RESEARCH ON THERMAL AND CENTRAL FLAME SPREAD BEHAVIORS OVER INSULATION MATERIAL EPS IN DIFFERENT CONCAVE STRUCTURE CASES

by

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The effect of different depth-width ratios, α, on the flame spread over molded polystyrene (EPS) at the central place ignition was studied. The variation laws of characteristic parameters such as flame structure, flame height, flame spread rate, flame temperature and mass loss rate were analyzed. The experimental results show that at the central flame spread, the extinction, re-ignition, and re-burning were found for the upward flame except at α = 1.5, while the downward flame didnot have these phenomena. At α = 1.5, the stability of upward flame spread was the best, as the extinction didnot occur, and the flame spread rate was the fastest. When α <1.5, the extinction of upward flame could be sorted to flame instability, while when α >1.5, the extinction could be attributed to the more hot smoke effect. If the average flame height of upward increased, the average flame height of downward decreased, and vice versa. Inner flame pressure model was built, which could better explain the characteristics of mutual inhibition between upward and downward flame heights.

Keywords: *central flame spread, concave structure, molded polystyrene, flame height, mutual inhibition*

Introduction

In recent years, in order to solve the increasingly serious energy shortage problem and respond to the energy-saving policies of the world, the use of thermal insulation materials for building exterior walls has become an effective measure. An excellent thermal insulation material, molded polystyrene (EPS) has been widely application in the external thermal insulation system of buildings. Meanwhile, the rapid development of construction industry has promoted the diversification of building facade forms. Especially, concave structures are found in buildings due to their excellent lighting and ventilation performance [1-3]. However, the unique concave structures often promote flame spread and raise the risk of fire. For example, a fire broke out in a high-rise apartment in Busan, South Korea in October 2014. The referred concave structure made the flame spread fast to the top floor.

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Many scholars have carried out a large number of experimental studies on the influence of concave structures on flame spread over insulation materials [4-13]. Zhou *et al.* [4] evaluated the effectiveness of vertical fire barriers in preventing flame spread over exterior insulation wall made of EPS panels. The whole geometry was similar to several concave structures. Cai *et al.* [5] studied the influence of the depth-width ratio, α, of the closed vertical channel on the downward flame propagation characteristics of extruded polystyrene (XPS), and found that the flame spread speed increased with the increase of α. An *et al.* [6-8] experimentally revealed XPS flame spread in different concave structures and curtain wall coverage rate. The flame spread rate increased with increasing structure factor α when curtain wall coverage rate β from 0.2 to 0.8. An *et al.* [9] also carried out experimental and theoretical study on upward flame spread over polymethyl methacrylate (PMMA) under different *U*-shaped structure factors. The correlation between flame height and pyrolysis length was established for different structure factors. Yan *et al.* [10] investigated vertical downward flame spread over XPS with and without sidewalls. It was found that, flame spread rate was proportional to induced air flow speed. The induced air flow increased with geometrical factor which was identical to concave structural factor. Yan *et al.* [11] further revealed the combined effects of altitude and *U*-shaped exterior wall on flame spread over insulation material polyurethane (PU). It was found that, the flame spread rate over *U*-shaped channel was much faster at a higher pressure, which was similar to flat-shaped geometry. Comas *et al.* [12, 13] found that when the oxygen content was sufficient, the flame spread most rapidly under closed conditions. While in the downward flame spread, the existence of concave channel sidewall would restrict the lateral air, resulting in the decrease of flame spread speed. Besides the studies on flame spread in concave structures, some researches focused on the influence of parallel curtain wall [14-16] and ejected fire on building façade [17,18]. However, the previous studies mainly focused on the vertical flame spread over PU and XPS in concave structures. In real building fires, the ignition point usually appears at the central of the building, and then the flame spread will process along upward and downward directions. Until now, the research on flame spread at the central of concave structure is very rare. Thus, it is urgent to carry out relative researches on flame spread over EPS in concave structures at the central ignition, which can give useful suggestions for fire protection design of high-rise buildings.

This paper experimentally studied central flame spread over EPS in concave structures with depth-width ratios of 0, 1, 1.5, 2, 2.5, 3, 3.5. The flame spread characteristics parameters including of flame structure, flame spread rate, flame height, mass loss rate and flame temperature *etc.* were analyzed in upward and downward directions, respectively. The special flame spread behaviors, such as re-ignition and flame height restriction were revealed.

Experimental

The experiments were carried out on a self-made flame spread experimental platform as shown in fig. 1(a), which mainly includes EPS sample, gypsum board, digital camera, *K*-type thermocouple sequence, electronic balance, data acquisition instrument, infrared camera, computer and concave structure. Figure 1(b) gives the top view of the concave structure. The depth-width ratio, α, presents the ratio of the depth of the side wall, D, to the width of the back wall, W. The α was chosen as 0, 1, 1.5, 2, 2.5, 3, 3.5 in this research as shown in tab. 1. The selected EPS was 4 cm width, 4 cm depth, and 90 cm length. Thus, by changing the side wall depth, D, the different, α, can be built. The emissivity in concave structure was about 0.92 [3].

