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Review

Review of Acoustic Agglomeration Technology Research

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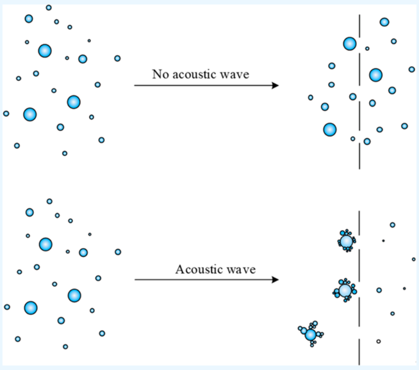
ABSTRACT: Acoustic agglomeration is employed as a precursor technique that modifies the sound field of fine particles to increase their size, thereby facilitating more efficient emission control. This paper reviews progress in the field of acoustic agglomeration technology, clarifies the mechanisms at play within the acoustic agglomeration process, and outlines its applicability in both gas−liquid and gas−solid phases. Furthermore, it analyzes the factors impacting the efficacy of acoustic agglomeration, summarizes the numerical simulation research of acoustic agglomeration, and proposes directions for technological enhancement.



1. INTRODUCTION

The effective mitigation of ultrafine particles continues to be a critical concern. Ultrafine particles are generally categorized into two types: droplet-based and solid. Their existence presents multiple challenges in diverse industrial sectors.

In the food and medical industries, the failure to completely remove microdroplet oil particles from compressed gas can lead to the erosion and corrosion of compressor blades, reducing the lifespan of the equipment. This problem may further cause degradation of food products and complications in medical procedures. In meteorology, the presence of fog consisting of ultrafine droplets decreases atmospheric visibility, adversely affecting transportation safety. Within the realm of power generation, the widespread use of wet desulfurization techniques in contemporary power plants encounters obstacles at the emission control stage. The excessive release of water vapor through chimneys, a secondary outcome of this method, results in inefficient recycling of cooling water and, to some extent, contributes to the formation of atmospheric haze.

The presence of ultrafine solid particles is linked to numerous environmental and health concerns. For instance, emissions from automobile exhaust, a major source of micron-sized solid particles, contribute significantly to atmospheric pollution. In industrial settings, particularly during boiler operations, the combustion of fuel generates a substantial quantity of solid particles in the flue gas. Although larger particles are effectively removed by dust extraction and desulfurization systems, the concentration of ultrafine particles often increases after treatment. These particles, once emitted into the atmosphere, combine with atmospheric water vapor to form haze, which adversely affects respiratory health. Furthermore, in incidents of fire, dense smoke containing toxic and hazardous particles is the primary cause of fatalities. These particles, carried by the hot air from combustion, present significant risks of inhalation and suffocation. Furthermore, ultrafine particle pollution originates from various sources, including mine dust and gas turbine emissions, etc.

Current particle agglomeration technologies, including thermal, electrostatic, chemical, and magnetic methods, are proficient in aggregating larger particles. However, their efficiency decreases with ultrafine particles. These methods also require significant ancillary energy inputs such as heat and electrical energy, which contribute to economic inefficiencies and hinder their broader application. Additionally, the space required for technologies like chemical and thermal agglomeration limits their utility in compact settings. To address these challenges, acoustic agglomeration has been introduced as a novel noncontact method. This approach employs acoustic waves to promote agglomeration by introducing an acoustic field that facilitates the formation of larger particles from smaller ones. Acoustic agglomeration offers numerous advantages, including higher efficiency, reduced energy consumption, operational simplicity, pollution absence, and minimal spatial requirements. Research on acoustic agglomeration, extending over a century, has accumulated a deep understanding of its mechanisms. Empirical studies demon-

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Table 1. Main Development Process of Acoustic Agglomeration

Time	Main Contributors and Main Content	
1927	Wood[1]	The acoustic agglomeration phenomenon was found for the first time.
1931	Patterson and Cawood[2]	The phenomenon of aerosol aggregation in the standing wave tube is found.
1932	Andrade[3]	Found the relationship between particle motion and acoustic wave action.
1950s	It was first applied to the recovery of sulfuric acid aerosols, but could not specifically explain the agglomeration effect, and was subsequently shelved.	
1955−1964	Fuks,[5] Moore[6]	To explore the influencing factors of aerosol agglomeration; explore the possibility of acoustic agglomeration for defogging.
1965	Mednikov[7]	Combined with previous studies, a complete acoustic agglomeration mechanism and orthokinetic interaction mechanism are proposed for the first time.
1970s∼1990s	Michael Volk, Jr.[8]	The Brownian agglomeration mechanism is coupled based on the Orthokinetic interaction mechanism.
	K. H. Chou[9]	Proposed acoustic turbulence is one of the main reasons for agglomeration.
	Tiwary[10]	The acoustic wake effect is studied by simulation, which is one of the main factors affecting agglomeration.
1970s∼1990s	Song[11]	The mechanism model is improved, and the acoustic scattering and the common radiation pressure are used as supplementary mechanisms.
1990s∼now	Through the combination of existing mechanisms and experimental research, the mechanism is further improved. Study the factors affecting the agglomeration effect; explore the practical application scenarios.	

strate that acoustic agglomeration can effectively reduce particle numbers and increase particle size within a short time frame. This technology is adaptable, applicable across various scenarios and devices aiming to eliminate ultrafine particles, and demonstrates significant scalability.

The widespread adoption of acoustic agglomeration technology in industrial applications is constrained by its limited range and effectiveness in extensive areas, highlighting the need for further research to enhance its efficiency. Moreover, the noise produced by acoustic waves curtails their use, particularly near residential zones, indicating a requirement for noise reduction strategies such as silencers. Despite these challenges, acoustic agglomeration continues to be an effective method for the removal of ultrafine particles, offering substantial potential for improvement and broader application.

2. DEVELOPMENT OF ACOUSTIC AGGLOMERATION TECHNOLOGY

In 1927, Wood[1] initially observed the phenomenon of acoustic agglomeration. Following this discovery, Patterson, Cawood,[2] and Andrade[3] conducted experiments demonstrating that particulate aerosols coalesce under the influence of acoustic waves. Subsequent studies have explored the potential of acoustic agglomeration in applications such as defogging and the recovery of sulfuric acid aerosols. However, challenges in elucidating the precise mechanisms of agglomeration and limitations related to the power of sound sources have temporarily impeded further development.[4] Despite these constraints, several qualitative experiments have substantiated the practicality of agglomeration applications.[5,6]

In 1965, Mednikov[7] initially proposed the orthokinetic interaction mechanism of acoustic agglomeration in his seminal work on the subject. This publication systematically elucidated for the first time the phenomenon and theoretical foundations of acoustic agglomeration, introducing the concept of agglomeration volume. This marked a pioneering contribution to the field of acoustic agglomeration theory.

In the 1970s, motivated by Mednikov's model and an intensified focus on pollution reduction, research into acoustic agglomeration received renewed attention. Subsequent studies revealed that orthokinetic interaction alone was insufficient to account for certain agglomeration phenomena, suggesting the presence of additional mechanisms, given the effectiveness of the process beyond merely acoustic wave amplitudes.

Numerous scholars have further elucidated the mechanisms underlying acoustic agglomeration through both numerical calculations and experimental research. These investigations primarily consider the disturbance caused by acoustic waves and the consequent interactions with fluid dynamics. For example, the inclusion of Brownian condensation within the orthokinetic interaction model has led to enhancements in the acoustic agglomeration model.[8] The turbulent inertial interaction caused by the turbulence generated by acoustic waves produces agglomeration.[9] These experiments validated the theory of aerosol deposition and agglomeration in strong sound fields. In addition, through simulation studies, it is found that the interaction between particles cannot be ignored, such as the wake effect generated by the movement between particles,[10] the scattering effect under the action of sound waves,[11] and the mutual radiation pressure effect between particles in the fluid.[9,13,14] In terms of agglomeration mechanisms, the orthokinetic interaction mechanism and the acoustic wake effect are widely recognized; however, the significance of other mechanisms within the agglomeration process remains a subject of debate. This period was crucial for the identification and demonstration of all primary mechanisms of acoustic agglomeration, thereby establishing a robust foundation for the optimization of related theoretical models.

Subsequent researchers have focused primarily on advancing the existing theory of sound wave agglomeration, aiming to identify the predominant mechanisms in the agglomeration process while refining the theoretical model. For instance, experimental research has revealed that the acoustic wake effect plays a significant role in enhancing agglomeration within the low-frequency sound field under a single dispersed phase.[15,16] In the multidispersed phase, the wake effect plays a significant role in the high-frequency sound field, while the orthokinetic interaction effect is stronger in the low-frequency sound field.[17] Additionally, incorporating multiple well-recognized dominant mechanisms can enhance the alignment of simulation results with experimental data.[18] It is widely accepted that the hydrodynamic mechanism affects a range of approximately 50 times the particle size.[19] Furthermore, the Brownian agglomeration mechanism is 3−4 orders of magnitude less effective compared to other mechanisms.

