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Article

Comparison of Fire Behavior of Thermally Thin and Thick Latex Foam Under Bottom Ventilation

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Abstract: Fire behavior of natural rubber latex foam under different thickness conditions(d=1,2and 5cm)were explored though a little of experiments by using the self-built small scale experimental platform. It can be shown that the flame spread law of thermally thin and thermally thickness are different. Natural rubber latex foam with thickness of 2cm show higher fire risk, which value of flame spread rate, maximum flame height, maximum mass loss rate and maximum temperature is 0.00293m/s, 851.875mm, 1.83g/s, 948K,repectively.That may because the thickness of residue formed of thermally thick materials is larger than the thin one, obstructing the contact of the natural rubber latex foam with fresh air .In addition, a special phenomenon is noticed that during the second stage, the bottom unburned zone located in the four edges(thermally thin material) and middle player(thermally thick material).

Keywords: natural rubber latex foam; fire behavior; thermally thin materials; thermally thick materials

1.Introduction

Nowadays, latex foam has been widely used as filler for high-end mattresses on account of its strong resilience, stability, good breathability, anti-mite sterilization, promotion of sleep and so on[1,2]. The microstructure of latex foam is three-dimensional porous structure as seen in fig.1(a)[3-5]. In addition, this materials are evenly distributed with some through-holes for improve the permeability of latex foam and degree of comfort when people use, as seen in fig.1(b). However, in the event of a fire, the cellular structure and the through-holes greatly facilitates the spread of the fire and increases the fully development of the combustion due to high specific surface and well ventilation, causing great casualties and huge property losses[6].

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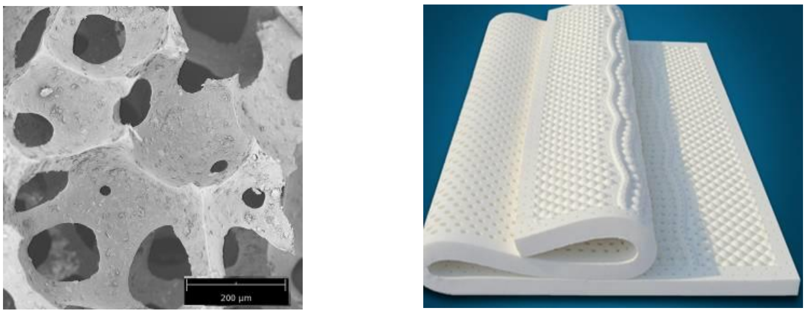

(**a**) (**b**)

Figure 1. Latex foam structure under: (a) SEM, and (b) Naked eye observation

Serious concerns have been raised over the flame spread behavior of different materials, such as polyethylene[7], polymethylmethacrylate(PMMA)[8], XPS foam and polyurethane foam[9,10], epoxy containing ester[11], and so on[12]. According to its thermal penetration depth , layered combustibles are often classified as thermally thin and thick materials[13]. Similarly, Jinlong Zhao[14] studied whether the four burning period(pre-heating, steady burning, thin-layer burning and extinguishment stage) will appear or not depends on the thickness of the fuel samples, and the results show that the heat flux feedback to sample surface is depend on the thickness of samples. Further more, some scholars focus on the influence of thickness on the flame spread with solid samples[13,15]. For example, the effect of thickness on plywood vertical spread have been studied by Xuanmeng Qing[15], which show that the thickness of samples will affect the regulation of flame spread ,and the flame spread rate will decrease when thickness of samples increases. Lin Jiang[13]give a similar conclusion . The effect of bottom ventilation[16], ignition position[17] on the flame spread of natural rubber latex foam has been studied by previous researches of our groups. It indicated that materials under bottom ventilation(BV) and center ignition position show more higher fire risk by comparing the value of flame temperature, flame height and mass loss rate et al. However, the flame spread behavior of thermally thin materials and thermally thick materials of natural rubber latex foam are rarely compared.