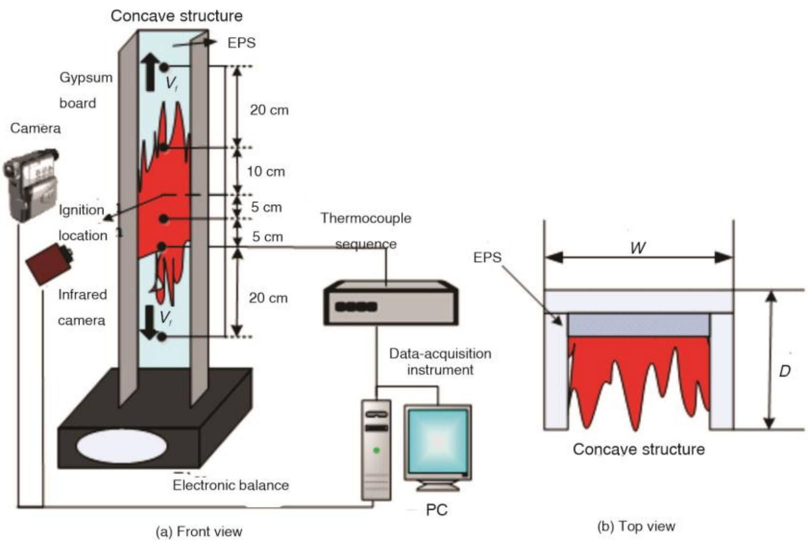

Figure 1. Experimental apparatus diagram of central flame spread

Table 1. The different depth-width ratio, α, values

α	0	1	1.5	2	2.5	3	3.5
Depth [cm]	0	4	6	8	10	12	14
Width [cm]	4	4	4	4	4	4	4

At the beginning of the experiment, a sequence of parallel lines was drawn on the surface of EPS at interval of 5 cm to help determine the position of the flame front. An aluminum foil with a thickness of 1 mm was wrapped on the bottom surface of EPS to prevent the molten EPS material from adhering to the gypsum board. Then, the sample was ignited at the center place by a line igniter with propane gas. It was made with a 4 cm long steel tube drilled small holes at 0.5 cm intervals on the surface. The thermocouples were placed on the upper surface and the lower surface of the sample, 10 cm and 30 cm away from the ignition position, respectively. At the same time, a thermocouple was arranged at 1.5 cm above the sample surface and 5 cm below the ignition source to measure the smoke gas temperature. A camera with a data acquisition frequency of 25 frames per second was used to record the whole flame spread process, in order to obtain the flame shape, flame height and flame spread rate. The infrared camera was applied to measure the temperature distribution of EPS. The mass change during the flame spread was recorded by an electronic balance with a precision of 0.01 g. The width of EPS was fixed at 4 cm, the test of each case was repeated three times so as to reduce the experimental error.

The experiments were conducted in Ma'anshan, China plain. The geographical and meteorological conditions of the place are shown in tab. 2.

Table 2. Geographical and meteorological conditions in Ma'anshan

Place	Altitude [m]	Atmospheric pressure [kPa]	Absolute oxygen concentration [kgm^{-3}]	Ambient temperature [°C]	Relative humidity [%]
Ma'anshan	50	101.8	0.269	12~16	30~42

Results and discussion

Flame structure

Figure 2 gives the schematic of central flame spread over EPS in concave structure. The typical flame spread behaviors can be divided into upward flame spread and downward flame spread, each of them including of the pyrolysis region, preheating region, and unburned region, respectively. The coupling combustion was formed during the entire process. For upward flame spread, conduction, radiation, and convection heat would influence the flame spread rate, while for downward flame spread, the heat could be attributed to conduction and convection, as the radiation heat was not large. The conduction heat was generated by the melting EPS and melt flowing EPS on the downward surface. As the induced air-flow rate would be greatly influenced by the different spread modes, which would make the flame behaviors complex. Meanwhile, the melt dripping EPS was accompanied during burning, which would form a pool fire on the ground. As the flame spread in the concave structure, the chimney effect was generated, which often made the fire spread rapidly and burn violently.

