

Article

Influence of Acoustic Frequency and Particle Residence Time on Fine and Ultrafine Particle Agglomeration for Air Quality Control Applications

Tautvydas Juknevičius ¹ and Aleksandras Chlebnikovas ^{2,*}¹ Department of Mechanical and Materials Engineering, Faculty of Mechanics, Vilnius Gediminas Technical University, LT-10223 Vilnius, Lithuania; tautvydas.juknevicus@vilniustech.lt² Institute of Mechanical Science, Faculty of Mechanics, Vilnius Gediminas Technical University, LT-10223 Vilnius, Lithuania

* Correspondence: aleksandras.chlebnikovas@vilniustech.lt

Abstract

With increasingly strict air quality standards and growing concerns about air pollution, fine and ultrafine particulate matter remains a major challenge for conventional air cleaning technologies. Due to their small size, these particles are difficult to remove using traditional filtration and separation methods. Acoustic agglomeration can be used as a pre-treatment technology to increase particle size in a high-intensity acoustic field and improve the efficiency of particle removal. This study investigates acoustic-induced agglomeration of solid aerosol particles in a dynamic airflow system. The effects of acoustic frequency were evaluated at 3, 5.5, 7.5, and 15 kHz under a sound pressure level of 135 dB and at two airflow velocities: 0.75 m/s and 1.5 m/s. These velocities corresponded to different particle residence times in the acoustic field. Arizona test dust was used as the test aerosol, and particle-number concentration and particle-size distribution were measured before and after the acoustic field. The results showed that acoustic agglomeration of fine and ultrafine particles was strongly affected by both acoustic frequency and particle residence time. The highest agglomeration efficiency, reaching up to 42%, was obtained at 3 kHz, 135 dB, and longer particle residence time. These findings indicate that acoustic agglomeration can promote particle-size redistribution in moving airflow and may be used as a pre-treatment method for improving particulate matter removal in air quality control systems.

Keywords: acoustic agglomeration; dynamic airflow system; sub-ultrasonic field

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1. Introduction

Air pollution with fine and ultrafine particles is an important topic of concern in modern society. Air pollution from these particles could be emitted from anthropogenic sources such as burning fossil fuels and industries such as cement manufacturing [1]. Other sources of fine or ultrafine particles are from natural sources like dust storms, wildfires, or volcanoes [2]. High levels of air pollution are commonly seen in highly populated cities with large industrial regions. In such environments, high concentrations of fine and ultrafine particles pose a significant risk to human health [3]. Fine particles, smaller than 10 µm, could enter the human bloodstream through the nose and throat, while reaching

the lungs, from which they could enter the blood vessels [4]. As environmental standards get increasingly stringent for manufacturers and fossil fuel users, there is more research done on the high-risk problems from fine and ultrafine particles. Research shows that fine and ultrafine particles could cause health problems like autism spectrum disorder [5]. Therefore, with advanced studies on environmental and health issues, it is critical to research higher efficiency methods for fine and ultrafine particulate matter separation.

Today, traditional methods of particulate matter separation like electrostatic precipitators, fibrous filters, HEPA filters, and cyclone separators are used to reach high or full removal of different-sized particulate matter [6–9]. Electrostatic precipitators have a high manufacturing price and high energy usage, but are effective for fine and ultrafine particulate matter separation [10]. Fibrous and HEPA filters have high energy consumption, a high risk of clogging, and need to be constantly replaced [11,12]. Cyclone separators could remove only particles larger than 5 µm and have a high pressure drop, so they are ineffective for ultrafine particulate matter [13]. For that reason, single traditional methods are not enough to reach high environmental regulations with their disadvantages. Combined or hybrid methods could be used to reach higher filtration efficiency. Like a hybrid electrostatic–fibric precipitator, with an electrostatic precipitator filtering a higher percentage of particulate matter, while the fibric filter is reached only by a small amount of particulate matter [14]. But even with traditional and hybrid filtration systems, it is hard to precipitate fine and ultrafine particulate matter. Thus, a pre-treatment stage could be used to increase the efficiency of traditional and hybrid filtration methods. Electrostatic agglomeration uses electrostatic forces to agglomerate particles with different charges [15]. Another pre-treatment technique is chemical agglomeration, in which chemical reactions are used to promote coalescence and growth of ultrafine particulate matter into larger agglomerates [16]. The third agglomeration method is acoustic agglomeration, in which acoustic wave forces are used to agglomerate particulate matter into larger clusters.

Acoustic agglomeration was observed for the first time in 1927 by Wood [17]. The researcher observed high-frequency acoustic waves in an oil bath generated by a piezoelectric oscillator. From that point on, more research was conducted on sound wave usage in particulate matter agglomeration. Acoustic agglomeration is driven by several interaction mechanisms happening in the acoustic field [18]. Orthokinetic interaction and acoustic wake effect are two main mechanisms on which acoustic agglomeration is based. Researcher S. Dong et al. [18] observed that orthokinetic interaction is more effective in the lower frequency range, while the acoustic wake effect is more effective in the higher frequency range and for smaller particulate matter. Orthokinetic interactions happen when airflow is affected by a high acoustic field, and particles in the airflow are entrained by it. Smaller particles tend to be more entrained in the field, while larger particles tend to lag, which is caused by inertia [19]. The acoustic wake effect is caused by an acoustic field that changes the attraction between them due to flow disturbance [20]. Acoustic wake effects tend to be more effective for particles of the same or similar size. The orthokinetic agglomeration coefficient is expressed as [21]

$$K_{ort} = 2 * (r_{1,c} + r_{2,c})^2 U_0 \eta_{s12} \quad (1)$$

where $r_{1,c}$ and $r_{2,c}$ denote the particle radius (m); U_0 is the sound wave velocity amplitude, (m/s); and η_{s12} is the relative entrainment factor between two particles.

