Modeling of water lighting process and calculation of the reactor- clarifier to improve energy efficiency

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Abstract. The article considers the current questions of technological modeling and calculation of the new facility for cleaning natural waters, the clarifier reactor for the optimal operating mode, which was developed in Novosibirsk State University of Architecture and Civil Engineering (SibSTRIN). A calculation technique based on well-known dependences of hydraulics is presented. A calculation example of a structure on experimental data is considered. The maximum possible rate of ascending flow of purified water was determined, based on the 24 hour clarification cycle. The fractional composition of the contact mass was determined with minimal expansion of contact mass layer, which ensured the elimination of stagnant zones. The clarification cycle duration was clarified by the parameters of technological modeling by recalculating maximum possible upward flow rate of clarified water. The thickness of the contact mass layer was determined. Likewise, clarification reactors can be calculated for any other lightening conditions.

1. Introduction

A new highly effective facility for underground and surface natural water preliminary cleaning – the Reactor- clarifier [1] was developed in Novosibirsk State University of Architecture and Civil Engineering.

In order to determine the main technological parameters and the Reactor- clarifiers optimizing work, we present the studies conducted on its model in the semi-production conditions of water cleaning station of Novosibirsk Academic Town's groundwater.

Model RC was a column of organic glass with 0.1 m diameter and 3 m height, loaded with a homogeneous contact mass with 0.5 mm fractions fineness and 1.2 m dense layer height (figure 1).

Initial water with constant consumption was served to a column from the bottom up, weighing the contact mass. Reagents were poured into the water during the modeling process. Clarified water was drained from the bottom up through the column's overflow. The column was equipped with piezometers and an ejector flushing device.

2. Materials and Methods

Geometrical structure of porous medium of suspended granular layer in the ascending stream is reflected by the known formulas [2]:

$$\mathrm{Re} = \frac{\rho \cdot V \cdot d}{6 \cdot \mu \cdot (1-m)} \qquad (1)$$

$$\psi = \frac{P \cdot m^3 \cdot d}{L \cdot \rho \cdot V^2 \cdot 6 \cdot (1-m)} \tag{2}$$

Here, ψ – is the coefficient of resistance; Re is the Reynolds number;
P/L – pressure drop per length unit;
ρ and μ – are liquid density and viscosity; V is the velocity of ascending stream;
.....m- is the fraction of free volume (porosity) in a layer;
d – is the grains diameter.

In the general case, which devotes to various problems of hydrodynamics, the theory of similarity and dimensionality leads to the RCiterion equation

$$\psi = f(\mathrm{Re}) \tag{3}$$

According to Professor D.M. Minz, at Re low values for a weighted layer (in Re = 0.3modeling experiments), the linear law of resistance is used.

$$\psi = C/\mathrm{Re} \tag{4}$$

Here C is a constant value, for fine sand C = 4.5 [2]

Our experimental studies of liquid motion through a minimally weighed clarifier KM layer showed the validity of the minimally fluidized layer dependence.

$$\psi = 4.1 \cdot \alpha^2/\mathrm{Re} \tag{5}$$

Here α is the coefficient of the grains shape

The laws acceptability of liquid flow through fixed porous layers for the analysis of initial stages of fluidization is indicated in the work of Leva M. [3, pp. 30-35].

M. E. Aerov. And O.M. Todes maintain that for the description of liquid motion through boiling fine-grained layers at Re <1 it is possible to use Kozeny-Karman formula [4].

By substituting (1) and (3) in (5) we obtained Kozeny-Karman formula for calculating the hydraulic gradient with an updated constant, which is equal to 198

$$i = \frac{198 \cdot V \cdot \alpha^2 \cdot \mu \cdot (1-m)^2}{\rho \cdot g \cdot d^2 \cdot m^3} \tag{6}$$

In IS system $\gamma = 9810\ n|m3$.
So, the formula for determining the hydraulic resistance during the laminar flow of the purified water through the fluidized layer of the contact mass will have such form as…

$$i = \frac{V \cdot \alpha^2 \cdot \mu \cdot (1-m)^2}{49.5 \cdot d^2 \cdot m^3} \tag{7}$$

