Study of coagulation efficiency of highly dispersed particles under the influence of high intensity ultrasonic vibrations

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Abstract. The article presents the results of experimental studies of the coagulation efficiency of fine-dispersed particles at the influence of high-intensity ultrasonic vibrations in various modes (including the standing wave mode). The study of the influence of various conditions of ultrasonic exposure on aerosol coagulation efficiency was conducted on the developed stand. The optimal distance from the ultrasonic emitter to the reflector has been established. This distance ensures maximum efficiency of aerosols coagulation at standing wave mode. Thus, it is possible to increase coagulation efficiency up to 2 times at optimal conditions.

1. Introduction

The problem of fine-dispersed particle capture in gases requires a solution to problems in many industry sectors [1-2]. This is especially important for improving the planet's ecology by capturing emissions of aerosol particles in the atmosphere. Besides, many industrial technologies are impossible without separation of the finished product in gases during technological processes (obtaining fine-dispersed silicon, nanocarbon particles, etc).

At present, various devices are developed and used for gas purification and capture of the finished product in the form of fine-dispersed particles (1-10 μm), which differ both in construction and in the method for capturing suspended particles [3-6]. The most widespread are dry inertial dust collectors (cyclones), precipitation chambers, and devices with counter-swirling flows. These devices have the efficiency of capturing dispersed particles up to 95-99% when capturing particles larger than 20 μm. Their efficiency decreases significantly when particle sizes of less than 10 μm [7]. Developers made many attempts to increase the effectiveness of such devices by changing constructions and motion modes of gas-dispersed phase, but they do not bring the desired results. The reason is the impossibility of the necessary exposure on each small particle carried away by the gas flow.

One of the ways to expose each particle effectively is to use high-intensity ultrasonic vibrations [8-10]. Such exposure is capable of changing the trajectories of particles moving in a flow and carrying out their preliminary coagulation (providing an increase in the efficiency of particle capture).

The exposure by ultrasonic vibrations on the gas-dispersed phase can be carried out in various ways. It is necessary to form a standing wave in gases to ensure maximum energy exposure during the process of acoustic coagulation of fine-dispersed particles. However, to date, there have been no comprehensive studies of the coagulation process when particles are exposed by high-intensity ultrasonic vibrations in a standing wave. The reason is the absence of ultrasonic vibrations sources that provide such exposure conditions.
For these coagulation problem solving and the creation of new sources of ultrasonic exposure, there is a need to research the coagulation process of particles with sizes less than 5 μm at energetically favorable standing wave mode.

2. Problem statement
Studies are necessary to find optimal modes and conditions of ultrasonic exposure (frequency of exposure, sound pressure level) for gas-dispersed flows of various parameters (with particles of different sizes, at different flow rates, exposure times, etc). The finding of such modes and exposure conditions will allow developing equipment for practical use in various technological processes.

It is necessary to solve the following tasks to prepare and conduct such studies:

- to develop and to make ultrasonic emitters to ensure the effect of ultrasonic vibrations with certain parameters on gas-dispersed phase;
- to create an experimental stand and to develop a methodology for research the coagulation process at conditions of a standing wave;
- to conduct experimental studies to confirm the effectiveness of various coagulation modes of fine-dispersed particles.

3. Development of emitters for exposure on gas-dispersed phase
Two prototypes of ultrasonic emitters based on piezoelectric transducers were proposed and manufactured for creating high-intensity ultrasonic vibration (more than 140 dB) in gases for research.

The emitting element of the first sample is made of a special shape (a disk of the stepwise variable cross-section). It converts longitudinal vibrations from the piezoelectric transducer into bending vibrations of the disk emitting surface [11-13]. The sketch of the ultrasonic vibrating system with a bending vibrating disk emitter is shown in figure 1a. The amplitude distribution of bending vibrations of disk emitting is shown in figure 1b.