For acoustic agglomeration research, both static and dynamic flow chambers are used. Static chambers generate standing acoustic waves, allowing the investigation of acoustic effects on particles under long residence times. In these chambers, particles and aerosols remain exposed to the acoustic field significantly longer compared to dynamic flow systems. Studies performed in static chambers often demonstrate high agglomeration efficiency. For example, at a sound pressure level of 141 dB and a frequency of 1.5

kHz, nearly complete removal of fire smoke was achieved after 2 min of acoustic exposure in a static chamber [22]. Dynamic flow chambers allow the evaluation of aerodynamic and acoustic field interaction. For example, three ultrasonic acoustic sources were used in a moving airflow with a velocity of 2.3 m/s to investigate acoustic agglomeration, under a frequency of 48.85 kHz and a sound pressure level of up to 147 dB, and an acoustic agglomeration efficiency of up to 53% was achieved [23]. Another study investigated oil droplets over a frequency range of 1000–5000 Hz and up to 145 dB sound pressure level, achieving a 8.75% decrease in oil droplets under a sine wave [24].

Therefore, the present study investigates the dependence of acoustic agglomeration efficiency on acoustic frequency in the sub-ultrasonic range. Although many previous studies have focused on frequencies below 3 kHz or on ultrasonic excitation, the influence of intermediate sub-ultrasonic frequencies on particle-size distribution in dynamic airflow systems remains insufficiently investigated. In this study, two different airflow velocities were used to vary the particle residence time in the acoustic field and to evaluate its influence on agglomeration efficiency. The aim of this research is to assess how the acoustic excitation affects particle-size redistribution and to determine the suitability of acoustic agglomeration as a pre-treatment technology for improving particulate matter removal in conventional air filtration and air quality control systems.

2. Materials and Methods

For experimental research of acoustic agglomeration, an acoustic chamber was created using 150 mm-diameter air duct elements reaching a total length of 5 m and a distance from particles entering the acoustic field to the acoustic device of 1.5 m. The acoustic device was installed at an angle of 30° relative to the airflow direction. Other research made in the acoustic agglomeration field showed that using this angle gives the highest results of sound pressure level, reduces sound field suppression, and increases acoustic agglomeration efficiency [25]. As a sound source, a Beyma CD10Fe (Beyma, Valencia, Spain) compression driver with a frequency range of 0.7–19 kHz and 109 dB 2.83 V @ 1 m sensitivity was used. This compression driver gives a wide range of acoustic frequencies and high acoustic pressure levels.

The acoustic pressure level was measured using a Brüel & Kjær Type 9727 measurement system, a Type PULSE 3560-B multichannel data acquisition unit (Hottinger Brüel & Kjær, Nærum, Denmark), a portable Dell personal computer, and a Brüel & Kjær Type 8104 hydrophone. Machine vibration signals were acquired and analyzed using Brüel & Kjær Machine Diagnostics Software Type 7910, Version 10.1. The hydrophone has a sensitivity of $-211 \text{ dB re } 1 \text{ V}/\mu\text{Pa} \pm 2 \text{ dB}$ and a frequency response of 0.1 Hz–100 kHz ($+1.5/-6.0 \text{ dB}$), which covers the frequency range investigated in this study. As shown in Figure 1, the acoustic pressure level measurements were performed at the center of the air duct under no-flow conditions to ensure stable acoustic pressure readings. The acoustic device was driven by an amplifier ADATA RS360 (ADATA Technology Co., New Taipei City, Taiwan) connected to a PeakTech 3 MHz DDS function generator (PeakTech Prüf und Messtechnik GmbH, Ahrensburg, Germany), which supplied sinusoidal signals.

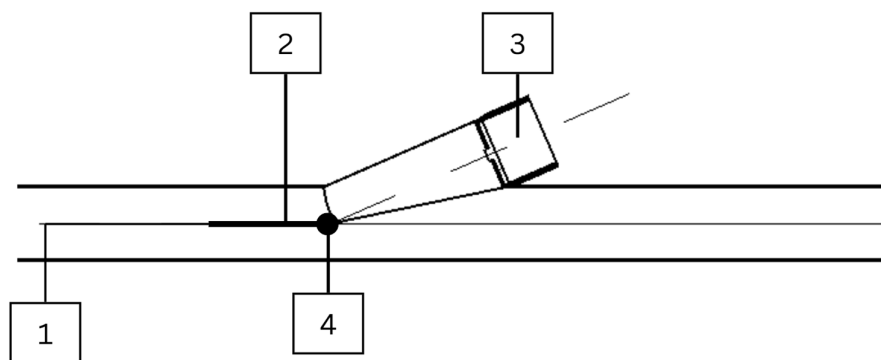


Figure 1. Test bench for acoustic pressure level measurement in the center of the air duct under the compression driver layout: 1—Bruel and Kjaer Type 9727 measurement system with Type 7910 universal software and Type PULSE 3560-B multichannel data block; 2—Bruel and Kjaer 8104 hydrophone; 3—Beyma CD10Fe compression driver; 4—measuring point of sound pressure level.

