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Experimental studies on the effects of spacing on dripping behavior of thin polymethyl-methacrylate slab

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ABSTRACT

Experiments were carried out to study the dripping behavior of vertical burning thermally thin polymethyl-methacrylate (PMMA) with different spacings parallel to the wall. With spacings of 7, 10, 13, 16, 19, 22, and 25 mm, the dripping behavior was studied by infrared video image analysis, and the mass retention was recorded by the load cells. As the spacing increased, the dripping time, dripping mass, and burnout growth distance first increased and then decreased. The minimum value was observed at the 13 mm case. The dripping behavior is assumed to correspond to the net heat flux to the surface, extensional viscosity, and gravitational force of melting PMMA. In this study, the dripping behavior was investigated using uniform PMMA samples with 200 mm height, 50 mm width, and 2 mm thickness.

1. Introduction

Thermoplastic polymethyl-methacrylate (PMMA), one of the best organic synthetic materials, has been widely used in interior decoration and insulation industries [1]. Therefore, many vertical walls are covered by large thermally thin PMMA materials, not only to beautify the environment, but also to ensure that the wall is not damaged. However, the potential hazards of these thermoplastics in fires are a matter of great concern. For instance, the dripping of burning polymers has been recognized as a great threat to the public, which can accelerate fire growth and spread fires between nonadjacent objects. When thermally thin PMMA materials are set in a vertical orientation, the molten materials drip because of the high mobility triggered by increasing temperature [2].

In the fire research community, many researchers [2–8] investigated the dripping behavior of burning thermoplastic materials. Wang et al. [2–4] carried out small-scale experiments for the dripping behavior of PMMA under the UL94 vertical test conditions [9]. The results indicate that flame spread and burning rate affect the dripping behavior of thermally thin PMMA materials. Under the UL94 vertical test conditions, the dripping behavior was categorized into two different types: small and uniform drops with a short first dripping time, and large and irregular drops with a long first dripping time. The activation energy of viscous flow and the ratio of the effective heat of combustion to the heat of gasification were also important properties of materials dominating the dripping types of polymers [2]. Regarding the factors influencing the dripping, it can be attributed to the reduction of viscosity not only due to physical melting, but also chemical degradation [2,3,7]. Xie et al. [5] demonstrated that a thinner thermoplastic sheet dropped faster and reached the peak heat release rate earlier than a thicker thermoplastic sheet. A thermally thick PMMA sheet exhibited softening, distortion, and surface

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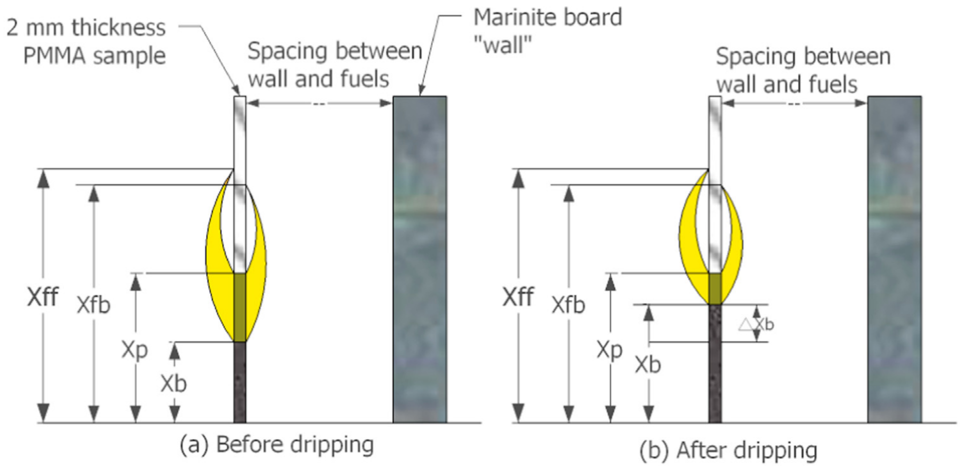

Fig. 1. Spacing effect on upward flame spread model.

bubbling; however, no dripping of the melted polymer was observed during the test by Zhang and Shields et al. [6]. Kandola et al. [8] established the relationships between the glass transition temperature and melt viscosity with the dripping behavior and burning intensity of PMMA.

All the studies mounted the polymer on a wall [5,6] or suspended [2,3,8] and subjected to a source of fire at the bottom during the tests. However, they did not consider the actual situation. Sometimes, the thin PMMA material is not completely attached to the wall, and a spacing exists between the wall and PMMA as shown in Fig. 1. When thermally thin PMMA materials in a vertical orientation were ignited at the bottom in this case, an upward flame spread was observed on the front side, and the back-side flame became one of the most important modes of parallel combustion between the back side of the sample and wall.

