Coagulation of submicron particles in gas-dispersed media due to high-intensity shock-wave exposure

V N Khmelev, A V Shalunov, V A Nesterov, P P Tertishnikov and R N Golykh

Biysk Technological Institute (branch) of the Altay State Technical University, 27, Trofimova st., Biysk, 659305, Russian Federation

E-mail: vnh@bti.secna.ru

Abstract. The article presents an approach to solving the problem of gas cleaning from high-dispersed aerosols with particles less than 2.5 microns. The proposed approach is based on the use of high-intensity shock-wave ultrasonic exposure, which provides an increase in the coagulation efficiency of high-dispersed particles up to 20 times (in comparison with harmonic ultrasonic exposure). The article considers an example of the implementation of the process of shock-wave exposure on aerosols using previously developed ultrasonic emitters. The results obtained are the basis for the make and use of a new class of gas cleaning equipment for capturing submicron particles in solving the problem of environmental and human protection.

1. Introduction

One of the consequences of rapid growth of industry is change for the worse of air. Natural, technogenic and technological wastes in the different branches of industry are accompanied by the emission of gas-dispersed systems, which pollute the environment.

The need to provide health of humanity requires constant struggle against smog, dust, fogs of harmful, poisonous and radioactive substances [1–4]. The efforts of scientists lead to the development of universal and special-purpose equipment for the particle catching from the gas-dispersed systems. The most efficient of them are based on the realization of inertial and centrifugal processes [1]. Such equipment is well-recommended at the catching of the particles with the size of more than 2.5…10 micron.

However, it is known, that maximum harm for people, animals and the environment does the aerosols consisting of fine-dispersed particles with the size of less than 1…2.5 micron. The total amount of such particles in the wastes of the thermal power stations and different production enterprises (number concentration) exceeds 95% of the total number concentration (total amount of the particles in the wastes) at insignificant mass fraction. Due to small sizes and mass such aerosols can be kept in air for a long time and they are able easily penetrate to the lung alveolus of people and animals causing irreversible changes in the organisms.

However, used equipment and known methods of the particle catching is ineffective at the catching of the particle with the size of less than 2.5 micron. At present such particles are not caught by the used industrial equipment, but it is difficult to reveal them in total number of foreign particles in the gas flows, as their total weight is less than 1% making wrong effect of their absence and respectively the absence of necessity to fight with them.
2. Problem statement
At the same time there is a promising method of the particle catching with the size of less than 2.5…10 micron. Such method is the ultrasonic coagulation realized at the propagation of high-intensity mechanical oscillations of ultrasonic frequency (more than 20 kHz) in gas-dispersed media [2-4]. The propagation of high-intensity (more than 140…150 dB) ultrasonic oscillations allows intensifying the coagulation and precipitation of any aerosols. It is especially important, as at present it is proved the possibility and the efficiency of ultrasonic coagulation for the particles with the size of more than 2.5 micron [2–5]. Different authors propose the conditions and the modes of coagulation, at which it is achieved maximum degree of coagulation, and recommend the variants of the special equipment design [3–11] for the particle coagulation both in open air and in closed volume. At that the main approach to the realization of such technology is in the installation of the ultrasonic radiators in existing technological chambers of used gas-purifying apparatuses for their efficiency increase without essential changes of their constructions.

The reason of the acceleration of small particle coagulation is that ultrasonic oscillations propagated in a gas-dispersed medium generate the motion of medium particle relatively to their position of equilibrium. The displacement of gas particles in the direction of oscillation propagation generates the zones of reduced pressure and elevated pressure inside the gas.

The particles of gas medium move relatively to the foreign particles acting upon them. Shocks of the gas particles having different speeds lead to the appearance of the flows and local pressure drops around the foreign particles. At that the foreign particles are involved into oscillating motion and at the external sides of the particles it is appeared the forces of radiation pressure exceeding the forces at the internal surfaces, i.e. it occurs hydrodynamic interaction of the particle flow fields and the particles are attracted. Moreover involved into the oscillating motion the foreign particles of different or the same sizes, but placed in various zones of the oscillating process (i.e. at the distance, which does not exceed half wave length of ultrasonic oscillations in gas) receive different motion speeds, move along oscillation propagation at different distances that cause the increase of the collision number and the particle coagulation.

