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The Mechanism of the Forming Foamy Reaction Layer Under the Combustion of the AFC

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***Abstract*— *The formation of a foamy reaction layer is a critical phenomenon in the combustion of Aerosol Forming Compositions (AFC), influencing both combustion dynamics and fire suppression efficiency. This study investigates the mechanisms driving foamy layer formation and its impact on combustion properties. The foamy reaction layer, a complex region characterized by gas bubbles embedded in a semi-liquid matrix, acts as a thermal insulator, regulates flame propagation, and enhances mechanical stability during combustion. Through experimental combustion tests and thermal imaging analysis, I examine the structural evolution, temperature profiles, and stability of the foamy layer. Findings reveal that the foamy layer modulates heat transfer and gas release, providing controlled combustion that can be crucial in pyrotechnics and fire suppression systems. This research would offer a deeper understanding of the foamy layer's role in combustion processes and highlight its potential for optimizing AFC formulations for safe and efficient fire management applications*.

***Keywords*— *Aerosol fire extinguishing agent, Foamy reaction layer, Combustion mechanism, Thermal stability, Fire suppression efficiency*.

I. Introduction of the Foamy Reaction Layer in the Combustion Process

Aerosol Forming Compositions (AFC) represent a class of pyrotechnic mixtures wherein most solid energetic materials (EM) undergo preheating in the combustion wave, often leading to the melting or softening of surface layers (for amorphous substances) [1]. Observations indicate that a liquid layer frequently covers the burning surface, where gasification reactions result in foaming, altering the effective concentration of substances in the reaction zone [2]. Additionally, the thermal conductivity of the solid substrate may vary due to gas bubble formation in the reaction layer, a phenomenon observed in several EM combustion processes [3].

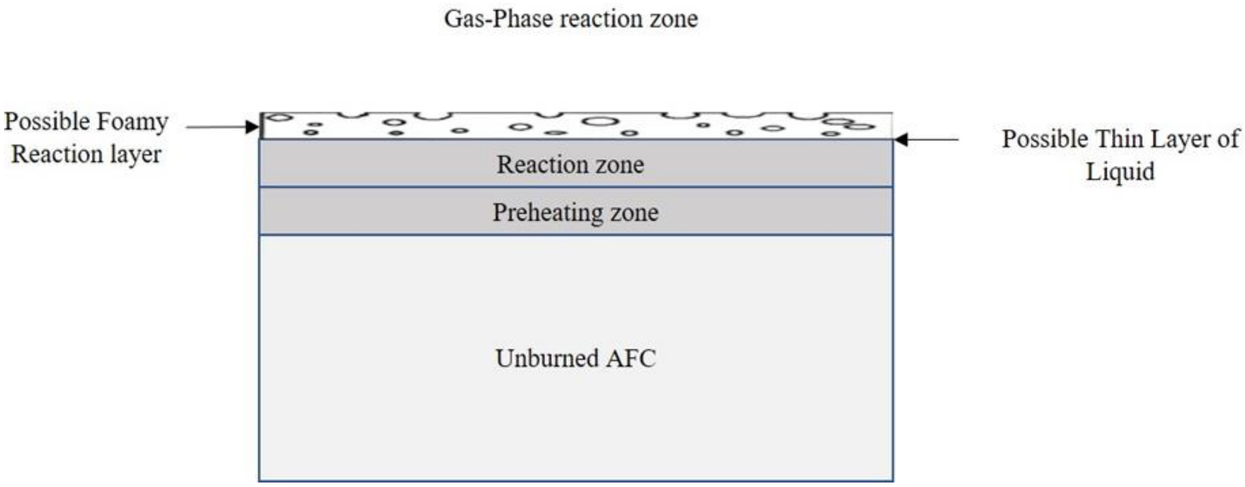

Fig.1 Diagram of the foamy reaction layer

The region of the Foamy Reaction Layer in the combustion: The foamy reaction layer, depicted in Fig.1, comprises a thin matrix of liquid and gas bubbles beneath the propellant surface. This complex region involves physicochemical processes, such as thermal decomposition, evaporation, bubble formation, and gas-phase reactions. The foamy layer is formed when the surface of a burning pyrotechnic material undergoes decomposition, resulting in gas bubbles that are trapped in the molten or semi-solid matrix. [4] These bubbles, containing gases like CO_2, H_2O vapor, and other volatiles, significantly impact the combustion properties of the material.