As a new type of upholstered furniture, natural rubber latex foam has been widely concerned, but there are few studies on its fire risk. Considering that different thickness of latex foam is widely used ,the purpose of studying the fire behavior of natural rubber latex foam under different thickness conditions is to understand the characteristics of fire spread, which can provide theoretical support for fire spread risk assessment of natural rubber latex foam .In this paper, the combustion behavior of latex foam with three different thicknesses (1cm,2cm and 5cm) is compared by using a small scale experiment platform, such as flame propagation speed, flame height, flame temperature, mass loss rate and so on to address the relevant fire risks. The research results provide a theoretical basis for fire risk assessment of typical cushion materials under spontaneous combustion conditions.

2.Experimental methodology

The small-scale platform which made by our group was adopted in this experiment, as shown in fig.2(a),which includes two parts: burning system and measurement system. The introduction of the burning system is detailed in article of our groups[16].

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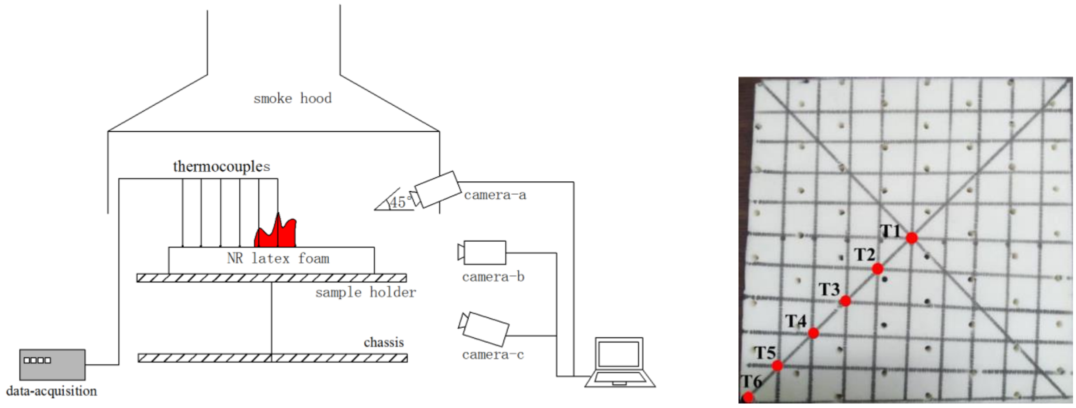

(**a**) (**b**)

Figure 2. (a) Schematic of small-scale flame spread setup in this study (b)Tested natural rubber latex foam sample and thermocouples positioned along the horizontal direction (T1 to T6).

The measurement system included thermocouples, HD video cameras, weighbridge, and data acquisition system. During each experiment , the temperatures along the horizontal direction of sample were recorded by some K-type-0.5mm thermocouples with a measurement range of -200℃ to 1300℃. The materials was ignited at the center point, as time go on, flame will spread from this ignition point to the four edges. So those thermocouples of T1-T6 were placed along a half-diagonal of the top surface from the center to the edge, as seen in fig.2(b).The universal several bus(USB) interface of 34908A module data-acquisition is used to connect with the personal computer for easy viewing and recording data.

Moreover, three HD video camera with angle of 45 °,0°,and-45° from the horizontal were used to photograph the experiment procedure. We draw a parallel line every 2.5 cm ,with a black marker, on the surface of the specimen to evenly divide the latex foam into square pieces with sides of 2.5 cm×2.5cm, as seen in Fig2(a)， which is not only helps us to determine the location of the fire front but also facilitates the proportional relationship between the picture space and the actual space. Based on this, the relevant image processing software can be used to obtain the morphological parameters of the flame, such as flame height, flame front position, etc.

Some 25 cm×25 cm natural latex foams with the thickness of 1, 2 and 5cm were prepared as shown in fig.2(b). The samples are divided into 100 small squares with black Mark pen to observe the change of the position of pyrolysis. All samples were selected from the same piece of natural rubber latex foam material with the same air pore size distribution to reduce the effect of uncontrollable parameters on the combustion characteristics of the sample.

