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Development of high efficiency gas-cleaning equipment for industrial production using high-intensity ultrasonic vibrations

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ABSTRACT: *The article presents the results of research aimed at increase of the efficiency of gas cleaning equipment based on the Venturi tube using high-intensity ultrasound. Carried out theoretical analysis of dust-extraction unit operation let determine the possibility of efficiency increase and dust reduction of gas at the output of the plant at the application of ultrasonic action, especially at collecting of high-disperse particles (for the particles with the size of 2 μm the efficiency of the plant rose from 74.8 % to 99.1 %). It was determined, that sound pressure level no less than 150 dB and frequency of ultrasonic influence 22 kHz provide maximum efficiency of the Venturi tube. It was stated, that the application of 2 ultrasonic radiators of 370 mm in diameter provides dust concentration at the output of the dust-extraction plant of no more than 0.255 g/Nm^3; four radiators – no more than 0.225 g/Nm^3; six radiators – no more than 0.2 g/Nm^3 at burning of coal from Kharanor coal deposit (dust concentration at the output without ultrasonic influence is more than 0.8 g/Nm^3). Evaluated modes and conditions of ultrasonic action allowed developing special ultrasonic transducer. The developed design of ultrasonic transducer with a heat exchanger provides continuous operation at high temperatures (170°C). The received theoretical and experimental results allow providing maximum efficiency of dust-extraction plant.*

Keywords - *Dust extraction plant, Venturi tube, ultrasonic impact, coagulation, dispersed particles*

I. INTRODUCTION

At present for collection of dispersed phase particles (1-10 μm) from industrial emissions different apparatuses, which differ from each other in construction and method of precipitation of suspended particles in gas, are developed and used.In industry wet dust-collecting apparatuses are widely used as a part of gas-cleaning unit, among which Venturi turbulent apparatuses (scrubbers) are the most efficient [1, 2]. They provide efficiency of collecting of dispersed ash particles up to 94-96%. However such efficiency of dust collecting is insufficient due to the modern environmental requirements. At that further efficiency increase of such types of the dust-collectors due to changes of the construction and modes of movement of gas-dispersed and liquid phases does not bring desired results. The reason is that it is impossible to increase probability of collision of dispersed particles with the particles of sprayed water. To increase the probability of collision of collecting dispersed particles with sprayed water drops is possible due to providing of vibrating motion to dispersed particle relative to heavier water particles. It can be realized the most effectively by acoustic action on gas-dispersed flow – ultrasonic coagulation of dispersed particles [3].

For estimation of efficiency of dispersed particle coagulation in Venturi tube and their collection degree in all dust extraction plant at the use of additional action of high-intensity ultrasonic vibrations it is necessary to solve the following tasks:

– to study coagulation mechanism of dispersed particles in Venturi tube;

– to determine optimum modes and conditions, at which ultrasonic action can provide maximum efficiency increase of dust extraction in the dust-extraction plant;

– to develop and study the operation of the ultrasonic radiators, which are able to act on gas-dispersed flow in the conditions of high temperatures;

– to determine number and location of the ultrasonic radiators in Venturi tube providing optimum conditions of ultrasonic action and protection of the radiators from abrasive wear by solid particles of flue gases.

II. Methods and Approaches Used at the Design of Dust-extraction Plant Model

Carried out analysis of the multiphase flow model showed, that Lagrange model considers fully the main factors influencing on the process efficiency of dispersed particles collecting in the dust-extraction plant (both at the presence and absence of ultrasonic action).

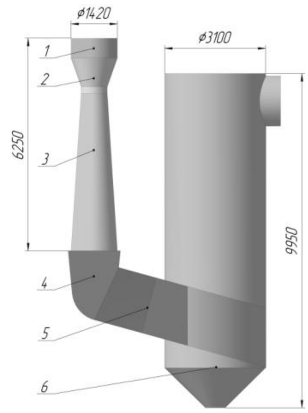
According to this model in polydisperse flow containing particles of various sizes coagulation effect occurs due to particle speed differential (orthokinetic coagulation), which influences mostly on intensity of particles collision.

At the absence of ultrasonic action under the action of inertial forces large particles move slower than little ones, and thereby probability of collision increases. At the presence of ultrasonic action large water drops are not involved into vibrational motion retaining initial trajectory, and small particles of ash (no more than 10 µm) vibrate on a large scale (i.e. with doubled amplitude) up to 100 µm increasing the space of effective interaction with water drops [4].

As existing procedures of calculation of gas-cleaning equipment do not take into consideration the possibility of ultrasonic action for the decrease of residual dust content of flue gases, we use universal methods of mathematical modeling of current and interaction of multiphase flows realized by numerical calculations on the computer with the application of special programs based on finite-element method. They let take into account a large number of determining factors, minimize assumptions and perform numerical calculations with high accuracy and at rather short period of time.

III. Determination of Optimum Modes of Ultrasonic Action Providing Maximum Efficiency of Dust-extraction Plant Operation

For carrying out calculations on operation efficiency of the dust-extraction plant we designed 3d geometric model consisting of Venturi tube and cyclone-drop catcher (Fig. 1). Geometry and standard size of the model correspond to existing constructions of the dust-extraction plant applied in industry [2].



