc, assuming the conditions of high thermal radiation from large fires. These fire tests have been used. CCM fire testing includes the following characteristics:

- Adjustable flux used to irradiate the test specimen, by changing the heater output.
- Simultaneous measurement of the calorific value, smoke density and production of gases (CO, CO2) throughout the test.
- Measurement of loss of mass during tests through the load cell.
- The test produces quantitative results, which are not influenced by whoever is performing the tests.

Given these characteristics, CCM was applied in this study to examine the effect of heat radiation from large fires on the combustion performance of materials.

2.2 Test specimens

The test specimens were selected from materials currently used on railway rolling stock in Japan. Table 1 provides a list of the test specimens used.
Poly vinyl chloride-based (PVC) floor coverings, rubber-based floor coverings, carpet material, and seat moquette were selected as fire retardant materials. Decorative board, aluminum (Al)-resin laminated board, and aluminum (Al)-foam resin laminated board were selected as noncombustible materials. Of these materials, decorative board and Al-resin laminated board already satisfy the revised CCM fire test. They can be used as ceiling materials in passenger cars on subways or bullet trains, etc.

The distinction between Al-resin and Al-foam resin lies in the difference in the resin conditioning. Al-resin is actually laminated with solid resin which has not been foamed, whereas Al-foam resin is laminated with foamed resin.

### Table 1 Test specimens

| Category | Item No. | Product name | Use | t/mm | m/g | Constitution in order of proximity to heater |
|----------|----------|--------------|-----|------|-----|--------------------------------------------|
| Fire retardant | R1 | PVC floor coverings, | floor | 2.5 | 31 | PVC sheet Glass fiber cloth |
|          | R2 | Rubber-based floor coverings | | 2.0 | 47 | Fire retardant rubber |
|          | R3 | Carpet material | | 6.0 | 48 | Polyester fiber rubber base |
|          | R4 | Seat moquette | seat | 3.0 | 6.0 | Polyester fiber |
| Noncombustible | N1 | Decorative board | wall | 1.9 | 33 | Decorative sheet AL board |
|            | N2 | Al-resin laminated board | ceiling | 3.0 | 58 | Painting AL board resin AL board |
|            | N3 | Al-foam resin laminated board | wall | 7.9 | 55 | Decorative sheet AL board foam resin AL board |

#### 2.3 Test method

The size of the test specimens was 100 mm × 100 mm, and thicknesses as shown in Table 1. The test specimen was fixed to a stainless steel holder and placed 25 mm directly below the cone heater as shown in Fig. 2. At the beginning of the CCM tests, the separator between the heater and test specimen is removed to commence irradiation of the specimen with the heat flux. At the same time, an electric spark 10 mm below the cone heater as shown in Fig. 2. At the beginning of the CCM fire test, the separator between the heater and test specimen ignites combustible gases produced. In addition to a heat flux of 50 kW/m² applied to a specimen of ceiling material of the kind employed in subways or bullet trains, a heat flux of 70 kW/m² was also applied to create the higher level of radiation associated with a large fire. In order to compare combustion performances, tests were also performed with heat fluxes of 15 and 35 kW/m².

CCM fire testing is not required for fire retardant materials in Japanese fire testing standards, therefore a heat flux of 50 kW/m² is already a very high level of radiation for fire retardant materials.

#### 2.4 Evaluation item

##### 2.4.1 Combustion product composition

Data was collected on the composition of combustion products to measure the ratio of each product in the composition.

#### 2.4.2 Heat release rate

In CCM fire testing, the heat release rate (HRR) is determined by the “oxygent consumption method” [4]. The calories produced through combustion change significantly depending on the mass of the material. However, the heat of combustion per unit mass of consumed oxygen is fairly constant at 13.1 MJ per 1 kg of oxygen, irrespective of the type of substance [5].

Figure 3 (a) shows the evaluated items: ignition time (s); maximum heat release rate (HRRmax); and, total heat release (THR). The data presented in this paper is the average of three measurements taken for each test specimen. Tests lasted 10 minutes. If the test specimen continued to combust after 10 minutes, the test was allowed to continue until extinction of the test specimen.

##### 2.4.3 Smoke production rate

The smoke from combustion of the test specimen passed through an exhaust duct and was monitored by the irradiation of a laser beam through the smoke. Smoke production was evaluated on the basis of alterations in the transmittance of the laser beam.

Figure 3 (b) shows the evaluated items: maximum smoke production rate (Smax), the total smoke production (TSP).

