buildings

MDPI

Review

Research Progress on the Impact of Acoustic Waves on the Agglomeration of Oily Fine Particles in Industrial Oil Mist Environment

Dekang Li [1], Xin Wang [1], Tian Li [1], Luying Yang [1], Yuhong Liu [1], Fei Wang [1,*], Yuwei Xu [1] and Yang Yang [2]

[1] School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai 200093, China; 212272050@st.usst.edu.cn (D.L.); wangxinshiyun@126.com (X.W.); litian991126@163.com (T.L.); yangluying2021@163.com (L.Y.); liuyuhong825@163.com (Y.L.); zq13153576757@162.com (Y.X.)

[2] School of Building Services Science and Engineering, Xi'an University of Architecture and Technology, Xi'an 710055, China; yangyang@xauat.edu.cn

* Correspondence: wangfei@usst.edu.cn; Tel.: +86-186-2180-5866

Abstract: Currently, undetectable damage to workers and factory products is caused by the large number of oily fine particles present in the industrial environment. Previous studies have shown that different intensities of sound waves can promote the coalescence of fine particles, and the combination of water vapor condensation can further enhance the effect of acoustic coalescence. However, the research on acoustic coalescence is not extensive enough at present, especially research on the mechanism of the coalescence and growth of oily fine particles under acoustic and water vapor complex fields, which is even less studied. This paper focused on summarizing domestic and foreign research results on the interaction mechanism of acoustic convergence on particles and the agglomeration and growth of particles under the action of acoustic convergence and combined water vapor condensation, so as to explore the technical path of using acoustic convergence and combined water vapor condensation to regulate the size of oily fine particles and improve the purification efficiency in industrial situations. This research has significant scientific significance and application value for industrial environmental control, pollutant emission control, and healthy environment construction.

Keywords: industrial applications; acoustic fusion; adhesive fine particle capture; water vapor condensation; purification technology

Citation: Li, D.; Wang, X.; Li, T.; Yang, L.; Liu, Y.; Wang, F.; Xu, Y.; Yang, Y. Research Progress on the Impact of Acoustic Waves on the Agglomeration of Oily Fine Particles in Industrial Oil Mist Environment. *Buildings* **2023**, *13*, 1937. https://doi.org/10.3390/buildings13081937

Academic Editor: Baojie He

Received: 13 June 2023
Revised: 13 July 2023
Accepted: 24 July 2023
Published: 29 July 2023

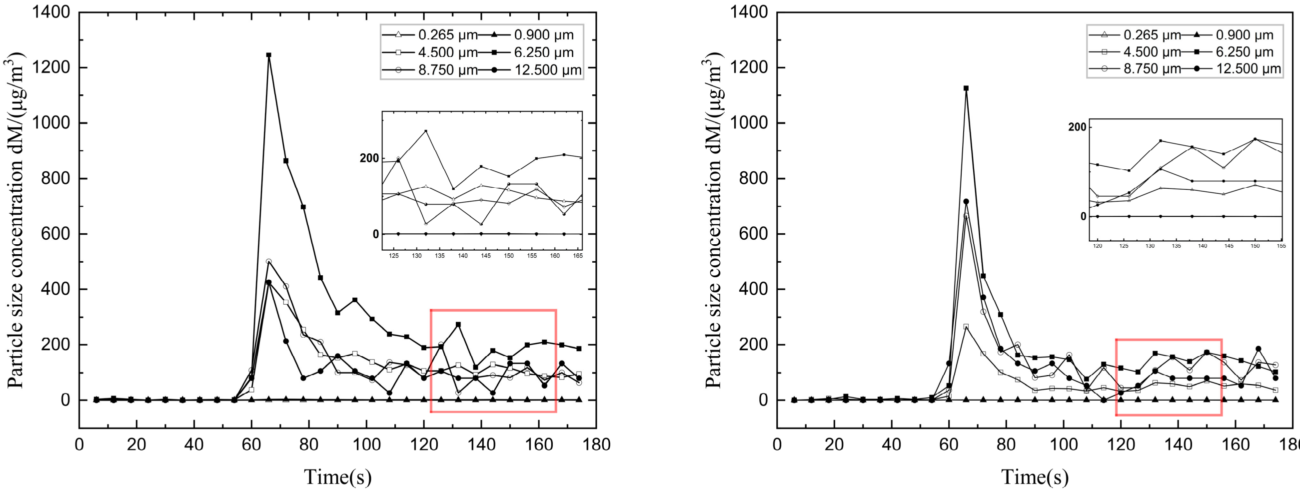
1. Introduction

Oil fine particles (PM2.5) have become an important type of pollutant within the industrial environmental scope in China [1]. Long-term exposure to high-concentration oil mist pollution of this type can be harmful to the health of production personnel and the quality of processed products [2,3]. The small size of the particle diameter makes it difficult to improve the purification efficiency of oil fine particles, resulting in serious over-concentration of oil mist in the factory building [4]. Therefore, the development of purification technology is urgently needed to reduce oil pollution in industrial production, reduce the risk of workshop personnel infection, and improve the quality of production line products. Particle enlargement pretreatment is a technology principle that converts small particle diameters into large particle diameters to improve the purification efficiency [5–7].