1 – input nozzle; 2 – confuser; 3 – diffuser; 4 – curved part of the air pipe (pipe bend); 5 – connecting pipe; 6 – cyclone-drop catcher

Fig. 1. 3D model of the dust-extraction plant on the base of Venturi tube

At the design of calculated model of Venturi scrubber it is assumed that:

– there is a laminar flow, i.e. gas moves in layers without mixing and pulsations(irregular and quick changes of speed and pressure);

– friction and adhesion of the particles on walls of Venturi pipe are not taken into consideration, at that inelastic reflection of the particles (ash and water drops) from the wall of Venturi tube is assumed;

– settling of ash and drop particles on the wall of the drop catcher;

– absence of heat transfer between the phases and as a consequence absence of water drop evaporation;

– one-way interaction of continuous and dispersed phases (influence of dispersed particles on gas flow does not take into account).

To calculate efficiency of the plant we take following initial data corresponding to the operating parameters of the most dust-extraction plants exploited at present:

1. The temperature of flue gases before the installation is 170º C, that corresponds to the density of gas flow of 0.78 kg/m^3;

2. Mean size of the drops of sprayed water is 150…250 µm;

3. The volume of output flue gases is 100000 m^3/h that corresponds to speed of gas flow at the input of Venturi tube equal to 17.4 m/s.

4. Dust content before the plant is 17.0 g/Nm³ that corresponds to mass output of ash of 0.35 kg/s;
5. Speed of flue gases in the confuser of Venturi tube is 50-70 m/s;
6. Water discharge on the spraying of Venturi tube is 10 t/h;
7. Size of ash particles formed at the combustion of coal is defined according to scientific-technical data [5, 6] and it can be of 2…90 μm.

The results of modeling of gas flow motion in the dust-extraction plant are shown in Fig. 2.

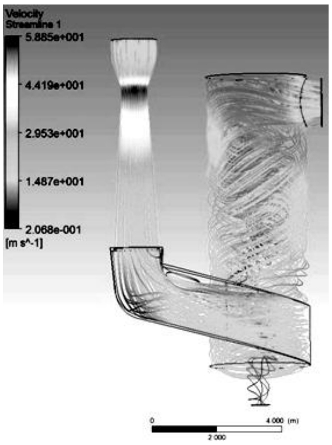


Fig. 2. Pattern of gas flow motion in the dust-extraction plant

As it follows from obtained results, speed of gas flow in the opening of Venturi tube achieves 58.8 m/s. At that in the papers [1, 2] the range of values is 50–70 m/s that proves adequacy of used model of gas flow motion.

The presence of ultrasonic vibrations in Venturi tube is taken into consideration as additional force acting on individual particle located in the ultrasonic field. This force consists of two components:

– orthokinetic (different degree of involvement of dispersed particles into vibrational motion, which is in inverse proportion to their diameter and mass);

– hydrodynamic (occurrence of forces of attraction between the particles caused by asymmetry of flow field of dispersed particles in the ultrasonic field).

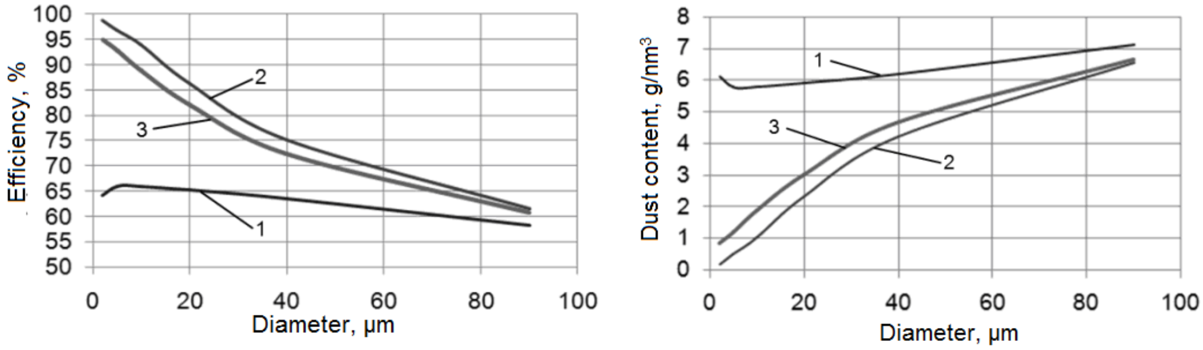
Moreover at the calculation of addition to force deviation of the form of ash particle from the spheric one was considered. Thus total addition to the force acting on ash particle from the side of gas flow caused by the presence of ultrasonic vibrations is defined by the equation (1):

$$\Delta F = 3\pi d\mu(k_B \cos^2\theta + k_N \sin^2\theta) \times (U_1 + U_2)\sin(2\pi f t), \quad (1)$$

where d is the largest diameter of the ellipsoid particle, m; μ is the viscosity of gas flow, Pa·s; θ is the angle between smaller semi-axis of the particle and the direction of ultrasonic field, rad; k_B is the streamlining coefficient of the particle at flow motion along smaller semi-axis; k_N is the streamlining coefficient of the particle at flow motion along larger semi-axis; f is the frequency of vibrations (22 kHz); U_1 is the amplitude of disturbance of gas flow speed from the side of initial ultrasonic field, m/s; U_2 is the amplitude of disturbance of gas flow speed from the side of water particles, m/s; t is the time, s.

The force addition from the side of gas flow at the calculations is taken into account only at the presence of the particles in the volume of Venturi tube.

