FACTA UNIVERSITATIS
Series: **Mechanical Engineering** Vol. 22, Nº 4, 2024, pp. 741 - 757
https://doi.org/10.22190/FUME241005050R

Original scientific paper

COMPUTATIONAL STUDY OF FREQUENCY IMPACT ONTO THE PARTICLE PARAMETERS AND CHANGE IN ACOUSTIC AGGLOMERATION TIME WITH THE NUMBER OF PARTICLES

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Abstract. *Air pollution, especially from particulate matter (PM), is a significant environmental and health issue worldwide. This research examines the use of acoustic agglomeration (AA) as a novel technique to diminish fine particle emissions, concentrating on the influence of frequency on particle characteristics and agglomeration duration. This study aims to improve the effectiveness of traditional filtration systems by investigating acoustic wave-induced particle agglomeration as an alternative method. The research integrates experimental and computational methodologies. Emissions from a 1.9 turbocharged 4-cylinder diesel engine using FAT80IP20 fuel were subjected to analysis in a custom-designed acoustic chamber. Frequencies of 21.2 kHz and 34.6 kHz were used, with particle measurements recorded using a Fluke 985 particle counter. Computational simulations using the Discrete Element Method (DEM) were performed to examine particle behaviour at different acoustic frequencies, accounting for first-order factors such orthokinetic interactions and acoustic wake effects. Results demonstrate that elevated frequencies (34.6 kHz) accelerate particle agglomeration, although the overall quantity of agglomerated particles diminishes. Experimental results indicated a 62.78% decrease in 5 µm particles and a 300% rise in 10 µm particles at 34.6 kHz. The findings correspond with the computer calculations, which indicated that heightened frequency enhances particle mobility and collisions while diminishing the likelihood of prolonged agglomeration inside the chamber confines. The results confirm the efficacy of acoustic agglomeration for emission control, emphasising a frequency-dependent trade-off between agglomeration speed and the volume of agglomerated particles. This study advances*

Received: October 05, 2024 / Accepted November 21, 2024
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the development of sophisticated filtering technologies and more environmentally friendly transportation alternatives.

Key words: *Particle emission, Acoustic Agglomeration, Computational simulation, Discrete element method, Orthokinetic interaction, Acoustic wake effect*

1. INTRODUCTION

The Environment Agency of the European Union has declared air pollution as Europe's most significant environmental health risk. According to a data published by Statista in 2023 [1], the transportation sector accounted for nearly 12% of global greenhouse gas emissions. It is estimated to be the second largest contributor to air pollution [2]. Of all emissions, particulate matter or particles are found to have a direct and immediate impact on human health and Environment [3,4]. These particles vary in size, with some particles being so small that they can only be seen through a microscope. The size of particles is an important factor in determining their potential impact on human health and the environment. Particles less than 10μm in diameter (PM10) can penetrate deep into the lungs and cause respiratory problems, while even smaller particles or fine particles (PM2.5) can penetrate into the bloodstream and have systemic effects on human health [5–7].

Although a significant reduction in fine particle matter is observed in the European Union by 37% between 2000 and 2020, emissions are now still considered to be at a harmful level [8]. To reduce the impact of particulate matter released from automobiles, countries around the world are taking measures such as monitoring and regulating higher emission standards [9,10] and by focusing on researching new effective solutions such as design of new combustion modes, use of blended fuels and developing advances in particulate filters [11–16].

To increase the efficiency of the conventional filter process and contain the fine particles from releasing into the environment, a particle agglomeration process is implemented [17]. Agglomeration is a technique in which smaller particles are excited through various sources and are forced to collide with each other to agglomerate and increase in size as a result of the formation of clusters. This can be achieved through the use of heat, sound, or electric field [18,19].

To achieve better filtration by aggregating the particles using sound waves is termed Acoustic Agglomeration. Researchers consider it an effective and efficient method of agglomerating the particles where the efficiency increases with increasing sound pressure levels [14,20–22]. In a research conducted by Dong Zhou et al., they observed almost 10% improved efficiency in filtering PM2.5 particles when operated at 1400 Hz and 148 dB [20,23]. Another experimental result shows that with an acoustic field of 21,400 Hz frequency, particles of size 10 μm are reduced by >90%, and fine particles (0.3 μm) are reduced by ~45% [24].

Acoustic Agglomeration (AA) is a process governed by various interactions between the particle and fluid or other particle. The predominant first-order effects that enable the agglomeration of 2 particles in a system are Orthokinetic collisions and Acoustic Wake Effect [14,25,26].

Orthokinetic interaction is the interactive agglomeration process formed as a result of the direct collision of particles of different velocities [23,27]. Particles with different sizes act differently in the system due to their difference in inertia. The primary drawback of this particular interaction is that it cannot be applied to particles with similar shapes and sizes [28].

The acoustic wake effect works in the hydrodynamic mechanism. It is a particle interaction process in which the acoustic wake causes a reduction in pressure behind the particle moving forward. If another particle follows this wake, it experiences with a drag reduction and moves with an accelerated speed towards the leading particle, causing agglomeration of the 2 particles [29,30]. The Acoustic wake effect is a first-order effect that is caused due to the action of hydrodynamic forces [31–33].

