Numerical modeling of reactor clarifier characteristics, taking into account the nonstationary motion of the loading particles

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Abstract. The physical model of the contact mass’ particles interaction and the process of filtration in a fluidized layer is investigated in the article. Differential equations, describing the occurrence of non-stationary pulsations in the reactor-filtering component are given here. The computational experiments made it possible to determine the main kinematic dependencies and the way of contact mass’ parameters influencing on them. An estimate of the nonstationary process parameters, such as a period and frequency of oscillations, was obtained, and the estimated energy losses due to the occurrence of self-oscillations were calculated.

1. Introduction
The development of modern technologies for the natural and groundwater purification requires the design developments expansion in the calculation and modeling of new clarifier reactors using water filtration technology. The physico-mathematical models of the above constructions, which had been previously proposed [2, 3] did not consider essentially nonstationary oscillatory processes [4] arising from the motion of contact-mass particles. The formation of self-excited oscillations is studied; the dependence of the kinematic and energy characteristics on the parameters of fluidized layer is investigated in the article.

2. Materials and methods. Statement of the problems
Let us consider the physico-mathematical description of the process, taking into account the simulation of the particle motion nonstationary characteristics in the fluidized layer of the contact mass. According to the basic scheme of the clarifier reactor (Figure 1), purified water is supplied to the reactor with the addition of coagulant-forming reagents through the channel I.

Figure 1. Scheme of the clarifier reactor.
The process of filtering the impurity in the II zone through a contact mass is carried out, weighted by the carrier cleansing stream. Hydrolysis products in the flakes form are adsorbed on the surface of the contact layer grains. During a certain time, highly effective water purification from the impurity occurs. Completion of the purification process is caused by the appearance of coagulant flakes separation from the grains and their transfer to the stream. According to the technological requirements, filtering layer is regenerated after that, and cleaning cycle can be resumed.

When the contact mass’ particles move, the pressure of the water flow to be purified keeps them in a suspended state, they are pressed by the gravity, the water pushing force, the resistance force in a moving process of a viscous liquid, and they are also affected by the surrounding particles.

The self-oscillatory motion of grains in a vertical channel is described by a system of ordinary differential equations

\[ m \frac{du}{dt} = -mg + \rho_0 Vg - F_c, \]
\[ \frac{dx}{dt} = u, \]

where \( F_c = 6\eta d R \nu \) is the resistance force of viscous liquid according to the Stokes law, \( \nu = u - U \) is the relative speed, \( U \) is flow velocity of the purified water, \( m \) is particle mass, \( R \) is particle radius, \( V = (4/3)\pi R^3 \) is its volume, \( \rho_0 \) is water density, \( \mu \) is viscosity coefficient.

The non-stationary oscillatory process with particle is due to collisions and c pulses exchange with particles of the filtering layer adjacent to the vertical channel. It is assumed that if at some point \( t_0 \) the particle collides with the neighboring one, so, a central reflection takes place (absolutely elastic, or with a partial loss of velocity). For the subsequent section of motion in the opposite direction for the function \( u(t_i) \) the initial condition is

\[ u(0) = -u(t_0), \quad t_i = t - t_0. \]

The pulsating motion of the particle is realized on the section \([0, L]\), the chosen value of the known experimental height of the contact mass' column is increased when it is filled with a purified water stream, and therefore \( L \) is approximately 10% of the particle size.

When the particle of the filtering layer moves downward, due to the sharp change (increase) in the Reynolds number, a phenomenon known as the "resistance crisis" occurs [5]. The point of the turbulent boundary layer separation is displaced downstream; as a result, the resistance of the body visibly decreases with its movement in a viscous fluid.

To integrate equations (1), we introduce the following notation:

\[ k = U - (mg - \rho_0 Vg)/(6\eta d R), \quad n = 6\eta d R / m. \]

So, we can write:

\[ \frac{du}{dt} = -n(u - k), \quad \text{or} \quad \frac{d(u - k)}{(u - k)} = -nt. \]

Integrating both sides of this equation with respect to \( t \) variable, we conclude the relation:

\[ \ln \frac{u - k}{C} = -nt. \]

Hence there is a general solution \( u(t) = Ce^{-nt} + k \). An arbitrary constant \( C \) is found from the initial condition

\[ u_0 = C + k, \quad C = u_0 - k. \]

This way,

\[ u(t) = (u_0 - k)e^{-nt} + k. \]

Vertical coordinate of the particles \( x(t) \) is calculated by integrating expression (2) in time:
\[ x(t) = x_0 + \int_0^t u(\tau)d\tau = x_0 + \int_0^t ((u_0 - p)e^{-q\tau} + p)d\tau = \]

\[ = x_0 + pt - (u_0 - p)\int_0^t e^{-q\tau}d(-q\tau)/q = x_0 + pt + (u_0 - p)(1 - e^{-qt})/q . \tag{3} \]

Before the design was started under the guidance of CNIIC them. Kucherenko carried out aerodynamic tests of the model of the "glass crust" according to [7]. Climatic loads are determined by in-situ tests in the wind tunnel (various combinations of wind and snow loads).