Some scholars have experimentally explored the primary parameters influencing acoustic agglomeration by combining experiments and simulations to determine how to achieve optimal agglomeration efficiency through specific parameters. For instance, by measuring the acoustic agglomeration coefficient across various acoustic frequencies, it has been determined that this coefficient is proportional to the square of the medium's vibration velocity. Additionally, it is observed that the presence of standing waves significantly enhances the agglomeration process.[20] By recording the agglomeration efficiency corresponding to different acoustic frequencies, it is found that the acoustic frequency plays a key role in the agglomeration efficiency, and there is an optimal frequency that can produce the maximum agglomeration efficiency.[21] When the water mist is sprayed into the coal-fired flue gas to increase the agglomeration humidity, the acoustic agglomeration efficiency can be increased by 25% ∼ 40% without changing the optimal agglomeration frequency.[22] By establishing a three-dimensional CFD-DEM simulation model, it is found that the acoustic agglomeration effect is significantly affected by the acoustic frequency and is positively correlated with the sound pressure level.[23] Table 1 shows the main development process of acoustic agglomeration.

Furthermore, numerous scholars have explored the practical applications of acoustic agglomeration. Initially, this technology was applied in dust removal and collection, notably in coal-fired boiler dust control and air purification in mines. Additionally, as an effective method for ultrafine particle removal, it has been employed to reduce atmospheric pollution, including particulate matter. For example, integrating acoustic agglomeration technology into air conditioning systems has proven effective in aggregating PM2.5 particles, thereby reducing indoor pollution. Similarly, combining chemical sprays with acoustic agglomeration has proven to be effective in dust removal in mining environments.[24,25] Moreover, this technology has been applied experimentally to dissipate smoke generated during combustion processes at fire scenes, aiding in the prevention of smoke poisoning and enhancing visibility to facilitate evacuation efforts.[26] Regarding droplet agglomeration, some researchers have investigated relevant application scenarios. Yang,[27] for example, conducted experiments on the use of low-frequency acoustic waves for the removal of oil droplets in gas, noting an increase in the removal efficiency of 0.3−5 μm micro-oil droplets by over 20%. Exploring diverse application environments, Sadighzadeh A[28] proposed using acoustic agglomeration for acidic droplet removal in sulfuric acid mist. In the 0.4−20 μm droplet range, the maximum acoustic agglomeration efficiency achieved was 86%, demonstrating its potential as an effective anticorrosion strategy for gas-entrained acids. Guo[29] employed an airborne ultrasonic transducer for aerosol agglomeration, observing a rapid increase in smoke transmittance to 60% within seconds under the influence of ultrasonic transducer sound waves.

3. MECHANISM OF ACOUSTIC AGGLOMERATION

3.1. Orthokinetic Interaction Mechanism. The concept of the orthokinetic interaction mechanism, the earliest recognized mechanism in the field, was significantly advanced in 1965 by Mednikov.[7] In his influential work, Melnikov synthesized the research of his predecessors and meticulously detailed the phenomenon of acoustic agglomeration. He notably proposed the orthokinetic agglomeration mechanism and introduced the pioneering concept of "agglomeration volume," as illustrated in Figure 1. This mechanism suggests that the agglomeration of particles of varying sizes within a sound field is primarily driven by sound waves. Larger particles, due to their greater inertia, are less influenced by sound waves compared to their smaller counterparts. These smaller particles, closely following the wave motion, collide with and adhere to the larger particles, forming aggregates. This process facilitates particle agglomeration within the sound field. Building on this foundation, numerous scholars have adopted the orthokinetic interaction mechanism as a principal driver of acoustic agglomeration and have developed various research models based on this concept.[8,18,30−32] However, as research in this area deepened, it became apparent that the orthokinetic interaction mechanism could not solely account for all aspects of the acoustic agglomeration phenomenon. Several issues were identified: (1) The theory posits that in a sound field containing monodisperse-aerosols, where particles are of uniform size, there should be no relative motion between particles based on the orthokinetic interaction mechanism, and hence no agglomeration. This hypothesis, however, contradicts experimental evidence,[33] where agglomeration among particles of identical sizes was observed. For instance, Hoffmann's experiments[34,35] directly observed the attraction and collision leading to agglomeration among similarly sized particles in a sound field. Similarly, González[36] employed high-speed cameras to directly observe agglomeration among particles of the same size. (2) The mechanism also inadequately addresses the behavior of large particles sweeping through an aggregate and collecting smaller particles. According to the orthokinetic interaction theory, it is assumed that small particles on the periphery of an aggregate are immediately swept up and continue colliding with larger particles, a concept not fully consistent with actual observations.[21] (3) Additionally, the orthokinetic interaction theory fails to explain why the range of particle agglomeration extends significantly beyond the amplitude of the acoustic wave. The theory suggests that particles, irrespective of their size, should vibrate within a range that is less than or equal to the wave's amplitude due to their mass.

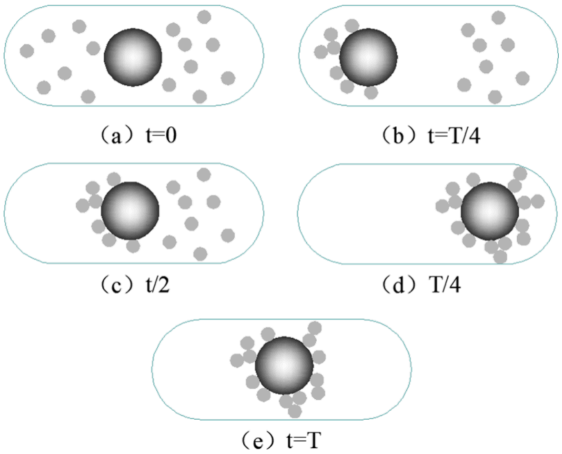

Figure 1. Orthokinetic interaction mechanism and agglomeration volume (a, b, c, d, and e denote the state of motion of particles in the agglomerate volume under different acoustic wave periods).

3.2. Fluid Dynamics Mechanism. Through meticulous observation and research, scholars have discovered that the mechanisms underlying acoustic agglomeration extend beyond the simple entrainment effect of acoustic waves to include hydrodynamic interactions between particles and the fluid medium within the sound field. This broader scope of interaction is primarily attributed to the viscosity between particles and the fluid medium. Introducing an additional sound field alters the flow state of both fluid and particles, thereby facilitating particle agglomeration. Researchers increasingly recognize this hydrodynamic effect as a principal mechanism of particle agglomeration, alongside the orthokinetic interaction mechanism. In-depth studies in this area have led scholars to propose various fluid mechanics theories to explain these phenomena, including turbulent inertial interaction, acoustic wave scattering effect, mutual radiation pressure effect, and acoustic wake effect. Each theory contributes to a more comprehensive understanding of the multifaceted nature of acoustic agglomeration, highlighting the complex interplay between acoustic and hydrodynamic forces in particle agglomeration processes.

3.2.1. Turbulent Inertial Interaction. When the intensity of the sound field reaches a specific threshold, pronounced oscillatory motion occurs within the flow field, leading to the congregation and agglomeration of fine particles. In 1965, Mednikov[7] first hypothesized that acoustic turbulence could facilitate the agglomeration of aerosol particles. This concept was further explored in 1981 by Chou et al.,[9] who conducted experimental studies on the turbulent effects during acoustic agglomeration. Their findings suggested that the turbulent inertial effect significantly enhances the acoustic agglomeration rate compared to the turbulent diffusion interaction. Later, in 1988, Malherbe et al. investigated the phenomenon of acoustic turbulence under varying sound intensities. They highlighted that acoustic turbulence plays a crucial role in influencing the coagulation velocity of particles within high-intensity sound fields.

3.2.2. Acoustic Wave Scattering Effect. This mechanism, initially proposed by Song,[11,12] serves as a detailed augmentation to the orthokinetic interaction and hydrodynamic mechanisms. According to Song's theory, particles in a sound field gain momentum, leading to particle entrainment and being subject to the scattering of acoustic waves on their surfaces. A phase difference exists between the primary sound wave and the scattered sound wave, causing particles to deviate from their original positions after completing periodic motions. This deviation results in areas of attraction and repulsion around the particles. Song's numerical calculations indicated that when the direction of acoustic wave motion aligns with the line connecting particles, repulsion occurs between the particles, and conversely, attraction is observed. In 1994, Song[12] further refined the numerical model of acoustic wave scattering. This research highlighted that small particles are influenced by nearby larger particles, manifesting a phenomenon of particle entrainment that renders the scattering wave field relatively weak, to the extent that its effects can be disregarded in calculations. However, when particle size is large or the frequency is high, the scattering wave field becomes more pronounced, necessitating consideration of the acoustic wave scattering effect mechanism. In 1996, Hoffmann[35] discovered that the interaction time interval of the acoustic wave scattering effect mechanism was exceedingly brief, rendering its impact on the agglomeration process minimal. Consequently, subsequent researchers have generally excluded the coscattering effect in numerical simulations of acoustic wave agglomeration, considering it to be inconsequential. However, by simulating the dynamic characteristics of two particles of different sizes in the sound field, Fan[37] found that the motion state of the particles may change significantly after the scattering effect is included. For the particle group, whether the acoustic scattering effect is one of the main effects needs to be further studied. Currently, in the study of various mechanisms of acoustic agglomeration, the acoustic scattering effect is not considered significant. As outlined, given the carrying effect of sound waves on tiny particles, the acoustic scattering effect, compared to other mechanisms, is deemed weak.