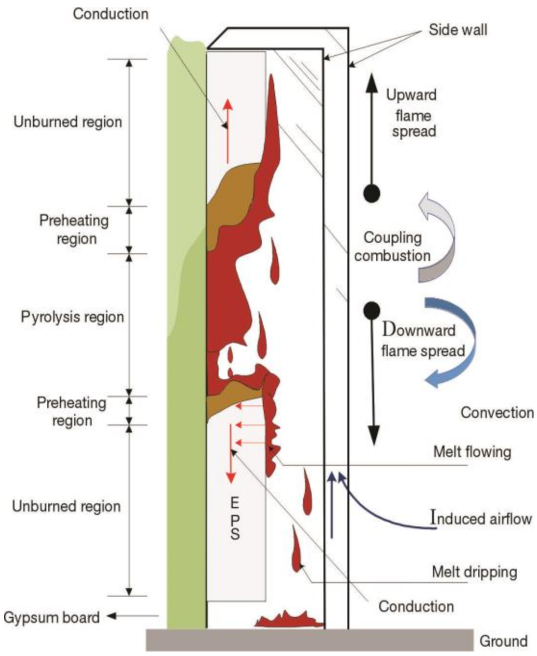

Figure 2. Schematic of central flame spread in concave structure

Figure 3(a) gives a sequence of camera flame images with seven depth-width ratios of 0, 1, 1.5, 2, 2.5, 3, 3.5 at times of 0 seconds, 40 seconds, 80 seconds, 120 seconds, and 140 seconds. It can be found that the combustion zone of EPS was composed of the viscous liquid wall fire zone and liquid pool fire zone. As EPS is easily to form liquid by heating, and the liquid EPS is adhesive, which would be attached to the facade wall, thus the viscous liquid wall fire zone was generated. At the same time, some liquid fuels would flow to the bottom of the material under the action of gravity, forming a small area of liquid pool fire on the top of the bottom flame. It can be found that, due to the effect of depth-width ratios, the upward and downward flame heights would be different at the same time, especially at the largest α of 3.5, the flame heights was the smallest. For the same α, the upward flame would spread fast than the downward flame. When α was relatively large, for upward flame spread, the flame would extinguish randomly, after that it would be ignited again, which will be defined as re-ignition of melting EPS.

Figure 3(b) shows the infrared flame images of seven α factors of 0, 1, 1.5, 2, 2.5, 3, 3.5 at times of 0 seconds, 40 seconds, 80 seconds, 120 seconds, and 140 seconds. With α increase, the flame combustion was inhibited in some degree, which can be seen from the separate small flames in the infrared images. When α at 1 and 1.5, the highest temperature area were relatively larger than others, which can be considered to the effective burning, as the side wall effect was not obvious.

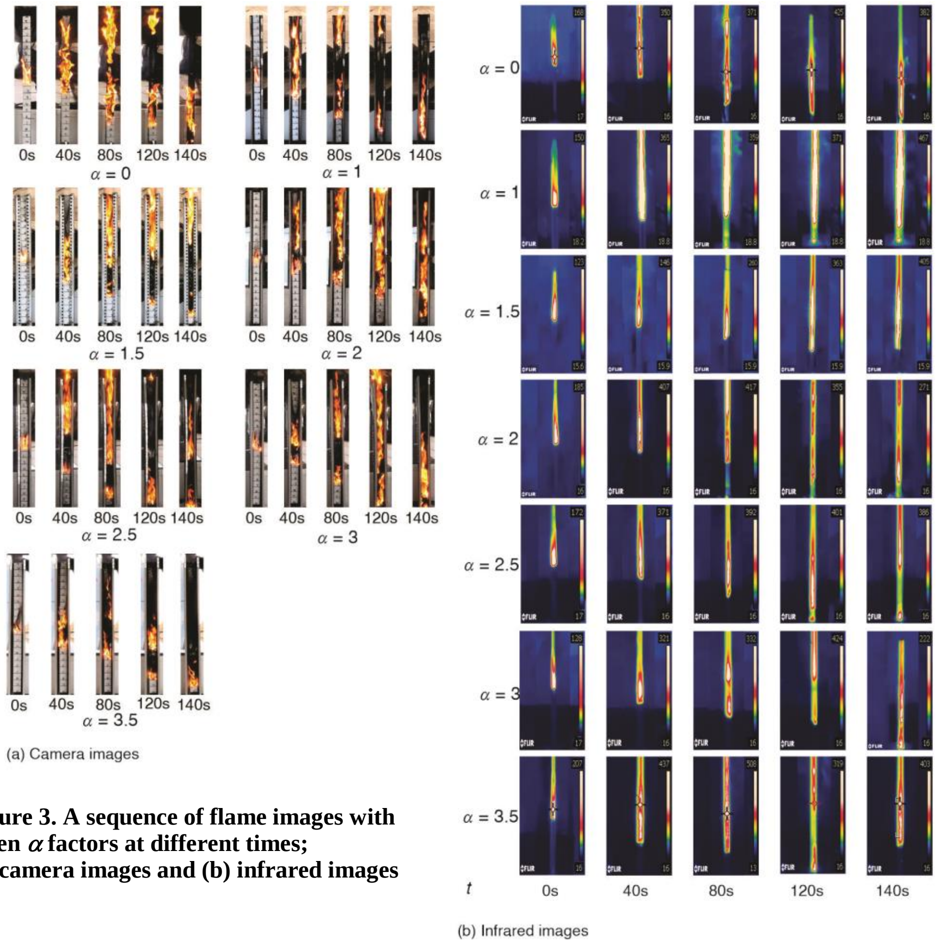

Figure 3. A sequence of flame images with seven α factors at different times; (a) camera images and (b) infrared images