Unfortunately, practical application of such technology is not widely spread, as the existing ultrasonic equipment is not efficient enough for the coagulation of the particles with the size of less than 2.5 micron and especially than 1 micron.

The main reason of it can be explained by the specific features of ultrasonic action of sinusoidal oscillations. Under such action firstly it occurs the involvement of the submicron particles into oscillating motion within the limits of the areas between the zones with minimums of the oscillating speed [5, 7, 12] and practical absence of their collisions within the limits of the areas. The cross-section area of particle collision with the size of 1 micron in such case is in 100 times less than for the particles of 20 micron [13-15].

The second reason of low efficiency of the traditional ultrasonic coagulation is caused by the fact, that the area, in which occurs the motion of the particles relatively to the position of their equilibrium and the area of reduced pressure, at the propagation of ultrasonic oscillations in gas-dispersed medium is large in comparison with the particle sizes, as it is half wave length of the propagated oscillations and at the frequency of 20 kHz it equals to 8…9 mm. The particles having very small sizes in comparison with the area of pressure change move with the same speeds and there are no additional forces promoting their aggregation.

Thus, the action of sinusoidal ultrasonic oscillations on the particles with the size of 2.5 micron is very insufficient and such particles are not aggregated.

At present there are some attempts to increase the efficiency of fine-dispersed particle coagulation by the reduction of the area sizes, in which the changes of pressure take place (the zones of reduced pressure generation) due to the increase of the operating frequency of ultrasonic action. As at the operating frequency of 100 kHz the sizes of the zones are increased in 2…3 mm at equal intensities of ultrasonic action (the amplitudes of medium particle oscillations) it leads to the growth of the degree of the small particle involvement into the oscillating motion, the appearance of the additional differences
in the motion speeds of the single small-size particles and the increase of probability of their aggregation. Carried out studies of different authors [16, 17] proves the possibility to provide the coagulation of 20% of submicron particles from their total number in gas wastes at the increase of the action frequency. However it is not possible to realize and apply industrial equipment for the ultrasonic coagulation at the frequencies of 100 kHz because of the following reasons:

- even at the reduction of the action area on the foreign particles of submicron size at keeping its sinusoidal character it does allow essentially increase oscillating motion of the particles, at that there is no differences in the speeds of their motion that does not lead to the occurrence of the pressure drops at their surfaces, which are enough for their aggregation;
- the realization of ultrasonic action of sinusoidal oscillations at increased frequencies requires essential energy costs and cannot be realized at present due to the absence of powerful ultrasonic radiators of increased frequency.

As it is impossible to solve practically the problems at the use of traditional ultrasonic sinusoidal action at different frequencies there is a need to search new methods of action on gas-dispersed systems, which are able to provide efficiency increase of the submicron particle coagulation with the size of less than 2.5 micron, and to create the conditions of the coagulation of the particles with the sizes of less than 1 micron.

3. Influence of shock-wave ultrasonic action on the particle coagulation

It is evident, that the coagulation speed of the particles is determined by the area of the equivalent cross-section of the collision and forces of the particle interaction.

That is why it is possible to increase efficiency of ultrasonic action not only due to the reduction of the zones of efficient action of the foreign particles (i.e. not due to elevation of ultrasonic action frequency), but due to the generation of in the action zones in comparison with sinusoidal oscillations for the formation of enhanced gradients of the pressure change and concentration of gas particles.

Such action is able to increase the efficiency of various mechanisms providing particle aggregation.

That is why one of the most efficient mechanisms of coagulation speed increase of the small-size particles (less than 1 micron) chaotically located in gas medium will be the enlargement of cross-section collision area that is shown in figure 1, 2.

As it follows from the figures due to the absolutely elastic and equally probable in all possible directions of the collisions of the molecules of gas phase with the foreign particles moving with increased speed, spatial particle position as a result of sequence of the elementary acts of the collision “particle-molecule of gas medium” changes leading to the growth of effective collision cross-section.

**Figure 1.** Influence of ultrasonic action on the area of the collision cross-section. The area of the collision cross-section without the account of ultrasonic action.
Figure 2. Influence of ultrasonic action on the area of the collision cross-section. The area of the collision cross-section with the account of ultrasonic action.