Samples were placed in a drying oven for 12 hours before the experiment started under the condition that the values of temperature and humidity are 20℃ and 40%. Subsequently, it was placed on the wire mesh and the surface of the sample is blown with high-speed air to remove surface dash. In the course of the experiment, every time we used the same lighter to ignite the center of sample while ensuring the other conditions are the same. In order to test the accuracy of the results, each experiment repeated twice showing a good repeatability.

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3.Results and discussion

3.1 Flame behavior

Comparison of the flame shapes of different thickness samples is helpful to explore the difference of the surface flame propagation behavior. The variation of the natural rubber latex foam flame sequences with thickness d=1,2,5cm is shown in fig. 3 Three HD video cameras , placed in the designated area, recorded the whole process of the fire spread, which helped us clearly observed the three different periods of the natural rubber foam combustion: Stage I is initial combustion phases stage(from the moment that the center point of material was ignited to the fire spread across the entire top surface), stage II, so called "stable combustion stage"(from the end of initial combustion phases stage to the moment that flame spread to all natural rubber latex foam surfaces), stage III means fire weaken stage (from the end of stage II to fray-out of flame moment), which is very similar to the combustion process of polyurethane foam[9,18,19].

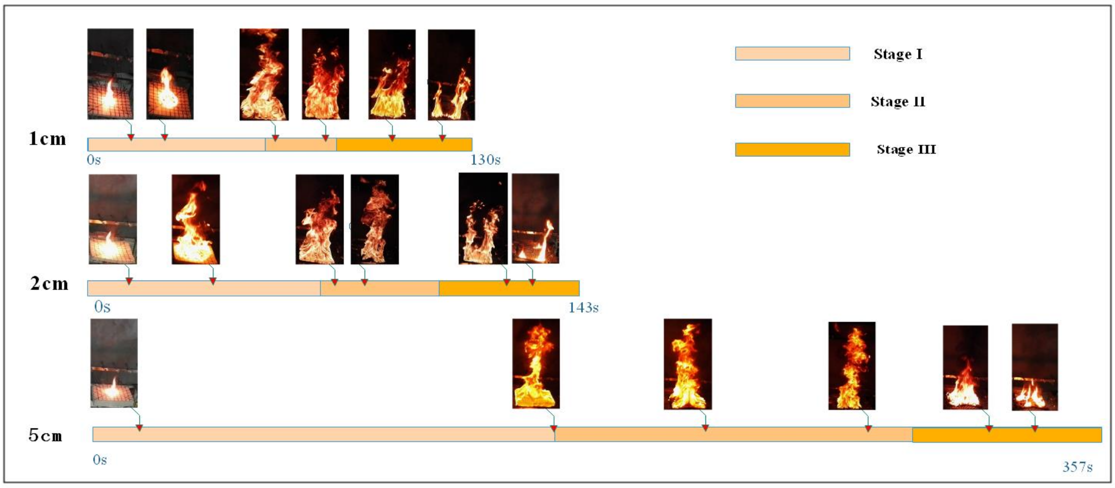

Figure 3. Flame spread process of natural rubber latex foam with different thickness (d=1,2 and 5cm)

The combustion process of all three kinds of materials can be divided into this three stages and the biggest difference is the duration of each stage. The duration of each stage under three thickness conditions and the average flame height are highlight in tab.1. As is apparently shown by the pictures above , stage one, the fire began to spread from the center spot to the marginal zone. The three stage combustion duration of natural rubber latex foam with thickness of 5mm is longer(357s) compared with those thin materials(1,2cm).In addition, during stage II, sample with 2 cm thickness burns most fiercely, and average flame height (0.68m) is higher than the materials with thickness of 1cm (0.53m)and 5cm(0.59m),as shown in tab.1 and fig.3. It shows a similar trend during the last stage that the flame gradually decreased until fire was extinguished when the combustible was gradually consumed. Meanwhile, we can clearly see that some sample residues attached to the stainless steel mesh.

