ISBN 978-83-927084-8-3
ISSN 0867-7964

ON THE CONDITIONS OF CLOGGING IN A HYDROCYCLONE

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The phenomenon of sedimentation of solid particulates on the surface of the devices of hydrocyclone type is considered.
For this aim the most simple process flow is modeled. A channel with distance D_c between walls is considered, through which a turbulent flow of the particulates of the same size is realized. Towards the channel walls, the centrifugal force due to the specially organized flow conditions acts on the particulates. The sedimentation with a settling velocity v_s is counteracted by flow turbulence. Far enough from the channel entrance, an equilibrium of the solid phase concentration is achieved across the channel.
The particulate concentration grows exponentially from the axes to the wall and could reach the values of solid concentration C_L in the sediment. Movement of particulates inside the sediment layer is practically impossible.
The conditions of formation, growth and entrainment of such a layer are analyzed. Thus, the critical conditions for hydrocyclone closure depending on the geometric parameters of the apparatus, settling velocity of the particulates v_s, turbulent diffusion coefficient D_t, and solid concentration at the inlet C_m are defined.

KEY WORDS: clogging, sedimentation, turbulent diffusion, theoretical model.

NOTATION

a	– centrifugal acceleration, m/s^2;
C_j	– concentration of the solid of j-th fraction, m^3/m^3;
C_0	– concentration far from the wall, m^3/m^3;
C_L	– concentration of solid in sediment, m^3/m^3;
C_m	–inlet solid concentration;
d_j	– partile size of j-th fraction, m;
D_c	– diameter of the hydrocyclone, m;
d_{of}	– overflow diameter, m,
d_{in}	– inlet diameter, m,
h	– section height of the apparatuses slot, free of sediment, m;
Δp	– inlet pressure, bar,
t_d	– diffusion time, s;

t_{sj} – sedimentation time, s;
u_{in} – inlet velocity, m/s;
w_{tan} – tangential velocity, m/s;
D_t – turbulent diffusion coefficient, m^2/s;
Q – flow of suspensions in a hydrocyclone, m^3/s;
Pe_j – dimensionless Peclet parameter;
s – relative sediment thickness, -;
$v_{d,j}$ – diffusion velocity, m/s;
v_{sj} – sedimentation velocity of j -th fraction, m/s;
ρ_f – density of water, kg/m^3;
ρ_s – density of solid material, kg/m^3;
ν – kinematic viscosity of water, m^2/s.

1. INTRODUCTION

A large class of industrial devices deals with particulate material processing (transportation, separation in phases, classification etc.). A feature of this technique is the possibility (desired or undesired) of material segregation.

An object of our attention is the increase of solid phase concentration at a local space. Such localization may impede the passage of material and can have an influence on technological processes.

Below is considered a phenomenon of sedimentation of solid particulates on the wall of the devices of hydrocyclone type. Classification processes in such devices are based on the action of a force directed transversely to the suspension flow which passes through the apparatus, Heiskanen, (1993), Schubert et al. (1990). Principal scheme of the hydrocyclone is shown in Fig. 1.

The drift of particulates caused by the centrifugal force leads to their deposition on the wall. In the absence of accompanying phenomena (unequal inlet conditions for different particulates and the complexity of flow including turbulence), the sharpness of separation would be absolute; all particulates smaller than a certain critical size d_c would escape from the apparatus, whereas large ones would be trapped. Really, due to turbulence the separation is not absolutely sharp, and instead of d_c use is made of the cut size d_{50} with 50% probability of separation.