3.2.3. Mutual Radiation Pressure Effect. The mutual radiation pressure effect represents a significant aspect of fluid mechanics, primarily based on the Bernoulli principle. When the axis connecting two particles is perpendicular to the direction of a sound wave, the particles within the sound field are propelled by the wave and interact with the surrounding medium. This interaction results in a higher velocity of the medium between the two particles compared to the external medium. Consequently, this differential in velocity leads to a lower internal pressure between the particles than externally, causing the particles to attract each other and collide, ultimately leading to agglomeration. Conversely, when the axis connecting the particles is parallel to the direction of the sound wave, the particles exhibit repulsive behavior. Figure 2 illustrates how the mutual radiation pressure operates. Numerical research and experimental studies have demonstrated that this attraction is inversely proportional to the fourth power of the distance between the particles.[36]

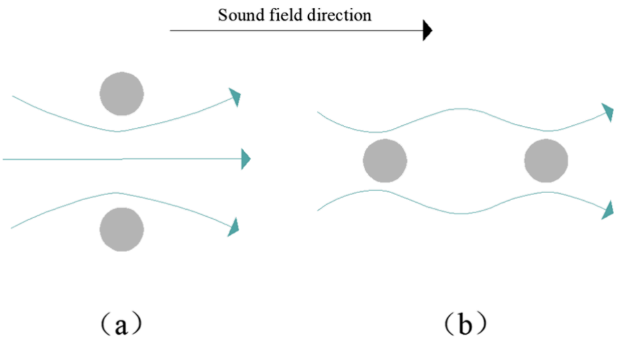

Figure 2. Mutual radiation pressure effect (the particle connection line is perpendicular to the acoustic direction (a), and the particle connection line is parallel to the acoustic direction (b)).

Compared to the acoustic wake effect, the mutual radiation pressure effect exhibits a shorter range and a force that diminishes rapidly with increasing distance. This effect becomes significant when the spacing between particles is exceedingly small. Initially, Hillary[13] determined through numerical calculations that the force exerted by the mutual radiation pressure effect is minimal and plays a minor role in the agglomeration process. It is inversely proportional to the fourth power of the distance between particles, decreasing sharply as this distance increases. The effect becomes relevant only when particle spacing is exceptionally close. Subsequently, Shaw[9] also concluded through numerical analysis that the mutual radiation pressure effect has a negligible impact on agglomeration. However, there are differing opinions regarding the influence of the mutual radiation pressure effect on agglomeration. Danilov,[14] for instance, posited through numerical research that considering fluid viscosity significantly amplifies the force of the mutual radiation pressure effect, making its impact on the agglomeration process non-negligible. Key factors influencing the magnitude of mutual radiation pressure, such as particle size and acoustic incident frequency, were summarized. Song,[11] in his simulation studies, concurred that considering fluid viscosity renders the effect significant, with higher sound wave frequencies correlating to greater force. González[36] verified the existence of the mutual radiation pressure effect through microscopic experiments. However, he agreed that compared to the acoustic wake effect, the mutual radiation pressure effect is not predominant, aligning with Hillary's observation that its force is inversely proportional to the fourth power of particle spacing. The historical research on this effect not only confirms its presence but has also led to several important conclusions. The current debate among scholars primarily revolves around the significance of the mutual radiation pressure effect in agglomeration processes. The current debate among scholars primarily concerns the significance of the mutual radiation pressure effect in agglomeration processes. Some numerical simulation studies have incorporated this effect, yielding conclusions consistent with experimental results.[17,18,38−40] Present-day numerical simulations typically consider the impact of the mutual radiation pressure effect on acoustic agglomeration, indicating that the underlying mechanism is well-established. However, some scholars have pointed out that significant deviations may occur between simulation results and experimental outcomes when considering the effect of mutual radiation pressure.[41] Therefore, this mechanism may not be suitable for all acoustic agglomeration scenarios. It is generally believed that the greater the viscosity of the fluid, the higher the acoustic frequency, and the larger the particle size, the stronger the influence of this effect.

3.2.4. Acoustic Wake Effect. The acoustic wake effect can be described as the asymmetry in the flow field surrounding a particle when it vibrates within a sound field. This phenomenon occurs when two adjacent particles are entrained by sound waves and consequently oscillate. During the initial half of the sound wave period, the leading particle creates a low-pressure wake region behind it as it moves forward. This pressure differential draws the trailing particle closer to the leading one. In the latter half of the cycle, the roles reverse, with the trailing particle now exerting an attraction toward the leading particle. After several such cycles, the two particles may eventually collide and undergo agglomeration. The conceptual diagram of this process is shown in Figure 3.

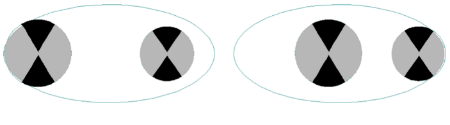
（a）The first half cycle (b)The second half cycle

Figure 3. Acoustic wake effect (the first half of the acoustic wave period (a) and the second half of the acoustic wave period (b)).

The concept of the acoustic wake effect was first introduced by Pshenai-Severin.[42] Subsequently, Dianov[43] applied a linearization approach to the convection term of the Navier−Stokes equation, eliminating second-order infinitesimals, and derived a formula for the average aggregation velocity of particles under the influence of the acoustic wake. This formula indicates that the acoustic wake effect is inversely proportional to the distance between particles. Unlike common radiation pressure, it exhibits slower attenuation and a broader range of action. D. T. Shaw[33] successfully measured the particle size distribution function of monodisperse aerosols, determining an acoustic agglomeration constant that closely aligns with theoretical predictions. Shaw's findings revealed that for particles larger than 0.5 μm in diameter within the audible frequency range, acoustic agglomeration primarily occurs due to collisions induced by the acoustic wake effect. In a numerical simulation study, Tiwary[10] discovered that the acoustic wake effect exerts a substantial force, suggesting its potential as a complementary mechanism to the theory of orthokinetic interaction. Finally, Temkin[44] designed an experiment that observed the acoustic wake effect for the first time, thereby validating its existence.

Hoffman[35,38] conducted extensive research on wake agglomeration. In his microscale experiments, he observed a unique pattern of particle agglomeration that resembled the shape of a tuning fork, hence termed "tuning fork agglomeration." He identified that the primary cause of this phenomenon was the attraction between particles aligned with the direction of acoustic wave vibrations, where the action distance significantly exceeded the particle diameter, approximately 200−300 μm. This effect was attributed to the wake effect induced by acoustic waves. Furthermore, Hoffman developed a new model for simulating acoustic agglomeration, incorporating both the orthokinetic interaction mechanism and the acoustic wake mechanism, and specifically emphasized the acoustic wake effect as a novel contributory mechanism. This model has been found to closely align with a multitude of experimental results.[45] González et al.[36] conducted experimental studies on the interaction of sound-induced particles in monodisperse aerosols, focusing specifically on the influence of single particles on their attraction process, particularly under the influence of sound wave wakes. Their findings revealed a wide range of effects facilitated by various acoustic entrainment coefficients, further substantiating the wake effect of sound waves. In Dong's[17] model, both the orthokinetic interaction mechanism and the acoustic wake effect were considered influential in agglomeration, with the latter being predominant in high-frequency regions. However, some scholars have contested the predominance of a single acoustic agglomeration mechanism. For instance, Dong et al.[17] compared the impacts of orthokinetic interaction, acoustic wake effect, and gravity on acoustic agglomeration through calculations and analysis of effective agglomeration length. They concluded that the impact of the acoustic wake effect was less significant compared to orthokinetic agglomeration.

In recent years, the wake effect of acoustic waves has garnered significant attention in research, primarily focusing on enhancing the theoretical model of this phenomenon. The acoustic wake effect is now widely recognized as one of the key theories in the field of acoustic agglomeration, a consensus shared by the majority of scholars. A notable contribution was made by Zhang,[21] who, through an improved grouping method, incorporated collision efficiency and introduced the acoustic wake effect as a fluid mechanics mechanism based on the orthokinetic interaction effect. This approach, supplanting the mutual radiation pressure effect, substantially enhanced experimental accuracy. Further, Zhang et al.[46] developed a new acoustic wake effect model through theoretical analysis of boundary conditions and computational fluid dynamics simulation, demonstrating that this new model offers greater precision than existing models. Additionally, Zhang et al.[47] conducted numerical simulations to explore the hydrodynamic interactions of aerosol particles driven by the acoustic wake effect. The results from these simulations were validated experimentally, leading to the conclusion that the acoustic wake effect plays a significant role in acoustic agglomeration. This effect might be the primary agglomeration mechanism for monodisperse aerosols and could also serve as the principal refilling mechanism for polydisperse aerosols, complementing the orthokinetic interaction.

