Research on the Influence of Environmental Pressure on the Combustion Characteristics and Fire Spread of Building External Wall Insulation Materials

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Abstract. Building external wall insulation materials are widely used in the construction industry, which is one of the main materials for building energy saving. In order to study the combustion characteristics and fire spread behaviour of typical exterior wall materials at different pressures. Four environmental pressures of 40KPa, 60KPa, 80KPa, and 101KPa were set in an experimental cabin, measuring the quality, temperature, heat radiation, and heat flow of rigid polyurethane foam (RPU) through experiments. The experimental results are as follows: the masses loss curve of RPU combustion approximately obeyed the quadratic curve, which was similar to the general solid fuel combustion law; the mass change was the most dramatic at 101KPa, the lower the pressure, the slower the mass change; as the pressure decreased, the flame temperature increased slightly, and the spread of the fire slowed down; as the pressure decreased, the peak value of the thermal radiation curve decreased, and the curve tends became flat, but the horizontal axis time increased, indicating that the total heat release remained the same.

Keywords. Environmental pressure; rigid polyurethane foam (RPU); combustion characteristics; fire spread.

1. Introduction

Rigid polyurethane foam (RPU) is widely used for insulation of building exterior walls and storage tanks due to its high thermal insulation properties and low water permeability [1], but RPU is highly flammable and extremely flammable. It is easily heated by external radiation. With the increasing application of RPU in modern industry, serious fire accidents occur frequently, causing serious casualties, property losses, and serious social consequences. There are some fire accidents, such as the Grenfell Tower fire in London in 2017, have killed at least 80 people and injured more than 70 people [2, 3]; the Shanghai Jing’an fire in 2010 and Beijing Daxing urban village fire in 2017 [4], causing immeasurable economic losses and casualties. Some of these fires were caused by building exterior
wall insulation materials. The fire hazard in building exterior wall insulation is obvious. At the same time, China has a complex terrain and large altitude spans. Less attention has been known to the fire situation of building exterior wall insulation materials under low-pressure conditions in high-altitude areas. Therefore, it is necessary to study the combustion characteristics and fire spread characteristics of building exterior insulation materials in different external environmental pressures.

In foreign research, Kleinhenz et al. [5] studied the spread of flames, the growth rate, the burning rate of thin and thick solids in laminar and turbulent flames. Wang, Kong and Zhang [6] studied the analysis of the flame spreading on the surface of solid fuels under various environmental pressures. Du [7] discussed the effect of pressure on the combustion behavior of materials. In terms of domestic research, Zhang [8] conducted a thermal degradation process in several stages for the ignition time and mass loss rate of rigid polyurethane foam (RPU) under different radiation conditions and established a corresponding numerical model. Zhang, Liu, Chen, Zhu, Sun and Fang [9] studied the effect of heat flow on the combustion characteristics of insulating materials (EPS, XPS, RPU) commonly used in external applications. Ma et al. [10] conducted laboratory-scale comparative experiments on the Lhasa Plateau (66.5KPa) and the Hefei Plain (99.8KPa) in China, the study of flame propagation characteristics is measured at different widths of the test site and atmospheric pressure. Ma et al. [11] studied the fire risk of rigid polyurethane (PU) foam in this environment on self-designed equipment. Huang et al. [12] studied the combustion behaviour of the material under low-pressure and low-oxygen concentrations.

Based on the above investigation, it can be seen that a large number of researchers have done a lot of experiments and simulations on the influence factors of the fire spread of exterior wall materials. However, less attention has been paid to RPU’s combustion characteristics under different pressure environments.

Therefore, based on pressure chamber and combustion experiments, this work mainly uses the experimental cabin (Self-made pressure test chamber) to create four different pressure environments to simulate relatively real altitude changes. Set the pressure gradient from 40KPa to 101KPa with a span of 20KPa, and monitor the heat flow, heat radiation, mass change, combustion time, temperature, and other flame conditions, and finally analyse the effect of pressure changes on the flame and get the conclusion.

2. Experimental Design

2.1. Experimental Purpose
Four external environmental pressures of 40KPa, 60KPa, 80KPa, and 101KPa were set in the experimental cabin for combustion experiments. The temperature, heat flow, thermal radiation, quality, and other changes of the RPU experimental materials were measured, to understand the combustion of external wall materials under different pressures, and to discuss the influence of the burning characteristics of insulation materials.

