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Combustion Process of Fog Aerosol and Its Influence on Condensation Nucleus Growth Behavior

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Abstract: By using of high-speed photograph techniques, thermogravimetric analysis (TG), differential thermal analysis (DTA) and scanning electron microscope (SEM), the combustion process of fog aerosol and formation of condensation nucleus were investigated. Results show that the high temperature and pressure air mass with a large amount of high temperature condensation nucleus is produced after the combustion of fog aerosol, and the temperature and pressure decrease rapidly with the air mass ascending. The particle size distribution of condensation nucleus is 0.2 – 1 μm and its main component is NaCl. The growing process of condensation nucleus and the forming of fog droplet are related with the supersaturation produced by the cooling and expanding of the air mass.

Key words: military chemistry and pyrotechnics; fog aerosol; combustion; thermal analysis; condensation nucleus

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1 Introduction

Many investigations show that almost all systems operating in the visible and infrared bands of the spectrum are subject to a severe performance degradation when they are used in fog[1-6]. The diffusion performance of fog in air has caused much attention[7-9]. Thus it is necessary to find out the influence of fog on photoelectric sensors, and produce new research methods and experiment conditions for cloud physics study by artificial method so as to control the environment of fog and cloud[10].

The fact that the combustion of fog aerosol and forming of condensation nucleus take place instantly and the temperature and pressure of reaction product change continually which brings trouble to the research of artificial fog. Zhu[11], Chen[12], Chen[13] et al have done much work on the rule of the flow ability of smoke cloud using the model of boundary layer and atmospheric dispersion model. However, it can not be appropriate to explain the physics process of artificial fog. In this paper, by means of photos of the combustion of fog aerosol, its thermal decomposition behavior with TG and DTA techniques, and the condensation nucleus with SEM, combustion process of the fog aerosol and forming process of condensation nucleus were studied by combining the experimental and simulation results.

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2 Experimental

2.1 Materials and instrument

Accoding to reference [14], the aerosol was prepared with perchlotate as oxidant, bond, hygroscopic catalyzer and additive.

High-speed photographs were taken using a Photron Fastcam-ultima camera with a screen velocity of 250 fps. Scanning electron microscope (SEM) images of the condensation nucleus were obtained on a Hitachi S-4800 microscope. Thermogravimetric analysis (TG) and differential thermal analysis (DTA) data were taken with a Shanghai CDR-34P thermoanalyzer with a heating rate of 10 ℃ · min^{-1} in air with the flux of 80 mL · min^{-1}.

2.2 Experimental

The fog aerosol was pressed into rod with a diameter of 20 mm and a height of 20 mm at 5 MPa. The experiments were done in smoke chamber with the volume of 33 m^3 (5 m × 2 m × 3.3 m). Fig. 1 gives the schematic diagram of experimental set-up. The hygroscopic catalyze was transformed into condensation nucleus with feat granularity and dispersion by the combustion of fog aerosol. Then water vapor coagulated on the condensation nucleus and fog droplets come into being.