U1 is a deterministic component of the velocity of the first particle due to acoustic fluctuations in the gas flow
U1 is a random component of the velocity of the first particle due to Brownian motion
U2 is a deterministic component of the velocity of the second particle due to acoustic fluctuations in the gas flow
U2 is a random component of the velocity of the second particle due to Brownian motion

However, the main mechanism of the efficiency increase is concluded in the fact, that at the generation and propagation of continuous oscillations or consecutive pulses, in which the compression area and the under-pressure area generated and propagated in gas-dispersed system vary in the value of pressure in no less than 10 times, it will be realized asymmetrical actions due to essential increase of the values of pressure differentials and the speed of the differential changes. Appearing at that the changes of gas density in the compression area and the under-pressure area will essentially vary in value, and the total density change during the oscillation period will differ from the zero value. The forces of the radiation pressure occurring at that essentially rise due to non-linear change of gas density at the oscillation propagation.

It all leads to the fact, that the probability of the aggregation of the submicron particles rises and the degree of their coagulation increases.

Such approach to the realization of ultrasonic coagulation allows not only increasing the coagulation efficiency of the submicron particles with the size of 2.5 micron and more, but creating real conditions of the particle coagulation of the particles with the sizes of less than 1 micron.

For the practical realization of the new approach to the ultrasonic coagulation it is proposed to form the non-linear acoustic oscillations in the ultrasonic frequency range by the application of opposite directing and in-phase oscillating at the multiple frequencies (21 kHz and 42 kHz) known ultrasonic radiators [2, 3] placed at the resonance distance (which is multiple of the half wave length of ultrasonic oscillations in air for the lowest of the frequencies) from each other. The construction of the equipment for the realization of the ultrasonic coagulation is shown in figure 3.

The effect of shock-wave action by the wavefront distortion at such coagulation process realization is caused by the fact, that spatial positions of the molecules of carrying gas phase, which are in the zones with the increased gas speed, in a period of time are equated to the spatial positions of the molecules, which were in the zones with decreased gas speed (the molecules “catch up each other”). As a result in the zones of the “intersection” of the spatial positions of two molecule sets (having increased and
decreased speed) it occurs additional growth of the gas phase density due to the difference of the speeds, i.e. the momentum transfer appears.

![Figure 3. Device of the ultrasonic coagulation with the radiators in the form of the plates located in parallel. 1 is Housing; 2 is inlet pipe; 3 is outlet pipe; 4 is radiating element; 5 is ultrasonic piezoelectric Converter; 6 is flow distributors; 7 is ultrasonic sprayer (sprinkler); \( N = 1...3 \); \( \lambda \) is the wavelength; \( n \) is number of half-waves in the environment; \( h \) is late thickness; \( \lambda \) is wavelength.]

It leads to the wavefront distortion right up to the generation of the breakage (jumping of the pressure along the coordinate), and the resonance growth in the gas gap between the radiators provides the formation of non-linearly distorted ultrasonic oscillations with the level of the acoustic pressure of up to 165…175 dB. At that if the distance between the radiators is set less (no more than \( \frac{1}{2} \) wavelength of ultrasonic oscillations in air) or equal, the phase of under-pressure of generated ultrasonic oscillations is mostly exposed to resonance distortion.

Preliminary experimental data obtained shows the efficiency of the coagulation by the shock-wave ultrasonic action at same value of input energy. It is determined, that shock-wave action with the preferential compression phase increases the coagulation speed up to 5 times for the submicron particles with the sizes of the range of 100…1000 nm only due to the changes of the conditions of the ultrasonic action. The action with the preferential compression phase due to the additional enlargement of the collision cross-section area (it is changed particle position uncertainty) increases the particle coagulation speed with the size of 500 nm in up to 8 times, and the particles with the size 100 nm in up to 20 times in comparison with the sinusoidal action. It proves the most efficiency of the shock-wave action for the small-size particle coagulation.

4. Conclusion
Proposed approach to the realization of the ultrasonic coagulation provides the efficiency increase of the submicron particle coagulation due to the realization of shock-wave action.

During the preliminary study it was determined the possibility of the particle coagulation acceleration with the size of up to 1 micron in up to 20 times at the use of the shock-wave ultrasonic action in comparison with the sinusoidal action.

It is proposed the variant of the practical realization of the coagulation process at the shock-wave ultrasonic action on gas media with the help of previously developed sources of ultrasonic action at the design of special conditions of the oscillations propagation.
The results of the studies can be the base of the design and the application of new class devices for the catching of the submicron particles under the conditions of modern high-tech productions and the solution of the problems of the environment protection.

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