Journal of Hazardous Materials 190 (2011) 766–771

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Effect of ignition condition on typical polymer's melt flow flammability

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ARTICLE INFO

Article history:
Received 27 December 2010
Received in revised form 15 March 2011
Accepted 30 March 2011
Available online 8 April 2011

Keywords:
Flame spread
Ignition condition
Heat release rate
Fire growth

ABSTRACT

Polymer's melt flow behavior has triggered great interest due to the mutual-enhancing loop effect between vertical polymer fire and the induced flowing pool fire. The aim of the study was to quantitatively investigate the effect of ignition conditions on the polymer's melt flow flammability. Polypropylene (PP) sheets with a thickness of 4 mm were selected as the test samples. An experimental rig was designed to study the interaction between the vertical PP sheet fire and the corresponding pool fire. Ignition was achieved at three locations, i.e. the lower right corner, the lower middle edge, and the whole lower edge of the PP sheets. All tests were conducted in an ISO9705 fire test room. Heat release rate, smoke temperature and other common parameters in fire hazard analysis were measured with the help of the fire room facilities. Results indicated that ignition conditions evidently impact on heat release rate development, peak heat release rate, smoke temperature, smoke generation and smoke toxicity. Furthermore, these experimental results preliminarily demonstrated the feasibility of the designed setup in studying interaction between vertical polymer sheet fire and the induced pool fire, although further modification may be needed.

1. Introduction

An increasing number of objects made of polymers can be found in buildings, including mattresses, decoration materials and some other furniture. These objects will cause considerably complicated flame spread dynamics in that the melting and dripping characteristics of polymers will induce a pool fire under the burning objects. The pool fire may accelerate the upward flame spread and thus generate more melting fuel to increase its intensity, which forms a loop effect. This phenomenon can inevitably render much more heat and heavier toxic smoke, and will be a potential hazard to occupants and fire fighters. Consequently, it is important to investigate mechanisms that dominate the specific flame spread mode.

When polymers are burning, melted liquid phase polymer flows downward due to gravity, and boosts flame spread speed when viscosity of the molten polymer is relatively high[1]. Meanwhile, the flaming drips can ignite combustibles under the burning polymer, and a pool fire, as is typical, can be formed eventually. The pool fire can be self-feeding, provided that its plume can generate enough heat to reach the burning object, and consequently the heat release rate of the burning system can be further enhanced [2]. Evidently, initial conditions can impact on or even be dominant in fire development in that their influence can be exacerbated by the loop mechanism and the overall burning process may be completely different. Flammability of polymers, which means the response of a polymer when it is exposed to an irradiative heat flux in the research, can consequently be significantly affected.

The study of polymer fire with melt flow behavior has been the focus of interest of many recent studies. Zhang et al. [3,4] claimed that the flame spread was eventually controlled by the pool fire formed at the base of a solid polymer. Sherratt and Drysdale[5] confirmed this discovery and reported the importance of flooring material in pool fire development. Chow investigated polymers' burning behavior under flashover in an ISO9705 fire test room, and demonstrated the difference in polymer's melting and charring characteristics in a flashover fire and an accidental fire[6,7]. Xie et al. [8] investigated the flowing distance of several polymer materials' pool fires with a T-shape rig, and polyethylene (PE) was found to be the most dangerous. Butler et al. [9] argued that viscosity is a key determinant of the melting behavior of polymers. Ignitability of flame retardant polymers was extensively investigated using a cone calorimeter [10–14]. Several earlier works also explored the influence of thickness on polymer flammability, and emphasized the importance of thickness in polymer combustion behavior [15–17].

Though repeated efforts have been made to study polymer's melt flow flammability, little research has been devoted to the impact of ignition conditions on polymer's melting and burning behavior. In real world, polymers may be exposed to various ignition sources, due to specific kinds of accidental or arson fires.

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doi:10.1016/j.jhazmat.2011.03.108

The corresponding flame spread may be different. Therefore, to quantitatively examine the effect of ignition conditions is indispensable for fire safety design, especially for the currently emerging performance-based design.