Flame spread rate

Figure 4 shows the curves of the flame tips and flame spread rates for the central upward and downward flame spread over EPS with different α factors versus time. The flame spread rate can be got from the derivative of flame tip position. For the central upward flame spread over EPS, at the early stage, the flame spread rate was relatively stable for the different α factors as shown in fig. 4(a),which can be attributed to the initial flame spread effect. The flame spread acceleration and concave structure influences are not obvious. With the flame spread processing, the flame spread rate firstly accelerated with the increase of α, due to the chimney effect of concave structure. The hot smoke flowed upward which would also increase the heat transfer to the preheating zone. Especially at α = 1.5, the flame spread rate was accelerated mostly. While with the increase of α to 3 and 3.5, the acceleration was not large. This is mainly because that, with the increase of α, the walls on both sides become wider and wider, and the burning of downward flame spread and combined generated smoke were more likely to affect the upward flame spread. The air entrainment will become harder with the larger α, thus the combustion efficiency will be decreased, and the generated smoke will be more easily gathered in the concave structure [11]. Eventually, the acceleration effect of upward flame spread will be weakened. By comparison, it was found that the central upward flame spread (CU) was different from single upward flame spread (SU) in concave structures. The SU was more prone to make the flame stagnation occur. As the flame acceleration of SU was larger than that of CU in concave structures, which would generate larger chimney effect and more hot smoke. Figure 4(b) shows the relationship between the position of the flame tip and flame spread rate for central downward (CD) flame spread. It can be seen that the flame spread rate basically remained constant for every α factor. When α = 1.5, the flame spread rate was the largest. Besides, the central downward flame spread rate was smaller than that of upward flame spread rate for the same α factor, respectively.

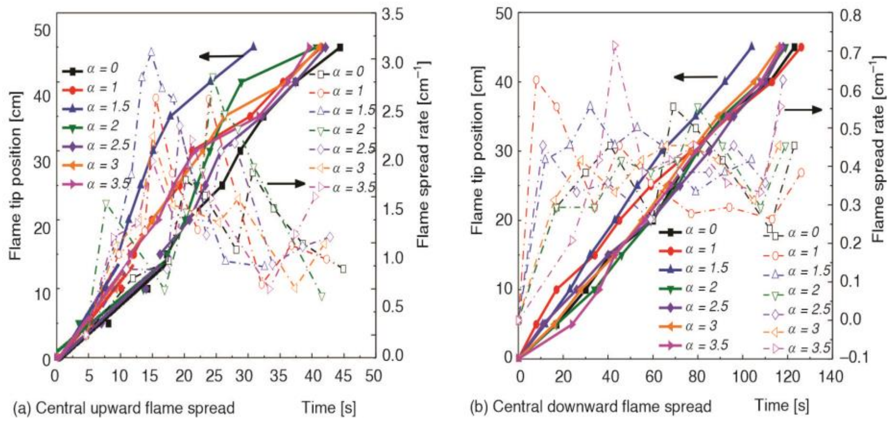

Figure 4. Flame tip position of central flame spread with different α factors; (a) central upward flame spread and (b) central downward flame spread

Flame and smoke temperature

In order to analyze the influence of depth-width ratios on the surface temperature distribution of the material, the surface temperatures at 10 cm and 30 cm on the upper and lower sides of the material and smoke gas temperature at 5 cm on the lower side are summarized in fig. 5. With the increase of α, the maximum surface and smoke gas temperatures basically showed an increasing trend. The measured upper surface temperature had obvious multiple peaks, which further confirmed the re-ignition phenomenon of the upward flame spread. With the increase of α, the measured temperature at the lower positions of 10 cm and 30 cm which presented the transient temperatures at the downward flame spread surface of EPS, showed a gradual increase trend especially for α at 3 and 3.5. This is mainly due to the obvious influence of concave structure on the buoyancy enhancement and the stretch of the lower flame, which makes flame adhere to the surface of material of EPS [11].

Flame height

Figure 6 shows the relationship between the upward and downward flame heights with time. At the early stage of flame spread, the upward flame height increased significantly, while the downward flame height increased slowly. As the preheating region receives much more heat for upward flame spread than for downward flame spread as shown in fig. 2,which makes the flame height increase more. When α = 1.5, the flame had the best burning status during the upward flame spread process, and the extinction of flame was not occurred. While when α <1.5 or α >1.5, the extinction of upward flame was found at the later process, which