Sound agglomeration is a promising technique for pre-treating fine particles in industrial applications. In a standing wave sound field, different intensities of sound waves are used to change the force state of fine particles suspended in a gas medium, promoting them to move together towards the standing wave nodes, thereby reducing the spacing between fine particles and increasing their collision probability, resulting in fine particle agglomeration behavior and an increase in particle size. This leads to a decrease in the concentration of small-sized particles and an increase in the concentration of large-sized particles, which can be more effectively removed as a whole particle group. However, early sound agglomeration technology had high energy consumption, and it was difficult to achieve the experimental conditions required. Currently, with the development of science and technology, the experimental equipment required for sound agglomeration is now relatively simple, adaptable, and has a short acting time, thus attracting the attention of researchers. With many advantages, aerosol sound agglomeration technology has emerged as an extremely promising new technology. Researchers have combined it with various aerosol aggregation technologies to achieve more efficient purification of dust and pollutants. As early as the last century, aerosol sound agglomeration theoretical models, such as co-flow interaction and sound wake effect, were proposed one after another. With the rapid development of computer technology and the continuous improvements in experimental techniques, numerical simulations and experimental tests using various software have become important means for the theoretical study of aerosol particle sound agglomeration. This greatly enhances the depth of research on sound agglomeration mechanisms. However, due to the many factors that can affect the sound agglomeration effect, some relevant theoretical explanations on the sound agglomeration mechanism are controversial, and the complexity of experimental conditions has led to a decrease in the reference value for subsequent studies. These issues seriously hinder the development of sound agglomeration technology. Some critical problems have not been authoritatively resolved in the industry, and further research is needed in the future.

In previous experimental tests [8], a research group found that compared with non-oil particles, the effect of sound agglomeration on increasing the particle size of oil particles is more significant. When the initial conditions were the same, oil fine particles with a diameter smaller than 2.5 μm agglomerated into particles with a diameter of 8.75 μm, and their mass concentration was about 1.6-times higher than that of non-oil particles agglomerated into particles of the same size, as shown in Figure 1. This indicates that under the collision and agglomeration effect in the acoustic field, the oil fine particles can form agglomerates, and under the dominant interparticle force (representing the combined acting force of van der Waals force and double-layer repulsion force, which is the main short-range force causing particle agglomeration), the adjacent particles are attracted to each other and adhere to form agglomerates [9], making the agglomerates more stable and suppressing their rebound or fragmentation. The experiment also indicated that acoustic agglomeration has a more significant control effect on oily particles and holds tremendous potential for application.

The large amount of heat generated during machining and manufacturing processes leads to the presence of a large amount of high-temperature and high-humidity water vapor in the oil mist environment of factories. After particles collide and form agglomerates, water vapor will condense around the agglomerates as nuclei and undergo heterogeneous nucleation and condensation on their surfaces, which can make oil agglomerates grow into larger dust-laden droplets and increase the particle size, further enhancing the effect of sound agglomeration. During the process of water vapor phase transition, water vapor molecules first gather into tiny nuclei, which grow into liquid droplets under appropriate conditions. The process of nucleus formation is a necessary stage of water vapor phase transition, called nucleation. In a supersaturated water vapor environment with particles, water vapor will gather on the surfaces of particles and undergo heterogeneous nucleation and condensation [10]. Thus, the process of oil fine particle agglomeration and growth under the combined effects of sound agglomeration and water vapor condensation is shown in Figure 2. Oil fine particles are a mixture of insoluble and soluble components formed during the use of metalworking fluids to lubricate workpieces in machining production [11,12]. The diversity of factors, such as the wetting ability, solubility, and physicochemical components of oil fine particles, forms the particularity of the process in which water vapor on the particle surface undergoes phase transition to a condensed state.



(**a**) oily particle (**b**) non-oily particle

Figure 1. Comparison between oily and non-oily particle experiments.

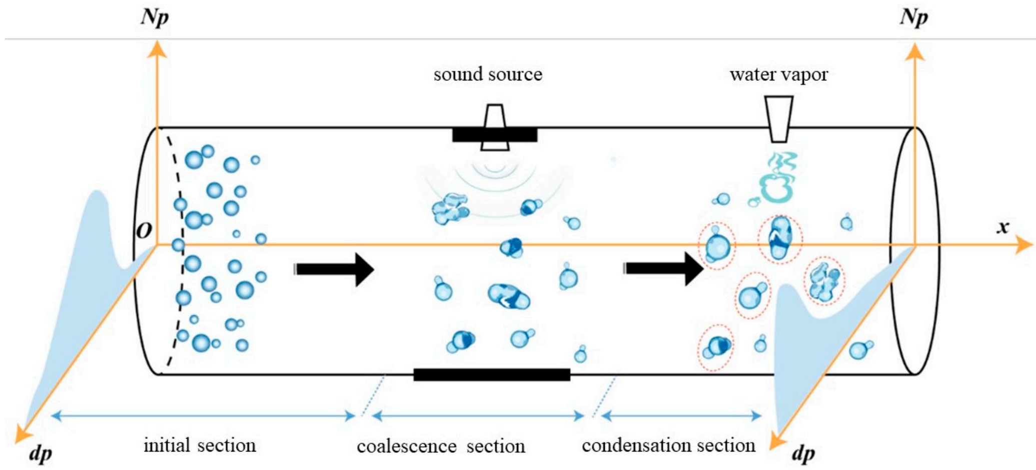


Figure 2. Schematic diagram of the coalescence and growth process of oily fine particles based on acoustic coalescence combined with water vapor condensation.

Currently, research on oil particle acoustic aggregation is not yet comprehensive, and more in-depth research is needed on the particle motion in the presence of a sound field. On one hand, compared with the research on sound agglomeration of non-oil particles [13,14], the kinematic phenomena of collision and adhesion in the background sound field make the agglomeration behavior of oil fine particles more difficult to predict. Acoustic streaming and vortices in the flow field also have a significant impact on particles [15]. Additionally, the physical properties of oil droplets themselves differ significantly from non-oil particles (dust), and the motion behavior in an acoustic field cannot be generalized. On the other hand, considering that the particles released during industrial production are mostly oil fine particles containing insoluble nuclei/soluble organic matter formed during the machining process, their nucleation characteristics are different from those of single-component particles due to their physicochemical properties, making the nucleation and condensation process of water vapor on the surface of oil fine particles more complex.

