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DEPOSITION OF PARTICLES FROM A TURBULENT FLOW ON THE WALLS OF PIPES AND CHANNELS

Sergey V. Fedosov [1], Alexandr V. Markelov [2],

[1] National Research Moscow State University of Civil Engineering, Moskow, RUSSIA

[2] Yaroslavl State Technical University, Yaroslavl, RUSSIA

Abstract: The formation of sediment on the walls of pipes and channels has a significant impact on the efficiency and reliability of technological equipment. The article considers the effect of sediment formation on the process of ultrafiltration of wastewater from the plant of reinforced concrete structures, representing water-oil emulsions with a high content of suspended solids. On the basis of the theory of turbulent particle migration developed earlier by E.P. Mednikov in a shear turbulent gas flow, a solution of the problems of particle deposition on the walls of circular channels from a viscous fluid flow in a wide range of Schmidt numbers is obtained. The equations for determining the mass transfer coefficient from the core of the flow to the channel walls for a two–layer boundary layer according to the Prandtl theory, a three-layer Pocket and a modernized three-layer Landau-Levich were obtained. The results of calculations of the mass transfer coefficient of particles from the flow core to the channel surface according to the proposed upgraded model showed the highest intensity of deposition of particles with a diameter of 10 to 40 microns. The adequacy of the model was verified by comparing the calculated parameters with the results of well-known domestic and foreign researchers and showed good verification.

Keywords: Turbulent migration, circular channel, mass transfer coefficient

ОСАЖДЕНИЕ ЧАСТИЦ ИЗ ТУРБУЛЕНТНОГО ПОТОКА НА СТЕНКИ ТРУБ И КАНАЛОВ

С.В. Федосов [1], А.В. Маркелов [2]

[1] ФГБОУ ВО «Национальный исследовательский Московский государственный строительный университет», г. Москва, РОССИЯ

[2] ФГБОУ ВО «Ярославский государственный технический университет», г. Ярославль, РОССИЯ

Аннотация: Образование осадка на стенках труб и каналов оказывают существенное влияние на эффективность и надежность технологического оборудования. В статье рассмотрено влияние образование осадка на процесс ультрафильтрации сточных вод комбината железобетонных конструкций, представляющие водомасляные эмульсии с большим содержанием взвешенных веществ. На основе развитой ранее Е.П. Медниковым теории турбулентной миграции частиц в сдвиговом турбулентном потоке газа получено решение задач об осаждении частиц на стенки круглых каналов из потока вязких жидкостей в широком диапазоне числа Шмидта. Получены уравнения для определения коэффициента массоотдачи из ядра потока к стенкам канала для двухслойного пограничного слоя по теории Прандтля, трехслойного – Кармана и модернизированного трехслойного Ландау-Левича. Результаты расчетов коэффициента массоотдачи частиц от ядра потока к поверхности канала по предложенной модернизированной модели показали наибольшую интенсивность осаждения частиц диаметром от 10 до 40 мкм. Адекватность модели была проверена путем сравнения расчетных параметров с результатами известных отечественных и зарубежных исследователей и показала хорошую верификацию.

Ключевые слова: турбулентная миграция, круглый канал, коэффициент массоотдачи

INTRODUCTION

Turbulent particle migration is the process of moving particles inside a liquid or gas that occurs under the influence of flow turbulence. This process is characterized by chaotic and unpredictable particle movements caused by vortices and turbulent pulsations in the flow [1, 2].

Turbulent particle migration can occur both in liquid media (for example, water or oil) and in gases (for example, air), and is of great practical importance in various industrial sectors and municipal services. economy, including [2, 3]:
- formation of corrosion, wear of equipment and pipelines;
- reduced efficiency and reliability of equipment;
- uncontrolled pollution of water and air resources.

All these aspects make turbulent particle migration an important area of research with significant applied and theoretical significance.

In the construction industry, waste water containing suspended particles, petroleum products, surfactants, and other pollutants is formed in reusable forms during the production of reinforced concrete structures [4].

For wastewater treatment, the process of ultrafiltration can be used, i.e., the separation of particles and molecules by size using semipermeable membranes [5].

Sediment formation can have a significant impact on the ultrafiltration process, due to:
- reducing the permeability and efficiency of the process;
- damage to the active layer of the membrane, increasing its wear and reducing the service life of the membrane;
- changes in the chemical composition and concentration of the initial liquid in the boundary layer, which, in turn, can affect the filtration characteristics of the membrane.