At low frequencies particularly for medium-sized particles, Orthokinetic Interaction forces are found to be more applicable and Acoustic Wake Effect is found to dominate at higher frequencies for particles of different sizes [34].

The simulation of Acoustic Agglomeration is carried out using the Discrete Element Method (DEM). In this computational method, the behaviour of particles under specific circumstances is studied and results are analysed. In DEM, each particle is considered as an individual, discrete element [35,36]. The movement of these individual elements, its influence on movement of other elements, and the physical forces between them are considered. By studying individual characteristics and the interaction between the particles, it is possible to estimate the agglomeration effect on a large scale [31].

The use of discrete elements in simulations allows for a more detailed and accurate understanding of particle-particle interaction than any other numerical simulation technique, such as finite element methods or computational fluid dynamics. This is particularly important in applications where the size and shape of individual particles play a significant role in the behaviour of the particulate system [37].

The properties of particles and the system, such as size, density, characteristics of particles, and acoustic medium properties, are predetermined. Different forces acting on individual particles and during the interaction with other particles are taken into consideration and studied. The acoustic field in which the particles interact is entered into the system to match the properties of the real world.

The result of the simulation consists of the analysis of the acceleration and velocity of the particle in the given medium. The forces acting on the particles, behaviour and change in the size of the particles in the presence of the acoustic field are observed. The formation of agglomeration can be analysed for the given number of particles, and they can also be projected for a larger number of particles which typically consumes huge amounts of data and processing time to simulate the numerical analysis.

This study explores the potential of acoustic agglomeration for particulate matter control, but it has limitations. The experiments were conducted in a controlled laboratory environment, which does not fully replicate real-world scenarios. The study focused on two acoustic frequencies, 21.2 kHz and 34.6 kHz, which may not be applicable to other fuel types or blends with different emission characteristics. The fixed boundaries and design of the chamber could influence particle behavior, potentially overestimating or underestimating agglomeration efficiency. The DEM simulations provided valuable insights into particle interactions, but they relied on assumptions that could impact real-world outcomes. The study focused on a specific range of particle sizes and distributions, not including ultrafine particles, which are more challenging to agglomerate but critical for health impacts. The energy consumption and feasibility of the acoustic field were not assessed, and the health and environmental impact of byproducts were not assessed. The experiments were conducted over limited durations, which may not fully capture long-term operational performance or potential wear and tear of the acoustic chamber.

2. Experimental Test

The impact of the change in frequency on the particles is tested on an experimental setup. The 1.9 turbocharged 4-cylinder diesel engine is used for testing. Engine exhaust emissions are passed through the in-house built acoustic chamber where particle agglomeration is subjected under the application of sound waves. Details of the test bench and agglomeration chamber are presented in some of the previous research works [24,38].

A fuel blended volumetrically at 80% FAT and 20% isopropanol was tested on 1.9 turbocharged 4-cylinder diesel engine. The particles are subjected to agglomeration under the application of sound waves in an in-house built acoustic chamber. The chamber is maintained at a sound pressure of 140 dB and an agglomerator voltage of 100 V. The change in number of particles are measured with an agglomerator frequencies of 21.2 kHz and 34.6 kHz. The Fluke 985 particle counter is used for the measurement of particles. Details of the test bench and agglomeration chamber are presented in some of the previous research works [24,38].

At lower frequency, the reduction of particles is found to be proportionate compared to higher frequency as shown in Table 1. This can be because with an increase in frequency, particle excitation increases, thereby affecting the probability of agglomeration. Although the results show that with increase in frequency, the agglomeration of 10 m in particles of size 10 μm increases but there is an insignificant reduction in small sized particles as presented in Fig. 1.

Table 1 Experimental results of FAT80IP20 fuel

Particle size [μm]	Without Agglomeration Particles amount, [number]	Change at frequency 21.2 kHz, [%]	Change at frequency (34.6 kHz), [%]
0.3	223,037	-23.07	-5.47
0.5	129,255	-29.83	-16.34
1	71,707	-25.25	-17.39
2	15,168	-13.22	-29.27
5	223	38.12	-62.78
10	3	233.33	300.00

The experimental results clearly show that there is a negative impact on the number of agglomerated particles at higher frequencies. To study the impact of presence of Acoustic waves on the particle properties, a theoretical model is developed which is used for a further computational study. In this study, different particle parameters such as size, position of particles, velocity are studied which are comparatively challenging to study on an experimental setup. These studies are done with a reduced number of particles and lower frequencies due to the simulation time involved, which is increased due to the complexions associated with a greater number of particles. To prove this, the change in agglomeration time is studied with an increase in the number of particles.