In the stationary filtering layer, near the contact points between the loading grains, there are stagnant zones, which reduce the free porosity, the specific surface and makes additional hydraulic filtering resistances. Additional constraint of the flow live section is caused by hydrated shells of solid particles that do not participate in the movement and expand the value of stagnant zones. According to theoretical calculations and experiments of academic L.S. Leibenzone, the volume of stagnant zones can reach 37% of the layer porosity, even for spherical shape particles. At the initial moment of solid particles weighing, these stagnant zones continue to exist, they only deform, leaving liquid bridges between particles, but they have already lost direct contact with each other [5, p.63]. We calculated the minimum value due to the charge expansion, which eliminates stagnant zones e = 0.12.
The clarifying ability of the pseudo-lively contact mass depends on the specific surface area of its grains, determined by the formula

$$\omega = \frac{6 \cdot \alpha (1 - m)}{d} \tag{8}$$

With a constant grain diameter, the specific surface increases with a porosity decrease, which is inversely related to the expansion degree of the RC layer. Thus, optimization of the Reactor- clarifier operation consists in determining the technological and design parameters with the minimum permissible degree of RC loading expansion e = 0.12. Another reason for the desirability of layer operation in minimal phase, or quiet fluidization, which provides weakly expressed mutual movement of grains, is the necessity of observing the non-abrasion condition of the RC material.
We obtained theoretically and experimentally confirmed the dependence for determining the grain diameter of the RC loading at any degree of contact mass expansion, taking into account the different conditions of filtration through the fluidized layer.

$$d_a = \left[\frac{V\alpha \cdot \mu^{0.54} (e+1)^{1.33}}{5(e+m_n)^{1.77}} \right]^{0.752} \tag{9}$$

When potassium permanganate and sodium hydroxide were introduced into water, iron and manganese were oxidized in water, hydrolyzed, contact coagulated hydrolysis products, and formed of precipitate-sorbent for metals and other impurities on grains of a weighted contact mass. As the sediment accumulated, the RC layer was expanding for the first few hours. The expansion was up to 10% of the original expanded layer height. Then, as the solid precipitate grid was formed, the expansion came to an end, losing the increased header pressure in layer, similar to the increase in the filters with a dense granular charge. The reduction of the total iron and manganese in water on the clarifier was about 90%. The cycle of water clarification in the RO finished when the sediment removal from the filter reached 5 mg / l by turbidity and further water supply to the second stage of purification (filtration) was considered impractical. Loading of the contact mass was subjected to ejection washing to restore its clarifying power.

It is known from hydrodynamics that hydraulic slope i and the tangential stresses τ arising on the surface streamlined by the flow and related by the relation: $\tau = \gamma \bullet i \bullet R$ (11)

where R is the hydraulic radius, $R = m / \omega$ (12)

On the basis of the relation 11 and experiments on modeling the process of water purification in the clarifying reactor contact layer, it can be assumed that the limiting hydraulic slope i_{np}, which characterizes precipitate strength, is proportional to the displacement stress

$$\frac{i_{sss}}{i_o} = \frac{\varphi \cdot \tau_{sss}}{\gamma \cdot R \cdot i_o} \tag{10}$$

By means of transformations, the formula for determining the limiting displacement stresses in contaminated contact mass RC was obtained.

$$\tau_{sss} = \frac{33 \cdot V \cdot \alpha \cdot \mu \cdot (1 - m_o)}{d \cdot m_{sss}^{\,2} (1 - m_{sss})} \tag{11}$$

Where m_o *and* m_{sss} - initial and ultimate porosities of the RC fluidized.
As a result of the Reactor- clarifier modeling, the following experimental technological parameters were obtained:

1. Contact mass (RC) - quartz sand: d_{equ}= 0.65; α = 1.16;

m_n = 0.41; the height of the RC dense layer L_n - 1,0m;

height of the RC expanded layer clean L_e -1.06 m;

height of the RC expanded layer of contaminated *Lec* -1.1 m;

limiting saturation density ρ = 0.67 kg/m^3
2. Flow velocity V= 8.8 m/h (2.4 mm/s);

water temperature - 9ºC; water viscosity $\mu = 1.38 \cdot 10^3$;
head loss Δh: in RC clean – 0.81 m, in contaminated KM – 0.9 m;
3. Iron content in water: initial 2.5 mg/l; clarified 0.1;
dose of NaOH – 60 mg/l;
clarification cycle duration Tc– 27 hours.
Calculated parameters of the Reactor- clarifier according to the simulation results:
Initial porosity of the fluidized contact mass

$$m_o^* = 1 - \frac{L_n}{L_o}(1 - m_n) = 1 - \frac{1}{1.06}(1 - 0.41) = 0.443 \quad (12)$$

