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Study of the interaction between particles in the acoustic cyclone separator

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Abstract

This paper investigates precipitation process of small particles in the secondary air flow of the cyclone separator. It was established that in presence of acoustic field particles smaller than 5 μm are stuck together, falling then to the bottom of conical section of the cyclone separator.

Keywords: acoustic coagulation, acoustic field, ultrasound, particles, cyclone separator, separation efficiency.

Introduction

It is known [1] that hard coarse particles moving in the flow of primary air of the cyclone drop out of the flow due to the action the gravity and centrifugal forces. Particles smaller the 5 μm remain suspended in the secondary air flow and are released into atmosphere. The separation efficiency of the cyclone can be sufficiently increased by acoustic treatment of the secondary air flow. It is very important for practical application of the method to study the behavior of the particles in the acoustic field. Such particles are acted on by air flow, impressed, resistance and interacting forces. Gravity, electrostatic and acoustic field forces are assigned as the impressed forces.

Forces acting on a moving particle usually aren‘t assigned as impressed forces [2, 3], only as resistance forces. In the presence of acoustic field resistance forces can be assigned as impressed forces. The action of all forces results in the relative motion of the particles in the air flow. Motion of the round parts in the viscous fluid is well-studied in [2, 4, 5], but in such a case moving particles aren‘t spheres, they have irregular shapes.

This work aims to investigate the behavior of particles in the flow of secondary air of the cyclone separator in presence of an acoustic field.

Mathematical study

To obtain force acting on a single particle, the Navier-Stokes equation [6] must be solved. Let us consider a hard particle with a generalized radius *r* moving in the flow of incompressible viscous fluid. The Navier-Stokes equation can be presented as follows:

$$\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}\nabla\mathbf{V} = -\frac{1}{\rho_s}\operatorname{grad} p + \upsilon\Delta\mathbf{V}, \qquad (1)$$

where $V = (u_s - u_p)$; u_s is the flow velocity; u_p is the velocity of the particle; ρ_s is the fluid density; t is the time; p is the pressure; υ is the kinematics viscosity ($\upsilon = \mu/\rho_s$, where μ is the dynamic viscosity); ∇ is the operator; $\nabla\mathbf{V}$ is the tensor derivative of the velocity vector; $\frac{\partial^2 \mathbf{V}}{\partial x^2} = \Delta\mathbf{V}$.

After solving this equation the force value was calculated [5, 7]:

$$\mathbf{F} = 6\pi\mu r\mathbf{V} + \frac{4}{3}\pi r^3\rho_s g + \frac{2}{3}\pi r^3\rho_s\frac{d\mathbf{V}}{dt} + \\ + 6r^2\sqrt{\pi\rho_s\mu}\int_0^t \frac{d\mathbf{V}}{dt_i}\frac{dt_i}{\sqrt{t - t_i}}, \qquad (2)$$

where g is the free fall acceleration; t_i is the characteristic time of function V(t) for inverse Fourier transform.

Eq. 2 is valid for small Reynolds numbers. Its first term represents the Stokes force while the flow velocity is constant. The flow velocity can be calculated as instantaneous velocity V for a given moment in time [2]. The second term of Eq. 2 represents the Archimedes force. The third and fourth terms represent resistance forces related to energy required for the flow. The fourth term related to use of energy for overcoming the internal friction or viscosity.

When the flow is acted on by a changing acoustic field, the velocity of the particle u_p and V are functions of the time. However velocity changes in time can‘t influence the character of viscous motion of the particles while the quazistationarity condition [5] is satisfied:

$$\frac{\partial \mathbf{V}}{\partial t}\upsilon\nabla^2\mathbf{V} \approx \frac{\omega r^2}{\upsilon} << 1, \qquad (3)$$

where $\omega = 2\pi f$ is the angular frequency.

Quazistationarity condition is essential for studying the acoustic oscillations of the particles in air flow.

The differential equation of motion of the single particle in the viscous medium can be presented as follows:

$$m_d\frac{du_p}{dt} = m_d g + \frac{4}{3}\pi r^3\rho_d\frac{du_s}{dt} - F, \qquad (4)$$

where $m_d = \frac{4}{3}\pi r^3\rho_d$ is the mass of the particle; ρ_p is the density of the particle.

