FULL-SCALE BURNING TESTS ON FLAME SPREAD OF PLASTIC MATERIALS

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ABSTRACT

Flame spread over the surface of three selected plastic samples will be discussed in this paper. These are polyvinyl chloride (PVC), polycarbonate (PC) and polymethyl methacrylate (PMMA), all commonly used in the market. Full-scale burning tests were carried out in a room calorimeter in China.

Fire behaviours of the plastic samples were assessed by two scenarios. Scenario I was under a small pool fire of size 0.35 m by 0.35 m to simulate an accidental fire. Scenario II was on a bigger pool fire of diameter 1 m to simulate an arson fire giving flashover. A total number of five tests were carried out to measure the heat release rate, the most important parameter in fire hazard assessment. In addition, vertical temperature profiles and heat fluxes at floor level were measured. Ignition behaviour, surface flame spread, melting and charring of the materials were observed.

1. INTRODUCTION

Plastics are commonly used in buildings as interior glazing, insulation, sidewall panels, advertising boards, placards, ceilings and floor coverings. There is always a concern on the potential fire hazards in using plastics. Upon ignition, flame might spread rapidly over the plastic samples. Melted plastics at high temperatures or flaming drips falling off can ignite other combustibles such as furniture or carpets. This would accelerate the fire growth in the compartment to give a shorter time to flashover.

There are standard tests [e.g. 1,2] on assessing the burning behaviours of plastics at different stages of a fire, which are developed under different principles. Different ignition sources such as matches, small gas burners, multiple jet burners and radiation panels were used in the standard tests. These ignition sources are very different in type, size, heat intensity and exposure time. Plastics were tested in different sizes and orientations like horizontal, inclined at 45^o and vertical positions. Most of the above tests are smaller bench-scale tests. Plastics passing a specific test might not necessarily pass another test. There are no obvious correlations on the testing results which can only demonstrate the behaviours of the plastics in those particular fire scenarios. Bigger scale tests on assessing the product, such as the medium-scale furniture calorimeter and the full-scale room calorimeter, were developed. However, there are queries on how the bench-scale, medium-scale and full-scale tests are correlated with real-scale fires [3-5].

Very limited information on testing plastics in bigger scale fires is available in the literature. There are even fewer data on testing plastics under a strong heat flux under flashover room fires, most of the data were on cone calorimeter with high heat fluxes. As pointed out before [6-8], arson fire might lead to flashover rapidly. Materials should be assessed under a flashover fire in areas with higher arson fire risk, such as train vehicles which had incidents before in Korea, Hong Kong and London.

In this paper, full-scale burning tests were carried out in a room calorimeter to assess and compare the behaviours of plastic materials under two selected scenarios. The first one was an accidental fire and the second one was an arson fire to onset flashover. Results are very useful for better understanding the behaviours of plastics in real fires.

Three different plastics were tested, including polyvinyl chloride (PVC), polycarbonate (PC) and polymethyl methacrylate (PMMA) boards. These materials are commonly used in the market with thermal properties and burning behaviours studied vigorously in the literature [1].

- PVC is one of the most popular thermoplastics used in the market due to its processability and wide range of applications. Hydrogen chloride is usually eliminated at about 200 °C to 300 °C during decomposition and leads to charring, which both cause self-extinguishment.

- PC usually foams up and chars when burning, which mainly results in charred residue and gaseous products. The flame self-extinguishes if the ignition source is removed.

- PMMA burns in almost complete combustion. It melts and volatilises on pyrolysis and remains no residue.

The PVC and PC boards tested in this set of tests were manufactured to consist a gap between two thin sheets to reduce the total weight. Those boards are commonly used as suspended ceilings and wall linings for water-proofing in humid areas such as bathrooms.

Typical properties of PVC, PC and PMMA [1] are shown in Table 1.

2. FULL-SCALE BURNING TESTS

Experiments were carried out in a full-scale burning facility developed by the leading author in Harbin, China [9]. Materials were tested in a room calorimeter similar to ISO 9705 [10] of 3.6 m long, 2.4 m wide and 2.4 m high. Natural ventilation was provided by a door of 0.8 m wide and 2.0 m high, giving a ventilation area of 1.6 m^2 as shown in Fig. 1. A two-layer fire-rated glass panel of 2 m long and 1 m high was installed on the left sidewall to observe the flame spread and for video-recording.

The plastic samples were cut into a size of 2.4 m wide and 2.4 m high (of area 5.67 m^2). All samples were mounted onto the rear wall following common construction practice. The materials were kept at 55 % relative humidity and 23 °C. Details of the materials tested in the full-scale tests are shown in Table 2.

There were two testing scenarios: Scenario I on an accidental fire and Scenario II on an arson fire as shown in Fig. 1b and 1c. All the three plastics were tested in Scenario I. PVC and PC were selected to be tested in Scenario II.

An exhaust hood was mounted above the doorway connected to a fan-duct system as in ISO 9705 [10]. Smoke and combustion gases generated during the tests would be collected. There is a 'duct section' with gas samplers fitted to an oxygen analyzer. The heat release rate was estimated from the collected data in every 5 s using the oxygen consumption method.

Instrumentation was put in the test room for measuring the upper layer gas temperature, fire plume temperature and heat flux at floor level. Data was sampled at intervals of 1 s.

A heat flux meter was located on the floor at 2.4 m away from the rear wall as shown in Fig. 1d for recording the heat flux at floor level.

The upper layer gas temperatures and fire plume temperatures were measured by 12 type K 1-mm inconel sheathed high-temperature rated thermocouples as shown in Fig. 1c and 1d. The upper layer gas temperature was measured at 0.03 m beneath the ceiling. Six points were used with one point (T1) mounted above the accidental fire source and five points (T2 to T6) mounted symmetrically under the ceiling as shown in Fig. 1d.