In this research, we sought to investigate the impact of ignition conditions on polymer's melt flow flammability. An experimental setup, which would be used to investigate the interaction between vertical flame spread and pool fire, was designed and tested in an ISO9705 fire test room. Previous research has revealed that polypropylene (PP) is the most suitable material to represent polymer melt flow behavior[18], therefore PP was selected as the test sample in the investigation. Three ignition positions were used during the tests, with the aim of demonstrating the significance of ignition conditions, and to provide insights into performance-based fire safety design in considering different fire scenarios.

2. Experimental setup

To quantitatively investigate not only the interaction between vertical fire and pool fire, but the influence of ignition conditions, especially the impact of different ignition sources and location on the burning system's overall behavior, an experimental rig was designed, and some important fire parameters, such as the heat release rate, were measured with the help of an ISO9705 fire test room. The detailed experimental information is shown in Fig. 1.

Fig. 1(a) gives the schematic of the fire test room inside which all tests were conducted. The inner dimensions of the room are 3.6 m long, 2.4 m wide and 2.4 m high. A door 0.8 m wide and 2 m high was opened in the front wall, giving a natural ventilation area of 1.6m^2. A fire-rated glass panel 2 m long and 1 m high was mounted in the observation window located in the side wall. An exhaust hood with the size of 3 m × 3 m × 1 m was placed in front of the door to collect smoke, and was connected to an exhaust duct. All tests were monitored via a video recorder placed in front of the door.

The most significant and distinctive element of the experimental setup is the interaction of pool fire and vertical fire simulation facility design. As shown in Fig. 1 (b), in the center of the fire test room, a steel trough with dimensions of 0.7m × 0.7 m was positioned on the floor, which was employed to collect melted polymer and simulate a pool fire. Meanwhile, all the test PP sheets, 1 m high, 0.6 m wide and 4 mm thick, were mounted on a supporting steel frame that could hold the sheets in the center of the pool, leaving a distance of 5 cm between the lower edge of the PP sheets and the bottom of the pool. The influence of vertical fire and vertical flame spread could thus be observed during the tests. In order to measure smoke temperature, five thermocouples numbered TC1-5 in Fig. 1 (b) were placed just below the ceiling, and the average temperature recorded was used in the results analysis. Moreover, a thermocouple tree was located at the near window side of the pool. The precise position is demonstrated in Fig. 1 (c).

Smoke generated during the tests was collected by the hood in front of the door and vented by an axial flow fan at the end of the exhaust duct. The heat release rate was measured based on the oxygen depletion principle, while the CO concentration in the combustion product and the smoke extinction coefficient was monitored every 5 s from samples pumped out of the exhaust duct. Calibration was precisely conducted before each test according to ISO9705 code[19]. Replication research was carefully conducted before the investigation, and results indicate that relative error is within 10% of the designed setup under the same experimental conditions[20].

Three tests were conducted in the investigation. In test 1, the ignition source was 20 ml alcohol confined in a cylindrical steel container with a radius of approximate 3 cm, and was removed immediately upon ignition of the PP sheet. Ignition location was at the lower right corner of the PP sheet. In test 2, the ignition source was the same as that in test 1, while the ignition position was at the center of the lower edge of the tested PP sheet. In test 3, the ignition source was completely different from that of the former two, in that a linear source was adopted. Curtain fabric, which consists of about 35% cotton and 65% terylene, was soaked in alcohol and positioned under the PP sheet in an even linear fashion, and the ignition source was not removed, since the ignition material was nearly burnt away once the PP sheet was ignited. After each test, a comparatively long period was needed to cool the fire test room. Therefore, the ambient temperature might have been several degrees different at the three different test times. Detailed parameters of the three tests are summarized in Table 1.

Table 1
Summary of parameters of test series.