Knowing the intensity of sediment formation will allow you to develop requirements for pretreatment, reasonable choice of the type of membrane, and timely monitoring and maintenance of such devices.

Research in the field of particle deposition under turbulent flow regimes has been carried out for more than 60 years, and there are a large number of scientific publications. However, even in the case of simplifying the formulation of the problem of precipitation of particles with a low concentration as a result of turbulent migration, complex analytical or numerical methods for solving it are required [2, 6-15]. Generalization of the theory and theoretical calculations in this area that are well consistent with experiments were obtained in the Russian scientific school founded by E. P. Mednikov [1].

In this paper, an attempt is made to adapt the theory of turbulent particle migration in aerosols to mass transfer in viscous liquids, taking into account phenomena in the boundary layers of circular channels.

1. Problem statement

Moving along the flow, particles at some stage of their movement reach the wall region and, when the distance to the wall becomes equal to their radius, touch it and settle on it, if the wall surface is "absorbing" [1].

The migration rate u_t characterizes the intensity of precipitation of particles from the turbulent flow onto the channel wall [1]

$$u_t = j / c\,, \tag{1}$$

where j - specific particle flow to the wall, kg/(m^2·s); c - concentration of particles in the solution, kg/m^3.

Then the specific flow of particles to the wall j is determined by the equation

$$j = u_t \cdot c\,. \tag{2}$$

Expression (2) is an analog of the well-known mass transfer equation [16]

$$j = \beta_d \cdot (c_R - c_w)\,, \tag{3}$$

where β_d - mass transfer coefficient, m/s; c_R - concentration of impurities in the flow core; c_w - concentration of impurities on the membrane surface.

Hence, it is possible to assume the identity of the deposition rate and the mass transfer coefficient of particles from the flow core to the membrane walls

$$u_t = \beta_d\,. \tag{4}$$

Theoretical methods for determining the mass transfer coefficient of the dispersed phase β_d will make it possible to perform calculations on the deposition of particles on the membrane walls with minimal use of experimental data.

We use a well-known approach, when the turbulent deposition of a finely dispersed phase is considered as a kind of diffusion process using the usual equations from the mass transfer theory [1].

The motion of very small particles practically does not differ from the motion of the carrier turbulent vortices of the medium, and then $D_P = D_S$, where D_P, D_S are the coefficients of turbulent diffusion of particles and the medium, m^2/s [1].

Consider a situation where the mass transfer resistance is concentrated in the boundary layer on the surface of a membrane element. Let *the y-axis* be directed normal to the surface of the membrane. In this case, using an analog of Fick's first law [1], the projection of the specific particle flux on *the y-axis* at any point of the boundary layer is written as

$$j(y) = (D_P + D_{Br})\frac{dc}{dy}, \qquad (5)$$

where D_{Br} - Brownian diffusion coefficient.

We introduce a new dimensionless quantity-the relative particle flux

$$j^* = \frac{j(y)}{j_w}. \qquad (6)$$

Then, using expression (6), we make a substitution in equation (5) to obtain

$$j^* \cdot j_w = (D_P + D_{Br})\frac{dc}{dy}. \qquad (7)$$

Then, separating the variables, we write the integral over the boundary layer thickness

$$\int_{c_w}^{c_R} \frac{dc}{j_w} = \int_0^{\delta} \frac{j^* \cdot dy}{D_P + D_{Br}}, \qquad (8)$$

where δ - turbulent boundary layer.

Using expression (3), we obtain

$$\frac{1}{\beta_d} = \int_0^{\delta} \frac{j^* \cdot dy}{D_P + D_{Br}}. \qquad (9)$$

Expression (9) is general and allows calculating the mass transfer coefficient based on the Brownian (molecular) and turbulent diffusion coefficients, as well as the relative specific particle flux in the boundary layer j^*.

In this model, the main resistance to mass transfer in the diffusion boundary layer is assumed, as well as the constancy of the flow across this layer $c_R = c_w$ hence $j^* = 1$.

2. Results and discussion

To obtain a universal solution of equation (9), we first reduce it to a dimensionless form by entering the following parameters:

- dimensionless distance along *the y-axis*

$$y^+ = y\frac{u^*}{\nu}, \qquad (10)$$

where u^* - dynamic flow velocity; ν - kinematic viscosity coefficient of the separated liquid.

In this case,

$$dy = \frac{\nu}{u^*} dy^+. \qquad (11)$$

Dimensionless mass transfer coefficient

$$\beta_d^+ = \frac{\beta_d}{u^*}. \qquad (12)$$

Dimensionless thickness of a viscous sublayer [2]

$$R_1^+ = \frac{u^* \cdot \delta_1}{\nu}, \qquad (13)$$

where δ_1 - value of the viscous sublayer.