As the spacing between the wall and fuels increased, the physical picture gradually changed by the following effects [10]: A fraction of the net heat flux to the surface from the back flame increased, the scale of the turbulent eddies increased by the wall, and the flow of oxygen available for the combustion in the gap increased. Although these effects influenced the rate of fuel production by the wall, the net effect associated with dripping behavior of burning PMMA is not very clear.

As shown in Fig. 1, the front flame height of PMMA is X_{ff}, the back flame height is X_{fb}, the pyrolysis height is X_p, the burnout length is X_b, and the burnout growth distance ΔX_b. The length of the pyrolysis zone is $L_p(L_p = X_p - X_b)$. Fuel vapors are released from the pyrolysis surface and participated in the flame, which is confined to the buoyancy-induced boundary layer. The regions $(X_{ff} - X_p)$ and $(X_{fb} - X_p)$, where the flame extends beyond the pyrolysis length, are known as the combusting plume region, and the heat transferred from this region to the virgin fuel above X_p is responsible for the upward spread of the flame [11]. A thermally thin PMMA material was used as the sample to investigate the effects of spacing on the dripping behavior. Thermally thin materials have unique properties: Thermally thin flues are assumed to have no spatial and internal temperature gradients, and the physical thickness, d, should be less than the thermal penetration depth [12]:

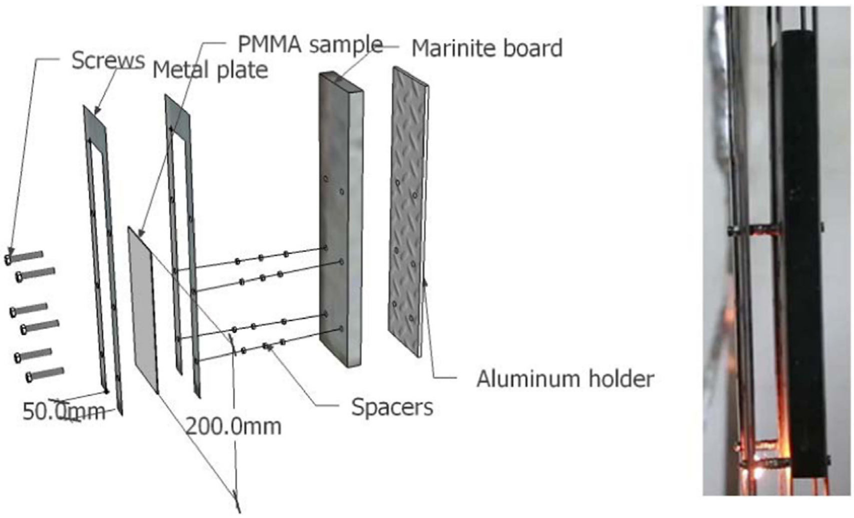

Fig. 2. Schematic of the experimental apparatus.

$$d << \delta_T \approx \sqrt{\alpha t} \approx \frac{k(T_s - T_0)}{\dot{q}''} \tag{1}$$

where d is the physical thickness of the fuel, δ_T is the thermal penetration depth, α is the thermal diffusivity, t is the time, k is the conductivity, T_s is the surface temperature, T_0 is the initial temperature, and $\dot{q}''$ is the heat release rate per unit area. The thermally thin PMMA material had a thickness of 2 mm[12].

In this study, a series of experiments for thermally thin PMMA (H is the height of 200 mm, W is the width of 50 mm, and d is the thickness of 2 mm) were carried out to compare the characteristics of the dripping behavior of vertical burning thin PMMA material with different spacings to the wall in the laboratory. By increasing the spacing b between the wall and PMMA, the dripping time t_d, dripping mass m_d, burnout growth distance ΔX_b, and surface temperature during the dripping T_d were investigated.

Because the dripping behavior play an important role in the fire hazards of thermoplastic PMMA materials, it is necessary to investigate the properties of dripping behavior with different spacings. To the best of our knowledge, the effects of spacing between wall and fuels on the dripping behavior of burning thermally thin PMMA material have not been reported.

2. Experimental setup

A range of experiments were designed to study the dripping behavior of a vertical burning thermally thin PMMA material with different spacings to the wall. A schematic of the experimental apparatus is illustrated in Fig. 2.