To ensure voltage repeatability and the safe operation of the amplifier and acoustic source, a Siglent SDS1104X digital storage oscilloscope (Siglent Technologies Co., Ltd., Shenzhen, China) was used. The oscilloscope was connected to the acoustic source circuit to monitor the input voltage supplied by the function generator and by the amplifier, and is shown as RMS (Root Mean Square).

For particulate matter generation, a PALAS RBG 1000 solid-particle dispenser (Palas, Karlsruhe, Germany) was used to inject particulate matter into the airflow. The device was used for stable and repeatable dispersion of particles into an airflow. Arizona 0–3 μm test dust was used for the experiments. Standardized test dust usage helps to ensure repeatability of experimental measurements. Each experimental measurement was conducted at least 3 times.

Figure 2 represents the schematic of the experimental setup. A fan (1) was used to generate airflow through the acoustic chamber, while the exhaust ventilation unit (7) was used to extract air from the system and maintain a stable flow through the chamber. Airflow velocity was measured using the Testo 440 dp measuring device (Testo, Titisee-Neustadt, Germany) with an accuracy of $\pm 0.03 \text{ m/s} + 4\%$. Table 1 shows air duct parameters, acoustic parameters, and aerodynamic and particle parameters of the experimental setup. Particle-size distributions at both measurement locations were determined using a Palas Welas 3000H digital aerosol spectrometer (Palas, Karlsruhe, Germany). This system recorded particle-size distributions using 64 particle-size channels over the measurement range of 0.2–10 μm . The measured channel data were used to calculate the particle-size distributions and particle-number concentrations presented in this study. Aerosol samples were extracted through isokinetic sampling tubes positioned along the horizontal axis of the measurement chambers to minimize sampling bias and ensure representative particle collection. The spectrometer provides real-time measurements of particle-number concentration and size distribution within the diameter range of 0.2–10 μm , enabling accurate characterization of fine aerosol particles upstream and downstream of the test section.

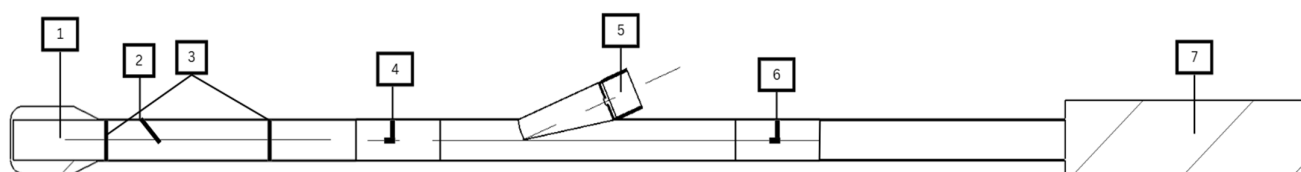


Figure 2. Acoustic agglomeration chamber schematics: 1—fan; 2—PALAS RGB 1000 particulate matter dispenser; 3—airflow straighteners; 4, 6—airflow velocity and particulate matter concentration measuring points upstream and downstream; 5—compression driver; 7—vent camera.

Table 1. Experimental conditions and main study parameters.

Air duct parameters		
Duct diameter	150	mm
Total duct length	5	m
Acoustic parameters		
Acoustic frequencies	3; 5.5; 7.5; 15	kHz
Sound pressure level	135	dB
Aerodynamic and particle parameters		
Airflow velocity	0.75; 1.5	m/s
Volumetric flow rate	0.013; 0.027	m ³ /s
Measurement duration	30	s
Particle-size range	0–2.6	µm
Test aerosol	Arizona dust	

Before the experiments, the Arizona Test Dust was dried for 24 h. During the experiments, the relative humidity in the acoustic chamber was approximately 26% RH and measured using a Testo 440 dP ($\pm 0.6\%$ RH + 0.7% of mv). To minimize potential particle electrical charge, the particle dispenser was decreased to a minimal air pressure, and the rotational speed of the dispersing brush was decreased to a minimum, too. The experimental procedure was repeated at least three times for each airflow velocity and acoustic frequency. First, the fan and exhaust ventilation unit were adjusted to obtain the required airflow velocity in the acoustic chamber. The airflow velocity was measured at the selected measuring points until the desired and stable flow conditions were achieved. The airflow velocity profile was evaluated using a multi-point measurement method, including one central point and four near-wall points in the duct cross-section. After stabilization of the airflow, the particulate matter dispenser was activated. Particle concentration was monitored until a stable aerosol concentration was obtained in the chamber. After the baseline particle concentration was recorded without acoustic excitation, particle-number concentration and cumulative particle-size distribution can be seen in Figure 3. The acoustic source was turned on at the selected frequency, and the particle concentration and size distribution were measured under the same airflow conditions. Each measurement was conducted for 30 s, and the average particulate matter concentration over this period was recorded.