It is assumed that gravity forces acting on small particles can be neglected and eliminated from Eq. 4. After simplification equation becomes one-dimensional motion equation, scalar-valued function. By substituting Eq. 2 into Eq. 4 we obtained:

$$\frac{m_d}{6\pi\mu r}\frac{d^2x_d}{dt^2}+\frac{dx_d}{dt}=\frac{dx_s}{dt}, \qquad (5)$$

where x_d is the amplitude of the particle; x_s is the amplitude of the flow.

According to [8] velocity of air flow acted on by plain acoustic wave can be calculated as follows:

$$V_s=2\pi f x_s\cos 2\pi f t. \qquad (6)$$

The solution of Eq. 5 taking into account Eq. 6 can be presented as follows [9]:

$$x_d=\frac{x_s}{\sqrt{1+\left(\frac{2\pi f m_d}{6\pi\mu r}\right)^2}}\sin\left(2\pi f t-\varphi\right)+ke^{bt}. \qquad (7)$$

After arrangement and simplification we obtained the final equation:

$$\frac{x_d}{x_s}=\frac{1}{\sqrt{\left(\frac{4\pi\rho_d r^2 f}{9\mu}\right)^2+1}}, \qquad (8)$$

where f is frequency of the acoustic field.

The graphical representation of the Eq. 8 is presented in Fig. 1 and Fig. 2.

It is evident from Fig. 1 that amplitude ratio decreases with increase of radius of the particles. Most effective for adhesion of coarse particle frequency interval is (2–20) kHz (Fig. 2).

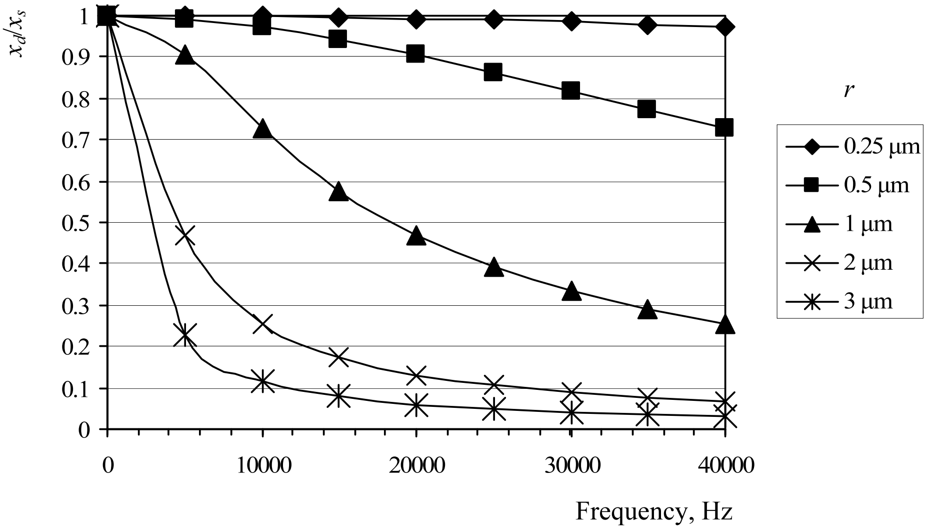

Fig. 1. **Amplitude ratio as function of the frequency of acoustic field and the radius of the particles *r***