2.2. Experimental Device
The experimental cabin (self-made pressure test chamber) is composed of the cabin body and pressure control system, an oxygen concentration system, and other auxiliary systems (e.g., lighting and monitoring systems). The experimental cabin is a rectangular structure (specification 3.0m×2.0m×2.0m), the cabin body is made of high-strength SUS304 stainless steel, and the left wall of the cabin body is embedded with a low-pressure, self-closing, and high-strength rectangular hatch. In order to facilitate observation and video during the experiment, an observation window is reserved on the front wall of the experimental cabin. The window glass adopts steel borosilicate glass, which has high bending strength and thermal stability. According to the structural strength and the tightness of the cabin, the designed working pressure of the cabin is between 10KPa and 101.6KPa, and the simulated altitude range is 0-14000m. In the test, the pressure changes in the cabin are stable and can reach the set pressure value.
2.3. Experimental Instrument Layout
The experiment simulates fires with different pressures of 40KPa, 60KPa, 80KPa, and 101KPa by using a small-sized test bench in the experimental cabin. The schematic diagram of the experimental cabin device layout is shown in figure 1 and the schematic diagram of the experimental bench layout is shown in figure 2. The sample (RPU) was placed on the bracket, a gypsum board with a thickness of 1 cm was placed under the sample, which is assumed to be an insulating surface and plays the role of protecting the equipment, and the balance was under the experimental platform. The quality changes during the experiment were recorded and the data is transmitted to the computer terminal. RPU’s size is 10 cm*50 cm*2 cm. The flame temperature at 0, 4, 8, 12, 20, 30, 40, and 50 cm was measured with thermocouple wire during the experiment (taking the ignition point as the origin). The flame state during the burning process of RPU was photographed by the camera, and the burning time was recorded at the same time, to calculate the fire spreading speed. Thermal radiation measuring instrument was placed on the same horizontal surface of the insulation material, 30 cm away from the burning material (RPU). Heat flow measuring instrument was also placed on the same horizontal surface, 65 cm away from the burning material (RPU) to collect heat radiation and heat flow. Measuring heat radiation, heat flow, and temperature, which were all transmitted to the computer terminal by the data line and collected in real-time for data analysis.

**Figure 1.** Schematic diagram of the experimental cabin device layout.

**Figure 2.** Schematic diagram of experimental bench layout.

2.4. Experimental Measurement Equipment
Electronic balance: The mass-loss rate of the RPU is derived from the electronic balance. The model of the experimental electronic balance is Shimadzu UW6200H. The main performance parameters: maximum range 6200g; accuracy 0.01g. Through the computer hardware serial port connection (RsCom) real-time collection and display of quality data.

Thermocouples: In this experiment, thermocouples were used to measure the flame temperature of RPU. There are 8 K-type thermocouples are used to form an array. Place them at 0, 4, 8, 12, 20, 30, 40, 50 cm respectively (take the ignition point as the origin). The layout of the thermocouple array throughout the experiment is shown in figures 3 and 4.

**Figure 3.** Layout of the thermocouple array.

2.5. Experiment Implementation
In this experiment, the RPU board was cut according to a square size of 50.0 cm in length, 10.0 cm in width, and 2.0 cm in thickness, and lines were drawn at 10, 20, 30, and 40 cm respectively. The experiment adopted comparative experiments and set four groups of working conditions as 40KPa, 60KPa, 80KPa, and 101KPa. There are three sets of repeated experiments are set for each group of working conditions. In the experiment, first, RPU was placed horizontally on the bracket outside, a picture was taken, and saved. Then it was sent to the balance in the experimental cabin, manually used a lighter to ignite a fire, and turned off all the lights. Data acquisition instruments such as cameras and...
computers were recorded in real-time. Refer to figures 1 and 2 for the relevant layout. After the combustion was over, saved the data of quality, temperature, heat radiant, flame burning. The toxic and harmful gases in the laboratory were pumped out through the pressure pump. Started the next set of experiments, a total of 12 sets of experimental conditions, as in table 1 followed.