Test	Ignition position	Ignition source
1	Right corner of lower edge	20 mL alcohol (removed after ignition)
2	Center of lower edge	20 mL alcohol (removed after ignition)
3	Entire lower edge	Curtain cloth soaked with alcohol(not removed after ignition)

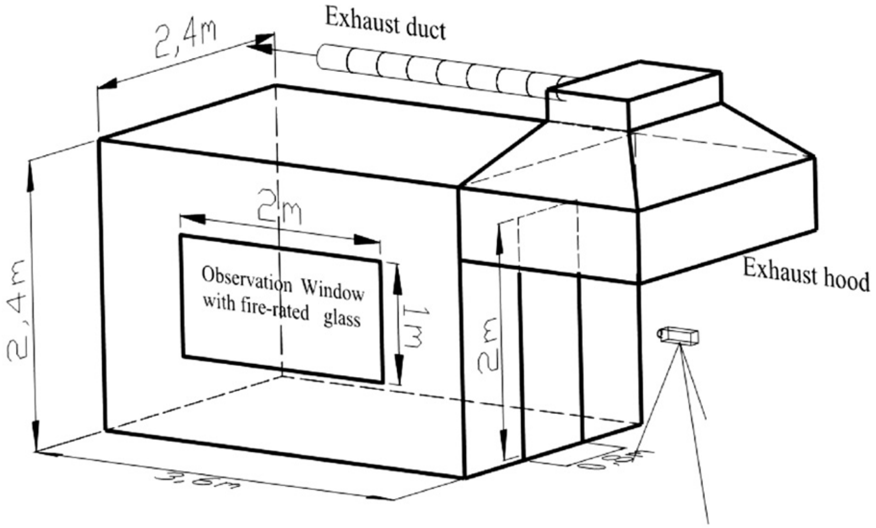
3. Results and discussions

As discussed above, three tests were conducted to explore the impact of ignition conditions on polymer's burning behavior. Fig. 2 gives the measured results of heat release rate and accumulated released heat of all the tests. As shown in Fig. 2(a), the peak heat release rate of test 1, test 2 and test 3 were 218kw, 295kw, and 195kw respectively, and the respective times to reach peak heat release rate were 1480s, 1040s and 2575s. The peak heat release rates results and total heat released are summarized in Table 2.

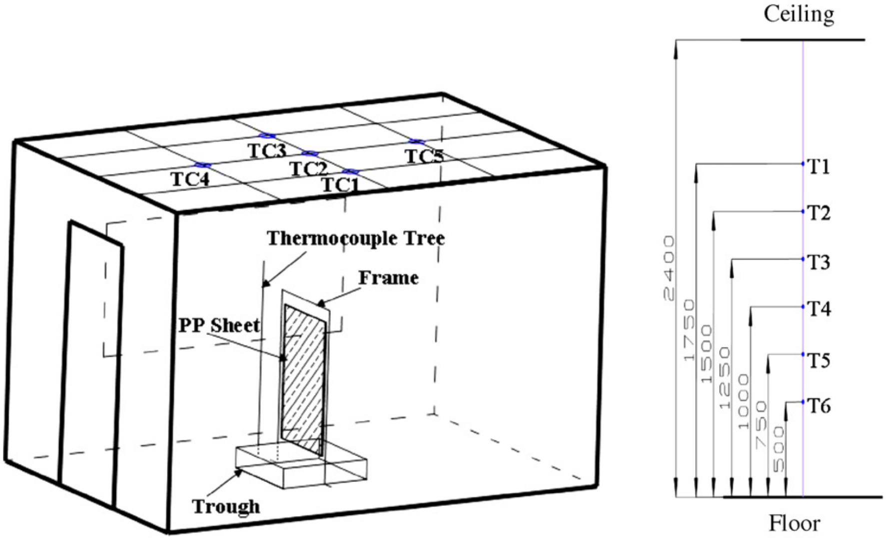
As expected, the peak heat release rate of test 2 was much higher than that of test 1, and increase rate of heat release rate was consistently larger than test 1. This is mainly because the ignition position in test 2 was at the center of the PP sheet, which resulted in a horizontal flame spread in two directions. In contrast, the flame spread in test 1 could only move from right to left horizontally. Therefore, after ignition, more PP was melted and supplied to the pool fire in test 2, and the larger pool fire size was able to feed more heat to the vertical flame spread. Consequently, the burning system, including the vertical fire and pool fire, displayed higher values and increase rate of heat release rate in test 2 compared with test 1. Not surprisingly, the PP sheet in test 2 was burnt out much earlier than that in test 1, and an earlier decrease in heat release rate from peak value was induced. Fig. 2 (b) gives the results of time-dependent accu-