Table 1. The duration of the three stages and the average flame height for the three thickness samples

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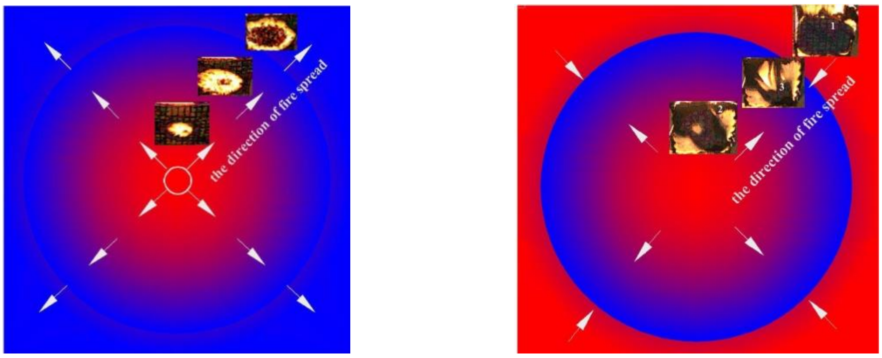
	1cm		2cm		5cm	
	Duration time(s)	Average flame height (m)	Duration time(s)	Average flame height (m)	Duration time(s)	Average flame height (m)
Stage I	0-62	<0.53	0-75	<0.68	0-174	<0.59
Stage II	63-77	0.53	76-111	0.68	175-310	0.59
Stage III	78-130	<0.53	112-143	<0.68	311-357	<0.59

According to video record, one can notice that the bottom of the three thickness samples are ignited during the experiments but the flame spread route is much different . In figure 4, red color represents the burning area and blue represents no burning region and the arrows represent the trend of flame spread. The flame of samples with d=1,2cm spread from the center to four edges. On the contrary, first of all, for the 5 cm sample, the fire spreads from the edge to the surrounding area. After a period of time, the bottom center is burned through and the fire spreads from the center and edge to the middle layer at the same time. The phenomenon show that the bottom flame spread law of natural rubber latex foam with different thickness is different，and the unburned zone ,during the second stage ,are located in four edges and middle layer ,respectively. We will further explore the parameters of flame height, mass loss rate and ,temperature and flame spread rate.



(**a**) (**b**)

Figure 4. The flame spreading law at the bottom of the sample with different thickness:（a）1cm and 2cm (b)5cm

3.2 Flame spread rate

The position of flame front was obtained by image sequences as seen in fig.5. The flame front under different thickness increases along the time showing a linear relationship. As we know, the rate of flame spread can be calculated via distance divided by time. So it can be calculated by the reciprocal of the fitting line slope. The equation of three fitting curves obtain from this experimental are y=3.43x+9.06,y=3.41x+10.53 and y=6.06x+17.44, which show that the slope of 1cm, 2 cm and 5 cm test are3.42cm/s, 3.41 cm/s and 6.06 cm/s. Correspondingly, the flame spread rate on the upper surface of 1cm test, 2 cm test and 5 cm test are about 0.292×10^{-2} m/s, 0.293×10^{-2} m/s, and 0.165×10^{-2} m/s respectively. For the test, the flame spread rate of natural rubber latex foam with thickness of 1cm and 2cm is similar and far greater than that of 5cm one , which may indicate that sample with a thickness of 1cm and 2cm showed higher fire risk than others.

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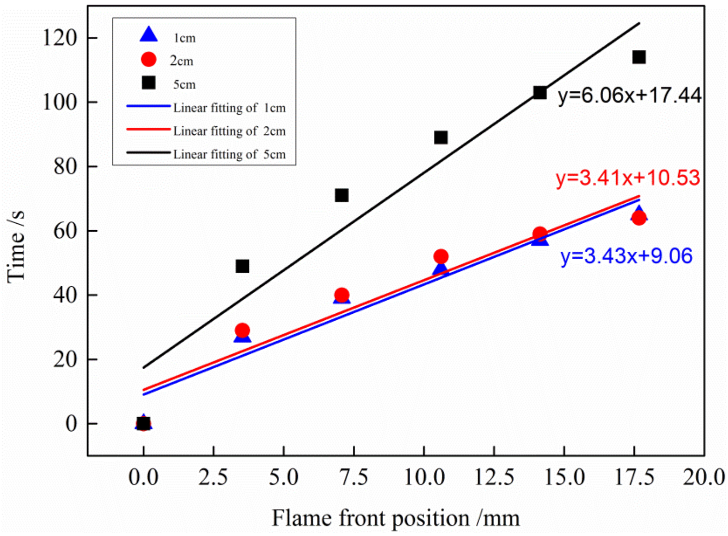