The theories discussed primarily focus on the agglomeration of microscopic particles. However, experimental evidence suggests that sound waves also exert macroscopic effects on aerosols, particularly under high-intensity sound fields. Notably, acoustic streaming and acoustic vortex phenomena are observed in these high-intensity environments. Therefore, studying these macroscopic effects is essential for a comprehensive understanding of how acoustic waves interact with aerosols.

3.2.5. Acoustic Streaming Effect. Acoustic waves, characterized as pressure or density waves, propagate through media by utilizing the medium's compressibility. Due to the medium's viscosity and the inhomogeneity of the sound field, viscous dissipation occurs during energy propagation, leading to a portion of the dissipated energy being converted into macroscopic fluid displacement. This phenomenon, known as the acoustic streaming effect, represents a nonperiodic smooth flow process and is a quintessential example of a nonlinear phenomenon. Rayleigh[48] demonstrated through the Kundt tube experiment that strong resonant tube sound waves can suspend particles, thereby affirming that acoustic streaming can mobilize tiny particles. Mitome[49] provided both theoretical and experimental evidence that the essence of acoustic streaming lies in the spatial inhomogeneity of the sound field and the fluid's viscous effects. Furthermore, Eckart[50] identified the net average flow generated by high-amplitude sources, known as Eckart acoustic streaming. The primary driver of acoustic streaming is sound wave dissipation, with the velocity of sound flow being linearly correlated to the square of the sound pressure. As distance increases, the loss of acoustic energy leads to the formation of a stable flow, resulting in a jet in the direction of sound wave propagation. Figure 4 shows the mode of action of Eckert acoustic streaming.

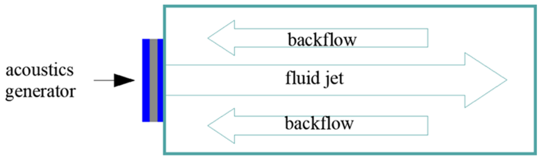

Figure 4. Eckert sound streaming diagram.

3.2.6. Acoustic Vortex Effect. Under specific conditions, acoustic waves can generate a vortex carrying orbital angular momentum, characterized by a spiral phase difference. Within this vortex field, sound waves exhibit a twisting motion along an axis as they propagate. This torsion leads to the cancellation of sound waves at the axis, creating a center with zero sound intensity.

Both acoustic streaming and the acoustic vortex arise from the nonlinear effects of sound waves and coexist simultaneously. As macroscopic effects on particles, their impact is significant. The acoustic streaming effect, driven by fluid jetting, facilitates particle collision and agglomeration. Meanwhile, the acoustic vortex induces particle rotation and collision through the angular momentum imparted by the rotating fluid.

3.3. Brownian Agglomeration Mechanism.

The Brownian agglomeration mechanism, also known as the molecular thermal motion mechanism, originates from the random thermal motion of gas molecules. This mechanism predominantly impacts very small particles and is significantly influenced by temperature. Notably, it is independent of the added sound field. However, to a certain extent, it can facilitate acoustic agglomeration.[30]

3.4. Gravity Sedimentation.

Different particles undergo relative motion under the influence of gravity, which facilitates collision and agglomeration among aerosol particles. It is postulated that larger particles actively capture smaller ones, a process independent of the added sound field, yet potentially serving as a supplementary mechanism to acoustic agglomeration.

In summary, within the spectrum of agglomeration mechanisms, most scholars concur that the Orthokinetic interaction mechanism and the acoustic wake effect are the primary mechanisms in the acoustic agglomeration process.[15,35,38,51] While other agglomeration mechanisms are acknowledged, in practical agglomeration scenarios, these mechanisms coexist, interact, and are interdependent. However, relative to Orthokinetic agglomeration and the acoustic wake effect, the impact of these additional mechanisms is considered minimal, thus rendering them less critical to the overall process of acoustic agglomeration. A few scholars argue that identifying essential mechanisms depends on perspective, noting that current models of agglomeration are sometimes imprecise and do not always match experimental results. Future studies should aim to understand how different mechanisms complement each other and improve models to better reflect experimental data.

4. INFLUENCE OF RELATED PARAMETERS ON ACOUSTIC AGGLOMERATION

Currently, research on acoustic agglomeration parameters is limited, focusing primarily on factors like sound intensity, frequency, agglomeration time, and particle concentration.

4.1. Sound Intensity.

Sound intensity plays a crucial role in acoustic agglomeration, where higher intensities enhance the process's effectiveness. At lower intensities, particles experience diminished relative displacement, leading to shorter motion distances and smaller pressure differentials based on fluid mechanics principles. This results in a lesser volume being swept by moving agglomerates, making the agglomeration effect less noticeable. Conversely, higher sound intensities increase particle motion amplitude, thereby amplifying the efficiency of agglomeration mechanisms, as confirmed by extensive experimental research.[9,32,52−54]

Although it is generally accepted that higher sound intensities significantly enhance the agglomeration effect, there are practical limitations. Excessively high sound intensities entail substantial energy consumption and can lead to a slowdown in the promotion of agglomeration, diminishing the economic feasibility of applying acoustic agglomeration. Additionally, excessive sound intensity can generate considerable noise, potentially impacting the work environment for personnel. Generally, to optimize the

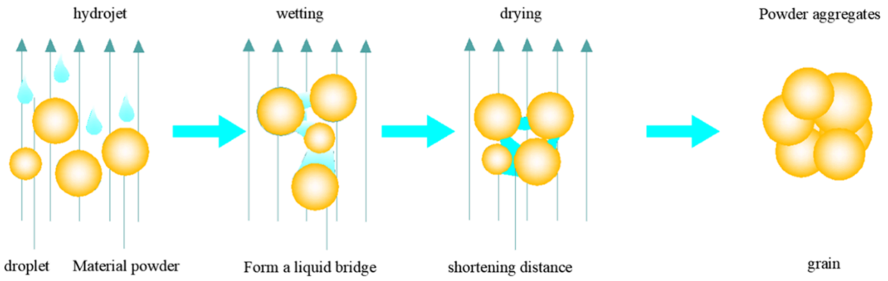

Figure 5. Schematic diagram of acoustic agglomeration coupling droplet additive to promote agglomeration.

agglomeration effect, the sound pressure level corresponding to the sound intensity is typically around 150 to 170 dB. Below 120 dB, it becomes challenging to produce a notable agglomeration effect.

4.2. Frequency.

Regarding acoustic frequency, current research universally concurs that there exists an optimal intermediate frequency that yields the most effective agglomeration. As per the orthokinetic interaction mechanism, lower frequencies result in greater sound wave amplitudes. However, excessively large amplitudes are not conducive to enhancing the relative motion of particles, thereby impacting the agglomeration effect. Conversely, higher frequencies lead to smaller acoustic amplitudes. Excessively small amplitudes render particles stationary, similarly hindering the enhancement of particle relative motion and affecting agglomeration. Consequently, an optimal intermediate frequency is identified. From the perspective of fluid dynamics mechanisms, higher frequencies are associated with stronger effects.[30]

A synthesis of existing research reveals common conclusions:

1. An optimal acoustic frequency exists for achieving the best agglomeration effect.
2. The agglomeration effect of high-frequency sound waves is more pronounced on small-sized particles (several microns) compared to low-frequency sound waves.
3. Low-frequency sound waves demonstrate a stronger agglomeration effect on larger-sized particles (tens of microns, hundreds of microns) than high-frequency sound waves.

Thus, the range of acoustic frequencies studied in existing literature is extensive, ranging from as low as 44 Hz to as high as 30 kHz. Studies across these varied acoustic frequencies have produced different degrees of agglomeration effects, indicating that the investigation of the optimal frequency necessitates further exploration. The selection of sound wave frequency should be tailored to the size of the particles being agglomerated. It is posited that for PM2.5 and submicron particles, which are currently the focus of much attention, higher-frequency sound waves are more effective.