For the Prandtl model R_1 =11.6 [2].

The dimensionless thickness of a turbulent boundary layer is determined by the expression

$$R_{\delta}^{+} = \frac{u^{*} \cdot \delta}{\nu}. \qquad (14)$$

The dimensionless thickness of a viscous sublayer on a rough surface will differ from $R_{1m}^{+} = 11.6$, that derived for a smooth plate [2].

For the boundary layer with various perturbations (roughness, two-phase, etc.), the expression [2] is obtained

$$R_{1m}^{+} = 11.6\sqrt{\frac{C_{f0}}{C_{fm}}}. \qquad (15)$$

After substituting the dimensionless quantities in equation (9), we obtain

$$\frac{1}{\beta_{d}^{+} \cdot u^{*}} = \int_{0}^{R_1} \frac{\nu \cdot dy}{(D_P + D_{Br}) \cdot u^{*}} \quad \text{or}$$

$$\frac{1}{\beta_{d}^{+}} = \int_{0}^{R_1} \frac{\nu \cdot dy}{(D_P + D_{Br})}. \qquad (16)$$

For particles subject to precipitation, the turbulent diffusion coefficient of particles can be determined by the expression [1]

$$D_P = \frac{D_S}{1 + \omega_E \cdot \tau_p}, \qquad (17)$$

where w_E - angular frequency of turbulent low-frequency pulsations of energy-intensive vortices; τ_p - relaxation time.

Usually, with a small error, they allow [1]

$$D_S \approx \nu_T, \qquad (18)$$

where ν_T - turbulent viscosity coefficient.

In expression (17), the angular frequency of turbulent low-frequency pulsations of energy-intensive vortices ω_E and the relaxation time τ_p are determined by expressions [1]

$$\omega_E = \frac{u^{*}}{0.1 \cdot r}, \quad \tau_p = \frac{\rho \cdot d_s^2}{18 \cdot \mu}, \qquad (19)$$

where d_s - diameter of impurity particles; μ - dynamic viscosity coefficient.

Various boundary layer models and functions for $\nu_T(y)$ are known in the literature, which can be classified according to the number of layers.

The Prandtl model. The two-layer Prandtl model suggests molecular transport in the viscous sublayer and turbulent transport beyond it [2].

In a viscous sublayer $\nu_T = 0$, and for $y > \delta_1$, $\nu_T = \chi \cdot u^{*} \cdot y$, where $\chi = 0.4$ is the Prandtl constant [2]. Then the transfer resistance of the fine phase in the boundary layer, using expression (9) and the model assumptions described above, is written as

$$\frac{1}{\beta_{d}^{+}} = \int_{0}^{R_1^{+}} \frac{\nu}{D_{Br}} \cdot dy^{+} + \int_{R_1^{+}}^{R_\delta^{+}} \frac{\nu}{D_P} \cdot dy^{+}. \qquad (20)$$

It is known that the ratio of the kinematic viscosity coefficient to the diffusion coefficient is determined by the Schmidt criterion [1]

$$Sc_{Br} = \nu / D_{Br}. \qquad (21)$$

In integral equation (20), we make substitutions using the expressions (10), (17), (18) and (21), we obtain

$$\frac{1}{\beta_{d}^{+}} = \int_{0}^{R_1^{+}} Sc_{Br} \cdot dy^{+} + \int_{R_1^{+}}^{R_\delta^{+}} \frac{(1 + \omega_E \cdot \tau_p) dy^{+}}{\nu_T} = \int_{0}^{R_1^{+}} Sc_{Br} \cdot dy^{+} + \int_{R_1^{+}}^{R_\delta^{+}} \frac{(1 + \omega_E \cdot \tau_p) \cdot u^{*} \cdot \nu \cdot dy^{+}}{\chi \cdot u^{*} \cdot y^{+} \cdot \nu}. \qquad (22)$$

We transform the expression (22) by taking the constant terms as the sign of the integral

$$\frac{1}{\beta_{d}^{+}} = Sc_{Br} \int_{0}^{R_1^{+}} dy^{+} + \frac{1 + \omega_E}{\chi} \int_{R_1^{+}}^{R_\delta^{+}} \frac{dy^{+}}{y^{+}} \cdot \qquad (23)$$