The evaluation time in this test was similar to time for the heat release rate measurements.

#### 2.5 Result of test to evaluate effect of thermal radiation of a large fire on the combustion performance of materials used in railway rolling stock

##### 2.5.1 Fire retardant materials

The appearances of the fire retardant test specimens

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The flux of 50 kW/m² used for the HRR is greater than the heat radiation using alcohol of the Japanese standard fire testing method, therefore, the resulting ignition times of the test specimens were shorter. The higher level of heat radiation accelerated combustible gas production from the test specimen, and the combustion range of the gas was reached more quickly. Compared to the flux of 50 kW/m², the ignition times with a flux of 70 kW/m² were even shorter, and the HRRmax was higher. The increase in HRRmax is due to the accelerated, higher production of combustible gas due to the larger heat radiation. In addition, in the case of PVC floor coverings, the THR increased based on the increase in combustible gas in accordance with the increase in radiated heat flux. With respect to the smoke production rate, by comparison with a flux of 50 kW/m², with a flux of 70 kW/m², TSP appeared to decrease. Smoke was produced for a shorter length of time when thermal decomposition was faster due to the larger heat radiation, therefore, at peak $S''_{max}$ indicated earlier, the TSP was similar or smaller.

The appearance of the noncombustible material test specimens before and after combustion are shown in Table 2. The corresponding test results are shown in Figs. 4-7. Table 3 summarizes the ignition time(s), HRRmax (kW/m²), THR (MJ), $S''_{max}$ (m²/m²/s), and TSP (m²/m²).

### Table 2 Appearance of fire retardant materials before and after CCM fire test

|      | R1 | R2 | R3 | R4 |
|------|----|----|----|----|
| Before | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |
| After  | ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |

Fig. 4 Result of CCM fire test for fire retardant materials (HRR · Radiated heat flux 50 kW/m²)

Fig. 5 Result of CCM fire test for fire retardant materials (HRR · Radiated heat flux 70 kW/m²)

Fig. 6 Result of CCM fire test for fire retardant materials ($S''$ · Radiated heat flux 50 kW/m²)

Fig. 7 Result of CCM fire test for fire retardant materials ($S''$ · Radiated heat flux 70 kW/m²)

### Table 3 Result of CCM fire test for fire retardant materials

| Radiated heat flux (kW/m²) | Combustion component | Ignition time (s) | HRRmax (kW/m²) | THR (MJ) | $S''_{max}$ (m²/m²/s) | TSP (m²/m²) |
|---------------------------|----------------------|------------------|----------------|----------|-----------------------|------------|
| 50                        | R1 (PVC floor coverings) | 0.85             | 17            | 322      | 39                    | 41         |
| 70                        | R2 (rubber-based floor coverings) | 0.91             | 11            | 429      | 45                    | 51         |
| 50                        | R3 (carpet material) | 0.48             | 37            | 330      | 48                    | 4.9        |
| 70                        | R4 (seat moquette) | 0.51             | 26            | 405      | 49                    | 5.9        |

### 2.5.2 Noncombustible material

The appearance of the noncombustible material test specimens before and after combustion are shown in Table 4. The corresponding test results are shown in Figs. 8-11. Table 5 summarizes the ignition time (s), HRRmax (kW/m²), THR (MJ), $S''_{max}$ (m²/m²/s), and TSP (m²/m²).

Noncombustible materials are not ignited and combusted in Japanese standard fire tests using alcohol. In CCM fire testing, however, ignition and combustion verifications are made. CCM fire testing is applied as the standard test for combustion resistance in Japan, and decorative board and the AL-resin laminated board satisfy the criteria shown in Table 5. In the case of the AL-resin laminated board, the ignition time was significantly shorter despite having the same structure as AL-resin laminated board. When the foamed resin was irradiated...
with the heat flux, it melted and shrank significantly. Consequently, it was unable to support an aluminum plate: the aluminum plate was deformed, which caused the ignition to the internal resin layer. In the case of decorative board and AL-foam resin laminated board, there was almost no change in the combustion component, which is thought to explain why only a small change in THR was observed, irrespective of the radiated heat flux.

The HRRmax rose as the radiated heat flux was increased. This behavior is based on the faster release rate of combustible gases produced by rapid thermal decomposition as the radiated heat flux was increased, and combustion propagated rapidly.