Foamy layer influence in combustion: The foamy reaction layer is structured as a matrix of gas bubbles within a semi-solid liquid film. Variations in bubble size and distribution are contingent on the material composition and combustion conditions, such as temperature, pressure, and additive presence [5].

Mechanisms of action:

(1) Thermal Insulation: The foamy reaction layer acts as a thermal barrier, moderating heat transfer to the underlying material, thereby stabilizing the combustion process and

preventing overheating.

(2) Flame Propagation: This layer influences flame dynamics across the material's surface, either retarding or enhancing flame spread, depending on its composition and properties.

(3) Gas Release: As the layer decomposes, gases are released that either sustain or retard the combustion, depending on their chemical nature and release rates.

(4) Mechanical Stability: The foamy layer maintains structural integrity within the decomposing material, supporting a controlled combustion rate and consistent process.

Importance in Combustion Processes: The foamy reaction layer plays a vital role in applications requiring controlled combustion, such as pyrotechnics, propellants, and industrial processes. Optimizing this layer's properties can lead to safer, more efficient combustion mechanisms. Studies focus on the impact of composition, environmental factors, and additives on this layer's characteristics [6].

The foamy reaction layer in combustion is a complex but crucial phenomenon that significantly impacts the efficiency and safety of burning processes. By acting as a thermal insulator, influencing flame propagation, controlling gas release, and maintaining mechanical stability, this layer ensures a controlled and efficient combustion process. Ongoing research aims to further understand and optimize this layer to improve combustion technologies in various applications.

II. EXPERIMENTAL STUDY ON THE FOAMY REACTION LAYER

The combustion test

AFC samples were mixed mechanically for 30 minutes and placed in a quartz tube (L = 5 cm, D = 10 mm) for testing. Ignition was achieved with a nitrocotton sliver in ambient air. A high-speed camera (FASTCAM Mini UX50) recorded the combustion process at 500 fps (exposure time: 1/460 s), as shown in Fig.1.1.

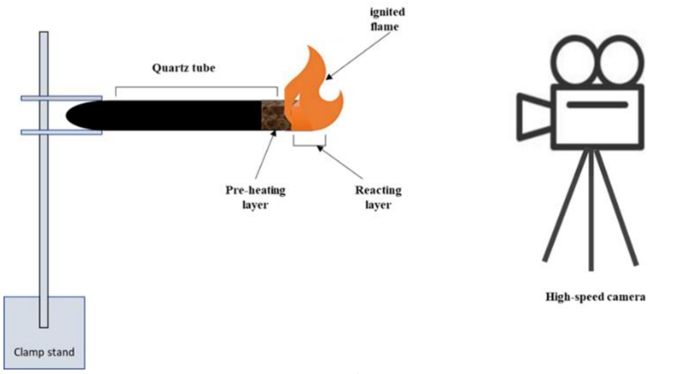

Fig 1.1 Schematic of combustion test

Observations and Discussion

The analysis of the high-speed camera footage provides a detailed visual progression of the combustion characteristics of the aerosol-forming composition (AFC). The experiment captured several key stages in the formation and behavior of the foamy reaction layer, which is essential for understanding the combustion dynamics of the AFC as presented in Fig 1.2.

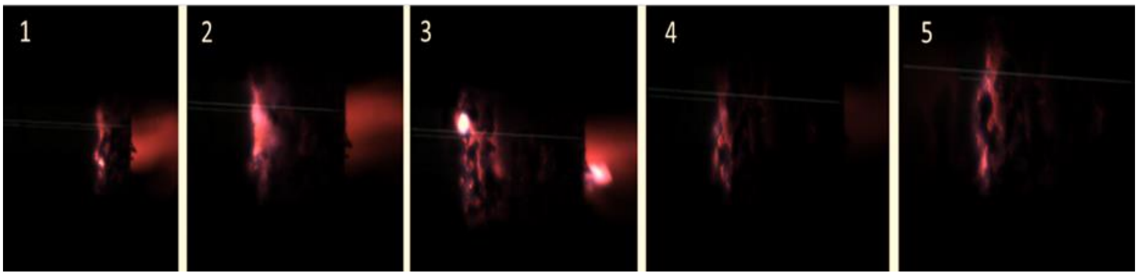

Fig 1.2 Thermal image for Foamy layer

The combustion process begins with the ignition of the AFC by a nitrocotton sliver in the first frame. The flame observed is small and concentrated, indicating the initial point of contact between the fuse and the AFC, thus highlighting the effectiveness of the ignition source. As the flame spreads, as shown in the second frame, a diffuse and expansive glow becomes visible. This marks the onset of foamy layer formation, suggesting rapid decomposition of the AFC and subsequent gas release. The appearance of the glow signals an increase in temperature and the start of exothermic reactions within the material.