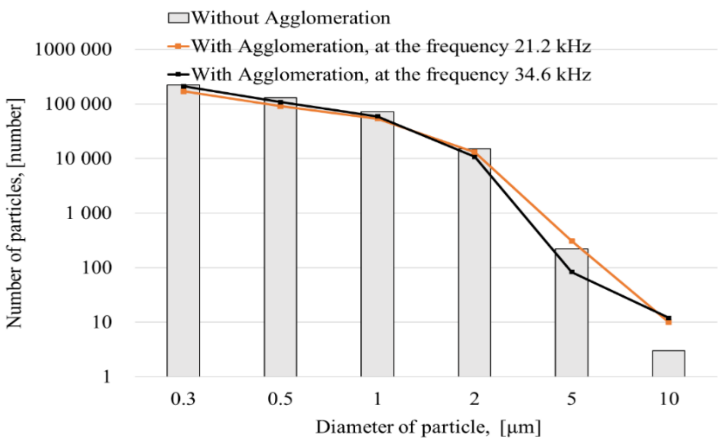


Fig. 1 Impact of frequency on particles

3. Theoretical Model

DEM can be developed within the framework of the Lagrangian approach, various recent research was successful in studying the behaviour of particulate solids using this approach [25,39]. The motion of each particle in DEM can be determined using Newton's second law of motion, which states that the mass of the particle and its acceleration is equal to the force acting on the particle.

The total forces acting on a single particle can be represented as:

$$m \cdot \frac{d}{dt}\left(\frac{dx}{dt}\right) = F_g + F_b + F_{flow} \tag{1}$$

where, m is the mass of the particle; $\frac{d}{dt}\left(\frac{dx}{dt}\right)$ is the acceleration of the particle with respect to time; F_g is gravitational force acting on the particle; F_b is the buoyancy force; F_{flow} is the flow of particles in the vibrating medium induced by the sound waves, expressed in drag force.

Gravitational force is determined by:

$$F_g = m \cdot g \text{ or } V \cdot \rho \cdot g \tag{2}$$

The Buoyancy force equals:

$$F_b = -V \cdot \rho_{air} \cdot g \tag{3}$$

where, g is 9.8 m/s^2; V is volume of the particle; ρ is density of the particle; ρ_{air} is the air density.

The velocity of the particle that is freely suspended in the medium (gas) which is frequently vibrated due to the presence of sound waves moves in the direction of the gas motion. The equation is generated ignoring complexities associated with fluid-particle interactions [33,37].

$$F_{flow} = 6 \cdot \pi \cdot \mu \cdot r \cdot v_{rel} \tag{4}$$

where, μ is dynamic viscosity of the gas; r is radius of the particle; v_{rel} is relative velocity between the particle and gas, also termed as v_g - v_p.

Considering the Orthokinetic Interactions and Acoustic Wake Effect as the additional forces acting on the particle. To reflect these forces on the drag force, further modifications are made in terms of velocity.

3.1. Orthokinetic Interactions

For the particles that are interacting in the acoustic filed, previous researchers were successful in determining the sound velocity represented in a sine wave [40,41].

The sound velocity for orthokinetic interaction can be given as follows:

$$v_g = V_g \cdot q_p \cdot sin(\omega t - x) \tag{5}$$

where v_g is the gas media velocity amplitude.

$$v_g = P_g / (c_g \cdot \rho_{air}) \tag{6}$$

where, P_g is the sound pressure amplitude; c_g is sound velocity; q_p is ratio of particle velocity; ω is angular velocity; f is the frequency.

3.2. Acoustic Wake Effect

To understand the effect of acoustic wake induced by a particle on the other particle, we are considering the theory proposed by Oseen referred by Giona et al. [42]. Considering the flowing particle to be a sphere, drag force of the particle can be expressed in simplified terms of Oseen regime.

$$F_{flow} = 6 \cdot \pi \cdot \mu \cdot r \cdot \left(1 + \frac{3}{16}\mathrm{Re}\right) \cdot (v_g - v_p) \tag{7}$$

where, R_e is the Reynolds number; μ is the dynamic viscosity, v_p is particle velocity; v_g is the gas velocity.

$$v_g = v_{g,ac} + v_{g,\,pv} \tag{8}$$

where, $v_{g,ac}$ is the vector of gas velocity due to acoustic motion.

We consider two particles (k and i) with different radii, R_k and R_i, respectively, positioned at a distance of r between the centre of two particles making an angle θ with respect to the horizontal x-axis passing through the centre of the Particle k. The perturbation gas velocity ($v_{g,\,pv}$) in the Cartesian coordinate system is determined using the Oseen regime by:

$$\begin{aligned} v_r &= \frac{3}{2}\upsilon R_k \cdot \left(1 + \frac{3R_k}{8\upsilon}|\upsilon_k|\right)\left[\frac{1}{r^2} - \frac{e^{-\frac{r(|\upsilon_k| - \upsilon_k \cos\theta)}{2\upsilon}}}{r^2} \cdot \left(1 + r \cdot \frac{|\upsilon_k| - \upsilon_k \cos\theta}{2\upsilon}\right)\right], \\ v_\theta &= -\frac{3}{2}\upsilon R_k \cdot \left(1 + \frac{3R_k}{8\upsilon}|\upsilon_k|\right)\left[\frac{1}{2r} - \frac{\upsilon_k}{\upsilon} \cdot \left(\sin\theta \cdot + e^{-\frac{r(|\upsilon_k| - \upsilon_k \cos\theta)}{2\upsilon}}\right)\right], \end{aligned} \tag{9}$$

where the relative velocity (v_k) is given as $v_{g,ac}$ - v_p and:

$$v_{g,pv,x} = v_r \cdot \cos\theta - v_\theta \cdot \sin\theta,$$
$$v_{g,pv,y} = v_r \cdot \sin\theta + v_\theta \cdot \cos\theta, \quad (10)$$

Equations (1-10) are used to analyse the influence of one particle on the trajectory of the other.