In the case of AL-resin laminated board in particular, despite almost no change in the combustion component, as shown in Table 6, the THR increased and the HRRmax decreased. With respect to the THR, the ignition time was relatively long and combustion lasted over 10 minutes in the case of 50 kW/m². These results were not covered by standard evaluation. With respect to the HRRmax, irradiation with a heat flux of 50 kW/m² deformed and cracked the aluminum plate, slowing ignition, melting, and combustion of the resin. However, the ignition time was faster at 70 kW/m², which suggests that combustion started even though the resin was not sufficiently melted. The decrease in HRRmax with larger heat radiation is based on these behaviors.

$S''_{\text{max}}$ results were similar for both 70 kW/m² and 50 kW/m² for the decorative board and the AL-foam resin laminated board. This is thought to be because of the smaller amount of combustion products generated than with fire retardant materials, and the lower likelihood of incomplete combustion. On the other hand, in the case of AL-resin laminated board, a decrease in $S''_{\text{max}}$ was observed as the radiated heat flux increased. This was also due to the faster release rate of combustible gas produced by faster thermal decomposition as the radiated heat flux increased, as described previously. The TSP decreased with all test specimens. The combustible component of the noncombustible product was small. Therefore, there should have been less incomplete combustion after the test specimen was thermally decomposed and partially combusted.

Table 4 Appearance of noncombustible materials before and after CCM fire test

|               | N1 | N2 | N3 |
|---------------|----|----|----|
| Before        | ![Image](before.png) | ![Image](before.png) | ![Image](before.png) |
| After         | ![Image](after.png) | ![Image](after.png) | ![Image](after.png) |

Table 5 Combustion resistance criteria for materials used for ceiling materials in passenger cars, on subways and bullet trains, etc., in Japan

| THR (MJ/m²) | Ignition time (s) | HRRmax (kW/m²) |
|-------------|-------------------|----------------|
| $\geq 8$    | -                 | $300 \leq$     |
| $8 \leq , \leq 30$ | $\leq 60$            | $300 \leq$     |

Table 6 Result of CCM fire test for noncombustible materials

| Radiated heat flux | Combustion component | Ignition time (s) | THR (MJ) | $S_{\text{max}}$ (m²/m³/s) | TSP (m³/m³) |
|--------------------|----------------------|-------------------|----------|----------------------------|-------------|
| 50                 | N1 (decorative board)| 0.08              | 28       | 103                        | 4.6         |
|                    |                      |                   |          | 24                         | 386         |
| 70                 |                      | 0.08              | 16       | 129                        | 4.9         |
|                    |                      |                   |          | 29                         | 200         |
| 50                 | N2 (AL-resin laminated board) | 0.19          | 480      | 279                        | 18          |
|                    |                      |                   |          | 6.1                        | 1611        |
| 70                 |                      | 0.17              | 320      | 213                        | 30          |
|                    |                      |                   |          | 3.4                        | 915         |
| 50                 | N3 (AL-foam resin laminated board) | 0.22         | 35       | 274                        | 26          |
|                    |                      |                   |          | 12                         | 784         |
| 70                 |                      | 0.24              | 21       | 384                        | 29          |
|                    |                      |                   |          | 13                         | 588         |
3. Relationship between radiated heat flux and combustion performance

3.1 Evaluation method

In order to understand the relationship between the radiated heat flux and combustion performance, CCM fire testing was performed while changing test conditions.

Test specimens were irradiated with four levels of heat flux: 10, 35, 50 and 70 kW/m² to evaluate the HRRmax. The test specimens were as shown in Table 1.

3.2 Evaluation result

The relationship between the radiated heat flux and the HRRmax of fire retardant materials are shown in Fig. 12. Under the radiated heat flux of 10 kW/m², the presence or absence of ignition in PVC-based floor covering was observed. Ignition was observed in test specimens other than the PVC-based floor coverings. However, no fire was observed because the ignited fire was extinguished within 10 seconds. In addition, all test specimens were ignited at a radiated heat flux of more than 35 kW/m². Since the HRRmax simply increased up to 70 kW/m² except in the case of seat moquette, there is a certain correlation between the HRRmax of test specimens and the radiated heat flux.

In the case of the seat moquette, the HRRmax became saturated at an early stage in the test with fluxes over 35 kW/m² due to its light weight.