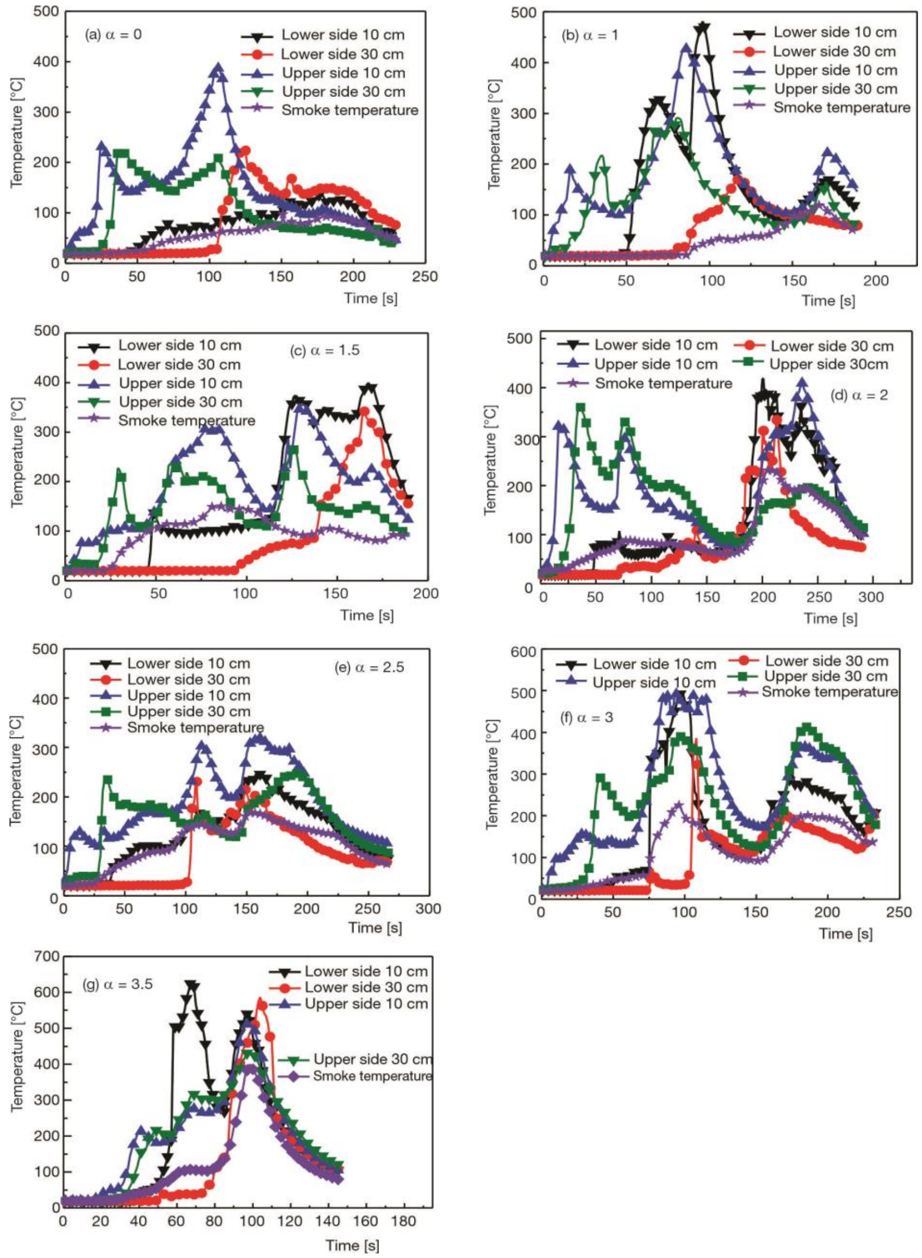

Figure 5. Measured upper and lower surfaces and smoke gas temperatures with time

makes the flame height to 0. This is because, with the upward flame spread going, the buoyancy induced flow can be strong enough to blow off the flame [19]. Especially when the Damkohler number, Da < 1 extinction or no flame spread may occur [20]. On the other hand, if α <1.5, the sidewall effect was weaken, and eventually the extinction could be sorted to flame instability. If α >1.5, the sidewall effect was enhanced correspondingly, which makes the chimney effect increase, thus the extinction could be attributed to the more hot smoke eff-