According to the results of carried out calculations the dependences of efficiency and residual dust content of gas flow of Venturi tube on the size of ash particles were obtained (Fig. 3).



a) b)

1 – without ultrasound; 2 – with ultrasound 150 dB; 3 – with ultrasound 145 dB

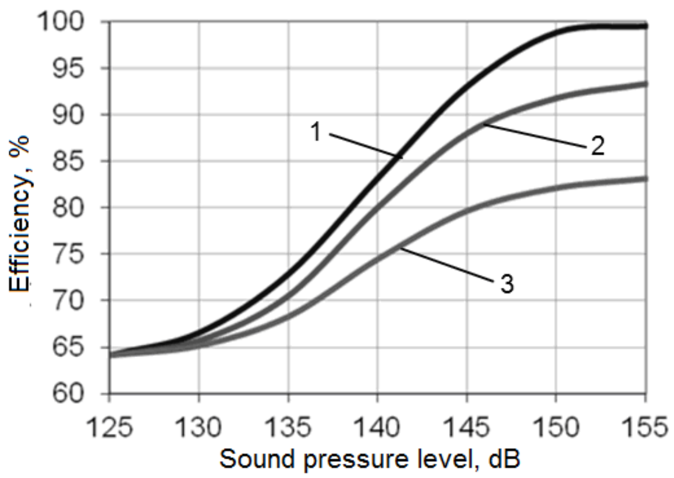
Fig. 3. Dependence of efficiency (a) and residual dust content (b) of Venturi tube on the size of ash particles at different levels of acoustic pressure

From presented results (Fig. 3) it follows, that the application of ultrasonic vibrations with the level of acoustic pressure of 150 dB provides no less than twofold dust reduction at the output of Venturi tube for the particles with the size of up to 20 μm and in 1.5 times for the particles with the size of more than 20 μm.

It proves high efficiency of the application of ultrasonic vibrations for coagulation of suspended particles and mainly thin-dispersed ones (2–5 μm), for which sixfold dust content reduction is provided.

Further the calculations of determination of optimum zone of ultrasonic action at different levels of acoustic pressure were carried out (Fig. 4).

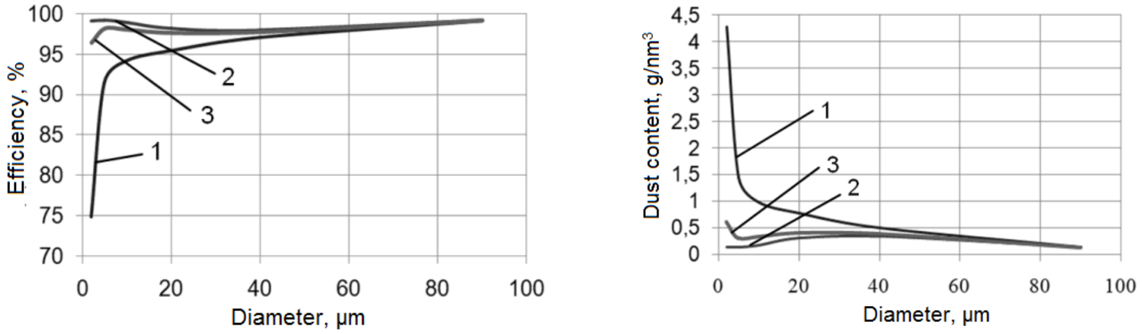
From obtained results it can be concluded, that to provide maximum efficiency of the coagulation process it is necessary to achieve uniform ultrasonic field in all volume of Venturi tube (simultaneous ultrasonic action on the confuser and the diffuser).



1 – Confuser+diffuser; 2 – Diffuser; 3 – Confuser

Fig. 4. Dependence of Venturi tube efficiency on the level of acoustic pressure at different zones of ultrasonic action

Fig. 5 shows the dependences of efficiency and residual dust content of the gas flow of all dust-extraction plant on the size of the ash particles.



a) b)

1 – without ultrasound; 2 – with ultrasound 150 dB; 3 – with ultrasound 145 dB

Fig. 5. Dependences of efficiency (a) and residual dust content (b) of the gas flow of all dust-extraction plant on the size of the ash particles at different levels of acoustic pressure

From the presented dependences, it follows, that the application of ultrasonic action provides essential efficiency increase of the operation of the dust-extraction plant especially in the zone of high-dispersed particles. So for the particles of 2 µm efficiency of the plant rises from 74.8 % to 99.1 %.

Thus the use of ultrasonic action with frequency of 22 kHz is the most efficient for the particles of less than 20 µm. Larger particles are influenced by ultrasonic vibrations to a lesser degree, however for the particles of 20 µm to 40 µm the efficiency of the dust-extraction plant increases from 95.4 % to 98.2 %.

Efficiency decrease after the application of ultrasound for large particles is leveled by high starting efficiency (without ultrasonic action) of collecting of such particles.

That is why, it can be concluded that the application of ultrasonic action for the efficiency increase of the dust-extraction plant on the base of Venturi tube is expedient to reduce the content of high-dispersed ash fraction in flue gases.

At the final stage of the analysis theoretically achieved gas dust content at the output of the dust-extraction plant at known powder of ash at the input was determined. Residual dust content of the gas was calculated on the base of obtained data on fractional efficiency of the dust-extraction plant (Fig. 5) by the following expression (2):

$$\eta_p = \frac{\sum_{i=1}^{N} \eta(d_i) W_i}{\sum_{i=1}^{N} W_i}, \qquad (2)$$

where η_p is the collecting efficiency of polydisperse ash, %; $\eta(d_i)$ is the dependence of collecting efficiency of monodisperse ash on the diameter d_i, %; i is the amount of the groups of ash particles sizes; d_i is the size of the particles of i-group, m; W_i is the mass fraction of ash particles of i-group.