The relationship between the radiated heat flux and the HRRmax in noncombustible materials is shown in Fig. 13. Ignition was not observed in any of the test specimens when irradiated with a heat flux of 10 kW/m². The decorative board and the AL-foam resin laminated board ignited with a flux of 35 kW/m², whereas the AL-resin laminate board did not. The decorative plate and the AL-foam resin laminated board had a printed film on their surface, which was very thin and combusted easily. The surface of the AL-resin laminated board had a coated film that was more fire resistant, and no ignition was observed. The AL-foam resin laminated board combusted not only on the surface but also inside the resin layer. The HRRmax was therefore higher than for the decorative board. The deformation of the aluminum plate is exacerbated by combustion of the printed surface film and the inside resin layer.

The HRRmax of the decorative board and the AL-foam resin laminated board simply increased with as the radiated heat flux was raised, so there is a certain correlation between the HRRmax of the test specimens and the radiated heat flux. It is assumed that it would be possible to estimate the HRRmax even when combustion was achieved with different radiated heat fluxes.

Fig. 13 Radiated heat flux and combustion performance (noncombustible materials)

4. Quantitative evaluation of the combustion category

In order to quantitatively evaluate the combustion category, CCM fire tests using a flux of 50 kW/m² were conducted on typical rolling stock interior materials, which have been used on Japanese railway rolling stock.

The test specimens were: fifteen kinds of noncombustible material, twelve kinds of fire retardant material, including the test specimens listed in Table 1. In addition, Polypropylene (PP) board, which is not used on railway rolling stock, was used as a combustible material. Combustion classifications were examined, based on the obtained results.

In CCM fire testing, the maximum average heat release rate (MARHE) which is the maximum value of the average heat release rate (ARHE) represented by (1) is applied as the evaluation index. As shown in Fig. 14, the ARHE is a time average of total calorific value at the time t from the start of the test. The MARHE has been used as a quantitative evaluation index of combustion classification in overseas fire testing for railway rolling stock [6], and was selected as an evaluation index in this paper, because it can offer a comprehensive analysis of combustion performance. Moreover, as shown in Table 5, the ignition time was used as a criterion of combustion resistance of a noncombustible material, and combined with the previously mentioned parameter and evaluated.

\[
ARHE(t_n) = \frac{\sum_{m=2}^{n} (t_m - t_{m-1}) \times q_m + q_{m-1}}{2} \quad t_{m-1} - t_1 \tag{1}
\]

The distribution between ignition time and MARHE is shown in Fig. 15.

The distribution, illustrated clearly in Fig. 15, shows that the respective combustion classes are groups in a specific region of distribution map. The distribution suggests that despite the higher level of radiation than in the Japanese standard fire test using alcohol, a relationship exists between the combustion classes.

Although some noncombustible materials are in the region close to fire retardant materials, the difference could be possibly clarified by changing the radiated heat flux applied.
Fig. 14 Overview of ARHE

Fig. 15 Distribution of combustion class and MARHE

5. Conclusion

In order to quantitatively evaluate the effect of higher thermal radiation due to large fires on combustion performance according to Japanese standard fire testing with alcohol, CCM fire tests were carried out on materials used inside railway rolling stock in Japan. In this study, various test conditions were applied, to evaluate various parameters. The correlation between the combustion performances and quantitative classification of the combustion class according to Japanese standard fire testing with alcohol were also examined. The findings obtained are described below.

(1) For fire retardant materials: shorter ignition times and an increase in HRR$_{\text{max}}$ were caused by an increase in the radiated heat flux. This behavior is based on the rapid thermal decomposition due to an increase in radiated heat flux and incomplete combustion from earlier test phases.

S"$_{\text{max}}$ also increased with the increase in irradiated heat flux with all test specimens. Based on rapid thermal decomposition, incomplete combustion likely to occur.

(2) For noncombustible materials: the ignition time is longer than for fire retardant materials. However, a test specimen with significantly shortened ignition time is observed under a large radiated heat flux. The increase of the HRR$_{\text{max}}$ was also obtained with an increase in irradiated heat flux.

Moreover, since the combustion component was small, changes in THR and S"$_{\text{max}}$ were also small. In addition, materials with a laminated structure can greatly change the combustion performances depending on the deformation of the aluminum plate.

(3) Based on the results of relationship between the radiated heat flux and the HRR$_{\text{max}}$, simple increases except for some of the test specimens were clearly observed. It was also possible to estimate the HRR$_{\text{max}}$ even when combustion was obtained with different radiated heat fluxes.

(4) Based on the selection of MAHRE as an evaluation index, it became clear that combustion classes concentrated in specific regions of the distribution map suggesting that a relationship existed between combustion classes even when the levels of radiation were higher than in Japanese standard fire testing with alcohol.

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