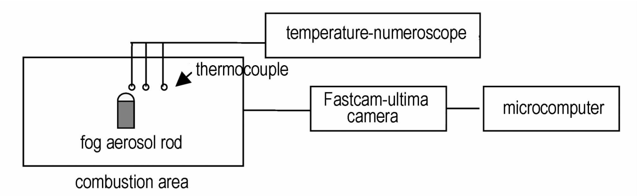


Fig. 1　Schematic diagram of experimental set-up

3　Results and discussion

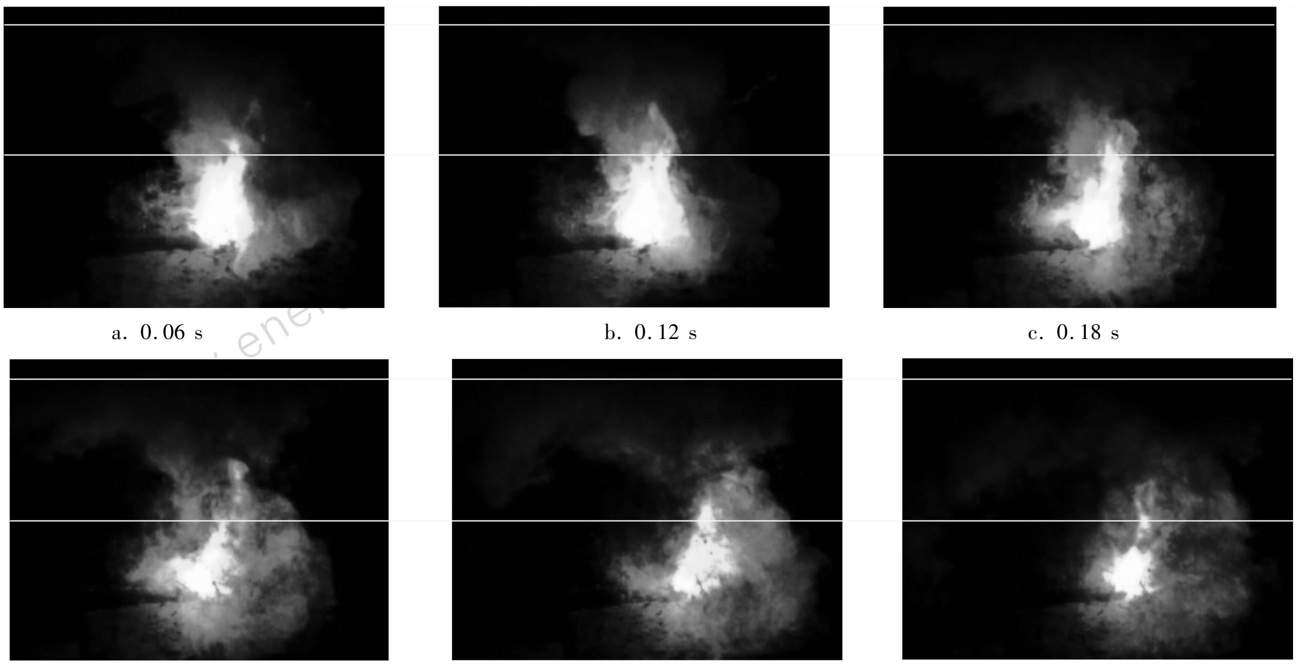
3.1　Analysis of combustion process

With Fastcam-ultima camera, change of hot air mass after combustion was observed clearly. Fig. 2 gives photos of the diffusion of hot air mass produced by combustion. We changed the background of the image to almost black in order to make flame and hot air mass more distinct. The change of air mass is especially shown in the pane. At the beginning, the air mass diffuses around freely with high velocity. Then as a result, the difference of the temperature and pressure of air mass with atmosphere the movement of hot air mass changes instantly.

From Fig. 2, it is seen the shape of air mass distorts in the ascending process of hot air. At last the anabatic air mass looks like mushroom cloud and mixes with outer air gradually. The distortion of air mass may be attributed to air resistance, energy exchange and liquid diffusion[12].

The change of the temperature of flame and around area was tested by thermocouple. Fig. 3 gives the curves of firebox temperature in the place of 0.2 m, 0.4 m and 0.6 m away from the center of combustion area. The temperature of the place of 0.2 m from the combustion center is the highest and steadily exceeds 1300 ℃ after instantly rising. The temperature of the place of 0.4 m from the combustion center is about 1300 ℃. The temperature of the place of 0.6 m from the combustion center is the much lower than the former two places and fluctuates in the range of 80 ℃ to 400 ℃. Therefore, the combustion area is an extreme special microenvironment with high temperature flame, hot airflow and hot condensation nucleus. In this microenvironment, the temperature decreases quickly as the firebox place become far away from the center of the combustion area.

In the process of combustion, it is difficult to measure the changes of temperature and pressure because of the continue diffusion and distortion of the air mass. So its changing process was studied by using the hydrodynamics theory and the Navier-Stoks equation and some valuable results were obtained. Fig. 4 gives curves of air mass temperature vs different distance away from the center of combustion area. It is evident that the temperature of the air mass has decreased to room temperature within 1 s.