4.3. Agglomeration Time.

For agglomeration duration, it is established that longer periods generally lead to more effective agglomeration. However, extending the agglomeration time necessitates an increased residence time in the sound field, which in turn demands an expansion of the agglomeration chamber volume, thereby escalating the investment costs. Furthermore, research indicates that the growth rate of the agglomeration effect diminishes with prolonged agglomeration time.[9,30] This finding is widely acknowledged among researchers in the field. Consequently, when considering economic factors, there appears to be an optimal duration for practical agglomeration applications. Moreover, excessively prolonged agglomeration can lead to overly large particle sizes, potentially resulting in particle breakage if not accompanied by enhanced sound intensity, which can adversely impact the agglomeration effect.[53,55]

4.4. Particle Concentration.

In terms of particle concentration, when it is excessively low, the relative distance between particles increases according to the agglomeration mechanism, diminishing the effectiveness of the hydrodynamic mechanism. In the context of the codirectional movement mechanism, the number of particles within the scanned agglomeration volume decreases, adversely affecting the acoustic agglomeration process. Considering the influence of sound intensity on agglomeration, it is deduced that a reduction in the total number of particles necessitates an increase in vibration amplitude to enhance the probability of collisions. Therefore, augmenting the sound field intensity can compensate for reduced agglomeration efficiency. This concept has been substantiated by researchers such as Scott[56] and Cheng,[30] who demonstrated that increasing sound intensity can improve agglomeration efficiency when the particle concentration is low.[18,53,54]

4.5. Humidity.

Concerning humidity, existing research findings indicate that it can significantly enhance the efficacy of acoustic agglomeration. The forces contributing to particle agglomeration are typically categorized into two types: van der Waals force and liquid bridge force. It is widely accepted that the liquid bridge force, which increases with the size of agglomerating particles, is considerably greater than the van der Waals force between particles. This results in a dual effect: first, in the collision agglomeration process, particles are more readily captured to form aggregates; second, once aggregates are formed, the strengthened bonding between particles renders them less susceptible to dispersion even at higher sound pressure levels, allowing for further enhancement of the sound pressure level to achieve particle agglomeration. Consequently, several scholars have experimented with coupling droplet agglomeration with solid particles, yielding more favorable results compared to single-solid particle agglomeration. For instance, Riera-Franco[57] posits that humidity assists in enhancing ultrafine particles like those produced by diesel combustion, reducing the number concentration of particles by up to 56% and improving the efficiency of acoustic agglomeration. Sarabia[58] discovered through experimentation that at 20 kHz, 6% humidity could augment the number concentration reduction of submicron particles from 25% to 56%. Garretón et al.[52] incorporated a water spray device in their experiment to regulate humidity, achieving a substantial agglomeration effect. Zhang[22] investigated acoustic agglomeration in coal fly ash aerosols by spraying droplets, finding that the use of water droplets can increase agglomeration efficiency by 55%, and broaden the optimal frequency range for maximum agglomeration efficiency. Luo Z,[59] through experimental research, introduced droplets into the agglomeration field, boosting the agglomeration efficiency to 74.7%, thus confirming that humidity can indeed enhance agglomeration efficiency. Additionally, with the introduction of sprayed water droplets, the residence time required to achieve maximum agglomeration efficiency also decreases. Furthermore, studies have shown that increased humidity can achieve comparable agglomeration efficiency at a lower sound pressure level.[60] Figure 5 shows the promoting effect of increasing humidity on acoustic agglomeration at the micro level.

4.6. Temperature. In terms of temperature, an increase in gas temperature results in higher viscosity, which, according to the orthokinetic agglomeration mechanism, reduces the agglomeration effect.[7] Additionally, elevated temperatures increase acoustic resistance, adversely affecting acoustic agglomeration. However, higher temperatures also enhance particle agglomeration and accelerate Brownian motion, thus, to some extent, promoting acoustic agglomeration. Therefore, the impact of temperature on acoustic agglomeration is 2-fold. Considering that industrial acoustic agglomeration often occurs in high-temperature environments, further investigation into the influence of temperature and the temperature field on acoustic agglomeration is essential. This includes exploring the temperature field's impact on the agglomeration effect.[61] Currently, few scholars have considered the influence of temperature on agglomeration effects. There is a lack of apparatus to control temperature under experimental conditions, and in practical applications, the temperature value is predetermined and difficult to modify. Consequently, the effect of temperature on agglomeration has often been overlooked. It is posited that future basic research could explore enhancing agglomeration efficiency by promoting Brownian motion in low-viscosity gas conditions.

5. APPLICATION OF ACOUSTIC AGGLOMERATION TECHNOLOGY AND THE CORRESPONDING IMPROVEMENT DIRECTION

5.1. Application of Acoustic Agglomeration Technology in a Gas−Solid Two-Phase Flow. Gas−solid two-phase acoustic agglomeration primarily involves solid particles subjected to acoustic agglomeration technologies. Since the 1970s, the issue of particulate matter emissions causing pollution has garnered significant attention globally. Moreover, acoustic waves have been identified as more effective for the agglomeration of small particles compared to other methods. Consequently, the application of gas−solid agglomeration technology has increasingly gained prominence.

In the domain of dust removal and collection, Shaw[62] introduced the concept of an acoustic agglomeration device as auxiliary equipment for electrostatic precipitators, enhancing their efficiency in eliminating smaller particle sizes. Gallego Juárez J. A[63] and Reethof G[64] proposed the acoustic agglomeration of fly ash from power plants for environmental and hot gas purification. Studies suggest that acoustic agglomeration is a technically viable and potentially cost-effective method to mitigate air pollution from particulate emissions in power plants. Garretón[52] utilized a stepped radiation plate transducer as a sound source for air purification in mines, supplemented by water spray to aid agglomeration. Zhan et al.[21] conducted experimental research on the acoustic agglomeration of coal-fired fly ash at low frequencies, observing its effectiveness in reducing emissions from power plant boilers. At a frequency of 1400 Hz and sound pressure level of 147 dB, total particle concentration and PM2.5 concentration were reduced by 68.4% and 75.6%, respectively. Scanning electron microscope images revealed the formation of larger particle aggregates. Zhou et al.[65] integrated an acoustic agglomeration device with an electrostatic precipitator (ESP) and bag filter, demonstrating significant improvements in dust removal efficiency and identifying the most effective frequency range for the combined system. Operating at 1400 Hz and 148 dB, the particle mass concentration removal efficiency of the bag filter increased by 7.9%, and that of the ESP by 10.23%. Shen[53] conducted experiments on coal-fired boiler fly ash with bimodal particle size distribution, focusing on particle size breakage. The results indicated that for fine (<10 μm) particles with an unimodal distribution, increased sound pressure levels did not cause particle breakage. However, for larger particles (0−170 μm) with a bimodal distribution, an optimal sound pressure level was identified, beyond which particle breakage occurred. Additionally, it was proven that water spraying can prevent particle fragmentation and enhance agglomeration efficiency. Subsequent research by various scholars has primarily revolved around these aspects, warranting no further elaboration.

Acoustic agglomeration technology has been substantiated as an effective means to mitigate PM pollution. Ng Bing Feng[66] integrated an acoustic agglomeration device into air conditioning and mechanical ventilation systems, utilizing the technology to filter fine particulate matter in the atmosphere, yielding significant results. Given that a substantial proportion of PM pollution originates from automobile exhaust emissions, numerous scholars have explored applying acoustic agglomeration to the coalescence and reduction of PM from vehicle exhaust. Riera[58] suggested employing acoustic waves to treat smoke emitted by diesel engines. Chen et al.[67] conducted experiments and observed that at a sound pressure level of 161.5 dB and frequency of 1 kHz within the acoustic agglomeration chamber, the number concentration of particles ranging from 0.023 to 10 μm decreased by 55.7%. This finding indicates that low-frequency, high-intensity sound fields can effectively curtail ultrafine particle emissions from diesel engines. In another study, Artūras Kilikeviius et al.[68] generated sound waves at 136 dB in a turbulent experimental cabin. They compared particulate matter concentrations in the cabin with and without sound waves, concluding that acoustic agglomeration is effective for particles in the 0.3−10 μm size range. Kristina Kilikevičienė et al.[69] investigated the acoustic agglomeration of exhaust particles in internal combustion engines, particularly when using a renewable fuel mixture (ROMEP). They found that high-frequency sound waves of 21400 Hz significantly agglomerated 5 and 10 μm particles, reducing their number by 44.5%.

In the context of reducing the detrimental effects of fire smoke, Mao[60] pioneered the use of acoustic agglomeration technology to mitigate smoke produced by cable combustion. Experimental studies have demonstrated that at a frequency of 1.5 kHz, the technology achieves optimal smoke agglomeration. Furthermore, it was observed that spraying water mist at 40g/m∧3 enables a reduction of sound intensity by approximately 14 dB while maintaining the same agglomeration efficacy, thus diminishing the potential auditory damage to personnel. Acoustic agglomeration has also been noted for its ability to rapidly enhance smoke visibility in fire scenarios.[54,70] Zhang[54] conducted experiments using polystyrene smoke to assess the feasibility of acoustic agglomeration in extinguishing fire smoke, identifying the optimal frequency for smoke elimination and delineating the efficiency dynamics of agglomeration. Additionally, the impact of acoustic agglomeration on various fire situations was quantitatively analyzed, leading to a series of findings regarding optimal agglomeration frequencies and smoke elimination durations.

5.2. Application of Acoustic Agglomeration Technology in Gas–Liquid Two-Phase Flow. Gas–liquid two-phase acoustic agglomeration is a technique in which acoustic waves interact with droplet particles within a gas phase, causing them to coalesce into larger particles. This technology's application scenarios have been explored by various scholars. In 1936, the Faraday Society in London initially proposed the use of acoustic waves for fog dissipation. However, its practical application was hindered at that time due to a significant lack of supporting theoretical frameworks.