Table 2
Summary of heat release rate and upper layer temperature.

Results	Test1	Test2	Test3
Peak HRR(kW)	218	295	195
Time to Peak HRR(s)	1480	1040	2575
Total Heat released (MJ)	20 MJ up to 1500s	72 MJ up to 1500s	31 MJ up to 1500s
Maximum upper layer temperature(°C)			
TC2	151	200	129
TC3	156	214	136
TC4	177	226	146
TC5	154	202	133

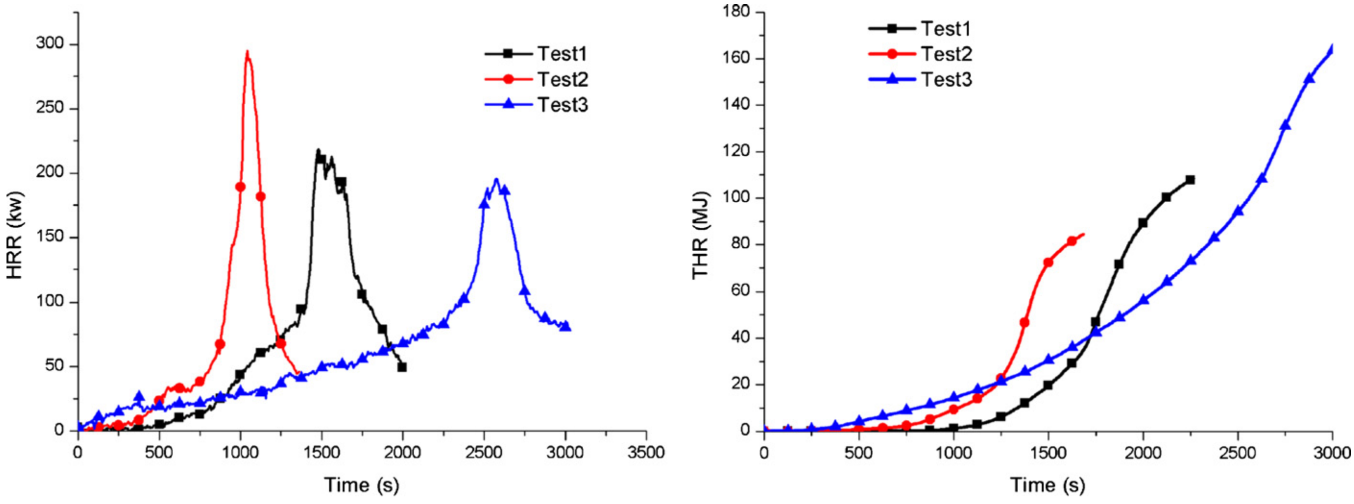


(a) Schematic of ISO9705 Fire Test Room



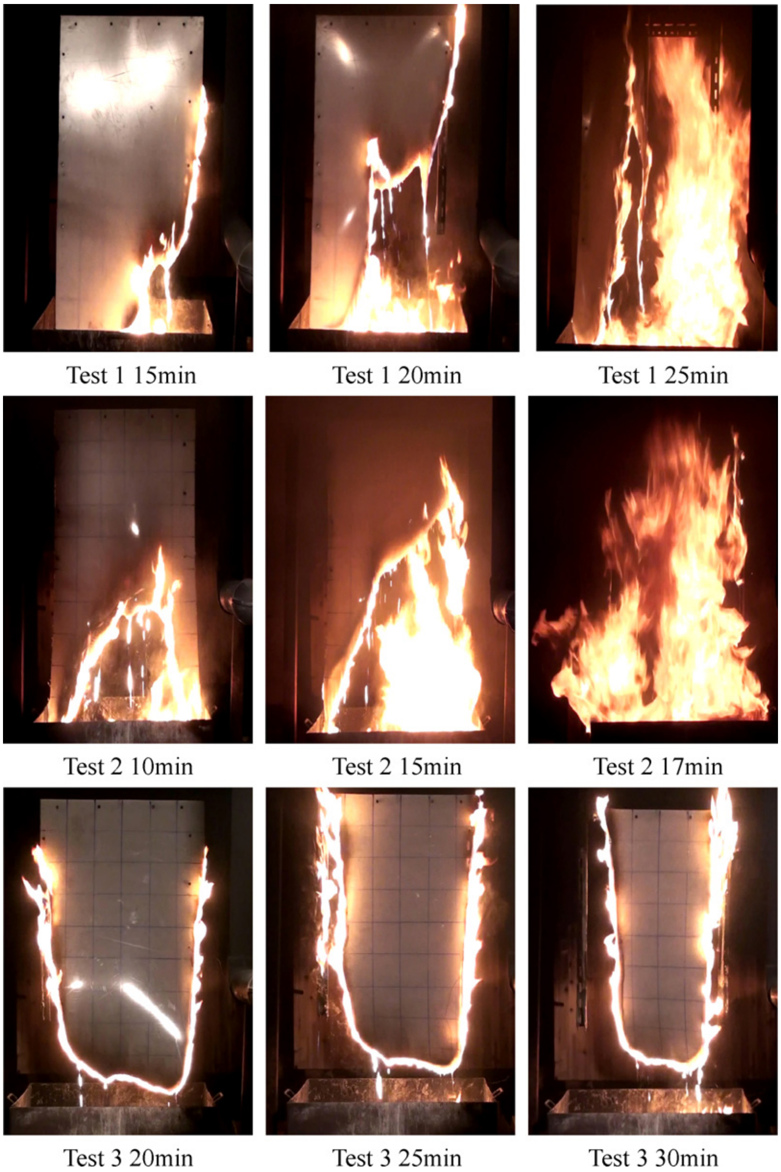
(b) Experimental rig (c) Thermocouple tree arrangement

Fig. 1. Experimental setup. (a) Schematic of ISO9705 Fire Test Room, (b) experimental rig (c) thermocouple tree arrangement.



(a) Heat Release Rate (b) Total Heat Released

Fig. 2. (a) Heat release rate and (b) total heat released.



Test 1 15min Test 1 20min Test 1 25min

Test 2 10min Test 2 15min Test 2 17min

Test 3 20min Test 3 25min Test 3 30min

Fig. 3. Photograph of the experimental process at various times.

mulated heat release in all the three tests. As can be seen from the data, total heat release in test 2 before PP was burnt out was always higher than that of test 1, which implies that in fire scenarios, polymer objects ignited in the center of a lower edge would generate more heat initially and constitute a greater fire hazard.

A comparison of test 3 with the other two provides some interesting results. It was expected before the tests that test 3 would generate the highest peak heat release rate and the test 3 PP sheet would take the shortest time to reach the peak HRR value due to the reason outlined when comparing test 1 and test 2. However, Fig. 2 (a) shows an entirely different result. Peak heat release rate in test 3 was the lowest of all the tests with a value of 195kw, while the time to peak HRR value for test 3 was 2575s, which was the longest in the test series.

To explain the specific phenomena of test 3, the experimental process needs to be reviewed. Fig. 3 supplies a snapshot of all tests at various times. As can be seen, there was an intensive pool fire during test 1 and test 2, while in test 3 only small pool fire can be discerned. This suggests that the dominant fire development mechanism in test 3 was different from that of the other two tests. In test 1 and test 2, there was a strong interaction between vertical flame spread and the pool fire, and pool fire was ultimately the determinant factor in heat release rate at last, which is shown in Fig. 3.