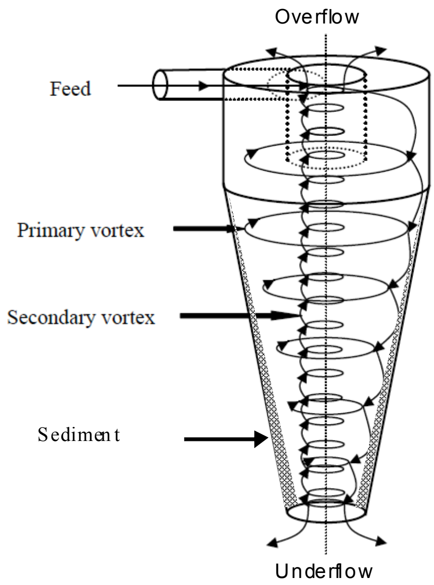

Fig 1. Principal scheme of the hydrocyclone

By the theoretical consideration we confined to the most simple process flow, formulated over 30 years ago, Schubert and Neesse (1980), but recently received a strong development with the use of modern computer facilities.
The approximate-analytical methods for analysis of hydrocyclones are summarized in Schubert et al. (1990) and examples of a numerical analysis of the processes therein is given in Dueck (2015), Minkov and Dueck (2012), Neesse and Dueck (2007). At the same time, a number of important aspects of the classification process is not yet considered.
One such problem is the significance of possible settling of particulates at the outer wall of a hydrocyclone. In this paper we analyzed the problem using a diffusion-turbulent model of the process in the apparatus, Dueck (2015), Schubert et al. (1990).

2. FORMULATION OF THE MODEL

We consider a classification apparatus as a flat channel with distance D_c between walls (Fig. 2), through which the swirling turbulent flow of suspended particulates of the same size is pumped. In the channel cross-section the centrifugal force acts on the particulates directed to the walls. The sedimentation is opposed by the diffusion due to turbulence.

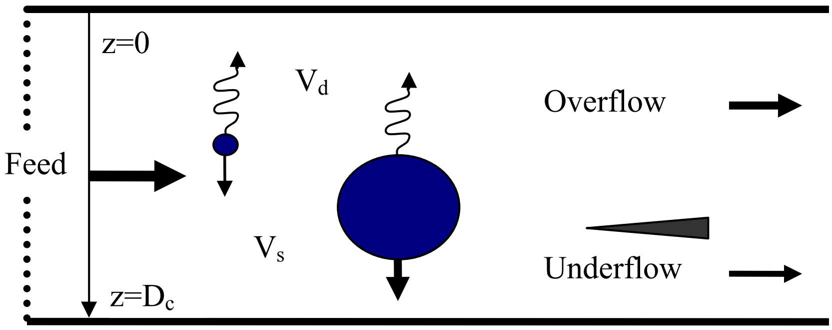

Fig.2. Diagram of the model classification device

The particulate flow is removed from the apparatus through underflow spigot (mostly coarse particulates) and through overflow vortex finder (fine material).
For simplicity we restrict ourselves with the case of a relative dilute suspension, so that the particulates of different size fractions do not interact. Each particle sediments with a certain velocity v_{sj}, which is the higher, the larger is a particle. Due to the turbulence the particulates involved in the chaotic motion, a diffusion flux arises directed from the bottom wall to the top wall (axes of apparatus).
Far enough away from the entrance to the channel an equilibrium concentration distribution of the solid phase across the channel is establish. The concentration C of particulates grows in direction to wall, and could reach the value of C_L when the slurry condensation will make practically impossible the movement of particulates in this sediment layer of a thickness equal to D_c - h (as shown in Fig. 3).
Mathematical description of the concentration field in a suspension of the particulates of the same sizes (therefore, index j is omitted) is given by the equation of equilibrium of diffusion and sedimentation fluxes across the channel:

$$v_s C = D_t \frac{dC}{dz} \qquad (1)$$

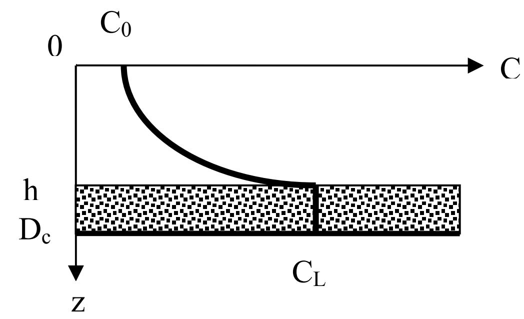

Fig. 3. Schematic of the concentration field

For simplicity, both of values v_s and D_t are assumed (understanding the limitations of such a strong hypothesis) to be constant. It should be noted that in hydrocyclones the value of v_s is completely determined by the centrifugal force.