Thermocouples were observed [11] to be easily detached from the burning surface of the material, especially when the melted plastics fell off. It is not too appropriate to measure the surface temperature of the plastics for determining the flame front positions. Further, melting of the plastics might affect the response time and accuracy of the thermocouples. Once there are melted residues stuck to the surface, the thermocouples cannot be used anymore. Therefore, gridlines of 0.3 m by 0.3 m were drawn on the surface of the plastics for observing the flame front from the glazed wall.

Table 1: Typical thermal properties [1]

Material	Bulk density / kgm^{-3}	Vicat softening point B / °C	Decomposition range / °C	Flash ignition temperature (ASTM D 1929) / °C	Self-ignition temperature (ASTM D 1929) / °C	Heat of combustion, ΔH / $MJkg^{-1}$
PVC	1870	70 - 80	225 - 275	> 530	> 530	10
PC	1200	150 - 155	350 - 400	520	No ignition	31
PMMA	1180	85 - 110	170 - 300	300	450	26

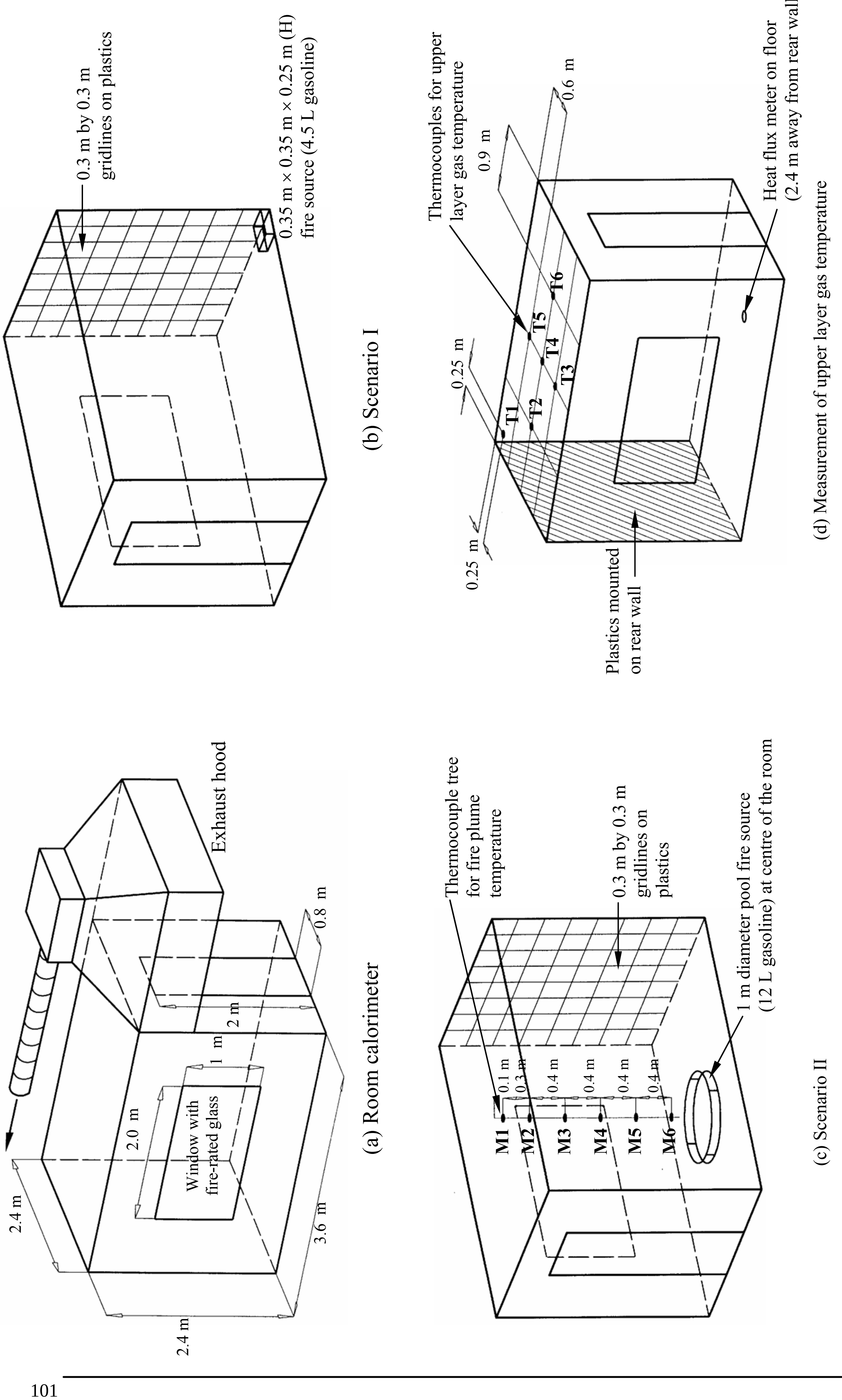


Fig. 1: Experimental setup

Table 2: The three tested plastic samples

Material	Size	Overall thickness	Sheet thickness	Air gap between two sheets	Density	Colour	Mounting
Hollow PVC sheet	2.4 m×2.4 m ($5.76 m^2$)	9 mm	0.7 mm	7.6 mm	1850 kgm^{-3}	White	Nailed to concrete wall
Hollow PC sheet	2.4 m×2.4 m ($5.76 m^2$)	10 mm	0.4 mm	9.2 mm	1260 kgm^{-3}	Blue & transparent	Nailed to concrete wall
Solid PMMA sheet	2.4 m×2.4 m ($5.76 m^2$)	4 mm	4 mm	-	1140 kgm^{-3}	Colourless & transparent	Nailed to concrete wall

3. SCENARIO I

A small fire source comparable to a severe basket fire was used to assess the flame spread behaviours of the plastics under an accidental fire. A square container of 0.35 m wide and 0.25 m high with 4.5 litre $90^{\#}$ gasoline was used. The fire source was located at the right rear wall corner as shown in Fig. 1b, such that the flame was in direct contact with the plastics behind it during the tests.

When the gasoline fire was burnt alone at the corner without plastics attached on the rear wall, the heat release rate was over 100 kW for 730 s and then over 80 kW for 470 s. The average heat release rate was 100 kW for 1200 s as shown in Fig. 2a. The plastics were assessed for 1200 s or until there was no further flame spread over the plastics.

