Review and prospect of fog elimination technology based on acoustic condensation

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Abstract. This paper summarizes the traditional artificial fog elimination technology and the principle and mechanism of acoustic condensation theory, reviews the simulation experiment research and application of acoustic condensation fog elimination technology. Compared with traditional fog elimination technology, sum up the advantages and disadvantages of acoustic condensation fog elimination technology. Put forward the existing problems and future research direction of acoustic condensation fog elimination field.

1. Introduction
Foggy weather has a great negative impact on people's daily life. It not only endangers people's health, but also severely reduces visibility and brings great safety risks to people's transportation. In the history of aviation at home and abroad, there have been serious accidents in which aircraft glide and collide in the fog. The emergence of fog has laid great hidden trouble for the air force to carry out missions, and posed severe challenges and higher requirements for our aviation security. The vast majority of maritime traffic accidents occur in foggy days with poor visibility [1].The specific operation of traditional artificial fog elimination is divided into two ways: artificial warm fog elimination and artificial cold fog elimination [2]. However, the traditional method of fog elimination consumes a large amount of energy and is highly corrosive, which is easy to cause secondary pollution. Sound wave fog elimination refers to the use of sound wave to the fog field radiation, so that the fog particles contact and collision, condense into larger particles, so as to achieve fog dissipation. Compared with the traditional method, it is more promising.

2. Overview of artificial fog dissipation technology
In order to implement artificial fog elimination economically and efficiently, according to the basic principle of artificial fog elimination, scientific and technical personnel around the world have designed various methods and carried out various forms of artificial fog elimination experiments according to the different characteristics of fog. The existing traditional fog elimination methods are mainly divided into artificial warm fog elimination and artificial cold fog elimination [2-11].
2.1. Artificial warm fog elimination
Warm fog refers to the fog whose temperature is >0 ℃, it is a very stable system, generally need to provide fog elimination energy by the outside. The main methods used in practice are heating method, dynamic perturbation method, seedding hygroscopic particles, etc.

2.1.1. Heating method. The ability of air to hold water vapor is improved by raising the temperature, and the relative humidity of air is reduced to make the fog droplets evaporate. Dissipate fog by heating method need to consume a great amount of heat to achieve fog dissipation effect, and the heating method can make the target zone's temperature raise, mist of peripheral areas converge and produce secondary fog, so it takes long time heating to eliminate the influence of secondary fog of visibility and at the same time, the heating method can only improve the visibility of low height [4].

2.1.2. Dynamic perturbation method (or mechanical mixing method). Fog elimination is realized by helicopter staying on top of fog layer or flying slowly. The downdraft generated under the helicopter can mix the dry clear air into the fog to vaporize the fog droplets. The fog elimination range is 10-20 times the size of the helicopter. The range of fog elimination depends on the size of the helicopter, the speed of advance and the thermal conditions of the fog.

2.1.3. Thermodynamic dynamic method (thermodynamic + dynamic). When the jet engine is fixed on the truck, the hot gas emitted by the engine forms a large area of high temperature, which evaporates the fog droplets to achieve the purpose of local fog elimination.
   The temperature increase caused by this method decreases gradually with the increase of distance. The maximum horizontal distance of temperature increase can reach 200 m, while the vertical range is only within 20 m. The temperature increase curve is parabolic and partial symmetric in the vertical distribution. On the cross section with a relative height of 3 m, the temperature increase curve is symmetrical, and the width of horizontal temperature increase is over 60 m [3].

2.1.4. Seeding hygroscopic particles. Helicopter or tethered balloon brought hygroscopic particles to the top of fog to spread, use hygroscopic material to absorb water vapor in the air, causing a water vapor unsaturated environment and make the droplets evaporate. At the same time, these hygroscopic material will be processed into suitable-size large particles before seeding, in the process of gravity settling droplets will coagulate and clear in the end.
   Commonly used hypersonic substances are sodium chloride, calcium chloride, urea, ammonium nitrate, hypersonic solution spray, etc. The defogging effect depends on the chemical characteristics of the particles, the macro and microscopic characteristics of the fog, the effects of turbulence and wind shear, etc. Studies have shown that a significant improvement in visibility during fogging operations at airports requires seeding several tons of sodium chloride powder, and the fog layer is generally several hundred meters thick. In addition, most of the hygroscopic agents suitable for weather modification are corrosive, causing certain pollution to the environment and difficult to be widely used [2].