In summary, although oil fine particles are widely present in industrial settings, research on their sound agglomeration is not yet sufficient, especially with regards to the mechanism of agglomeration and growth of oil fine particles under the combined effects of sound and water vapor. Research on the sound agglomeration technology of oil fine particles will be of great significance in industrial environmental control, pollutant emission control, and healthy environment creation. Therefore, this article focuses on summarizing the research results of the mechanism of the mutual motion of particles under sound agglomeration and the agglomeration and growth of particles under the combined effects of sound agglomeration and water vapor condensation in domestic and foreign studies. This aims to explore the technical path of using sound agglomeration with water vapor condensation to regulate the particle size of oil fine particles and improve the purification efficiency in industrial settings. These studies may provide new research directions for the development of oil fine particle purification technology and have significant scientific significance and application value for industrial environmental control, pollutant emission control, and healthy environment creation.

2. Research Progress on the Mechanism of Sound Agglomeration on the Mutual Motion of Particles

Currently, research on sound agglomeration mainly focuses on investigating the effect of operating parameters, such as sound pressure, sound frequency, particle size distribution, and gas composition, on particle agglomeration through experiments [16,17]. Additionally, there has been research on the enhanced effect of particle agglomeration under the combined action of sound agglomeration and other mechanisms [18,19]. However, there is relatively little research on the mutual motion and mechanism of oil fine particles in sound agglomeration. Sound agglomeration involves complex phenomena and processes, such as the effects of the sound field on particles, the influence of particle motion on the sound field, and the scattering of sound waves. As a result, there are various mechanisms of the sound field on the mutual motion of particles, with the most widely studied being same-direction interaction and the acoustic wake effect [20].

Same-direction interaction refers to the vibration of the gas medium caused by sound waves, which, in turn, causes the attached particles to move. Due to differences in inertia, particles of different sizes have different capacities to be carried by the sound field, resulting in different distances of motion in the sound field, with a certain probability of collision and agglomeration [21]. Mednikov et al. [22] established a particle motion model under same-direction interaction, which provided an important reference for subsequent theoretical and numerical studies. On this basis, researchers have introduced the effects of Stokes force and non-steady forces (pressure gradient force, virtual mass force, Basset force) [23,24], considered the collision process of particles [25], and conducted characteristic analysis of the particle drift amount as a function of initial position, particle size, and sound field parameters [26]. The specific formula for particle motion can be expressed simply as follows:

$$m_p \frac{du_p}{dt} = \delta m_p \frac{du_g}{dt} + \frac{1}{2}\delta m_p \frac{d(u_g - u_p)}{dt} + 6\pi\mu R(u_g - u_p) + 6R^2\sqrt{\pi\mu\rho_g}\int_{-\infty}^{t} \frac{d(u_g - u_p)}{d\eta} \cdot \frac{d\eta}{\sqrt{t-\eta}}$$

The four terms on the right represent pressure gradient force, virtual mass force, Stokes force, and Basset force.

Acoustic wake effect refers to the formation of a low-pressure wake region behind the leading particle when particles of the same size are carried by sound waves, causing the trailing particle located in this region to accelerate and approach the leading particle, thereby colliding and aggregating [27]. Researchers have proposed methods for calculating the acoustic wake effect [28], and experimental observation of the mutual motion between particles has provided support for the existence of the acoustic wake effect [29]. Based on this, an expression for the average particle agglomeration velocity based on the acoustic wake effect has been derived [30]. Based on this, Gonzalez et al. established a model of mutual motion between particles under the combined action of same-direction interaction, gravity, and the acoustic wake effect. Theoretical calculations and numerical analysis were performed on the process of mutual motion between particles and the collision time and agglomeration velocity. They conducted experimental studies on mutual motion between particles under different entrainment coefficients [31], as well as characteristic research on particle agglomeration behavior under different particle size ranges [32–35]. They also corrected the disturbance velocity generated by the acoustic wake effect and improved the model of mutual motion between particles under sound agglomeration [36].

The characteristics of the sound field, such as the frequency and sound pressure level of the sound waves, also have a significant impact on the agglomeration effect of the sound waves. Hoffmann [37] conducted experiments on fly ash particles during coal combustion and found that sound waves with an ultra-low frequency of 44 Hz can also achieve satisfactory agglomeration effects with lower energy consumption. Zhang [38] and others studied the influence of sound pressure level on agglomeration under low-frequency sound wave conditions using coal dust. The results showed that the higher the sound pressure level, the better the agglomeration effect, and the best agglomeration effect was obtained at 147 dB in the experiment. However, it does not mean that the higher the sound pressure level, the better the agglomeration effect. The appropriate acoustic characteristics for agglomeration depend on the particle source, experimental objectives, and experimental conditions, and there is no universally optimal conclusion, which means it is difficult to find results that satisfy all conditions.

This article summarizes the main progress in the theory, numerical calculation, and experimental research of particle movement under the action of sound agglomeration, as shown in Tables 1 and 2. Table 1 shows that there are many research approaches that can be drawn upon, especially the model of mutual motion between particles under the combined action of same-direction interaction and acoustic wake effect established in previous studies, which can provide important theoretical references for this study to establish a model of mutual motion between oil fine particles under sound agglomeration. Additionally, when the particle size is small (usually with a diameter less than 100 μm), the inter-particle cohesive force is similar to its own gravity and fluid dynamics, and adjacent particles can attract each other under the action of cohesive force and cause adhesion and agglomeration [39]. Furthermore, the high viscosity unique to oil fine particles makes the effect of adhesion more specific to their mutual motion.

Table 1. The research progress in theoretical models and numerical calculation of particle interaction under acoustic convergence.