The specific surface of the fluidized contact mass according to formula (9)

$$\omega = \frac{6 \cdot \alpha \cdot (1 - m_o)}{d} = \frac{6 \cdot 1.16 \cdot (1 - 0.443)}{0.65 \cdot 10^{-3}} = 5964$$

The limiting porosity of the RC fluidized by formula (8) through the limiting hydraulic slope $i_{sss} = \Delta h_{sss} / L_{sss}$

$$\frac{(1 - m_{sss})^2}{m_{sss}^3} = \frac{\Delta h}{L_{sss}} \cdot \frac{49.5 \cdot d^2}{V \cdot \alpha^2 \cdot \mu} = \frac{0.90}{1.1} \cdot \frac{49.5 \cdot 3.6 \cdot 10^3 \cdot 0.65^3 \cdot 10^{-6}}{8.8 \cdot 1{,}16^2 \cdot 1.38 \cdot 10^{-3}} = 3.769 \quad (13)$$

From the cubic formula solution m_{sss}= 0.438

Limit saturation of fluidized contact mass by sediment

$$\Delta m_{sss}^* = m_{opt}^* - m_{sss}^* = 0.443 - 0.438 = 0.005 \ m^3/m^2 \quad (14)$$

Specific saturation

$$\Delta m_{sss}^* / \omega = 0.005 / 5964 = 8.4 \cdot 10^{-6} \quad (15)$$

The limiting tangential stresses (precipitation strength for a displacement) τ_{sss}, corresponding to the limiting value of the sediment removal from contact mass, are determined by the formula (14)

$$\tau_{sss} = \frac{33 \cdot V \cdot \alpha \cdot \mu \cdot (1 - m_o)^2}{d \cdot m_{sss}^2 (1 - m_{sss})} = \frac{33 \cdot 8.8 \cdot 1.16 \cdot 1.38 \cdot 10^{-3} (1 - 0.443)^2}{3600 \cdot 0.65 \cdot 10^{-3} \cdot 0.438^2 (1 - 0.438)} = 0.572 Pa \quad (16)$$

Precipitation strength for a displacement, as the most general parameter of clarification process and geometric structure of contact mass, is the basis for of technological modeling technique and calculation of the Reactor- clarifiers.
Dirt capacity of the contact mass

$$C_g^* = \rho^* \cdot L_a = 0.67 \cdot 1.06 = 0.71 \ kg/m^3 \quad (17)$$

The weight concentration of sediment in the fluidized contact mass layer is determined by the formula 219 [2]

$$\Delta m_{sss}^* = \rho^* / \gamma^* \quad (18)$$

$$\gamma^* = C_g^* / (\Delta m_{sss}^* \cdot L^*) = 0.71 (0.005 \cdot 1.06) = 134 \ kg/m^3 \quad (19)$$

We checked the coincidence of the experimental duration of clarification cycle with the calculated

$$T_{cs}^{*} = \frac{\Delta m_{sss}^{*} \cdot L_{a}^{*} \cdot \gamma^{*}}{V^{*}(C_o - C_t)} = \frac{0.005 \cdot 1.06 \cdot 134}{8.8 \cdot (0.005 - 0.002)} = 26.9 \ hours \quad (20)$$

Where C_o и C_t- are the averages for the clarification cycle of the concentration of suspended matter in initial water after the reagent introduction and in the clarified water, kg/m^3; By the formula 43 [6]

$$C_a = 20\ (Fe_o - Fe_t) = 20\ (0.00025 - 0.0001) = 0.005 \text{ kg/m}^3, \quad (21)$$

wereFe_o and Fe_t- are iron concentrations in the initial and clarified water, kg/m^3

3. Results

The estimated of clarification cycle T_{cs}^{*} duration coincided with the experimental one, so the simulation parameters are determined correctly, and it is possible to calculate the Reactor- clarifier for optimum mode of its operation.