2.1.5. The static method. In 1999, Chernikov et al. Developed a fogging device containing heating and electrostatic action, but the effect of this method has yet to be further verified. [47]

2.2. Artificial cold fog elimination
For artificial cold fog elimination (mainly composed of water droplets below 0℃), it mainly tries to change the phase structure in the fog, that is, to generate an appropriate amount of ice crystals in the fog to destroy the structural stability of the fog. The main methods used in practice are seeding artificial ice cores and releasing refrigerants.
2.2.1. Seeding artificial ice cores. Using aircraft or other tools to sow AgI and other artificial ice core in the fog, can make subcooled fog droplets evaporate, water vapor condense to the ice core to form ice crystals, ice particles gradually grow to form snowflakes fall to the ground, to achieve the effect of defogging.

2.2.2. Seeding refrigerant. By seeding refrigerants such as dry ice, liquid nitrogen, liquid propane, and liquid air, the local air is temporarily reduced to below -40℃, and the ice particles generated by condensation or freezing of fog droplets become ice cores, so as to stimulate the Bergeron Process to eliminate cold fog [6]. At present, the most popular method of cold fog elimination at home and abroad is the use of liquid nitrogen as refrigerant, the use of mobile vehicle device spraying, or the use of tethered balloon carrying liquid nitrogen for air seeding. Some important highways in foreign countries have installed automatic controlled liquid nitrogen seeding systems on both sides, but the one-time investment of such devices is too large. Beijing weather modification office has systematically studied the method of using liquid nitrogen to eliminate cold fog, and achieved certain results [7,8,11].

2.2.3. "sow - supply" method. 2003, Moller et al. Put forward a new "sow - supply" fog dissipation method, through injecting large ice crystals to fog particles to accelerate the supercooled water collision between particles and ice particles, each flying ice particles can crash some cloud particles on its trajectory, because temperature is different, they will grow into big ice particles or supercooled water droplets, and then fall by gravity. [46]

3. Mechanism and principle of acoustic condensation technology

Acoustic condensation is a technology to condense and polymerize liquid fine particles through the action of sound waves. Currently, there are few studies on the condensation of liquid particles in fog state, but its principle is interacted with the acoustic agglomeration of suspended fine particles. At present, some achievements have been made in the study of the main mechanism of acoustic agglomeration, but complete theory has not been established [12]. There are five main mechanisms of sound coagulation: Orthokinetic interaction mechanism, acoustic wake mechanism, mutual radiation mechanism [13], gravity sedimentation mechanism and Brownian motion mechanism [14].

3.1. Orthokinetic interaction mechanism

Orthokinetic interaction mechanism was proposed by Brand [15] in 1936, and was introduced in detail by Mednikov [16] in his works. The principle of orthokinetic interaction condensation is the acoustic periodical oscillation make the medium oscillate periodically, so that the suspended particles move with the medium in sound field [17]. Particles with different particle sizes are driven by sound waves to different degrees in the sound field. Large particles have large inertia and are not easy to be captured and remain relatively static, while fine particles tend to follow the vibration of the medium, so particles of different sizes have relative motion. The large particles act as collecting nuclei and adhere the colliding small particles to its surface [18], thereby, reducing the fine particles and increasing the average particle size.

3.2. Mutual radiation pressure force mechanism

When the particles are entrained to move in the sound field, the fluid velocity between the particles is larger than that outside the particles. According to Bernoulli equation, this difference in velocity will create a net pressure for the particles to attract each other. This force is inversely proportional to the fourth power of the particle distance, and decreases rapidly with the increase of distance, and is only important when it is very close [19].
3.3. **Acoustic wake effect mechanism**

The acoustic wake effect is based on the asymmetric flow field around the particles under the Orson flow condition. That is, when two adjacent particles are driven by sound waves to oscillate, the particles in front will leave a wake in the region behind, generate a negative pressure difference, attract the particles behind, and make the two particles close to each other. In the second half of the cycle, the roles of the two particles are reversed and the attraction continues. After several cycles, particles approach each other until they collide [13]. The wake effect of sound wave is different from the effect of common radiation pressure and common scattering. It is believed that when the particles are parallel to the direction of sound wave, they attract each other, whereas, repel each other.