Figure 5. Flame front versus time under the three thickness tests

3.3 Mass loss

Meanwhile, the mass loss rate of samples with d=1,2,5cm is depicted in fig.6. Obviously, the quality of different thickness samples all decrease slowly and then decrease sharply, and the mass loss rate of samples with d=2cm is the most greatest. The peak mass loss rates of samples with d=1,2and 5cm are 1.83,1.91,0.79 %wt/s, respectively ,which all appear near the end of the second stage ,and the mass loss rate increased significantly after bottom ignited.

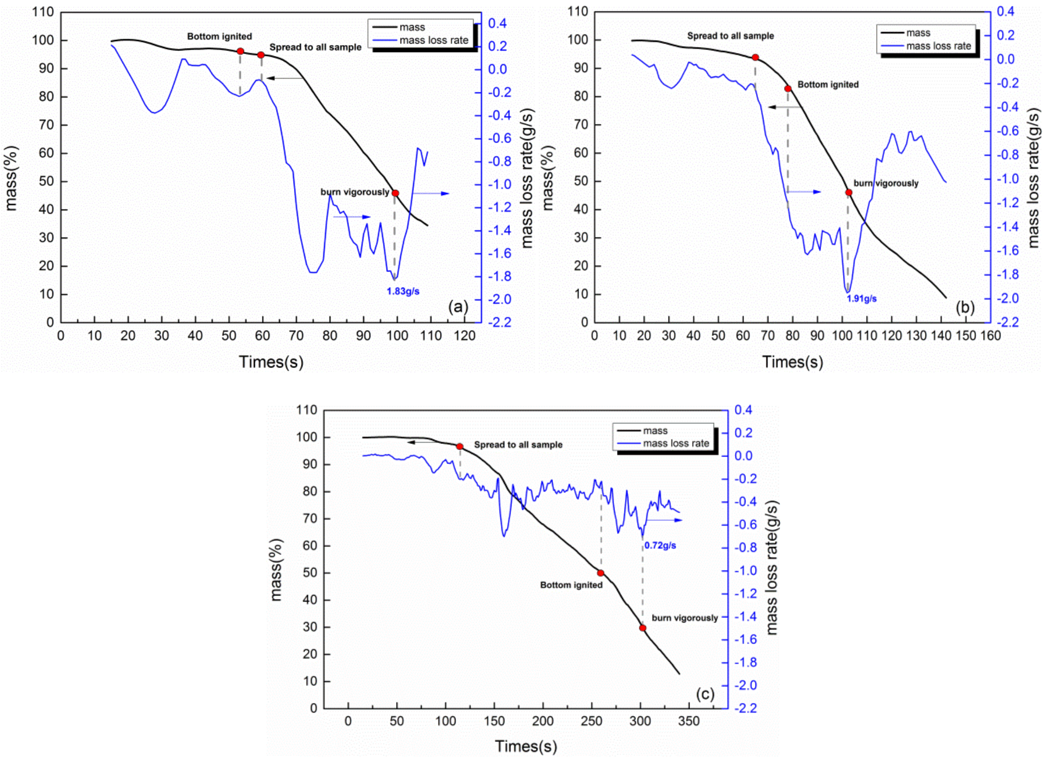

Figure 6. Mass loss rate of different thickness samples:(a)1cm,(b)2cm, and(c)5cm

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3.4 Flame height

During the experiments, the change of flame height was reflected by video. For the natural rubber latex foam with thickness of 1, 2 and 5cm, the flame height were measured from the moment the center point of material was ignited to flame out. The variation of flame height is shown in fig.7 (The frequency of flame fluctuation is reflected by the standard deviation of flame height).

