Ultrasonic coagulation of suspended particles in resonant gas gaps

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Abstract. The article describes a method for ultrasonic coagulation of suspended fine particles in the air gap between a flat radiator and reflector. Using the developed experimental stand, the efficiency of coagulation was investigated at various distances between the radiator and the reflector. During the experiments, the presence of a peak value in the dynamics of the coagulation process at a distance of 14 mm (which corresponds to 1 wavelength of ultrasonic oscillation in air at an operating frequency of 25 kHz) was revealed. It is shown that at this distance the maximum efficiency of ultrasonic coagulation is achieved, which is 95%, and the level of sound pressure reaches its maximum equal to 132 dB.

1. Introduction

Currently, up to 1 billion tons of various aerosols are emitted into the atmosphere by industrial enterprises, annually. A significant part of these emissions are made up of chemical and mining industry, thermal energy, and metallurgical plants. Such emissions affect human health and the environment. And in connection with this problem, the question of cleaning emissions from dispersed impurities is acute. To date, for the purification of industrial emissions from dispersed particles, various apparatuses have been developed and are being put into practice that differ in construction and are based on various physical mechanisms for capturing suspended particles larger than 5 μm in size. But, effectiveness of these apparatuses is significantly reduced when trapping particle with sizes less than 2.5 μm. Due to their small size and mass, such particles can be held in the air for a long time and can adversely affect the environment and human health [1].

In fact, effective means and methods of combating atmospheric pollution with fine particles do not exist, which determines the urgency of solving this problem. A promising direction is the intensification of the gas cleaning process due to exposure to the aerodispersion system high-intensity ultrasonic oscillations in order to enlarge the particles - ultrasonic coagulation. The phenomenon of ultrasonic coagulation is to increase the frequency of the union of homogeneous and heterogeneous particles into agglomerates [1-6].

Currently, ultrasonic technology is widely used in various industries. Exposure to high-intensity ultrasonic oscillation provides an improvement in the properties of known substances and materials, and makes it possible to intensify various technological processes. But, as research shows, the ultrasonic effect is not effective enough for coagulation of highly dispersed particles [6]. The reason for this is:
using a low frequency of ultrasonic exposure (less than 22 kHz), in which all particles less than 2.5 μm in size are involved in the oscillational motion equally, which does not contribute to their collisions [7-8];

- the exclusion of the hydrodynamic component of coagulation due to the absence of disturbance in the field of flow around particles, due to small diameter a particles;
- impact on airspace volumes with linear dimensions many times greater than the wavelength of ultrasonic oscillations in the air and not providing the conditions for the occurrence of a non-linear effect;
- low efficiency of ultrasonic coagulation with increased particles distances, characteristic of highly dispersed aerosols [7-9].

Therefore, in this article, the process in a thin resonant gap between emitter and reflector is proposed to be implemented. This will provide a resonant increase in sound pressure level in the air gap.

With a resonant distance between emitter and reflector in the air gap, conditions are created for the appearance of intense acoustic microflows and vortices, which contribute to the coagulation of highly dispersed particles and the deposition of their aggregates on the surface of reflector.

The lack of suitable and efficient emitters, the high need for the practical implementation of technological processes in gaseous media necessitate the creation of highly efficient ultrasonic emitters for gaseous media.

2. Problem statement
The main aim of paper is to research the process of ultrasonic coagulation of highly dispersed particles in a thin gap between emitter and reflector, to determine the modes and effectiveness of the intensification of ultrasonic coagulation process of high dispersed particles.

3. The design of the experimental stand
The design of the stand in shown in figure 1. The experimental stand provides various conditions for ultrasonic exposure. The stand allows measuring the effectiveness of coagulation by optical transparency at the output of the coagulation chamber.

The experimental stand designed for research of the process of ultrasonic coagulation of high dispersed particles in gas medium using acoustic effects of ultrasonic frequency in a thin gap consists of the blocks:

- coagulation chamber, inside of ultrasonic oscillation act on the gas media;
- ultrasonic oscillation system (USOS) with a flat flexural-oscillating disk, with a diameter of 104 mm;
- the ultrasonic generator of the signal (USG), feeding the oscillation system;
- an aerosol generator with a droplet size of 2.5 μm, which are the most dangerous to human and the atmosphere;
- a measuring block, which is designed to obtain an aerosol concentration measurement by its optical transparency.

