774. Tribological adhesion of particles in acoustic field

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Abstract. This paper investigates interaction between two particles in acoustic field. It is shown that additional oscillating movements of particles occur as a result of plain acoustic wave action. This sufficiently increases the probability of collisions between particles. Micro-displacements in the collision zone help to remove various pollutants, oxidation products and adsorbed gas molecules from surfaces of particles. Strong adhesive bonds are formed in the contact area between the particles.

Keywords: acoustic field, particles, adhesion, aggregation.

Introduction

Surfaces of solid particles dispersed in the atmosphere are fouled by oxidation products and have high moisture content [1]. Chemical bonds (short-range forces) between surfaces of particles reach their peak value under the action of these pollutants [2]. If two particles come into contact with each other only Van Der Waals interaction become sufficient for adhesion, because chemical bonds reach peak value and total thickness of fouling layer is bigger than action interval of mentioned surface forces. However, if the interaction of particles takes place in the presence of acoustic field, additional tangential force occurs. This force can break the fouling layer thereby removing pollutants and increasing the contact area between the particles. It is considered that small displacements occur on the separation surfaces of particles under the action of tangential forces. This results in several-fold increase in adhesion and higher degree of aggregation of particles.

When two particles approach one another, Van Der Waals attraction forces start to act between them. These forces occur due to fluctuations in the charge distribution of atoms and molecules of particles. These charges form continuously moving dipoles. As a first solid body approximation, it can be considered that Van Der Waals force acting between atoms or molecules has additive character. Therefore total force can be calculated by summing pairs of atoms of the both surfaces. With this assumption, Casimir [3] first derived the formula for adhesion force acting on interface of two mirror polished surfaces: $F_A = \hbar c \pi^2 A / 240 z_0^4$, where: $\hbar = h/2\pi$, h is the Planck's constant, c is the speed of light, z_0 is the separation between surfaces, $A >> z_0^2$ is the area.

It is established [4] that Van Der Waals adhesion force acts between all the materials which are brought together at the nanometric distance. If the separation between surfaces is less than 1 nm, various chemical bonds are formed between surfaces depending on chemical composition of surfaces.

Fuller and Tabor [5] proposed the "adhesive parameter": $\theta = E z^{3/2} \beta^{1/2} / \beta \Delta\gamma$, where E is the effective Young modulus, z is the separation of average lines of two bodies, β is the curvature radius of asperities, $\Delta\gamma$ is the variation of surface energy. Quantity $\beta\Delta\gamma$ is related to the adhesion force and quantity $E z^{3/2} \beta^{1/2}$ – to the surface force between asperities which appears when surfaces are torn apart.

If Fuller-Tabor parameter is small the adhesion plays a central role, if large – asperities dominate, adhesion becomes weak.

This work investigates the impact of acoustic field on particle adhesion for large values of θ.

Object of investigation

The interaction between two general shape SiO_2 particles 1 and 2 (Fig. 1) in the acoustic field was chosen as object of investigation. Let the radii of the particles be r_1 and r_2 respectively, separation between them is denoted by l. Value of interaction angle φ may vary and can be stochastic.

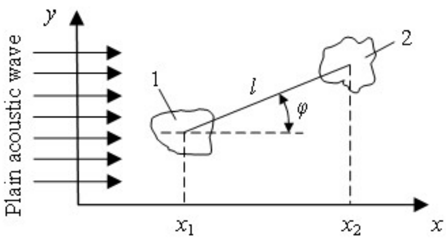


Fig. 1. Scheme of particle motion in the acoustic field: 1, 2 – particles, l – separation between particles, φ – interaction angle, x – coordinate

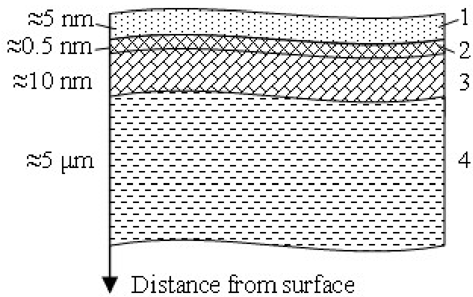


Fig. 2. Approximate composition of surface layer of the particle: 1 – fouling layer, 2 – adsorbed gas layer, 3 – oxidation products, 4 – particle material

The scheme of the surface layer of particles before collision can be presented as shown in Fig. 2.