Year	Related Literature	Particle Type	Research Results
1936	[21]	smoke particles	Based on the Stokes force acting on particles, a theoretical expression for particle velocity was derived.
1965	[22]	monodisperse particles	A coalescence model for particles with parallel interactions was established.
1959	[28]	PM2.5 particles	Based on direct simulation Monte Carlo method, the acoustic coalescence of PM2.5 particles under the effects of parallel interaction, gravity settling, and Brownian diffusion was simulated, and it is believed that the acoustic coalescence is mainly controlled by the parallel interaction mechanism and gravity settling mechanism.
1981	[40]	particles with a diameter of 0.1–1 μm	Through simulation, the acoustic coalescence effects under different sound intensities and particle mass loads were compared, and it is found that the standing wave coalescence effect is better than the traveling wave effect.
1990	[41]	fly ash particles	A scattering effect coalescence model was established. The parallel interaction and fluid mechanics mechanisms of fly ash particles are simulated, and the contribution of the fluid mechanics mechanism to the coalescence rate is quantitatively determined for the first time.
1995	[23]	spherical rigid particles	Non-steady forces are included in the acoustic particle dynamics model.

Table 1. *Cont.*

Year	Related Literature	Particle Type	Research Results
2003	[13]	monodisperse particles	A two-dimensional model of particle interaction was established under the combined effect of parallel interaction, gravity, and acoustic wake.
2011	[25]	PM2.5 particles	The dynamic process of two particles approaching each other gradually under the action of parallel interaction mechanism and gravity, forming a double particle aggregate, and continuing to move was simulated.
2012	[24]	spherical aerosol particles	A dimensionless motion equation for particles under the action of acoustic Stokes force and non-steady force was established.
2016	[35]	particles with an average diameter of 0.8 μm	A two-dimensional model of particle interaction was established, considering the parallel interaction mechanism, acoustic wake effect, and co-radiation pressure effect, and it is believed that the acoustic wake effect is the main coalescence mechanism.
2019	[6]	fly ash particles, dehydrogenation particles	Using the COMSOL Multiphysics software's computational fluid dynamics acoustics and particle tracking modules, the region of the ratio of broken and unbroken particle diameters was simulated.
2020	[42]	liquid droplets with a diameter of 10 μm.	Using a three-dimensional CFD-DEM model, the acoustic coalescence of droplet clusters was studied, and the results show that the coalescence performance of aerosols is better under high sound intensity and high temperature and pressure conditions.

Table 2. The research progress in experimental study of particle interaction under acoustic convergence.

Year	Related Literature	Particle Type	Research Results
1976	[43]	black carbon particles	Using an electron microscope, sound coagulation phenomena of black carbon aerosol particles with a diameter of 0.01–0.1 μm were observed.
1979	[27]	monodisperse particles with a diameter of 0.17 μm	Sound coagulation phenomena were observed in a monodisperse phase aerosol with a diameter of 0.17 μm in a standing wave sound field.
1996	[20]	quartz particles glass microbead particles	The sound coagulation process of monodisperse glass microbeads (with diameters of 8.1~22.1 μm) and polydisperse quartz particles (with diameters of 25~35 μm) were recorded, and the tuning fork coagulation effect was found, verifying the acoustic radiation force effect.
2007	[44]	coal particles	The motion trajectory of individual coal fly ash particles (with a diameter of 0.75 μm) and particle clusters (with a diameter of 3 μm) in a standing wave sound field was recorded using a high-speed camera, and an S-shaped trajectory was observed.
2016	[17]	soot particles	The sound coagulation phenomenon of ultrafine particles was measured using a scanning mobility particle sizer, and it was found that sound waves at a frequency of 20 kHz had a coagulation effect on particles with diameters of 10~487 nm.
2016	[45]	smoke particles	The motion velocity of monodisperse particles with a diameter of approximately 7.5 μm in both traveling and standing wave sound fields was obtained.
2020	[46]	smoke particles	The experiment found that the smoke removal rate could reach 70% at a sound frequency of 1500 Hz, and the smoke removal efficiency increased as the smoke temperature decreased. When the sound pressure level exceeded 120 dB, the smoke removal rate was significantly improved.
2022	[47]	Ultrafine droplets	A type of airflow sound source with aerosol separation characteristics, which can effectively remove aggregated indoor droplets within 10 s. The higher the sound pressure level, the better the aggregation effect. The optimal aggregation effect is achieved at 0.3 MPa.

Therefore, based on the two mechanisms of sound agglomeration and adhesion agglomeration, it is important to reveal the agglomeration behavior of oil-based fine particles. After increasing the probability of particle collision with the external sound field, adhesion agglomeration is used to stabilize the agglomerates. The key issue is to incorporate the inter-particle cohesive force into the model of mutual motion between oil fine particles, as shown in Figure 3, and obtain the effective range and operating conditions of adhesion agglomeration (such as the cohesive number, which is the ratio of inter-particle cohesive force to inertial force, and inter-particle spacing), as well as the corresponding range of adjustable sound field parameters.

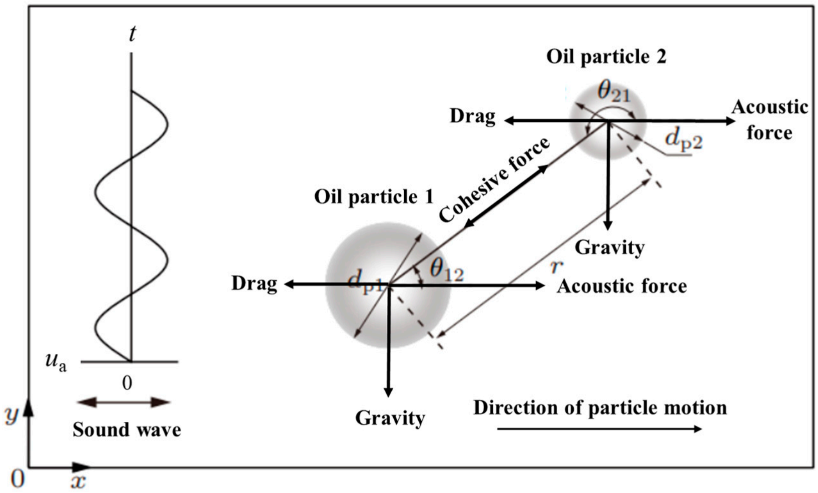


Figure 3. Schematic diagram of the force model between oily fine particles including cohesive forces.

