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Criteria for Modelling the Gravity Clarifier

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***Abstract* — This article contains a new approach to the problem of modeling devices for the sedimentation separation of two-phase systems. It is shown that, regardless of the separation forces of the phase (gravity, centrifugal), the separation efficiency decisive parameter is the velocity gradient of the carrier phase (collinear sedimentation velocity, determined by the difference in density and dynamic viscosity of the carrier phase). The theoretical consideration is complemented by experimental research on a models assemblage (with horizontal flow and vertical deposition), with the invariant value of the specified gradient of the horizontal flow velocity.**

Keywords* — *modeling; sedimentation; Reynolds number; similarity test.

I. Introduction

It is known that sedimentation processes (precipitation of water droplets in an oil-in-water emulsion or, conversely, the emergence of oil globules in the reverse) is a complex integral result of various interdependent factors influence. This means that these factors influence field cannot be reduced to the separate examination of the influence and their reduction (summation) into one mathematical model. This also means that it is necessary to build a multi-factor model of the process and conduct an appropriate optimization experiment [1, 5–9].

To conduct such an experiment, we have developed pilot plants that allow modeling the process of oil dehydration in conditions close to real. However, it is clear that the implementation of conditions and modes from a pilot plant in full-scale objects must be preceded by certain guarantees of the adequacy of such an implementation. But this, as is known [1], is not indisputable in most cases and requires additional research. Therefore, the issue of modeling the processes of gravity sludge in the apparatus of dehydration (or, conversely, water treatment) is studied. The results of this study, which allows developing the conditions for the above-mentioned adequacy of the pilot plants operation modes implementation to field objects, are presented below.

II. Modelling gravity clarifier process problem state

Studies of the particles sedimentation processes (sedimentation of solid suspended particles in water and oil, the emergence of oil globules in water and the deposition of water droplets in oil) are conducted both on models and on natural objects. Research on models prevails on sharp the time and cost of conducting experiments reduction.

However, the lack of reliable criteria for building such models (the complexity lies, among other reasons, in the practical impossibility of modeling the flows of two-phase or multiphase mixtures [2–4]) determines that laws obtained on models are not always adequate to full-scale objects, they need to be corrected in the application to full-scale objects or even completely erroneous. Moreover, it is known [1] that the modeling of gravity sludge apparatus is impossible in the traditional sense. This is due to the fact that in the equation

$$\psi(H_0, Fr, Eu, Re, \delta) = 0\,, \tag{1}$$

expressing the connection between dimensionless hydrodynamic parameters [6], to simultaneously satisfy the Frud and Reynolds criteria (in full-scale and model flow), a model fluid with a viscosity much lower than that of the full-scale fluid is required, namely

$$\nu_m = \nu_f \cdot \lambda^{-1,5}. \quad (2)$$

Where common terms are adopted, respectively, $H_0 = V \cdot t/L$ – Strouhal number of flow, $Eu = \frac{\Delta P}{\rho \cdot V^2}$ – Euler number, $Fr = \frac{V^2}{g \cdot L}$ – Frode number, $Re = V \cdot D/\nu$ – Reynolds number, $\delta = L/D$ – geometrical similarity parameter, $\lambda = L_f / L_m$ imitation parameter (the ratio of the characteristic linear dimensions of the full-scale (f) and model (m) objects), V, ρ – average flow and density velocity, D – effective diameter of the object, t – characteristic time of stream velocity fluctuation, ΔP – drop in hydrostatical pressure

Formula (2) can be explained as follows. From the condition of equality of the Froude and Reynolds numbers on the field and model objects

$$\mathrm{Fr_f} = \mathrm{Fr_m},\ \mathrm{Re_f} = \mathrm{Re_m}, \quad (3)$$

follows

$$\begin{cases} \dfrac{V_f^2}{gL_f} = \dfrac{V_m^2}{gL_m}, \\ \dfrac{V_f D_f}{\nu_f} = \dfrac{V_m D_m}{\nu_m}, \end{cases} \Rightarrow \frac{V_f^2}{V_m^2} = \frac{L_f}{L_m} = \lambda.$$

It follows

$$\frac{V_f^2}{V_m^2} = \frac{\nu_f^2 D_m^2}{\nu_m^2 D_f^2} = \frac{\nu_f^2 \cdot D_m^2 \cdot L_f^2 \cdot L_m^2}{\nu_m^2 \cdot D_f^2 \cdot L_m^2 \cdot L_f^2} \Rightarrow \lambda = \frac{\nu_f^2 \delta_f^2}{\nu_m^2 \delta_m^2 \lambda^2}.$$

It follows, taking the parameters of geometric similarity equal $\delta_m = \delta_f$, we get

$$\lambda^3 = \nu_f^2 / \nu_m^2, \quad (4)$$

which coincides with the formula (2).

