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Experimental study on vertical temperature profile of EPS external thermal insulation composite systems masonery façade fire according to JIS A 1310 method

Biao Zhou[1,3] | Hideki Yoshioka[2] | Takafumi Noguchi[3] | Kai Wang[1]

[1]Beijing Key Laboratory for Precise Mining of Intergrown Energy and Resources, China University of Mining & Technology (Beijing), Beijing, China

[2]Department of Fire Engineering, Building Research Institute, Tsukuba, Japan

[3]Department of Architecture, Faculty of Engineering, The University of Tokyo, Tokyo, Japan

Correspondence
Biao Zhou, Beijing Key Laboratory for Precise Mining of Intergrown Energy and Resources, China University of Mining & Technology (Beijing), Beijing 100083, China.
Email: zhoubiao1088@bme.arch.t.u-tokyo.ac.jp

Summary

Thermoplastic Expanded Polystyrene (EPS) External Thermal Insulation Composite Systems (ETICS) has caused serious results due to the ravages of frequent fire disasters. The fire propagation over EPS ETICS surface was observed to be very fast. High temperature threatens the safety of exterior building wall. However, vertical temperature distribution of EPS ETICS façade fire (without cavity) is not available until now. Presently, a quantitative correlation was investigated through a series of theory derivation and experiment tests, which involves vertical temperature distribution of EPS ETICS façade surface, window fire intensity, thermal parameters and fire propagation potentials of EPS ETICS specimen. The theory consists of three parts, window-spilled fire model, thermal parameters and fire propagation index (FPI) method. In JIS A 1310 standard tests, widow fire intensity changes from 600 to 1100 kW, thermal response parameter differs from 163.9 to 276.8 $kW \cdot s^2/m^2$ and FPI varied from 17.1 to 28.9 $(m/s^{1/2})/(kW/m)^{2/3}$. Finally, an adequate approximation for vertical temperature in the form of a dimensionless temperature is proposed based on test results. It provides a potential correlation to obtain vertical temperature distribution prior to the intermediate-scale test.

KEYWORDS

external thermal insulation composite system (ETICS), fire propagation speed, JIS A 1310 façade fire test method, temperature distribution over the exterior building wall, thermal response parameter (TRP), thermoplastic expanded polystyrene (EPS)

1 | INTRODUCTION

External thermal insulation composite systems (ETICS) have been used in buildings for several decades due to their thermal advantages, low cost and ease of application.[1] The principal design of an ETICS includes wall construction, insulation material, cement bound mortar with reinforcement, rendering and fixation by dowels and mortar.[2] Recently in China, several ETICS fire cases involving extreme fire spread upon exterior combustible claddings have occurred, and caused serious property damage and life loss. For example, an expanded polystyrene (EPS) ETICS fire happened in Chongqing on January 1st, 2020. In the north part of China, an EPS ETICS fire occurred on December 3rd, 2019 in Shenyang. Another case is located in the Nangjing, which happened on May 24th, 2019. The attention on façade fire was increased sharply recently.[3] It is known to all that core material of most ETICS fire is EPS, which is one of the common thermal insulation thermoplastic materials used on external walls of buildings in the previous time.[4] Although EPS is not encouraged to be installed in the new building in China, a great many buildings performed with EPS ETICS façade (without cavity) was constructed in the past 10 years. With natural weathering goes on, EPS ETICS façade is in a high fire risk. The fire propagation over EPS ETICS surface was observed to be very fast from several real fire cases. High temperature imposed by severe fire threatens the safety of exterior building wall. Until now, vertical temperature distribution of EPS ETICS façade fire is rare reported. A fire modeling for it is necessary and urgent.

It is widely acknowledged that EPS ETICS are comprehensive systems, which involve adhesive, EPS insulation material, cement, reinforcing mesh and finishing coat and so on. Reaction-to-fire performance evaluation of the single material may make little contribution for the understanding real EPS ETICS façade fire. Main emphasis of available EPS ETICS fire researches are focused on probabilities of fire spread assessment,[5-7] fire safety evaluation,[8] fire rescue analysis,[9] fire barrier[10] and incident heat flux[11,12] and so on. Only few art involves quantitative discussion of vertical temperature over EPS ETICS surface. Peak temperature of each position from T1 to T5 is fully investigated during EPS ETICS JIS A 1310 façade fire tests.[13] Temperature evolution at the different window positions was limitedly presented according to large-scale EN 13823 method.[11] Vertical temperature performed by a series of measurement during large-scale EPS ETICS façade fire is detailed.[14] In general, most of available works are just focused on the temperature comparison of different window fire or ignition fuel types without further study. However, the deep understanding of relationship among vertical temperature distribution over EPS ETICS façade surface, window fire intensity, thermal parameters and fire propagation potentials of EPS ETICS specimen is of great necessity. Little knowledge about it is available now.

Vertical temperature profile of EPS ETICS facade fire varying parameter of EPS ETICS and window spilled fire intensity, is conducive to building design. The vertical temperature is impacted by two parts, the heat imposed on façade surface from a window spilled fire, and combustion of ETICS façade materials. To obtain experimental results, an intermediate-scale standard façade fire test JIS A1310 method is employed here.

In this contribution, a dimensionless model for understanding vertical temperature profile of EPS ETICS facade fire is set up on the basis of EPS ETICS thermal parameters and window spilled fire. A series of EPS ETICS facade specimens differing from parameters are tested under various conditions according to JIS A1310 method.

2 | EXPERIMENT AND METHOD

2.1 | JIS A 1310 façade fire test standard method

The experiment method was according to the JIS A 1310 façade fire test method from Japan.[15] The description of calibration test (without combustible façade) is shown in Figure 1. The experimental layout in laboratory is shown in Figure 1A and a simple sketch of experiment is described in Figure 1B. Fire test facility consisted of propane gas combustion chamber 1 (size in $L \times W \times H$ = 1350 mm × 1350 mm × 1350 mm), window opening (size in $L \times W$ = 910 mm × 910 mm), gas burner (size in $L \times W$ = 600 mm × 600 mm), specimen substrate and specimen support frame. The opening size and opening aspect n are $W \times H$ = 910 mm × 910 mm and n = 2, respectively. The chamber was with a 10.1069 m^2 of inner surface area. The burner was used to produce different heating intensity fire, which was conducted by controlling the high purity propane combustion. The gas burner was filled with the ceramic beads to ensure propane gas with a uniform speed. The specimen substrate was made by laying two pieces of 12 mm thickness calcium silicate board and the joint of the first layer was not overlapped with joint of second layer. Specimen support frame made of stainless steel was employed to support specimen substrate and the specimen tested. Interior surface of chamber was coated by a thickness of 25 mm ceramic fiber blanket. The temperature and heat flux density

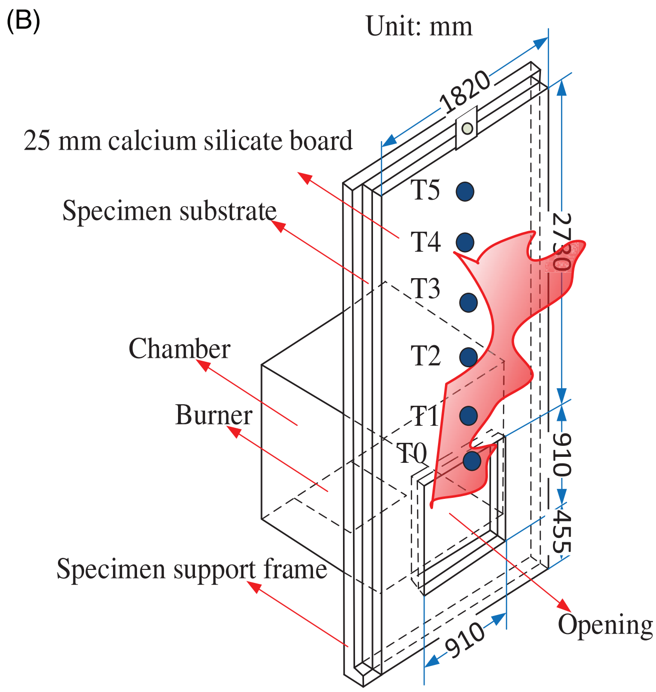


FIGURE 1 The experimental layout of calibration test in our lab. (A) The configuration of calibration test. (B) A simple sketch of experiment

information varied with test time are recorded by utilization of a series of k-type thermocouples and Gardon heat flux meters on finishing coat surface of façade specimen in the height of 0 mm (T0 for temperature), 500 mm (T1 for temperature, HF1 for heat flux density), 900 mm (T2, HF2), 1500 mm (T3, HF3), 2000 mm (T4, HF4) and 2500 mm (T5, HF5) away from the top of opening, respectively. Heat release rate (HRR) and total heat release rate (THR) were calculated by Oxygen Consumption Calorimetry (OC). During OC measurement, gas-analysis equipment was used to record oxygen concentration ranged from 0.009% to 20.9% in every 2 seconds. K-type thermocouple has an accuracy of ±2.2°C. The gas-analysis has an accuracy of ±0.02% O_2, ±0.02% CO and ± 0.02% CO_2. Before façade fire test, 4-L alcohol combustion was used to calibrate the whole equipment condition. Then window fire intensity in kW was determined by controlling mass flow of high purity propane. Temperature and heat flux density distribution of calibration test over façade surface varying test time are listed in Table 1.