Table 2 presents the main progress in experimental research on inter-particle interaction. As shown in Table 2, the current experimental research mainly focuses on particles with sizes above 7 μm, and the experimental results are almost all about the interaction process of monodisperse particles. However, the actual industrial applications of sound agglomeration involve mainly polydisperse particles with sizes ranging from 0.1 to 10 μm. Therefore, further in-depth research is needed on the micro-dynamics of mutual motion between fine particles.

3. Research Progress on Particle Agglomeration and Growth under the Combined Effect of Sound Agglomeration and Water Vapor Condensation

In order to achieve efficient sound agglomeration with low energy consumption, some scholars have conducted research on particle agglomeration and growth under the combined effect of sound agglomeration and water vapor condensation. In the presence of particles in a humid environment, water vapor will accumulate on the surface of the particles, undergo heterogeneous nucleation and condensation, and form stronger and less breakable agglomerates. Furthermore, the agglomerates can continue to bridge each other and form even larger ones [10]. Because the nucleation characteristics play a decisive role in water vapor condensation and particle growth [48,49], many scholars have studied the heterogeneous nucleation properties of water vapor on particle surfaces. The existing theories that describe heterogeneous nucleation of supersaturated water vapor on fine particle surfaces mainly include classical heterogeneous nucleation theory, molecular dynamics theory, and density functional theory. Since the first proposal, classical heterogeneous nucleation theory has been continuously developed and extended to particles with rough [50] and uneven [51] surfaces, taking into account the influence of line tension [52] and the surface adsorption water diffusion mechanism [53]. However, theoretical analysis and numerical simulation studies have mainly focused on insoluble particles, and the research on oil fine particles containing soluble organic matter in machining production emissions is still insufficient. Even though Fan et al. [54] utilized numerical simulation to investigate the heterogeneous nucleation properties of water vapor on the surface of particles containing both insoluble spherical nuclei and soluble inorganic salts, such as NaCl, based on the characteristics of municipal solid waste incineration particles, a water vapor saturation degree of nearly 1.45 was utilized in the study, for which it is difficult to provide reference for the engineering application of water vapor condensation technology to remove industrial oil fine particles.

In 2000, R. Sarabia et al. [55] used a standing wave sound field with a sound pressure level of 150 dB and a frequency of 20 kHz to control diesel engine tailpipe particles (0.02–0.7 μm) and found that the removal efficiency of particles increased significantly after humidification. A study by Yan et al. [56] also found that the removal efficiency of coal-fired fine particles (PM2.5) under a 150 dB sound field combined with water vapor condensation can reach 53–80%. Tao et al. [57] used low-frequency sound waves and conducted experiments to obtain the optimal aggregation efficiency of coal dust under pure sound wave conditions, which was found to be 44.84%. However, by adding a spray device, the aggregation efficiency increased to 66.48%. This shows that the combined effect of sound agglomeration and water vapor condensation has good application prospects. However, most of the existing research focuses on the nucleation of water vapor on non-oil particles or on the surface of single-component particles, and research on the nucleation properties of water vapor on the surface of oil fine particles is clearly insufficient. The wettability, solubility, and physicochemical properties of oil fine particles are significantly different from those of existing studies on aerosol particles, and, more importantly, the components of oil fine particles emitted from different production processes are diverse and significantly different. Therefore, it is necessary to study the nucleation properties of oil fine particles to explore and understand the mechanisms and influencing factors of oil fine particle agglomeration and growth under the combined effect of sound and water vapor fields, and to provide a research basis and guidance for the application of this technology in the purification and removal of oil fine particles.

4. Discussion and Conclusions

Experimental and numerical simulation studies on the agglomeration of oily adhesive microparticles are currently quite limited. Previous studies have mostly focused on rigid, non-oily particles, and there is a lack of research specifically on the application of agglomeration of adhesive microparticles in industrial settings. However, in many industrial processing processes, a large amount of metalworking fluid (containing a significant number of oily components) is used. Its function is to lubricate, cool, and prevent the oxidation and corrosion of processed products during cutting processes. During workpiece machining, the high-speed rotating cutting tools fling and break up the metalworking fluid, causing it to disperse throughout the workplace environment. Traditional local ventilation techniques have limited efficiency in capturing such oily adhesive microparticles, and most particles are suspended and spread in a disorderly manner in the factory's workplace environment, leading to poor health conditions for the workers. On the other hand, phase transition effects are relatively mature in current research, and their promoting effect on acoustic particle agglomeration is also evident. This paper provides an overview and summary of research on the impact of sound waves on the agglomeration of fine particles:

(1) Sound agglomeration is a phenomenon that is formed via multiple mechanisms, such as co-directional aggregation and fluid mechanics. It involves complex phenomena and processes, such as the effect of sound field on particles, the influence of particle movement on sound field, and the scattering of sound waves. A deep understanding of the agglomeration effect of sound is necessary before conducting numerical simulation and sound agglomeration experiments, and the study of micro-agglomeration basic theory of aerosols is essential. Currently, most of the theoretical studies on the mutual movement of particles under sound agglomeration focus on co-directional interaction and the sound wake effect. The agglomeration effect of sound is influenced by factors, such as sound intensity, sound frequency, aerosol concentration, sound wave form, particle size

distribution, and temperature and humidity, which are not independent. One factor can also affect the effect of other factors on the efficiency of sound agglomeration. Scholars mostly explore the principles and laws of sound agglomeration based on this. Through the induction and analysis of existing research, it is planned to establish a model of the mutual movement of oil fine particles under sound agglomeration to reveal the agglomeration behavior mechanism of oil fine particles. In addition, it is urgent to develop research on the mutual movement of multi-dispersed fine particles under sound agglomeration in industrial practical applications to overcome the limitations of future micro-kinetic theory.

