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Experimental Study on the Agglomeration of Oily Fine Particles by Sound Wave

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Abstract: Oily fine particles are an important air pollutant in industrial environments. Workers exposed to oil mist for a long time face great health risks. Particle growth pretreatment is a technical principle to increase particle size and improve purification efficiency. Acoustic waves are commonly used to acheive particle growth, and a large number of acoustic wave agglomeration experiments have been carried out on non-oil fog. However, studies on oily particles are few. On the basis of previous studies on acoustic agglomeration of non-oily particles, this experiment designed a set of experimental equipment to compare the agglomeration effect of oily and non-oily particles. It was found that the agglomeration effect ratio of oily and non-oily particles to φ1oiliness/φ1non-oily particles was greater than 1. Therefore, the agglomeration effect of oily particles under stationary acoustic waves was more obvious. Results clearly show that oily particles have a higher agglomeration ability. In this study, a traditional ventilation and purification technology was expanded to include sound agglomeration technology into the pretreatment stage of purification and dust removal, thereby demonstrating feasibility of improved purification efficiency of an oily fine particle purification system, and laying a foundation for engineering applications.

Keywords: industrial environment; oily particles; acoustic coagulation; test bench verification

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1. Introduction

Workers in industrial settings are often exposed to high levels of oily pollutants in the air, and this exposure can be harmful. Chen [1] studied the exposure of processing line workers in the firmware manufacturing industry to inhaled particles, specifically, the impacts in different areas of the respiratory tract. They found that the inhaled particle concentration in the alveolar area was much higher than the level associated with 'increased risk of lung injury' (0.20 mg/m^3). Similarly, Tsai [2] et al. found that exposure to environments with high oil mist concentrations would increase the probability of lung cancer and skin cancer. However, oil mist exposure has many sources in industrial processing. Traditional ventilation is the use of natural or mechanical methods to allow wind to pass through without obstruction, so that it can reach a room or sealed environment sufficiently to maintain health and safety, and may include other suitable air environment technologies. Traditional dust removal effects in industrial plants full of oil mist is not very obvious. In addition to direct exposure in processing, condensation of lubricating oil and particle-entrained workpiece exchanges [3] can cause indirect exposures, which undoubtedly leads to great difficulties in oil mist control. Previously, field investigations on processing workshops of different sizes and processes have been conducted [4]. The results showed that the concentrations of oil mist in different workshops were not evenly distributed in time and space, i.e., the dispersion of oil mist was irregular. In addition, merely increasing the ventilation volume cannot effectively control the exposure level of oil mist in the workshop because its particle size is extremely small. Thus, the removal efficiency of traditional purification and dust removal systems cannot be improved in that way. A more efficient and easy-to-apply purification method is required as an enhancement to traditional ventilation or other purification techniques that addresses the characteristics of oil mist emission.

Particle growth pretreatment can increase particle size and improve purification efficiency. For fine particles, various agglomeration technologies are available, including acoustic agglomeration [5–7], electrical agglomeration [8], thermal agglomeration [9] and magnetic agglomeration [10]. These methods can be used to unite particles. The basic principle of these methods is that van der Waals attraction and double electric layer repulsion exist between particles, and the external action intensifies the motion of particles and simplifies agglomeration, as shown in Figure 1. In the factory environment, forces on particles can be very complex. The acoustic-field force studied can cause collisions and coalescence amongst ultrafine particles by modulating the flow field, which increases the particle size and improves the purification efficiency of the purification collector. Ultrafine particles vibrate in a high-frequency standing wave sound wave, and each particle's vibration velocity and amplitude are unique; thus, the probability of collision between particles is high, resulting in particle agglomeration [11]. The mechanisms of sound fields have been fully studied; the most important of which are the co-direction agglomeration mechanism and wake effect. Other mechanisms include the acoustic radiation pressure effect, acoustic turbulence effect and Brownian agglomeration effect. The study of agglomeration mechanisms of particles by acoustic field forces can provide better technical support for industrial production design and engineering.

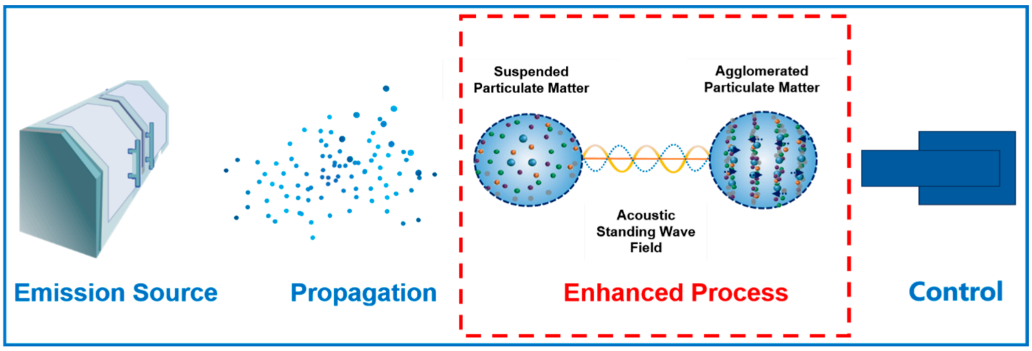

Figure 1. The basic principle of agglomeration.