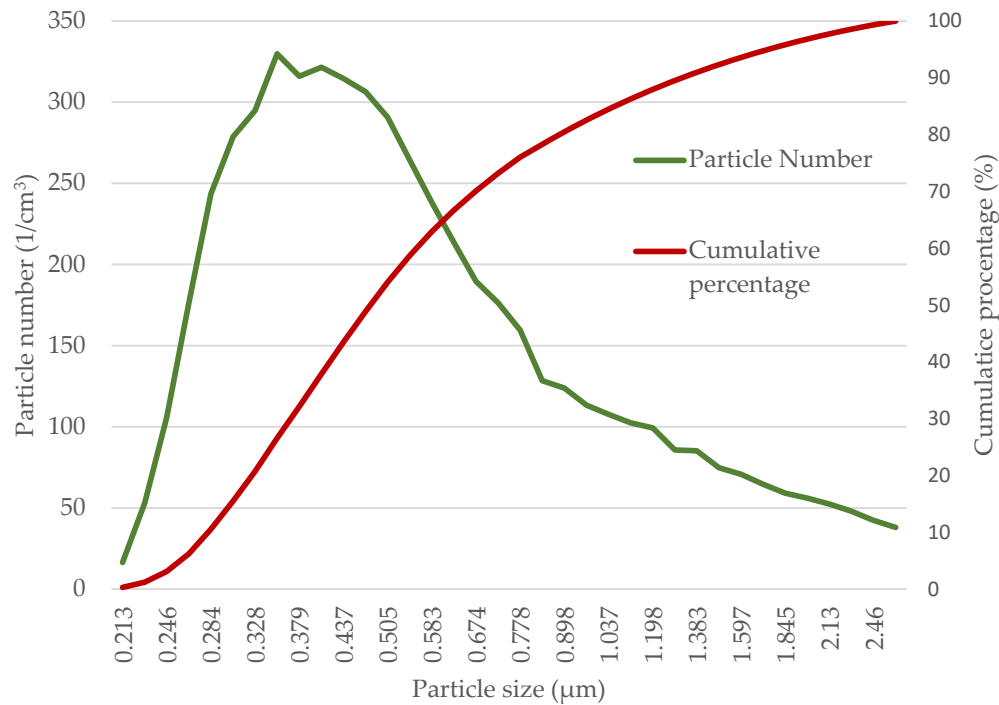


Figure 3. Particle-number concentration and cumulative particle-size distribution.

The acoustic agglomeration efficiency was calculated by comparing the total particle-number concentration measured before the acoustic source and under acoustic conditions:

$$\eta_A = \frac{N_0 - N_a}{N_0} * 100 \quad (2)$$

where η_A is the acoustic agglomeration efficiency (%); N_0 is the particle number before the acoustic source (particles/cm³); and N_a is the particle number after the acoustic source (particles/cm³).

Acoustic agglomeration efficiency depends not only on sound pressure level, but on particle residence time in the acoustic field. That means that the more particles are in the acoustic field, the more effective the acoustic agglomeration will be. The average residence time t is defined as [24]

$$t = \frac{L}{v} \quad (3)$$

where t is the residence time (s); L is the length of the acoustic field (m); and v is the airflow velocity in the acoustic chamber (m/s).

3. Results

3.1. Sound Pressure Level Measurement Results

Sound pressure level is one of the key acoustic parameters influencing acoustic agglomeration efficiency. Piezoceramic transducers are often used in acoustic agglomeration studies because they can generate high sound pressure levels exceeding 135 dB [23,25,26]. However, these transducers usually operate most efficiently near their resonance frequency, which limits the investigation of a wider frequency range. In contrast, many studies using conventional acoustic sources focus on low-frequency excitation, typically below 5 kHz [24,27]. Therefore, the compression driver used in this study, with a frequency range of approximately 0.7–20 kHz, provides the possibility to investigate acoustic agglomeration over a wider low-, mid-, and high-frequency range below ultrasonic excitation. From a practical application perspective, acoustic agglomeration is a promising pre-

treatment technology because it can enhance particle removal without directly introducing a significant additional pressure drop into the filtration system. However, its implementation should not substantially increase the overall electrical energy consumption. Therefore, sound pressure level measurements were performed at different driving voltages to evaluate the acoustic source performance and determine suitable operating conditions. Operating the compression driver at lower driving voltages can reduce electrical power consumption, limit overheating, and improve long-term operational stability while maintaining sufficient acoustic intensity for particle agglomeration. Sound pressure level measurements of the acoustic compression driver are presented in Table 2.

Table 2. Sound pressure level measurements of the compression driver in the center of the air duct under the compression driver.

Frequency, kHz	Sound Pressure Level, dB Re 20 μ Pa	Input RMS Voltage, V
3	135	12.45
3.5	127	10
4	130	11.5
4.5	130	4.77
5	130	3.15
5.5	135	5.99
6	130	7.9
6.5	130	11.4
7	135	4.14
7.5	130	5.98
8	130	4.32
8.5	130	4.88
9	130	6.98
9.5	130	12.44
10	127	<13
10.5	120	<13
11	130	9.25
11.5	120	9
12	122	8.6
12.5	128	10
13	125	5
13.5	130	7.4
14	130	8.8
14.5	130	8.6
15	135	9.64

The results show that the required driving voltage depends on the excitation frequency. In general, higher acoustic frequencies require higher driving voltages to achieve the target sound pressure level, which may increase the electrical power demand of the acoustic source. Therefore, the selection of operating frequencies was based not only on the generated sound pressure level, but also on the safe and efficient operation of the compression driver. The frequency of 3 kHz was selected as the low-frequency operating point because it reached a sound pressure level of 135 dB without requiring excessive driving voltage. The frequencies of 5.5 kHz and 7.5 kHz were selected to represent the mid-frequency range, as they provided sufficient acoustic output while remaining within safe operating conditions. For the high-frequency range, nothing in the 9.5 kHz to 14 kHz range was acceptable for safe use of the compression driver, so 15 kHz was selected because the sound pressure level decreased at several intermediate frequencies, whereas 15 kHz allowed the compression driver to again reach the required sound pressure level of

135 dB. Figure 4 shows measured RMS under different sound pressure levels, in which 10 kHz and 10.5 kHz were not measured because the compression driver was not generating enough acoustic pressure to reach 120 dB. Red dots show the chosen frequency and its RMS.