The theoretical model combining general forces acting on the particle with orthokinetic and AWE (acoustic wake effect) presented above is used to compute the particle motion in the acoustic field. The same model is further replicated in the discrete element method (DEM) to numerically simulate and analyse the motion and agglomeration effect on particles.

4. Simulation Results and Discussion

The generated theoretical model is used as a basis of the computational simulation. 10 particles that are randomly generated with different sizes (Table 2).

Table 2 Name and Size of the generated particles

Particle Number, [-]	Particle Name, [-]	Particle Radius [m]
1	P1	1.024E-09
2	P2	5.036E-08
3	P3	1.987E-08
4	P4	1.309E-08
5	P5	3.522E-09
6	P6	1.256E-06
7	P7	3.111E-06
8	P8	3.284E-06
9	P9	1.807E-08
10	P10	1.010E-06

Each such generated particle is assigned with predetermined properties such as mass, shape, and other physical properties. These properties define the particle interaction and its environment. The sound intensity of the acoustic field is maintained at 140 dB throughout the test time. The algorithm of the DEM determines which particles are in contact and calculates the forces acting on those particles. Besides the gravitational and buoyancy force, Orthokinetic interactions and Wake Effect are considered and applied to the simulation. The same procedure is continued for a desired period using the equation of motion. The position and velocities of the particles are updated accordingly. Upon the simulation, the results are further visualized and analysed to understand the behaviour of the particles and their properties such as frequency, size, velocity, and simulation time.

4.1. Effect on Particle Parameters with Change in Frequency

4.1.1. Size

All 10 particles are subjected to sound waves at three different frequencies (2 kHz, 3 kHz, and 5 kHz) and the exhibited agglomeration of particles is recorded.

At 2 kHz, the change in size of three of the tested particles is presented. The sudden spike in the size of the particle (y-axis) after certain steps (x-axis) indicates the agglomeration of particles. While 6 of 10 tested particles excited out of the agglomeration testing range, remaining 4 particles agglomerated to form three agglomerated particles at the 11th, 51st, and 61st step (P6, P2, and P10, respectively). It is observed that, at step 11, P7 (3.111E-06 m) agglomerated with P6 (1.256E-06 m) and formed a new particle with a size increase of 153 % compared to P6 and an increase of 2.1 % relative to P7 (3.177E-06 m) as presented in Fig. 2.

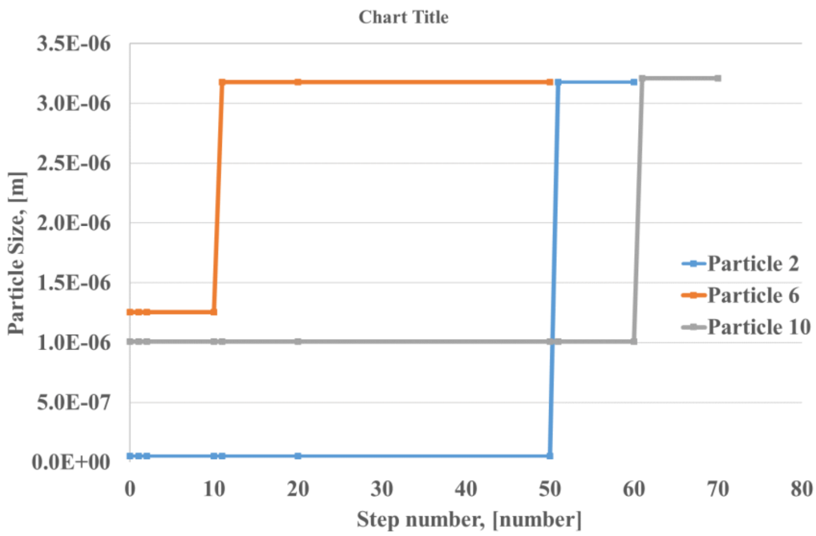


Fig. 2 Agglomeration of particles at 2 kHz

At step 51, P2 (5.036E-08 m) and the new P6 (3.177E-06 m) agglomerated and formed a particle with a sharp increase of 6210 % in terms of P2 and almost 0 % with 4.216E-12 m compared to P6. The last two particles left in the test range were agglomerated in the 61st step to form a new particle (3.211E-06 m) with a size increase of 1.05 % compared to newly agglomerated P2 (3.177E-06 m) and a 218 % increase in terms of P10 (1.010E-06 m). The increase in the size of the agglomerated particle de-pends on the impact of collision between the particles. It will vary for each particle depending on its velocity and properties.

With an increase in frequency to 3 kHz, 5 of 10 tested particles excited out of the agglomeration testing range, P6, which was agglomerated in the 11th step at 2 kHz, is now agglomerated in the 9th step with increases in frequency by 1 kHz.

