Numerical analysis of the influence of vortex acoustic flows on the efficiency of agglomeration

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Abstract. It is known and experimentally proven many times that ultrasonic vibrations in the gas phase contribute to the appearance of stationary acoustic flows. Since the flows are caused by energy losses during absorption of oscillations, and they do work against the frictional forces that cause this absorption, then these flows have a vortex character. According to numerous studies and developments in the field of inertial dust separation, at a centripetal acceleration of 10 m/s² or more, local compaction of particles is observed near the periphery of the vortex flow. Due to this, particles are captured in existing devices based on the inertial dust separation principle. In this regard, the article presents the results of the theoretical studies of the potential for the use of acoustic flows for a local increase in the concentration of particles and, consequently, an increase in the efficiency of agglomeration. A model of the influence of vortex acoustic flows on the efficiency of agglomeration is proposed. As a result of the numerical analysis of the model, the fundamental possibility of a significant (more than 4 times) increase in the efficiency of ultrasonic agglomeration of submicron particles due to the formation of vortex acoustic flows in the resonant intervals was revealed.

1. Introduction

When solving the problems of increasing the efficiency of gas cleaning processes [1–4], special attention is paid to finding ways to clean the air from particles less than 2.5 µm in size. This is due to the enormous danger of such particles caused by their high total surface (more than 55% of the total surface of particles emitted into the atmosphere) and counting concentration (more than 95% of the total counting concentration even with an insignificant mass fraction, less than 1% of the total fraction of aerosols, contained in the atmosphere). At the same time, due to their small size and mass, such aerosols can be held in the air for a long time and can easily penetrate into the alveoli of the human lungs, causing irreversible changes in the body.

Removal of such particles, even with the help of ultrasonic (US) vibrations, is a difficult task for the following reasons:

• insufficient probability of collision of such particles due to the small collision cross-sectional area. In this case, large particles with a size of 10 microns or more collide more efficiently due to the increased collision cross-sectional area;
An analysis of known studies indicates that the inertia of particles and the degree of their entrainment into vibrational motion can be reduced (up to 80% or less) using high frequencies of ultrasonic exposure (for particles less than 2.5 μm, this is 100 kHz or more) [7]. Unfortunately, the creation of high-frequency emitters (high losses in the material of the emitter, high losses for the absorption of oscillations in the gas phase, etc.) is technically difficult to implement. The additional introduction of an auxiliary aerosol to reduce the distance between particles (and, consequently, to increase the forces of hydrodynamic interaction, inversely proportional to the fourth power of the distance) is not always feasible and often leads to negative consequences.

In this regard, it becomes necessary to search for and study other nonlinear effects in an ultrasonic field that can ensure the convergence of particles and their deposition.

Obviously, to increase the probability of agglomeration, it is necessary to consider such effects that can affect the concentration of particles in the processed volume. Since the density of particles is high compared to the density of the gas phase and, as a consequence, gas oscillations do not lead to significant elastic deformations of particles (particles less than 2.5 μm in size are difficult to deform even in a liquid aggregate state, not only because of their high density, but also because of due to the high surface tension force), it is necessary, first of all, to consider the effects occurring in the volume of the gas phase (interparticle space).

As was established by the authors of [5, 6], ultrasonic oscillations in the gas phase contribute to the appearance of stationary acoustic flows. Since the flows are caused by energy losses during the absorption of vibrations, and they do work against the frictional forces that cause this absorption, then these flows have a vortex character.

According to numerous research and development in the field of inertial dust separation, with a centripetal acceleration of 10 m / s² and more local compaction of particles is observed near the periphery of the vortex flow. Due to this, particles are captured in existing devices based on the inertial principle of dust separation.

Hence follows the potential possibility of using acoustic flows for a local increase in the concentration of particles and, consequently, an increase in the efficiency of agglomeration. However, the experimental determination of the efficiency of agglomeration under the action of acoustic flows and the value of the concentration of particles in the zones of local compaction is difficult, since:

- the scale of acoustic flows is comparable to half the ultrasonic wavelength and the time during which one vortex turns around at a velocity capable of causing local compaction of particles does not exceed 0.05 s. While the existing instruments and methods for analysing the dispersed composition of aerosol have a characteristic response time of more than 0.1 s;
- the concentration of aerosol and the velocities of acoustic currents are characterized by characteristic inhomogeneity with a gradient scale of no more than a quarter of the ultrasonic wavelength (no more than 0.04 m) not detectable with modern particle analysers.