Description of EPS ETICS façade fire test is shown in Figure 2. The layout of test conditions is described in Figure 2A. Figure 2B shows a simple model of experiment layout. Figure 2C indicates the description of EPS ETICS specimen. The EPS ETICS specimen consists of polymer cement mortar (PCM), cement mortar (CM), reinforcement mesh layer and EPS, just as shown in Figure 2D. The preparation process is detailed in a previous work.[13] The main polymer is styrene butadiene rubber (SBR). All experiments were finished in the Building Research Institute of Japan located in Tsukuba. The details of specimen is shown in Table 3. The EPS thickness varies from 100 to 300 mm, the density of EPS differs from 15 to 18 kg/m^3 and the window fire intensity changes from 600 to 1100 kW. All the opening edge of chamber window is treated by back-wrapping method. Physical parameters of EPS ETICS specimens are listed in Table 2. A k-type thermocouple tree is used to measure temperature of façade surface (Surface). It is in the height of 0 mm (T0), 500 mm (T1), 900 mm (T2), 1500 mm (T3), 2000 mm (T4) and 2500 mm (T5) away from the upper of the opening, respectively.

2.2 | Cone calorimeter according to ISO 5660-1 standard method

To get the input for calculation of fire propagation index (FPI), a Dual Cone Calorimeter from Fire Testing Technology Ltd. with the help of TSV (Tokyo System Vac., Inc.) in Japan. The set-up, calibration and measurements were in accordance with the ISO 5660-1 standard method.[16,17] Samples were mounted horizontally by using a specimen holder with edge frame. The bottom of holder was lined with ceramic fiber blanket. The bottom and sides of each sample were wrapped with a 0.02-mm thick aluminum foil. The heat release calculations were based on measurement of oxygen, carbon monoxide and carbon dioxide concentrations in dried exhaust gas. Duplicate tests were conducted at heat fluxes of 30 and 50 kW/m^2. Ambient temperature is 20.3°C. Barometric pressure is 100 993 Pa. Relative humidity is 19.0%. The optional retainer frame in the horizontal orientation reduce the exposed area to 0.094 m × 0.094 m. Samples were prepared by cutting an EPS ETICS panel (53 mm thick) into 100 mm × 100 mm square pieces. The HRR was calculated from changes in oxygen, carbon monoxide and carbon dioxide concentrations in dried exhaust gas by using the following[18]:

$$\dot{q} = E\left(\dot{m}^0_{O_2} - \dot{m}_{O_2}\right) - (E_{CO} - E)\Delta\dot{m}^{CO}_{O_2} - (E_s - E)\Delta\dot{m}^{s}_{O_2}$$

where E_{CO} and E_s are the net heat release per unit mass of O_2 consumed to oxidize carbon monoxide and soot to CO_2 respectively. $\Delta\dot{m}^{CO}_{O_2}$ and $\Delta\dot{m}^{s}_{O_2}$ are the mass consumption rate of oxygen to oxidize carbon monoxide and soot respectively. HRR and sample mass were recorded as a function of time.

3 | RESULTS AND DISCUSSION

3.1 | The description of fire tests results

The EPS ETICS façade fire is a comprehensive phenomenon which is relative to the window spilled fire and fire propagation performance of ETICS building materials. To have an understanding of EPS ETICS façade fire, the heat imposed by window spilled fire is presented first with the discussion of time-averaged temperature and heat flux density results varying test conditions. Then a typical reaction-to-fire performance of EPS ETICS under an 1100 kW window fire is detailed. In addition, the Cone test is reported for the calculation of FPI. Finally, influence of window spilled fire and fire propagation of EPS ETICS parameters on vertical temperature is investigated here.

3.1.1 | The description of window spilled fire

Window spilled fire is controlled by differing the fire intensity in kW. It is realized by the accurate control of propane gas inside chamber. The

TABLE 1 The temperature results of test without combustible facade according to JIS A 1310 method

Fire intensity /kW	Opening/°C	T0/°C	T1/°C	T2/°C	T3/°C	T4/°C	T5/°C
400	773	605	312	267	163	163	143
600	1128	929	479	395	254	234	198
900	1227	1134	840	670	415	402	344
1000	1203	1119	881	686	450	385	322
1100	1218	1144	1099	932	641	527	430

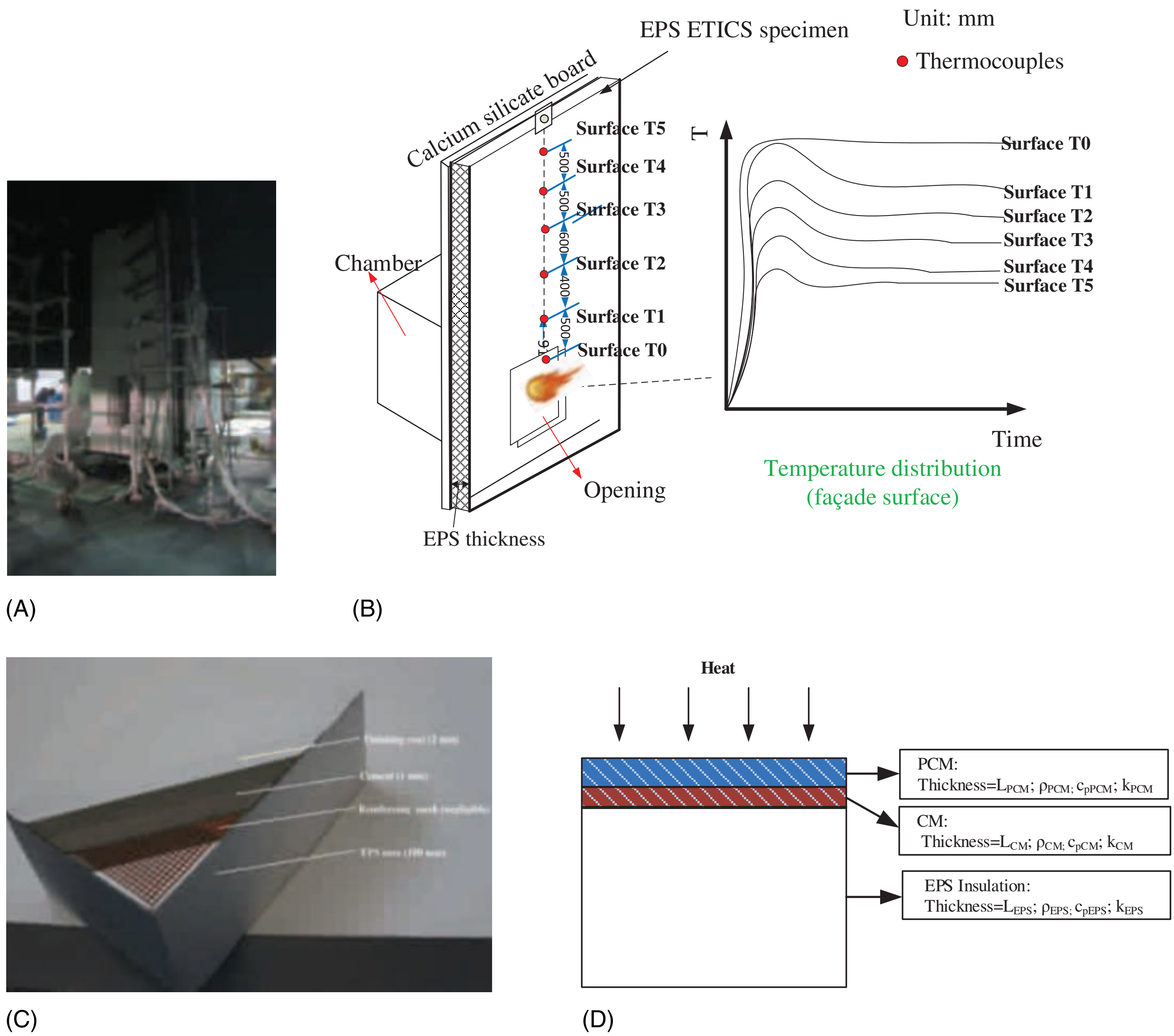


FIGURE 2 The description of experimental layout. (A) The layout of test conditions, (B) a simple model of experiment layout, (C) the description of EPS ETICS specimen, (D) a simple sketch of EPS ETICS specimen

TABLE 2 The heat flux density results of test without combustible facade according to JIS A 1310 method

Fire intensity/kW	HF1/kW/m^2	HF2/kW/m^2	HF3/kW/m^2	HF4/kW/m^2	HF5/kW/m^2
400	8.5	5.5	4.3	3.4	2.9
600	17.9	11.3	7.9	5.9	4.7
900	/	38.6	19.8	12.3	10.4
1000	77.6	75.4	20.3	13.6	9.4
1100	120.1	98.9	38.0	20.9	14.1

flame description of window fire varying fire intensity is shown in Figure 3. It is observed that the flame spilled out from open and re-attached to facade wall. As the fire intensity in kW changes from 400 to 1100 kW, flame height is lengthened accordingly. The time-averaged temperature and heat flux density results of different window fire intensity according to JIS A 1310 method are described in Tables 1 and 2.