As the burning process would be slightly different in different tests, such results on heat release rate were taken as a reference only. The pyrolysis rate of both the gasoline and plastics depended on the radiation feedback from the burning object and the hot gas layer formed beneath the ceiling. The heat release rate and hence the fire growth rate inside the room depend on such conditions in real fires. That is why testing the plastic materials under a flashover fire is necessary.

4. SCENARIO II

In scenario I, the plastics were only tested under a growing fire. If there is an arson fire to onset flashover in a room, the resulted high heat fluxes (20 kWm^{-2} at floor, 35 kWm^{-2} at wall and 50 kWm^{-2} at ceiling) would ignite all combustibles inside the room. The burning behaviours of the materials would be very different from those under a growing accidental fire. To estimate the contribution and the actual heat release rate of the materials in flashover, a large enough fire (but not too large on later contribution) should be used to give thermal radiation on all the materials.

A bigger pool fire of diameter 1 m with 12 litre $90^{\#}$ gasoline was located at the centre of the room as shown in Fig. 1c. This was tested experimentally many times such that the fuel is good enough to give flashover but the fire itself can only last for a short period inside the room. This fire source itself would be burnt out without affecting the other stored materials. Further, the pool fire was placed 1.3 m away from the rear wall. The flame of the fire source was kept away from the tested plastics without touching them.

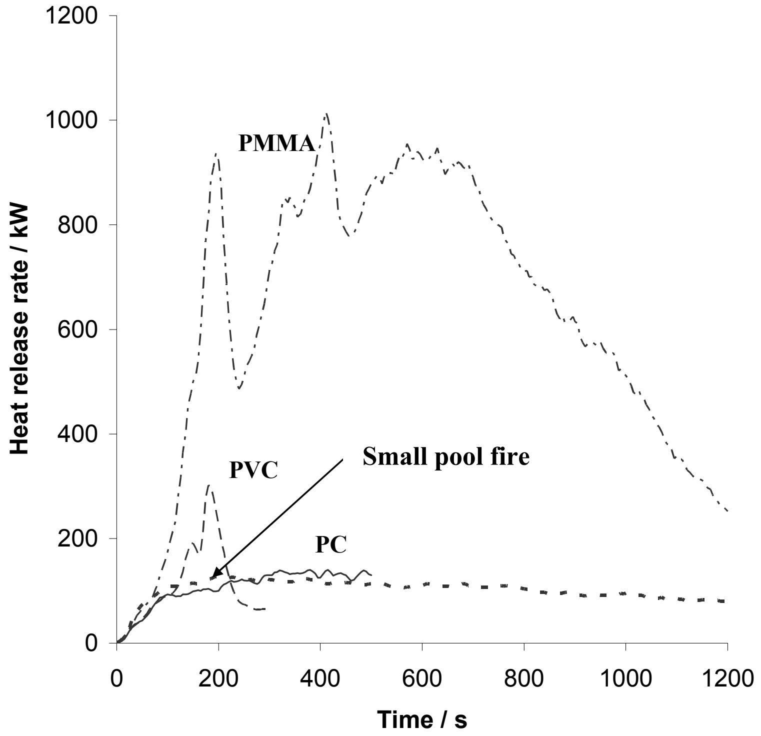
The peak heat release rate of the pool fire was 2.3 MW. The time to peak heat release rate was 85 s as shown in Fig. 3a. The total heat release rate was 410 MJ at 300 s. The upper layer gas temperature was about 650 ^{o}C and the heat flux at floor level, 0.3 m from the fire source was over 15 kWm^{-2}.

Materials burning by itself were assessed as the pool fire was burnt out.

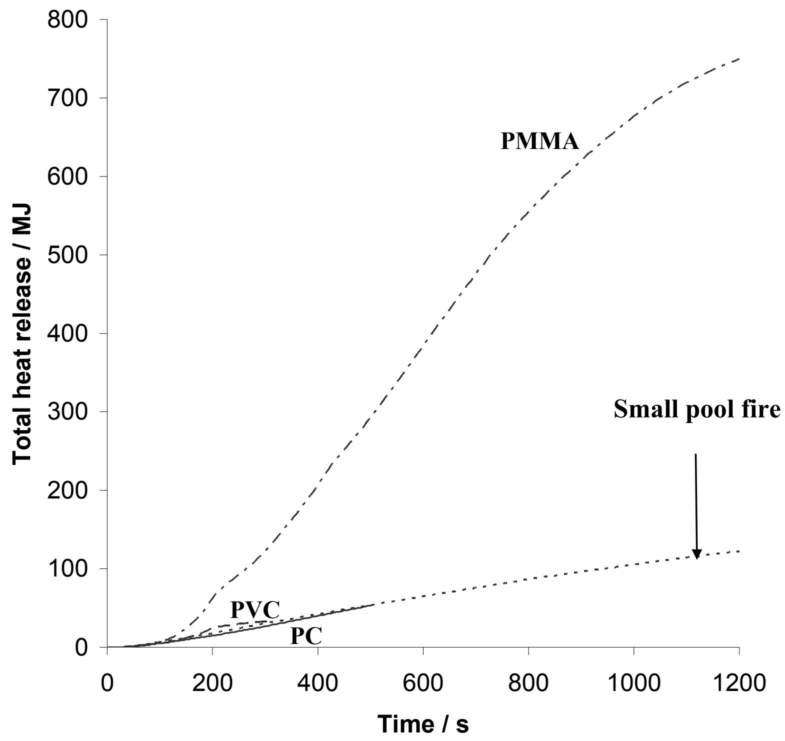
Vertical temperature profiles of the source fire plume were measured along a thermocouple tree at the centre of the room in Scenario II as shown in Fig. 1c. Six thermocouples (M1 to M6) were mounted above the pool fire for confirming the onset of flashover.