For objective efficiency estimation of the application of ultrasound the data on powder of flue ash obtained from reliable free sources [6] were used.

Fig. 6 shows the results of calculation for ash obtained after burning of brown coal of Kharanor deposit ground by the mill MV 50–160 in the boiler BKZ 210–240 of Vladivostok heat station-2.

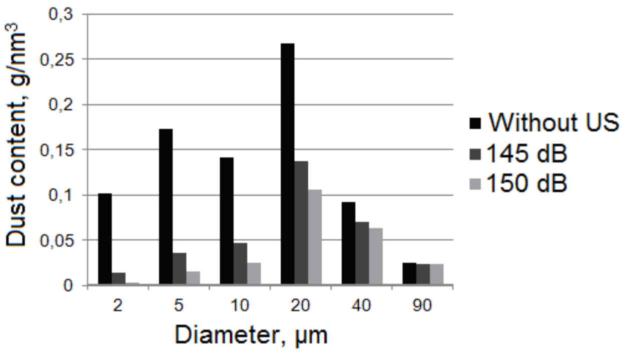


Fig. 6. Ash powder at the output of the dust-extraction plant

From obtained data it follows, that at the output of the dust-extraction plant with the application of ultrasonic action with the level of acoustic pressure of 150 dB fractions with the size of particles of 2-5 μm are not observed (less than 0.05 g/Nm^3). Total dust content at the output of the dust-extraction plant is: without ultrasonic action – 0.802 g/Nm^3 (the efficiency is 95.2535 %); at the level of acoustic pressure of 145 dB – 0.329 g/Nm^3 (the efficiency is 98.065 %); at the level of acoustic pressure of 150 dB – 0.237 g/Nm^3 (the efficiency is 98.611 %).

Thus obtained results prove efficiency and prospects of the application of ultrasonic vibrations for efficiency increase of the dust-extraction plants on the base of Venturi tubes.

In order to achieve maximum efficiency of dust-extraction plant operation it is necessary to provide ultrasonic action at the frequency of 21…24 kHz and level of acoustic pressure of 145…150 dB.

IV. Development and Study of Ultrasonic Radiator Operation for the Action on Gas-dispersed Flow Providing Defined Action Modes

For ultrasonic influence on gas-dispersed flow acoustic radiator in the form of stepped-variable disk with the diameter of 370 mm was developed [7]. The form of the radiator and distribution of its vibration amplitudes are shown in Fig.7.

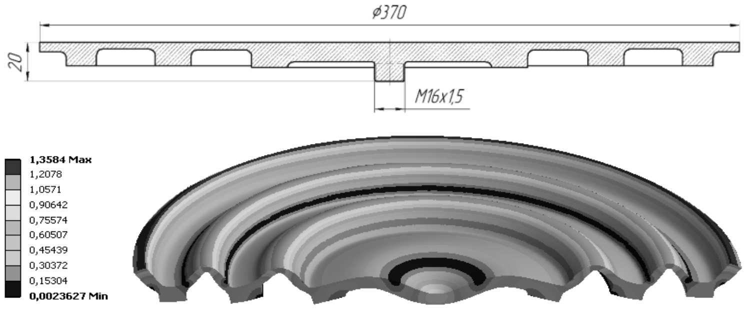
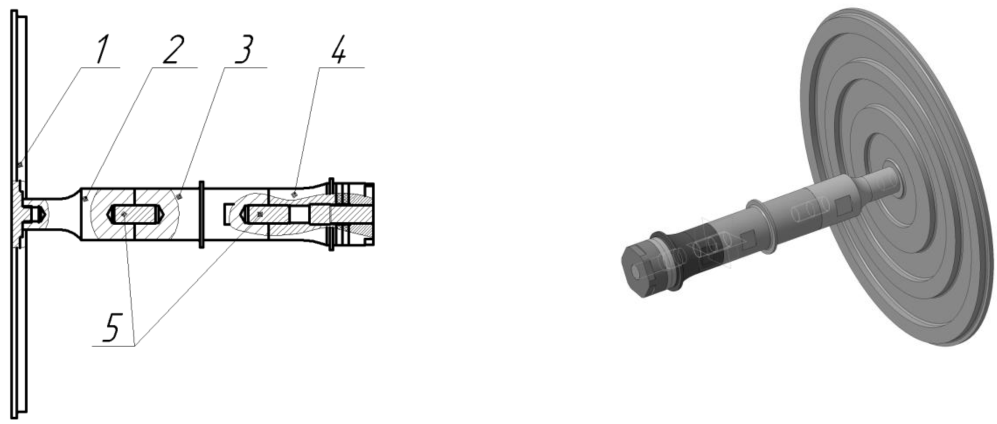


Fig. 7. Form of ultrasonic disk radiator with the diameter of 370 mm and distribution of vibration amplitudes (in relative units)

For excitation of vibrations of the disk at specified frequency the ultrasonic vibrating system shown in Fig. 8 was designed.