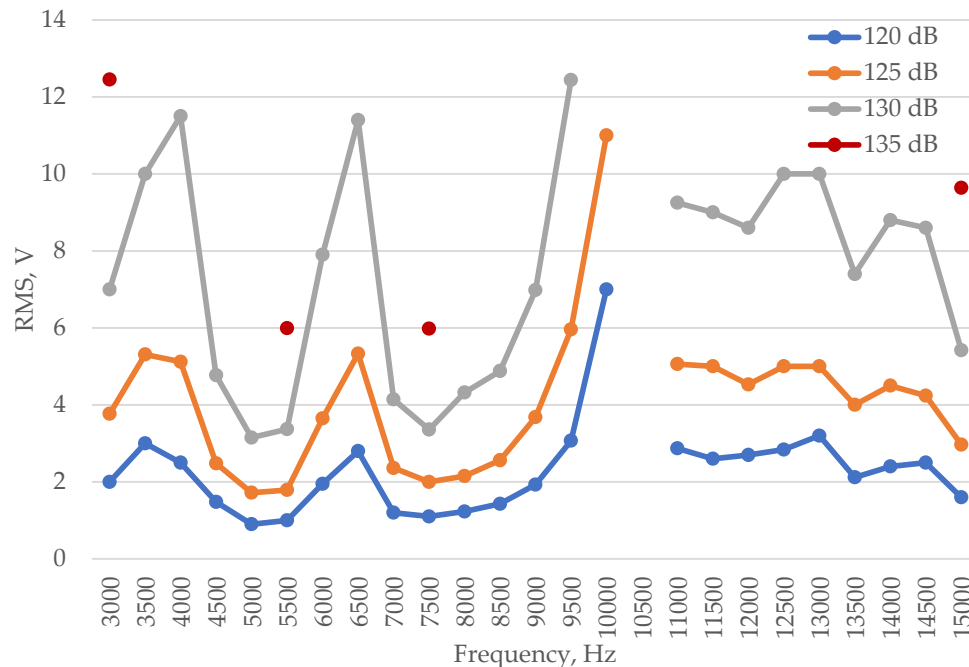


Figure 4. RMS measurement under different sound pressure levels of the compression driver.

After measuring the acoustic pressure level in the range of 120–130 dB, the operating conditions were selected based on the lowest RMS voltage required at each frequency to protect the acoustic source and prevent overheating. Four operating points were selected to achieve an acoustic pressure level of 135 dB at frequencies of 3, 5.5, 7.5, and 15 kHz.

3.2. Acoustic Agglomeration Measurement Results

Acoustic agglomeration is mainly driven by orthokinetic interaction and the acoustic wake effect. The acoustic wake effect is more effective for particles of the same or similar size, while orthokinetic interaction is associated with the different dynamic response of particles of different sizes to the acoustic field. Previous studies have often investigated these mechanisms in vertical or horizontal chambers with standing acoustic waves. However, for acoustic agglomeration to be used as an efficient pre-treatment technology, its performance should also be evaluated under moving airflow conditions. Therefore, this study investigates the influence of acoustic frequency and particle residence time on acoustic agglomeration efficiency in a dynamic airflow system.

Particles entering the acoustic field are affected by the oscillating motion of the gas. This causes the particles to vibrate, and because particles of different sizes respond differently to the acoustic field, relative motion occurs between them. As a result, the probability of particle collisions increases, promoting agglomeration. One of the key factors influencing acoustic agglomeration efficiency is particle residence time in acoustic fields. As shown in Equation (2), the residence time directly depends on the airflow velocity and the length of the acoustic chamber. In this study, two airflow velocities were selected: 0.75 ± 0.06 m/s and 1.50 ± 0.09 m/s. The particle residence time represents the duration for which particles are exposed to the acoustic field. Therefore, the airflow velocity of 0.75 m/s was

selected to represent the longer residence time, while 1.5 m/s was used to represent a residence time approximately two times shorter.

Figure 5 shows the acoustic agglomeration efficiency for particles ranging from 0.229 μm to 2.643 μm under shorter particle-residence-time conditions. The efficiency varied from approximately 6% to 24%, depending on the particle size and applied acoustic frequency. The highest values were generally observed at 15 kHz, where the efficiency increased over a wide particle-size range and reached approximately 20–23% for larger particles. In comparison, lower frequencies produced weaker and more fluctuating responses. This suggests that, when the residence time is reduced due to higher airflow velocity, higher-frequency acoustic excitation may be more effective in inducing particle motion and increasing the probability of particle–particle collisions. High-frequency acoustic waves could influence fine and ultrafine particles' agglomeration more efficiently than lower-frequency waves.

Rectangle (1) shows the agglomeration efficiency of 0.5–0.9 μm particles, which ranges from 15% to 20%. Rectangle (2) shows the highest agglomeration efficiency at 15 kHz and a particle size range of 1.1–2.6 μm , reaching above 20%. The higher efficiency observed at 15 kHz may be related to stronger acoustic-induced gas oscillations and local flow disturbances in the acoustic chamber. These effects can enhance the relative motion between particles and increase the collision frequency, especially under shorter residence-time conditions. The lowest efficiency was observed at 7.5 kHz frequency, which could indicate that this frequency did not provide enough acoustic force to agglomerate particles under the investigated airflow velocity.