(2) Significant progress has been made in the in-depth study of sound agglomeration, but the purification efficiency of sound agglomeration and adhesion agglomeration still has significant uncertainties. The effective range and conditions of adhesion agglomeration on stable particle agglomeration bodies, as well as the corresponding range of adjustable sound field parameters, require a large number of experiments and numerical simulations. It is urgently necessary to develop comprehensive mathematical models and numerical simulation methods that can overcome different theoretical limitations. Additionally, it is necessary to further strengthen the development of experimental techniques to verify the theoretical and numerical simulation results of the mutual movement model of oil fine particles under sound agglomeration.

(3) Previous research has shown that the combined action of sound field and water vapor condensation has a significant effect on the removal of insoluble particulate matter. Water vapor condenses heterogeneously on the particle surface, promoting the formation of more stable and larger agglomerates from smaller particles, thus affecting the purification efficiency of the engineering environment. However, there is currently a lack of research on the nucleation characteristics of water vapor on the surface of oil fine particles. Considering the characteristics of oil fine particles and the complexity of actual industrial production, the accurate evaluation of the impact of sound–water vapor composite fields on oil fine particles remains a challenge.

Therefore, for industrial oil fine particles, the core scientific objective is to explore the control of particle growth through the combined action of sound agglomeration and water vapor condensation, and to develop more efficient purification technologies and equipment. To achieve this, it is necessary to strengthen theoretical, experimental, and numerical simulation studies on the mechanisms of agglomeration and growth of oil fine particles under sound–water vapor composite fields, as well as to apply the theory of agglomeration and growth in the development of new purification equipment. These studies will provide a fundamental basis for achieving a breakthrough in the theoretical control of oil fine particle growth under sound–water vapor composite fields and have significant theoretical reference and engineering application value for the development of oil fine particle purification technologies based on the theory of agglomeration and growth.

Author Contributions: Conceptualization, D.L. and X.W.; methodology, D.L. and X.W.; software, T.L.; validation, D.L. and T.L.; formal analysis, Y.L. and L.Y.; investigation, Y.X.; resources, F.W.; data curation, D.L. and T.L.; writing—original draft preparation, D.L.; writing—review and editing, D.L.; visualization, D.L.; supervision, Y.Y.; project administration, X.W.; funding acquisition, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: Wang, X., Machinery Industry Innovation Platform Construction Project: 2019SA-10-07; Wang, X., Shandong Construction Department Research and Development Project: K2019370; Li, Y., Sponsored by Shanghai Sailing Program: 20YF1432000.