However, it is evident that upward flame spread was dominant in heat release rate development in test 3, with minimal pool fire. This might have been due to the enrollment of fresh air. Upon linear ignition, much more fresh air was enrolled from the two sides of the PP sheet, while air could only reach the fire on the other parts of PP sheet from the front and back(for lower edge corner, air was also accessible from one side), as is illustrated in Fig. 4. A quick upward flame spread at the two vertical sides was thus induced.

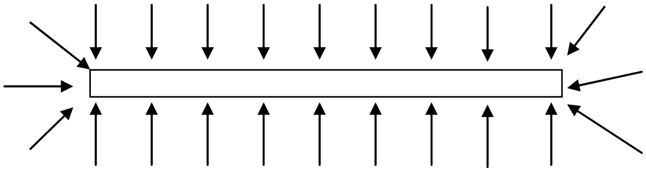
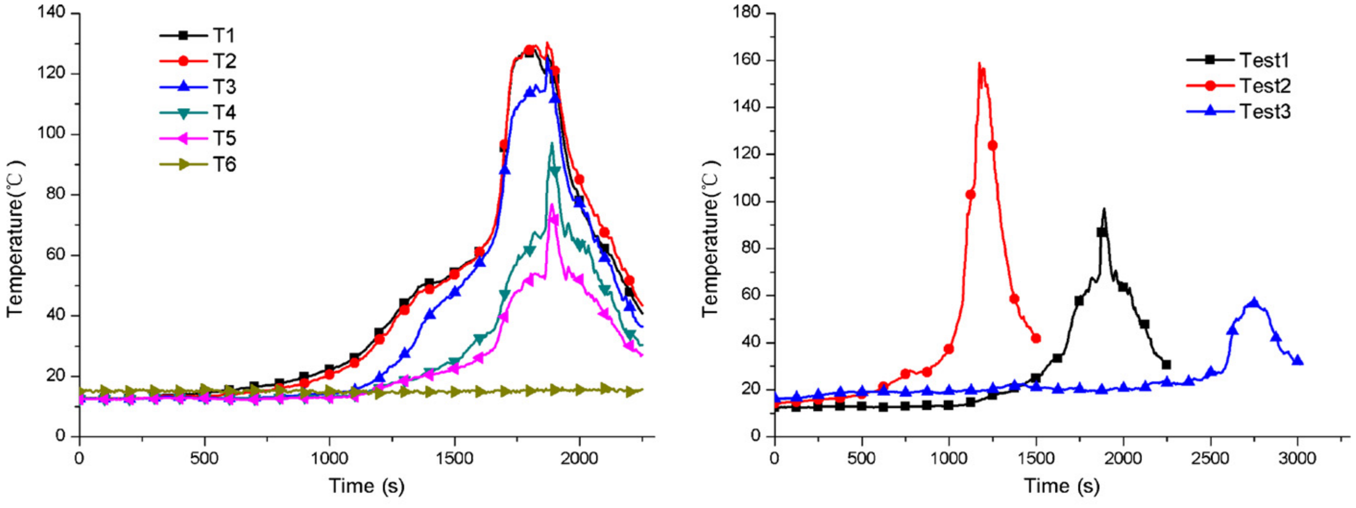


Fig. 4. Schematic of air enrollment at lower edge of PP Sheet.



(a) Thermocouple Tree Temperatures in Test1

(b) T4 Temperatures in the Three Tests

Fig. 5. Thermocouple Tree Temperatures. (a) Thermocouple tree temperatures in Test 1 (b) T4 temperatures in the three tests.