The experimental apparatus contained a vertical sample of clear PMMA 200 mm in height, 50 mm in width [11,13], and 2 mm in thickness. The tests were carried on the same type of PMMA with the same parameters such as the ignition temperature and density, thus reducing the experimental error and flame fluctuation [14]. The samples were covered with two metal plates, and a wall (Marinite board) was placed behind the samples. In this study, the sample width was fixed at 50 mm to minimize the amount of variance between the tests, because a smaller sample size may affect the amount of combustible gases generated by the fuel owing to a significant diffusion of the fuel to the sides of the sample [11,15,16]. A Marinite board with 350 mm height, 90 mm width, and 20 mm thickness was used as the vertical wall. They were mounted on an aluminum sheet holder with four screws as shown in Fig. 2. Four groups of spacers were installed between the wall and fuels to maintain a distance and to ensure that the fuel was parallel to the wall. The experimental apparatus was hung by two load cells, with an accuracy of 0.01 g and 22 kg capacity, which were used to measure and record the mass loss from the samples at half-second intervals during the test. A HD digital camcorder recording at 20 frames per second was set at the side of the samples to obtain a side view of the front and back flame heights. The progress of the pyrolysis front was determined by analyzing the infrared video recordings of each experiment set at the front of the fuels. The sketch map of the setup is shown in Fig. 3.

A high-frequency infrared thermal imager (MAGNITY-MAG32HF) had an uncooled focal plane array microbolometer, and the emissivity adjustable range was 0.01–1.0. With a selection range of spectral response of 8–12 μm [17,18] in the tests, the infrared thermography filtered the emission bands from those of carbon dioxide, which emits strongly at 2.7 and 4.3 μm [18–20], and water vapor, which emits strongly at 2.7 and 6.3 μm [21]. Parent et al. [22] performed experiments on a vertically mounted PMMA slab of identical width; the infrared images showed that the background contribution of the soot was hardly visible, minimally affected the extracted temperatures, and contributed very homogeneously.

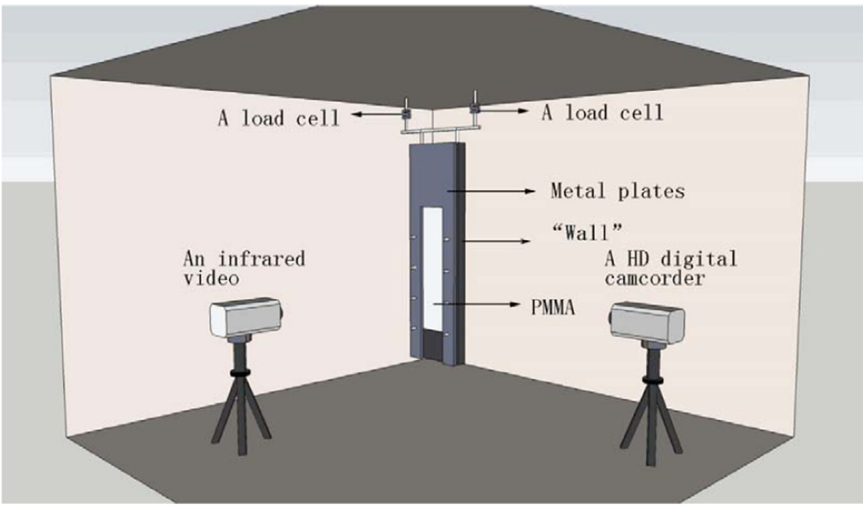

Fig. 3. Sketch map of the experimental setup.

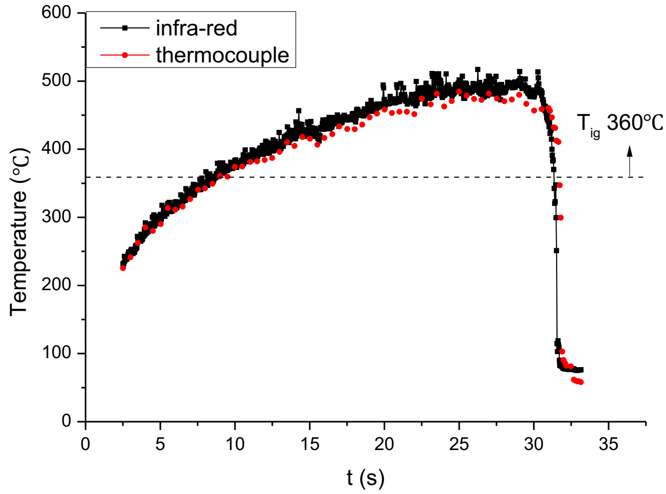

Fig. 4. Raw data obtained from thermocouples and infrared camera for a sample validation test.