Data Availability Statement: Authors are not authorized to share data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, X.; Yang, L.; Liu, Y.; Wang, F.; Zhou, Y.; Jiang, X.; Zhang, Y. Emission characteristics of oil mist and its capture control effect of machine tools in machining workshops. *Heat. Vent. Air Cond.* **2023**, *53*, 178–184. (In Chinese)
2. Donguk, P. The Occupational Exposure Limit for Fluid Aerosol Generated in Metalworking Operations: Limitations and Recommendations. *Safe Health Work* **2012**, *3*, 1–10.
3. Brinksmeier, E.; Garbrecht, M.; Heinzel, C. Current Approaches in Design and Supply of Metalworking Fluids. *Tribol. Trans.* **2009**, *52*, 591–601. [CrossRef]
4. Wang, F.; Wu, Z.; Jiang, X.; Zhou, Y.; Wang, X.; Song, B.; Shao, M. Field measurement of oil mist particle concentration distribution in machining workshops. *Heat. Vent. Air Cond.* **2022**, *49*, 130–137. (In Chinese)
5. Gallego-Juárez, J.A.; De Sarabia, E.R.-F.; RodrÍguez-Corral, G.; Hoffmann, T.L.; Gálvez-Moraleda, J.C.; RodrÍguez-Maroto, J.J.; Gómez-Moreno, F.J.; Bahillo-Ruiz, A.; MartÍn-Espigares, M.; Acha, M. Application of acoustic agglomeration to reduce fine particle emissions from coal combustion plants. *Environ. Sci. Technol.* **1999**, *33*, 3843–3849. [CrossRef]
6. Lu, M.; Fang, M.; He, M.; Liu, S.; Luo, Z. Insights into agglomeration and separation of fly-ash particles in a sound wave field. *RSC Adv.* **2019**, *9*, 5224–5233. [CrossRef] [PubMed]
7. Shen, G.; Huang, X.; He, C.; Zhang, S.; An, L.; Wang, L.; Chen, Y.; Li, Y. Experimental study of acoustic agglomeration and fragmentation on coal-fired ash. In Proceedings of the 2nd International Conference on Energy Engineering and Environmental Protection (EEEP), Sanya, China, 20–22 November 2018. [CrossRef]
8. Wang, X.; Li, D.; Zhang, Q.; Li, T.; Cao, Z.; Wang, F. Experimental Study on the Agglomeration of Oily Fine Particles by Sound Wave. *Buildings* **2023**, *13*, 1660. [CrossRef]
9. Edward, B.; Bernhard, V.; Meiburg, E. A Collision Model for Grain-resolving Simulations of Flows Over Dense, Mobile, Polydisperse Granular Sediment Beds. *J. Comput. Phys.* **2017**, *340*, 105–127.
10. Alexandre, G.; Jacques, B. Wet agglomeration of powders: From physics toward process optimization. *Powder Technol.* **2001**, *117*, 221–237.
11. Guo, S.; Huang, Y.; Wang, Y.; Lu, K.; Guo, J.; Fan, J.; Fu, W. Pollution characteristics of the generated particles during finishing rolling process and concentration monitoring in the occupied zone. *Chin. J. Environ. Eng.* **2021**, *15*, 307–315. (In Chinese)
12. Zhang, J.; Yuan, S.; Long, Z. Physicochemical characterization of oily particles emitted from different machining processes. *J. Aerosol Sci.* **2016**, *96*, 1–13. [CrossRef]
13. Marco, T.; Francesco, D.N.; Antonio, S.; Amedeo, L. Heterogeneous condensation of submicron particles in a growth tube. *Chem. Eng. Sci.* **2012**, *74*, 124–134.
14. Itziar, G.; Juan, A.; Gallego, J.; Enrique, R. The influence of entrainment on acoustically induced interactions between aerosol particles—An experimental study. *J. Aerosol Sci.* **2003**, *34*, 1611–1631.
15. Lin, C.; Zhang, G.; Ma, Z.; Wang, J.; Gu, H.; Yuan, D. Research on micro-mechanism of acoustic agglomeration of fine particles. *Tech. Acoust.* **2021**, *40*, 587–593. (In Chinese)
16. Liu, J.; Wang, J.; Zhang, G.; Zhou, J.; Cen, K. Frequency comparative study of coal-fired fly ash acoustic agglomeration. *J. Environ. Sci.* **2011**, *23*, 1845–1851. [CrossRef]
17. Kang, Y.; Zhu, Y.; Lin, F.; Zhang, W. Influencing factors of acoustic agglomeration of ultrafine particles. *J. Shanghai Jiao Tong Univ.* **2016**, *50*, 551–556. (In Chinese)
18. Chen, H.; Luo, Z.; Jiang, J.; Zhou, D.; Lu, M.; Fang, M.; Cen, K. Effects of simultaneous acoustic and electric fields on removal of fine particles emitted from coal combustion. *Powder Technol.* **2015**, *281*, 12–19. [CrossRef]
19. Yan, J.; Chen, L.; Yang, L. Combined effect of acoustic agglomeration and vapor condensation on fine particles removal. *Chem. Eng. J.* **2016**, *290*, 319–327. [CrossRef]
20. Thomas, L.H.; Gary, H.K. Visualization of acoustic particle interaction and agglomeration: Theory and experiments. *J. Acoust. Soc. Am.* **1996**, *99*, 2130–2141.
21. Brandt, O.; Hiedemann, E. The aggregation of suspended particles in gases by sonic and supersonic waves. *Trans. Faraday Soc.* **1936**, *32*, 1101–1110. [CrossRef]
22. Mednikov, E.P. *Acoustic Coagulation and Precipitation of Aerosols*; Consultants Bureau: New York, NY, USA, 1965.
23. Dodemand, E.; Prud'homme, R.; Kuentzmann, P. Influence of unsteady forces acting on a particle in a suspension application to the sound propagation-ScienceDirect. *Int. J. Multiph. Flow* **1995**, *21*, 27–51. [CrossRef]
24. Cleckler, J.; Elghobashi, S.; Feng, L. On the motion of inertial particles by sound waves. *Phys. Fluids* **2012**, *24*, 033301. [CrossRef]
25. Wang, Z.; Zhong, X.; Yan, Y.; Ge, R. Particles collision model of PM2.5 in sound field. *Chin. J. Environ. Eng.* **2011**, *5*, 2839–2843. (In Chinese)
26. Song, X.; Fan, F. Analysis of the factors influencing the drift of inhalable particles in a standing wave acoustic field. *J. Eng. Therm. Energy Power* **2016**, *31*, 75–82. (In Chinese)
27. Shaw, D.T.; Tu, K.W. Acoustic particle agglomeration due to hydrodynamic interaction between monodisperse aerosols. *J. Aerosol Sci.* **1979**, *10*, 317–328. [CrossRef]
28. Pshenai-Severin, S.V. On the convergence of aerosol particles in a sound field under the action of the Oseen hydrodynamic forces. *Dokl. Akad. Nauk SSSR* **1959**, *125*, 775–778.
29. Shirokov, N.L.; Éknadiosyanta, O.K. Interaction of aerosol particles in an acoustic field. *Sov. Phys. Acoust.* **1966**, *11*, 346–348.