Figure 7 presents the change of flame height with times under different thickness. Based on the Fig.1, the burning process can be detailed and the average flame height for the sample of three different thickness (1cm,2cm,5cm)are 0.53m,0.68m,0.59m respectively, as shown in Table1. During stage I, the thickness has little influence on the flame height. During stage II, the flame height of the sample reached its maximum for all thickness samples. Clearly, the maximum flame height of 2cm thick sample is higher than the others. This may because, like the 1cm one, the bottom of the 2cm sample burns out quickly and has more combustibles than 1cm, it shows a higher flame height. Meanwhile, an obvious phenomenon deserves our attention, stable stage duration of samples with different thickness is longer with increasing sample thickness and the stable combustion stage of 5cm one is much longer than that of the others. In the last stage (stage III), the value of the flame height dropped sharply with residue, and this process has the same tendency with all thickness(1,2,5cm) natural rubber latex foam.

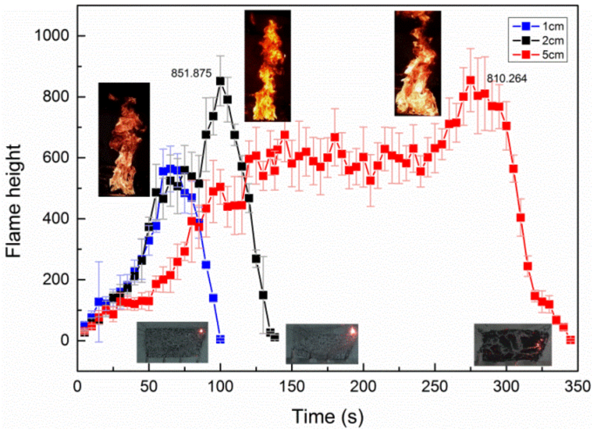

Figure 7. Flame height versus time for the three thickness samples

3.5 Temperature profiles

Flame spread is the process that the test specimens are heated and ignited by the energy from the burned region in essential[20].In this paper, understanding the temperature profile is contribute to explore the regulation of flame spread of with different thickness of natural rubber latex foam. Fig.8 shows the temperature profiles of the natural rubber latex foam surface with different thickness(d=1,2and5cm) during the flame spread process .As we have seen in fig.8(a)-(c),all the trend of surface temperature increased firstly then declining, which is similar to flame spread regulation of polyurethane foam[19]. It can be proved by Fig.3 and Fig.8 that flame spreading over natural rubber latex foam surface undergoes three stages.

Figure indicated that the temperature change trend and the surface average temperature are very similar during stageI for the different thickness samples. The maximum temperature at most of TC point is around 400-500°C.This maybe because that those thermocouples were located on the pyrolysis region. However, a special phenomenon that temperature of TC6,as seen in fig.8(c), rose sharply from the lower one to 680°C . It probably because that the edge of the sample shrunk

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resulting in TC6 separated from the surface and shifted to flame region rapidly.

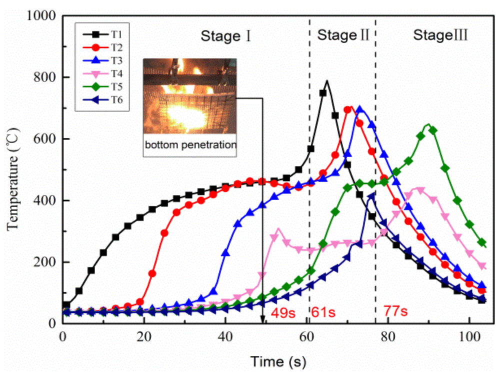
During stage II, according to fig.8(a)and(b),the temperature under the conditions of thickness of 1cm and 2cm reach to peak value, which is around 700-900°C. But for the 5cm one ,it keeps stable, which is about 600°C except TC6, and it reaches the maximum at the early time of the third stage, as shown in fig.8(c). There is a marked increase change in temperature of all thermocouples under three different conditions, which all increased from 400°C to the maximum value . Moreover, the jump of temperature of six thermocouples that located on the top surface of samples with different thickness (d=1,2 and 5cm) have been compared in the tab. 2, and the average jump of the temperature of six thermocouples is 240.761°C, 296.216°C and 237.765°C respectively , which can show the intensity of combustion. That is to say the 2cm one burn more fiercely.