Orthokinetic interaction was first proposed by Brand [5] in 1936. He showed that sound waves cause the air in the flow field covered by their sound field to vibrate, and that particulate matter vibrates with the sound wave, a mechanism known as the entrainment theory of sound waves. Mednikov et al. [7] established a particle motion model under the same direction interaction, which provided an important reference for subsequent theoretical and numerical studies. On this basis, researchers also introduced the influence of Stokes forces and unstable forces (pressure gradient force, virtual mass force and Basset force) [6,12], considered the collision process of particles [13] and carried out characteristic analysis on the variation rule of particle drift based on initial position, particle size and sound field parameters [14]. The acoustic wake effect indicates that when particles with the same particle size are carried by sound waves move, a low-pressure wake area is formed behind a leading particle; thus, another particle following the lead accelerates to approach the leading particle, and they achieve collision convergence [15]. Therefore, a method to calculate the acoustic wake effect was proposed [16], and the process of particles moving in the experiment was recorded to support the acoustic wake effect [17].

Furthermore, the expression of average particle-coalescing velocity based on the acoustic wake effect was derived [18]. On this basis, González [19] et al. established a model of interparticle motion under co-direction interactions, gravity and the acoustic wake effect, carried out theoretical calculations and numerical analyses on the interparticle motion process, convergence velocity and collision time, and conducted experimental studies on interparticle motion under different entraining coefficients. Moreover, the characteristics of agglomeration behaviour amongst particles in different particle size ranges were studied [20–23], and the disturbance velocity generated by the acoustic wake effect was corrected to improve the interaction model of particles under acoustic agglomeration [24].

The systematic study of acoustic agglomeration theory is the basis of subsequent experiments, which can be better applied to the study and application of the agglomeration effect. Hoffmann [25] captured the acoustic coalescations of monodisperse glass beads (with diameters of 8.1–22.1 μm) and polydisperse quartz particles (with diameters of 25–35 μm). Kang [26] measured the acoustic coalescence of ultrafine particles of carbon smoke particles with scanning-electromobility particle size spectrometer and found that acoustic waves with a frequency of 20 kHz had a coalescence effect on particles with a size of 10–487 nm. Zhou [27] used flue-gas particles to obtain the motion velocity of monodisperse particles with a diameter of approximately 7.5 μm in the traveling wave and standing wave sound field. Li [28] found experimentally that when the audio frequency was 1500 Hz, the flue-gas removal rate could reach 70%. The flue-gas removal efficiency increased with the decrease in flue-gas temperature. The flue-gas removal rate is greatly improved when the sound pressure level exceeds 120 dB. The experimental contents describe the phenomenon and effect of acoustic agglomeration, but were limited to particles more than 7 μm in size. Almost all experimental results include the interaction process of monodisperse particles. Real-world industrial applications of acoustic convergence commonly involve polydisperse particles, with sizes ranging from 0.1 to 5 μm. In addition, most studies on acoustic agglomeration are focused on non-oil fog (aerosol solid particles), and the studies on acoustic agglomeration of oil fog should be further developed.

In conclusion, this research aims to experimentally study the effect of acoustic waves on the aggregation of oil mist, and compare this effect to the aggregation effect of non-oily particles. At the same time, we further analyse the influence of oil mist concentration, agglomeration time, number of oscillators and agglomeration holding time on the acoustic agglomeration effect and its principle. The results of this study demonstrate the need for further research on the mechanism of acoustic agglomeration of oil mists, thereby ensuring machining quality, improving the working environment for production personnel and promoting the development of new purification principles and devices of industrial oil mist. The significance of this research is to fill the research gap in the field of acoustic agglomeration of oil mist. By exploring the mechanism and characteristics of acoustic agglomeration of oil mist through experiments, reliable validation of the mechanism research can be provided, and the foundation can be laid for numerical and computational research. In addition, combined with other technologies, it can guide the application of specific equipment or technologies in the purification of oil mist in the industrial field.

2. Materials and Methods

2.1. Experimental Equipment and Apparatus

This experiment uses an air compressor, as shown in Figure 2, to provide power for the oil mist generator. An air pump can compress the air into the tank. The pressure range of the tank is 0–3 Mpa. A check valve is used to control the output pressure range. A standard synthetic base oil, low-viscosity polyalphaolefin (PAO), is selected as the mist reagent for the TDA-4B mist generator, shown in Figure 3. At the same time, 2 m rubber tubes are cut into appropriate lengths, the diameters of which are 6 and 5 mm. A non-oil mist generator is also purpose-built, as shown in Figure 4. The equipment mainly includes two small air pressure pumps, non-oil mist generators, two colour-changing silicone drying pipes, two rotor flowmeters (with a range of 50 L/min and an accuracy of 2 L/min) and several connected rubber pipes and valves. For the non-oil mist experiment, the standard PLS particles were selected as the non-oil mist reagents, which were evenly dispersed in the solvent; the particle size was 0.12 μm. For the experimental site, we built a high-permeability acrylic plate reunion chamber, as shown in Figure 5. The chamber is 300 mm long, 12 mm wide (the length is the wavelength length of the acoustic frequency of

28 kHz), 80 mm high and 4 mm thick. The base size is 400 mm × 80 mm. It is equipped with three pairs of 28 kHz vibrators with a single power of 60 W, and the diameter of the radiant surface is 58 mm. The frequency oscillator is selected according to the relation between acoustic entrainment coefficient and frequency provided by Brandt [5]. A sound wave of approximately 20 kHz has a good agglomeration effect on particles below 0.7 μm. Considering that 20 kHz is still within the range of human ear and finer particles in the size of oil mist particles are found in industrial settings, 28 kHz is finally selected as the vibrator frequency of this experiment. An aerosol optical-particle-size spectrometer, with an accuracy of 0.01 $\mu g/m^3$, was used by the GRIMM spectrometeras shown in Figure 6. The measurement is made by connecting the agglomeration chamber with a plastic three-way valve, and another piece of auxiliary equipment is included.