![Figure 1](image-url)  
**Figure 1.** The sketch of the ultrasonic vibrating system with a disk emitter (a), amplitude distribution of the disk emitter (b), apperance of the ultrasonic vibrating system (c): 1 is disk emitter; 2 is piezoelectric transducer; 3 is case; 4 is flange; 5 is fan.

| Table 1. Technical characteristics of ultrasonic emitters for gases. |
|-------------------|-------------------|-------------------|
| Parameter                  | Value                          |
| Type of emitting element | Disk flexural- vibrating radiator | Piston vibrating radiator |
| Diameter, mm              | 104                           | 104                           |
| Working frequency, kHz    | 23.5                          | 23.3                          |
| Power consumption, W      | 60                            | 90                            |
| Sound pressure level in focus, dB | 160 (on distance 150 mm) | 162 (on distance 200 mm) |
| Sound pressure level at a distance of 1 m, dB | 141                            | 145                           |
The emitting element of the second sample is made as a cylindrical body of resonant (half-wave) length. The sketch of the ultrasonic emitter with an ultrasonic vibrating system is presented in figure 2a. The vibration amplitude distribution of a piston-type emitter is shown in figure 2b. The technical characteristics of the developed ultrasonic emitters for gases are shown in table 1.

The created ultrasonic emitters can provide the necessary exposure for the coagulation of submicron particles in gas flows.

![Figure 2](image1)

**Figure 2.** The sketch of the ultrasonic vibrating system with a piston-type radiator (a), the amplitude distribution (b), the appearance of the ultrasonic vibrating system (c): 1 is ultrasonic emitter; 2 is concentrator; 3 is piezoceramic elements; 4 is reflective pad; 5 is case; 6 is flange; 7 is hanger bolt.

4. Development of an experimental stand for ultrasonic exposure in the standing wave mode

The experimental equipment was developed. Its appearance is shown in figure 3.

![Figure 3](image2)

**Figure 3.** The appearance of the developed experimental stand for ultrasound coagulation in the standing wave mode: 1 is ultrasonic disk emitter; 2 is aerosol generator; 3 is ultrasonic generators to supply the disk emitter; 4 is coagulation chamber; 5 is reflector.
The equipment provides various conditions for ultrasonic exposure (including the standing wave mode).

The stand consists of a coagulation chamber (pos. 4), at the ends of which an ultrasonic emitter (pos. 1) and a reflector (pos. 5) are mounted. A reflector can move along a coagulation chamber. The coagulation chamber on both sides has an inlet (pos. 6) and an outlet (pos. 7) pipe. An inhaler (pos. 2) is connected to the inlet pipe (pos. 6) to supply an aerosol to the coagulation chamber. The ultrasonic emitter is supplied by an ultrasonic electronic generator (pos. 3). The inhaler (pos. 2) was replaced by an ejection type atomizer when solid particles were fed into the coagulation chamber. Silica particles were poured into its hopper.

The standing wave mode is ensured by a certain distance (a multiple of half the wavelength in gas) between the front surface of the emitter and the reflector plane.

The standing wave mode in gases is the most advantageous in this case. This mode allows maximum efficient use of the energy of ultrasonic vibrations in the process of acoustic coagulation of fine-dispersed particles.

Thus, the standing wave mode in the chamber of the preliminary processing of the gas-dispersed flow can significantly increase the coagulation efficiency by increasing the concentration and convergence of particles in the nodal areas.

A fan was mounted at the coagulation chamber outlet for creating a vacuum in the chamber volume at study the coagulation process of water aerosol in the presence of airflows. The receiver and transmitter of the concentration meter were mounted on the output pipe.

The formula for calculating coagulation efficiency:

$$K = 1 - \frac{N_{Us}}{N} \cdot 100\%$$

where $N_{Us}$ is the aerosol concentration at the outlet under ultrasonic exposure, g/m$^3$; $N$ is the aerosol concentration at the outlet without ultrasonic exposure, g/m$^3$.

Thus, the coagulation efficiency is 100% at the complete precipitation of particle agglomerates in the coagulation chamber.