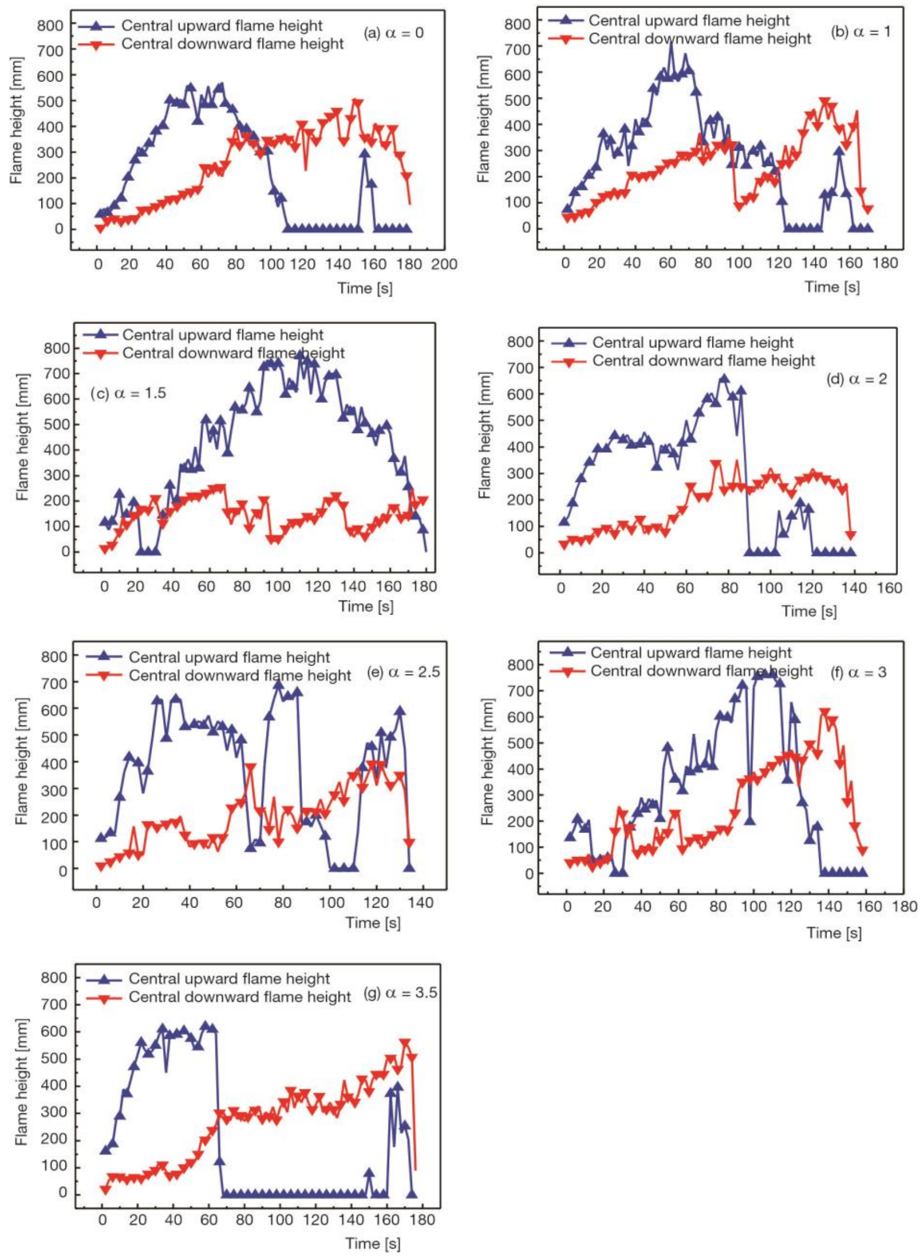

Figure 6. Relationship between upward and downward flame heights with time

eect. Especially when $\alpha = 3.5$, the extinction and re-ignition phenomena were very obvious at the later flame spread. As the α was larger, a large number of hot flue gas was gathered in the concave structure easily, which caused insufficient oxygen supply on the upper side of the concave structure, resulting in flame extinction. With the spread going, the accumulated smoke gas flowed out continuously. When the temperature reaches the ignition temperature of molten EPS which adhered to the gypsum board, the re-ignition will occur.

Meanwhile, the average flame height with different depth-width ratios are compared in the single and central spreading directions, as shown in fig. 7. It can be seen that, when $\alpha > 0$, the average flame height follows: single upward flame spread (SU) > central upward flame spread (CU); central downward flame spread (CD) > single downward flame spread (SD). This is mainly because for central flame spread, there are both concurrent and downstream air flowing, which formed the positive chimney effect and the reverse chimney effect. The positive chimney effect and the reverse chimney effect were often offset in some degree. Thus for SU, the higher speed of air flow makes the flame height larger. While for SD, the higher speed of reverse air flow makes the flame height shorter than CD.

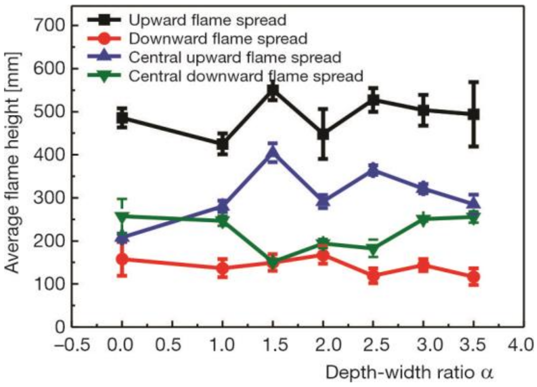

Figure 7. Variation of average flame height with depth-width ratio

It was interesting finding that, upward and downward flame heights had the characteristics of mutual inhibition as shown in fig.7. When the upward flame height became larger, the downward flame height would become shorter, and vice versa. It should be said that the central flame spread had a great impact on the smoke and pressure in the concave structure for upward and downward, which would eventually decide the change of flame height. Figure 8 gives the inner flame pressure during central flame spread. At $t = t_1$,the material of EPS was ignited. The upper and down flame pressures were presented by P_{up} and P_{down}, having: $P_{\mathrm{up}} = P_{\mathrm{down}} = P_\infty$,where P_∞ was the environmental air pressure. When the flame spread at time $t = t_2$, the separate flame zones were generated, which include the upward flame zone and the downward flame zone. The ignition place pressure was described by P_{middle}. The flame height, temperature and density were defined as h_{up}, T_{up}, and ρ_{up} for upward flame zone, and correspondingly these were defined as h_{down}, T_{down}, and ρ_{down} for downward flame zone, respectively. Meanwhile, the upward and downward tip flame pressures were described by P_{up} and P_{down}. The environmental air density and temperature were given by ρ_∞ and T_∞.