The model of the coagulation chamber (figure 2), which consists of parts:

- area in which sounding of the gaseous medium occurs;
- the input channel, made in the form of a branch pipe of a liquid aerosol generator, to prevent settling of water droplets;
- the output channel, where a fan is installed for suction of the aerosol;
- holes for installing sensors of the aerosol optical transparency determination system;
A MUSSON medical inhaler was used as a liquid aerosol generator. Thanks to the use of ultrasonic atomization of water in it, there is an opportunity to get mist – a random mixture of droplets with a diameter of from 0.01 μm to 3 μm.

To reflect ultrasonic waves, a glass base was used, which also allows observing the filling of the chamber with an aerosol.

The fan generates air flow, which is the transport agent for the aerosol generated by the medical inhaler. The aerosol passes through the trumpet and coagulation chamber and enters the output.

For getting high-intensity ultrasonic oscillation (more than 130 dB) in gaseous media during research, of ultrasonic emitter based on the use of piezoelectric transducer was proposed and manufactured.

The apparatus for ultrasonic coagulation of high dispersed particles (figure 3) consists of flat disk emitter and ultrasonic generator. The base of emitter is a disk with a diameter of 104 mm with a flat surface (figure 3a), which performs bending oscillation at a frequency of 25000 Hz and converts longitudinal oscillation transmitted from the piezoelectric transducer into bending oscillations of the radiating surface of the disk [7-8]. Ultrasonic generator is given in figure 3b.
The apparatus for ultrasonic coagulation of high dispersed particles. a) flat disk emitter, with a diameter of 104 mm; b) electronic generator.

Figure 3. The apparatus for ultrasonic coagulation of high dispersed particles. a) flat disk emitter, with a diameter of 104 mm; b) electronic generator.

The use of flexural-oscillation of the disk gives an increase in the energy output (more 65%) into the gas medium, and the radiation from the surface of areas of various thicknesses ensures the coherence of the emission ultrasound waves. Highly emission efficiency and the absence of mutual compensation of waves from different points on the surface of emitter allows generating oscillations with a level of sound pressure of more than 130 dB even at intervals more than the diameter of disk itself [10-13].

A system for determining the optical transparency of aerosol builds on a microcontroller of the AVR family. Its block diagram is depicted in figure 4.

Figure 4. Measuring device block diagram. 1 is infrared LED; 2 is infrared photodiode; 3 is operational amplifier; 4 is microcontroller; 5 is power supply; a, b, c, d are channels for measuring.

The aerosol is absorbed in by the air stream with the help of a fan, passes through of the coagulation chamber to the output of the stand. USOS creates an ultrasonic frequency field [10, 14-15].

Reflector gives the addition of the reflected wave and the incident wave at resonant intervals – their resonant amplification. This intensifies of the ultrasonic coagulation of high dispersed particles and the deposition of their agglomerates on the reflector [9-13, 16-20]. Then the air purified by ultrasound is removed by a fan from their chambers.

Measuring device fix the change in the optical transparency of aerosol at the entrance and exit from the coagulation chamber at the same time. Upon request, the measuring device transmits the received data to a personal computer using of the serial COM port.

4. Experimental results
The sound pressure level in the coagulation chamber was measured at different interval between emitter and reflector at the same point. At the time of this experiment, the supply of aerosol was turned off. Step of the control points was chosen equal to 1 mm. The wavelength was calculated by the formula:

$$\lambda = \frac{c}{f} ,$$  \hspace{1cm} (1)
where \( c \) is the sound speed in the air medium (340 m/s), \( f \) is the frequency of acoustic oscillation (25 kHz or 25000 Hz).

With the use of the available values in formula (1), a value for the wavelength is obtained:

\[
\lambda = \frac{340}{25000} = 0.014\text{(m)}.
\]

Basing on data of experiments, a graph of the dependence of the level of sound pressure on the interval between the USOS and reflector was plotted (figure 5).

![Figure 5](image)

**Figure 5.** The graph of the dependence the level of sound pressure in the coagulation chamber on interval between emitter and reflector.