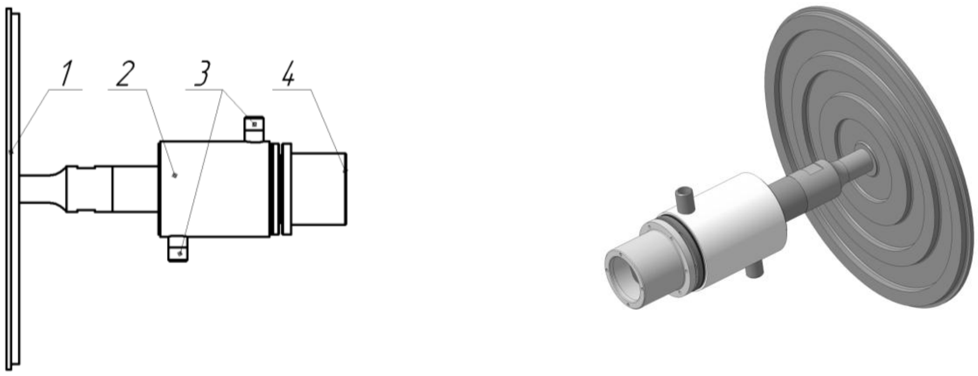


1 – source of ultrasonic pressure in the form of the disk; 2 – concentrator
3 – waveguide; 4 – piezoelectric transducer; 5 – studs
Fig. 8. Ultrasonic vibrating system with the disk radiator

The development of the piezoelectric transducer was carried out on the base of known procedures described in the papers [8, 9].

Taking into account the fact that temperature of gas in Venturi tube is about 170°C, during action of the ultrasonic radiator on gas-disperse flow at high temperatures the efficiency of the transducer decreases, vibration amplitude of the disk radiator drops and the level of acoustic pressure falls due to low efficiency of the piezoelectric conversion in the materials of the transducer [10].

To provide optimum temperature mode of the operation of the piezoelectric transducer in the construction of the vibrating system there is an additional (intermediate) section of the waveguide for the installation of thermal cutoff unit providing fluid cooling of the transducer during the operation (Fig. 9).



1 – Ultrasonic vibrating system with the disk radiator; 2 – heat exchanger; 3 – branch pipes for input and output of cooling liquid; 4 – case of the piezoelectric transducer

Fig. 9. Draft of designed ultrasonic vibrating system with the heat exchanger

In order to verify the operation efficiency of the thermal cutoff unit the calculations of thermal modes of the ultrasonic vibrating system operation were carried out. The initial temperature condition of the disk radiator and the concentrator was established equal to the temperature of the operating medium 200^{o}C. As it follows from the results of calculation liquid cooling maintains temperature of the reflecting cover-plate at the level of 40-45 ^{o}C. The application of liquid cooling of the reflecting cover-plate of the piezoelectric transducer and the waveguide provides establishing stationary temperature mode in 1000 sec. At such mode the piezoceramic rings are heated to the temperature of no more than 80 ^{o}C.

Thus carried out calculations allow determine, that cooling of the ultrasonic vibrating system with the disk radiator for providing of required temperature mode should be assured by water (with the temperature of no more than 60 degrees Centigrade) with the consumption of no less than 12–15 l/h.

Further researches were aimed at the determination of the disk radiator parameters. At the first stage vibration amplitude on the surface of the disk radiator was measured for the comparison with the results of the theoretical calculations.

For the study of distribution of vibration amplitude two diametral straight lines were drawn on the disk surface, on which studied points and vibration zeros were marked. Figure 10 shows the distribution of vibration amplitudes on the disk surface in studied points.

The measurements were carried out with the help of developed test bench (Figure 6) at the temperature of the radiator of 20 ^{0}C. As a result of the measurement it was determined, that the ratio of experimental values of vibration amplitudes in different zones of the disk to vibration amplitude in its center varies with theoretical ones in no more than 10%. It proves the adequacy of used model of vibrating solid.

Maximum level of acoustic pressure was observed at the distance of 25 cm and it was 158 dB.

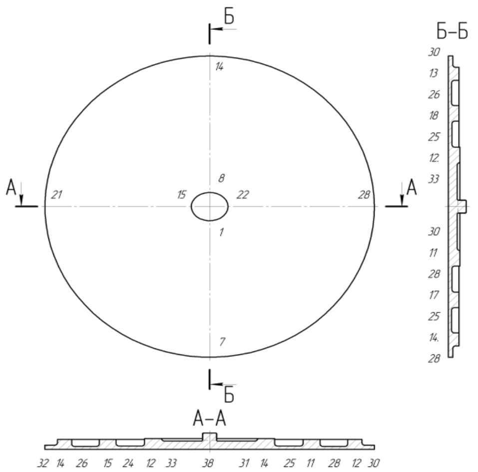
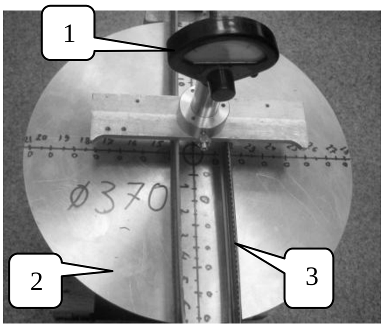