3.4. **Gravity sedimentation mechanism**

The gravity sedimentation velocity of particles with the same density and different particle size or the same particle size and different particle size is different, so that the particles will have relative motion under the action of gravity, which can promote the collision and agglomeration of suspended particles [17]. Under the same conditions, the coagulation effect of gravity sedimentation mechanism is much weaker than that of orthokinetic interaction mechanism, acoustic wake effect mechanism and mutual radiation pressure force mechanism.

3.5. **Brownian motion mechanism**

The liquid particles are in irregular motion all the time, and in the process of motion, the particles collide with each other and condense. It plays an important role in the agglomeration of particles, especially fine particles. The fog usually contains a large number of micron and submicron particles, so Brownian motion cannot be ignored in the condensation process, especially in the absence of acoustic action. Compared with other mechanisms, the coagulation effect of Brownian motion mechanism is much less than that of other mechanisms. In the case of no sound wave action, the coagulation effect of Brownian motion mechanism is still less than two orders of magnitude compared with the gravitational sedimentation mechanism [17].

4. **Development of acoustic condensation technology in artificial fog elimination field**

There is a long history of research on the acoustic condensation (sound wave agglomeration) effect [15]. In 1931, Patterson and Caeood [20] first observed acoustic condensation in standing wave field in gas. At the early stage of the discovery of the phenomenon, Amy discussed the feasibility of acoustic condensation as a means of artificial fog elimination. The period from 1940s to 1960s was the explosion period of theoretical and experimental research, and large-scale industrial testing began to appear in foreign countries.

The early defogging experiments in China can be traced back to 1966 or earlier. In 1984, in order to ensure the success of the National Day military parade, in the Western suburbs, Nanyuan airport also carried out the fog elimination test. The first effective and successful defogging experiment was carried out at shahe airport in 1994. Subsequently, liquid nitrogen defogging facilities were installed at the capital airport and there were several reports of successful defogging (15th December 1995, 17th December 1997) [21]. However, all of above reports are traditional fog elimination methods, acoustic condensation fog elimination technology is not mature, as a practical means has not been obvious progress.

Since 1963, Zhang Xiaorong, Yu Changming and Wei Rongjue [22] of Nanjing University carried out an experimental study on the effect of acoustic wave on water fog dissipation in the laboratory, and preliminarily concluded that it was possible to dissipate fog under acoustic field conditions. In the experiment, they studied the dissipation of distilled water fog and brine fog in the case of various traveling and standing wave fields with frequencies ranging from 500 to 2400Hz and sound pressure level from 90 to 127dB, and found that the optimal frequency of fog elimination under the action of sound waves of other sound levels was 1500Hz, except the distilled water fog in the traveling wave field. The sound pressure level has a threshold of about 100dB, beyond which the fog elimination effect
is very obvious. The obvious wave nodes and wave loops were observed in the standing wave field, the fog elimination time of wave loops is shorter than that of wave nodes.

Academician Ma Dayou, a famous acoustics expert, attaches great importance to the research and application of acoustic condensation technology. In the 1970s and 1980s, professor Xi Baoshu et al. [23] of Tsinghua University tried to develop and test the mechanism, feasibility and experimental device of acoustic wave fog elimination, established the experimental device of acoustic wave fog elimination, and carried out outdoor demonstration and verification tests in Huangshan scenic area. By reducing the frequency of acoustic wave, the changes of the defogging time and droplet spectrum in the fog chamber under the action of strong acoustic wave below 50Hz were investigated. The experiment shows that the acoustic wave has a very obvious effect on the fog dissipation, and the lower frequency and the higher intensity sound wave are more conducive to the fog elimination.

In 1979, Shaw et al. [24] adopted a low-frequency electric horn (1 ~ 3kHz) and a high-frequency siren (10 ~ 20kHz), two sets of sound sources to conduct acoustic agglomeration experiments on single-dispersed phase aerosols. It was found that the agglomeration effect was better at low frequencies, while the attenuation of sound waves was more serious at high frequencies. Rajendran et al. [25] compared the acoustic agglomeration effect of aerosols under flow and static conditions, and found that the agglomeration effect was reduced under flow conditions. The reason, he thinks, is that under the flow conditions, the airflow suppresses the turbulence generated by the sound waves, making the turbulence cause less agglomeration.