5. RESULTS FOR SCENARIO I

The measured heat release rate curves for PVC, PC and PMMA are shown in Fig. 2. Appearances of the three plastic samples after the tests are shown in Fig. 4. The peak heat release rates and total heat released in the tests are summarized in Table 3. The heat flux was measured at 2.4 m from the rear wall, i.e. 2.7 m away from the fire source. The peak heat flux recorded in burning the gasoline fire alone was less than 0.3 kWm^{-2}. The heat flux reached 10 kWm^{-2} when burning PMMA, which was five times the peak values of about 2 kWm^{-2} as measured in the tests of PVC and PC.

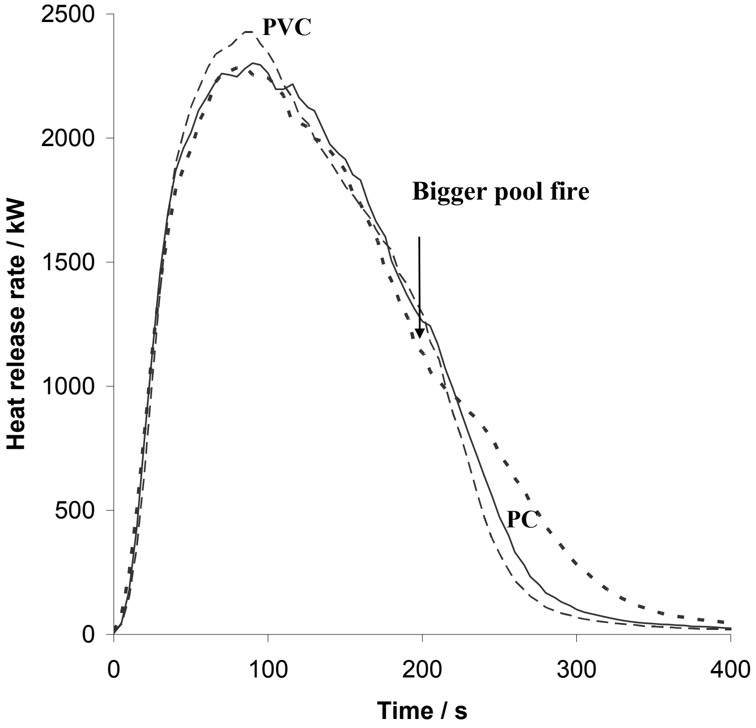


(a) Heat release rate

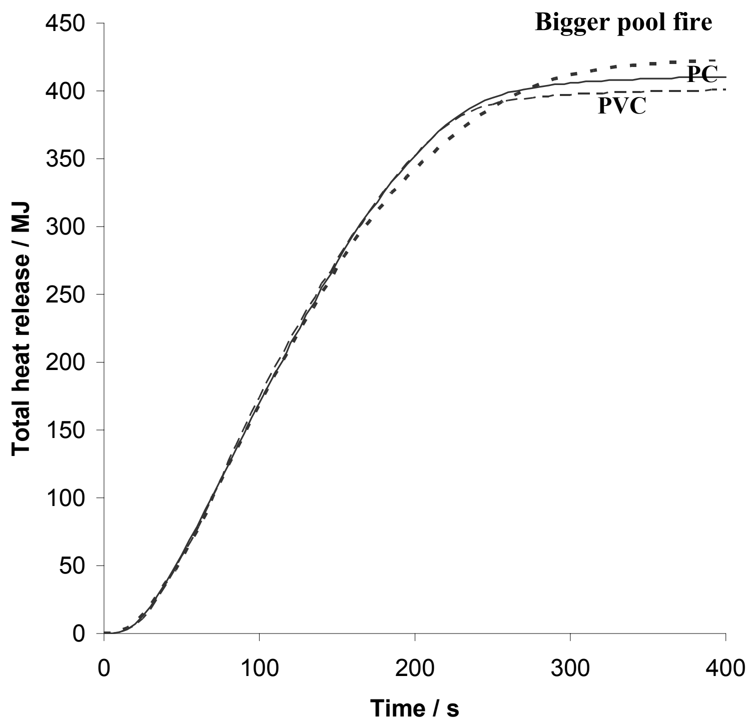


(b) Total heat released

Fig. 2: Heat release rate and total heat released for scenario I

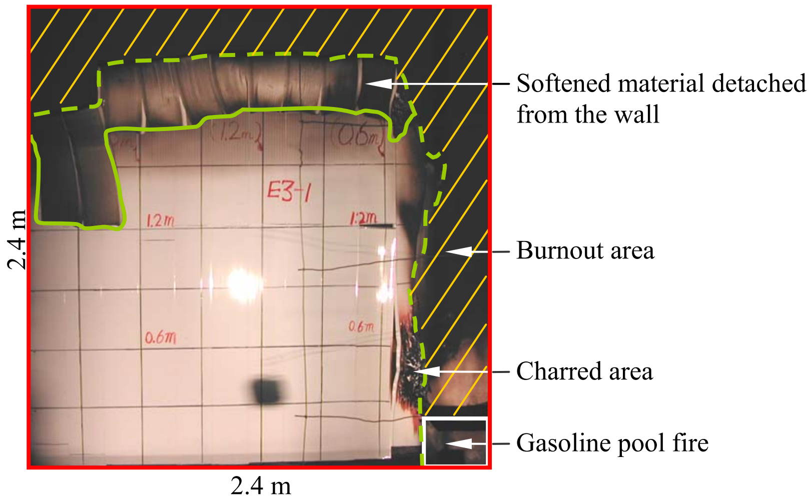


(a) Heat release rate

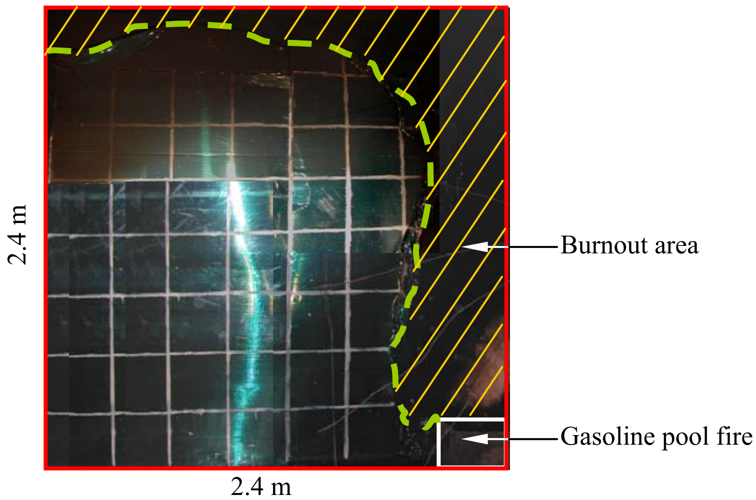


(b) Total heat released

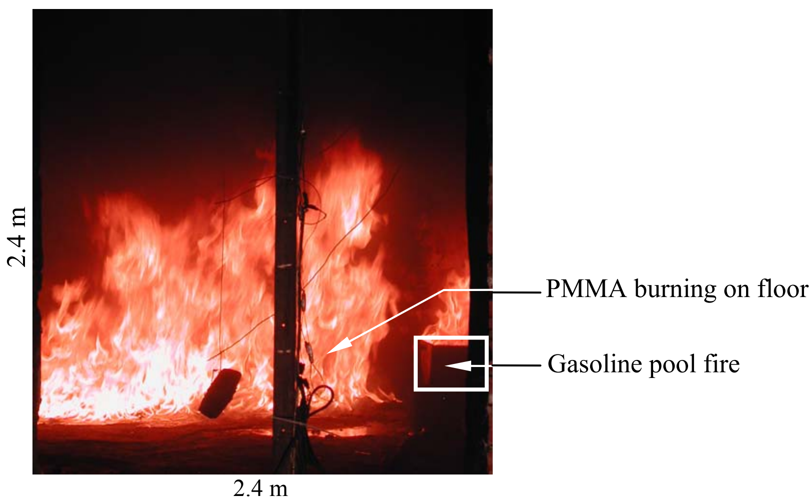
Fig. 3: Heat release rate and total heat released for scenario II



(a) PVC



(b) PC



(c) PMMA

Fig. 4: Appearance of the plastic samples after the test for scenario I

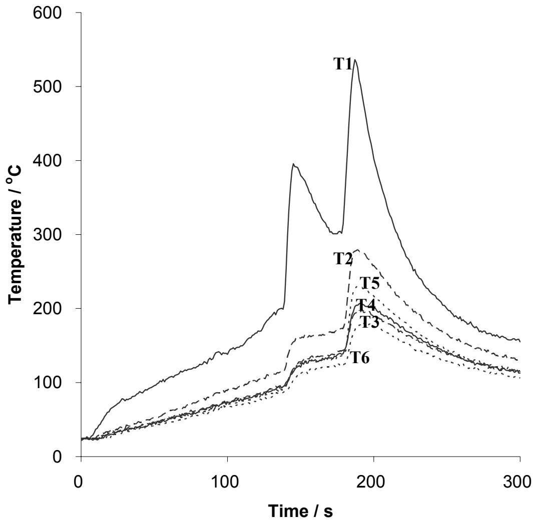
The temperature data are summarized in Table 3 and the temperature-time curves are shown in Fig. 5. The temperature recorded at T1 above the gasoline fire source reached the highest peak values in all the tests. In burning the gasoline fire only, the maximum value of T1 was 238 °C. Maximum values of T2 to T6 were between 130 °C to 163 °C.

The PVC board was observed to ignite at 82 s, followed by a rapid increase in the heat release rate and burning area in the upward region above the fire source. At 132 s, the material started to detach from the wall. 40 s later, part of the PVC fell into the gasoline fire pool. The heat release rate increased to 302 kW at 180 s as shown in Fig. 2a. There was no further lateral flame spread and the