Similarly, with a further increase in frequency to 5 kHz, five particles excited off the testing range immediately after the first step of application of frequency, but P6 is found to be agglomerated at the 8th step. Of the 10 particles, P6 and P7 are two of the top three particles in terms of size. This proves that the larger particles have a significant chance of agglomerating due to its higher inertia and resonance frequency.

The Aggregation of P6, which occurred at all three frequencies, is found to occur earlier with an increase in frequency, as shown in Fig. 3. As frequency increases, particle agglomeration occurs more rapidly, but the quantity of agglomerated particles decreases.

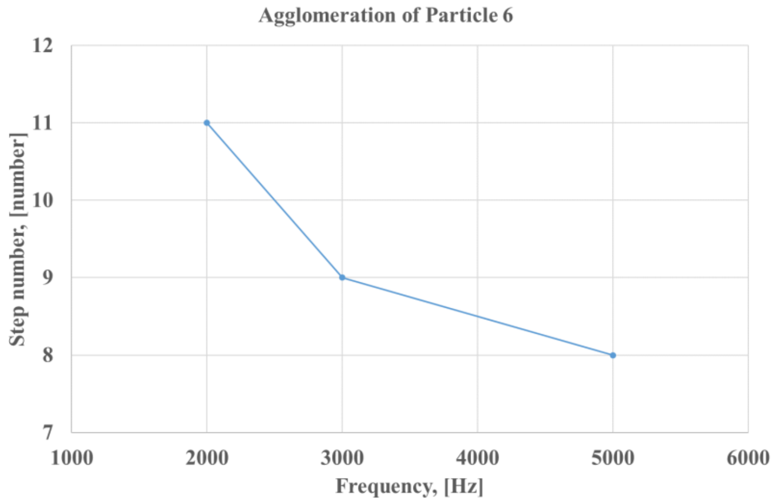


Fig. 3 Agglomeration of P6 at different frequencies

Due to the limited boundary condition of the testing area, some particles are found to be excited out with the presence of frequency within Step 1. While three particles agglomerated at 2 kHz, only one particle agglomerated at 3 kHz and 5 kHz. This may be because, in the field of high frequency, the tendency of particles getting more excited and exiting out of the testing area early increases, decreasing the chances of particles colliding with each other and agglomerating. The experimental results of the tested fuel are found to be in line with the computation results.

4.1.2. Position of Particles (Coordinates)

The position of a single particle is one of the parameters that is difficult to analyze through experimental tests. The position of the particle within the probability of boundary impacts the collision between particles. Particles that are closely placed have the least chance of significant collision, enough to overcome their interparticle forces and agglomerate, unless the velocity of the particle is comparatively higher. The chance of a collision is also impacted by the spatial arrangement. Uniformly distributed particles have higher chances compared to random distribution, particularly when the tested particles are limited. The positions of the particles (P6 and P7) that are found to be agglomerating under all 3 frequencies are studied and presented in a 3-cordinate system (x, y, z) in Figs. 4-6.

Interestingly at smaller frequencies, the x-coordinate of the agglomerated particle is found to be greater than that of P6 and P7, except at 5 kHz agglomerated particle is at velocity 3.22E-04 which is slightly lesser compared to P7 (velocity is 3.32E-04).

In all cases the y-coordinate of the agglomerated particle, is lesser compared to both the particles. In all frequencies, z-coordinate of the agglomerated particle is more inclined towards that of P7.

There is no specific tendency observed while calculating the distance between P6 and P7 and its impact on the position of the agglomerated particle.

Distance between two particles is described as:

$$r = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{11}$$

Additionally, there is no specific tendency observed in the change in the position of the agglomerated particle with increase in the frequency.

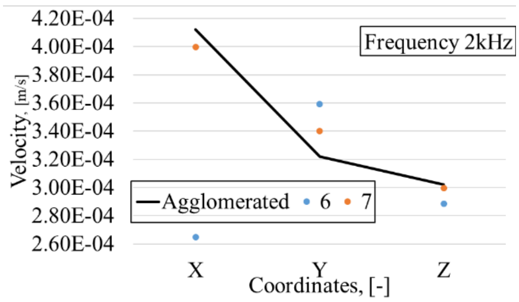


Fig. 4 Coordinates of agglomerated particles at 2 kHz

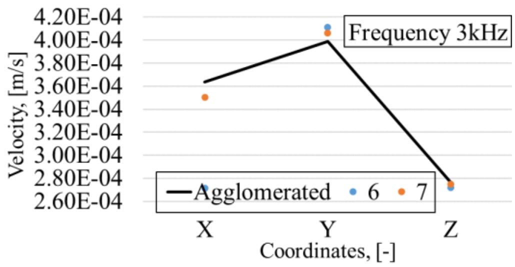


Fig. 5 Coordinates of agglomerated particles at 3 kHz

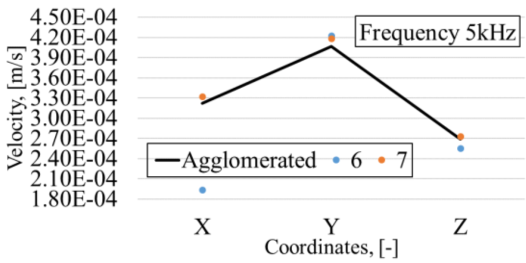


Fig. 6 Coordinates of agglomerated particles at 5 kHz

4.1.2. Velocity of Particles

In DEM simulations, the impact of particle velocity on agglomeration behavior can be significant and is influenced by several factors.