3.1.2 | The reaction-to-fire performance of EPS ETICS with an 1100 kW window fire

EPS is one of common thermal insulation thermoplastic materials used on external walls of buildings. When the vertically installed EPS is exposed to heat, melt-flow or melt-drip process consisting of EPS melting and molten flowing will take place first. It increases difficulty in the understanding of reaction-to-fire performance compared with non-melt-flow material, for example, wood façade. HRR is one of the most important reaction-to-fire properties of materials and it is important to characterize the fire performance of a material for fire safety design of buildings.[18] However, it is found in our previous research, only HRR history seems hard to clarify the fire risk of EPS ETICS façade fire varying EPS thickness. The typical fire performance of EPS ETICS is introduced by conducting an EPS (thickness = 200 mm) ETICS façade fire test with an 1100 kW window fire (Table 3).

The test scene and results of EPS (200 mm) ETICS façade under 1100 kW fire intensity are described in Figure 4. Figure 4A shows façade test experimental configuration before test. When EPS ETICS façade exposed to window fire for 3 minutes, the façade fire entered into a severe whole combustion (just as shown in Figure 4B). After test, a hole is found at the upper of window opening, just as shown in Figure 4C. When the residual surface was removed, no EPS molten was found (see Figure 4D). Figure 4E gives the façade surface temperature distribution varying test time. The typical temperature history varying test time consists of three typical peaks. Taking T5 curve for example, just as shown in Figure 4E, peak 1 stands for the combustions of PCM, peak 2 means the combustion of EPS foam panel and peak 3 represents the combustion of styrene gas with a fresh air because of a broken covering. When the EPS ETICS exposed to a window fire, the surficial PCM is ignited soon and combusted to form a first peak 1 at t = 1.54 minutes. As the test time goes on, a small hole located near T2 and T3 is made because of high temperature over 900°C. Then a process including EPS melt-flow and pyrolysis is conducted due to a high temperature over 430°C. The styrene, main pyrolysis product of EPS, is combusted with fresh air at the position where a hole is located. The peak 2 appears at t = 5.16 minutes after a period of heating time. Then the temperature decreases slowly since

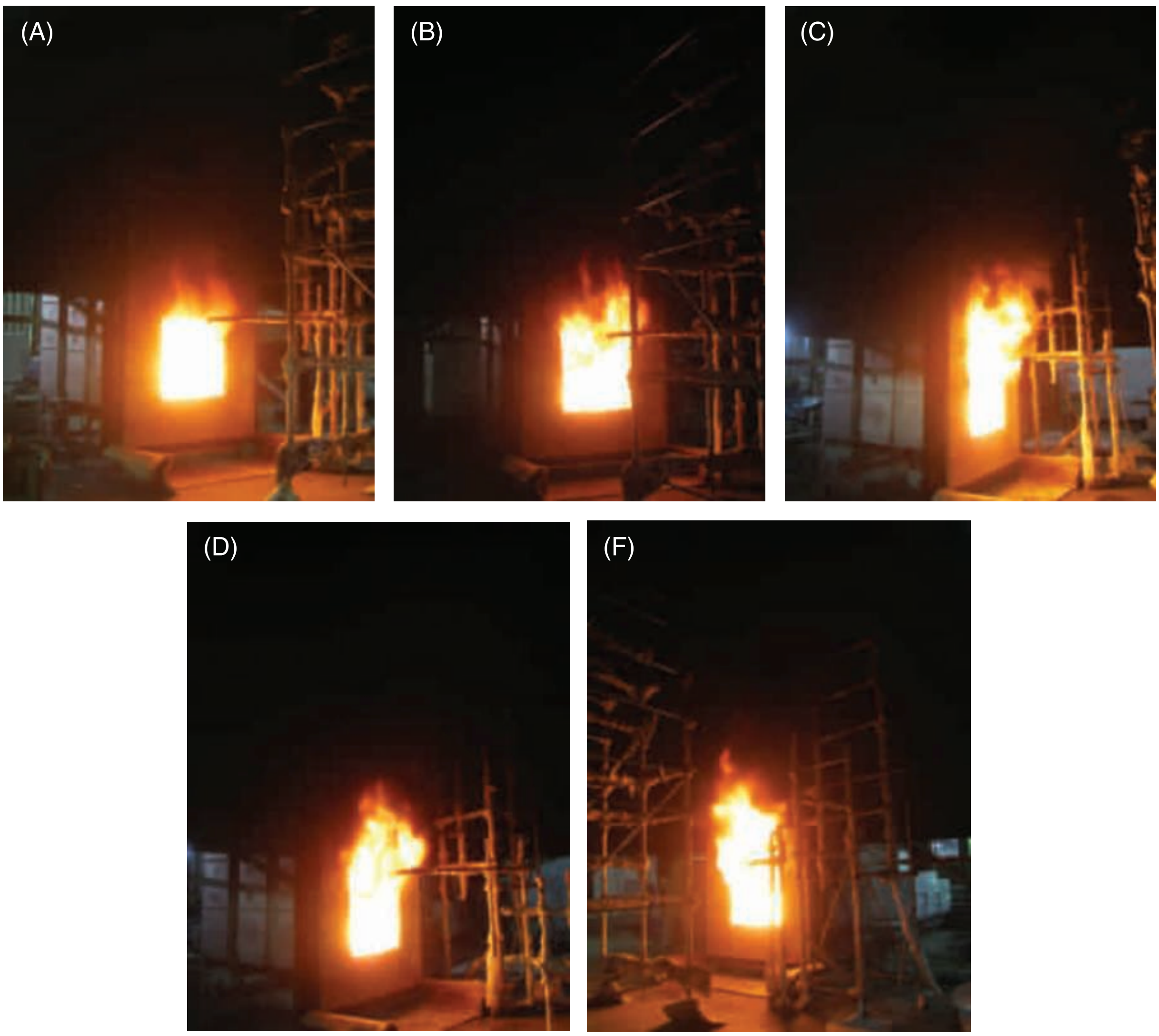


FIGURE 3 The flame description of window fire performed with different fire intensity (A) 400 kW (B) 600 kW (C) 900 kW (D) 1000 kW (E) 1100 kW

TABLE 3 The details of EPS ETICS specimens and testing condition

Items	EPS thickness/mm	EPS density/kg/m^3	Reinforcement mesh net layer	PCM	Heating intensity/kW	Opening treatment
1	100	18	1	SBR	1000	Back-wrapping
2	100	15	1	SBR	1100	Back-wrapping
3	150	15	1	SBR	1100	Back-wrapping
4	150	15	1	SBR	1100	Back-wrapping
5	200	15	1	SBR	1100	Back-wrapping
6	200	18	1	SBR	1000	Back-wrapping
7	200	18	1	SBR	600	Back-wrapping