Table 2. Jump of temperature of thermocouples

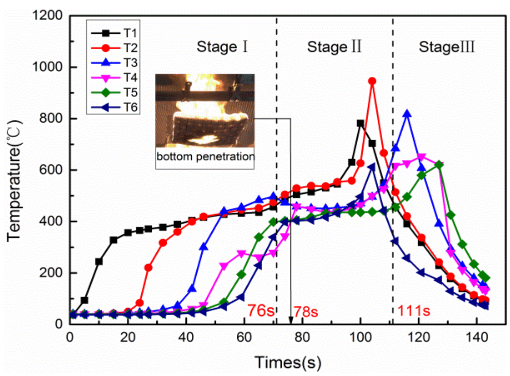
Thickness of samples (cm)	**T1 (℃)**	**T2 (℃)**	**T3 (℃)**	**T4 (℃)**	**T5 (℃)**	**T6 (℃)**	**Average temperature (℃)**
1	323.323	262.266	231.049	180.299	194.17	253.461	240.761
2	267.227	392.232	358.153	213.077	179.06	205.545	296.216
5	177.503	208.899	255.377	176.917	120.762	487.13	237.765

The reason for these differences is that the 1cm and 2cm materials are burned out quickly, and the top and bottom surfaces of the samples are burned simultaneously, which makes the combustion more intense. On the contrary, because the sample with a thickness of 5 cm is one surface combustion initially, there is a longer stable combustion stage before the bottom combustion.

Based on the experiment video footage recording by the camera c, we have noticed that the bottom ignition time for the three samples is 49s,78s,257s,respectly. Moreover, the maximum temperature of 2cm sample is 948K,which is higher than that of sample with thickness of 1cm(791°C,) and 5cm(893°C) . As time went by, those thermocouples escape from upper surface and shifted to flame zone leading to improvement of temperature. As the combustion came to stage III, under all thickness conditions, the material was gradually exhausted and the temperature obtained by TC1 -TC6 dropped sharply.



(a)



(b)

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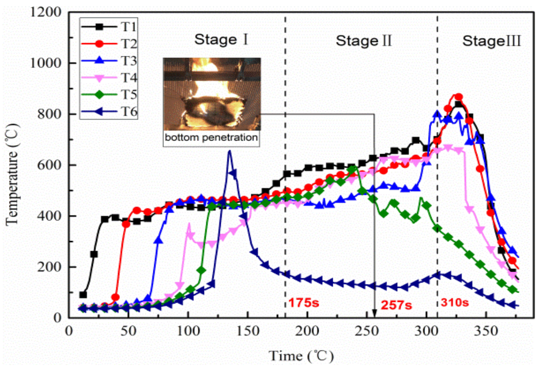

(c)

Figure 8. Surface temperature field changes of natural latex foam: (a)1cm;(b)2cm;(c)5cm

4.Further discussion

First of all, the value of thermal penetration depth(δ_t) in flame spreading is about 3.8cm according to previous studies of our group[16]. When the specimen thickness is no less than the heat-penetration thickness, the material is regarded as a thick material. Otherwise, the result turns out contrary. Thus, in this paper, samples with a thickness of 1, 2cm are considered as thin-thermal material and 5 cm thick natural rubber foam are called thermal thick material. The TG test results show that after the combustion of the natural rubber latex foam, the residual residue is about 24.8% of the original, which is not a thermoplastic material[3]. Moreover, Due to the different combustion modes, the existence of the residue is found to be different. As shown in fig.9, a half-section view, yellow color represents the natural rubber latex foam and black represents residue after combustion and the some neat holes represent the through-hole of natural rubber latex foam with an aperture of 6mm and a spacing of 30mm.The residue foamed during the combustion of the natural rubber latex foam with d=2cm and the thickness of residue of thermally thick materials is lager than the others. Differently, seen in Fig.10,thermally thin materials(d=1,2cm), the residue is thin. Consequently, the relative surface area of air contact with latex foam is larger that the fresh air can help the burning, that is to say thermally thin natural rubber latex foam can burn more fully than the thick one. Moreover, because of the different distribution patterns of combustion residue, the flame spreading modes of thermal thick and thin natural rubber latex foam are different. As shown in fig.5and fig.6, the value of flame spread rate and mass loss rate of thermally thin materials is larger than the thick one. At the same times, during this burning process, the value of profile temperature and flame height of samples with d=2cm are the largest, as seen in fig.8 and tab.2. In other words, the fire spread speed of thermally thick material may lower than that of thin materials.