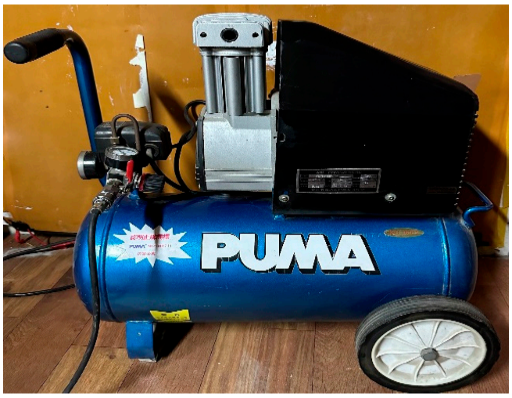

Figure 2. Air compressor.

Figure 3. Oil mist generator.

Figure 4. Non-oil mist generator.

Figure 5. Aggregation chamber.

Figure 6. Grimm measuring instrument.

2.2. Design of the Experimental Platform

The oil test platform is composed of the drying system, gas supply system, oil mist generation system, ultrasonic agglomeration system and particle collection and measurement system. The schematic of the test platform is shown in Figure 7. The non-oil test platform is composed of drying system, gas supply system, non-oil mist generating system, ultrasonic agglomeration system and particle collection and measurement system. The schematic of the test platform is shown in Figure 8.

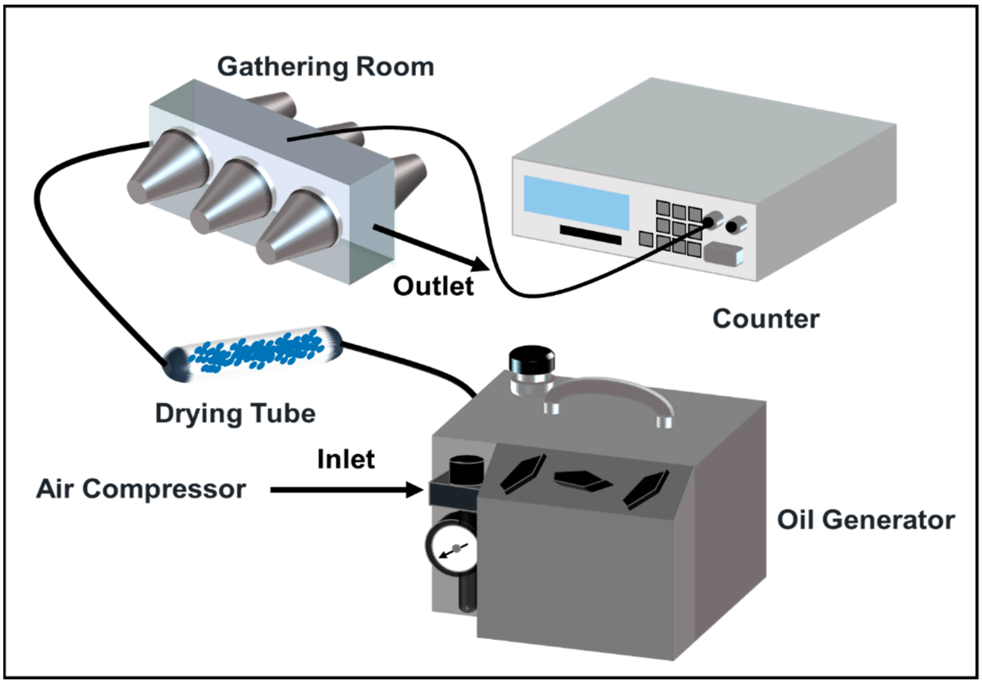

Figure 7. Diagram of oil test bench.

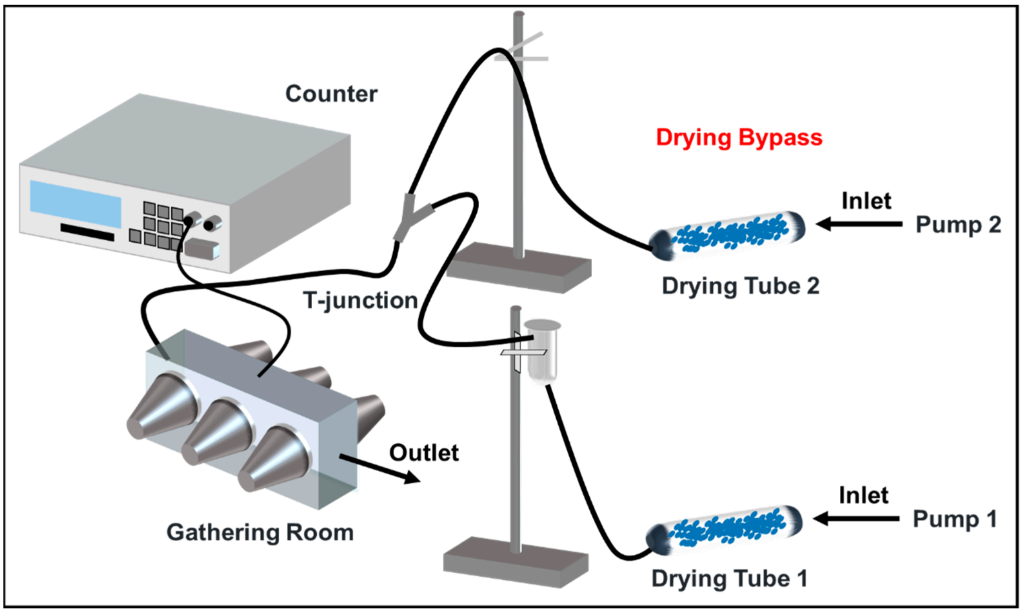

Figure 8. Diagram of non-oily test bench.

2.3. Experimental Process

2.3.1. Oily Fine Particle Test Procedure

At the start of the experiment, the air compressor, oil mist generator and agglomeration chamber are connected together, and the gas tank is inflated. The three knobs of the oil mist generator are then adjusted to determine the appropriate oil mist particle size. In this experiment, the particle size adjustment button is shown in Figure 9, and the particle size of the oil mist is less than 2 μm.