In 1995, German ph. Caperan et al. [26] studied the entrainment effect of ultrasonic field on ethylene glycol aerosol by designing a test bench, and adopted ultrasonic wave with frequency of 20kHz and sound pressure level of 150dB. The results show that the ethylene glycol droplet aerosol can produce obvious condensation effect under long time radiation. Sound condensation is affected by the amplitude of sound wave and is proportional to the quadratic square of the amplitude of sound wave. In the condensation process, due to the similar size of particles, the condensation effect is more affected by fluid dynamics, which is different from the research of most scholars. Sahinoglu, Ercan, Uslu et al. [27] studied the condensation effect of ultrasonic condensation on bubbles in liquid, and proposed a visualization method to describe the molecular trajectory of the aggregation process, which is of great help to the study of ultrasonic condensation simulation and model.

In 2002, Hou Shuangquan of Tsinghua University [28] investigated the dissipation effect of low-frequency sound wave (< 50Hz) on water fog, and qualitatively concluded that lower frequency and higher sound intensity are conducive to the dissipation of water fog. In addition, it is believed that in Wei Rongjue et al. (1963) 's fog elimination experiment [22], because the glass tube used is too small, the wall surface becomes the main factor affecting the experimental results, and the low frequency (< 500Hz) fog elimination experiment is not carried out, so the identification basis of the optimal frequency is insufficient, and it is not practical in industry due to noise.

Liu Shuyan et al. [29] of Beijing Institute of Technology obtained the low-temperature condensation field by reducing the temperature of the acoustic condensation environment, and observed the degree of tightness and coagulation efficiency between particles, results are unsatisfactory. Yuan Zhulin et al. [30] of Southeast University used numerical simulation to study the mechanical and motion characteristics of gas particles in ultrasonic field. It is concluded that both the longitudinal wave field and the standing wave field can produce the agglomeration effect, but the effect size is different, because the motion state and principle of the particle in these two fields are different.

Professor of Tsinghua University Xi Baoshu’s team respectively in 1999 and 2010, cooperated with Beijing XiBiShi mechanical and electrical technology co., LTD., Beijing Vetta new technology development co., LTD., developed low frequency acoustic wave fog elimination equipment[31-32], using 20 ~ 100 Hz low frequency sound waves, fog in 300 ~ 400 m can be dissipated within 10 minutes, and fog dispersal effect and the concentration of the mist are positive correlation. The acoustic condensation technology was applied in practice not only theoretical research.

In 2013, Peng Liang [33] from Northeast University carried out a study on the mechanism of oil mist condensation by ultrasonic wave through numerical simulation. According to the simulation results, the
condensation effect of particles becomes better with the increase of temperature, and worse with the increase of pressure. The increase of ultrasonic frequency is not conducive to the agglomeration of particles. The coagulation effect is the best when the ultrasonic frequency is at 20KHz. As the coagulation effect decreases monotonously with the increase of the acoustic frequency in the simulation process, 20KHz is not the optimal frequency, and whether the ultrasonic wave is a favorable frequency band for acoustic coagulation also remains to be considered.

In 2018, Yu Fangzhou [34] from Beijing Jiaotong University carried on the simulation and experiment of the ultrasonic condensation process of water mist. Because it is easier to cause between the particle hydrodynamics cohesion function, condensation effect in standing wave sound fields is better than the average sound field. After design, simulation and verification test for temperature, pressure, frequency and sound pressure level four factors, he got the optimal combination: condensation temperature of 360 K, pressure of 100000 Pa, frequency of 28000 Hz, sound pressure level of 180 dB. Under this condition, the condensation rate reached 70%.

Before the middle of the 20th century, acoustic condensation technology mainly remained in the research stage of mechanism. After the mid-20th century, the domestic and foreign simulation and experiments on acoustic condensation fog elimination technology began to increase, research focus shift from theoretical research to experimental verification, The low-frequency defogging device developed by professor Xi Baoshu et al. [31-32] has achieved certain defogging effect in the application experiment. Since the 21st century, the application of acoustic condensation technology in China has mainly focused on the research and application of fine particulate emission reduction and other environmental protection fields [35-45]. Acoustic condensation fog elimination technology appears two application directions -- ultrasonic fog elimination and low-frequency acoustic wave fog elimination.

5. Advantages, disadvantages and development direction of acoustic condensation fog elimination technology

5.1. Advantages and disadvantages of acoustic condensation fog elimination technology

Compared with other traditional methods, acoustic wave fog elimination has great advantages. Firstly, it is suitable for both warm and cold fog elimination. Secondly, it also has the characteristics of less energy consumption, low cost, flexible and convenient use. Thirdly, it has almost no pollution to the environment. As it is a kind of non-contact means, it has little damage to the instrument itself, and the instrument life and reliability are greatly increased.