Moore et al.[6] documented and analyzed the phenomenon of rain postlightning, deducing that sound waves aid in cloud condensation, potentially contributing to artificial rainfall. Tulaikova T V et al.[71] further explored the theoretical underpinnings and practicability of acoustic methods in enhancing rainfall. Li[72] et al. utilized the point particle motion equation to simulate cloud droplets' movement induced by ground-emitted traveling acoustic waves, examining the influence of droplet size, acoustic frequency, and sound pressure level on droplet velocity and displacement. For droplets measuring 50 μm, the conditions for significant displacement fluctuations were identified as 10 Hz and 88.2 dB. Insufficient sound pressure and excessively high frequencies were found ineffective for inducing rainfall. Smaller droplets exhibited more pronounced responses to sound waves. Additional research corroborated the viability of sound waves in promoting cloud precipitation, concluding that low frequencies and high sound pressure levels significantly impact cloud droplet condensation.[73−76]

In the 1950s, acoustic agglomeration was employed for the recovery of sulfuric acid aerosols, but it faced challenges related to energy consumption and the power of the sound source. Once the agglomeration research matured, Asghar Sadighzadeh[28] suggested its application in removing sulfuric acid mist from airflows, studying the impacts of sound pressure level, frequency, droplet concentration, and gas flow rate on agglomeration efficiency. An optimal filtering efficiency of 86% was achieved at a resonance frequency of 852 Hz. The maximal agglomeration efficiency was recorded at 165 dB sound pressure level. Higher initial concentrations of sulfuric acid mist and reduced air velocity were found to enhance acid mist agglomeration. This technology proved effective for sulfuric acid mist removal in airflows.

Additionally, Shaw[62] proposed the utilization of acoustic agglomeration for sodium fire aerosol suppression in nuclear reactor core meltdown scenarios. Theoretical predictions indicated that acoustic agglomeration could be exponentially more efficient than gravity agglomeration, contributing to core safety.

Compared to gas–solid applications, gas–liquid phase applications of acoustic agglomeration are less widespread. This disparity stems from the availability of numerous nonacoustic droplet removal methods that boast longer periods of technical development and greater maturity. However, acoustic agglomeration offers several advantages, including noncontact interaction with the working medium, rapid response, low energy consumption, and pollution-free operation. It is anticipated that future applications across various fields will underscore its promising research prospects.

5.3. Acoustic Agglomeration Reunited with Other Technologies. Acoustic agglomeration, when integrated with other agglomeration technologies, can enhance the agglomeration effects significantly. This includes the combination of additive agglomeration, electric field agglomeration, and phase change condensation technologies.

In the realm of additive coupling technology, it is recognized that increased humidity bolsters agglomeration. Various researchers have investigated the impact of introducing additional material particles into the target agglomeration substances. Hoffmann[77] initially experimented with adding lime seed particles of larger sizes during acoustic agglomeration. These larger particles serve as collecting cores, facilitating the collision and adherence of smaller particles, thereby enhancing agglomeration and growth. Additionally, this process amplifies the swept agglomeration volume for smaller particles, resulting in a substantial improvement in their agglomeration efficiency. Zhao[78] et al. incorporated poly(methyl methacrylate) seed particles for the agglomeration of fine particles, attaining a removal efficiency of 82% for particles primarily sized at 0.07 μm. Wang[79] employed lime seed particles, observing a 15.5% increase in agglomeration efficiency. This addition also broadened the acoustic frequency range suitable for agglomeration. Yan et al.[80] linked fine particle agglomeration effectiveness in a sound field to the wettability of droplet seed particles. Improved wettability equated to enhanced particle agglomeration. They discovered that adding Sodium Dodecyl Sulfonic Salt (SDS) and Modified Polysilanol Surfactant (Silanol W22) droplets yielded a significantly higher removal efficiency than water droplets alone, and helped in forming stable aggregates resistant to disruption by high-strength fields. Zhang et al.,[81] exploring the mechanics behind droplet-spraying to aid agglomeration, found that droplets could expand the range of optimal agglomeration frequencies for original acoustic agglomeration. Compared to water droplets, droplets with longer polymer chains and higher viscosity proved more efficacious in improving agglomeration efficiency. Among Xanthan Gum (XTG), Kappa Carrageenan (KC), and Polyferric Sulfate (PFS), XTG demonstrated the most effective agglomeration. While coupling additive agglomeration technology can reduce the equipment's land footprint, it has drawbacks, including the necessity of substantial amounts of agglomeration agents, leading to higher costs and reduced economic viability. Future studies could explore the effects of other cost-effective agglomerating agents or varying concentrations on agglomeration efficiency.

Electric field agglomeration technology aims to utilize an electric field to augment particle charge, thereby enhancing particle movement and facilitating agglomeration through Coulomb and mirror forces. Fragile particles, in particular, can efficiently recombine postbreakage under electrostatic forces. Recent studies have delved into acoustic wave coupling with electric field agglomeration. Chen et al.[82] employed this coupling technology, integrating a traveling wave with wire-tube electrostatic precipitation, to agglomerate flue gas particles in coal-fired power plants. Experimental results indicated that the coupled technology's agglomeration efficacy surpassed that of a sole sound field. Additionally, it was

Table 2. Comparison of Acoustic Wave Coupling Multiple Agglomeration Technologies

technology program	technological superiority	technical disadvantage
Acoustic coupling additive agglomeration technology	Low energy consumption, high agglomeration efficiency, small footprint.	Using a large number of agglomeration agents, the cost is relatively high.
Acoustic coupling electric field agglomeration technology	The agglomeration effect of particles below 1 μm is better, and it can synergistically oxidize and degrade sulfur and nitrogen pollutants in flue gas.	With high energy consumption, agglomeration at low concentrations is not economical.
Acoustic coupling phase change condensation technology	It is suitable for high moisture content flue gas, stable working conditions, high agglomeration efficiency, and can achieve waste heat recovery synergistically.	There is a corrosion problem, and it is not conducive to use in a dry environment.

observed that with an increase in discharge voltage, the optimal sound pressure level for peak agglomeration efficiency decreased. The pulsed electric field exhibited superior performance compared to the DC electric field. At a constant voltage, there exists an optimal sound pressure level and frequency for maximizing removal efficiency. As voltage increases, the optimal frequency tends to rise while the optimal sound pressure level diminishes. Extending particle residence time in the sound field can enhance removal efficiency, but this should be moderated in higher particle concentrations. Zhou[65] integrated an acoustic agglomeration device as a pretreatment unit before particles enter the electrostatic precipitator and bag filter. The study revealed that this integration boosted the particle mass concentration removal efficiency of the electrostatic precipitator from 89.05% to 99.28%, and the bag filter from 91.29% to 99.19%. Furthermore, Zhou[59] explored a novel fine particle agglomeration and capture process using pulse corona discharge and spray droplet-enhanced acoustic coupling. This approach showed that fine particle agglomeration efficiency could reach 74.7% when applying pulsed corona discharge in the sound field. Introducing droplets, particularly surfactants, during the agglomeration process significantly reduced penetration efficiency and promoted agglomeration. He[83] utilized pulse corona discharge coupling technology for flue gas particle agglomeration in power plants, concluding that higher pulse voltages correlate with increased agglomeration efficiency, reaching up to 98.3% at 55Kv-100 Hz and 143 dB-1600 Hz. Liu[84] examined the agglomeration and charging mechanisms of particles under electric and sound field coupling, analyzing the impact of sound field waveform, sound pressure level, and sound field velocity on particle movement through numerical analysis. The research found that higher voltages lead to more charged particles, thus facilitating agglomeration; higher sound pressure levels also ease agglomeration, while frequency effects are nonlinear. Under optimal conditions, acoustic-electric coupling fields achieved a 62% particle reduction rate, signifying a substantial agglomeration effect. The acoustic wave coupling electric field agglomeration technology effectively removes small particles and can synergistically oxidize and degrade pollutants such as nitrogen oxides and sulfur oxides. This reduces the cost of air pollution and waste gas treatment to an extent and shows substantial potential. It is widely believed that pulsed electric fields outperform DC fields, and sound pressure level has a more pronounced impact on agglomeration than frequency. However, achieving higher agglomeration efficiency necessitates increased pulse voltage, which, at lower particulate matter concentrations, may diminish economic viability. Hence, further research is warranted to explore more efficient and energy-saving coupling methods of sound field and electric field agglomeration.

The acoustic coupling phase change condensation technology involves the interaction of saturated steam and steam phase change within a sound field, facilitating particle agglomeration while condensing saturated water vapor into droplets. This process significantly enhances agglomeration efficiency. Yan's study on coal-fired flue gas indicates that agglomeration efficiency is augmented at a steam supersaturation of 1.2, with higher supersaturation correlating to greater efficiency. At lower sound pressure levels, such as 130 dB, the combined agglomeration removal efficiency can reach 63%.[85] Lin[86] explored the fine particle removal characteristics in wet flue gas desulfurization (WFGD) systems using acoustic agglomeration coupled with supersaturated steam condensation. The findings indicate that at a supersaturation level of 1.15 and a sound pressure level of 151 dB, particle removal efficiency exceeds 70%. Particle removal efficiency stabilizes when residence time in the sound field exceeds three seconds. This method, which involves coupled vapor phase change condensation, achieves higher particle removal rates at lower sound pressure levels, suggesting the utility of employing multiple horns with low sound intensity to enhance particle removal efficiency while minimizing energy consumption. Li[87] proposed a novel dust removal method combining boiler flue gas condensation with acoustic agglomeration. This combined approach outperforms singular acoustic wave or condensation fields, achieving maximum removal efficiencies of 70% under specific conditions: a sound frequency of 1500 Hz, a sound pressure level of 141 dB, and a cooling water flow rate of 560 L/h. The agglomeration effect of sound waves is optimal within a certain frequency range, and particle removal efficiency significantly increases when the sound pressure level surpasses a threshold. This innovative dust removal method, which also facilitates waste heat recovery, presents an efficient and economical solution. It is particularly suited for waste heat recovery in saturated wet flue gas postdesulfurization in power plants and water capture scenarios. Additionally, the heat export during the gas phase change can be recycled, effectively reducing energy consumption. However, a limitation lies in the corrosive nature of the condensed flue gas water postphase change, necessitating water treatment equipment and incurring higher costs. This technology is not suitable for dry environments such as dust removal. Application development in specific scenarios is needed for its promising prospects. Table 2 summarizes the characteristics of acoustic agglomeration combined with other agglomeration technologies.