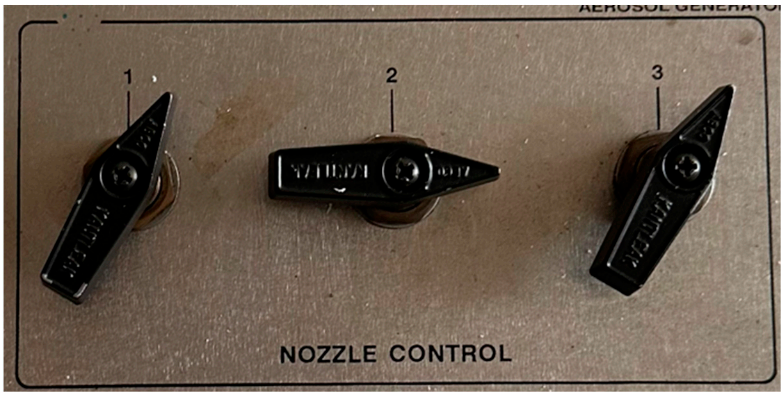

Figure 9. Oil mist generator particle size adjustment button (rough adjustment).

In addition, the aerosol optical particle size of the spectrometer Grimm (hereinafter referred to as Grimm) and the agglomeration chamber are connected, the time is calibrated, and the data recording frequency is set to record data every 6 s. Before the start of the experiment, the inlet and exhaust holes of the agglomeration chamber are opened, as well as the valve of the air compressor tank, which is slowly adjusted until the scale of the rotor flowmeter is stable at 10 L/min. After a period of time, when the particle concentration in the agglomeration chamber is stable, the inlet and exhaust holes of the agglomeration chamber are closed, as well as the valve of the air compressor tank. At this time, the Grimm is opened to record the distribution concentration and quantity of oil mist particles in the aggregate chamber. Prior to the start of each group of experiments, the agglomeration chamber was fully ventilated to prevent the larger particle size formed in the previous experiment from settling or adhering to the agglomeration chamber, thereby affecting the experimental results.

2.3.2. Non-Oily Fine Particle Test Procedure

Prior to this experiment, the discoloured silicone drying tube was heated in a flow drying furnace at 120 °C for 2 h to obtain complete evaporation of water in the drying tube, to ensure the reliability and accuracy of the experimental results. In the experiment, when the color of the drying tube is not blue, it should be reheated until it reaches the required state. Moreover, an aerosol particle solvent with 1% volume concentration with a particle size of 0.12 μm was poured into the container of the particle generator and connected to the particle generator and the agglomeration chamber. The particle generator used in this experiment produces a large amount of water vapor when it is emitted, potentially seriously affecting the experimental results. To solve this problem, we set a by-pass pipeline and mixed dry air with the generator airflow, reducing the airflow humidity below 5%. Then, the airflow speed was adjusted to 10 L/min to start the experiment. Subsequently, the Grimm was connected with the agglomeration chamber; it was adjusted and operated the same as in the oily fine particle test.

During the experiment, the aim is to reduce interference factors as much as possible in the operation process to ensure the accuracy of the experimental results. The ambient temperature, humidity and other factors in all experiments were the same, and a certain number of experimental groups were carried out to eliminate or reduce the influence of interfering factors.

2.4. Evaluation Index

The aim of this study is to compare the aggregation effect of oily and non-oily particles in acoustic field. To this end, we adjusted the initial mass concentration by controlling the ventilation time, and then conducted ventilation at different time intervals in the closed aggregation chamber to approximate an actual industrial situation. We defined the ventilation time and used 10 s per ventilation as a unit to control the initial mass concentration of particles. Prior to the experiment, we examined the relationship between ventilation time and mass concentration, and the results are shown in Figure 10. In this experiment, the ventilation times were set to 10 s, 20 s, 30 s, 40 s, and 60 s. The figure shows that increasing the ventilation time can stabilise the increase in mass concentration. After 60 s, the concentration in the agglomeration chamber no longer changes. Therefore, in the follow-up experiment, we conducted the experiment 60 s after the gas passed into the agglomeration chamber to ensure the stability of each experiment.

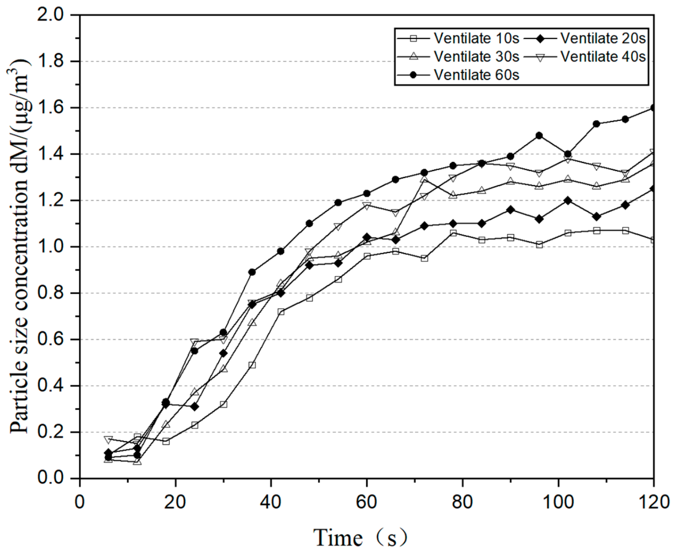

Figure 10. Approximate relationship between ventilation time and mass concentration.