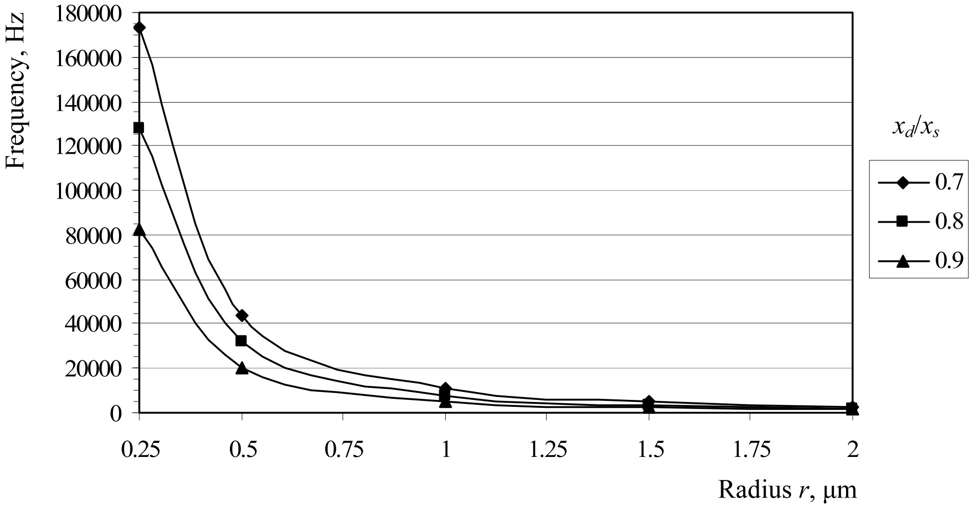

Fig. 2. **Frequency of acoustic field as function of the radius of the particles *r* and the amplitude ratio**

Experimental procedure

The special set up (Fig. 3) was designed and manufactured for experimental investigations. Its scheme presented in Fig. 4. The set up consists of pipes with integrated analyzers 1, acoustic chamber 2 with tone generator, throttle 3, dispenser 5, fan 4 and HEPA filter 6. “Lasair II” and “Dilufer ATI TDA-D100” particle detecting and counting system was used.

The acoustic field was created in the acoustic chamber 2 by means of a special generator, which sound levels are presented in Fig. 5. The results of experiments are presented in Fig. 6.

The obtained results show that audio frequency acoustic field can be effectively used in case of coarse particles (i. e. from 0.75–1 μm) only. Fine particles must be processed by ultrasonic acoustic field.

Fig. 3. **Photo of the experimental stand**

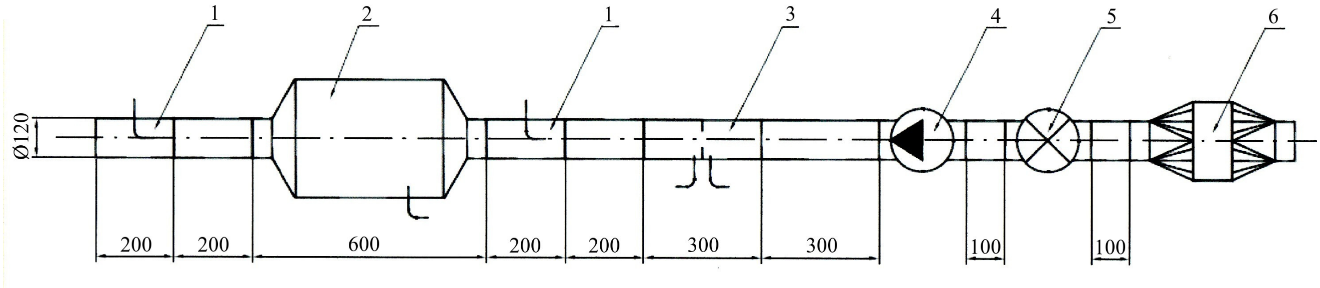

Fig. 4. **Scheme of experimental set up: 1 – pipe with analyzer; 2 – acoustic chamber; 3 – throttle; 4 – fan; 5 – dispenser; 6 – HEPA filter**