6. COMMENTS ON RESEARCH RELATED TO ACOUSTIC AGGLOMERATION

6.1. Current Configuration of Acoustic Agglomeration Chambers.

The agglomeration chamber is a crucial component of the acoustic agglomeration experimental apparatus, with its configuration and dimensions significantly influencing the agglomeration process. This section provides a summary and commentary on the configurations of agglomeration chambers based on current research.

Predominantly, scholars have focused on vertical agglomeration chambers. In these chambers, acoustic waves propagate from top to bottom, aligning with the fluid flow direction. The fluid inlet and outlet are located on the upper and lower sides of the chamber, respectively. Agglomerated particles are collected and quantified in a device located beneath the chamber. As illustrated in Figure 6 and Figure 7, the benefits of this configuration include:

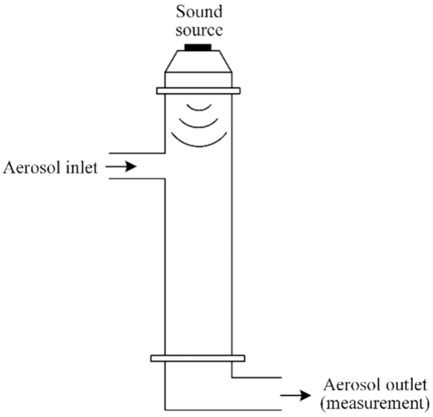

Figure 6. Typical vertical agglomeration chamber configuration.

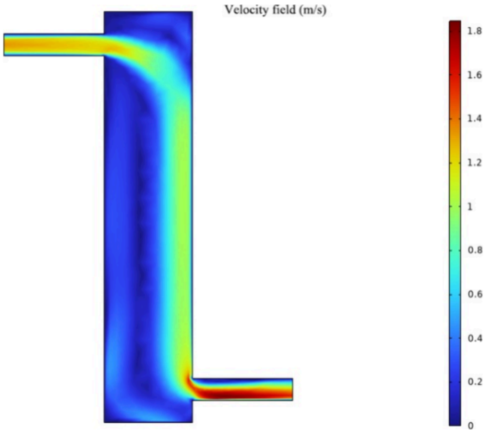

Figure 7. Flow state of fluid in a vertical agglomeration chamber (air flows from the upper left horizontal tube at a speed of 1 m/s; velocity field distribution of the agglomeration chamber).

Enhanced interaction of acoustic waves—whether traveling or standing waves—with the fluid volume within the chamber, potentially increasing acoustic wave efficiency; The vertical alignment aids in the gravitational settling of agglomerated particles or droplets into the sampling device at the chamber's base, simplifying the sampling process; The chamber's arrangement aligns with gravity, favoring the agglomeration of pollutant particles and minimizing pollution and loss within the chamber.

Despite these advantages, the vertical agglomeration chamber design also presents drawbacks:

Nonuniform fluid flow within the tube, primarily concentrated near the outlet, results in uneven acoustic wave interaction, adversely affecting agglomeration; This configuration introduces the challenge of excessive flow resistance. Typically, an induced draft fan is required at the outlet to facilitate fluid flow; In industrial applications where transverse flow is common, the acoustic field is limited to the vertical direction of the flow; The chamber's open bottom may lead to interference from unexcited fluid with the settled sampling particles, potentially impacting sampling accuracy.

Given these considerations, it is evident that the design of the agglomeration chamber plays a pivotal role in the efficacy of acoustic agglomeration processes. Future research and practical applications should account for these factors to optimize the agglomeration chamber's design, ensuring efficient and accurate particle collection.

Several scholars and institutions have explored horizontal configurations for the agglomeration chamber, where the fluid flow is transverse, and acoustic waves are oriented perpendicular to the flow direction. As illustrated in Figure 8 and Figure 9, the advantages of this configuration include 1) Uniformity in the flow field, which mitigates issues of poor agglomeration due to flow field irregularities; 2) Arrangement of acoustic waves perpendicular to the pipeline flow, enhancing the influence of multiple acoustic fields and effectively boosting the agglomeration process; 3) Reduced flow resistance, often eliminating the need for an induced draft fan, thus facilitating experimental development and minimizing the spatial footprint of the setup.

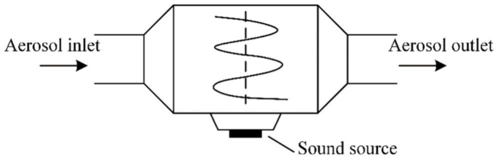

Figure 8. Typical horizontal agglomeration chamber.

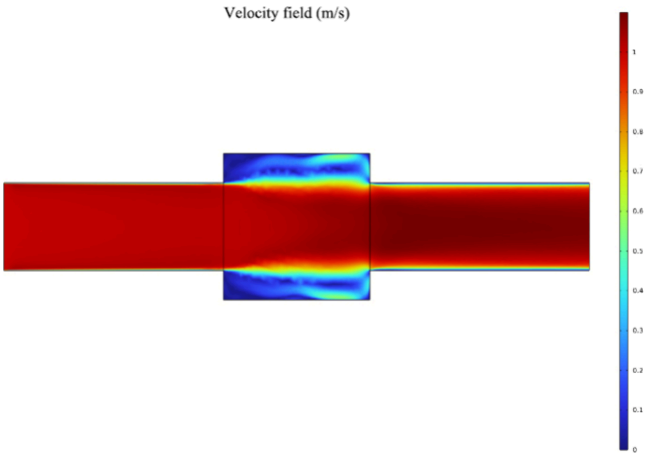

Figure 9. Flow state of a variable cross-section horizontal agglomeration chamber (air flows from the left at a speed of 1m/s; velocity field distribution of the agglomeration chamber).

However, this horizontal agglomeration chamber also presents certain disadvantages: 1) The interplay of gravity and acoustic wave interactions may lead to agglomerated aggregates settling on the chamber walls, causing accumulation, flow disruption, and potential chamber contamination; 2) The material flow rate at the outlet is substantial, complicating the collection process. Consequently, most current applications of this chamber configuration are in experiments involving agglomerated droplets, while studies focusing on agglomerated solid particles predominantly utilize vertical agglomeration chambers. The choice of the agglomeration chamber's structure should be made after determining the research subject. This decision is pivotal to the efficiency and effectiveness of the agglomeration process, ensuring optimal conditions for the specific material or particles being studied.

Recent advancements have led to the proposal of an innovative agglomeration chamber design, primarily focused on reducing the length of the horizontal agglomeration chamber. This new design incorporates multiple circular tubes strategically placed to create disturbances in the fluid flow within the chamber. Figure 10 illustrates how the flow range can be significantly improved by using spoilers. Due to the inertial properties of the particles, these flow disturbances are hypothesized to increase the probability of particle collisions. This enhancement in collision frequency is anticipated to augment the overall efficiency of the agglomeration process.

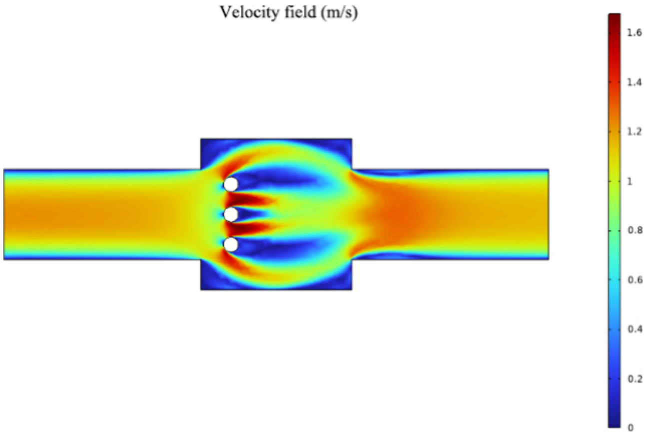

Figure 10. Improved velocity distribution of flow field in a turbulent agglomeration chamber (air flows from the left at a speed of 1m/s, and the white circle is the spoiler device, velocity field distribution of the agglomeration chamber).

6.2. Numerical Simulation of the Acoustic Agglomeration Process.

Comparative analysis reveals that employing numerical simulation to model acoustic agglomeration processes can significantly economize experimental materials and infrastructure costs. This method has garnered considerable attention among scholars. Presently, numerical simulation research bifurcates into two primary categories: one that integrates macro-level cluster aggregation functions representing various mechanisms into the Population Balance Model (PBM) for particle groups; and another rooted in microlevel Lagrangian particle-based simulations.