As a result of integrating (23), we obtain

$$\frac{1}{\beta_d^+} = Sc_{Br} \cdot R_1^+ + \frac{1+\omega_E}{\chi}\left[\ln(R_\delta^+ / R_1^+)\right]\cdot \quad (24)$$

Thus, the expression (24), after the corresponding transformation, can be represented as

$$\beta_d^+ = \frac{1}{Sc_{Br} \cdot R_1^+ + \frac{1}{\chi}\left(1+\omega_E\right)\ln(R_\delta^+ / R_1^+)}\cdot \quad (25)$$

In dimensions (25), it will look like

$$\beta_d = \frac{u^*}{Sc_{Br} \cdot \frac{u^* \cdot \delta_1}{\nu} + \frac{1}{\chi}\left(1+\omega_E\right)\ln(\delta / \delta_1)}\cdot (26)$$

Karman Model. In the three-layer Karman model, the turbulent exchange functions have the form [2]:
– in a viscous sublayer at $y^+ < 5$, $\nu_T = 0$;
– in the transition region at $5 < y^+ < 30$,

$$\nu_T = u^* y / 5 - \nu; \quad (27)$$

– in the turbulent region at $y^+ > 30$,

$$\nu_T = \chi u^* y - \nu. \quad (28)$$

Assuming that for $y^+ > 5$ (outside the viscous sublayer) $D_{CP} >> \nu$, the particle transport resistance is written as

$$\frac{1}{\beta_d^+} = \int_0^{R_1^+} \frac{\nu \cdot dy^+}{D_{Br}} + \int_{R_1^+}^{R_2^+} \frac{\nu \cdot dy^+}{D_P} + \int_{R_2^+}^{R_\delta^+} \frac{\nu \cdot dy^+}{D_P}. \quad (29)$$

The value of the viscous sublayer δ_1 [1, 2]

$$\delta_1 = 5\nu / u^*; \quad (30)$$

Value of the transition sublayer [1, 2]

$$\delta_2 = 30\nu / u^*. \quad (31)$$

Then the dimensionless thickness of the viscous sublayer from equations (13) $R_1^+ = 5$, and the value of the transition sublayer from (14) $R_2^+ = 30$.

After integrating equation (28), taking into account the boundary conditions (27) by analogy with expression (20), we obtain the expression in the dimensionless form

$$\beta_d^+ = \frac{1}{5 \cdot Sc_{Br} + a \cdot \left[10,07 + 2,5 \cdot \ln\left(1 - \chi \cdot R_\delta^+\right)\right]},$$

where $a = 1 + \omega_E \tau_p$. (32)

When converting to dimensional values

$$\beta_d = \frac{u^*}{5 \cdot Sc_{Br} + a\left[10,07 + 2,5 \cdot \ln\left(1 - \frac{\chi \cdot u^* \cdot \delta}{\nu}\right)\right]}. \quad (33)$$

In the upgraded three-layer Landau-Levich model [17], it is assumed that the change in turbulent viscosity in a viscous sublayer is proportional *to* $\nu_T \sim y^4$, and in this case both Brownian and turbulent diffusion will act in it.
Then the expression (28) will take the form

$$\frac{1}{\beta_d^+} = \int_0^{R_1^+} \frac{\nu \cdot dy^+}{D_{Br} + D_P} + \int_{R_1^+}^{R_2^+} \frac{\nu \cdot dy^+}{D_P} + \int_{R_2^+}^{R_\delta^+} \frac{\nu \cdot dy^+}{D_P}. \quad (34)$$

Based on the Landau-Levitch theory, the following functions are used for each sublayer [17]:

$$\frac{\nu_T}{\nu} = 0,01\chi^4 \cdot (y^+)^4, \quad y^+ \le 5; \quad (35)$$

$$\frac{\nu_T}{\nu} = 0,2y^+ - 0,959, \quad 5 \le y^+ \le 30; \quad (36)$$

$$\frac{\nu_T}{\nu} = 0,4y^+ - 1, \quad y^+ \ge 30. \quad (37)$$

Consider the first integral of the right-hand side of equation (33)

$$\int_0^{R_1^+} \frac{\nu \cdot dy^+}{D_{Br} + D_P} = \int_0^{R_1^+} \frac{\nu \cdot dy^+}{(\frac{D_{Br}}{D_P} + 1) \cdot D_P} = \\ = \int_0^{R_1^+} \frac{(1 + \omega_E \cdot \tau_p) \cdot \nu \cdot dy^+}{(\frac{D_{Br}}{D_P} + 1) \cdot \nu_T} \quad . \quad . \quad (38)$$