a. 0.06 s　b. 0.12 s　c. 0.18 s

d. 0.24 s　e. 0.30 s　f. 0.36 s

Fig. 2　Diffusion processes of hot air mass produced by combustion of fog aerosol

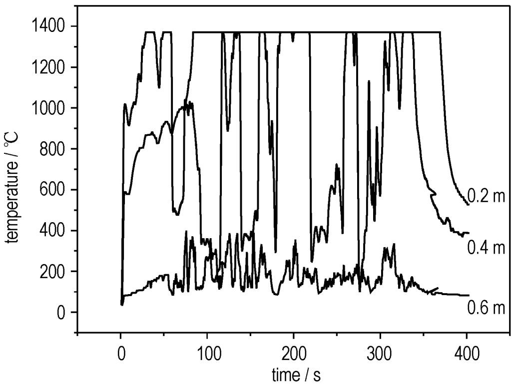


Fig. 3 Curves of firebox temperature in different place

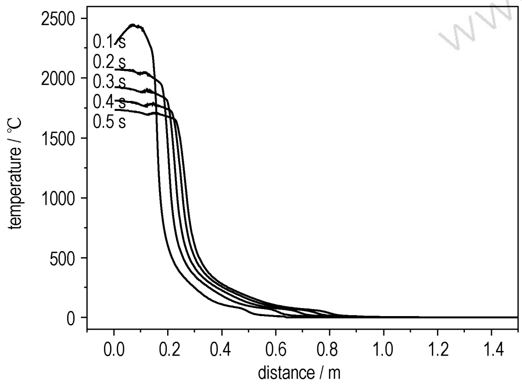


Fig. 4 Comparison of curves of air mass temperature vs distance

Fig. 5 gives the curves of pressure vs time at different distances away from the center of combustion area. The pressure of hot air mass increases to as high as 107 MPa in less than 0.1 ms and decreases to 1 MPa in 3 ms. Fig. 6 gives the curves of pressure vs distance at different time. The pressure of air mass diminishes rapidly as the distance increases. The pressure at the place of 0.6 m away from the center point is nearly 60 MPa within 0.1 s, while the pressure of the place of 1.2 m away from the center point is nearly 1 MPa within 0.5 s.

The hot air mass is produced after the combustion of fog aerosol and contains a large amount of high temperature condensation nucleus. Based on the above the results it is approximately understood the change and diffusion of the temperature and pressure of the hot air mass. The original pressure of air mass is much bigger than 1 MPa and the temperature is higher than 1000 ℃. In the ascending and diffusing process of air mass, the high original pressure drives the air mass expand and exchange heat energy with the environment. Then the temperature and pressure of the air mass begin to fall off, and the air mass completely mixes with the environment gradually.

The hot air mass produced after the combustion of fog aerosol can be regarded as a microenvironment where temperature and pressure change instantly. This microenvironment offers special condition for the condensation nucleus which can accelerate the growing velocity of fog droplet and affect the performances of fog.

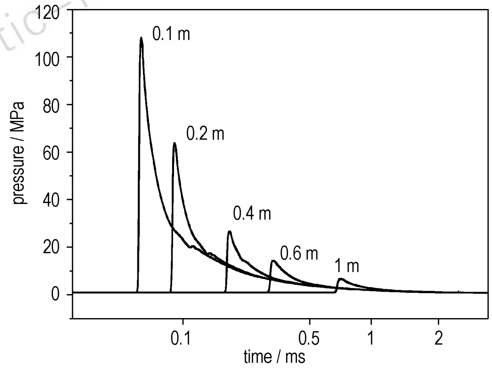


Fig. 5 Curves of pressure vs time in different place

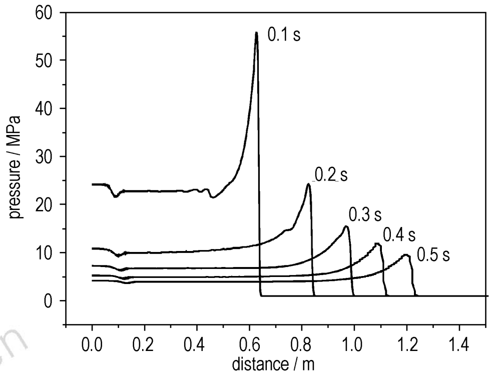


Fig. 6 Curves of pressure vs distance at different time

3.2 Thermal analysis

Fig. 7 shows the TG and DTA curves of fog aerosol at a heating rate of 10 ℃ · min^{-1}. In the thermal decomposition process two exothermic peaks and two endothermic peaks appear. The weight loss occurs from the temperature of 50 ℃ due to the decomposition of the organic component. The first exothermic peak at 436.4 ℃ and the second exothermic one at 488.1 ℃ are assigned to the decomposition of the oxidant and bond of the fog aerosol. The TG curve shows two major weight losses and the first one is 55.8% loss in the temperature range of 50 – 488.1 ℃. This reveals that oxidant and bond have decomposed and the majority of fog aerosol have transformed into CO_2, H_2O and O_2 gas. The first endothermic decomposition peak at 791.1 ℃ and the second endothermic decomposition one at 988.8 ℃ without evident weightlessness are assigned to the melting of NaCl according to the description of the fog aerosol (The melting point of NaCl is 801 ℃). The weight loss of 41.7% in the range of 490 – 988 ℃ which is in good agreement with the proportion of NaCl in the description indicates that NaCl component melts entirely and volatilizes under the temperature of 1000 ℃.

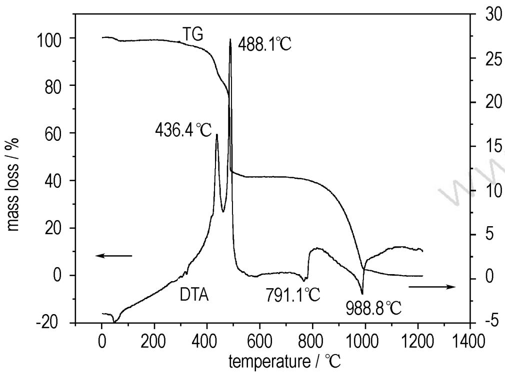


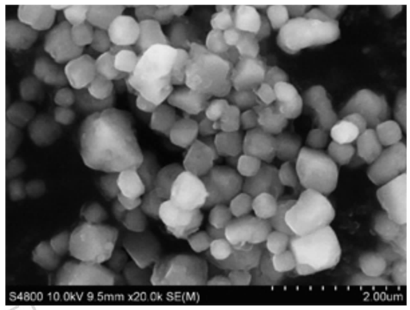
Fig. 7　TG-DTA curves of fog aerosol ($\beta = 10$ ℃ × min^{-1})