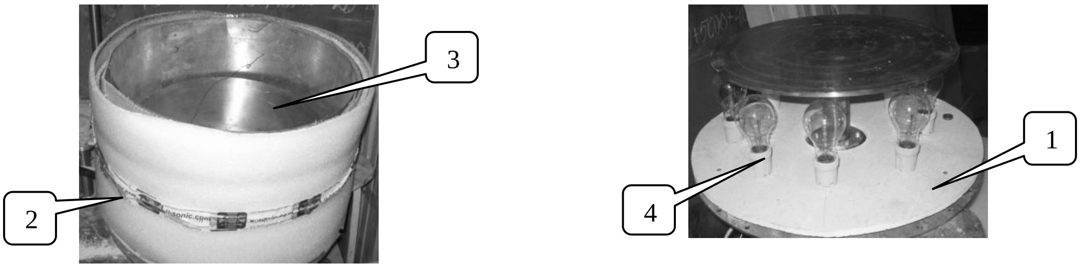
Fig.10. Distribution of vibration amplitudes in studied points (in μm)



1 – travel indicator of watch-type (the scale interval is 1 μm); 2 – ultrasonic disk radiator; 3 – skids

Fig. 11. Test bench for measurements of vibration amplitudes

The estimation of influence of operating medium temperature on the parameters of the ultrasonic radiator (resonance frequency, level of acoustic pressure, consumed power and distribution of vibration amplitude) during its operation was carried out on developed test bench, shown in Figure 12.



1 – collar with cooling volume; 2 – cylinder sidewall; 3 – ultrasonic vibrating system with the disk radiator; 4 – heating elements

Fig. 12. Photo of the test bench for heating and measuring of vibration amplitude of the disk radiator surface

The test bench consisted of cylinder operating chamber with the diameter of 450 mm and height of 400 mm made of noncombustible material, in which the ultrasonic vibrating system with the heat exchanger was placed. The internal volume of the chamber was heated by incandescent lamps. To reduce heat losses the chamber was covered by thermal insulation material outside. Water was used as a cooling fluid for the ultrasonic vibrating system.

The results of measurements of the resonance frequency depending on the temperature of the disk radiator are shown in Fig. 13.

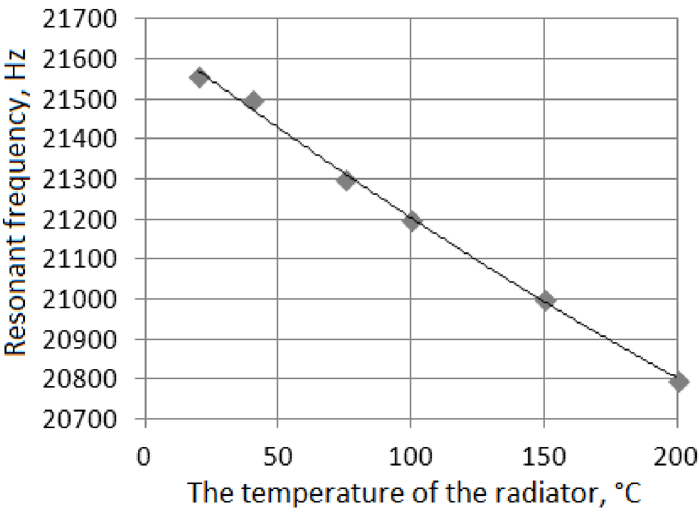


Fig. 13. Dependence of resonance frequency of the ultrasonic vibrating system on the temperature of the disk radiator

As it is evident from the graph, that the resonance frequency decreases linearly with the temperature increase in the range under study.

To determine dependences of the level of acoustic pressure on the temperature the measurements were carried out at the distance of 0.25 m and 1 m from the surface of the disk radiator. Obtained dependences are shown in Fig. 14.

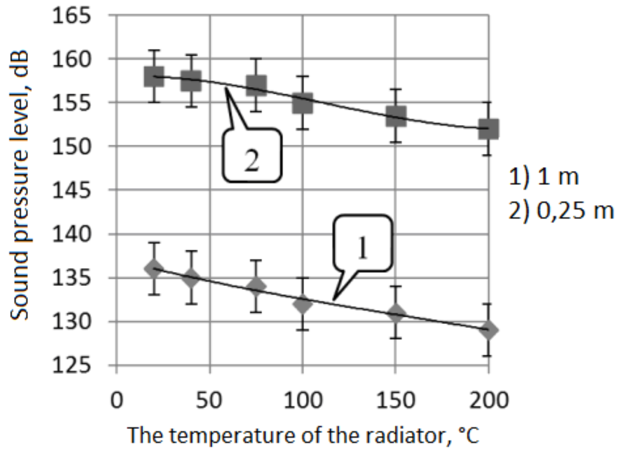


Fig. 14. Dependence of the level of acoustic pressure on the temperature of the ultrasonic disk radiator

The analysis of the obtained dependences allows determine, that the level of acoustic pressure decreases with the temperature increase that is caused by the reduction of density of heated gas. At the same time temperature increase of the radiator causes insufficient rise of vibration amplitude of the disk surface.

V. Determination of Number and Places of the Ultrasonic Radiators Providing Maximum Efficiency of Dust Collecting in the Dust-Extraction Plant

Taking into account obtained distribution of vibration amplitude on the surface of the disk radiator of 370 mm in diameter we calculated the distribution of level of acoustic pressure in the volume of Venturi tube with the application of boundary element method. The method is based on the fact, that calculation of distribution of acoustic pressure is carried on the surface of measurement environment, and then acoustic pressure is defined in the volume by the surface values.