In the third frame, there is a noticeable expansion in the volume of the foamy reaction layer. The texture of the combustion products becomes voluminous and cloud-like, indicative of a mature foam structure. This expansion likely results from gases being liberated and trapped within the viscous molten material of the AFC, forming a stable and structured foam.

By the fourth frame, the foamy layer reaches a phase of stability, maintaining its structural integrity and size. This stability suggests an equilibrium between the rate of gas generation and atmospheric pressure, which helps maintain the foam's structure. Changes in luminosity and color within this frame indicate ongoing chemical reactions and cooling processes within the foam. The final frame shows the commencement of the dissipation phase, with a slight thinning of the foamy layer. This thin layer could result from a reduction in gas production as the AFC material is consumed.

The sequential analysis of these frames underscores the dynamic nature of the AFC's combustion process, particularly highlighting the efficient formation and stability of the foamy reaction layer. This layer plays a crucial role in influencing the burn rate and temperature regulation during combustion. These insights not only enhance our understanding of AFC behavior

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under fire conditions but also could help in optimizing compositions for specific applications, particularly in scenarios that require controlled burn rates and temperature management.

III. Study on the Formation Mechanism of the Foamy Reaction Layer

Method of thermal imaging and temperature profile

The AFCs with mass ratios of 65:15:15:5 were chosen for the experimental study. mass ratios were mixed in a mechanical mixer for 30 min before testing. The AFC loose powders were placed in a cylindrical cast iron container (d ¼ 2 cm, h ¼ 2.5 cm) and ignited by a nitrocotton in the air environment. The mass of the sample in the test was 3.0 g. The flame was observed at an infrared thermal imager (ImageIR 8355, VarioCAM HD head type, spectral response range 3.5~5μm).

Temperature data analysis

Fig 2.1 is a thermal representation showing the flame and indicating the presence of a foam layer at multiple points. The thermal image uses a color scale to represent temperature variations, with yellow and red indicating higher temperatures and blue and green indicating lower temperatures. The foamy layer is observed, suggesting a significant presence during the combustion process. Fig 2.2 presents graphs that depict the temperature changes over time for two distinct points labeled A and B. At point A, represented by the red line, the temperature rises rapidly, peaking at around 500°C within approximately one second. Following this peak, there's a sharp decline in temperature, which stabilizes at around 100°C after roughly two seconds. In contrast, point B, represented by the black line, shows a similar rapid temperature increase, peaking just below 500°C. However, the decline in temperature at point B is more gradual, remaining above 200°C even after seven seconds.

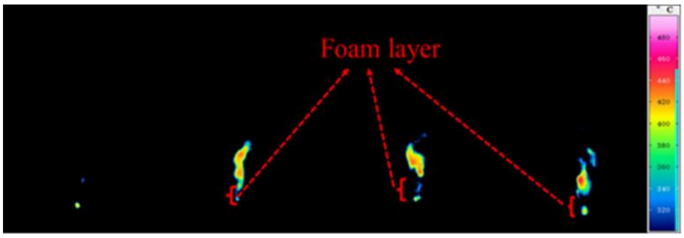

Fig 2.1 Thermal image for Foamy layer

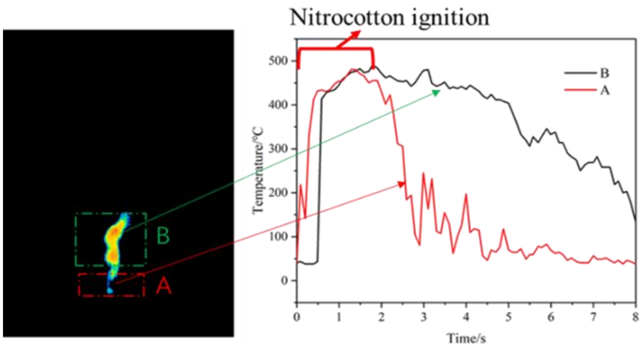

Fig 2.2 Temperature vs. Time Graph and Corresponding Thermal Image

Comparison and Implications

The comparison of the temperature profiles for points A and B reveals distinct differences in their thermal behaviors during the combustion process. Point A exhibits a rapid temperature rise, peaking at approximately 500°C within the first second, followed by a sharp decline, stabilizing around 100°C after about two seconds. Conversely, Point B shows a similar initial temperature peak but decreases more gradually, remaining above 200°C even after seven seconds. This suggests that point A experiences quicker heat release and dissipation, while point B retains heat longer. The thermal image further supports these observations by highlighting the presence of a foam layer at various points, which could contribute to localized heat retention and distribution.