Particles with higher velocities possess the chance of more significant collisions. It can be said that the velocity of the particles is directly proportional to the number of collisions between the particles. Faster-moving particles will experience a higher collision frequency.

The velocity affects the kinetic energy of the particles. Higher-velocity particles carry more energy, leading to more collisions that are impactful. Oftentimes, the impact of energy of fast-moving particles is sufficient to overcome the inter-particle forces leading to agglomeration.

The frequency of sound itself does not affect the speed of individual particles in the material directly. Primarily the forces and interactions of the particles in the material or medium determine the velocity of the particles. Sound waves composed of pressure variations or compression waves, spread through the medium, but do not change the velocity of the particles directly. Conversely, it is observed that velocity, which makes the particles excite and collide with each other to form agglomerates, is found to increase with the increase in frequency.

Velocities of the particles remaining after their 1st step are presented in Tables 3-5.

With an increase in frequency from 2k to 3k, the average velocity of particles in the x-axis is found to increase by 3.02 % and in the z-axis by 152.3 %. Similarly, with further increase from 3k to 5k, the average velocity of particles is found to increase by 9.26 %, 1.52 % and 20.50 % respectively in the x, y, and z axis. This increase in the velocity of the particles with frequency is the reason for the faster agglomeration of particles as the particles with higher velocity have higher chances of agglomeration.

Table 3 Velocity of particles at frequency of 2 kHz

Particle Number, [-]	v_x, [m/s]	v_y, [m/s]	v_z, [m/s]
2	-1.19E-03	-3.53E-04	-3.38E-04
6	-3.10E-01	1.83E-04	7.49E-04
7	-1.72E-01	-1.53E-03	-1.04E-04
10	-2.41E-01	-2.97E-04	-1.66E-05

Table 4 Velocity of particles at frequency of 3 kHz

Particle Number, [-]	v_x, [m/s]	v_y, [m/s]	v_z, [m/s]
2	-1.33E-03	-5.16E-04	-7.29E-04
6	-3.43E-01	1.49E-04	1.61E-03
7	-1.20E-01	-8.76E-04	-5.32E-04
8	-1.08E-01	-2.41E-03	3.38E-04
10	-3.07E-01	-1.40E-04	2.30E-04

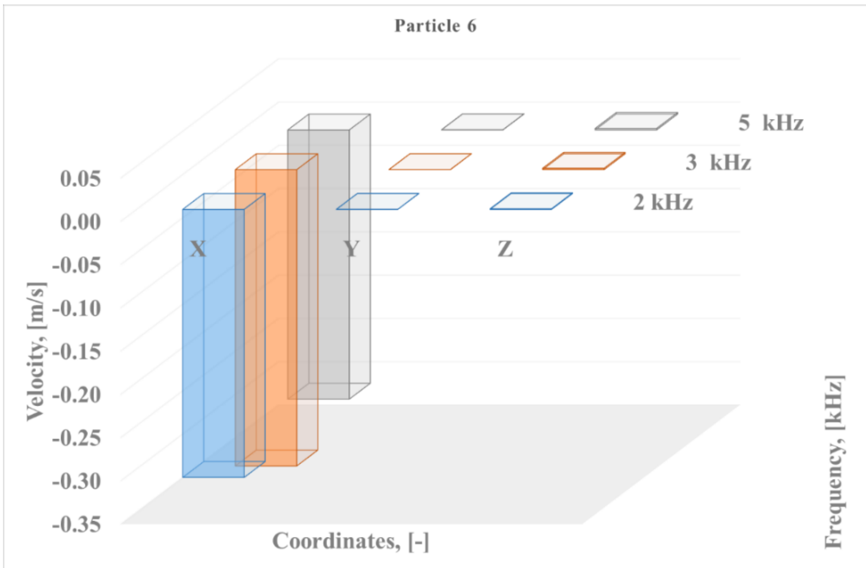
Table 5 Velocity of particles at frequency of 5 kHz

Particle Number, [-]	v_x, [m/s]	v_y, [m/s]	v_z, [m/s]
2	-9.72E-04	-5.36E-04	-6.45E-04
6	-3.11E-01	2.22E-04	1.79E-03
7	-7.37E-02	-8.60E-04	-6.00E-04
8	-6.55E-02	-2.41E-03	3.13E-04
10	-3.45E-01	-1.51E-04	2.48E-04