Aggregation time was set considering the minimum counting interval of the Grimm, and the sum is obtained successively with 6 s as the unit time. The number of oscillator groups can be set as a group of relative oscillators; for the experiment, these were group 1, group 2 and group 3. When the conditions are provided, the agglomeration effect of oily and non-oily can be judged by observing the increasing degree of mass concentration of large particle size and defining agglomeration efficiency. The agglomeration efficiency is defined as follows:

$$\varphi 1 = \left| \frac{m_0 - m_1}{m_0} \right| \times 100\%$$

where m_0 is the mass concentration of the large particle size measured at the beginning of the experiment, $\mu g/m^3$ and m_1 is the mass concentration of particle size measured after agglomeration, $\mu g/m^3$.

3. Results and Discussion

3.1. Comparison of Oil-Based and Non-Oil-Based

The coalescence effect of oily particles (PAO) and non-oily particles (PLS) was tested on the established experimental platform. The results were as follows: the coalescence effects of acoustic waves on oily and non-oily fine particles were significant when the initial concentration in the controlled coalescence room was the same. In the initial stage, the particle sizes of the two particle types generated in the agglomeration chamber were below 2.000 μm. After fully dispersing to stability, the ultrasonic generator was turned on at approximately 60 s. The findings indicate that the number and concentration of large particle sizes increase significantly, and the agglomeration occurs after 30 s. For example, for a particle size of 6.25 μm, the oily and non-oily particles surge to 1000 $\mu g/m^3$ when the vibrator is turned on, and then stabilise at approximately 200 $\mu g/m^3$. After the convergence reached the stable stage, the concentration of oily fine particles of 12.500 μm diameter was stable at 130 $\mu g/m^3$, whereas that of non-oily fine particles was below 100 $\mu g/m^3$. The mass concentration of other large-size oily particles is higher than that of the non-oily particles. The experiment clearly shows that the coalescence effect of oily particles is better than that of non-oily particles. The experimental results are shown in Figures 11 and 12. Figure 13 shows the comparison of the 6.25 μm particle size.

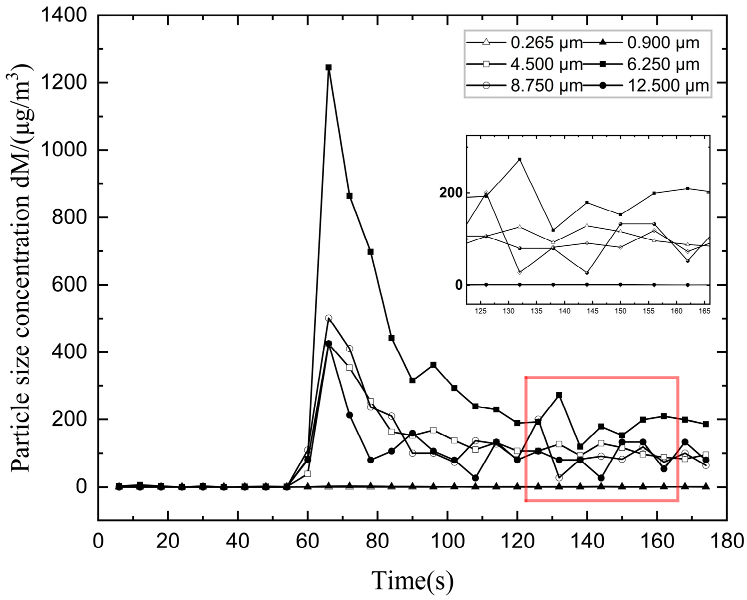

Figure 11. The results of the oily particle experiment.

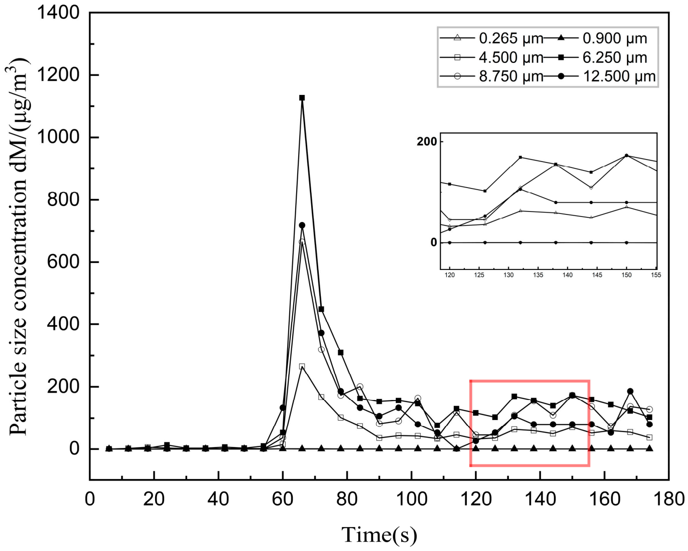

Figure 12. Experimental results of non-oily particles.

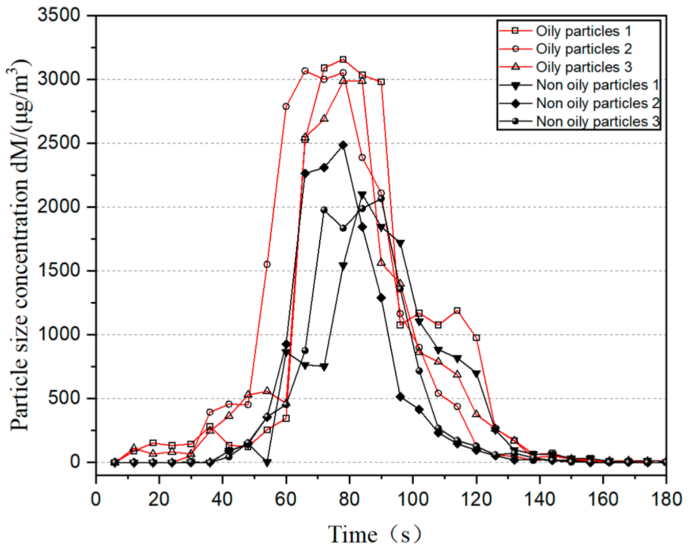

Figure 13. Comparison of 6.25 μm oily and non-oily particles.