![Figure 3. Thermocouple layout before combustion.](image1)

![Figure 4. Thermocouple layout after combustion.](image2)

**Table 1.** Experimental conditions of RPU under different pressures.

| Types of building exterior wall insulation materials | Pressure /KPa | Temperature /°C | Humidity /% | Insulation material size/cm³ | Experiment number | Fire spreading method |
|-----------------------------------------------------|---------------|-----------------|-------------|------------------------------|------------------|----------------------|
| RPU³                                                | 101           | 5               | 19          | 50.0 × 10.0 × 2.0            | NO.1-1           | Level                |
|                                                     | 101           | 5               | 19          |                              | NO.1-2           |                       |
|                                                     | 101           | 5               | 19          |                              | NO.1-3           |                       |
|                                                     | 80            | 4               | 24          | 50.0 × 10.0 × 2.0            | NO.2-1           | Level                |
|                                                     | 80            | 4               | 24          |                              | NO.2-2           |                       |
|                                                     | 80            | 4               | 24          |                              | NO.2-3           |                       |
|                                                     | 60            | 5               | 29          | 50.0 × 10.0 × 2.0            | NO.3-1           | Level                |
|                                                     | 60            | 5               | 29          |                              | NO.3-2           |                       |
|                                                     | 60            | 5               | 29          |                              | NO.3-3           |                       |
|                                                     | 40            | 4               | 30          | 50.0 × 10.0 × 2.0            | NO.4-1           | Level                |
|                                                     | 40            | 4               | 30          |                              | NO.4-2           |                       |
|                                                     | 40            | 4               | 30          |                              | NO.4-3           |                       |

Note: ³: The density is 0.0440 g·cm⁻³; the heat capacity is 1750-2350 kW·m⁻¹·K⁻¹; the thermal conductivity is 0.024 kJ·kg⁻¹·K⁻¹; the heat of combustion is 23.1 MJ·kg⁻¹.
3. Experimental Results and Analysis

3.1. Mass Loss Rate and Combustion Fire Spread Rate

The rate of mass loss not only reflects the rate of decrease in the quality of the insulation material but also reflects the size of the fire and the rate of fire spread to a certain extent. Under the condition that the external environmental conditions are the same, the combustion rate can be studied after the ignition of the steam fire, and the combustion rate can be represented by the mass-loss rate. Figures 5 and 6 depict the mass loss ($W$) of the RPU after burning under different pressures and the mass loss rate ($W'$) curve obtained. It can be seen from figures 5 and 6 that the quality of thermal insulation materials first slowly decreased, then rapidly decreased, and finally tended to a stable trend. This is due to the presence of a preheating zone when the RPU is burned. With the development of combustion, the fire gradually spread along the horizontal direction, and the burning rate of RPU was accelerated, which is also one of the important reasons for the accelerated mass loss. The mass loss under each group of working conditions was the same, all from 12 g to 4 g, but the time required was different. As the air pressure decreased, the relative slope of the mass time diagram became larger and larger, but because the mass burning was decreasing, and the slopes were all negative. Therefore, it showed that the quality changes more and more slowly. The mass change at 101KPa was the most dramatic, and the mass change was completed within 150 seconds; the average rate of mass change at 80KPa was slower than that at 101KPa, and it took about 220 seconds to complete the mass change; the average rate of mass change at 60KPa was slower than that of 80KPa, the mass change was completed in 250 seconds; the average rate of mass change under 40KPa was slower than that of 60KPa, and it took about 440 seconds to complete the mass change. At 101KPa, the burning time was shortened, and the degree of fluctuation was quite severe. The amplitude spanned nearly 0.9 g/s, and the upper limit was as high as 1.0 g/s. However, the situation was different when it reached 40KPa. The overall fluctuation reduced except for extreme fluctuations at individual moments. The amplitude of the rest was extremely small, basically less than 0.4 g/s. The peak of the main part was about 0.2 g/s. Excluding individual prominent moments, the main peak was about 0.4 g/s, and the lowest value was about 0.05 g/s. As a result, it can be concluded that as the external pressure decreased, the time required for burnout became longer and longer, the combustion rate became slower and slower, and the fluctuation of the mass loss rate became more stable, with little fluctuation.