To validate the measurement error, the test was simultaneously carried out using thermocouples and recorded using an infrared camera, indicating an emissivity of 0.92 [23] for the infrared images. Fig. 4 shows the temperature profiles obtained from both the infrared camera and thermocouples from a validation test in which the infrared spot measurements were recorded at approximate thermocouple locations. The average percentage difference between the temperatures obtained from the infrared data and thermocouples was 2.9%.

Because thermoplastic PMMA is a special fuel for thin materials, the burning PMMA dripped and stick to the thermocouples, affecting the accuracy of the temperature data. Moreover, the thermocouples perturbed the flow of hot gases. In contrast, the infrared images and measurements produced a much clear picture of the pyrolysis front than the thermocouple measurements, and the temperature measured by the infrared camera was assumed as the surface temperature of thermally thin PMMA material. In summary, the infrared images could be used in the tests.

The sample was ignited at the bottom of the fuel surface using a heated nichrome wire in contact with the sample. All the experiments showed approximately 2 mm burnout length and 7 mm pyrolysis height at the beginning of the experiment. Two video cameras (an HD digital camcorder and an infrared video) arrangement allowed the simultaneous measurement of the front and back flame heights, pyrolysis height, and burnout length as shown in Fig. 5. Each test was repeated three times for each spacing scenario to obtain the most accurate data. In order to read directly from the graph, the average values were drawn into the pictures.

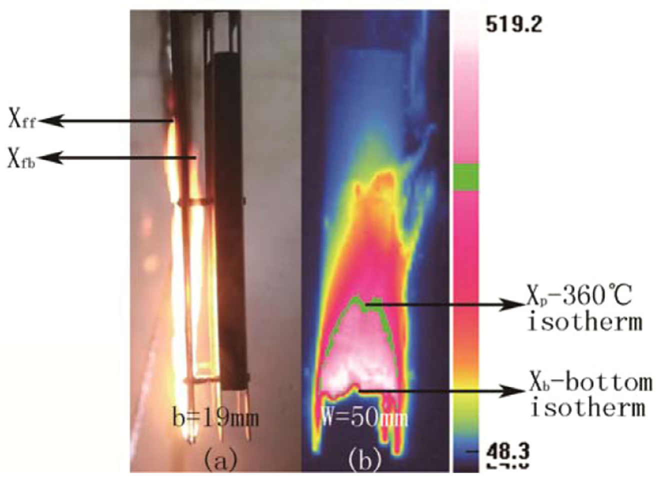

Fig. 5. An HD digital camcorder and an infrared video measured the front and back flame heights, pyrolysis and burnout length simultaneously. (a) HD image and (b) infrared image.