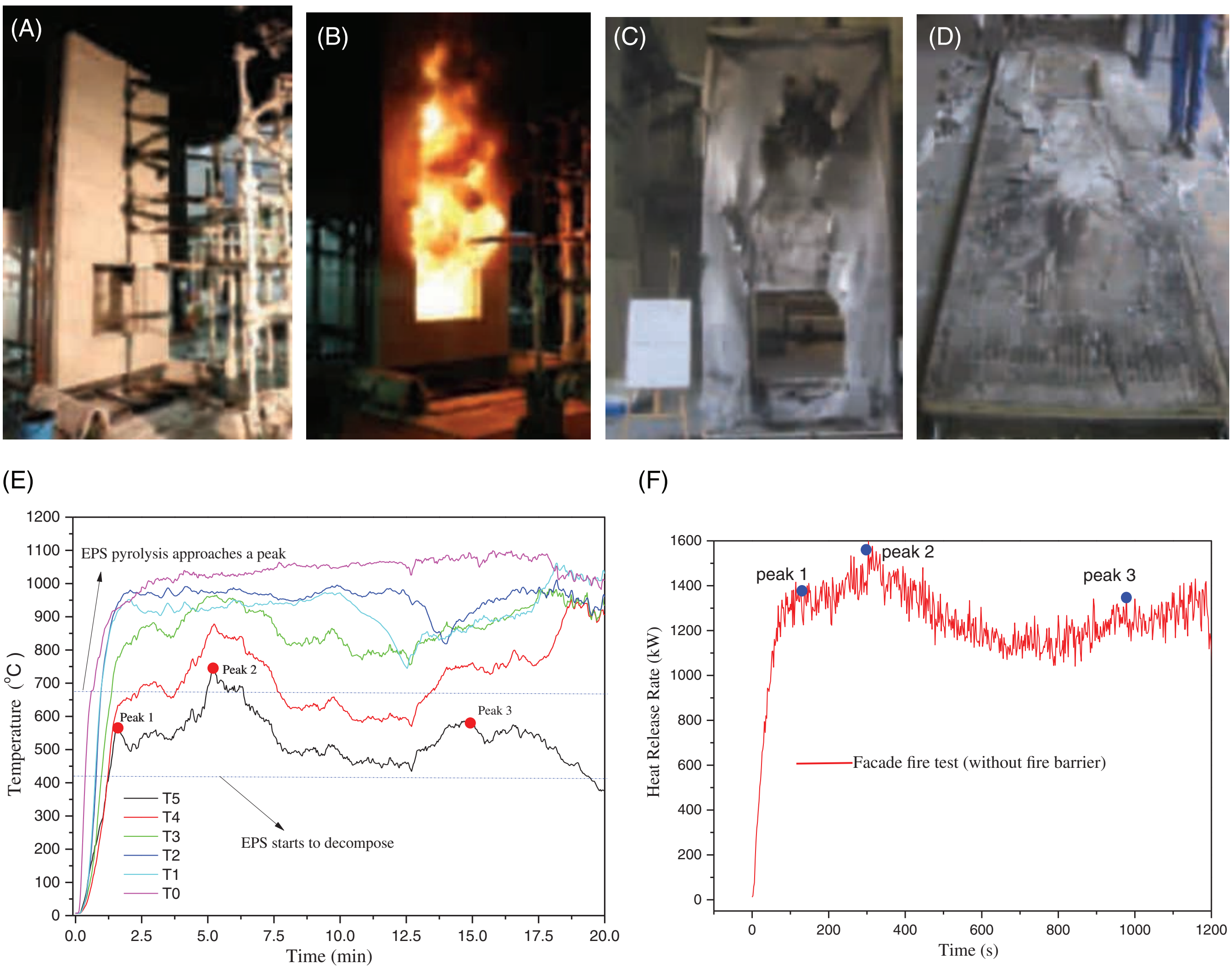


FIGURE 4 EPS ETICS façade (thickness = 200 mm) fire test results under 1100 kW heating intensity. (A) Façade fire test layout according to JIS A 1310 method, (B) flame description of test at t = 3.0 minutes, (C) the specimen after façade fire test, (D) the specimen description after the residual surface was removed, (E) façade surface temperature distribution varying with test time, (F) HRR histories of façade fire test

the EPS molten inside the ETICS flow down to the bottom of specimen. The hole is enlarged by the continuous high temperature, resulting in an increase in oxygen concentration near hole. The styrene gas spreads from the bottom of specimen to the hole to form a serious combustion, which leads to a new peak 3 at t = 14.8 minutes. After fire test, a big hole is found, just as shown in Figure 4C. And nearly all of the EPS was burnt out by a special manner, without EPS molten. It is concluded that taking some actions to reduce the area of hole is important, which could avoid peak 3. The average temperature of T0, T1, T2, T3, T4 and T5 are 1044.2°C, 921.7°C, 957.1°C,

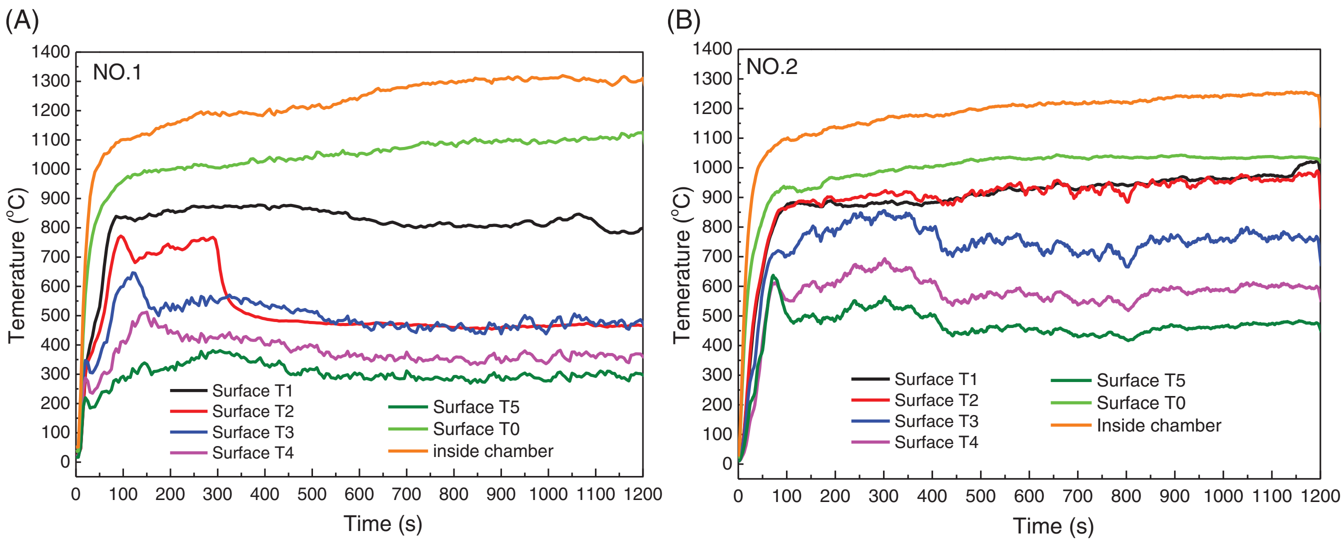


FIGURE 5 The temperature histories of EPS (thickness = 100 mm) ETICS façade fire test varying with test time (A) test No.1, (B) test No.2

TABLE 4 The maximum temperature of positions located in the surface of façade

Items	Surface T0	Surface T1/°C	Surface T2/°C	Surface T3/°C	Surface T4/°C	Surface T5/°C
1	1122	882	775	648	514	376
2	1044	961	949	856	693	637
3	1099	949	997	905	732	662
4	1091	952	996	961	876	743
5	1090	865	973	943	888	765
6	1078	1004	/	895	699	644
7	992	905	678	547	517	313

874.0°C, 723.9°C and 531.3°C, respectively. The three typical peaks are also found in the incident heat flux histories varying test time. The dependence of temperature on test time indicates the main combustion takes place at the positions of T2 and T3 at t = 5.16 minutes. It means that the fire is mainly located at the positions where is 0.5-1.5 m away from the upper of the window opening. The THR and pHRR are calculated as1489.7 MJ and 1598.7 kW, respectively.

3.1.3 | The temperature profiles of tests No.1 to No.7

The temperature histories of EPS (thickness = 100 mm) ETICS façade fire test varying test time are given in Figure 5. The dependence of surface maximum temperature on test time for various specimens is summarized in Table 4. The temperature histories of EPS (thickness = 150 mm) ETICS façade fire test varying test time are described in Figure 6. Figure 7 shows the temperature history during façade fire test varying test time of EPS (thickness = 200 mm) ETICS façade. Figure 8 indicates the dependence of temperature on test time during façade fire test varying test time of EPS (thickness = 300 mm) ETICS façade.

3.1.4 | The Cone tests of EPS ETICS specimen

Cone tests were conducted to obtain chemical HRR per unit width in kW/m, which is necessary for FPI calculation. Just as discussed above, the combustion mainly takes place in the height of 0.5-1.5 m away from the upper of window opening. Here, the heat flux intensity of the position HF2 (0.9 m away from the opening) is used to get the reasonable HRR per unit varying window fire intensity. When window fire intensity increases from 600 to 1100 kW, the heat flux density imposed to facade changes from 11.3 to 98.9 kW/m^2. In addition, regarding the SBR materials, HRR is positive linear correlation with external heat flux.[19] The details of Cone test are listed in the following.