However, at present, the study of its mechanism is not thorough enough to form a complete system; There is no practical application of the case, so, whether it can achieve the theoretical effect in practice still remains to be verified.

5.2. Existing problems and research directions

(1) fog generally has the characteristics of wide-range, renewable, in order to make the acoustic agglomeration technology economically applied in the field of mist, must study the influence of various parameters in the process, find out 'the best operating parameters', make it work under the best conditions, reduce energy consumption, so acoustic condensation may become a practical technology. However, until now, the optimal operating parameters of acoustic coagulation, especially the determination of the optimal acoustic frequency, are still controversial. In the existing literature, the frequency range used by various researchers is very large, ranging from as low as 20Hz to as high as 30kHz. In these studies using different frequencies of sound waves, certain effects of condensation has been obtained. So the researchers thought they were using the optimal frequency. Due to the great differences in different research and experimental conditions, equipment, aerosol types and concentrations, sound field and action time are all different, so it is not accurate to compare the coagulation efficiency horizontally.

At present, there is not a convincing scientific conclusion on the optimal frequency of acoustic condensation defogging. Professor Zhang Guangxue of China Jiliang University [45] used an adjustable frequency sound source to conduct an experimental study on solid aerosol (fly ash from coal burning)
under both high and low frequencies under the same experimental conditions. The particle size and physical characteristics of fly ash from coal burning are different from that of water mist, but the coagulation principle is the same, so the results are worth learning from.

According to Zhang's experiments, there is a significant difference between low frequency sound waves and high frequency sound waves. First, the size range of the agglomeration objects is much larger. Furthermore, the agglomeration effect of low frequency sound wave is far better than that of high frequency sound wave, and the total concentration of fly ash can be reduced by more than 70%. Low frequency sound wave is more suitable for industrial application than high frequency sound wave because of its strong penetration in flue gas and low attenuation and higher conversion efficiency. His optimal frequency was 1400Hz ~ 1700Hz, which was consistent with the conclusion of Mr. Wei Rongjue [22]. However, the low-frequency defogging device developed by professor Xi Baoshu [31] uses a frequency range of 30 ~ 100Hz, which also achieves a good effect. Therefore, the optimal frequency of acoustic condensation fog elimination still needs further research and demonstration.

(2) There have been some achievements in the study on the mechanism of acoustic condensation (agglomeration), but a complete system has not yet been formed. Currently, the known condensation mechanisms include orthokinetic interaction mechanism, acoustic wake mechanism, mutual radiation mechanism, gravity sedimentation mechanism and Brownian motion mechanism. Among them, orthokinetic interaction mechanism as the major mechanism of coagulation, but is not applicable for the droplets are monodisperse aerosol. Fluid mechanics (acoustic wake mechanism and mutual radiation mechanism) also play an important role, they can make up for the lack of orthokinetic interaction mechanism, at the same time explain condensation volume's 'Refill' phenomenon" [45] during condensation process. In the existing literature, for the simulation of the condensation process, most of the models are built by the orthokinetic interaction mechanism, but in the actual condensation process, the five mechanisms exist at the same time, influence each other. Therefore, it is necessary to form a complete mechanism system for the development of acoustic condensation fog elimination technology.

(3) At present, there is still lack practical application's experimental results of acoustic condensation fog elimination. Only in the practical application can the shortcomings of acoustic condensation technology be found. There are many parameters of acoustic condensation, and the influence of many parameters such as acoustic wave waveform, particle size distribution and temperature field on acoustic condensation is still unclear. The acoustic coagulation research only stays in the simplest sinusoidal wave under cold state condition, has not yet reached the application degree. More application experiments are needed to find the right combination of parameters in different scenarios.

6. Summary
To sum up, the application of acoustic condensation technology in artificial fog elimination has incomparable advantages compared with traditional fog elimination methods and has a good development prospect. After decades of development, the acoustic condensation technology has made great progress in mechanism research and experiment. The application of acoustic condensation technology in China is mainly focused on the research and application of fine particulate emission reduction and other environmental protection fields. There are few research literature on fog elimination, and the existing theoretical model is relatively rough, which cannot predict the experimental results well. Therefore, it is necessary to further strengthen the mechanism and theoretical research. The influence of operating parameters on the condensation effect needs to be further studied. On the basis of the existing acoustic condensation fog elimination device, the application test is the focus of future research, and further improve the acoustic condensation technology.

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