5. Experimental results

Water aerosol (aerosol from the inhaler $d_{32} = 5 \mu$m), as well as particles of silicon dioxide (aerosol 175, $d_{32} = 1 \mu$m), were supplied to the inlet pipe of the coagulation chamber during experiments. The studies were carried out at the following conditions: sound pressure level – 147 dB, gas flow rate - 0.2 liters per second, aerosol concentration - 30 g/m$^3$. The coagulation of a water aerosol in a standing wave is shown in figure 4.

![Figure 4. Coagulation in a standing wave: 1 ultrasonic disk emitter; 2 reflectors; 3 outlet pipe; 4 particle agglomerates.](image-url)
The particles agglomerated and precipitated in 1 ... 2 seconds of ultrasonic exposure at the absence of air flows in the coagulation chamber was revealed during the experiment.

Formed particle agglomerates (pos. 4) were located at the nodes of the standing wave at ultrasonic exposure of solid particles. Beside, particle agglomerates were formed in the form of disks with a nominal diameter of up to 5 mm. The thickness of the agglomerates was about 0.3 mm.

Particle agglomerates were also located in the nodes of the standing wave at ultrasonic exposure of water aerosol. Moreover, the shape of the agglomerate was spherical due to the surface tension of the liquid. The diameter of the droplets reached 2-3 mm.

Thus, the experiments have confirmed the high efficiency of ultrasonic exposure with standing wave mode for accelerating of the particle coagulation process. A photograph of settled water droplets on the walls of the coagulation chamber is shown in figure 5.

![Figure 5. Distribution of aerosol droplets on the wall of the coagulation chamber.](image)

An aerosol was supplied to the inlet pipe in research. The distance between the radiator and the reflector changed at the research to study the influence of the standing wave mode.

Two developed ultrasonic radiators (bending-vibrating and piston) were used in research. The dependence of ultrasonic coagulation efficiency on the distance between the emitter and the reflector when using a bending-vibrating disk emitter is shown in figure 6.

![Figure 6. Dependence of the coagulation efficiency on the distance of the emitter to the reflector (bending-vibrating disk emitter).](image)

Next, envelopes of the dependencies were obtained for the maximum coagulation efficiency using both a disk emitter and a piston-type emitter (figure 7).

Analysis of the data showed that coagulation efficiency substantially depends on the conditions of ultrasonic exposure. Moreover, the standing wave mode significantly (up to 2 times) increases coagulation efficiency.
Figure 7. Dependences of the coagulation efficiency on the distance of the emitter to the reflector: 1 is bending-vibrating emitter; 2 is piston-type emitter.

Thus, maximum efficiency is achieved at distances in the range from 170 to 200 mm when using both types of emitters. However, it is necessary to ensure the standing wave mode. In this case, a standing wave is provided only if the multiplicity of the distance is half the wavelength in the gases. A small change in the distance leads to a decrease in the coagulation efficiency (on average by 20%) due to the violation of ultrasonic exposure in the standing wave mode.

The analysis of the dependencies (presented in figure 7) also showed that coagulation efficiency is higher when using a piston-type emitter. This is achieved by providing a larger effective area of the vibrating surface.

6. Conclusion
The results of the experiments confirmed increasing of the coagulation efficiency in the standing wave mode and the possibility it implementing in practical constructions.

During researches:

- two types of ultrasonic emitters are proposed and developed suitable for exposure on gas-dispersed phases. In this case, a bending-vibrating disk emitter provides a sound pressure level in the focus of at least 160 dB, and a piston-type emitter of at least 162 dB;
- the developed experimental stand made it possible to study the influence of various conditions of ultrasonic exposure, and to identify the conditions for the resonant amplification of vibrations in the standing wave mode;
- the experimental studies made it possible to obtain the necessary data on the modes and conditions of ultrasonic coagulation and the achievement of maximum coagulation efficiency in the standing wave mode.

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