flame on the PVC self-extinguished due to charring. The test was terminated at 300 s and the total heat released was 33 MJ. Upward flame spread was observed. Only the region above the pool fire was burnt out as shown in Fig. 4a. By estimation, about 0.9 m^2 of PVC was burnt out in the test. Part of the PVC close to the pool fire was charred and this limited the lateral flame spread over the material. Materials close to the ceiling were heated by the hot gas layer, losing rigidity, deformed and detached from the wall. As observed from Fig. 5a, T1 was over 500 °C. The maximum temperature recorded at T2 to T6 (which were symmetrically mounted beneath the ceiling) was only 280 °C. The PVC panel close to the ceiling-wall was softened and deformed by the emitted heat flux.

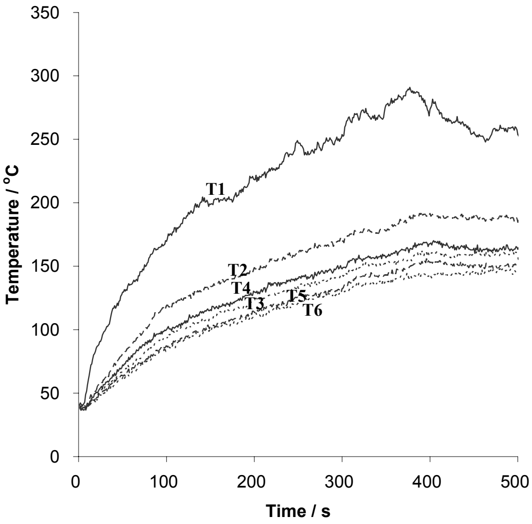
The PC board started to melt at about 50 s due to the pool fire. Melting continued throughout the test and the melting PC moved away from the gasoline flame. No flame was observed over the PC surface. Some of the melted PC near to the pool fire flame fell into the container. The heat release rate increased with the extended melting area. However, the measured heat release rate was only slightly above the reference values of the gasoline fire. The peak heat release rate was 140 kW at 380 s as shown in Fig. 2a. The region above the burner and part of the region close to the ceiling were melted as shown in Fig. 4b. There was no further flame propagation or melting away from the vicinity of the fire source. There was no significant heat released for the duration of the test and the test was ended at 500 s. The total heat released was 53 MJ. About 1.23 m^2 of the PC board was totally melted and 0.27 m^2 was partly melted with residues left. The peak temperature of T1 was only 290 °C as shown in Fig. 5b. The upper layer gas temperature (T2 to T6) was less than 200 °C, but was high enough to melt the upper region.