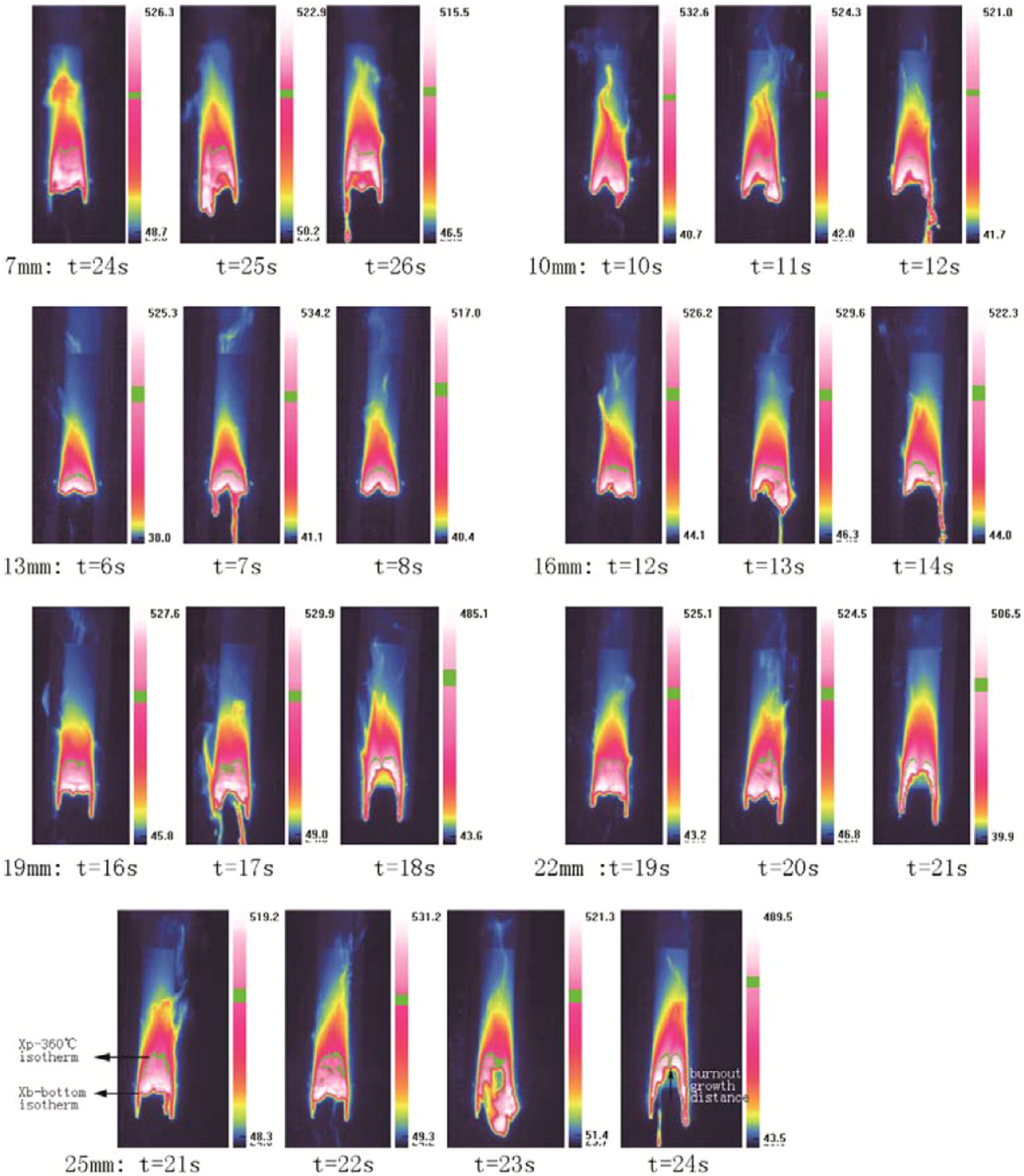

Fig. 6. PMMA dripping behavior for different spacing cases. Pyrolysis and burnout isotherms and burnout growth distance were observed by infrared video recordings.(For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

3. Results and discussion

Fig. 6 shows the infrared images of samples obtained using an infrared camera, which was set at the front of fuels. The green isotherm is pyrolysis isotherm, and the bottom of burning PMMA has a distinct isotherm. The temperature of the pyrolysis region reached 520 °C, which is above the edge of bottom isotherm. The bottom isotherm shown below is burnout zone, and its temperature is close to ambient temperature. The data on the pyrolysis area demonstrated that the

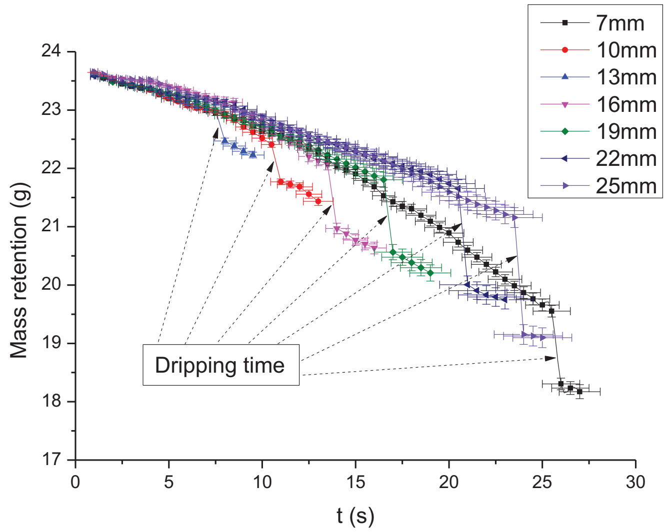

Fig. 7. Mass retention curves of PMMA specimens for different spacing scenarios.

temperature was between 360 °C and 530 °C, a nonuniform distribution. As shown from the infrared images of samples for different spacing scenarios, some cracks generated at the highest temperature location of the pyrolysis zone and expanded horizontally, causing dripping. However, the discrepancies were dripping time and mass. In a sequence of images taken at 1 s interval of an experiment in the 25 mm spacing case, between 21 and 24 s, a part of pyrolysis region melted and dripped down. Notably, the burnout position dramatically increased due to the dripping behavior. At 21 s, the pyrolysis region of PMMA was unabridged (between 360 °C and bottom isotherm), and no unzipping was observed. At 22 s, the upper part of the pyrolysis region was unzipped (red markings). At 23 s, a large area of the burning PMMA dripped, and the pyrolysis area decreased. At 24 s, the pyrolysis region became stable, and the combustion continued.