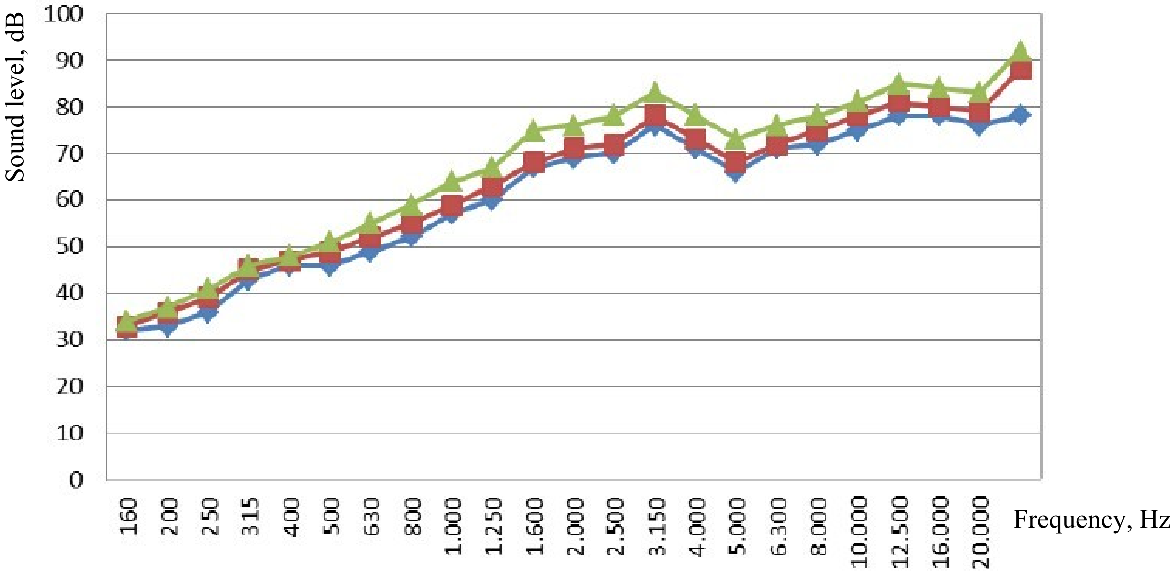

Fig. 5. **Characteristics of the generator**

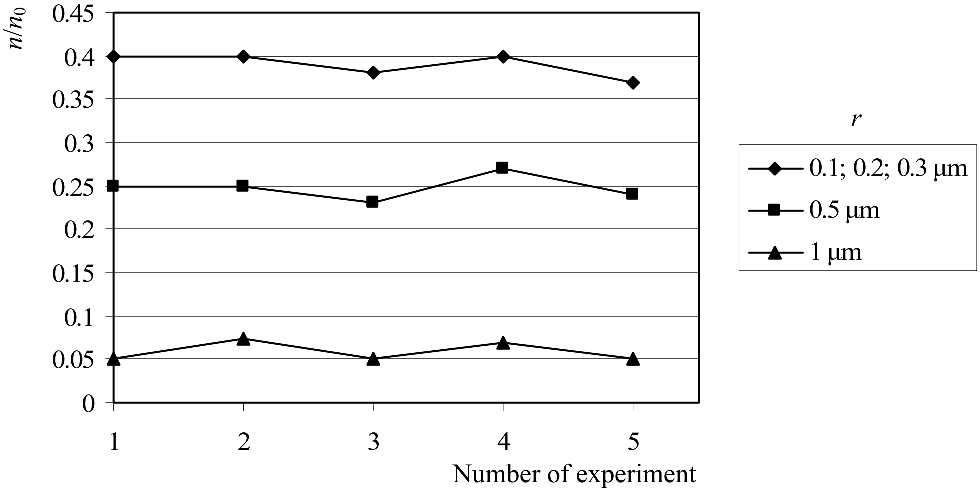

Fig. 6. **Changes of concentration of the particles in the air flow: n_0 – number of particles in 1 m^3 of air before the acoustic impact; n – number of particles in the 1 m^3 of air after the acoustic impact; r – radius of the particle**

Conclusions

1. Acoustic field causes an increase of the amplitude of oscillations of the particles and increase of the number of the collisions between particles in the air flow.
2. Audio frequency acoustic impact is most effective for coarse particles (more than 0.75 μm), whereas ultrasound impact is more effective for finer particles

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Dalelių sąveikos akustiniame ciklone tyrimai

Reziumė

Nagrinėjamas smulkiųjų dalelių nusodinimas ciklono antriniame oro sraute. Parodyta, kad veikiant antrinį oro srautą akustiniu lauku smulkiosios, iki 5 µm dydžio, dalelės sukimba ir nusėda ciklono kūginėje dalyje.

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