Replace the ratio ν_T/ν with equation (35)

$$\int_0^{R_1^+} \frac{(1 + \omega_E \cdot \tau_p) \cdot \nu \cdot dy^+}{(\frac{D_{Br}}{D_P} + 1) \cdot \nu_T} = \\ = \int_0^{R_1^+} \frac{(1 + \omega_E \cdot \tau_p) \cdot dy^+}{(\frac{D_{Br}}{D_P} + 1) \cdot 0,01 \cdot \chi^4 \cdot (y^+)^4} = \\ = \int_0^{R_1^+} \frac{(1 + \omega_E \cdot \tau_p) \cdot dy^+}{(\frac{D_{Br}(1 + \omega_E \cdot \tau_p)}{\nu_T} + 1) \cdot 0,01 \cdot \chi^4 \cdot (y^+)^4} = \\ = \int_0^{R_1^+} \frac{(1 + \omega_E \cdot \tau_p) \cdot dy^+}{(\frac{D_{Br}(1 + \omega_E \cdot \tau_p)}{\nu \cdot 0,01 \cdot \chi^4 \cdot (y^+)^4} + 1) \cdot 0,01 \cdot \chi^4 \cdot (y^+)^4} = \\ = \int_0^{R_1^+} \frac{(1 + \omega_E \cdot \tau_p) \cdot dy^+}{Sc_{Br}(1 + \omega_E \cdot \tau_p) + 0,01 \cdot \chi^4 \cdot (y^+)^4}.$$

Introducing new variables

$$(1 + \omega_E \cdot \tau_p) = a; \;\; Sc_{Br}(1 + \omega_E \cdot \tau_p) = b; \\ 0,01 \cdot \chi = c \quad . \quad (39)$$

Let us transform equation (38) using (39) to the form

$$\int_0^5 \frac{a \cdot dy^+}{b + c \cdot (y^+)^4} \, . \quad (40)$$

As a result of integration, we get

$$\int_0^5 \frac{a \cdot dy^+}{b + c \cdot (y^+)^4} = 0,17 \cdot a \cdot \left(\frac{b}{c}\right)^{1/4} \times \\ \times \ln\left(\frac{\left(\sqrt{\frac{b}{c}} + 25 + 7,07\left(\frac{b}{c}\right)^{1/4}\right)}{\left(\sqrt{\frac{b}{c}} + 25 - 7,07\left(\frac{b}{c}\right)^{1/4}\right)}\right) + 0,35 \cdot a \cdot \left(\frac{b}{c}\right)^{1/4} \times \\ \times \left[arctg\left(\frac{\left(\frac{b}{c}\right)^{1/4} + 7,07}{\left(\frac{b}{c}\right)^{1/4}}\right) - arctg\left(\frac{\left(\frac{b}{c}\right)^{1/4} - 7,07}{\left(\frac{b}{c}\right)^{1/4}}\right)\right]. \quad (41)$$

Finally, for the first term of equation (33), we have

$$\int_0^{R_1^+} \frac{a \cdot dy^+}{Sc_{Br} \cdot a + 0,01 \cdot \chi^4 \cdot (y^+)^4} = \\ 0,17 \cdot a \cdot \left(\frac{Sc_{Br}(1 + \omega_E \cdot \tau_p)}{0,01\chi}\right)^{1/4} \times \\ \times \ln\left(\frac{\left(\sqrt{\frac{Sc_{Br} \cdot a}{0,01\chi}} + 25 + 7,07\left(\frac{Sc_{Br} \cdot a}{0,01\chi}\right)^{1/4}\right)}{\left(\sqrt{\frac{Sc_{Br} \cdot a}{0,01\chi}} + 25 - 7,07\left(\frac{Sc_{Br} \cdot a}{0,01\chi}\right)^{1/4}\right)}\right) + \\ +0,35 \cdot a \cdot \left(\frac{Sc_{Br} \cdot a}{0,01\chi}\right)^{1/4} \times \\ \times \left[\begin{array}{l} arctg\left(\frac{\left(\frac{Sc_{Br} \cdot a}{0,01\chi}\right)^{1/4} + 7,07}{\left(\frac{Sc_{Br} \cdot a}{0,01\chi}\right)^{1/4}}\right) - \\ -arctg\left(\frac{\left(\frac{Sc_{Br} \cdot a}{0,01\chi}\right)^{1/4} - 7,07}{\left(\frac{Sc_{Br} \cdot a}{0,01\chi}\right)^{1/4}}\right) \end{array} \right] \quad (42)$$