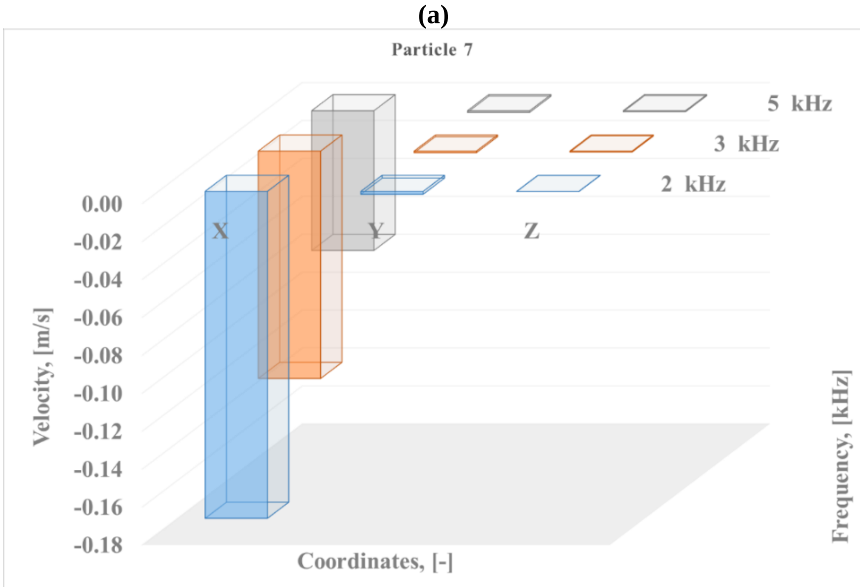
The comparison of the velocity of the P6 and P7 particles that collided and agglomerated across all frequencies is presented in Fig. 7. While X coordinate values are relatively small, the velocities of higher frequencies at 3 kHz and 5 kHz are comparatively higher, which may result in the particles agglomerating faster.

The resultant velocity of the agglomerated particle for all three frequencies is calculated using the Pythagorean Theorem and presented below in Table 6.

$$(|v|) = \sqrt{x^2 + y^2 + z^2} \tag{12}$$



(a)



(b)

Fig. 7 Velocity of particles at different frequencies: (a) – six particles; (b) – seven particles

The overall velocity of the agglomerated particle is found to decrease with an increase in frequency. There is no direct relation between the reduction in velocity and the change in frequency. The inter-particle force, velocity, or impact of collision of the colliding particles can be determined as some of the reasons for the observed tendency.

The impact on velocity of the newly formed agglomerated particle across all three frequencies, presented in Fig. 8, is further studied.

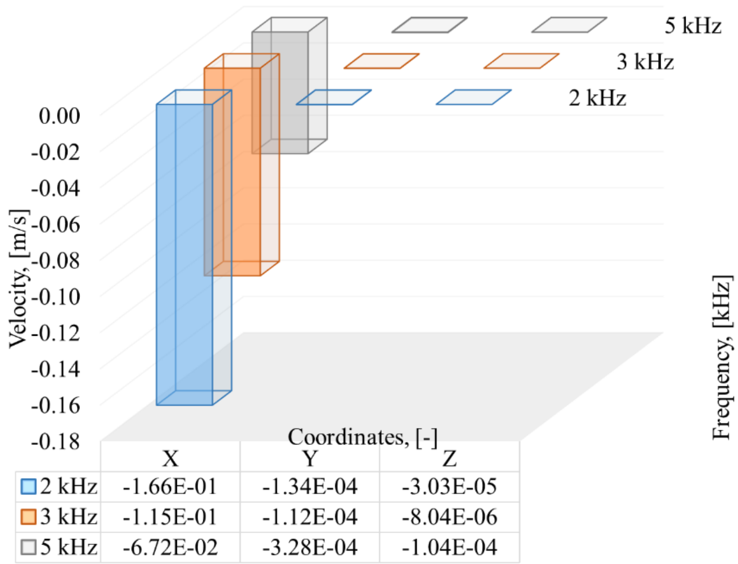


Fig. 8 Agglomerated Particle Velocity Comparison

The resultant velocity of the agglomerated particle for all three frequencies is calculated using the Pythagorean Theorem and presented below in Table 6.

Table 6 The resultant velocity of the agglomerated particle

Frequency [kHz]	Resultant velocity [m/s]
2	1.66E-01
3	1.15E-01
5	6.72E-02

4.2. Change of Agglomeration Time with Increase in Number of Particles

Inside the confined testing range and frequency, with increase in the number of tested particles, time taken to agglomerate to one particle is presented in Table 7 and Fig. 9. At 2 kHz and 140 dB of sound intensity, tests are conducted with 9-15 particles until one particle is left in the agglomeration testing range. Reduction of particles can happen either through particle-particle interaction (acoustic agglomeration of particles) or by leaving the particle boundary box. Particles leaving the boundary box can be interpreted as agglomeration of particle with the boundary wall. Either way, the tests are performed until the volume of the particles falls down to 1. The time is measured in steps where each step is accounted for 0.01 seconds (for example, time taken for 20 steps is 0.2 seconds).