The observations show that the drops of PMMA were large [2], because the size of the specimen before and after the dripping varied significantly. This is consistent with the dramatic descend at the dripping time of the mass retention curve as shown in Fig. 7. The error bars for this set of the data indicate the range of levels in the three tests. Based on the recorded masses of specimens in the spacing increasing test, the mass retention was defined as the real-time mass divided by the original mass of the PMMA specimen.

Table 1 shows the time at which the dripping occurred, the mass of the drop, burnout growth distance, and dripping temperature for different spacing scenarios. A clear spacing effect on the dripping behavior was observed: Starting from the location of the sample next to the wall (spacing was 7 mm), the trajectory of t_d, m_d, and ΔX_b first decreased as the spacing increased and then increased. Although the data do not define this very accurately, the value of the spacing where the data reached the minimum was 13 mm approximately. Notably, the burning PMMA did not drip until the surface temperature was above 520 °C.

This paper does not consider the case of spacing less than 7 mm, as burning PMMA sheet may become soft and cling to the insulated fire board during the experiments. This is disadvantageous for the development of vertical wall burning and dripping behavior. Because oxygen can be supplied for the burning sheet from only one side instead of two sides once the thermoplastic sheet clings closely to the fire board.

As shown in Table 1, the spacing between wall and thin PMMA affects the dripping time and mass significantly. Some studies investigated the spacing effect of the upward flame spread between two vertical parallel materials [10, 24–26].

Table 1
Summary of dripping behavior for different spacing scenarios.

b (mm)	t_d (s)	m_d (g)	ΔX_b (mm)	T_d (°C)
7	24–26	1.31 ± 0.1	16.24 ± 1.24	522.6 ± 4.3
10	10–12	0.79 ± 0.07	8.32 ± 0.88	524.7 ± 5.6
13	6–7	0.54 ± 0.05	6.27 ± 0.64	532.4 ± 7.2
16	12–14	1.11 ± 0.09	12.07 ± 0.92	528.7 ± 6.3
19	16–18	1.56 ± 0.13	16.8 ± 1.42	526.1 ± 5.6
22	19–22	1.88 ± 0.15	20.71 ± 1.72	525.4 ± 5.1
25	22–25	2.06 ± 0.16	24.82 ± 1.76	525.3 ± 4.8
∞	23–25	2.13 ± 0.12	25.42 ± 1.26	524.1 ± 3.3

b: spacing; t_d: time when dripping occurs; m_d: mass of the drop; ΔX_b: burnout growth distance; T_d: surface temperature when dripping occurs;∞: single sample case.

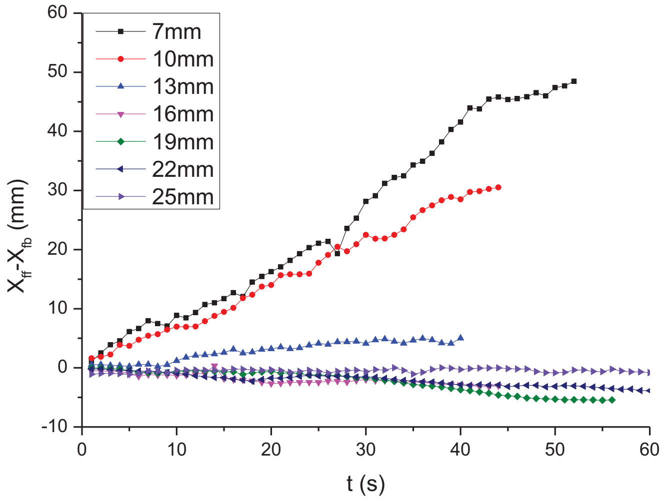

Fig. 8. Subtraction of the front flame height form the back flame height.

Tamanini and Moussa [10] studied the turbulent burning of vertical parallel walls and reported that the space between two walls is an important parameter, affecting the fire behavior of the two burning walls. If the spacing between the two walls is sufficiently far apart, the interaction is minimal, and the rate of burning becomes the same as that of the single wall case. Wang and Joulain [24,25] conducted a theoretical study to investigate the fire structure, heat transfer, and pyrolysis rate between the vertical parallel burning surfaces with a fire-induced flow. The results indicate that with the decrease in the wall spacing/sample height ratio, the convection and radiation fluxes decreased. Tsai [26] used three configurations (on a flat surface, in a corner, and between parallel surfaces) to confirm that a vertical parallel wall fire can lead to a more rapid fire growth. However, all the studies [10,24–26] involved only an upward flame spread between two vertical parallel materials. They did not consider the effects of spacing on dripping behavior.