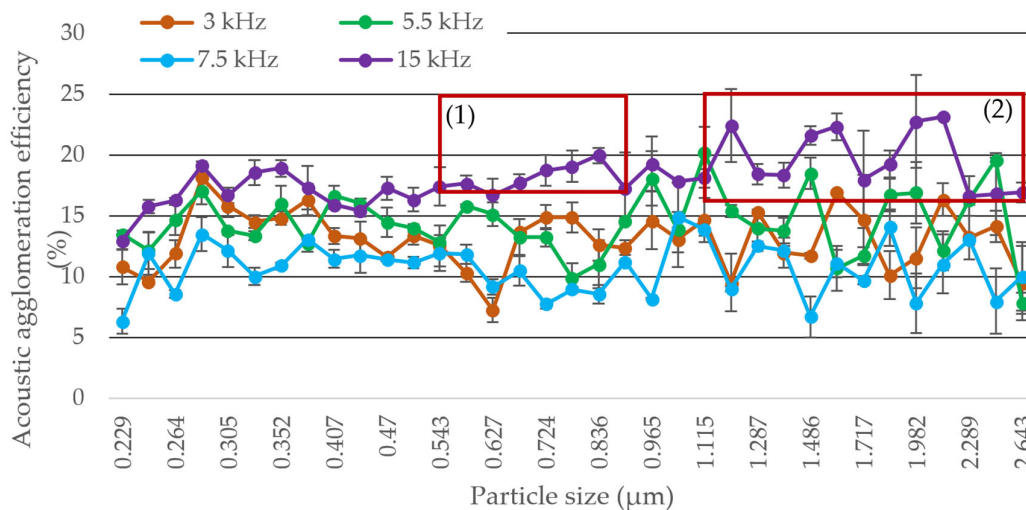


Figure 5. Acoustic agglomeration efficiency at frequencies of 3, 5.5, 7.5, and 15 kHz and a sound pressure level of 135 dB under shorter particle residence time at an airflow velocity of 1.5 m/s.

When the airflow velocity decreased from 1.5 m/s to 0.75 m/s, the particle residence time in the acoustic field increased approximately two times. A longer residence time allows particles to remain exposed to the acoustic field for a longer period, thereby increasing the probability of particle–particle collisions and agglomerate formation. Therefore, Figure 6 presents the acoustic agglomeration efficiency under longer residence-time conditions. Although longer residence time is generally expected to improve acoustic agglomeration, the results in Figure 6 show a different particle-size-dependent response compared with the shorter-residence-time case presented in Figure 5.

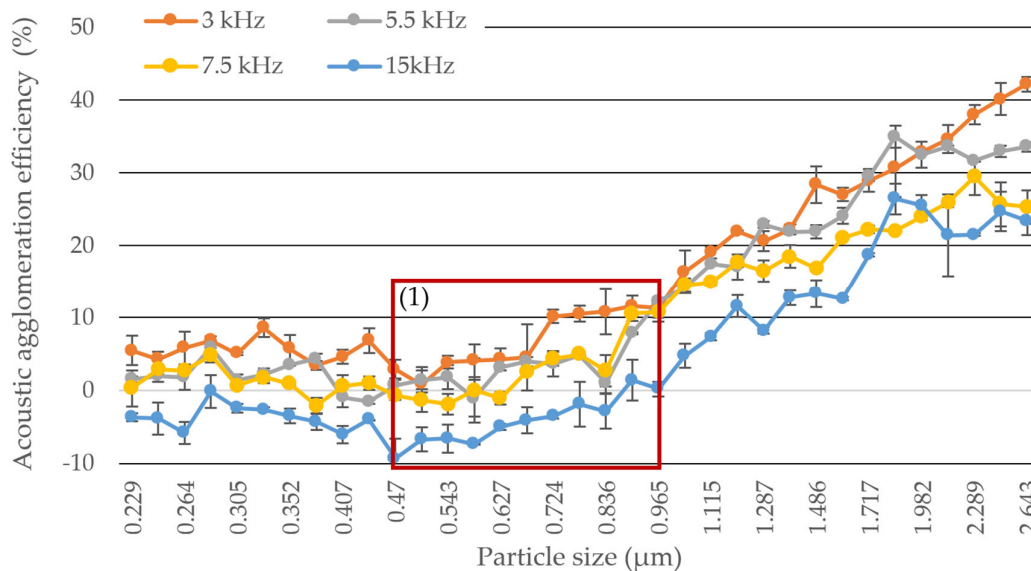


Figure 6. Acoustic agglomeration efficiency at frequencies of 3, 5.5, 7.5, and 15 kHz and a sound pressure level of 135 dB under longer particle-residence-time conditions at an airflow velocity of 0.75 m/s.