Figures 8, 9 shows a picture of an EPS ETICS specimen prior to, during, and following a Cone Calorimeter test. During tests, two irradiation levels 30 and 50 kW/m^2 are investigated. According to EPS ETICS specimen Cone Calorimeter test results, it is found that there

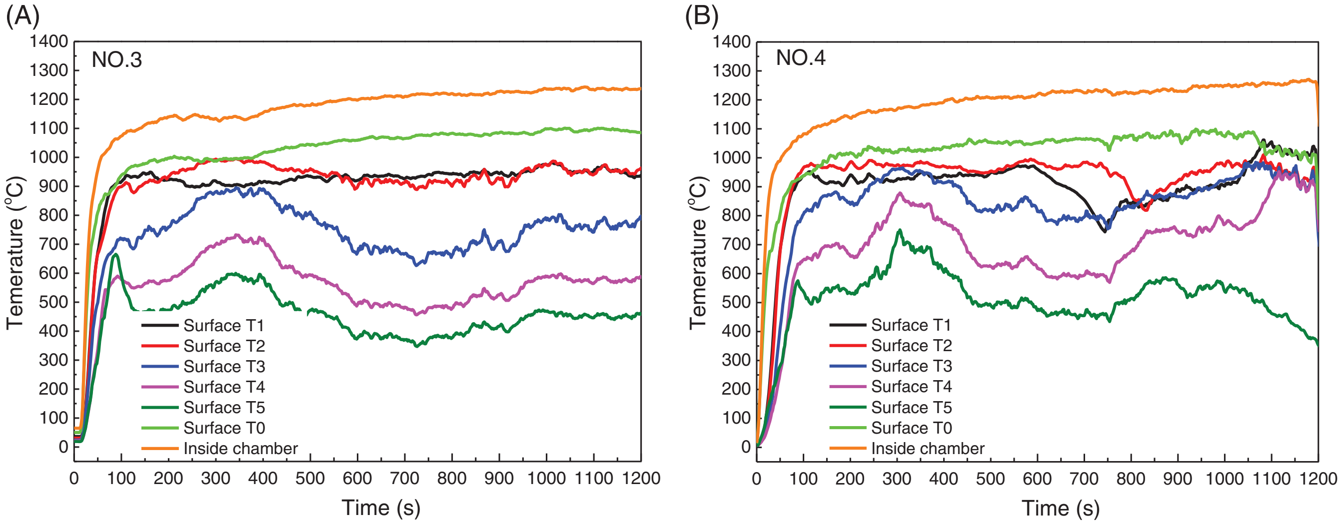


FIGURE 6 The temperature histories of EPS (thickness = 150 mm) ETICS façade fire test varying with test time (A) test No.3, (B) test No.4

are two peaks existing in the HRR histories. The first peak is attributed to PCM combustion since exterior PCM was ignited first. The second peak is mainly believed to be a result of EPS combustion. When the EPS ETICS specimen is under 30 kW/m^2 irradiation for 96 seconds, the surface of specimen will be ignited. And when the EPS ETICS specimen is under 50 kW/m^2 irradiation for 52 seconds, the surface of specimen will be ignited. This can be used to understand the fast vertical spread of EPS ETICS façade fires.

Regarding EPS ETICS, when it is heated under 30 kW/m^2 irradiation after 20 minutes, following results were got: THR is 38.9 MJ/m^2; the pHRR derived from PCM is 173.0 kW/m^2 at 130.0 seconds and the pHRR derived from EPS is 114.7 kW/m^2 at 420.0 seconds; HRR (mean 60 seconds) is 122.85 kW/m^2; HRR (mean 180 seconds) is 78.7 kW/m^2; HRR (mean 300 seconds) is 86.06 kW/m^2; T_{ig} is 96.9 seconds; $T_{extinguishing}$ is 583.1 seconds; combustion time is 486.2 seconds; mean heat of combustion is 29.0 MJ/kg; mean mass loss rate is 2.8 g/s m^2; specific extinction area is 412.5 m^2/kg. When it is heated under 50 kW/m^2 irradiation after 20 minutes, the following results were got: THR is 42.34 MJ/m^2; the pHRR derived from PCM is 218.13 kW/m^2 at 88.10 seconds and the pHRR derived from EPS is 132.0 kW/m^2 at 244.1 seconds; HRR (mean 60 seconds) is 144.99 kW/m^2; HRR (mean 180 seconds) is 101.73 kW/m^2; HRR (mean 300 seconds) is 108.11 kW/m^2; T_{ig} is 51.7 seconds; $T_{extinguishing}$ is 546.1 seconds; combustion time is 494.1 seconds; mean heat of combustion is 30.59 MJ/kg; mean mass loss rate is 3.2 g/s m^2; specific extinction area is 692.09 m^2/kg.

In general, the correlation between peak HRR (Y) and external irradiation levels (X) as $Y = 2.25X + 105.5$. Thereby, the peak HRR of SBR under 11.3 kW/m^2, 38.6 kW/m^2, 75.4 kW/m^2 and 98.9 kW/m^2 are 130.9 kW/m^2, 192.4 kW/m^2, 275.2 kW/m^2 and 328.0 kW/m^2, respectively. The chemical HRR per unit width in kW/m could be got by peak HRR (kW/m^2) × width (1.82 m). Regarding the SBR of PCM, the $T_{ig} - T_0$=220. The thermal response parameter (TRP) in the unit of kW s^2/m^2 of No.1 to No.7 is described as 276.84, 268.41, 219.24, 219.24, 189.90, 198.87, 198.87, 163.89, respectively. Finally, the FPI in the unit of (m/s$^{1/2}$)/(kW/m)$^{2/3}$ of No.1 to No.17 is ranked as 17.1, 17.6, 21.6, 24.9, 23.8, 23.8 and 28.9, respectively.

3.1.5 | The vertical temperature of EPS ETICS facade varying window fire intensity

The EPS ETICS façade fire is a comprehensive phenomenon which is relative to the window spilled fire and fire propagation performance of ETICS building materials. Peak temperature during façade fire, acted as an important index, has been used to evaluate EPS ETICS reaction-to-fire performance in previous works.[13]

Regarding EPS (with a thickness of 100 mm) ETICS specimen, when the window fire intensity changes from 1000 to 1100 kW, the peak temperature of Surface-T1, Surface-T2, Surface-T3, Surface-T4 and Surface-T5 of test No.2 are increased by 141°C, 215°C, 208°C, 179°C and 261°C comparing with results of test No.1, respectively. Regarding the EPS (with a thickness of 200 mm) ETICS specimen, when the window fire intensity changes from 600 to 1000 kW, the peak temperature of Surface T1, Surface-T2, Surface-T3, Surface-T4 and Surface-T5 of test No.8 are increased by 99°C, 31°C, 348°C, 182°C and 331°C comparing with results of test No.9, respectively. When window fire intensity changes from 1000 to 1100 kW, peak temperature of Surface-T2, Surface-T3, Surface-T4 and Surface-T5 of test No.8 are increased by 326°C, 48°C, 189°C and 121°C comparing with results of test No.9, respectively. Therefore, window fire intensity plays an important role in the vertical temperature distribution.

3.1.6 | The vertical temperature of EPS ETICS facade varying FPI

The fire propagation behavior of materials under flame-radiating conditions prevalent in large-scale fires could be well evaluated by FPI.[20]

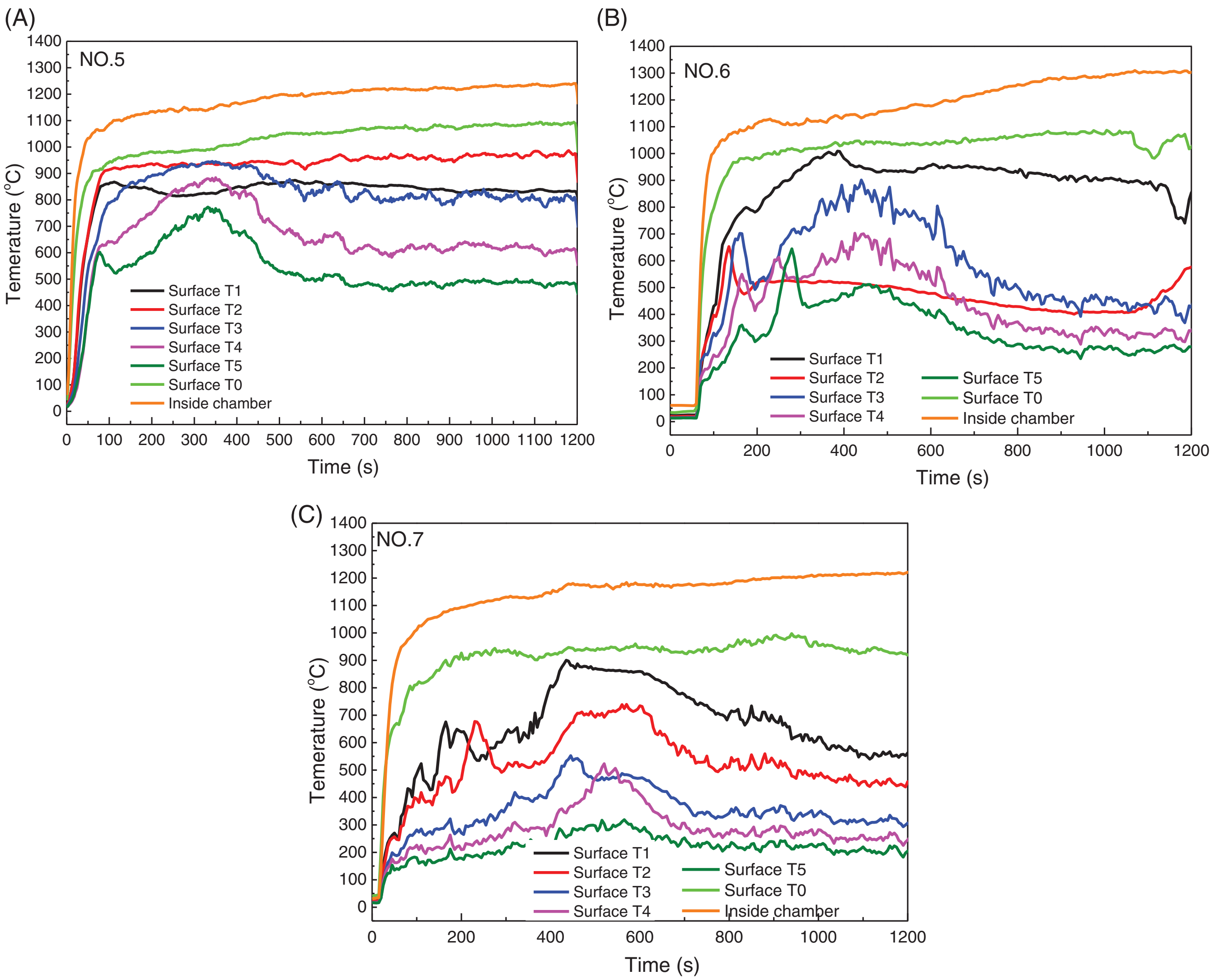


FIGURE 7 The temperature histories of EPS (thickness = 200 mm) ETICS façade fire test varying with test time (A) test No.5, (B) test No.6, (C) test No.7