A side-view camera was used to observe the arrival of the flame at the set markers to determine the front and back flame heights simultaneously, as shown in Fig. 5. Rangwala et al. [11] applied the thresholds of video images to determine the extent of flame. Audouin et al. [27] determined the flame heights by importing videos into a Matlab program written to analyze the flame heights. After the ignition, a flame was generated that spread upward.

Fig. 8 shows the difference between the front and back flame heights ($X_{ff} - X_{fb}$). In the 7 mm spacing scenario, the back flame was observed slightly beyond the pyrolysis area ($X_p - X_b$), and the flame size was smaller. This is probably because of a decrease in the oxygen available between the wall and fuel during the combustion. In the 13 mm spacing scenario, the front flame height was slightly higher than the back flame height, and the flame height difference ($X_{ff} - X_{fb}$) decreased. As the spacing was increased to 19 mm, the back flame height slightly increased than the front flame height. Because the flow of oxygen available for combustion in the gap increased and stack effect. In the 25 mm spacing case, the interaction was the minimal, and the difference in the front and back flame heights became the same as that of the single sample case.

As the spacing increased, the back flame size increased. Moreover, the back heat losses of surface reradiation and convection increased (the back net heat flux to the surface per unit surface area of the material varied). These results can be represented by the following energy balance:

$$\dot{q}''_n = \dot{q}''_{nf} + \dot{q}''_{nb} = (\dot{q}''_{ff} - \dot{q}''_{lossf}) + (\dot{q}''_{fb} - \dot{q}''_{lossb}) \tag{2}$$

where $\dot{q}''_n$ is the net heat flux to the surface per unit surface area of the material, $\dot{q}''_{nf}$ and $\dot{q}''_{nb}$ are the front and back net heat fluxes to the surface per unit surface area of the material, $\dot{q}''_{ff}$ and $\dot{q}''_{fb}$ are the front and back flame heat fluxes per unit surface area of the material, $\dot{q}''_{lossf}$ and $\dot{q}''_{lossb}$ are the front and back heat losses due to the surface reradiation and convection. The front and back flame heat fluxes per unit surface area of the material can be described as follows:

$$\dot{q}''_{ff} = \dot{m}'' \Delta H_c \chi_{eff} \tag{3}$$

$$\dot{q}''_{fb} = \dot{m}'' \Delta H_c \chi_{eff} (1 - F_f) \tag{4}$$

where $\dot{m}''$ is mass-loss rate per unit area, ΔH_c is the heat of combustion of the fuel, χ_{eff} is the combustion efficiency factor. The view factor F_f[10], for the exchange between two parallel strips is infinitely long, of width W separated by the distance $b - d_f$[28], is expressed as follows:

$$F_f = \sqrt{\left(\frac{b - d_f}{W}\right)^2 + 1} - \frac{b - d_f}{W} \tag{5}$$

where b is the spacing and d_f is the flame thickness. The contribution by the front and back heat losses can be described as follows:

$$\dot{q}''_{lossf} = \dot{q}''_{rf} + \dot{q}''_{cf} = \varepsilon\sigma(T_s^4 - T_0^4) + h_c(T_s - T_0) \tag{6}$$

$$\dot{q}''_{lossb} = \dot{q}''_{rb} + \dot{q}''_{cb} = \varepsilon\sigma(T_s^4 - T_w^4)(1 - F_s) + h_c(T_s - T_w)(1 - F_s) \tag{7}$$

where $\dot{q}''_{rf}$ and $\dot{q}''_{cf}$ are the components of $\dot{q}''_{lossf}$ associated with the front heat loss of surface reradiation and convection, $\dot{q}''_{cb}$ and $\dot{q}''_{rb}$ are the components of $\dot{q}''_{lossb}$ associated with the back heat loss of surface reradiation and convection, $h_c$is convective heat transfer coefficient, T_s is the sample surface temperature (thermally thin flues are assumed to have no spatial and internal temperature gradients, and the temperature of the front and back surfaces was equal), T_0 is the initial temperature, T_w is the wall temperature, ε is the surface emissivity, and σ is the Stefan–Boltzmann constant. The view factor F_s[10] can be expressed as follows:

$$F_s = \sqrt{\left(\frac{b}{W}\right)^2 + 1} - \frac{b}{W} \tag{8}$$

These equations should be regarded as a study on the effect of heat losses due to surface reradiation and convection, because another factor, the change in wall spacings, associated with varying net heat flux to the surface, has been removed.