As the modeling is impossible (due to the impracticability of condition) (2), other methods were proposed. In 1950, A.Surin proposed modeling sedimentation tanks only for the rate of fluid removal under geometrical similarity. American scientists J. Willimont and G.A. Rohl in 1962 proved that modeling on the backing-out speed is more preferable compared to modeling using the Froude parameter (without observing the Reynolds parameter [1]).

III. Gradient Criterion of Similarity of the Sedimentation Process in Settlers

However, it is possible to simulate the conditions of sedimentation (sedimentation or floating) of particles from the flow for such systems, using the principle of equality of gradients of the horizontal flow velocity over the flow cross section (partial derivative of the horizontal velocity along the vertical Z axis) in full-scale and model objects: $\langle \mathrm{gradV} \rangle_f = \langle \mathrm{gradV} \rangle_m$

Thus, the following is valid for devices of gravitational horizontal sludge type (regardless of the purpose - water separators, pipe separators of phases, flotation towers, etc.).

Consider the behavior of a sedimentation particle in a horizontal flow in the framework of the so-called deterministic model, in contrast to the stochastic model [5, 10]. Then, from the condition of sedimentation time equality with velocity V_y and time of horizontal movement of a particle in a stream with velocity V_x (Figure 1), we obtain the length of the settling part of the apparatus (Figure 2)

$$L = \frac{D \cdot V}{U - \sigma_\omega} \quad (5)$$

where D is the diameter, U is the hydraulic particle size (minimum specified for extraction), usually specified as the uniform deposition velocity (ascent) of the dispersion phase in a dispersed medium, Q is the fluid flow, σ_ω is the dispersion of the vertical component of the flow (for laminar flows velocity would be considered equal to zero), S is the flow area, $S = Q/V$, where V is the average flow velocity:

$$V = \frac{\int_0^R V(r) \cdot 2\pi\pi \cdot dr}{S} \quad (6)$$

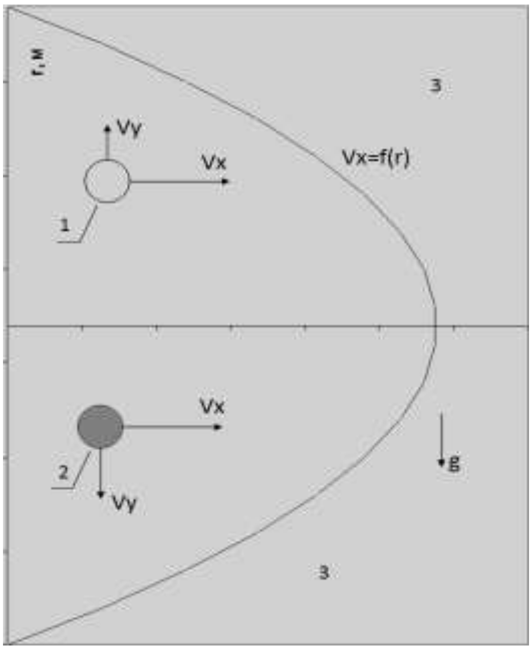

Fig. 1. The flow velocity profile in the clarifier: 1 - gas, 2 - water, 3 - oil, g – gravitaty acceleration.

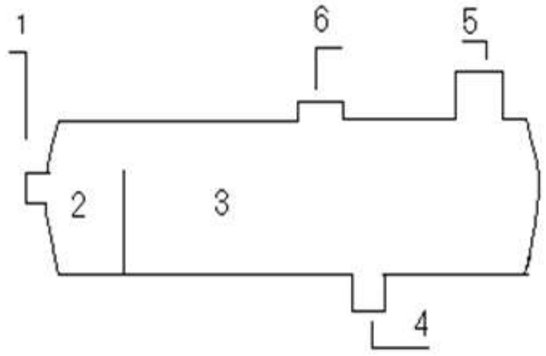

Fig. 2. Key diagram of the clarifying part: 1- product inlet, 2- flow calm zone, 3- sediment zone, 4- water outlet, 5- oil outlet, 6- excess gas discharge (safety valve).

Figure 1 it demonstrates that the process of sedimentation in such an idealized flow is completely determined (other things being equal) by the conditions of transition from one layer to another.

