Experimental study on acoustic condensation fog elimination in traveling wave tube

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Abstract. Acoustic condensation artificial fog elimination has the advantages of wide application range, good economy, flexible and controllable operation area, and does not affect traffic operation. The characteristics of the fog, the frequency and intensity of the acting sound waves have an important influence on the effect of condensation and fog elimination. This paper studies the influence of the frequency of fog on the microscopic particle size distribution and the change of light transmission in the process of fog elimination from both theoretical and experimental aspects. The research results show that for natural fog conditions with low concentration, the time of pure sound wave action takes several minutes to tens of minutes. Under the condition of high-concentration artificial fog, the anti-fog time can be shortened to tens of seconds. Simulations and experiments have both confirmed that sound waves can significantly promote fog elimination, and there is an optimal frequency between 200Hz-700Hz.

1. Introduction

Fog, as a weather phenomenon that can significantly reduce visibility, is very harmful in the daily life. The normal and safe operations of civil aviation, highways and shipping have all caused large economic losses due to the impact of heavy fog. The ideal artificial fog elimination method should meet the requirements of operation effect, economy and timeliness. Traditional methods such as spreading catalyst, air disturbance method and local heating method are greatly affected by environmental weather, topographical conditions, and fog structure. There are limitations in warm fog elimination, such as unstable effect and high cost.

Acoustic artificial fog elimination uses the principle of polydisperse aerosol acoustic wave agglomeration. Low-frequency strong sound waves interact with the polydisperse particles in the fog, causing relative movement between the droplets and colliding and condensing, forming larger droplets and settling, triggering gravity collision and further settling during the descending process, and finally changing the microscopic characteristics of the fog, reducing the water content, thereby improving atmospheric visibility. Acoustic agglomeration and fog elimination is a new non-contact physical operation method. It uses the natural settlement of fog droplets to reduce energy consumption. In theory, it has controllable operation effect, is not affected by the type of fog, does not affect the transportation system, and can flexibly change the operation region through sound field control.

In recent years, research on acoustic agglomeration has mainly focused on environmental protection applications [1] [2] [3], focusing on the analysis of the orthokinetic interaction of micron/submicron
particles. It is generally believed that the agglomeration effect is affected by the characteristics of aerosols and acoustic parameters. A higher initial concentration and higher sound intensity are beneficial to improve the collision efficiency of particles; the agglomeration efficiency is related to frequency, and the optimal frequency decreases with the increase of particle size. There are few studies on the agglomeration mechanism and law of cloud particles with larger sizes. Mr. Wei Rongjue et al. [4] studied the dissipating process of water mist with frequencies of 500 to 2400 Hz, sound pressure levels of 90 to 127 dB in traveling wave fields and standing wave fields, and obtained the best frequency of 1500 Hz and the threshold of sound pressure level of 100 dB. Xi Baoshu et al. [5] used fluid sound and obtain higher sound intensity sound wave conditions, examined the defogging time of low-frequency sound waves below 50 Hz in the fog chamber and the change of the fog drop spectrum, and carried out outdoor experiments in Huangshan Scenic Area. Experiments show that sound waves have a significant effect on the dissipation of water mist, and lower frequencies and higher sound intensity are more conducive to mist elimination.

The practical application of acoustic anti-fog requires attention to the frequency and the concentration of fog. On the one hand, the low-frequency sound wave radiation efficiency is low, and the design of the mist elimination device is closely related to the operating frequency. The different conclusions about the optimal frequency in different studies may come from the difference in the microscopic characteristics of the fog and the experiment environment. On the other hand, the particle number concentration of natural fog is relatively low, and the maximum density of dense fog is generally within 1000/cm³. According to the general reunion law, to achieve the ideal elimination effect, a relatively high sound intensity of 130 to 140 dB and a long action time of several minutes to ten minutes are required.

In order to clarify the required action parameters under the natural fog environment, analyze and improve the performance of agglomeration and fog elimination under the limit of the existing acoustic wave generation systems, this paper considers the main agglomeration mechanisms such as orthokinetic interaction and mutual radiation, based on the widely used sectional method to solve the particle dynamic equation of polydisperse droplets, a numerical simulation model for agglomeration and fog elimination is established, and a large dynamic range experimental system is built based on the low-frequency fluid sound and ultrasonic atomization device. The results of agglomeration under different working conditions (including natural fog conditions) are compared.

2. Theoretical basis of acoustic condensation

The condensation simulation model based on sectional method [2] has the advantages of high calculation efficiency and good stability. The droplets are partitioned according to volume or particle size, and the discrete aerosol dynamic equation is solved by numerical methods. Knowing the sound wave frequency, sound pressure level, particle density, aerosol initial concentration and particle size distribution, number of partitions, etc., obtain the time evolution of fog particle size distribution under specific acoustic wave action and relevant statistical results.