Interaction between particles

Interaction force acting between two oscillating particles can be expressed as follows [6]:

$$F_p = \frac{3}{2}\rho_f \pi \frac{r_1^3 r_2^3 u_f^2}{l^4}\left(1 - 3\cos^2\phi\right), \tag{1}$$

where ρ_f is the density of the flow, r_1 and r_2 are the radii of particles, u_f is the velocity of the flow, l is the separation between particles (Fig. 1), φ is the interaction angle (Fig. 1).

Velocity of the flow can be obtained from plain acoustic wave equation [7]:

$$u_f = 2\pi f x_f \cos 2\pi f t, \tag{2}$$

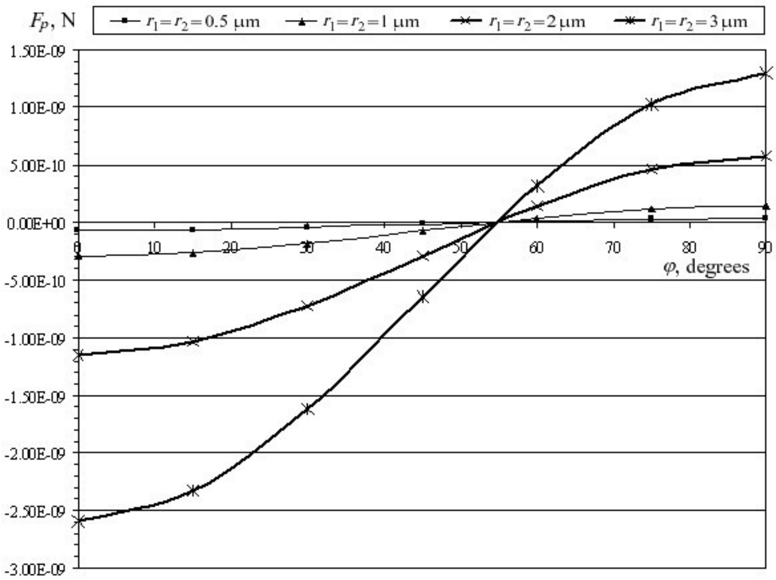
where f is the frequency of the acoustic field, x_f is the amplitude of the flow, t is the time.

The force that makes the particles and flow oscillate can be expressed as follows [8]:

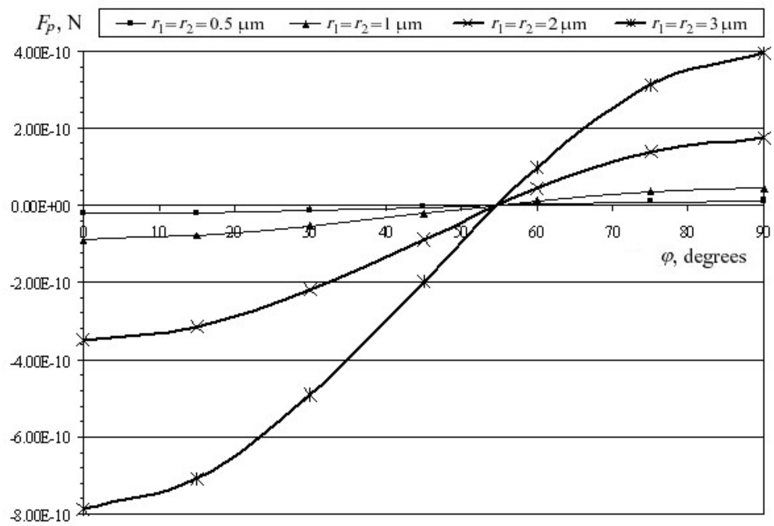
$$F_s = \frac{10}{3}\frac{\pi^2 r^3 fJ}{c_s^2}\sin\left(\frac{4\pi f x}{c_s}\right), \tag{3}$$

where J is the sound intensity, x is the coordinate, c_s is the speed of sound.