When considering the chart, we can conclude that the level of sound pressure varies depending on interval between reflector and emitter, and takes the maximum value of 131 dB on the interval of 14 mm - 1 wavelength. Significant fluctuations in the graph are caused by the appearance of resonance phenomena in the air gap between emitter and reflector (pos. 1 and pos. 6 in figure 1, respectively).

Ultrasonic coagulation begins at levels of sound pressure of more than 130 dB, and the efficiency of the process increases with increasing sound pressure [15]. The detected distance equal to 1 wavelength is the desired resonant gap, which can be considered optimal interval for the intensification of the ultrasonic coagulation process.

Measurements at distances greater than 30 mm were not carried out, so it cannot be said that, all other things being equal, at this distance, the process of acceleration of ultrasonic coagulation of high dispersed particles in a gas media will flow well.

The coagulation efficiency was controlled by the optical transparency of the aerosol at the input and the output of experimental stand.

When determining the optical transparency of aerosol, the unit of measuring adopted a dimensionless quantity that expresses the ratio of the signal at the output \( A_i \), to the current measurement, to the output signal \( A_0 \), corresponding to the state of the air medium free from various impurities. Dimensionless quantity is determined by the following equality:

\[
\delta = \frac{A_i}{A_0} \%.
\]

Values of \( A_0 \) and \( A_i \) are found from the following equality:

\[
A = \frac{\sum_{j=1}^{n} A_j}{n},
\]
where \( A_j \) is a separate element in the measurement sequence, \( j \) is number of element, \( n \) is the quantity of elements of the measuring sequence [18-20].

In order to determine the effectiveness of ultrasonic coagulation, the optical system was tuned by ensuring the equality of signals from the photodiodes at the input and output in the absence of aerosol filling.

After tuning the optical system of measuring device and installation of a fan, emitter moves to the farthest position from USOS. A medical inhaler is connected to the input channel. An ultrasonic generator and a measuring device were supplied with power. The level of measuring signal was recorded at input and output of the coagulation chamber using a special program on a personal computer.

Then the aerosol generator is turned on, a time of 1 min was measured, this period of time is enough to fill the coagulation chamber with aerosol. Level of signal was fixed at the input and output of the resonance value, after which the output signal level was recorded for 1 min (for further statistical processing). The experiment was repeated at 30 control points with a step of 1 mm and continued until reflector reached the last point (1 mm from reflective surface). The results of an experimental study of the effectiveness of the ultrasonic coagulation process at maximum power are presented in figure 6.

![Figure 6. Bar chart of the dependence of the efficiency of coagulation aerosol on the interval between emitter and reflector at maximum power.](image)

Significant fluctuations in the graph, as in figure 5 are caused by the occurrence of resonance phenomena in the air gap between the emitter and the reflector. Moreover, the efficiency of aerosol coagulation (optical transparency) increased to 25%.

When considering the graph in figure 6, the presence of maximums of optical transparency of the aerosol at the exit from the resonance value on the intervals of half the wavelength and 1 wavelength between the ultrasonic oscillation system and reflector was revealed. This made it possible to determine the interval between the surface of emitter and reflector, at which the process under study has the highest efficiency equal to 1 wavelength (optical transparency \( \delta = 95\% \)).

Low efficiency on the interval of less than half the wavelength is explained by small distance between emitter and reflector, the air flow transfers part of the aerosol outside zone of the coagulation. The decrease in coagulation efficiency at distance above 1 wavelength is due to an increase in the space of the coagulation chamber.

5. Conclusion
As a result of experimental studies, resonance phenomena in a thin air gap between emitter and reflector significantly (up to 25%) was shown to increase the efficiency of ultrasonic coagulation of aerosol with sizes less than 2.5 \( \mu m \), determined by the optical transparency of the aerosol.

Optimal distance equal to the resonance gap 1 of the wavelength between emitter and reflector at which the maximum efficiency of the ultrasonic coagulation process (\( \delta = 95\% \)) is revealed. Also, at a distance of 1 wavelength, the sound pressure level reaches a maximum of 131 dB. The decrease in
coagulation efficiency on the interval above 1 wavelength is due to an increase volume of the coagulation chamber; and low efficiency on the interval of less than 1 wavelength is due to tiny interval between the ultrasonic oscillation system and reflector, air flow passes zone of the coagulation.