Let us examine the connections arising from the postulation of the equality of average gradients of flow velocities on the model and full-scale objects as the main condition for modeling the sedimentation of particles. To do this, we assume that in natural and model objects (Figure 2):

- fluid densities and viscosities are equal $\rho_f = \rho_m$, $\nu_f = \nu_m$;
- particle diameters (or their hydraulic size) are equal: $a_f = a_m$, $U_f = U_m$;
- traveling time along the settling axis (horizontal) is equal to the time of sedimentation:

$$\left(t_x = t_y\right)_f, \quad \left(t_x = t_y\right)_m \tag{7}$$

Obviously, due to the different linear dimensions of the full-scale and model objects, these times vary greatly among themselves. Then from the condition $\langle \mathrm{gradV} \rangle_f = \langle \mathrm{gradV} \rangle_m$, applying the usual estimate, for the average value of such a gradient we obtain:

$$\left(\frac{V}{R}\right)_f = \left(\frac{V}{R}\right)_m \tag{8}$$

From the last formula follows

$$\frac{V_f}{V_m} = \frac{R_f}{R_m} \tag{9}$$

And from the correlation $t_x = t_y$ we get

$$\left(\frac{L}{V} = \frac{D}{U}\right)_f, \quad \left(\frac{L}{V} = \frac{D}{U}\right)_m \tag{10}$$

After dividing in the last formula the first equation by the second, we obtain, taking into account the equality $a_f = a_m$, $U_f = U_m$

$$\frac{L_f}{L_m} = \frac{D_f \cdot U_m \cdot V_f}{D_m U_f V_m} = \frac{D_f}{D_m} \cdot 1 \cdot \frac{V_f}{V_m} = \frac{R_f V_f}{R_m V_m}$$

And combining formulas (9) and (10), we get $R_m = R_f \cdot \lambda^{-0,5}$; $V_m = V_f \cdot \lambda^{-0,5}$.

Then for the Reynolds numbers of flows, given the ratio $\rho_f = \rho_m$, $\nu_f = \nu_m$, we have:

$$\frac{Re_f}{Re_f} = \frac{V_f D_f \nu_m}{V_m D_m \nu_f} = \lambda^{0.5} \cdot \lambda^{0.5} = \lambda \tag{11}$$

And for ratio of throughflow

$$\frac{Q_f}{Q_m} = \frac{\left(\pi R^2 \cdot V\right)_f}{\left(\pi R^2 \cdot V\right)_m} = \lambda \cdot \lambda^{0.5} = \lambda^{1.5} \tag{12}$$

The table shows the values of throughflow rates, sizes and other parameters of full-scale (λ = 1) and model objects (sediment part) for λ = 5...200.

TABLE I. DIMENSIONS AND OPERATION MODES OF CLARIFIERS WITH DIFFERENT MODEL PARAMETERS (1, 5, 25, 50, 100, 200)

Parametr λ	**The length of clarifier, L, m**	**Diametr, D, m**	**Reynolds number**	**Trowflow Q, 10^{-6} m^3/s**	**Settling time, s**	**hydraulic load**	
						Q/S, m/d	**Q/V, 1/d**
1	10/5	0.5	2000	786	42/21	341	34/68
5	2/1	0.224	400	66.7	19/9.4	152	76/152
10	1/0.5	0.158	200	23.6	13/6.6	108	109/215
25	0.4/0.2	0.1	80	6.0	8/4	68	170/340
50	0.2/0.1	0.071	40	2.1	6/3	48	240/480
100	0.1/0.05	0.05	20	0.73	4/2	34	340/680
1	10/5	1.5	2000	2300	128/64	112	11/22
10	1/0.5	0.47	200	73.7	40/20	35	35/70
25	0.4/0.2	0.31	80	18.4	26/13	32	56/112
50	0.2/0.1	0.21	40	6.5	18/9	16	80/160
100	0.1/0.05	0.15	20	2.3	13/6	11	112/224
1	10/5	3.0	2000	4490	250/125	58	6/12
10	1/0.5	0.95	200	150	79/40	18	18/36
25	0.4/0.2	0.62	80	38	50/25	12	30/60
50	0.2/0.1	0.42	40	13.4	35/18	8	41/82
100	0.1/0.05	0.3	20	4.8	25/13	5.8	58/116
200	0.05/0.03	0.212	10	1.7	12/6	4.1	84/169
Note: Columns 2, 6, 8 show the values for objects (full-scale) of the same diameter and different lengths of the settling part (numerator and denominator - column 2, respectively).							

Further, the research task was to study the gradient invariance impact and the connections arising from it on the adequacy of the conditions mapping of particles sedimentation on various models.

IV. Conclusion

1. As a result of the study, it was demonstrated that the gradient of the horizontal velocity (vertical) is an acceptable criterion for modeling.

2. The dependences obtained as a result of experimental verification of the criterion (12) performance demonstrated very good results in a wide range of variations in the λ-imitation parameter.

3. In the field of practical values of λ (5 ... 200), we can assume that function (11) is independent of λ, provided that the modeling criterion (12) is met in the form:

$$\langle\frac{\partial V}{\partial r}\rangle \approx \frac{V}{R} \approx \frac{Q}{R^3} = const$$

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