Graphical representation of Eq. (1) is presented in Fig. 3.



a)



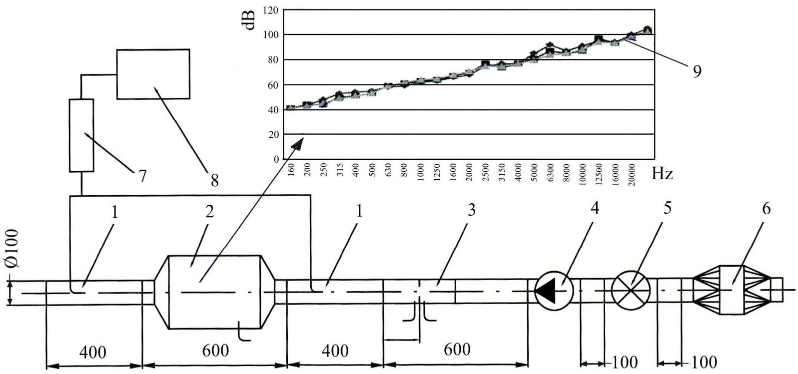
b)

Fig. 3. Interaction force F_p as function of size of particles and interaction angle φ:
a) f = 10 kHz, x_f = 0.5 mm, t = 2 s, $l = r_1 + r_2$; b) f = 20 kHz, x_f = 0.5 mm, t = 2 s, $l = r_1 + r_2$

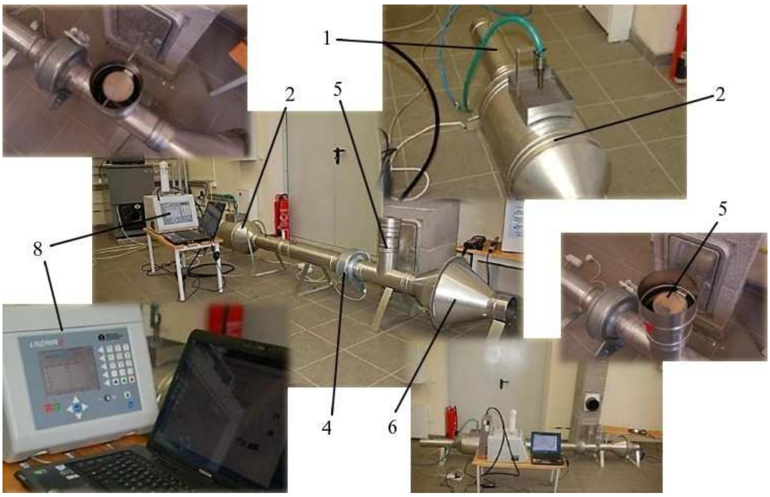
Experimental investigations

Special setup (Fig. 4) was designed and manufactured for experimental investigations. The scheme of the setup is presented in Fig. 4a. It consists of pipes 1 with integrated analyzers, acoustic chamber 2 with tone generator, throttle 3, dispenser 5, fan 4 and HEPA filter 6. “Lasair II” particle detecting and counting system was used. Particle shape and size analysis was performed using optical microscopy.