The acoustic agglomeration process of fog can be described by the discrete Smoluchowski equation [3]:

\[
\frac{dn_i}{dt} = -\frac{1}{2} \sum_{j \neq i} K_{ij} n_i n_j - \sum_{j \neq i} K_{ij} n_i n_j
\]

(1)

Where \( n \) represents the number density of fog particles in the regions \( i, j, \) and \( k \), and \( K \) is the agglomeration kernel function, which is defined as the number of agglomeration collisions between two particles in a unit volume and unit particle number density within a unit time. The agglomeration kernel function between \( i \) and \( j \) can be expressed as:

\[
K_{ij} = \frac{dN}{n_i n_j dt}
\]

(2)

In the formula, \( N \) is the number of collisions; \( n_i \) and \( n_j \) are the number densities of particles \( i \) and \( j \), respectively.
Orthokinetic interaction and hydrodynamic interaction are the two major mechanisms of acoustic agglomeration of polydisperse aerosols. The mechanism of the orthokinetic interaction means that the droplets in the fluid medium are entrained by sound waves, and the droplet oscillation speed lags behind the sound wave vibration speed. The droplets of different sizes collide with each other due to the difference in movement speed, which is proportional to the particle speed of the sound field. Hydrodynamic interactions include mutual radiation and acoustic wave effects. Mutual radiation effect means that when the particle's center line is perpendicular to the direction of the incident sound wave, when the medium disturbed by the sound wave passes through the area between the droplets, the relative flow area becomes smaller and the flow speed increases, so that the area between suspended droplet forms a low pressure zone and attracts particles to each other.

The size of natural fog droplets is on the order of micron to ten microns. Only the mechanism of orthokinetic interaction and mutual radiation is considered. The kernel function of orthokinetic interaction agglomeration and mutual radiation are expressed as:

$$K_{ij}^\text{Or} = \frac{1}{2}U_a \left(d_i+d_j\right)^2 \frac{\omega \left[r - r_d\right]}{\sqrt{1+(\omega r_d)^2}} + \frac{\sqrt{3}D_0^2 d_i d_j (d_i + d_j)^2}{1152 \pi \mu r^4} g_{ij}$$

Among them, $U_a$ is the vibration velocity amplitude of the particle in the sound field, $d$ is the particle diameter, $\omega$ is the sound wave angular frequency, $\tau$ is the relaxation time related to the particle density and diameter; $g_{ij}$ is the interaction force function, $u$ is the radial component of the velocity, $H$ is the step function, $r$ is the distance between the droplets, and $\theta$ is the angle between the connection line between the droplets and the velocity of the particles in the sound field.

3. Equipment and system for acoustic condensation
In order to meet the experimental requirements of acoustic wave condensation and fog elimination, we independently designed and built an acoustic wave condensation experiment system with sound field testing and condensation and fog elimination functions, providing a good infrastructure for later research, as shown in the fig 1.

The experimental system consists of a sound system, a sound field measurement system, and a fog elimination test system. The sound system is composed of an air compressor, a siren, and a siren controller; the sound field measurement system is composed of a multi-channel B&K 4941 microphone, a 3050 noise analyzer and a data analysis and processing computer; the fog elimination test system includes a droplet spectrometer, ultrasonic atomizer, thermometer and hygrometer.

![Figure 1. The composition of the fluid sound and fog elimination experimental system](image)

The traveling wave tube acoustic wave condensing chamber is composed of a coupling chamber with thickness of 0.01m and square cross-section, a condensing chamber in series, as shown in Figure 2. The cross section of the coupling chamber is 0.825m and the length is 2m. The cross section length of the condensate chamber is 0.825m, and it is composed of two sections of cabins with an axial length of 3m in series. At the end of the last section of the cabin, a sound-absorbing sponge is installed to absorb sound waves and eliminate sound reflections to create a traveling wave environment that conforms to natural conditions. An air-sound separation device is installed between the coupling cabin and the
agglomeration cabin, which is composed of a perforated plate and oxford cloth to block the compressed air flow of the air compressor from entering the aerosol cabin to dilute the aerosol and reduce the interaction between aerosols and sound waves. The duration of action affects the results of the experiment. The air flow blocked by the partition is exhausted from the exhaust port near the end of the siren. At the same time, one end of the coupling cabin is connected with the horn array, so that the entire standing wave tube is driven by the sound source array, so that the sound field below 1.7kHz can be generated in the condensing cabin. Both sides of the two condensing cabins are equipped with transparent organic glass window, which can observe the macroscopic effect of the sound wave condensation of the fog droplets in the condensing cabin, and set up the light source-illuminance test system through the transparent glass windows on both sides to obtain the sound wave fog elimination quantitative data.