Table 3: Summary on heat release rate and upper layer gas temperatures

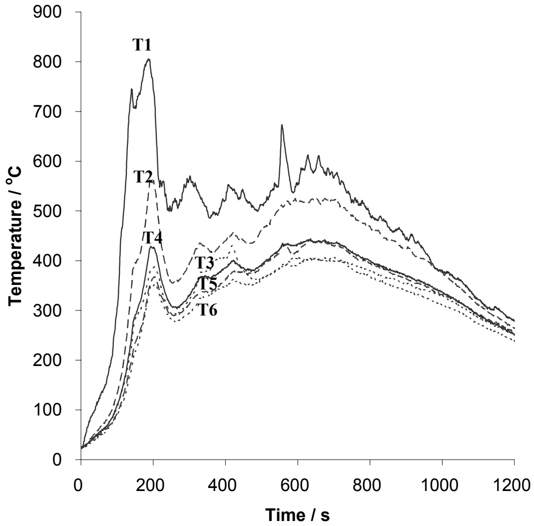
Results		Scenario	PVC	PC	PMMA	Gasoline fire source
Time to ignition (Visual observation) / s		I	82	Melting at 50 s	22	0
		II	-	-	-	0
Peak HRR / kW		I	302	140	1016	About 100 kW
		II	2427	2302	-	2289
Time to peak HRR / s		I	180	380	411	-
		II	85	90	-	85
Total heat released / MJ		I	33 MJ up to 300 s	53 MJ up to 500 s	750 MJ up to 1200 s	122 MJ up to 1200 s
		II	401 MJ up to 400 s	410 MJ up to 400 s	-	423 MJ up to 400 s
Maximum upper layer gas temperature / °C	T1 (above accidental fire source)	I	536	291	806	238
		II	489	508	-	549
	T2	I	280	192	565	163
		II	720	678	-	677
	T3	I	198	163	431	147
		II	808	730	-	732
	T4 (centre of the ceiling)	I	207	170	444	140
		II	741	715	-	711
	T5	I	230	158	442	141
		II	698	697	-	670
	T6	I	182	154	406	130
		II	697	651	-	663



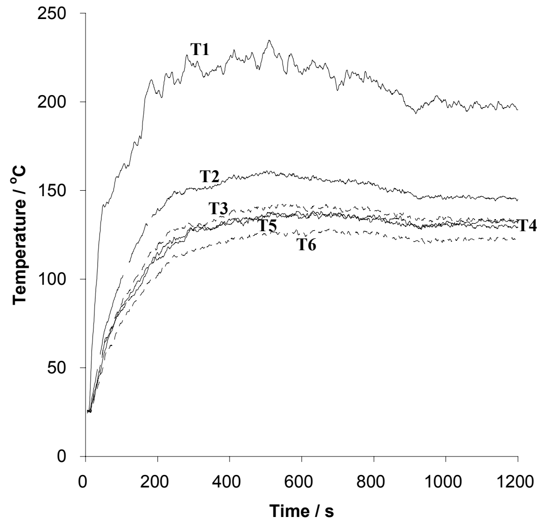
(a) PVC



(b) PC



(c) PMMA



(d) Small gasoline fire source

Fig. 5. Upper layer gas temperature for scenario I

The highest peak heat release rate was observed in burning PMMA. Almost the whole sheet was consumed in the test. The region behind the fire source was observed to ignite at 22 s with rapid upward flame spread. The heat release rate then increased. When the flame reached the ceiling at 195 s, the burning region detached from the wall, covering the unburnt part of the material and caused rapid lateral flame spread. A peak heat release rate of 1016 kW was measured at 410 s as shown in Fig. 2a. All the material fell off and burnt on the floor till the end of the test (1200 s) as shown in Fig. 4c. The total heat released was 750 MJ. As observed from Fig. 5c, T1 reached 806 ^{o}C. The upper layer gas temperature at the centre of the room (T4) reached 400 ^{o}C and it was up to 600 ^{o}C at T2. This would provide strong radiation feedback to ignite all other combustibles.

6. RESULTS FOR SCENARIO II

Only PVC and PC samples were tested under this scenario. Upon ignition of the gasoline pool fire, the whole room was filled with flame and dark smoke. It was difficult to observe the part of plastic board being ignited, unable to locate the flame front.

Nearly all PVC was consumed in the flashover fire. The peak heat release rate obtained in burning PVC was 2427 kW as shown in Fig. 3a. The PVC was charred, deformed and shrank. Only about 13 % of PVC was left on the floor after the test.

As shown in Fig. 3a, the peak heat release rate given out in burning PC was about 2.3 MW. The value was very close to that in burning the gasoline fire alone. Most of the material was burnt out in the fire. Some melted residues of area about 10 % of the total specimen area were left on the floor after the test.

With PVC and PC on the rear wall, the total heat released were 401 MJ and 410 MJ respectively. The results on the peak heat release rates and total heat released are summarized in Table 3. In view of the oxygen consumption as shown in Fig. 6, the oxygen concentration inside the room in the test of PVC was the lowest among the three tests (15.3 %), 1.5 % lower than the minimum value in the tests of burning PC with gasoline.

Temperatures recorded by the thermocouples M1 to M6 above the gasoline fire ranged from 700 ^{o}C to 800 ^{o}C. As shown by the temperature-time curves, the pool fire started to burn out at 250 s for the tests of PVC as in Fig. 7a and of PC as in Fig. 7b. Temperature of M6 at 0.4 m above the pool fire dropped to below 400 ^{o}C. In burning the gasoline fire alone as in Fig. 8c, M6 remained at 600 ^{o}C at 250 s.