![Figure 5](image1.png)  ![Figure 6](image2.png)

**Figure 5.** Quality loss: NO. 1, NO. 2, NO. 3, NO. 4. **Figure 6.** Quality change: NO. 1, NO. 2, NO. 3, NO. 4.

The mass loss of RPU is due to form a process in which volatiles are emitted, RPU decomposes flammable gas when heated, and forms a carbonized layer after being fired. As shown in figure 7, after
being ignited from one end of the RPU, this area is defined as the preheating zone of the RPU fire spreading process; then, as the combustion progresses, due to the convection, conduction, and radiation effects during the combustion process, this area is defined as the pyrolysis zone. The pyrolysis zone occupies a large area in the middle of the RPU. When the RPU is about to burn out, there is no pyrolysis fuel along the fire-spreading direction. This area is defined as the burnout zone of the RPU.

![Mechanism diagram of fire spread process of RPU.](image)

**Figure 7.** Mechanism diagram of fire spread process of RPU.

**Table 2.** The fire spread characteristics of RPU.

| Experiment number | Types of building exterior wall insulation materials | Environmental parameters | Burning fire spread rate/(cm/s) |
|-------------------|---------------------------------------------------|---------------------------|--------------------------------|
|                   |                                                   | Environmental pressure/s  | Temperature/℃ | Humidity/% | T₁-T₃ (8cm spacing) | T₄-T₇ (30cm spacing) |
| NO. 1-1           |                                                   | 101                       | 5              | 19         | 0.20                | 0.29                |
| NO. 1-2           |                                                   | 101                       | 5              | 19         | 0.23                | 0.32                |
| NO. 1-3           |                                                   | 101                       | 5              | 19         | 0.20                | 0.33                |
| NO. 2-1           |                                                   | 80                        | 4              | 24         | 0.19                | 0.35                |
| NO. 2-2           |                                                   | 80                        | 4              | 24         | 0.21                | 0.35                |
| NO. 2-3           |                                                   | 80                        | 4              | 24         | 0.19                | 0.30                |
| NO. 3-1           |                                                   | 60                        | 5              | 29         | 0.22                | 0.21                |
| NO. 3-2           |                                                   | 60                        | 5              | 29         | 0.22                | 0.22                |
| NO. 3-3           |                                                   | 60                        | 5              | 29         | 0.22                | 0.22                |
| NO. 4-1           |                                                   | 40                        | 4              | 31         | 0.11                | 0.13                |
| NO. 4-2           |                                                   | 40                        | 4              | 30         | 0.12                | 0.13                |
| NO. 4-3           |                                                   | 40                        | 4              | 31         | 0.12                | 0.13                |

Table 2 summarizes the T₁-T₃ (8cm spacing) burning fire spread rate and T₄-T₇ (30cm spacing) burning fire spread rate of the RPU building exterior wall insulation materials in the experiment. According to table 2, the fire spreading speed of T₁-T₃ is generally slower than that of T₄-T₇. This may be because the first half of the flame has just burned up and cannot spread well. As the flame spreads...
to the second half, the fire spreads and the speed had increased. This is because the fire spreading speed largely depends on the size of the heat radiation received by the burning material. As the combustion progressed, the surrounding temperature of the burning material and the heat radiation received had greatly increased compared with the initial stage. As a result, according to the combustion progressed, the spread of pyrolytic forwards was getting faster and faster.

3.2. Flame Temperature

Figure 8 depicts flame temperature changes with time under different ambient pressures. From the comparison of the temperature curves of each working condition, the pressure decreased, and the maximum temperature of each point rose. This is probably because the pressure decrease will cause the flame shape and as the height changes, the flame will decrease with the pressure, and the body size will increase, therefore, make it more fully in contact with the air, resulting in an increase in temperature. From the time required for each group of working conditions to reach the peak temperature, it is obvious that the time required to reach the peak was prolonged under the condition of reduced pressure, the curve was smoother. In the first half of the image, the distance between the thermocouples was too close, which was not obvious. The difference can be seen in the T₄-T₇ section where the distance between the thermocouples is 10 cm. The focus was on comparing 40KPa and 101KPa. The corresponding curve of 101KPa was steeper, and the zero-return time of the corresponding temperature curve of the T₇ thermocouple can also be seen when the gap is 101 KPa, which took to burn out was less than 300 s. At 40KPa, the T₇ thermoelectric return to zero had been extended to after 500s. Therefore, the low pressure increased the time that burned the same experimental material.