According to the ideal gas equation, the upward flame zone can be expressed:

$$P_{\mathrm{up}}V_{\mathrm{up}} = n\mathrm{R}T_{\mathrm{up}} \tag{1}$$

where V_{up} is the volume of the upward flame zone, n – the number of mole, and R – the universal gas constant. With the flame spread processing, the combustion intensity increases, thus T_{up} will become large. Using eq. (1), it can conclude that P_{up} will increase, and the increased amount is defined as ΔP. As the flame spread in the concave structure, the flame behaves against sidewall. Owing to the confinement effect, the flame height H_f can be expressed as [21]:

$$H_f / D \sim \gamma \dot{Q}^{*2/5}$$

where D is the diameter of fire source, γ – the confinement efficient, $\dot{Q}^*$ – the dimensional heat release rate. The $\dot{Q}^*$ can be written as:

$$\dot{Q}^* = \dot{Q} / \rho_\infty c_p T_\infty g^{1/2} D^{5/2}$$

where $\dot{Q}$ is the heat release rate of the fire and c_p – the specific heat at constant pressure. At the flame height H_f, $\dot{Q}$ has the relationship with ΔP as [21]:

$$\dot{Q} \sim \Delta P^2$$

Thus, the following equation can be established:

$$H_f / D \sim \Delta P^2 / gD \tag{2}$$

So, for the upward flame height H_{up}, eq.(2) can be rewritten as:

$$H_{up} \sim \Delta P^2 \tag{3}$$

Thus, the upward flame height will increase. The ignition place pressure for upward flame P_{middle} can be expressed as:

$$P_{\mathrm{middle}} = \rho_{\mathrm{up}} g h_{\mathrm{up}} + \Delta P + P_{\mathrm{up}} \tag{4}$$

Meanwhile, the ignition place pressure for downward flame P_{middle} will be decreased to $P'_{\mathrm{middle}} - \Delta P$. The downward flame tip pressure P_{down} will be changed to:

$$P_{\mathrm{down}} = P'_{\mathrm{middle}} - \Delta P - \rho_{\mathrm{down}} g h_{\mathrm{down}} \tag{5}$$

The decreased pressure of P_{down} will make the downward flame height H_{down} become short according to eq. (2). On the other hand, when the downward flame height H_{down} becomes large, we can also conclude that the upward flame height H_{up} will decrease, according to the previous analysis.

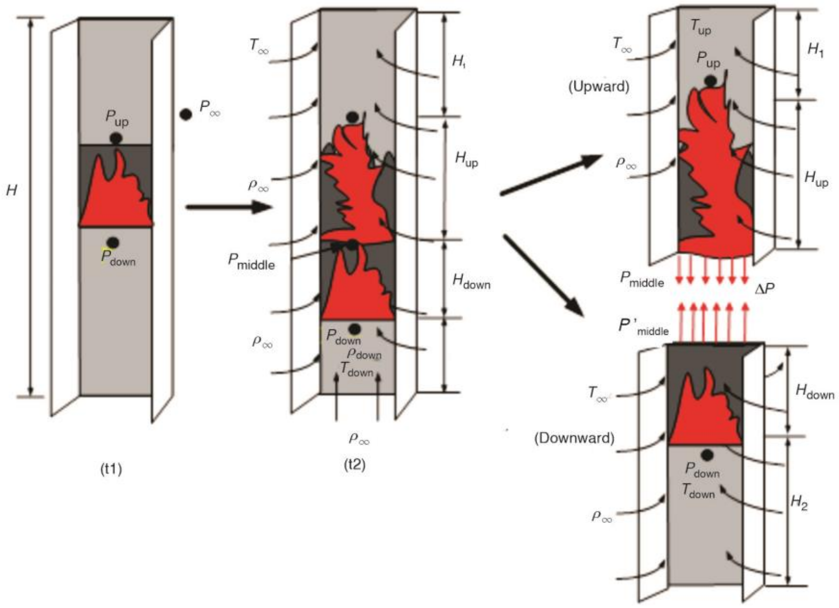

Figure 8. Inner flame pressure during central flame spread

Mass and mass loss rate

Figure 9 shows the curves of mass and mass loss rate of EPS with time at different α factors during central flame spread. There were three main stages of mass loss rate as: the development stage, the oscillation acceleration stage, and the burnout stage. At the development stage, the flame had the characteristics of increasing development. When the combustion came from the development stage to the oscillation acceleration stage, the mass loss rate basically presented the phenomenon of oscillation acceleration, which was mainly due to the special behaviors during upward flame spread, which made the mass loss rate oscillating increase. As the stagnation and extinction of the upward flame, the mass loss rate became smaller. After that, the re-ignition and re-burning made the mass loss rate increase again. The cycle was