Therefore, in order to identify the optimal modes and conditions of ultrasonic action that ensure the formation of acoustic flows that can make a significant contribution to increasing the efficiency of agglomeration, it is necessary to develop a numerical model of the influence of such flows on the efficiency of ultrasonic agglomeration of submicron particles.

2. Model of the formation of acoustic flows during the formation of vibrations in a flat layer

To date, for the formation of ultrasonic vibrations in gaseous media, 2 types of emitters are most widely used - performing plane vibrations (piston radiator) and bending vibrations (flexural vibrating membrane) [22, 23, 24].
A schematic of the formation of oscillations using each emitter is shown in figure 1.

Regardless of the form of distribution of oscillations of the surface of the emitters, the mathematical formulation of the problem is formulated as follows. The process is considered in the air gap between the emitting and reflecting surfaces. In this case, the thickness of the air gap does not exceed the ultrasonic wavelength in the gas. The choice of a small thickness of the air gap is due to the need to create conditions that ensure the maximum resonant amplification of oscillations (due to the in-phase addition of the primary and reflected waves).

The initial data of the problem are the geometrical dimensions of the air gap - diameter $D$ and thickness $H$; the diameter of the initial particles $d_0$ and the density of the dispersed phase substance $\rho_p$; the density of the carrier gas phase - $\rho_0$; dynamic $\eta$ and kinematic $\varsigma$ viscosity of the carrier gas phase; absorption coefficient of ultrasonic vibrations in the gas phase $k$; relative distribution of amplitudes of oscillations of the surface of the emitter $a(r)$; sound pressure level near the centre of the radiator in the absence of a reflector - $L_{SP}$; oscillation frequency of the emitter - $f$.

To identify the possibility of vortex acoustic currents formation, the acoustic field near each emitter was initially calculated.

According to the calculations, a piston radiator is not able to create conditions conducive to an additional increase in the efficiency of particle agglomeration. The choice of a certain distance between the emitter and the reflector can lead to an increase in the sound pressure level due to the resonance phenomenon. However, even with a resonant layer thickness ($7.77 \text{ mm}$), the generated sound field will not allow for effective agglomeration of particles due to their short residence time in the gas gap. For example, at a gas flow rate of $0.1 \text{ m/s}$, the residence time of particles in the layer will not exceed $3 \text{ s}$.

In turn, a flexural oscillating radiator, like a piston one, is capable of providing a sound pressure level of more than $170 \text{ dB}$ at a resonant thickness of the air gap. In this case, the maximum sound pressure level near each of the considered emitters in the absence of a reflector is $150 \text{ dB}$ (corresponds to an oscillation amplitude of the centre of the emitter of $16 \mu\text{m}$).

However, with a flexural oscillating radiator, the amplitude gradient of the sound pressure (and since there is vibration absorption, there will be a phase gradient) has nonzero components along all coordinate axes. In this case, depending on the position of the observed point in space, the amplitude gradient can be directed at a different angle (from $0$ to $2\pi$) to the surface of the emitter. This means that the equivalent volumetric force capable of initiating the "sonic wind" has similar directions, creating a vortex motion. In this case, the surface of the emitter and reflectors do not impede the movement of the gas flow and, therefore, the occurrence of acoustic flows with a flexural oscillating radiator is possible.

In addition, since the agglomerated particles in the layer have inertia, the influence of acoustic currents on the probability of agglomeration of these particles is possible. To study the occurrence of acoustic flows.
The distribution of the velocities of vortex flows in the air gap and the shape of streamlines are completely determined by the stream function \( \psi(r) \). The initial data of the sub model is the distribution of the complex amplitudes of the sound pressure \( P(r) \), calculated according to the sub model of the acoustic field described in the previous section.