As shown in Figure 6, the most effective frequency for acoustic agglomeration under longer residence-time conditions was 3 kHz, which was the lowest frequency investigated in this study. At 3 kHz, the agglomeration efficiency for particles smaller than 1 μm ranged from approximately 5% to 11%, while particles larger than 1 μm showed considerably higher efficiency. This indicates that lower-frequency acoustic fields may be more effective in promoting the growth of larger agglomerates when particles remain exposed to the acoustic field for a longer period. At 5.5 kHz and 7.5 kHz, the agglomeration efficiency followed a similar trend, increasing with particle size. However, the maximum efficiency at 5.5 kHz reached approximately 35%, whereas at 7.5 kHz, it increased to about 30%. This suggests that both mid-range frequencies contributed to particle agglomeration, although their effect was weaker than that observed at 3 kHz under longer residence-time conditions. At 15 kHz, the acoustic agglomeration efficiency for particles larger than 1 μm was comparable to that observed at lower frequencies. However, an increase in the number of particles smaller than 1 μm was observed. The switch between an increase in particles and a decrease in particle number is marked by rectangle (1). This suggests that high-frequency acoustic excitation caused a different particle-size redistribution pattern compared with lower frequencies. The increase in the submicron fraction may be related to the formation of new agglomerates from particles below the lower measurement range or to partial breakup of weak agglomerates. Nevertheless, additional measurements would be required to confirm deagglomeration.

3.3. Acoustic Agglomeration Theoretical Analysis

To provide an explanation for particle agglomeration for particles of different sizes, the orthokinetic interaction coefficient is used. Orthokinetic interaction mainly depends on particle size, frequency, Stokes number, and relative entrainment factor. As mentioned in the introduction, the orthokinetic interaction formula (1) is made from the relative entrainment factor between two particles. The orthokinetic interaction formula was expanded with the Stokes number:

$$K_{ort} = 2 * (r_{1,c} + r_{2,c})^2 U_0 \frac{|St_1 - St_2|}{\sqrt{1 + St_1^2} \sqrt{1 + St_2^2}} \quad (4)$$

The Stokes number for acoustic agglomeration is calculated using

$$St_i = 2\pi f \tau_i = \frac{2\pi f \rho_p d_i^2 C_{c,i}}{18\mu}, \quad (5)$$

where τ_i is the particle relaxation time (s); f is the frequency (Hz); ρ_p is the particle density (kg/m³); d is the particle diameter (m); $C_{c,i}$ is the Cunningham slip correction factor; and μ is the dynamic viscosity of air (Pa*s).

Acoustic frequency increases the acoustic Stokes number, while differences in particle size result in different Stokes numbers and, consequently, different particle responses to the oscillating gas. This is represented by the orthokinetic interaction coefficient shown in Figure 7.

Theoretical calculations were performed for two particle-size pairs, 0.5–0.9 μm and 1.1–2.6 μm . These size ranges were selected because they represent the main particle groups observed in the experiments. Different trends were obtained for the two particle pairs. For the smaller particles, the orthokinetic kernel increased with frequency and reached the highest value at 15 kHz. This increase was caused by a larger difference in the acoustic response of the two particle sizes. For the larger particle pair, the kernel was already high at 3 kHz, reached the highest values at 5.5–7.5 kHz, and decreased at 15 kHz. Therefore, larger particles showed a bigger difference in acoustic response already at lower frequencies, while smaller particles required higher frequencies to reach a similar effect.

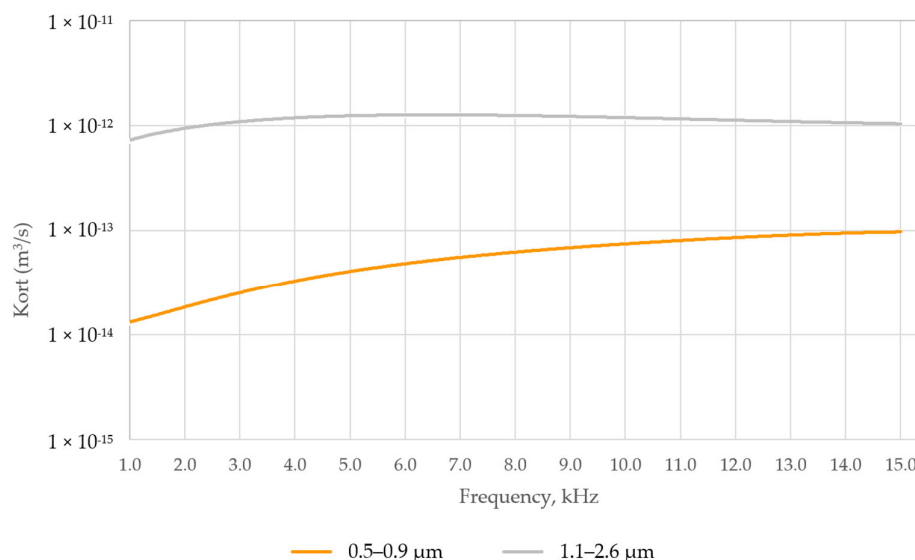


Figure 7. Orthokinetic interaction coefficient calculation for different-sized particles.

4. Discussion

Acoustic agglomeration as a pre-treatment technology is promising for future environmental engineering and air-quality-control applications. While many previous studies have focused on low-frequency acoustic fields or ultrasonic excitation, the present study evaluates the agglomeration of solid aerosol particles over a wider sub-ultrasonic frequency range of 3–15 kHz and under different particle-residence-time conditions. This approach allows the influence of acoustic frequency and exposure time on particle-size redistribution to be assessed in a dynamic airflow system.