And a comprehensive fire risk evaluation INDEX method of EPS ETICS based on EPS burn area and façade surface temperature profiles of JIS A 1310 tests has been proposed on the basis of FPI.[20]

FPI values have been successfully used to classify fire propagating materials during both small- and large-scale fire propagation tests.[21] Regarding EPS ETICS specimens under a 1000 kW window spilled fire (No.6 and No.1), when FPI of specimen changes from 17.1 to 23.8 $(m/s^{1/2})/(kW/m)^{2/3}$, the peak temperature of Surface-T1, Surface-T3, Surface-T4 and Surface-T5 of test No.8 is increased by 122°C, 247°C, 185°C and 268°C comparing with results of test No.1, respectively. Regarding EPS ETICS specimens under a 1100 kW window spilled fire (No.5, No.4 and No.2), when FPI of specimen changes from 17.6 to 21.6 $(m/s^{1/2})/(kW/m)^{2/3}$, the peak temperature of Surface-T2, Surface-T3, Surface-T4 and Surface-T5 of test No.6 are increased by 6°C, 105°C, 249°C and 106°C comparing with results of test No.2, respectively. When FPI of specimen changes from 21.6 to 24.9 $(m/s^{1/2})/(kW/m)^{2/3}$, the peak temperature of Surface-T3, Surface-T4 and Surface-T5 of test No.7 are increased by 38°C, 156°C and 103°C comparing with results of test No.6, respectively.

3.2 | The correlation of window fire, thermal parameters and fire propagation of EPS ETICS façade

It is known to all that vertical temperature distribution of EPS ETICS façade surface varies from window fire intensity, thermal parameters and fire propagation potentials of EPS ETICS specimen. The followings are detailed.

3.2.1 | Window spilled fire theory

Regarding a fixed compartment, the position of neutral plane usually changes with variation of HRR. Assuming the neutral plane = 0.5H is

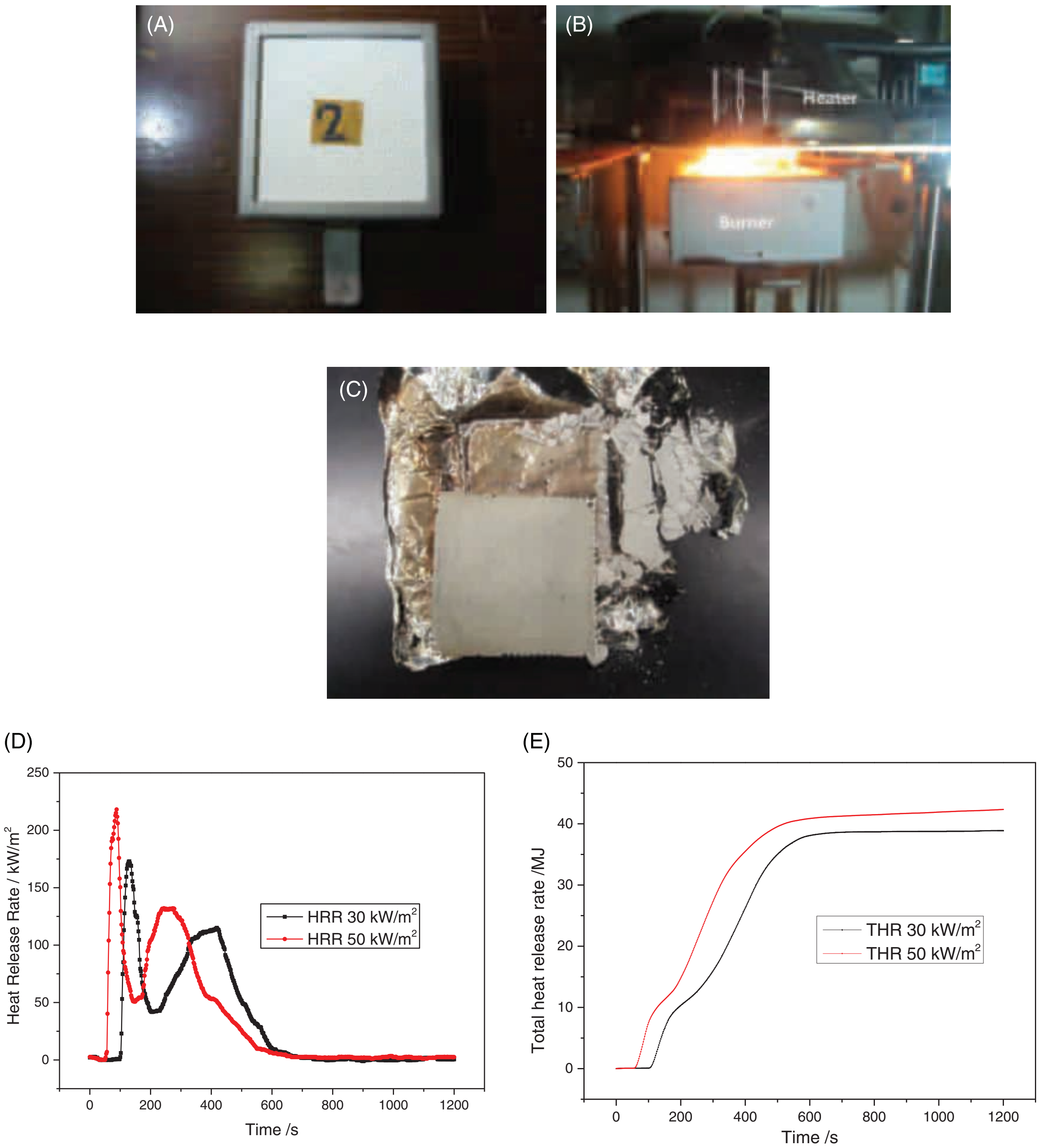


FIGURE 8 The description of EPS ETICS Cone Calorimeter test (A) EPS ETICS specimen mounted in the specimen holder, (B) EPS ETICS specimen exposed to 30 kW/m^2 after 154 seconds, (C) EPS ETICS specimen following testing, (D) HRR history vs time, (E) THR history vs time

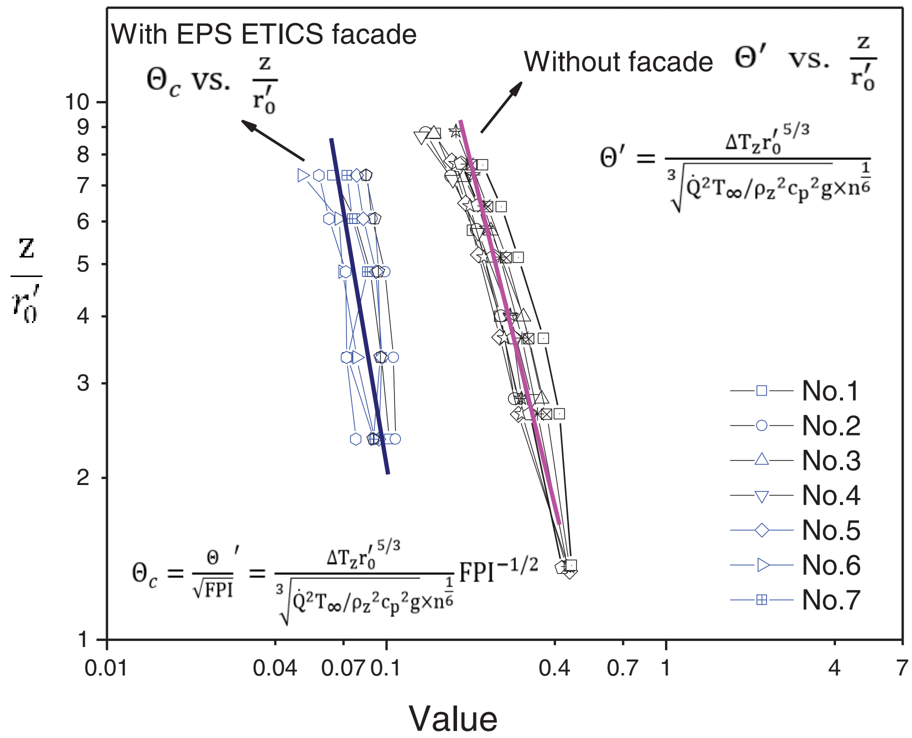
inappropriate for a well-ventilated fire. In this contribution, a reasonable expression of the neutral plane (N.P.) is written as xH ($0 < x < 1$) of the window height, then convective flow at the window could be got by using Yokoi's equation[22,23]:

$$\dot{Q} = C_d c_p \rho_g \Delta T_g W \int_0^{(1-x)H} v dz \tag{1}$$

Usually, flow coefficient at the opening C_d=0.7, c_p and ρ_g are defined as specific heat and density of hot gases, respectively. ΔT_g represents the gas temperature difference between hot layer inside the enclosure and ambient. With this, outflow velocity v at location Z above the N.P. is obtained as the following equation[24,25]:

$$v = \sqrt{\frac{2gZ\Delta T_g}{T_\infty}} \tag{2}$$

FIGURE 9 Description of correlation between Θ_c vs $\frac{z}{r_0'}$ performed by vertical peak temperature



The varied convective heat flow rate at the exit could be got by inserting Equation (2) to Equation (1), and integrating Equation (2) over position Z:

$$\dot{Q} = \frac{2}{3}\sqrt{2}C_d c_p \rho_g \Delta T_g W(1-x)^{3/2} H^{3/2}\sqrt{\frac{g\Delta T_g}{T_\infty}} \tag{3}$$

With the help of above equation and the equivalent radius $r_0' = \sqrt{\frac{W(1-x)H}{\pi}}$, the dimensionless temperature Θ could be expressed as the following form:

$$\frac{\Delta T_z r_0'^{5/3}}{\sqrt[3]{\dot{Q}^2 T_\infty/\rho_z^2 c_p^2 g}} = 0.4528\frac{1}{(1-x)^{\frac{1}{6}}}\left(\frac{T_g}{T_z}\right)^{\frac{2}{3}}\left(\frac{\Delta T_z}{\Delta T_g}\right)n^{\frac{1}{6}} = \text{function}\left(\frac{z}{r_0'}\right) \tag{4}$$

The new correlation Equation (4) is derived as the following form to increase the continuity of plot and to ignore the influence of opening aspect n[22]:

$$\Theta' = \frac{\Delta T_z r_0'^{5/3}}{\sqrt[3]{\dot{Q}^2 T_\infty/\rho_z^2 c_p^2 g \times n^{\frac{1}{6}}}} = \frac{0.4528}{(1-x)^{\frac{1}{6}}}\left(\frac{T_g}{T_z}\right)^{\frac{2}{3}}\left(\frac{\Delta T_z}{\Delta T_g}\right) = \text{function}\left(\frac{z}{r_0'}\right). \tag{5}$$

In this equation, neutral plane (N.P.) is obtained by $x = \frac{z_0}{H} = \frac{1}{1+1.04\left(\frac{T}{T_a}\right)^{1/3}}$. $\Delta T_z = T_z - T_a$. T_z represents vertical maximum temperature of fixed locations during facade fire test. T_a stands for the temperature of atmosphere. The new length scale r_0' was defined as $r_0' = \sqrt{\frac{W(1-x)H}{\pi}}$ (x is ratio of neutral plane position z_0 and window opening height H) without the assumption that neutral plane = 0.5 H.

3.2.2 | Thermal parameters of EPS ETICS specimens

It is reported that FPI values could be used to classify materials as either propagating and non-propagating based on a series of small- and large-scale fire propagation test data.[26] The good correlation of flame propagation rate is found both in the small-scale and large-scale apparatus, which can satisfy the engineering relationships derived from the fundamental flame propagation theories.[27] The flame propagation rate could be expressed as the following equation.[28]

$$\upsilon^{1/2} = \frac{\delta^{1/2}\dot{q}_{fs}''}{\Delta T_{ig}\left(\frac{\pi}{4}k\rho c_p\right)^{\frac{1}{2}}} \tag{6}$$

In it, ΔT_{ig}, k, ρ and c_p are the ignition temperature of the polymeric material above ambient in K, thermal conductivity in kW/m/K, density in kg/m^3, specific heat in kJ/kg/K of the solid, respectively. Where u is the upward fire propagation rate in mm/s. δ stands for the characteristic forward heat transfer distance, which is generally assumed to be constant in m.

The flame heat flux transferred ahead of the pyrolysis front has been reported as the following equation[29]:

$$\dot{q}_{fs}'' \propto \frac{\dot{Q}_{rad}'}{X_f} \tag{7}$$

where X_f represents the flame height for upward fire propagation in m and $\dot{Q}_{rad}'$ stands for the radiative HRR per unit sample width in kW/m. In general, $\dot{Q}_{rad}'$ is written as the following form:

$$\dot{Q}_{rad}' = \frac{\chi_{rad}}{\chi_{ch}} \dot{Q}_{ch}' \tag{8}$$

In it, χ_{rad} is the radiative fraction of the combustion efficiency, $\dot{Q}_{ch}'$ stands for chemical HRR per unit width (kW/m). The flame height, X_f, could be got by the following equation:

$$X_f \propto '(\dot{Q}_{ch})^{2/3} \tag{9}$$

On the basis of above Equations (7), (8), (9), the following could be got:

$$\dot{q}_{fs}'' = \left(\frac{\chi_{rad}}{\chi_{ch}} \dot{Q}_{ch}'\right)^{1/3} \tag{10}$$

With the help of Equation (6), the following is obtained:

$$\upsilon^{1/2} = \frac{\delta^{1/2}\left(\frac{\chi_{rad}}{\chi_{ch}} \dot{Q}_{ch}'\right)^{1/3}}{\Delta T_{ig}\left(\frac{\pi}{4} k \rho c_p\right)^{\frac{1}{2}}} \tag{11}$$

FPI could be recognized in the format of a simplified Equation (11). Thereby, TRP could be identified as the following form:

$$\mathrm{TRP} = \left(\frac{\pi}{4} k \rho c_p\right)^{\frac{1}{2}} (T_{ig} - T_0) \tag{12}$$

where, T_{ig} and T_0 represent the surface ignition temperature (K) and ambient temperature (K), respectively. In this contribution, the thermal parameters of EPS ETICS specimen could be evaluated by the utilization of TRP calculation.

3.2.3 | Fire propagation of EPS ETICS facade

FPI has been used to characterize the fire propagation performance under a window spilled fire, which is expressed in the following form of equation[19]:

$$\mathrm{FPI} = 750 \frac{\dot{Q}_{ch}'^{\,1/3}}{\mathrm{TRP}} \tag{13}$$

In the above equation, $\dot{Q}_{ch}'$ is chemical HRR per unit width (kW/m), which could be got and calculated from Cone results. Regarding the multi-layers building materials, just as EPS ETICS specimen, basic parameters of the materials could be got by a simple method. The calculation method of density, thermal conductivity and specific heat is introduced in the followings:

Density:

$$\rho = \frac{\rho_{PCM} \times L_{PCM} + \rho_{CM} \times L_{CM} + \rho_{EPS} \times L_{EPS}}{L_{PCM} + L_{CM} + L_{PCM}} \tag{14}$$

Thermal conductivity:

$$k = \frac{L \times k_{PCM} \times k_{CM} \times k_{EPS}}{L_{PCM} \times k_{CM} \times k_{EPS} + L_{CM} \times k_{PCM} \times k_{EPS} + L_{EPS} \times k_{PCM} \times k_{CM}} \tag{15}$$

where $L = L_{PCM} + L_{CM} + L_{EPS}$

Specific heat:

$$c = \frac{c_{pPCM} \times \rho_{PCM} \times L_{PCM} + c_{pCM} \times \rho_{CM} \times L_{CM} + c_{pEPS} \times \rho_{EPS} \times L_{EPS}}{\rho_{PCM} \times L_{PCM} + \rho_{CM} \times L_{CM} + \rho_{EPS} \times L_{EPS}} \tag{16}$$

where, T_{ig} is the surface ignition temperature (K) which is got by the Cone test. TRP is calculated using the Equations (14), (15) and (16).