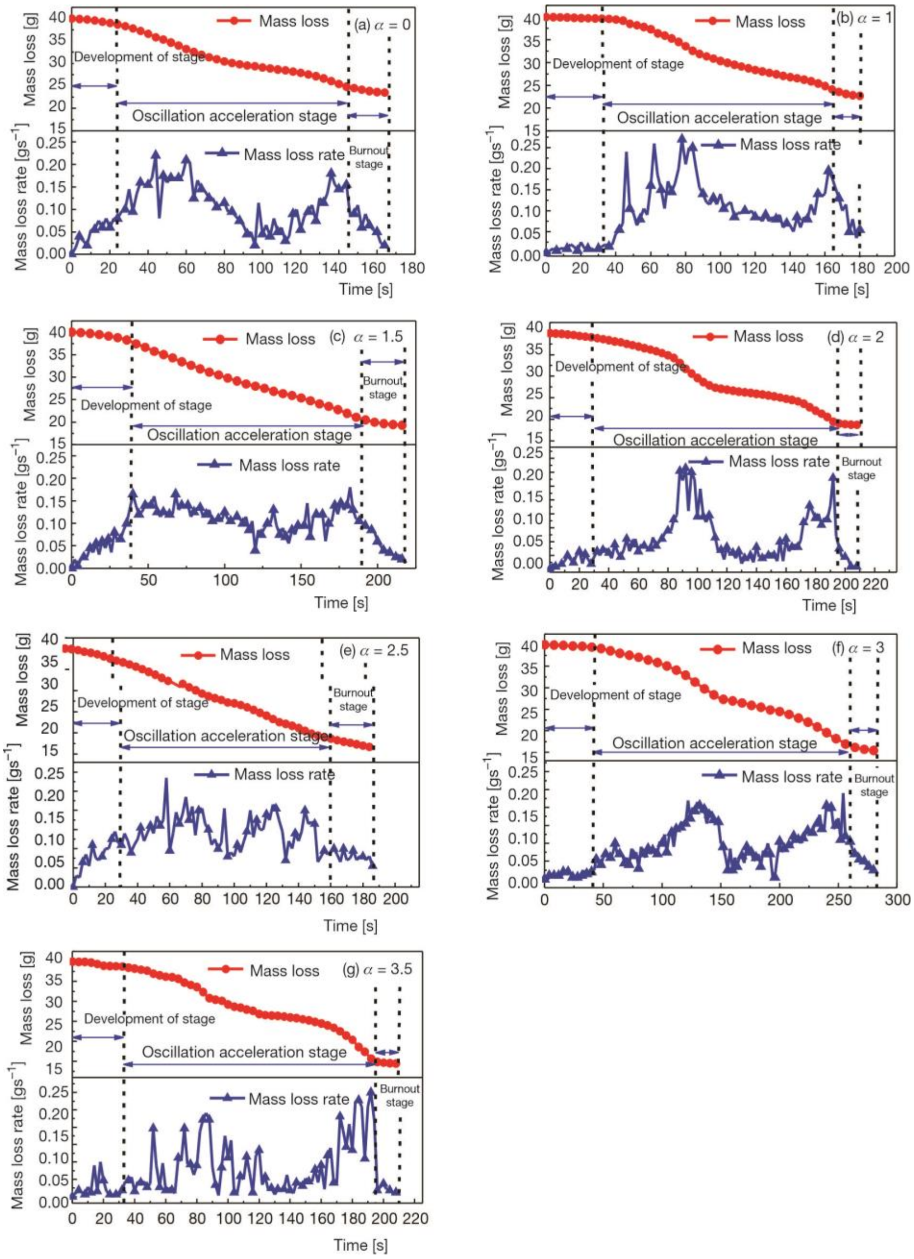

Figure 9. The curves of mass and mass loss rate *vs*. time at different depth-width ratios

repeated, then the mass loss rate was accelerated in the oscillation. When $\alpha = 1.5$, this phenomenon was not obvious, because the flame was relatively stable, which was consistent with the previous analysis of flame height. At the burnout stage, due to the length of the material EPS, the flame spread stop, the burning just worked on the molten EPS, thus the mass loss rate gradually decreased.

Conclusion

In this paper, a series of central flame spread was carried out on EPS with different depth-width ratios of 0, 1, 1.5, 2, 2.5, 3, 3.5. The changes of flame structure, flame spread rate, flame temperature, mass loss rate and flame height were theoretically and experimentally analyzed. The main conclusions are summarized as following:

In the central flame spread, the extinction, re-ignition and re-burning were found for the upward flame except $\alpha = 1.5$,while the downward flame could keep in the stable flame spreading.

When $\alpha = 1.5$, the stability of upward flame spread was the best, as the extinction didnot occur, and the flame spread rate was the fastest.

There are three main stages of mass loss rate as: the development stage, the oscillation acceleration stage, and the burnout stage. The oscillation acceleration was influenced by the extinction and re-burning of upward flame mainly.

When $\alpha < 1.5$, the extinction of upward flame could be sorted to flame instability, while when $\alpha > 1.5$, the extinction could be attributed to the more hot smoke effect.

Inner flame pressure model was built during central flame spread, which could better explain the characteristics of mutual inhibition between upward and downward flame heights.

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