The observed frequency dependence may be interpreted by considering both particle residence time and the number of acoustic cycles. At 3 kHz, particles are exposed to 3000 acoustic cycles per second with a longer wavelength, whereas at 15 kHz, they are exposed to 15,000 cycles per second with a shorter wavelength. Five times more cycles during the

same exposure period. Under the shorter residence time, the number of acoustic cycles may become relatively more important, which could explain the higher agglomeration efficiency observed at 15 kHz under shorter residence time, as particles experience a much larger number of repeated acoustic interactions with limited time available. On the other hand, under the longer residence time, the duration of particle exposure to the acoustic field may become relatively more important, allowing lower-frequency particle interactions over a longer period, which could explain the higher efficiency observed at 3 kHz under shorter residence time. Yang et al. showed that agglomeration efficiency initially increased with increasing residence time until the agglomeration decreased under longer residence time [26]. This indicates that extending residence time does not necessarily lead to a proportional increase in agglomeration efficiency. Furthermore, Chen et al. demonstrated effective particle agglomeration in the sub-ultrasonic frequency range, indicating that effective agglomeration is not restricted to a single frequency band [28]. Therefore, the present results suggest that the optimal acoustic frequency depends on the combined effects of frequency, particle residence time, and specific experimental conditions, rather than on frequency alone.

For practical air quality control applications, acoustic agglomeration can be considered a suitable pre-treatment method for conventional filtration or separation systems [29], because it promotes the formation of larger particle agglomerates that can be more easily removed by downstream devices like an electrostatic precipitator. In addition, if the acoustic source is operated at an appropriate frequency and driving voltage, this technology may improve particle removal without introducing a significant additional pressure drop into the system. Therefore, acoustic agglomeration has potential for integration into air quality control systems as a pre-treatment stage before traditional filtration. Although acoustic agglomeration shows promising results as a pre-treatment technology, several practical trade-offs must be considered. The present laboratory system operated at airflow rates of approximately 0.013 and 0.027 m³/s at air velocities of 0.75 and 1.5 m/s, respectively. Scaling the system to an industrial level while maintaining a similar particle residence time would require a larger acoustic treatment volume, multiple acoustic sources, or a modified chamber design, thereby increasing both equipment size and energy demand. A direct energy-cost comparison with HEPA filtration or electrostatic precipitation cannot be made from the present results because total electrical energy consumption and particle mass removal were not measured. The high-intensity acoustic field is another important limitation. The reported 135 dB value represents the sound pressure level inside the acoustic chamber are high. Nevertheless, industrial implementation would require acoustic enclosure, source isolation, restricted access, and appropriate hearing protection where necessary. These measures would affect operating costs. Therefore, acoustic agglomeration should presently be considered a pre-treatment step intended to improve downstream particle collection rather than a replacement for conventional filtration or electrostatic precipitation.

Despite the observed positive effect of the acoustic field, several aspects of acoustic agglomeration remain insufficiently understood. Further research is needed to determine how agglomeration efficiency can be improved when particles have limited residence time in the acoustic field. This is important for practical air treatment systems, where airflow velocity cannot always be reduced. Another important issue is the selection of the optimal acoustic frequency, since the present results showed that a higher frequency was more effective under shorter residence-time conditions, while a lower frequency performed better under longer residence-time conditions.

The reported SPL of 135 dB should be interpreted as the nominal maximum acoustic pressure level measured at the duct centerline under no-flow calibration conditions rather than as a spatially uniform SPL throughout the entire acoustic chamber. Under dynamic

airflow conditions, the local sound pressure field may vary due to airflow interaction and reflections from the duct walls. Therefore, particles traveling through the chamber may be exposed to different local sound pressure levels during their residence time.

An increase in the number of submicron particles was observed at 15 kHz and an airflow velocity of 0.75 m/s. The present measurements do not provide direct evidence to determine the mechanism responsible for this increase. Possible explanations may include deagglomeration of weakly bound particle structures or agglomeration of particles initially below the lower detection limit of the measurement device. Additional particle morphology measurements, such as SEM or single-particle imaging using a validated sampling method capable of preserving fragile airborne agglomerates, would be required to clarify the underlying process.

5. Conclusions

In this study, the acoustic agglomeration of solid particulate matter was investigated over a wide range of acoustic frequencies and under different particle-residence-time conditions in a dynamic airflow system. The main conclusions are as follows:

- (1) The compression driver used in this study was suitable for generating acoustic fields over a wide frequency range. However, the sound pressure level strongly depended on the applied frequency and driving voltage. Therefore, SPL measurements are necessary to select efficient and safe operating conditions for acoustic agglomeration experiments.
- (2) Under shorter particle-residence-time conditions, corresponding to an airflow velocity of 1.5 m/s, higher-frequency acoustic fields were more effective. The results showed that acoustic agglomeration efficiency increased at 15 kHz and reached values above 25% for selected particle-size ranges. This indicates that high-frequency acoustic fields can improve particle agglomeration when the exposure time in the acoustic field is limited.
- (3) Under longer particle-residence-time conditions, corresponding to an airflow velocity of 0.75 m/s, acoustic agglomeration efficiency increased more effectively at lower frequencies. The highest efficiency was observed at 3 kHz, reaching approximately 40%. This shows that longer particle residence time can improve agglomeration efficiency, but the most effective acoustic frequency depends on airflow velocity and particle exposure time.

Overall, the results confirm that acoustic agglomeration can be used in industrial exhaust and combustion systems as a pre-treatment method for particulate matter control, but its efficiency depends strongly on the combined effect of acoustic frequency, sound pressure level, airflow velocity, and particle residence time.

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