The maximum temperatures recorded at T1 to T6 in the tests are summarized in Table 3. The temperature-time curves are shown in Fig. 8. The upper layer gas temperature at the centre of the room (T2 to T6) reached over 600 ^{o}C within 50 s, suggesting the onset of flashover. However, T1 at the rear wall corner of the room at 1.8 m away from the centreline was about 500 ^{o}C in all the tests. As T1 was only located at 0.25 m from the surface of the tested plastics, the upper part of the tested plastics can be taken as lying within a hot gas layer of 500 ^{o}C.

7. DISCUSSION

When PMMA was tested under a small accidental fire as in Scenario I, the material was ignited shortly after 22 s with rapid flame spread both vertically upward and laterally. It was softened when burning and collapsed from the wall easily. The rate of burning increased and the whole PMMA sheet was burning within 3.5 minutes. Flashover is likely to occur if the other walls are also covered by PMMA materials or there are other combustibles inside the room.

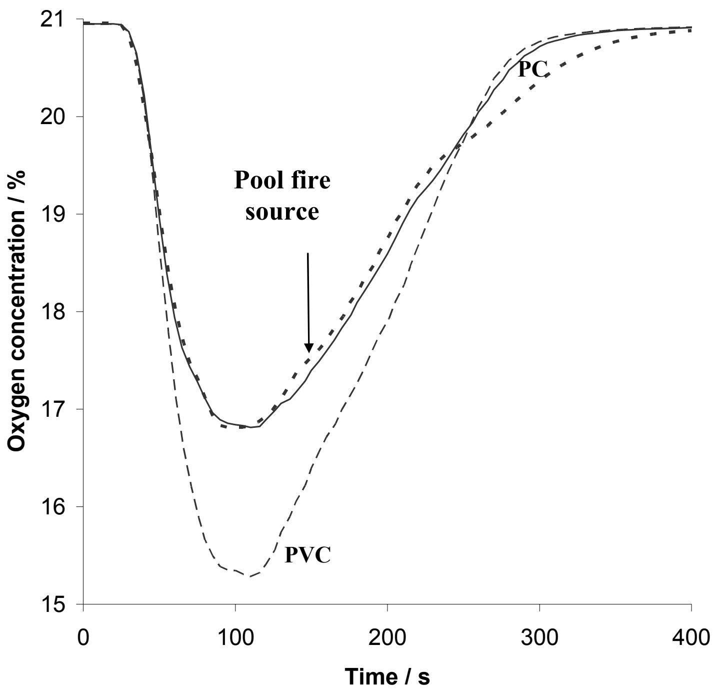
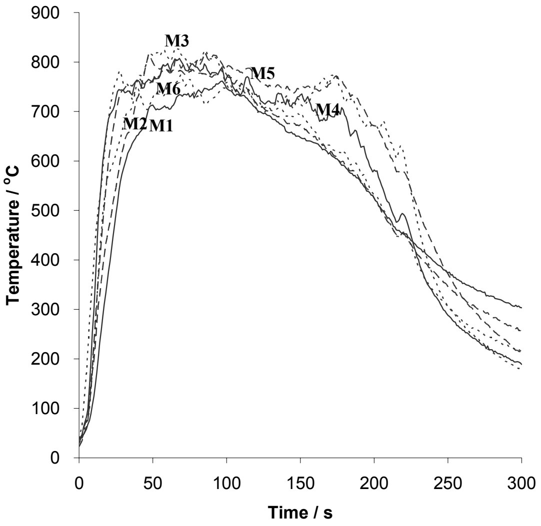
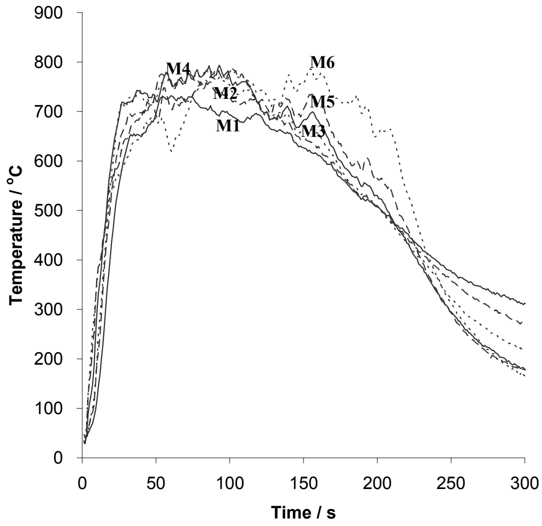


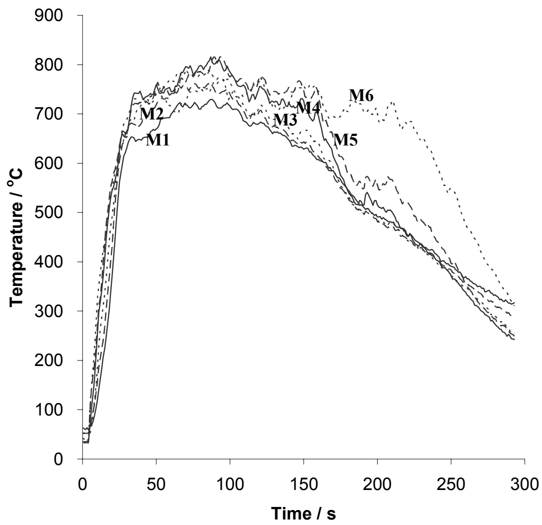
Fig. 6: Oxygen concentration for scenario II