According to the results of aerodynamic tests (Figure 6, 7) the calculated snow load was obtained, which varies from 200 to 500 kg/m² in different zones, and the standard wind load, which varies from -30 to +20 kg/m² in different zones, which correlates well with [8]

All climatic loads, including temperature and pulsation, were applied to the surface of the mesh shell by parameterization of the computational model using a visual programming language.

3. Calculations Results

Using relations (2, 3), the dependences of particles’ velocity and their vertical coordinate on \( t \) time are determined for different values of the main parameters of carrier stream’s velocity model, viscosity coefficient, density and the grain size of the loading.

As an example, the corresponding graphs are taken in Figure 2.

With the considered values of the given problem’s physical variables, it is possible to determine the period of oscillations of the contact mass’ particles:

\[ T = T_1 + T_2 = 0.015c \], where \( T_1 \) and \( T_2 \) – parameters of the first and the second motion segments, according to the relations: \( x(T_1) = L \) and \( x(T_2) = 0 \).

Accordingly, the frequency of self-oscillations is found from the formula: \( f = 1/T \).

The phase portrait of the self-excited oscillations is shown in Figure 3.

![Graph](image)

**Figure 2.** Dependence of velocity and vertical coordinate particles from the carrier flow velocity (solid line - \( U = 0.002 \), dotted line - \( U = 0.0018 \)).
Obviously, in order to maintain the steady self-oscillating process, additional energy consumption is required, connected with the size of "lens" area depicted in the phase portrait.

The particle trajectory in the vibrational motion consists of two sections corresponding to the curves 1 (rise) and 2 (descent) on the phase portrait of self-oscillations (see Figure 3), compiled for the velocity module. We determine the particles' average kinetic energy in each of the sections by the formula:

\[ W_{i} = \frac{1}{T_{j}} \int_{t_{i}}^{T_{j}} \frac{m_{i} u_{i}^{2}}{2} dt_{i}, \quad i = 1, 2. \quad (4) \]

If the difference in energy expenditure on the motion sections is equivalent to zero, then, the process does not require additional expenditure of external energy under the steady-state self-oscillations, in addition to losses for dissipation. Otherwise, self-oscillations maintenance occurs due to an increase in the loss of hydraulic pressure in the system of purified water supply. To calculate this difference in energy expenditure, we use the representation (4):

\[ W_{2}T_{2} - W_{1}T_{1} = \frac{m}{2} \left( \int_{0}^{T_{2}} u_{2}^{2} dt_{2} - \int_{0}^{T_{1}} u_{1}^{2} dt_{1} \right) \]

Taking into account that

\[ u_{i} dt_{i} = dx_{i}, \quad x_{i}(0) = 0, \quad x_{1}(T_{1}) = L, \quad x_{2}(0) = L, \quad x_{2}(T_{2}) = 0, \]

we get:

\[ W_{2}T_{2} - W_{1}T_{1} = \frac{m}{2} \left( \int_{0}^{L} u_{2} dx_{2} - \int_{0}^{L} u_{1} dx_{1} \right) = \frac{m}{2} \left( \int_{0}^{L} u_{2} dx_{2} - \int_{0}^{L} u_{1} dx_{1} \right). \]

Finally,

\[ W_{2}T_{2} - W_{1}T_{1} = \frac{m}{2} \int_{0}^{L} (|u_{2}| - |u_{1}|) dx = \frac{m}{2} S_{12}, \]

where we use \( S_{12} \) as "lens" area shown on the phase portrait of the self-oscillation process is indicated (Figure 3).

4. Conclusion

The article presents the results of the physical and mathematical description and computational experiments on the nonstationary oscillatory processes modeling in a fluidized contact mass layer. Algorithms for solving the motion equations are constructed, which make it possible to obtain kinematic characteristics of the particles, and also to analyze the influence of such parameters as carrier velocity, viscosity coefficient, density and grain size of the charge on them. The nonstationary vibrational motion of the filter structure grain is taken into account in order to obtain more accurate
estimates of the clarifier reactor operating parameters. Based on the approach associated with the construction of the self-oscillations phase portrait, estimates of the energy losses due to the particles’ vibrational motion are found.

References
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