The different agglomeration effects may be caused by the short-range forces between particles, considering that the direct and indirect effects of acoustic fields on the two types of particles are the same. A formula describing the motion velocity of particles in the sound field is derived using the vibration model of particles in the sound field. Amongst them, the entraining effect of sound field air flow on particles is reflected by drag force, and the mutual adhesion and cohesion effect between particles is reflected by cohesion (the resultant force of van der Waals force and double electric layer repulsion force between particles, from the Vowinckel method [29]). Then, the expression of particle motion velocity can be derived. The motion formula of oily fine particles in the sound field can be described as follows:

$$m_p \frac{du_p}{dt} = f_{Pressure\ gradient\ force} + f_{Fluid\ acceleration\ force} + f_{Stokes\ viscous\ drag\ force} + f_{Basset\ force} + f_{con} + f_{lub} + f_{coh}$$

where $f_{con}, f_{lub}, f_{coh}$ are direct contact force, damping force and cohesion force, respectively. The three forces contain basic parameters that characterise the dynamic difference between oil mist particles and non−oil mist particles, such as damping coefficient, d_n, and cohesion number, Co. Oily particles are affected by higher short-range forces, and thus exhibit a greater chance of agglomeration than non-oily particles.

3.2. Effect of Initial Concentration Contrast

When the control on the three pairs of vibrators is fixed, the initial concentration is controlled at 10 s, 20 s, 30 s, 40 s and 60 s, and the agglomeration time is controlled at 12 s. Figure 14 shows the effect of initial concentration on the agglomeration of oily particles, and Figure 15 shows the effect of initial concentration on the agglomeration of non-oily particles. A particle size of 6.25 μm was selected as an example. When the ordinate of the image at the inflection point is equal to 0, the vibrator is turned on and work is started. The small-sized particles begin to agglomerate, and oily and non-oily large particle sizes increase rapidly. The findings indicate that the oily agglomeration effect is better than the non-oily effect. According to the defining formula of agglomeration efficiency, the ratios of oily to non-oily can be calculated, and the experimental values are shown in Table 1, when $\frac{\varphi_{1oiliness}}{\varphi_{1non-oily}} > 1$. These data show that the agglomeration effect on oily particles is better than that on non-oily particles.

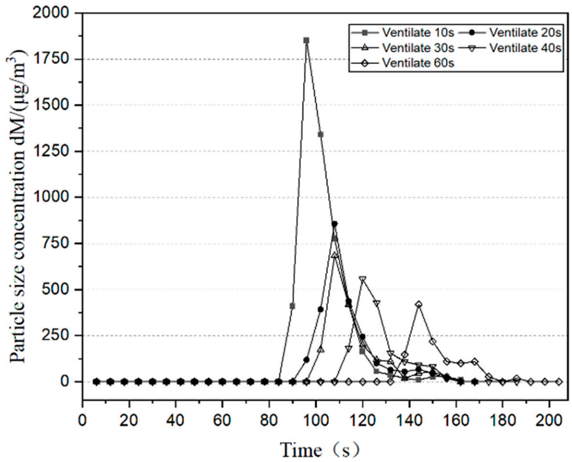

Figure 14. Effect of agglomerating time on oily particles.

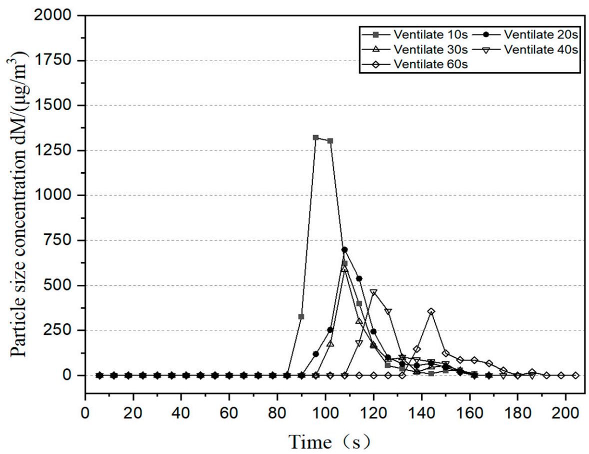

Figure 15. Effect of agglomerating time on non-oily particle.

Table 1. Ratio of agglomeration effect between oily and non-oily particles at different ventilation times.

Ventilation Time	10 s	20 s	30 s	40 s	60 s
$\frac{\varphi_{1oiliness}}{\varphi_{1non-oily}}$	1.31	1.27	1.19	1.18	1.28

However, with greater initial particle concentration in the agglomeration chamber, the concentration of the aggregated 6.25 μm-sized particles decreases, indicating that, at large initial concentrations, the oily and non-oily particles are not conducive to agglomeration by sound waves. Previous experimental studies also found that the agglomeration effect on non-oily particles (coal burning) with a large concentration decreased [30], and this experiment also found that oily particles demonstrate this phenomenon. To achieve a good agglomeration effect, the energy provided by the sound wave must match the particle concentration, which may be related to the power of the sound wave, the frequency of the sound wave and the arrangement of the sound microphone.