3.3 | A dimensionless Θ_c for vertical fire distribution over EPS ETICS facade

Based on the above discussion, it is a fact that vertical temperature over EPS ETICS surface involves window fire intensity, thermal parameters of EPS ETICS and fire propagation potentials of EPS ETICS façade. Therefore, a dimensionless temperature Θ_c is defined as the following form:

$$\Theta_c = \frac{\Theta'}{\sqrt{\mathrm{FPI}}} = \frac{\Delta T_z r_0'^{\,5/3}}{\sqrt[3]{\dot{Q}^2 T_\infty / \rho_z^2 c_p^2 g \times n^{\frac{1}{6}}}} \mathrm{FPI}^{-1/2}$$
$$= \frac{0.4528}{(1-x)^{\frac{1}{6}}} \left(\frac{T_g}{T_z}\right)^{\frac{2}{3}} \left(\frac{\Delta T_z}{\Delta T_g}\right) \mathrm{FPI}^{-1/2} = \mathrm{function}\left(\frac{z}{r_0'}\right). \tag{17}$$

Where the neutral plane (N.P.) could be got by the utilization of equation $x = \frac{z_0}{H} = \frac{1}{1 + 1.04\left(\frac{T_g}{T_a}\right)^{1/3}}$. The length scale r_0' was got by $r_0' = \sqrt{\frac{W(1-x)H}{\pi}}$.

For simplification, the following form is derived:

$$\Theta_c = \frac{\Theta'}{\sqrt{\mathrm{FPI}}} = \mathrm{function}\left(\frac{z}{r_0'}\right) \tag{18}$$

The result of correlation Θ_c vs $\frac{z}{r_0}$ is calculated and found to be adequate for engineer approximation, which is shown in the Figure 9. In it, $\Delta T_z = T_z - T_a$ is used. In addition, correlation Θ' vs $\frac{z}{r_0}$ of calibration test (identified as Yokoi's correlation) has been validated to be linear widely.[23] Here, it is described in Figure 10 for a reference.[22] It indicates that dimensionless Θ_c is found to be approximately linear with $\frac{z}{r_0'}$ with respect to EPS ETICS façade (without cavity). An adequate and useful approximation could be got by an equation $\frac{z}{r_0'} = -180.40 \times \Theta_c + 17.26$.

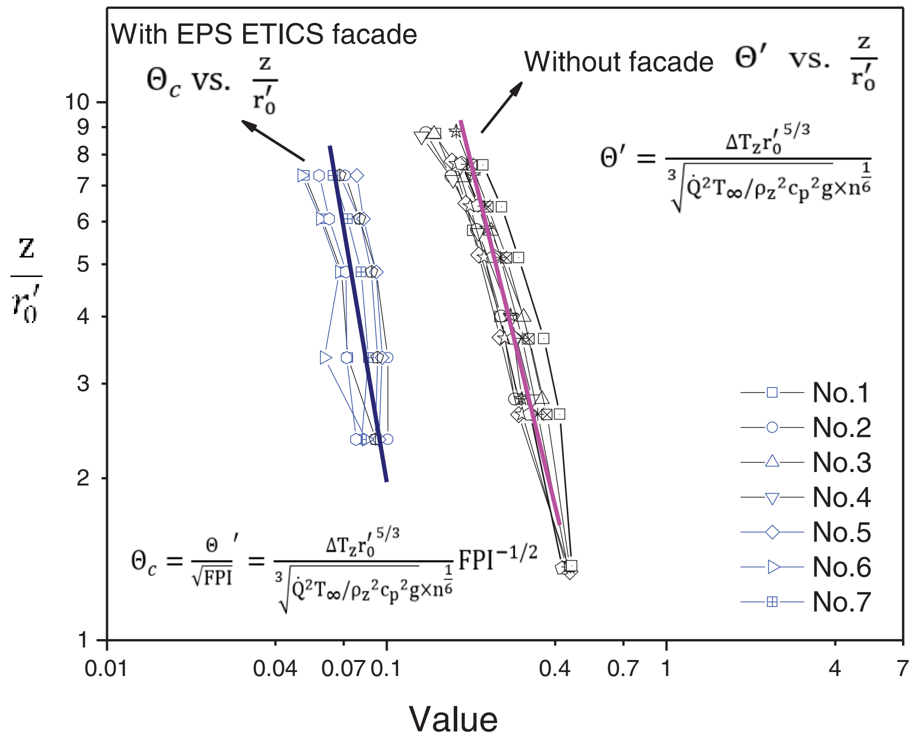


FIGURE 10 The description of correlation between Θ_c vs $\frac{z}{r_0'}$ performed by 20 minutes time-averaged temperature

The calculation Θ_c performed with $\Delta T_z = T_{zmin} - T_a$ is used to validate the correlation Θ' vs $\frac{z}{r_0'}$ in the current contribution, where T_{zmin} represents 20 minutes time-averaged temperature of fixed locations during facade fire test. It is found that results of two calculation methods are consistent with each other. It provides a potential correlation to obtain the vertical temperature distribution based on the given conditions, which is useful for building design. For example, knowing that window fire intensity and EPS ETICS façade parameter prior to the intermediate-scale test, the vertical temperature distribution during EPS ETICS façade fire could be adequate approximated. The precondition of this engineer equation is listed as the followings: (1) Wind influence is ignored during the whole test. (2) Back-wrapping method is used for the opening treatment. (3) EPS thickness varies from 100 to 200 mm and window fire differs from 600 to 1100 kW. (4) Specimens are prepared without cavity.

However, the ETICS façade configuration varies at each country in detail. The typical calculation method for each types of façade should be further studied.

3.4 | Uncertainty analysis during façade fire tests

The radiation heat from a combustion flame has been reported to show a heavily influence on the accuracy of temperature measurement during large-scale fire test.[30] The radiation heat flux profiles of EPS (EPS thickness = 50 mm, 300 kW window fire intensity) ETICS façade surface during JIS A 1310 test indicated heat flux density of location HF1(0.5 m) and HF2 (0.9 m) are much higher than other position.[13] Therefore, radiation heat perhaps arise the uncertainty of thermocouples. With an aim to investigate the repeatability of large-scale test results, the calibration tests are carried out in four different times with the same test condition within 2 years. The SD error of repeatability test was found to be very small.[20] Furthermore, a ceramic fiber tube was installed on the bead of thermocouple to avoid receiving heat from other places.

In addition, the duplicate large-scale test was conducted in this contribution. For example, test No.3 and test No.4 are nearly the same specimen, although the preparation time was different. The peak temperature difference of four fixed location during two tests are found in 8°C, 22°C, 1°C, 56°C and 81°C, respectively. Comparison of temperature results, just as shown in Figure 6, indicates the vertical temperature distribution is coincident. It could be used for evaluation of EPS ETICS façade fire.

4 | CONCLUSION

In this work, vertical temperature profile of EPS ETICS façade during JIS A 1310 test from Japan is discussed by a series of tests and theoretical analysis. The window spilled fire was produced by using a 1.35 m (*L*) × 1.35 m (*H*) × 1.35 m (*W*) fire compartment. Widow fire intensity changes from 600 to 1100 kW, TRP differs from 163.9 to 276.8 kW · s^2/m^2 and FPI varied from 17.1 to 28.9 (m/s$^{1/2}$)/(kW/m)$^{2/3}$. The followings are obtained:

1. The typical temperature histories varying test time consists of three peaks. Peak 1 stands for the combustions of PCM, peak 2 means the combustion of EPS foam panel, and peak 3 represents the combustion of combustible pyrolysis gas with a fresh air due to a broken hole.

2. Based on the discussion, a dimensionless temperature Θ_c of vertical temperature over EPS ETICS surface varying window fire intensity and FPI is proposed based on the following precondition: (1)

Wind influence is ignored during the whole test. (2) Back-wrapping method is used for the opening treatment. (3) EPS thickness varies from 100 to 200 mm and window fire differs from 600 to 1100 kW. (4) Specimens are prepared without cavity. The

$$\Theta_c = \frac{\Theta\ '}{\sqrt{\mathrm{FPI}}} = \frac{\Delta T_z {r'_0}^{5/3}}{\sqrt[3]{\dot{Q}^2 T_\infty / {\rho_z}^2 {c_p}^2 g \times n^{\frac{1}{6}}}} \mathrm{FPI}^{-1/2} = \mathrm{function}\left(\frac{z}{r'_0}\right)$$

Where the neutral plane (N.P.) is calculated by the equation

$$x = \frac{z_0}{H} = \frac{1}{1 + 1.04\left(\frac{T_g}{T_a}\right)^{1/3}}.$$

The length scale r'_0 was defined as $r'_0 = \sqrt{\frac{W(1-x)H}{\pi}}$.

An adequate and useful approximation is obtained in the form $\frac{z}{r'_0} = -180.40 \times \Theta_c + 17.26$. It provides a potential correlation to obtain the vertical temperature distribution based on the given conditions. With it, the vertical temperature distribution during EPS ETICS façade fire could be adequate approximated prior to the intermediate-scale test.

However, the ETICS façade configuration varies by countries. The typical calculation method for various types of facade should be further studied, which is useful for building design.

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ORCID

Biao Zhou https://orcid.org/0000-0003-3517-699X
Hideki Yoshioka https://orcid.org/0000-0003-3875-0600

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