Microscope images of particles are shown in Figs. 5 and 6. Particles have irregular shapes as is evident from the figures. Aggregates of particles can be clearly observed in Fig. 6.



a)



b)

Fig. 4. Experimental setup: a) – scheme; b) – photography; 1 – pipe with analyzer, 2 – acoustic chamber, 3 – throttle, 4 – fan, 5 – dispenser, 6 – HEPA filter, 7 – aerosol diluter “Ati TDA-D100”, 8 – particle detecting and counting system “Lasair II”, 9 – sound level in acoustic chamber

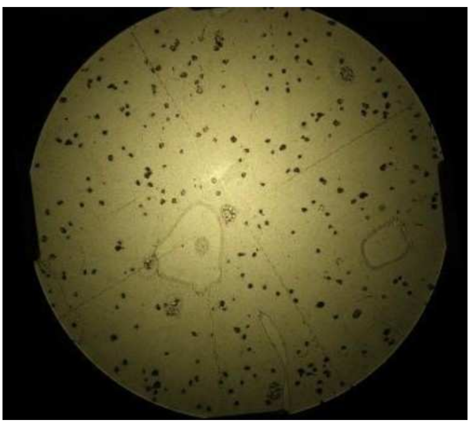


Fig. 5. Quartz sand particles after the action of acoustic field (photo from the optical microscope, magnification ×20)

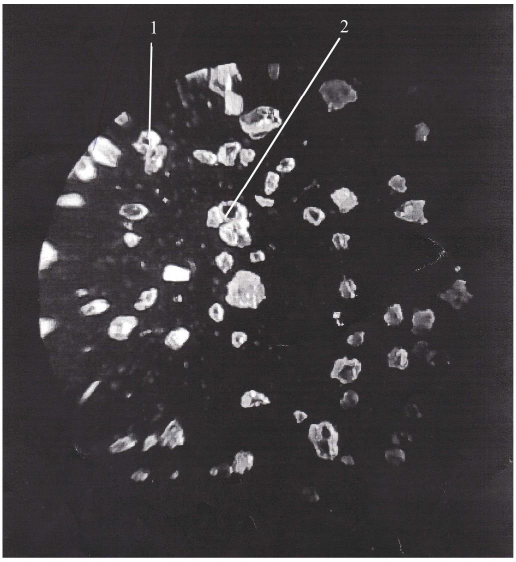


Fig. 6. Quartz sand particles aggregation caused by the action of acoustic field (photo from the optical microscope, magnification ×200): 1 – two-particle aggregate, 2 – three-particle aggregate

Conclusions

1. Theoretical investigations show that interaction between particles occurs only if the value of interaction angle φ exceeds 50º. Interaction force increases as frequency of acoustic field decreases.
2. Theoretical and experimental investigations demonstrate that the rate of particle aggregation depends on frequency of acoustic field and value of interaction angle. When interaction angle increases the force created by surface roughness occurs, i.e. the friction factor increases.
3. Microscopic analysis of aggregated particles reveals that their surfaces have an irregular shape and approximately coincide with the surfaces shown in Fig. 6.

References

[1] **Schmaltz G.** Technische Oberflächenkunde. Berlin: Springer-Verlag, 1936.
[2] **Czichos H.** A Systems Approach to the Tribology. Moscow: Mir, 1982.
[3] **Casimir H. B. G.** On the attraction between two perfectly conducting plates. Proceedings of the Royal Netherlands Academy of Arts and Sciences, Vol. 51, 1948, p. 793 – 795.
[4] **Briscoe B. J., Tabor D.** Surface forces in friction and adhesion. Faraday Special Discussions of the Chemical Society, Issue 2, 1972, p. 1 – 6.
[5] **Fuller K. N. G., Tabor D.** The effect of surface roughness on the adhesion of elastic solids. Proceedings of the Royal Society A, Vol. 345, No. 1642, 1975, p. 327 – 342.
[6] **Bergman L.** Ultrasound and its Application in Science and Technique. Moscow: Publishing House of Foreign Literature, 1957.
[7] **Vekteris V., Zaremba R., Striška V.** Tribology and adhesion of particles in acoustic field. Proceedings of 13th International Research/Expert Conference “Trends in the Development of Machinery and Associated Technology”, TMT2009, Hammamet, Tunisia, 16 – 21 October, 2009, p. 645 – 648.
[8] **King L. V.** On the acoustic radiation pressure on circular discs: Inertia and diffraction corrections. Proceedings of the Royal Society A, Vol. 153, No. 878, 1935, p. 1 – 16.