30. Dianov, D.B.; Podolskii, A.A.; Turubarov, V.I. Calculation of the hydrodynamic interaction of aerosol particles in a sound field under seen flow conditions. *Sov. Phys. Acoust.* **1968**, *13*, 314–319.
31. Itzar, G.; Thomas, L.H.; Gallego, J.A. Precise measurements of particle entrainment in a standing-wave acoustic field between 20 and 3500 Hz. *J. Aerosol Sci.* **2000**, *31*, 1461–1468.
32. Zhang, G.; Liu, J.; Wang, J.; Zhou, J.; Cen, K. Numerical simulation of acoustic wake effect in acoustic agglomeration under Oseen flow condition. *Chin. Sci. Bull.* **2012**, *57*, 2404–2412. [CrossRef]
33. Zhang, G.; Liu, J.; Wang, J.; Zhou, J.; Cen, K. Theoretical study of acoustic wake effect in acoustic agglomeration. *J. Chem. Eng. Chin. Univ.* **2013**, *27*, 199–204. (In Chinese)
34. Markauskas, D.; Kacianauskas, R.; Maknickas, A. Numerical particle-based analysis of the effects responsible for acoustic particle agglomeration. *Adv. Powder Technol.* **2015**, *26*, 698–704. [CrossRef]
35. Algirdas, M.; Darius, M.; Rimantas, K. Discrete element simulating the hydrodynamic effects in acoustic agglomeration of micron-sized particles. *Part. Sci. Technol.* **2016**, *34*, 453–460.
36. Zhang, G.; Zhang, L.; Wang, J.; Chi, Z. A new model for the acoustic wake effect in aerosol acoustic agglomeration processes. *Appl. Math. Model.* **2018**, *61*, 124–140. [CrossRef]
37. Hoffmann, T.L.; Chen, W.; Koopmann, G.H.; Scaroni, A.W.; Song, L. Experimental and numerical analysis of bimodal acoustic agglomeration. *J. Vib. Acoust.* **1993**, *115*, 232–240. [CrossRef]
38. Zhang, G. *Theoretical and Experimental Research on Acoustic Agglomeration of Coal Fly Ash Aerosols*; Zhejiang University: Zhejiang, China, 2010.
39. Vowinckel, B.; Withers, J.; Luzzatto-Fegiz, P.; Meiburg, E. Settling of Cohesive Sediment: Particle-Resolved Simulations. *J. Fluid Mech.* **2019**, *858*, 5–44. [CrossRef]
40. Chou, K.H.; Lee, P.S.; Shaw, D.T. Aerosol agglomeration in high-intensity acoustic fields. *J. Colloid Interface Sci.* **1981**, *83*, 335–353. [CrossRef]
41. Song, L. *Modeling of Acoustic Agglomeration of Fine Aerosol Particles*; Pennsylvania State University: University Park, TX, USA, 1990.
42. Shi, Y.; Wei, J.; Qiu, J.; Chu, H.; Bai, W.; Wang, G. Numerical study of acoustic agglomeration process of droplet aerosols using a three-dimensional CFD-DEM coupled model. *Powder Technol.* **2020**, *362*, 37–53. [CrossRef]
43. Volk, M., Jr.; Moroz, W.J. Sonic agglomeration of aerosol particles. *Water Air Soil Pollut.* **1976**, *5*, 319–334. [CrossRef]
44. Zhao, B.; Yao, G.; Yang, L.; Chen, H.; Shen, X. Comparison of dynamical behavior between fine particles and aggregates from coal combustion. *Proc. CSEE* **2007**, *27*, 1–4. (In Chinese)
45. Zhou, D.; Luo, Z.; Fang, M.; Lu, M.; Jiang, J.; Chen, H.; He, M. Numerical calculation of particle movement in sound wave fields and experimental verification through high-speed photography. *Appl. Energy* **2016**, *185*, 2245–2250. [CrossRef]
46. Li, K.; Wang, E.; Wang, Q.; Husnain, N.; Li, D.; Shagufta, F. Improving the removal of inhalable particles by combining flue gas condensation and acoustic agglomeration. *J. Clean. Prod.* **2020**, *261*, 121270. [CrossRef]
47. Pang, Y.; Zhang, G.; Lv, H. Acoustic characteristic and aerosol agglomeration rate of a new type air-jet generator. *J. Appl. Acoust.* **2022**, *41*, 948–955.
48. Tetsuo, Y.; Yasuo, K.; Kikuo, O. Growth of aerosol particles by condensation. *Ind. Eng. Chem. Fundam.* **1976**, *15*, 37–41.
49. Heidenreich, S.; Vogt, U.; Büttner, H.; Ebert, F. A novel process to separate submicron particles from gases—A cascade of packed columns. *Chem. Eng. Sci.* **2000**, *55*, 2895–2905. [CrossRef]
50. Xiong, G.; Xie, J.; Yang, L. Numerical simulation of effect of roughness on heterogeneous nucleation of water vapor on fine particle surface. *CIESC J.* **2021**, *72*, 4304–4313. (In Chinese)
51. Yan, J.; Yang, L.; Fan, F.; Shen, X. Numerical analysis of water vapor nucleation on fine particles from coal combustion based on fractal model. *Proc. CSEE* **2009**, *29*, 50–56. (In Chinese)
52. Hienola, A.I.; Winkler, P.M.; Wagner, P.E.; Vehkamäki, H.; Lauri, A.; Napari, I.; Kulmala, M. Estimation of line tension and contact angle from heterogeneous nucleation experimental data. *J. Chem. Phys.* **2007**, *126*, 094705. [CrossRef]
53. Xu, J.; Yu, Y.; Zhang, J.; Zhong, H. Kinetics study of droplet growth on surface of coal-fired fine particles. *J. Southeast Univ. Nat. Sci. Ed.* **2017**, *47*, 506–512. (In Chinese)
54. Fan, F.; Yang, L.; Yan, J.; Yuan, Z. Numerical analysis of water vapor nucleation on PM2.5 from municipal solid waste incineration. *Chem. Eng. J.* **2009**, *146*, 259–265. [CrossRef]
55. Sarabia, E.R.; Gallego-Juárez, J.A.; Acosta-Aparicio, V.M.; Rodriguez-Maroto, J.; Dorronsoro, J.L.; Sanz-Rivera, D.; Gómez-Moreno, F.J.; Martín-Espigares, M. Acoustic agglomeration of submicron particles in diesel exhausts: First results of the influence of humidity at two acoustic frequencies. *J. Aerosol Sci.* **2000**, *31*, 827–828. [CrossRef]
56. Yan, J.; Chen, L.; Zhong, L. Removal of fine particles from coal combustion in the combined effect of acoustic agglomeration and seed droplets with wetting agent. *Fuel* **2016**, *165*, 316–323. [CrossRef]
57. Tao, W.; Xu, C.; Zhong, Z. Experimental study on acoustic agglomeration and combined spray optimization of fine particles at low concentration. *Environ. Eng.* **2020**, *38*, 162–168+127.