Consider the second term of the right-hand side of equation (34)

$$\int_{R_1^+}^{R_2^+} \frac{\nu \cdot dy^+}{D_P} = \int_0^5 a \cdot \frac{\nu \cdot dy^+}{\nu_T} = a \int_5^{30} \frac{dy^+}{(0,2y^+ - 0,959)} =$$
$$= a \cdot \frac{1}{0,2} \cdot \ln \frac{30 \cdot 0,2 - 0,959}{5 \cdot 0,2 - 0,959} = 24 \cdot (1 + \omega_E \tau_p). \quad (43)$$

Consider the third term of the right-hand side of equation (34)

$$\int_{R_2^+}^{R_\delta^+} \frac{\nu \cdot dy^+}{D_P} = \int_{30}^{R_\delta^+} a \cdot \frac{\nu \cdot dy^+}{\nu_T} = a \int_{30}^{R_\delta^+} \frac{dy^+}{0,4y^+ - 1} =$$
$$= a \cdot \frac{1}{0,4} \cdot \ln \frac{R_\delta^+ \cdot 0,4 - 1}{30 \cdot 0,4 - 1} = 2,5 \cdot (1 + \omega_E \tau_p) \times \quad (44)$$
$$\times \ln \left(\frac{R_\delta^+ \cdot 0,4 - 1}{11} \right).$$

After integration, expression (34) takes the form

$$\frac{1}{\beta_d^+} = 0,17 \cdot a \cdot \left(\frac{Sc_{Br} \cdot a}{0,01\chi} \right)^{1/4} \times$$
$$\times \ln \left(\frac{\left(\sqrt{\frac{Sc_{Br} \cdot a}{0,01\chi}} + 25 + 7,07 \left(\frac{Sc_{Br} \cdot a}{0,01\chi} \right)^{1/4} \right)}{\left(\sqrt{\frac{Sc_{Br} \cdot a}{0,01\chi}} + 25 - 7,07 \left(\frac{Sc_{Br} \cdot a}{0,01\chi} \right)^{1/4} \right)} \right) +$$
$$+0,35 \cdot a \cdot \left(\frac{Sc_{Br} \cdot a}{0,01\chi} \right)^{1/4} \times$$
$$\times \left[arctg \left(\frac{\left(\frac{Sc_{Br} \cdot a}{0,01\chi} \right)^{1/4} + 7,07}{\left(\frac{Sc_{Br} \cdot a}{0,01\chi} \right)^{1/4}} \right) - \right.$$
$$\left. - arctg \left(\frac{\left(\frac{ScBr \cdot a}{0,01\chi} \right)^{1/4} - 7,07}{\left(\frac{ScBr \cdot a}{0,01\chi} \right)^{1/4}} \right) \right] + \quad (45)$$
$$+ a \cdot \left(24 + 2,5 \cdot \ln \left(\frac{R_\delta^+ \cdot 0,4 - 1}{11} \right) \right).$$

3. Model verification

To obtain the calculated values of the mass transfer coefficient, the following initial data were selected according to the proposed model:
- working fluid: water-oil emulsion in the form of waste water from a plant for the production of reinforced concrete structures;
- a tubular ceramic membrane element with an internal diameter of d =0.006 m, a length of L=0.8 m, and a membrane porosity of e = 0.6, manufactured by KeramikFilter LLC, Moscow;
- the average permeate flow rate W_p = 0.07-0.1 m/s;
- the concentration of suspended substances c = 0.01 kg/kg;
- sediment density ρ_s = 2100 kg/m^3;
- density and viscosity of the water-oil emulsion ρ = 900 kg/m^3 and m =0.0101 Pa·s;
- the flow rate of the emulsion in the membrane module u = 10 m/s.

An acoustic particle analyzer APS-100 was used to measure the contamination particles.

The results of calculating the mass transfer coefficient are presented in Table 1 and Figure 1.

Table 1. Results of calculating the mass transfer coefficient

Sc_{Br}	5	15	25	50	75	100	200	300	400
$d_s \cdot 10^6$, м	12	18	21	27	31,6	34,8	43,8	50,2	55,3
$\beta_d \cdot 10^3$									
(25)	91	41	27	14	9,7	7,6	3,7	2,5	1,9
(32)	63	28	18	9,4	6,4	4,8	2,45	1,6	1,2
(45)	44	21	15	9,5	7,2	5,9	3,8	2,9	2,4

From the calculated data obtained, it follows that the highest value of the mass transfer coefficient β_d and deposition intensity corresponds to the particle size ds from 10 to 35 microns.