**Figure 2.** Acoustic condensate chamber

4. Experimental results and analysis

4.1. Sound field test results and analysis

The frequency spectrum obtained by changing the rotating speed of the siren is shown in Figure 3~6. When the number of siren holes is 50, the rotating speed is basically equal to the frequency, and the unit difference between the rotating speed (r/s) and the frequency (Hz) is 4, which is very stable. When connecting an air compressor, keep the valve fully open, and the sound pressure level is stable at 140dB with an error of ±4dB. It can be considered that the sound pressure level is only related to the state of the air compressor and the number of serial connections, and is not affected by the state of the siren. In the acoustic signal spectrum results, there are significant fundamental frequency and harmonic components. The harmonics come from the fluid sound transduction process and the nonlinearity of close-range strong sound propagation. Among them, the sound wave energy is mainly concentrated in the fundamental frequency, and the fundamental frequency’s sound pressure level is 10 to 30dB higher than the harmonics, which is beneficial to enhance the condensation effect.

**Figure 3.** The frequency spectrum (a) the siren rotating speed 300/s. (b) the siren rotating speed 400/s. (c) the siren rotating speed 500/s. (d) the siren rotating speed 600/s.
Figure 7 shows the relationship between sound pressure level and frequency response in the cabin. It can be seen that there is a nonlinear relationship between sound pressure level and frequency, and the maximum fundamental sound pressure level is at 80 Hz. The frequency response results of the sound pressure level in the cabin show a certain degree of volatility, and the sound pressure level of the measurement point corresponding to different frequencies is quite different. Because the air-acoustic separation structure has a certain amount of sound insulation, most frequencies correspond to the fundamental frequency sound pressure level below 140dB. The reflection and superposition of the incident wave and the sound waves on each indoor wall cause the indoor sound field distribution to be more complicated. Moreover, there are ventilation holes in the lower part of the condensed cabin to facilitate fog filling, which makes the sound waves leak in the cabin and makes the sound field environment more complicated. Obviously, it is necessary to measure the sound field conditions before the fog elimination experiment.

4.2. Fog elimination test results and analysis

4.2.1. Natural dissipation of artificial fog and system repeatability verification.

The natural dissipation process of fog is closely related to the ambient temperature. The set illuminance change range is 100 to 14000lx. The measurement results of the illuminance change of fog filling and defogging at 27°C show that the ultrasonic atomizer used can fill the fog chamber in three minutes. The light intensity changes fastest in the first 25s, and gradually slows down as the fogging time increases. Set the illuminance increase to 90% under the condition of no fog as the dissipation time. It takes 1068s to dissipate naturally in the fog chamber. The fog dissipates faster in the first 300s, and then slows down, as shown in Figure 8.

Three times of fog filling and defogging experiments under the same environmental conditions have formed a system repeatability verification. It can be seen from Figure 8 that the three test curves are in good agreement, indicating that the experimental system has good performance and ensuring the correctness and repeatability of the experimental results.
4.2.2. Micro characteristics of artificial fog. Inland fog can be divided into advection radiation fog, advection fog, radiation fog, and rain fog according to the different causes of formation. Different types of natural fog have different microphysical structures [6]. Advection fog is the most common in cities, and various parameters tend to be the median of the four types of fog. The number density is about 100/cm$^3$, and the average droplet diameter is about 3 to 4 $\mu m$, and the spectral width is generally greater than 45 $\mu m$. The number of droplets generally presents a normal distribution with size. As shown in Figure 9(a), it is the measured advection fog model in Nanjing area [6]. The average droplet diameter is 3.5 $\mu m$, the minimum diameter is 0.2 $\mu m$, the maximum diameter is 45 $\mu m$, and the initial number concentration is 100/cm$^3$. Figure 9(b) shows the particle size distribution of the traveling wave tube condensation chamber when it is full of fog measured by a droplet spectrometer. The measured parameters are the average concentration of 879 $\mu m^3$/cm$^3$, the volume concentration of 432 $\mu m^3$/mm$^3$, the water content of 0.432 g/$m^3$, and the average diameter of 8.87 $\mu m$. The effective diameter is 11.5 $\mu m$, the sample gas flow rate is 17.9 m/s, and the ambient temperature is 36 ℃.