Table 7 Steps taken to agglomerate to one particle

Particles, [number]	Steps, [number]	Steps per particle, [-]
9	22	2.44
10	61	6.78
11	11	1.22
12	25	2.78
13	209	23.22
14	65	7.22
15	86	9.56

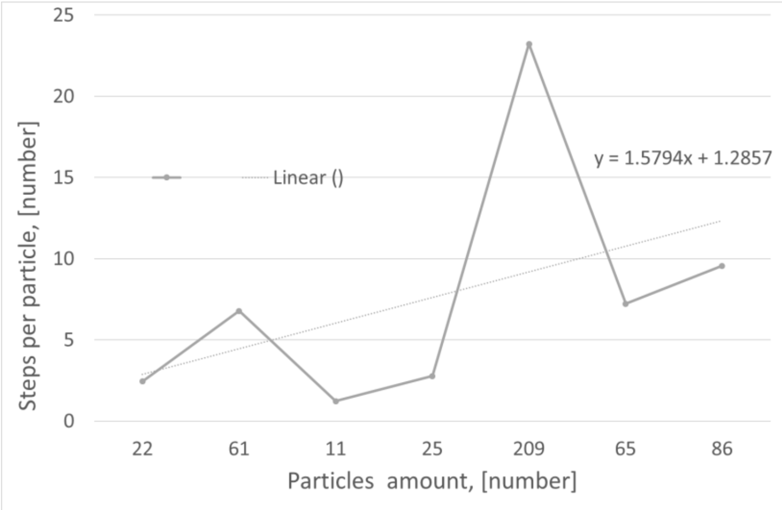


Fig. 9 Steps per particle and number of particles

It is found that at all seven tested conditions, the steps taken with increasing number of particles is found to increase. Although there is a mixed tendency observed in Table 7, when plotted on a graph, the tendency is found to be increasing. A linear expression is obtained for the tendency observed from the test results. Using this equation, we can estimate the steps 'y' (or time) that is expected to take when 'x' particles are tested.

As presented in Fig. 9, it is found that with increase in the number of tested particles, the time taken to agglomerate to one particle is found to increase. This is because with increasing number of particles inside the confined testing range, the combination of interactions increases between the particles and during the long process of combinations, particle gets excited and exits the testing area due to the increased particle-particle interaction shielding effect.

5. Conclusion

A fuel blended volumetrically at 80 % FAT and 20 % isopropanol (FAT80IP20) is used on an experimental setup to determine the impact of frequency on acoustic agglomeration of particles. It showed that with increase in frequency from 21.2 kHz and 34.6 kHz, the number of particles agglomerated are comparatively decreasing. At 21.2 kHz, particles of size 5 and 10 μm are found to be increasing at 38.12 % and 233.33 % respectively, while at 34.6 kHz, there is a 62.78 % reduction of 5 μm particles and 300 % increase in 10 μm particles.

Theoretical Model of AA which is developed from the law of motion considering the gravitational, buoyancy forces along with Orthokinetic interaction and AWE acting on the particle. Considering the limitations of other numerical simulation techniques in understanding the particle-particle interaction, the discrete element method is chosen over finite element methods or computational fluid dynamics.

Under specific boundary condition and 140 dB of sound intensity of the acoustic field. The results of the computation study of influence of frequency on the particle parameters showed that with increasing frequency, total agglomerated particles decreased (three particles at 2 kHz frequency and one particle at 3 and 5 kHz). The experimental results of the tested fuel are found to be in line with the computation results. This may be because, in the field of high frequency, the tendency of particles getting more excited and exiting out of the testing area early increases, decreasing the chances of particles colliding with each other and agglomerating inside the boundary condition.

The agglomeration of P6, which occurred at all three frequencies, is found to occur earlier with an increase in frequency. At 2 kHz, agglomeration of this particle happened at the 11th step, whereas at 3 kHz frequency, it is reduced to the 9th step, and, at 5 kHz, P6 agglomerated at the 8th step. This leads to an estimated understanding that as frequency increases, particle agglomeration occurs more rapidly, but the quantity of agglomerated particles decreases.

It is observed that with an increase in frequency, the velocity of the agglomerated particles is found to be decreasing. The frequency of sound itself does not directly affect the speed of individual particles in the material. The force, velocity, or impact of the collision of the colliding particles can be the reasons for the observed tendency.

At 2 kHz frequency, when particles are subjected to 140 dB of sound intensity, time taken to agglomerate to one particle is found to be increasing with increase in the number of tested particles. This is due to the increase in complexities associated with increase in number of particles. A linear equation is developed using the simulation data which can be used to estimate the steps or time (y) taken to agglomerate ‘x’ number of particles.

The study suggests that acoustic agglomeration has significant potential in reducing particulate emissions. However, further research is needed to optimize key acoustic parameters, test with diverse fuels and particle types, integrate with existing filtration technologies, assess the feasibility of acoustic agglomeration in real-world scenarios, and develop particle behavior modeling and simulation techniques. The study also emphasizes the need to investigate the efficiency of acoustic agglomeration in targeting ultrafine particles, which have significant health implications. Additionally, a life-cycle analysis of the acoustic agglomeration technology, considering environmental impact, operational costs, and potential energy savings, could help establish its sustainability and market viability compared to existing emission control technologies. These areas of research will help to improve the practical applicability and scientific understanding of acoustic agglomeration.

Acknowledgement: *The paper is a part of the research done within the project funded from the Research Council of Lithuania (LMTLT), agreement No: S-PD-22-69. This research was supported by the center of excellence project „Civil Engineering Research Centre" (Grant No. S-A-UEI-23-5).*

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