Mechanism based on detailed temperature observations

At the point of ignition and initial reaction, temperatures soar to 480°C, driving the decomposition of the aerosol-forming composition (AFC) and rapidly releasing gases. This initial heat and gas release phase is critical as it sets the stage for the subsequent combustion dynamics. As these gases might be trapped and the foam expands, the reaction zone's temperature begins to stabilize. The varying temperatures observed across points A and B indicate how the foam's insulating properties modulate the combustion process. The foam expansion plays a key role in maintaining these temperatures, providing a buffer that influences how heat is distributed and managed within the reaction zone. The cooler temperatures and more gradual changes observed at Point B suggest that the foam's structure might act to sustain the combustion process more evenly. By regulating the release of gases and maintaining a steady heat output, the foam helps ensure a more controlled and sustained combustion. This thermal stability is essential for applications where a consistent and prolonged heat source is required, demonstrating the foam's significant impact on the overall combustion dynamics.

IV. Discussion of Foamy Reaction Layer Effects

Thermal Insulation: The foamy layer's significant thermal insulation property is crucial for maintaining high temperatures within the reaction zone, vital for achieving complete combustion. Thermal imaging has shown areas covered by the foamy layer to retain heat effectively, underscoring the layer's role in trapping heat.

Physical Barrier: The layer serves as a physical barrier that slows the rate at which oxygen reaches the combustible material, controlling the combustion rate and allowing for a more stable reaction.

Chemical Stability: Chemically, the foamy layer interacts with free radicals and other reactive species produced during combustion, reducing the overall reaction rate and contributing to a more stable combustion environment.

Temperature Regulation: The foamy layer regulates temperature across the combustion zone, mitigating sharp temperature spikes and enhancing the safety and efficiency of the combustion process.

Enhanced Burn Time: The insulating and chemical properties of the foam extend the duration of the burn, crucial for ensuring complete combustion, especially in industrial applications where controlled reaction rates are necessary.

The experimental findings clearly demonstrate the

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multifaceted role of the foamy reaction layer in enhancing combustion stability. Acting as a thermal insulator, physical barrier, chemical stabilizer, and temperature regulator, the foamy layer is instrumental in optimizing the combustion process of aerosol fire extinguishing agents. This research provides a solid foundation for future studies aimed at further improving and optimizing the performance of fire extinguishing systems.

V. Conclusion

The formation of a foamy reaction layer during the combustion of Aerosol Forming Compositions (AFC) plays a pivotal role in influencing combustion behavior, thermal stability, and efficiency. This study has demonstrated that the foamy layer, which forms as a dynamic matrix of gas bubbles within a semi-solid structure, serves multiple functions critical to controlled combustion processes. Acting as a thermal insulator, the foamy layer moderates heat transfer, protecting underlying materials from excessive temperature increases and thereby stabilizing the combustion process. Additionally, the layer functions as a physical barrier, reducing the rate at which oxygen reaches the reaction zone, which supports a more sustained and controlled combustion rate.

Thermal imaging and temperature profiling in this study revealed the complex thermal behaviors within the foamy layer, with localized variations in temperature profiles at different points on the AFC surface. These variations underscore the layer's insulating properties, allowing heat retention in specific zones while regulating overall temperature. Furthermore, the foamy layer's interactions with reactive species generated during combustion add a layer of chemical stability, contributing to a steady burn rate and preventing erratic combustion, which is critical in applications requiring precise control over reaction dynamics.

The multifunctional properties of the foamy reaction layer—its roles as a thermal insulator, flame propagation moderator, and chemical stabilizer—highlight its potential for enhancing the safety and efficiency of AFC-based fire suppression and pyrotechnic applications. This research provides a foundational understanding of the foamy layer's influence on combustion, opening avenues for optimizing AFC formulations. Future work should focus on refining material compositions and environmental conditions to maximize the desirable effects of the foamy reaction layer, aiming to improve the performance of AFC systems in fire management and controlled combustion applications.

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