(a) PVC



(b) PC

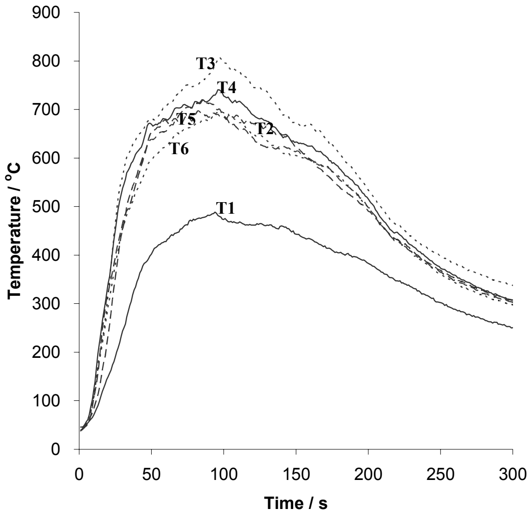


(c) Gasoline fire

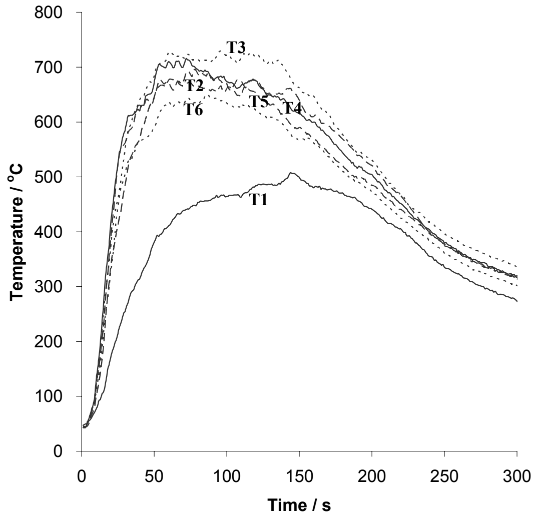
Fig. 7: Fire plume temperature for scenario II

Both the PVC and PC boards showed limited burning in Scenario I. The PVC board burnt vertically above the fire source only. Some of the parts with flames fell off from the wall. This would ignite other combustibles in real fires. The upper region close to the ceiling-wall corner was deformed and detached. Charring of PVC would limit the lateral flame spread.

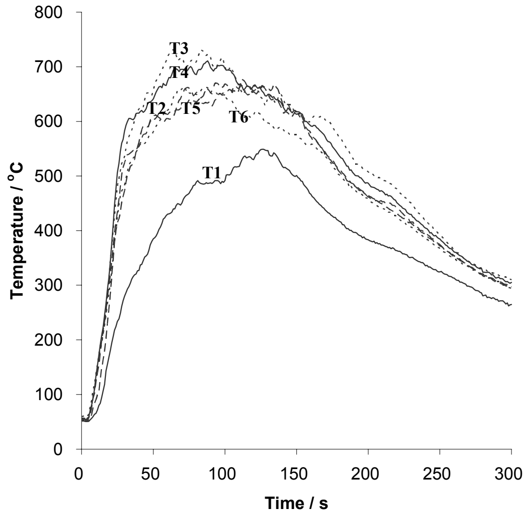
PC melted shortly after the starting of the test under scenario I. There was no flame over the surface though PC continued to melt. As observed, PC of area about 0.1 m^2 (0.3 m by 0.35 m) behind the flame of the pool fire took 50 s to burn out. The upward burnout front advanced 0.3 m at 50 s later, and it took about 80 s for the burnout front to proceed 0.15 m laterally. The lateral melting region width was less than 0.1 m. The upward melting region was comparatively larger and was up to 0.2 m due to the bigger preheated area resulted from the high flame length of the pool fire. The melting region or the pyrolysis region was kept in a small area with a high burnout rate. The melting rate decreased significantly away from the pool fire. The heat release rate in burning PC with the pool fire was only slightly higher than that of burning the gasoline pool fire alone. There were no flaming drips but the melted parts falling off might ignite other combustibles with lower ignition temperatures.



(a) PVC



(b) PC



(c) Gasoline fire

Fig. 8: Upper layer gas temperature for scenario II

In Scenario I, the PVC and PC boards had no further flame spread after 300 s and 500 s respectively. Flame spread upward, not downward in both cases. The burnout region was limited to the vertical zone above the pool fire and the upper region close to the ceiling immersed in the hot gas layer. Only about 16 % PVC and 21 % PC of the total area were burnt out in 300 s and 500 s respectively. The charring behaviours of those plastics would limit the extent of burning and lateral flame spread. The flame spread phenomenon depended on the flaming region and the heat flux of the ignition source to supply heat for degradation.

In Scenario II, the plastics were exposed to a much stronger heat flux of over 15 kWm^{-2} than the growing fire case in Scenario I. Almost all the PVC and PC boards were burnt out within 400 s. Only 13 % of PVC and 10 % of PC were left, deformed and melted on the floor. Obviously, the burning behaviours of those plastics and their contributions to the large fire were very different from those in the small accidental fire. It is difficult to apply the results from laboratory and bench-scale tests to estimate the potential hazard of those plastics in real fires. This part on analyzing the heat release rate had been reported in a separate article [12]. Further, the flame spreading under flashover fire will also be reported [13]. However, more detailed experimental results were reported in this article.

8. CONCLUSION

Five full-scale fire tests were conducted [12,13] for better understanding the flame spread behaviours of plastics in real fires. Three plastic materials widely used in the construction industry were selected. Those included PVC and PC boards commonly used for suspended ceilings and PMMA sheet. The plastics were mounted on the rear wall of the room calorimeter and tested under two scenarios.

In Scenario I, plastics were tested under an accidental fire starting at the corner. In Scenario II, plastics were exposed to a flashover fire. The heat release rate, upper layer gas temperature, fire plume temperature, heat flux at floor level, ignition and flame spread were measured and observed.

It is observed that the burning of those plastics will be affected by the room fire environment. The burning region was kept in limited sizes in the small growing fire due to the rapid burnout rates under low heat fluxes. Lower heat release rates were then measured. However, about 90 % of the plastics were consumed in the flashover fire with higher heat fluxes. The heat given out was much higher as reported in the above. Materials such as PVC and PC might not be ignited in small accidental fires. However, these would burn vigorously under flashover. Most of the standard fire tests are laboratory bench-scale tests. To understand the behaviours of plastic materials in real fires, full-scale burning tests under flashover are required.

ACKNOWLEDGEMENT

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