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References
[1] Uzhov V N, Wakdberg A U, Myagkov B I and Reshidov I K 1981 Purification of industrial gases from dust (Moscow: Chemistry) p 392
[2] Vetoshkin A G 2005 Dust cleaning processes and apparatus: study guide (Penza: Publishing State University) p 210
[3] Kozlova S A, Shalaev I M, Raeva O V and Kiselev A V 2007 Gas purification equipment for Industrial furnaces (Krasnoyarsk: Siberian Federal University) p 156
[4] Seya K, Nakane T and Otsumo T 1957 Agglomeration of aerosols by ultrasonically produced water mist Ultrasonic symposium proceedings (Electronic materials) 583-4
[5] Ladygichev M G and Berner G Ya 2004 Foreign and domestic equipment for gas purification (Moscow: Teplotekhnik) p 696
[6] Gershgal D A and Fridman V M 1987 Ultrasonic Technological Equipment (Moscow: Energia) p 318
[7] Khmelev V N, Shalunov A V, Golykh R N and Nesterov V A 2018 Ultrasound Gas purification (Byisk: Publishing house Altay State Technical University) p 534
[8] Gallego-Juarez J A, Rodriguez G, Acosta V and Rierra E 2010 Power ultrasonic transducers with extensive radiators for industrial processing Ultrasonic Sonochemistry 17 953-64
[9] Andres R R, Acosta V M, Lucas M and Rierra E 2018 Modal analysis and nonlinear characterization of an airborne power ultrasonic transducer with rectangular plate radiator Ultrasonic 82 345-56
[10] Gallego-Juarez J A, Rodriguez-Corral G and Gaete-Garreton L 1998 An ultrasonic transducer for high power applications in gases Ultrasonic 16(6) 267-71
[11] Sheng C D and Shen X L 2007 Simulation of acoustic agglomeration processes of poly-disperse solid particle Journal of Aerosol Science and Technology 41 1-13
[12] Andres R R, Pinto A, Martinez I and Rierra E 2019 Acoustic field generated by an innovative airborne power ultrasonic system with reflectors for coherent radiation Ultrasonic 99 1-13
[13] Liu J, Wang J, Zhang G, Zhou J and Cen K 2011 Frequency comparative study of coal-fired fly ash acoustic agglomeration Journal of environmental science 23(11) 1845-51
[14] Rierra E, Gonzalez-Gomez I, Rodriguez G and Gallego-Juarez J A 2015 Ultrasonic agglomeration and preconditining of aerosol particles for environmental and other applications Power Ultrasonics: Application of High-Intensity Ultrasonic 38 1023-61
[15] Kudryashova O B, Akhmadeev I R, Paylenko A A, Arkhipov V A and Bondarchuk S S 2009 A method for measurement of disperse composition and concentration of aerosol particles Proceedings of ISMTII 178-83
[16] Riera-Franco de Sarabia E, Elvira-Segura L, Gonzalez-Gomez I, Rodrigues-Maroto J J, Munoz-Bueno R and Dorronsoro-Areal J L 2003 Investigation of the influence of humidity on the ultrasonic agglomeration of submicron particles in diesel exhausts Ultrasonic 41(4) 277-81
[17] Gallego-Juarez J A, Riera E, Corral G, Hoffmann T and Galvez-Morelada J 1999 Application of Acoustic Agglomeration to Reduce Fine Particle Emissions from Coal Combustion Plants Environmental Science and Technology 33 3843-8
[18] Khmelev V N, Shalunov A V, Dorovskikg R S, Nesterov V A and Kozhevnikov I S 2017 Ultrasonic coagulation to improve the efficiency of the gas cleaning system 18th International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices 294-7
[19] Gallego-Juarez J A 2010 High-power ultrasonic processing: recent developments and prospective advances Phys 3(1) 35-47

[20] Khmelev V N, Shalunov A V, Nesterov V A and Golykg R N Studies of the Formation of Submicron Particles Aggregates under Influence of Ultrasonic Vibration American Journal of Engineering Research 2(1) 265-75