The adequacy of the calculated values of the mass transfer coefficient was verified by the model validation method.

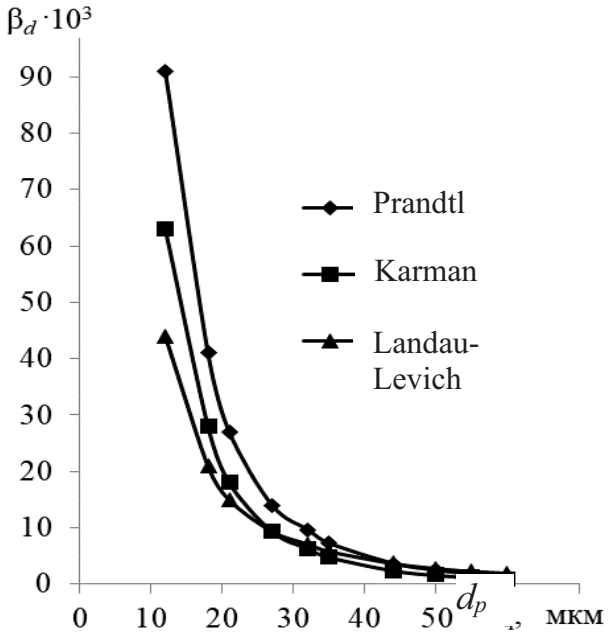


Figure 1. Changes in the mass transfer coefficient β_d an average flow rate u = 10 m/s

Since the known results on the deposition of particles on the walls of circular channels were obtained for various media with different physicochemical properties from the considered viscous heterogeneous systems, it is better to use dimensionless values for model validation.

In our case, it is convenient to consider the dependence (Fig. 2) of the dimensionless value of the mass transfer coefficient (deposition rate) β^+ on the inertia parameter τ^+ (dimensionless relaxation time).

The inertia parameter is determined taking into account the equation by the expression

$$\tau^+ = \frac{u^{*2} \cdot \tau_p}{\nu} = \frac{u^{*2} \cdot d_s^2}{18 \cdot \nu^2} \quad . \qquad (46)$$

To compare the data, the Reynolds criterion Re+ was used, based on the dynamic velocity and channel radius

$$\mathrm{Re}^+ = \frac{u^* \cdot r}{\nu}. \qquad (47)$$

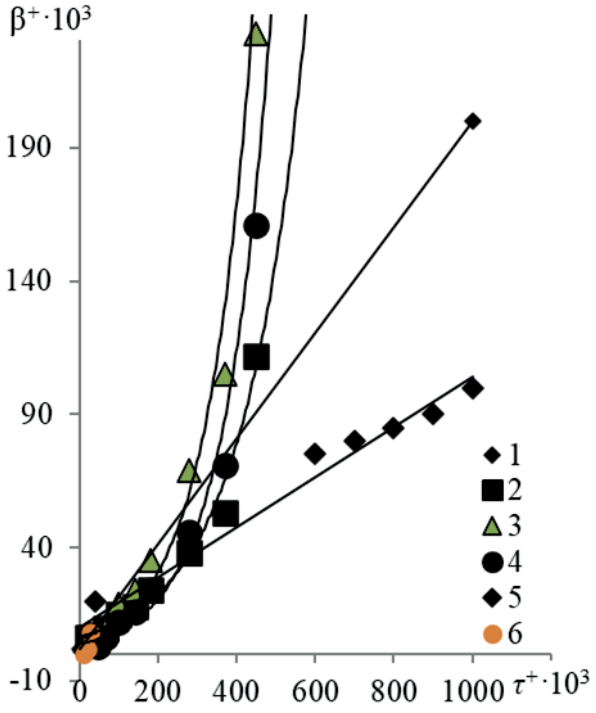


Figure 2. Dependence of the deposition rate on the inertia parameter:
1-empirical correlation (Sc_{Br} = 106, Re^+ = 150) [18]; 2, 3, 4 - data obtained from the developed models for the boundary layer according to the Landau-Levitch, Karman, and Prandtl theory, respectively (Sc_{Br} =5÷400, Re^+ = 100); 5 - direct numerical simulation data (Sc_{BR} = ∞, Re^+ = 150) [19]; 6 – data obtained in the paper (Sc_{Br} =1,310 106, Re^+ = 400÷1300) [20]