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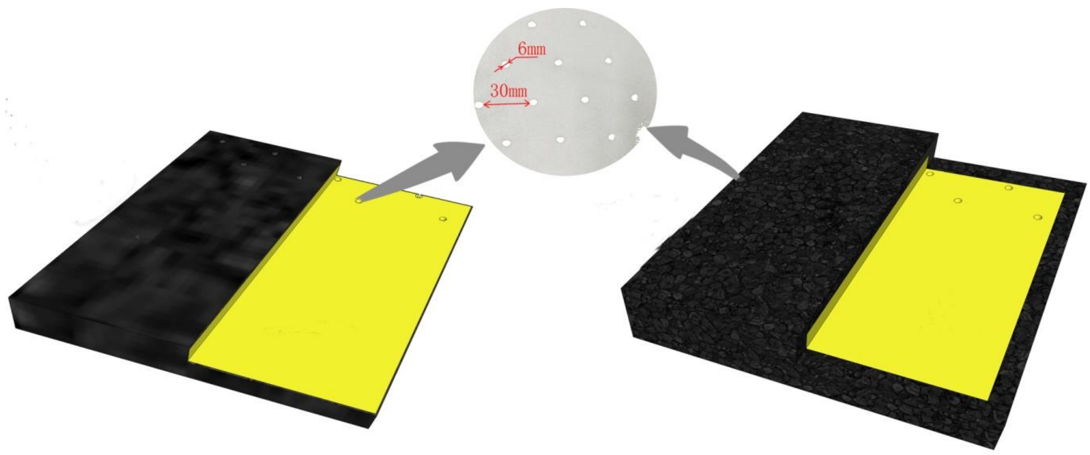

Figure 9. Existence form of residue during the burning process

5.Conclusion

In this work ,the flame spread law of natural rubber latex foam with different thickness (d=1,2and5cm)was explored experimentally. Main conclusions include:

(1) First of all ,The flame spread rate of natural rubber latex foam with d=1,2and5cm are about 0.292×10^{-2} m/s, 0.293×10^{-2} m/s and 0.165×10^{-2} m/s. Moreover, the maximum value of flame height are 578.98mm, 852.875mm and 810.264mm. At last , the maximum temperature of top surface are 791K, 948K ,893K,expectively.The maximum mass loss rate are 1.83,1.91and 0.79g/s. A variety of experimental phenomenon indicate that the NR latex foam with thickness of 2cm show higher fire risk ,which also can proved by the value of average flame height(0.53m,0.68m and 0.59m).

(2) Bottom flame spread law of thermally thin and thick materials is different，and the unburned zone ,during the second stage ,are located in four edges and middle layer ,respectively.

(3) Due to the different combustion modes, the existence of the residue is found to be different and because of the different distribution patterns of combustion residue, the flame spreading modes of thermal thick and thin natural rubber latex foam are different. The thickness of the thermally thin surface is thinner than that of the thermally thick one.

Author Contributions: investigation, Huang D.M. and Yuan Q.; conceptualization, Huang D.M. and Shi L.; methodology, Huang D.M. and Yuan Q.; data analysis, Hu Y.W, Shen. L.M. and Zhang M.Z.; writing—original draft preparation, Yuan Q.; writing—review and editing, Yuan Q.， Huang D.M. and Shi L.; project administration, Huang D.M.; funding acquisition, Huang D.M.

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