The first approach, the PBM method, solves the population balance equation for aerosol particles. This more conventional method has seen extensive application across a spectrum of aerosol agglomeration challenges. To numerically resolve this equation, researchers have innovated several techniques, such as the sectional algorithm,[88−90] the moments method,[91−93] and the Monte Carlo method.[18,94−96] This simulation paradigm presupposes a homogeneous and even distribution of aerosol particles within the gaseous medium. Crucially, solving the PBM necessitates an agglomeration kernel function aligned with the underlying agglomeration mechanism. As agglomeration numerical simulations have evolved, so too have the corresponding mechanism-specific agglomeration kernel functions. These functions, and the expressions of the comprehensive agglomeration kernel function under various agglomeration effects, have been experimentally validated. For instance, Zheng[97] introduced the concept of amalgamating diverse agglomeration kernel functions via a root-mean-square approach, culminating in a root-mean-square kernel function. This model has demonstrated superior accuracy in simulating actual acoustic agglomeration compared to straightforward additive methods. Future research should pivot around this root-mean-square aggregation kernel function, exploring more efficacious combinations of agglomeration kernel functions.

The second approach to numerical simulation employs Lagrangian particle methods, which derive the dynamic behavior of aerosols through statistical analysis of the microscopic movements of numerous particles. A notable technique within this domain is the discrete element method (DEM), which computes aerosol particle agglomeration efficiency by calculating their velocities and trajectories. The underlying principle of DEM is anchored in Newton's second law, incorporating forces such as drag, gravity, buoyant lift, Basset, and Brownian forces. Unlike the population balance model (PBM), DEM calculates actual particle motion without utilizing an agglomeration kernel function and eschews the assumptions inherent in PBM. This method is perceived as a highly accurate agglomeration simulation technique.[38,98−101] However, due to its requirement for minute time steps, it is computationally intensive, both in terms of time and cost, rendering it less suitable for large-scale particle flow agglomeration simulations. To address the issue of extended computation times, some researchers have adopted multitime step algorithms to expedite simulations. This involves task-specific time step subdivisions, such as fluid, particle, and collision time steps, reducing computational time by an order of magnitude.[46,102,103] Research into particle fragmentation, particularly of droplets, in the context of acoustic fields, remains sparse. A few experimental studies have observed bimodal particle size distributions under intense acoustic fields, indicating fragmentation.[53] However, the underlying mechanisms of droplet breakup and strategies to mitigate this effect remain underexplored. Recent advances in acoustic levitation offer promising avenues for understanding the fragmentation-agglomeration mechanism by incrementally increasing acoustic field intensity to levitate single or dual droplets. Integrating these insights with acoustic agglomeration techniques could significantly enhance agglomeration efficiency.

6.3. Application Expansion of Acoustic Agglomeration.

Current research on acoustic agglomeration has primarily focused on the agglomeration of solid particles, with limited studies into droplet agglomeration, particularly for applications like demisting and droplet elimination. In line with current industrial trends, this paper proposes a novel application scenario for acoustic agglomeration. The concept entails integrating an acoustic agglomeration device into the exhaust flue of a coal-fired boiler following a wet desulfurization tower. The primary objective is to remove minuscule corrosive acid mist and excess condensed water mist, along with fine solid particles, emitted from the desulfurization tower. This approach not only aims to conserve water resources but also to reduce pollutant emissions further. There is a need to explore the combined application of acoustic agglomeration in gas−liquid−solid three-phase flow and to investigate the phenomenon of enhanced particle breakage during agglomeration. Further research in this field is essential.

Addressing the issue where acoustic agglomeration shows limited efficacy in real industrial settings, especially with small particles, this technology is envisaged to be integrated with other particle collection and agglomeration methods. This integration is aimed at reducing the burden on traditional particle filtration technologies, thereby improving the removal of ultrafine particles. Additionally, increasing the number of acoustic sources is suggested as a strategy to broaden the scope of particle agglomeration and enhance removal efficiency.

7. ADVANTAGES AND LIMITATIONS OF ACOUSTIC AGGLOMERATION

In practical applications, acoustic agglomeration technology presents unique advantages over alternative agglomeration methods.

1. Acoustic agglomeration facilitates the collision of smaller particles to form larger aggregates, demonstrating an effective removal process. This makes it an ideal pretreatment step in certain particle removal applications.
2. Utilizing sound wave energy, acoustic agglomeration does not directly interact with the working medium, making it suitable for handling hazardous particles, including explosive, toxic, or corrosive types.
3. The equipment required for acoustic agglomeration is generally more compact compared to other methods, enhancing its suitability for onsite deployment.

Despite these benefits, several challenges hinder the broader adoption of acoustic agglomeration technology:

1. Enhancing agglomeration efficiency typically involves increasing sound pressure levels, which consequently raises power consumption. Identifying low-energy sound sources, such as pneumatic sound sources, remains a crucial area for future research.
2. Acoustic agglomeration can generate high-decibel noise, potentially affecting the industrial environment and posing health risks.
3. The underlying mechanism of acoustic agglomeration still lacks comprehensive understanding and clarity.

8. CONCLUSION

In summary, acoustic agglomeration presents promising prospects for contemporary industrial applications. Building on the foundational contributions of early researchers, significant strides have been made in understanding the mechanisms and conducting experimental research in this field. Key insights gleaned from these studies include:

1. Currently, most scholarly research on acoustic agglomeration posits that its efficiency can be enhanced by at least 20% or even achieve efficiencies exceeding 60%. For technologies that combine acoustic waves with agglomeration, efficiencies can surpass 90%. Consequently, it is posited that acoustic agglomeration technologies have significant applicability in relevant scenarios. Present studies highlight the necessity for practical investigations into relevant parameters, especially within engineering applications, to effectively tackle real-world challenges.
2. Enhanced algorithms are necessary to refine existing theoretical models to ensure closer alignment with empirical data. For example, in simulations using the Population Balance (PB) model, recent studies have predominantly added various agglomeration kernel functions linearly, neglecting the root-mean-square approach for calculating the total kernel function. Incorporating this modification could significantly improve the accuracy of simulations.[97] Future research should integrate experimental outcomes with weighted distributions of different kernel functions to discover more experimentally congruent conclusions and identify universal trends. It is crucial to determine which mechanisms predominantly influence agglomeration in diverse environments. Moreover, the Monte Carlo model currently does not account for agglomeration in turbulent flows,[39,40] necessitating the inclusion of a turbulent agglomeration kernel function in future Monte Carlo simulations.[19] Recent studies have employed three-dimensional Computational Fluid Dynamics and the Discrete Element Method (CFD-DEM) to simulate acoustic agglomeration, focusing on flow pattern influences.[23,98,104] This approach is particularly suitable for turbulent flow conditions, yielding superior results compared to those obtained under simple laminar flow conditions. Currently, within the algorithms utilizing the Population Balance (PB) model, the simulation method employing the adaptive Monte Carlo technique exhibits the highest degree of fit with experimental values, with an approximate error of 1%. The simulation results generally exceed the experimental values. The error between the numerical simulation results obtained through the Discrete Element Method (DEM) and the experimental values is about 5%. However, as the model undergoes continuous optimization, this error is progressively reduced. Overall, both numerical simulation methods exhibit distinct advantages and disadvantages and should be developed concurrently. For complex flow fields, the Computational Fluid Dynamics-Discrete Element Method (CFD-DEM) is suitable. Conversely, for stable laminar flows, the PB model can achieve more accurate calculations at lower computational costs.
3. Acoustic agglomeration is notably effective in high-intensity sound fields, yet these conditions may hinder aggregate formation or cause breakage. Recent developments in acoustic droplet suspension control offer new avenues for experimentation,[105] with computational models being established to refine microfluidic manipulation mechanisms based on acoustic suspension.[106] Future studies could explore collision-rebound and collision-agglomeration-crushing-reagglomeration dynamics experimentally, employing this technology to elucidate underlying principles.
4. Integrating various agglomeration techniques can enhance their effectiveness. Recent methodologies that combine acoustic agglomeration with turbulent flows have demonstrated the potential for increasing fine particle agglomeration efficiency. However, integrating different agglomeration technologies complicates the development of numerical simulation models and increases computational costs. Moreover, the economic feasibility of concurrently employing multiple agglom-

eration techniques has not yet been established. Future research should focus on analyzing the cost-effectiveness of practical applications and utilize integrated functions such as kernel functions to reduce computational demands, thereby facilitating the broader adoption of agglomeration technology.

5. Research on the effects of agglomeration at high temperatures is limited, and the influence of multiple sound sources on acoustic agglomeration has not yet been explored. Consequently, developing new algorithms to continuously improve the accuracy of theoretical models for acoustic agglomeration is crucial. Additionally, creating a new generation of high-energy, efficient sound sources or arrays is essential. Future research efforts will focus on the combined application of diverse agglomeration techniques and their efficacy in high-temperature environments.

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Notes

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