3.3　Characterization of condensation nucleus

Fig. 8 gives the SEM image and energy spectrum to make sure the component and surface morphology of the condensation nucleus. The morphology of the condensation nucleus is nearly spherical exclude some big cubic ones. The size distribution range is 0.1 – 2 μm. Most nucleus are in even size and good dispersed phase including a few parts agglomerate. The energy spectrum indicates the condensation nucleus mainly contains three elements: Na, Cl and O. Consequently it is approved fog condensation nucleus is mainly composed of NaCl. The result is consistent with the former results from thermal analysis and the description of fog aerosol.

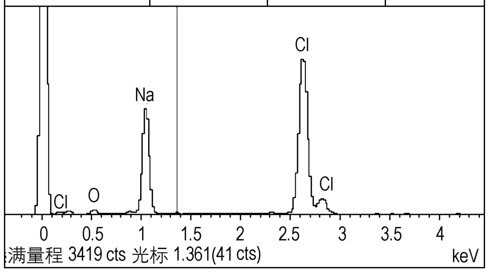
3.4　Influence of combustion on the condensation nucleus

Based on the experiment results it is indicated that the hot air mass produced after combustion of fog aerosol is mixture of high temperature condensation nucleus and manifold gas including high temperature water vapor. Because the pressure and temperature of the air mass are much different from atmosphere it can be seen as a micro-environment isolated from out air instantaneously. In the process of mixing with atmosphere the hot air mass expands and does work. The temperature and pressure of the air mass decreases instantly and its relatively humidity changes deeply.



a. SEM image

element	O	Na	Cl
wt%	6.01	29.62	64.37



b. energy spetrum

Fig. 8　SEM image (a) and energy spectrum (b) of condensation nucleus

It is calculated from the description of the fog aerosol that the air mass produced by combustion of 1000 g of fog aerosol brings out 8.84 mol CO_2, 4.08 mol H_2O and 2.5 mol O_2. Supposed the origin condition of the air mass is: the temperature is 1400 ℃, and the pressure is 107 MPa, and volume is 1.80×10^{-2} m^3. According to the ideal gas equation: $PV = nRT$, the final condition is obtained as: the temperature of 20 ℃, the pressure of 1 MPa, and its volume of 3.76×10^{-1} m^3. The water vapor density (humidity) α_t is 195.32 g · m^{-3}, while the saturation water vapor density (α_0) of 20 ℃ is 17.32 g · m^{-3}, so α_0 is much more bigger than α_t. After expanding and cooling in a second the air mass is super saturation and the super saturation degree is more than 1000%. Based on the Köhler equation[15], the condensation nucleus could be active and begin to condense water vapor in supersaturation and grows up to fog droplet. The artificial fog is composed of condensation nucleus and water vapor from air. The super saturation of air mass offers a very avail condition for the condensation nucleus and dominates the forming process of fog droplet.

4　Conclusions

The experiment results and theory calculated results indicate the hot air mass produced by combustion of fog aerosol is mixture of high temperature condensation nucleus and manifold gas which can be seen as a microenvironment with extreme special condition. The instantly change of the temperature and pressure of the anabatic air mass in the process of expanding and cooling produce super saturation condition. The TG, DTA and SEM results show that the condensation nucleus is composed of NaCl with the size distribution range of 0.2 - 1 μm. The microenvironment supplies supersaturation condition and strong impetus for the growth behavior of the fog condensation nucleus and the forming of artificial fog.

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造雾剂燃烧过程研究及其对凝结核生长行为的影响

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摘要： 通过高速摄影技术拍摄造雾剂燃烧过程、利用热失重法（TG）、差示扫描量热法（DTA）、扫描电子显微镜（SEM）技术分析造雾剂的燃烧过程及其对凝结核生长行为的影响。测试结果和理论计算结果表明，造雾剂燃烧后生成携带高温凝结核的热气团，热气团上升过程中其内部温度和压力迅速下降。TG、DTA 和 SEM 分析表明，造雾剂燃烧反应后产生的凝结核主要组分为 NaCl，粒度分布范围为 0.2 ~ 1 μm。热气团在膨胀冷却过程中温度和压力瞬间变化而造成的巨大的过饱和度对凝结核的生长过程起到关键作用。

关键词： 军事化学与烟火技术；造雾剂；燃烧；热分析；凝结核

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