To determine the stream function, the equation of conservation of gas momentum in a vortex flow under the action of an equivalent force determined on the basis of sound pressure distributions obtained in the previous subsection.

\[
\begin{aligned}
\left\{ \begin{array}{c}
\frac{\partial \psi}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r \frac{\partial \psi}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \varphi} \frac{\partial \psi}{\partial \varphi} = -u_r \frac{\partial \psi}{\partial z} = \begin{pmatrix} -\gamma \cr x \cr 0 \end{pmatrix} \cdot \text{rot} \ F \\
\end{array} \right. \quad (1)
\end{aligned}
\]

\[
\alpha \rho_0 \text{rot} \ F = 2 \kappa_\omega \left( \nabla (\Re P) \times \nabla (\Im P) \right) - \frac{\mu \nu_f}{c^2 \rho_0} \Delta \left( \nabla (\Re P) \times \nabla (\Im P) \right); \quad (2)
\]

In this case, at the boundary of the air gap, the stream function is identically equal to zero. The solution of the presented system of equations allows calculating the stream function of the formed vortices.

**Figure 2.** Streamlines of vortex acoustic flows in the gas phase with different types of radiators.

As follows from the presented figures, the streamlines with a flexural oscillating radiator have a large curvature and, therefore, contribute to the local compaction of particles. Therefore, further we consider the effect on the efficiency of agglomeration only of acoustic flows formed by a flexural oscillating radiator.

3. **Model of particle agglomeration taking into account vortex acoustic flows**

To calculate the efficiency of agglomeration, a kinetic equation is obtained that takes into account the vortex motion.

\[
\begin{aligned}
\frac{\partial n_k}{\partial t} (\psi,t) + \frac{\partial n_k}{\partial \psi} (\psi,t) \frac{d\psi}{dS} + n_k (\psi,t) \frac{d}{dS} \frac{\text{div}(u_{ph,p})}{|\psi|} = \frac{\beta_{\psi} (P(r))}{|\psi|} ; \quad (3)
\end{aligned}
\]

where \( \beta_{\psi} \) – is the probability of collision of particles, which depends on the amplitude of the sound pressure \( P(r) \) and is determined by the forces of orthokinetic and hydrodynamic interaction of particles in the ultrasonic field.
The resulting equation (13) is solved by expanding \( n_k \) and the coefficients \( \frac{\partial n_k}{\partial \varphi} \), \( n_k \) in a power series \( \varphi \). This made it possible to reduce the problem to a system of ordinary differential equations of the first order.

Below are the results of a numerical study of the efficiency of agglomeration, taking into account the influence of acoustic flows on the basis of the obtained system of equations.

The efficiency of agglomeration was considered as the ratio of the current counting concentration to the initial

\[
\xi = \frac{\int_{x^2+y^2 \leq \frac{D^2}{4}, z \leq \frac{H}{2}} f_k (r, u, r, t) \, du \, dr}{\int_{x^2+y^2 \leq \frac{D^2}{4}, z \leq \frac{H}{2}} f_k (r, u, r, 0) \, du \, dr} = \frac{\int_{V} n_s (\varphi(r), t) \, dV}{\int_{V} n_s (\varphi(r), 0) \, dV}.
\]

The lower this ratio (the lower the residual concentration), the higher the efficiency.

![Graphs showing relative concentration versus time at different sound pressure levels](image)

**Figure 3.** Relative concentration versus time at different sound pressure levels.

The presented dependences make it possible to determine the range of sound pressure levels providing the greatest contribution of vortex flows. The presented dependences allow us to consider such a range of values from 150 to 155 dB (without a reflector, this range corresponds to the range of oscillation amplitudes of the emitter from 15 to 25.5 μm), at which the sintering time when using a flexural oscillating radiator is reduced by at least 22% compared to a piston radiator (at a sound...
pressure level of 150 dB). Hereinafter, the agglomeration time is understood as the time required to decrease the countable concentration by exactly 20 times. At a sound pressure level of 155 dB, the agglomeration time is reduced by more than 4 times.

4. Conclusions
A model of the influence of vortex acoustic flows on the efficiency of agglomeration is proposed. As a result of the numerical analysis of the model, the fundamental possibility of a significant (more than 4 times) increase in the efficiency of ultrasonic agglomeration of submicron particles due to the formation of vortex acoustic flows in the resonant intervals was revealed.

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