The principal parameters controlling the melt-flow rheology are shear and extensional viscosities. The small-sized dripping would primarily depend on the shear viscosity η or melt flow index (MFI) of the polymer, whereas the large-sized dripping would be dominated by the melt strength (MS) or extensional viscosity η_e[2]. For the uniaxial extension of Newtonian fluid, the extensional viscosity is three times the shear viscosity. For the non-Newtonian fluid of polymer melts, the extensional viscosity is much higher than the shear viscosity. Especially at high shear rate, the extensional viscosity is even two magnitudes higher than the shear viscosity [29]. Thus, it is reasonable that the extensional viscosity can support greater drop mass than the shear viscosity. The dripping of PMMA has been defined as large-sized dripping [2], and a large-sized dripping may be caused by the temperature increase (i.e., the net heat flux to the surface) of the specimen, extensional viscosity, and stress on the vertical direction resulting from the gravitational force of the melting PMMA. The relationship between the net heat flux and temperature rise rate can be expressed as follows [12]:

$$\dot{q}''_n = \rho c_p d\frac{dT}{dt} \tag{9}$$

where ρ is the density and c_p is the specific heat. The dependence of viscosity on temperature can be expressed by the Arrhenius equation [29]:

$$\ln\eta = E_\eta/RT + \ln A \tag{10}$$

where η is the shear viscosity, A is a constant for a given polymer, E_η is the activation energy for viscous flow, R is the molar gas constant, and T is the absolute temperature. Ideally, large-size dripping PMMA is only affected by gravity (stress in the vertical direction); thus, relationship between the degradation time of the bearing capacity of material τ and the effect of stress in the vertical direction σ_n can be expressed by the Eyring theory formula[29]:

$$\ln\tau = B + (E_\tau - V_a\sigma_n)/RT_s \tag{11}$$

where B is a constant, E_τ is the activation energy for the fracture, V_a is the molar activation volume.

Because of the lack of a complete theory of the effects of spacing on dripping behavior of thermally thin materials and the current transient transfer models for flame spread and burning rates of thermoplastics do not consider the dripping and melting behavior, we assumed that the effects of spacing between wall and PMMA on the dripping behavior of vertical burning thin PMMA were controlled by the net flame heat flux to the surface, extensional viscosity, and gravitational force of dripping mass. At a low wall spacing (7 mm case), the size of back flame was small, as well as the back net heat flux to the surface (consisting of flame heat flux and heat losses due to surface reradiation and convection). As spacing increased, the net heat flux to the surface increased, thus increasing the temperature rise rate. This decreased the extensional viscosity and the degradation time of bearing capacity. Thus, the value of dripping time and mass and burnout growth distance decreased as the spacing increased from 7 mm to 13 mm. As spacing increased to 13 mm, the net heat flux to the surface reached the critical value, as well as the value of dripping time and mass and burnout growth distance. As spacing increased from 13 mm to 25 mm, the net heat flux to surface decreased (the flame heat flux reached the maximum value, but the back heat losses of surface reradiation and convection increased as the spacing increased). Then, the temperature rise rate decreased, leading to the increase in extensional viscosity and degradation time of bearing capacity. Thus, the value of dripping time and mass and burnout growth distance increased as the spacing increased as shown in Table 1. If the wall is sufficiently far apart (spacing more than 25 mm), the interaction is minimal, and the net heat flux became the same as the single sample case.

4. Conclusion

The experimental results obtained in this study provide a hypothesis for the dripping behavior of vertical burning PMMA materials with different spacings to the wall using pure PMMA samples with 200 mm height, 50 mm width, and 2 mm thickness. Different dripping behaviors were observed depending on the spacings of 7, 10, 13, 16, 19, 22, and 25 mm, and the spacing effects were analyzed.

The dripping process was observed using an infrared camera. As the spacing increased, the dripping time and mass and burnout growth distance first decreased and then increased. The predicted critical value occurred at a spacing of 13 mm. No effect was observed when the spacing exceeded 25 mm. The large-size dripping behavior was assumed to correspond to the net heat flux to the surface, extensional viscosity, and gravitational force of melting PMMA.

This work was intended for an in-depth analysis and a better understanding of the mechanism of the effects of spacing between wall and thin PMMA material on the dripping behavior under vertical burning conditions. Further studies are necessary to study the effects of dripping behavior on the upward flame spread over thin PMMA.

Acknowledgements

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