The distribution of acoustic pressure in Venturi tube was calculated by Helmholtz equation (3) describing propagation of acoustic vibrations in the medium:

$$\Delta p + k_*^2 p = 0\,, \qquad (3)$$

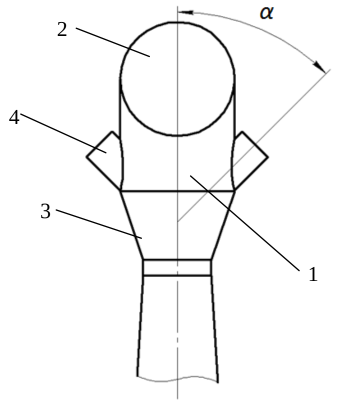
where k_* is the efficient wave number of gas medium taking into account absorption of ultrasonic vibrations in the medium, m^{-1}; p is the complex amplitude of acoustic pressure in gas medium with boundary conditions (4)

$$4\pi^2 f^2 \rho A_n = (\nabla p, \mathbf{n})\,, \qquad (4)$$

where $\mathbf{n}$ is the vector of outer normal line to the radiator surface; f is the frequency of ultrasonic vibrations equal 22 kHz; ρ is the density of gas medium, kg/m^3; A_n is the function of distribution of normal vibration amplitude on the radiator surface.

To calculate level of acoustic pressure it is necessary to determine installation position of the disk radiators. Installation position should exclude possibility of abrasive wear of the disk surface by ash dispersed particles.

One of possible variants excluding abrasive wear of the ultrasonic radiators is their location on the cap of Venturi tube in the place of joining to the confuser (Fig. 15) at an angle to the axis providing the most even distribution of acoustic field in Venturi tube.



1 – cap; 2 – input pipe; 3 – confuser; 4 – pipe for installation of the ultrasonic radiator; α – angle between the axis of Venturi tube and the ultrasonic radiator

Fig.15. Scheme of installation of the ultrasonic radiators into the cap of Venturi tube

The installation of 2 radiators is minimal for providing of uniformity of acoustic action in the volume of Venturi tube.

The calculations of distribution of acoustic pressure at different installation angles of the ultrasonic radiators in Venturi tube and specified level of acoustic pressure of 145 dB (near the center of the radiating surface at the operation of the radiator in unlimited space) were carried out. Further taking into consideration obtained data mean value of the level of acoustic pressure in all volume of Venturi tube was calculated by the following formula:

$$L_{avg} = \frac{\int_V L(\mathbf{r}) \partial V}{V}, \quad (5)$$

where L(**r**) is the level of acoustic pressure in point *r*; *V* is the volume.

Obtained results are shown in Fig. 16.

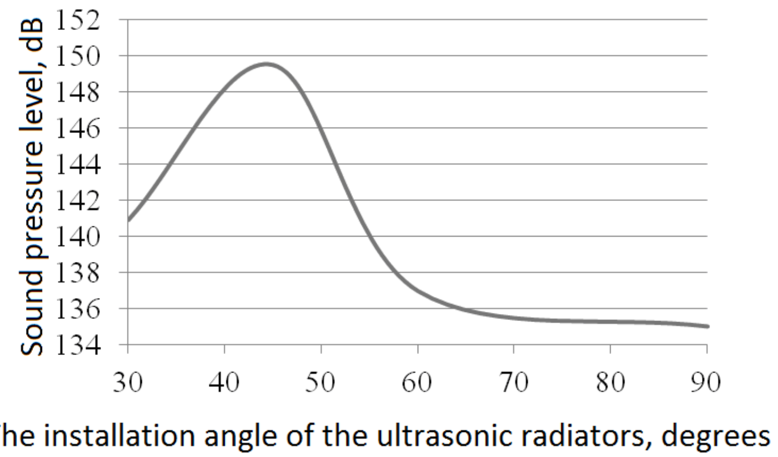
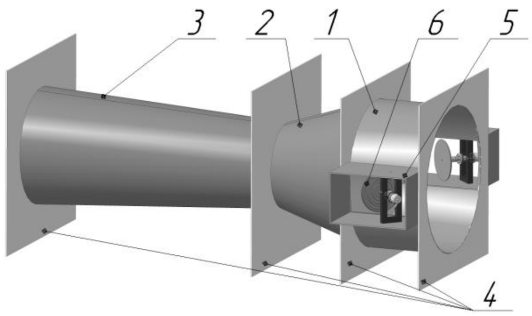


Fig. 16. Dependence of mean value of the level of acoustic pressure on the installation angle of the ultrasonic radiators

From presented dependences it follows, that optimum installation angle of the ultrasonic radiators is 45º, at which mean value of the level of acoustic pressure in Venturi tube is maximum. Moreover at the optimum angle maximum level of acoustic pressure is achieved in the confuser and the diffuser of Venturi tube.

For carrying out experiments on distribution of level of acoustic pressure in the volume of Venturi tube with the application of developed ultrasonic radiator we designed laboratory setup (model) of Venturi tube at a scale of 1:1, shown in Fig. 17.



1 – cap of Venturi tube; 2 – confuser; 3 – diffuser; 4 – framework; 5 – rotating unit; 6 – ultrasonic disk radiator

Fig. 17. 3D model of the laboratory setup

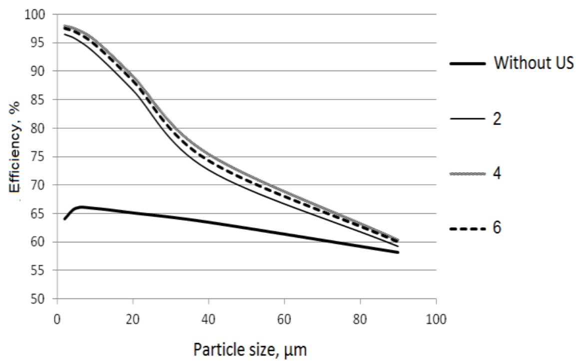
On the cap of Venturi tube two opposite-directed rotating units, in which there were two disk radiators, were placed. The rotating unit is intended for the installation of the disk radiator at different angles in order to provide maximum level of acoustic pressure and even distribution of ultrasonic vibrations in the volume of Venturi tube.