3.3. *Influence of Reunion Time*

When the control on the three pairs of vibrators is fixed, the initial concentration is ventilated for 10 s, and the agglomeration times are set to 12 s, 24 s, 36 s, 48 s, and 120 s. Because a change in reunion time will only cause the continuous reunion steps to increase, 120 s is set as the maximum reunion time, to contrast with the previous one. Figure 16 shows the effect of agglomeration time on the agglomeration of oily particles, and Figure 17 shows the effect of agglomeration time on the agglomeration of non-oily particles. A particle size of 8.750 μm was selected as an example. When the ordinate of the image at the inflection point is 0, the vibrator is turned on, and the aggregation time is controlled as variable. Evidently, no large particles are found in the oil mist at the beginning. The oily and non-oily large particle sizes increase rapidly with agglomeration. In addition, the agglomeration effect on oily large particle size is significantly greater than that on the non-oily particle. However, with increases in agglomeration time, the duration of large particles increases, but the particle concentration has no evident change. Therefore, a certain amount of agglomerating time allows oily particles to achieve excellent agglomerating effect. However, simply increasing the agglomerating time does not necessarily result in a better effect. The calculated ratios of oily to non-oily particles is shown in Table 2.

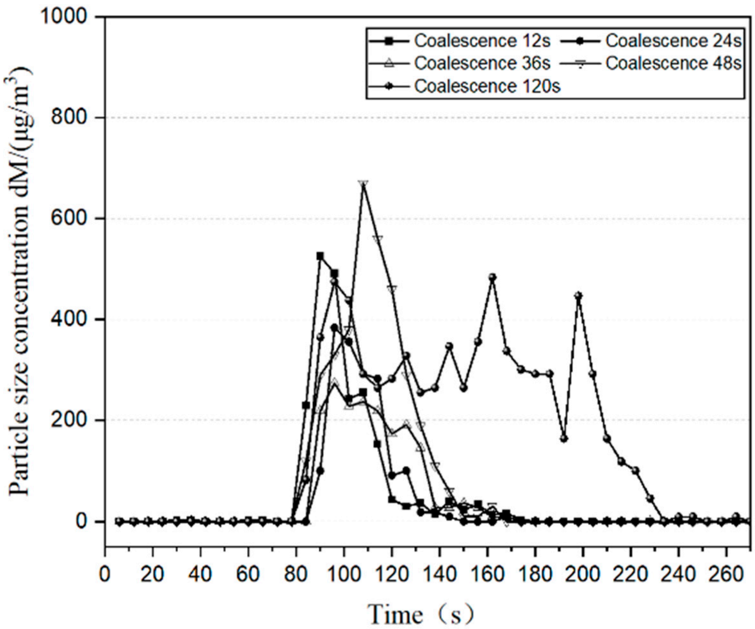

Figure 16. Effect of agglomeration time on the agglomeration of oily particles.

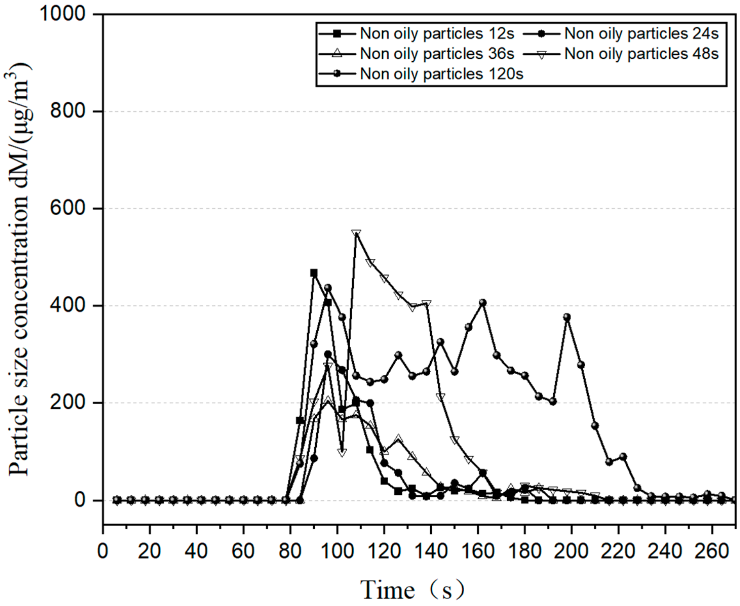

Figure 17. Effect of agglomerating time on agglomerating of non-oil particles.

Table 2. Ratio of agglomeration effect between oily and non-oily particles at different agglomeration time.

Reunion Time	12 s	24 s	36 s	48 s	120 s
$\frac{\varphi_{2oiliness}}{\varphi_{2non-oily}}$	1.26	1.20	1.31	1.18	1.10

3.4. Effect of the Number of Oscillators

When the initial concentration was controlled at 20 s ventilation time and 30 s agglomerating time, the number of opening vibrators was compared between oily and non-oily particles. The experiment of one starting pair of vibrators is shown in Figure 18, and the experiment of the three starting pairs of vibrators is shown in Figure 19. Moreover, the particle size of 8.750 μm is selected as an example. When the ordinate at the inflection point of the image is 0, the vibrator is turned on and starts to work. Initially, the agglomeration effect of the three pairs of oscillators on the two types of particles is significantly better than that of a single oscillator, and the agglomeration effect on oily particles is significantly better than that of the non-oily particles. In addition, the agglomeration stability of the two particles is more evident when more vibrators are opened, indicating that the construction of a suitable acoustic field range is beneficial to the agglomeration of oily particles.