It is nonetheless a few melted PP drips could reach the pool floor since there was a long distance between the melting position and the floor. Melted PP liquid might have been burnt or attached to the PP sheet during the transport process. It can thus be observed from Fig. 3 that there were more flame tips along the PP sheet flame in test 3 than in the other tests. Though some dripping and flaming liquid reached the floor, interaction between the vertical fire and the pool fire was rare since the pool fire flame could not reach the PP sheet, due to the growing distance between lower edge of PP sheet and the floor. Therefore, little heat could feed back to the vertical fire and consequently little fuel was supplied to the pool fire accordingly. There was only a small pool fire at last in the test.

A thermocouple tree was placed at the side of the experimental rig to record temperature distribution at various heights. Fig. 5 (a) gives thermocouple tree temperatures in test 1. As can be seen, temperature increased with elevated height. The curves of thermocouples T1 and T2 almost overlap each other, which suggests that room temperatures at T1 height and T2 height had almost the same distribution during the test. Room temperature distribution at an elevated height basically can represent smoke layer height inside the test room. It was observed that the T6 temperature remained at an ambient value, and this indicates that the neutral height was higher than 0.5 m. Results obtained form the thermocouple tree in the other two tests show very similar trends. Fig. 5 (b) illustrates the temperature from thermocouple T4 in the three tests. It can be observed that the temperatures have considerably similar trends to those of HRR.

Smoke temperature is a significant parameter in fire development in that it not only brings thermal hazards to occupants but feeds heat back to fuel by radiation, increasing fire spread. The five thermocouples located under the ceiling in our experiment were used to analyze smoke temperature. The maximum temperatures of these thermocouples are summarized in Table 2. It should be noted that TC1 was found to have been destroyed in earlier tests when analyzing experimental data, so the maximum temperature of TC1 is not listed. Moreover, the average temperature of the other four thermocouples is adopted as smoke temperature, and the results are shown in Fig. 6. The maximum temperatures of the three tests were 159 °C, 210 °C and 136 °C respectively. This confirms that initial conditions can affect peak smoke temperature to a large extent.

Toxic smoke ingredient concentration is a significant parameter in fire safety analysis. Previous research has revealed that CO is the principal deadly toxic gas in fires [21–23], and it can travel to

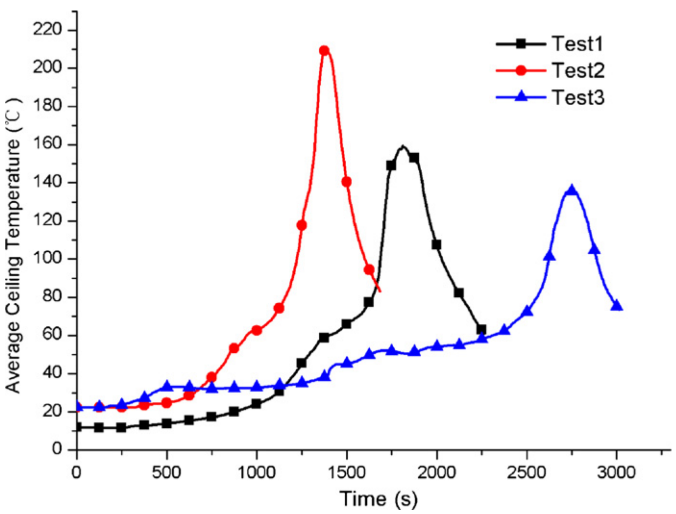


Fig. 6. Average temperature of thermocouples under the ceiling.

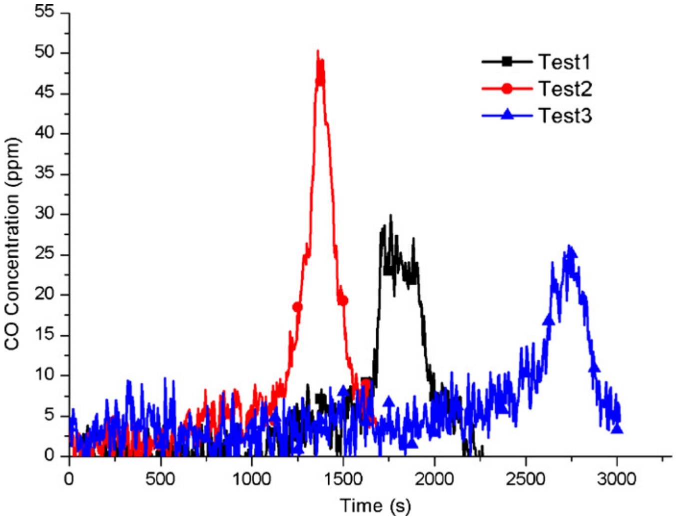


Fig. 7. CO concentration comparison.