![Figure 6](image)

**Figure 6.** Particle size distribution (a) Natural fog (b) Artificial fog.

4.2.3. Simulation and experiment of acoustic condensation fog elimination.

4.2.3.1 Simulation results of the influence of frequency on acoustic condensation fog elimination. The particle size of the mist is logarithmic distribution, the average diameter of the droplets is 3.5 $\mu m$, the minimum particle size is 0.2 $\mu m$, the maximum diameter is 45 $\mu m$, the initial number concentration is $10^8$/cm$^3$, and the sound pressure level is 140 and 160dB, respectively. The particle size of the fog under the action of frequency sound waves is shown in Figure 10.

![Figure 7](image)

**Figure 7.** Simulation results of droplet size distribution under different acoustic frequencies. (a) SPL=140dB, effect 9500s. (b) SPL=160dB, effect 1300s.

Under the action of sound waves, the fog changes from an initial unimodal distribution to a bimodal distribution, reaching peaks at 2–4 and 10–16 $\mu m$, and troughs at 4–10 $\mu m$. The effect of sound waves causes many small particles to condense into large particles, which increases the number of particles...
above 20 μm, while the overall number decreases. High frequency sound waves have a better effect on agglomeration of small particles below 6 μm, while low frequency sound waves have a better effect on agglomeration of large particles above 6 μm. This is because the low-frequency sound wave has a larger entrainment coefficient, and the ability to entrain the droplets to vibrate with the sound wave is stronger, so the agglomeration effect is more obvious for the large particles that are difficult to carry by the high-frequency sound wave. It can be seen from the simulation results that the influence of frequency on the condensation effect is not a simple linear relationship, but there is a certain optimal frequency. The time when the condensation efficiency reaches 90% is selected as the comparison value, and the time used is the smallest at 600Hz under different sound wave intensities, and 160dB takes the shortest time, and the reunion can be completed in 21 minutes.

4.2.3.2 Experimental results of the influence of frequency on acoustic agglomeration fog elimination. Figure 11 shows the illuminance measurement results during the fog elimination process under the action of different frequencies of sound waves (the sound field conditions are shown in Figure 7). Comparing the natural dissipation time of more than 1000 s in Figure 8, it can be seen that the dissipation time of the fog is significantly shortened after the sound wave is applied. Figure 12 shows the completion time of condensation for different working conditions, all working conditions can be dissipated within 450s. Among them, the time required for below 100Hz is the longest, 700 to 1000Hz is medium, and the effect is best at 300Hz. It only takes about 64s to complete the dissipation, and the time to eliminate fog is reduced by 94% compared with the natural state. Compared with the natural state in Figure 8(b), under the action of sound waves, the slope of the curve becomes steeper in the early rapid condensation stage, and the later curve has less fluctuations and is smoother, and the condensation state is more stable. Taking into account the differences in the results of sound pressure levels at different frequencies in Figure 7, the experiment shows that the optimal frequency for agglomeration is 300-500Hz.

![Figure 8](image)

Figure 8. The measurement results of the illuminance change with time during the elimination of sound waves of different frequencies.

Comparing with the simulation results, it is found that the condensing completion time of the experimental results is significantly shortened, and the condensing optimal frequency shifts to low frequency. There are several main reasons: 1. Compared with natural fog, artificial fog has a tenfold increase in concentration. It has been confirmed in research [7] that the concentration is positively correlated with the condensation efficiency, so the condensation time obtained by the experiment is much lower than the simulated value; 2. In natural fog, the average particle size increases a lot, and the low-frequency entrainment capacity of large particles is much higher than high-frequency sound waves, so the optimal frequency shifts to low-frequency; 3. In the simulation model of this article, only the orthokinetic interaction and the mutual radiation condensation mechanism is considered, there are still many other mechanisms that play an important supplementary role in the condensation process, so the simulated value has an error compared with the experimental value.
On the whole, simulation and experiment confirm each other. Firstly, sound waves can promote the condensation of fog droplets; secondly, the optimal frequency of condensation can be determined in the frequency band 100-1000Hz, the effect of low frequency (below 100Hz) sound waves on cohesion is not obvious.

![Figure 9](image.png)

**Figure 9.** The time it takes for the sound wave to condense (90%) at different frequencies.

5. Concludes

In this experiment, the experimental research on acoustic defogging was initially completed. It lays a foundation for the practical application of acoustic condensation and fog elimination in the future. The experimental conclusions obtained are as follows: (1) Acoustic waves have a significant promoting effect on the elimination of fog droplets, and the condensation time can be reduced by up to 94% compared with natural dissipation; (2) Optimal The frequency range is between 300-500Hz; (3) The longer the sound wave action time, the more thoroughly the mist dissipates, but there is a node. When the sound wave condenses about 80%, the fog changes from a rapid condensing stage to a slow condensing stage.

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