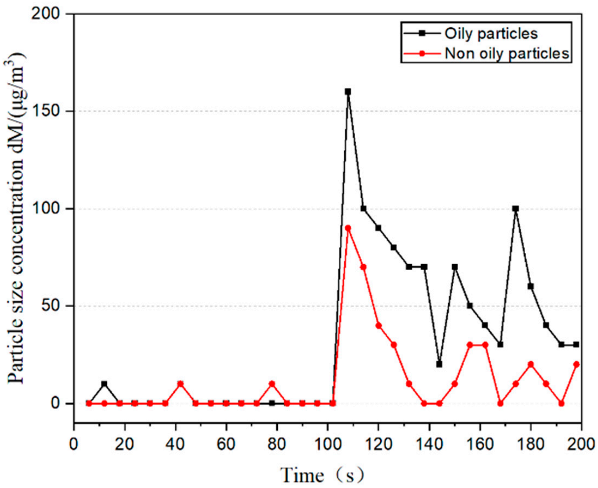

Figure 18. Effect of a pair of vibrators on agglomeration of oily and non-oily particles.

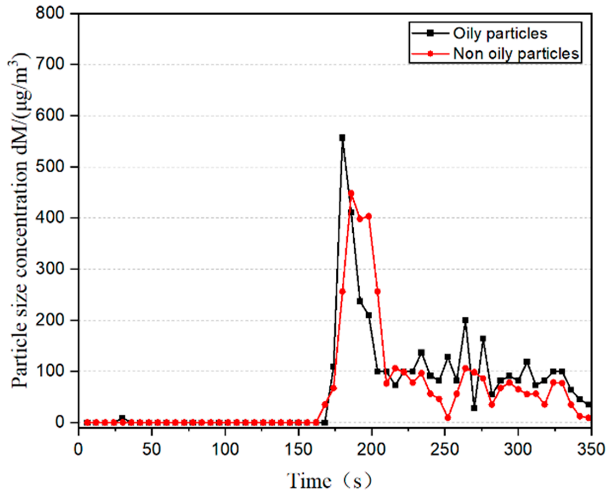

Figure 19. Effect of three pairs of vibrators on agglomeration of oily and non-oily particles.

3.5. Aggregation Holding Time after the Oscillator Is Turned Off

The potential for the particles to continue aggregating after the oscillator is turned off should be considered. Further capture processing may be required after particles are aggregated by acoustic waves. To address this, we conducted an experiment on the agglomeration holding time after the oscillator is turned off. When the initial concentration was controlled at 10 s ventilation time and 30 s agglomerating time, the retention time of large particles was compared between oily particles and non-oily particles after the vibrator was turned off. The experiment is shown in Figure 20. The particle size of 8.750 μm was selected as an example. When the ordinate at the inflection point of the image is 0, the vibrator is turned on and starts to work. The residence time of particles in the agglomeration chamber was observed after the convergence time of 30 s. The findings indicate that non-oily large particles are discharged from the air vent of the agglomeration chamber at approximately 150 s, and oily large particles are slowly discharged from the air vent of the agglomeration chamber at approximately 180 s. Oily particles require 30 s or longer to be completely removed from the aggregate chamber exhaust in this situation, compared to non-oily particles. After the oscillator was turned off, the oily and non-oily small particles were partially aggregated in the agglomeration chamber for approximately 10 s, and then the particle size concentration slowly decreased. The agglomeration time of oily particles is longer than that of non-oily particles after the oscillator is turned off. This demonstrates that the sustained agglomeration effect of oily particles is better than that of non-oily particles.

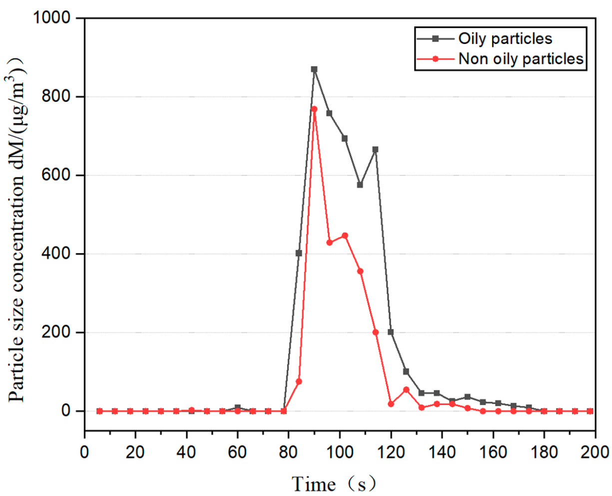

Figure 20. Comparison of aggregation holding time after the oscillator is turned off.

The finding that good aggregation of oily particles continues after the oscillator is turned off may be due to the cohesion between particles, as described in Section 3.1, which allows the particles to remain agglomerated for a longer time. Even in the absence of a sound field, the longer time agglomeration state provides more possibilities for further application.

4. Conclusions

This article experimentally compared the agglomeration effect on oily particles (PAO) and non-oily particles (PSL) at a standing wave frequency of 28 kHz. Under the action of sound waves, the agglomeration effect on oil mist (PAO) was better than that on non-oil mist (PSL). At the same time, the effects of initial particle concentration, agglomeration time, number of transducers, and agglomeration retention time after shutting off the transducers during the agglomeration process were studied. The combination of findings validates that the coagulation effect of oily particles is superior to that of non-oily particles, and provides some possible explanations. This paper discussed research and development on the use of acoustic dust removal technology in industrial plants, specifically in the area of ultrafine particle agglomeration. The study provides research results and experience in ultrafine particle agglomeration, as well as basic data and methodology for future comparisons of the agglomeration effects on oil-based particles and non-oil-based particles. Applying these data to industrial applications using sound waves to solve oil mist purification and capture problems is promising. However, more research is needed to gain a deeper understanding of the principles and equipment technology involved. Regarding the parameters and characteristics of sound waves, their application in specific situations is affected by environmental factors such as temperature, humidity, wind speed, and direction. The impacts on industrial processes and personnel health need to be comprehensively considered and addressed in practical applications to further promote the development of ultrafine particle sound wave aggregation purification technology.

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