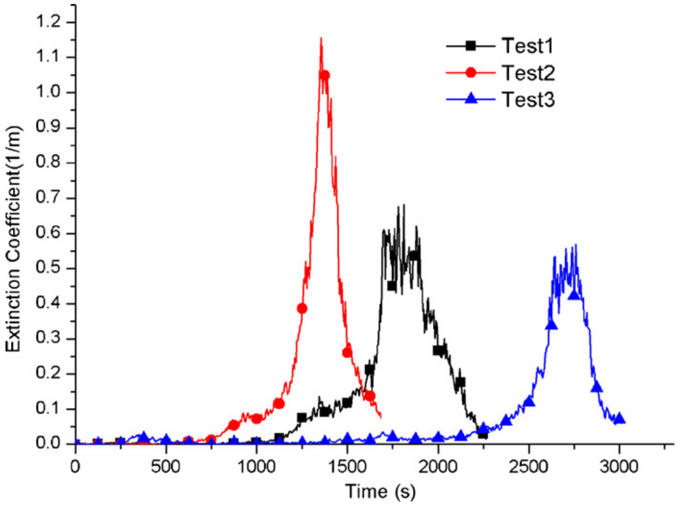


Fig. 8. Extinction coefficient of all tests.

remote rooms away from fires [24]. In this investigation, CO was chosen as a representative toxin. As is shown in Fig. 7, peak CO concentration was 30 ppm, 50 ppm and 26 ppm in test1, test 2, and test 3 respectively, and the CO concentration levels were remarkably similar to those of HRR. This suggests that ignition conditions affect CO generation, due perhaps to the impact of ignition conditions on the development of HRR, and CO concentration might be affected accordingly. When burning is intensive, more CO will be produced, due to the oxygen deficit.

Fig. 8 maps the extinction coefficient of all the tests. In fire protection design, visibility in a fire scenario is important for safety analysis, and the extinction coefficient is a representative parameter in analyzing smoke concentration. The peak extinction coefficients in test 1, test 2 and test 3 were 0.68/m, 1.16/m and 0.57/m respectively, and the trends in all the tests were likewise similar to those of HRR.

4. Conclusions

A specific experimental rig was designed to investigate the effect of ignition conditions on the fire behavior of typical polymers. PP sheets with a thickness of 4 mm were selected as the test sample. Three ignition positions, namely the lower right edge, the lower edge center and the whole lower edge of the PP sheet, were adopted to explore the influence of initial conditions on polymer's melt flow flammability.

Results confirmed that initial conditions impact considerably on nearly all the important fire parameters, including peak HRR, time to peak HRR, released heat, smoke temperature, CO concentration and the extinction coefficient. When ignition occurred at a single point (test 1 and test 2), an intense interaction between the vertical fire and the pool fire was observed, while a principally vertical flame spread was found with a linear ignition source (test 3). Ignition modes can thus affect flame spread type. Center lower edge ignition (test 2) was found to burn the most fiercely, while linear ignition was observed to be the least aggressive.

This work could be useful in performance-based design in considering fire scenarios, in that initial conditions were identified as one of the major concerns in fire development. Therefore, it is suggested that possible ignition modes, including both accidental fire and arson fire, should be carefully considered when selecting fire source power. Further research into critical ignition position and power between the two fire spread modes is still needed.

Acknowledgements

The authors are grateful for the language help from Geraldine Carton.

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