The experience of long-term operation of the reactor-clarifiers production in the general composition of groundwater treatment facilities from iron, manganese and salt compounds showed the rationality of the 24-hour minimum duration of the clarification cycle between washing-outs [7]. This duration of inter-regeneration period of the Reactor- clarifiers operation was accepted by us for the estimated duration for the rational design and technological parameters of the RO operation [8].

Clarifier calculation for the optimum operating mode was carried out for the most unfavorable period of the year (spring flood) in the following sequence:

1. The maximum possible rate of ascending flow of purified water was determined, based on the 24 hour clarification cycle duration.
2. The fractional composition of the contact mass was determined with minimal expansion of contact mass layer, which ensured the elimination of stagnant zones.
3. The clarification cycle duration was clarified by the parameters of technological modeling by recalculating maximum possible upward flow rate of clarified water.
4. The thickness of the contact mass layer was determined. [9, 10]

New maximum possible rate of ascending water flow is

$$V = \frac{T_{cs}^{*}}{T_{cs}} \cdot V^{*} = \frac{26.9}{24} \cdot 8.8 = 9.9\ m/h \quad (22)$$

New average grain diameter of the contact mass during the layer expansion e = 0.12 was determined by the formula (10). New initial porosity with the expansion e = 0.12 was determined by formula (15)

$$m_o = 1 - \frac{1}{1.12}(1 - 0.41) = 0.473 \quad (23)$$

The specific surface of the fluidized contact mass according to formula (9)

$$\omega = \frac{6 \cdot \alpha \cdot (1 - m_o)}{d} = \frac{6 \cdot 1.16 \cdot (1 - 0{,}473)}{0.65 \cdot 10^{-3}} = 6113\ m^2/m^3 \quad (24)$$

The new limiting porosity is determined by formula (19) with the known precipitation strength for a displacement $\tau_{sss} = 0.572$

$$m_{sss}^{2}(1 - m_{sss}) = \frac{33 V \alpha \mu (1 - m_o)^2}{d \cdot \tau_{sss}} = \frac{33 \cdot 9.9 \cdot 1.16 \cdot 1.38 \cdot 10^{-3} (1 - 0.473)^2}{3600 \cdot 0.65 \cdot 10^{-3} \cdot 0.572} = 0.117 \quad (28)$$

From the cubic formula solution m_{sss}=0.468. New irreducible saturation by the formula (17)

$$\Delta m_{sss} = 0.473 - 0.468 = 0.005\ m^3/m^2 \quad (25)$$

New specific saturation by formula (18)

$$\Delta m_{sss}/\ \omega = 0.005\ /6113 = 8.2\cdot 10^{-6} \quad (26)$$

New clarification cycle duration is determined by formula (23)

$$T_{cs} = \frac{\Delta m_{sss}\cdot L_a\cdot \gamma}{V\ (C_o\ -\ C_t)} = \frac{0.005\cdot 1.12\cdot 125}{9.9\cdot (0.005-0.002)} = 24 \text{ hours} \quad (27)$$

The maximum possible rate of purified water ascending stream, taking into account the 24-hours of the clarification cycle duration, was 9.9 m / h.
The loading layer thickness is determined by the empirical formula

$$L = k\ \cdot V\ \cdot \mu\ /(\omega\cdot \tau_{sss})\ M \quad (28)$$

Where k - the coefficient, $k = 10^7 m^{-1}$;
V - is the velocity of ascending stream, *m/s;*
μ - the viscosity*;*
τ -precipitation strength for a displacement*;*
ω - is grains' specific surface area of fluidized contact mass, m^2/m^3*;*
d - is the average grain diameter of contact mass.

$$L = 10^7\cdot 9.9\cdot 1.38\cdot 10^{-3}/(3600\cdot 6\cdot 10^{-3}\cdot 6113\cdot 0.572) = 1.8\text{m} \quad (29)$$

4. Conclusions

A calculation example of a structure on experimental data is considered. The maximum possible rate of ascending flow of purified water was determined, based on the 24 hour clarification cycle duration.

The fractional composition of the contact mass was determined with minimal expansion of contact mass layer, which ensured the elimination of stagnant zones. The clarification cycle duration was clarified by the parameters of technological modeling by recalculating maximum possible upward flow rate of clarified water. The thickness of the contact mass layer was determined. Likewise, clarification reactors can be calculated for any other lightening conditions.

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