As well-known results, we used the data presented in the works of Koji Fukagata, Said Zaraya, and Fritz H. Bark, who obtained an empirical correlation of the deposition rate for the turbulent diffusion of copper particles with a size of 70 microns and glass particles with a size of 50 microns in a circular channel [18], Marchioli S., Picciotto M., Soldati A., who studied turbulent diffusion of copper particles with a size of in a vertical channel, based on the solution of the Navier-Stokes equation by direct Numerical Simulation [19], as well as data from Wells A. K. and Chamberlain A. K., which were used to study the deposition of radioactive particles in the form of polystyrene spheres with a diameter of 5 microns, containing 51Cr, drops

of tricresyl phosphate with a diameter of 2.1; 1.1 mm. and 0.65 microns with an activity of 32P and natural Aitken nuclei labeled ThB (212Pb) from air flows to vertical surfaces [20].

As can be seen from Figure 2, there is a satisfactory convergence of the results of calculating β^+ about ± 10%, calculated from expressions (25), (32) and (45) with the data known in the scientific literature within the inertia parameter τ^+ from 0 to $400 \cdot 10^{-3}$, which corresponds to a particle size from 12 to 40 microns at the flow velocity in the channel is 10 m/s, and allows us to recommend this method for calculating the mass transfer coefficient from the flow core to the channel walls for practical application.

CONCLUSIONS

The obtained expressions for determining the mass transfer coefficient have found practical application in the development of hardware design of the water-oil emulsion separation process. Before ultrafiltration of wastewater, they were pretreated on a centrifugal separator model SOG-913. The separator separation factor at maximum RPM was 10000. Figure 3 shows a fragment of quantitative analysis of dirt particles with sizes from 5 to 100 microns after centrifugal separation.

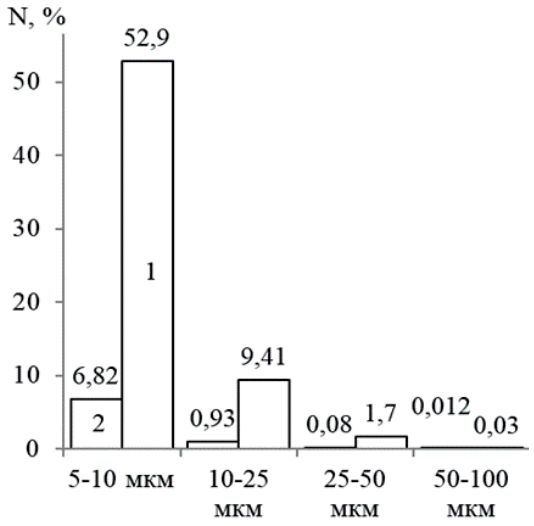


Figure 3. Proportion of dirt particles depending on their size: 1-before separation; 2-after separation

As can be seen from Figure 3, the proportion of particle sizes that meet the proposed mathematical model and are deposited on the channel walls is 50-60% before centrifugal separation, and 6-8% after separation. A large proportion of particles after pretreatment (80-90%) have a size of 1 to 3 microns.

These particles will not significantly affect the formation of sediment, as they completely follow the turbulent pulsations of the medium.

The results obtained indicate the adequacy of the upgraded model of turbulent migration of particles on the channel walls and give grounds to recommend it for practical use.

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Sergey Viktorovich Fedosov – Academician of the RAACS, Doctor of Technical Sciences, Professor of the Department of Technology and Organization of Construction Production, National Research Moscow State University of Civil Engineering, 26, Yaroslavl Highway, Moscow, Russia, fedosov-academic53@mail.ru.

Alexander Vladimirovich Markelov – Candidate of Technical Sciences, Associate Professor of the Department of Infrastructure and Transport of the Yaroslavl State Technical University, 88, Moskovsky Prospekt, Yaroslavl, 150023, Russia, aleksandr203.37@mail.ru.

Сергей Викторович Федосов – академик РААСН, д.т.н., профессор кафедры технологии и организация строительного производства ФГБОУ ВО «Национальный исследовательский Московский государственный строительный университет» , ФГБОУ ВО «НИУ МГСУ», 26, Ярославское шоссе, г. Москва, Россия, fedosov-academic53@mail.ru.

Александр Владимирович Маркелов – к.т.н., доцент кафедры инфраструктуры и транспорта ФГБОУ ВО «Ярославский государственный технический университет» ФГБОУ ВО «ЯГТУ», 88, Московский проспект, г. Ярославль, 150023, Россия, aleksandr203.37@mail.ru.