The measurements of the level of acoustic pressure in the laboratory setup were carried along 5 cross-sections, in 17 points of each cross-section by the noise and vibration analyzer “Assistant”.

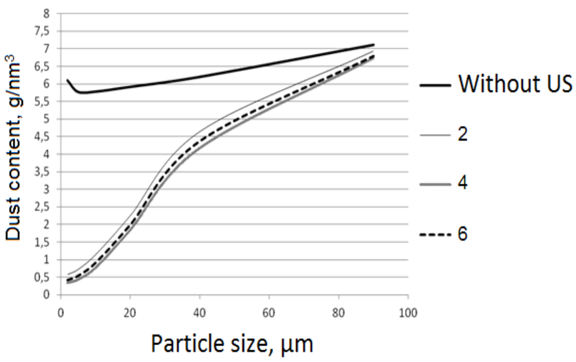
Obtained results proved the presence of optimum angle (45º), at which maximum level of acoustic pressure in the mouth of Venturi tube achieved 145 dB.

As results of measurements showed, the difference between theoretical and experimental data was 5 dB. It was caused by the following factors, as inelastic reflection of ultrasonic waves from the walls (at the theoretical calculations absolute elasticity was assumed).

Further theoretical calculations of the determination of dependence of Venturi tube and the dust-extraction plant efficiency on the size of ash particles for different number of developed ultrasonic radiators of 370 mm in diameter were carried out. Obtained results are shown in Fig. 18, 19.



a)

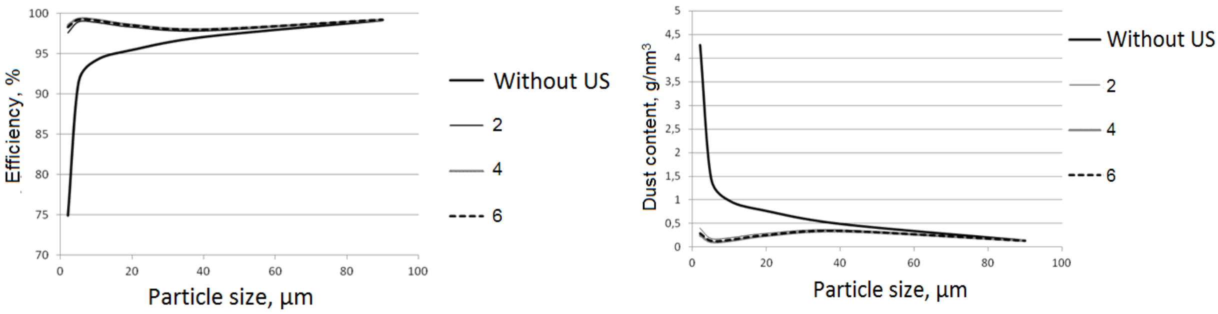


b)

Fig. 18. Dependence of Venturi tube efficiency (a) and dust concentration at its output (b) on size of ash particles at different number of the ultrasonic radiators

It was stated, that the application of 2 ultrasonic radiators of 370 mm in diameter provides dust concentration at the output of the dust-extraction plant of no more than 0.255 g/Nm^3; four radiators – no more than 0.225 g/Nm^3; six radiators – no more than 0.2 g/Nm^3 at burning of coal from Kharanor coal deposit.

Further efficiency increase of dust extraction is concerned with the increase of number of applied ultrasonic radiators. However the installation of more than 4 radiators is economically unpractical and is caused by constructional limits of Venturi tube.



a) б)

Fig. 19. Dependence of efficiency of the dust-extraction plant (a) and dust concentration at its output (b) on the size of ash particles at different number of the ultrasonic radiators

To increase output acoustic power and as a sequence efficiency of dust-extraction plant operation it is necessary to enlarge area of radiation surface, i.e. the diameter of the ultrasonic radiators.

Thus, obtained results allow determining optimum number and installation position of the ultrasonic radiators providing fulfillment of necessary requirements on efficiency and residual dust concentration at the output of the dust-extraction plant.

VI. Conclusion

After carrying out studies following results are obtained:

1. it is determined, that the process of ultrasonic coagulation occurs due to orthokinetic (different degree of involvement of dispersed particles into vibrational motion, which is in inverse proportion to their diameter and mass) and hydrodynamic (occurrence of forces of attraction between the particles caused by asymmetry of flow field of dispersed particles in the ultrasonic field) mechanisms;
2. theoretical calculations show, that the use of ultrasonic action provides essential efficiency increase of the dust-extraction plant operation especially for high-dispersed particles (for the particles of 2 µm the efficiency of the dust-extraction plant increases from 74.8 % to 99.1 %);
3. the construction of the ultrasonic radiator excluding overheating of the piezoelectric transducer at the operation in the conditions of high temperatures is developed;
4. the number and position of the ultrasonic radiators in Venturi tube providing optimum conditions of ultrasonic action and protection of the ultrasonic radiators from abrasive wear by solid particles of flue gases are determined.

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