3.3. Heat Radiant

Figure 9 depicts RPU insulation material heat radiant. With the decrease of pressure, the peak value of thermal radiation has been significantly reduced. It can be seen on the curve that the curve of thermal radiation became sharp and steep. It can also be seen from the data that the heat was under 101KPa, the radiation peak was about 65 W/m², the thermal radiation peak at 80KPa was about 70 W/m², the thermal radiation peak at 60KPa was about 50 W/m², and the thermal radiation peak at 40KPa was about 30 W/m². As the pressure decreased, not only the peak value decreased, but the image also tended to be flat, and there were more fluctuations, especially at 40KPa and 60 KPa. The reason may be because the pressure decreased, the test material did not ignite. The decrease in pressure did not lead to the total amount of energy released by the combustion of the combustible. When the time spent on combustion was prolonged, it led to a decrease in the peak thermal radiation, but the area enclosed by the thermal radiation curve (the energy dissipated during the combustion process) and the horizontal axis time was constant, or the difference was extremely small. Due to insufficient combustion caused by the pressure drop, the energy was lost. Therefore, as the pressure decreased, the peak of the heat radiation curve of the combustion product decreased, but the combustion time was prolonged, the area enclosed by the heat radiation curve and the time axis remained the same.
(a) 101KPa: $T_0$-$T_3$, the ignition end is separated by 4cm in sequence.

(b) 101KPa: $T_4$-$T_7$, the end is separated by 10 cm in sequence.

(c) 80KPa: $T_0$-$T_3$, the ignition end is separated by 4cm in sequence.

(d) 80KPa: $T_4$-$T_7$, the end is separated by 10 cm in sequence.

(e) 60KPa: $T_0$-$T_3$, the ignition end is separated by 4cm in sequence.

(f) 60KPa: $T_4$-$T_7$, the end is separated by 10 cm in sequence.

(g) 40KPa: $T_0$-$T_3$, the ignition end is separated by 4cm in sequence.

(h) 40KPa: $T_4$-$T_7$, the end is separated by 10 cm in sequence.

**Figure 8.** Flame temperature changes with time under different pressures.
Figure 9. RPU insulation material heat radiant.

3.4. Flame Shape
Comparing the flame shapes at four different pressures in figure 10, it can be found that the flame height was similar at 101KPa, 80KPa, 60KPa, and it was slightly lower at 40KPa. The combustion of the flame required a sufficient supply of oxygen. When the pressure in the experiment chamber simulated high altitude conditions, a large amount of oxygen was also extracted. The decrease in oxygen concentration made the combustibles unable to obtain sufficient oxygen for combustion, which led to a decrease in the height of the flame. Therefore, as the flame height decreased at 40KPa, it may be because the oxygen concentration was too low, which made combustion difficult.

(a) 101KPa burning flame image.  (b) 80KPa burning flame image.
(c) 60KPa burning flame image.  (d) 40KPa burning flame image.

Figure 10. Flame shape at different pressure.

4. Conclusion
In this paper, an experimental cabin is carried out to study the combustion characteristics and fire spread behaviour of the RPU by burning and horizontally adhering to the wall under different pressures. The mass-loss rate, flame temperature, and heat radiant were measured and analysed. The main conclusions are as follows:

(1) After the RPU burned, the mass gradually decreased (the mass loss curve approximately obeyed the quadratic curve), until all became carbon black, which was similar to the general solid fuel combustion law.

(2) Carried out multiple repeated combustion experiments and obtained three stages of combustion temperature changes during the fire spreading process of building exterior wall insulation materials:
melting pyrolysis stage; stable combustion stage; extinguishing stage. Finally, RPU decomposes flammable gas when heated, and forms a carbonized layer after being fired.

(3) As the pressure decreased, the flame temperature rose slightly. As the pressure decreased, the burning time was prolonged and the fire spreading speed slowed down. As the pressure decreased, the peak value of the heat radiation curve decreased, and the curve tended to be flat, but the horizontal axis time increased, the total heat release remained unchanged. As the pressure decreased, the height of the flame also increased, and when it reached 40KPa, the flame height decreased due to the low oxygen concentration.

(4) Repeated experiments show that the mass loss did not change with pressure. Polyurethane can still burn completely at a low pressure of 40KPa, but the mass loss rate was greatly reduced, and the fluctuation of the mass change rate slowed down as the pressure decreased, and the rate of quality change was significantly reduced.

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