3. FIELD OF SOLID PHASE CONCENTRATION

From equation (1) an expression follows for the concentration profile:

$$C = C_0 \exp\left(\frac{v_s z}{D_t}\right) \qquad (2)$$

Here C_0 is concentration far from the wall, when $z = 0$. This value can be calculated through a known average concentration of the slurry in the layer, which is equal to the inlet solid concentration.

$$C_m = \frac{1}{D_c}\int_0^{D_c} C dz = \frac{1}{D_c}\left\{C_0 \frac{D_t}{v_s}\left[\exp\left(\frac{v_s h}{D_t}\right) - 1\right] + C_L\left[D_c - h\right]\right\} \qquad (3)$$

If the sediment is not formed then $h = D_c$. In this case,

$$C_0 = C_m \frac{D_c v_s}{D_t}\left[\exp\left(\frac{v_s D_c}{D_t}\right) - 1\right]^{-1} \qquad (4)$$

The concentration on the cannel wall for the case of no sediment is given by

$$C_{D_c} = C_0 \exp\left(\frac{v_s D_c}{D_t}\right) \qquad (5)$$

Sediment begins to form when this value reaches the limit value C_L. The condition for this event can be written corresponding to Eq. (4) as

$$C_L = C_m Pe\left[1 - \exp(-Pe)\right]^{-1}, \quad Pe = \frac{D_c v_s}{D_t}. \qquad (6)$$

Thus it is possible to specify a limit of the concentration of slurry fed to the channel, at which no sediment is formed:

$$C_m / C_L = \left[1 - \exp(-Pe)\right]/Pe. \qquad (7)$$

The corresponding curve is shown in Fig. 4.

Naturally, in a real suspension there are fractions of particulates of different size, but Fig. 4 indicates that the largest rapidly deposited particulates are primarily responsible for sediment formation.

When the conditions for the formation of sediment are achieved and the average solids concentration exceeds the value given by the expression (7), then equation (5) should be used to find the C_0 in the form:

$$C_0 = C_L \exp\left(-Pe \frac{h}{D_c}\right) \qquad (8)$$

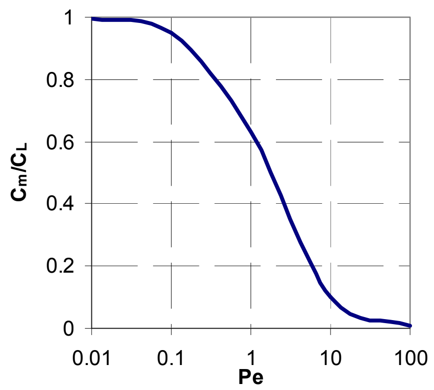

Fig. 4. Critical conditions of sediment formation

With account of equations (8) and (3), the equation for sediment thickness s takes the following form:

$$\frac{C_m}{C_L} = \frac{1}{Pe}\left[1 - \exp(-Pe(1-s)\right] + s \text{, where } s = 1 - \frac{h}{D_c}. \quad (9)$$

The diagram for the general case similar to Fig. 4 is given in Fig. 5.

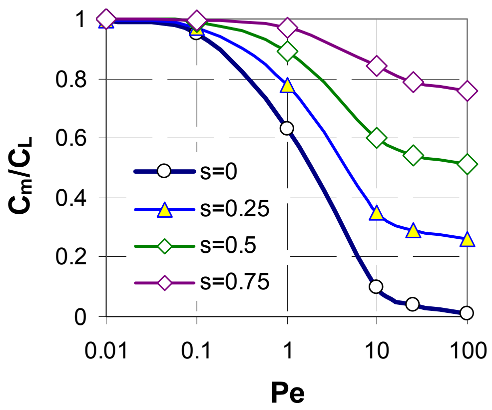

Fig. 5. Relative input concentrations C_m/C_L of the solid phase sufficient to form a sediment layer of thickness *s* depending on Pe - number

We are rather interested in the sediment layer thickness *s* depending on the concentration of suspension for different sizes of particulates. Equation (9) cannot be solved explicitly, and the numerical values of the desired dependency are presented in Fig. 6. Also obvious here is especially strong influence of large particulates on the sediment building.

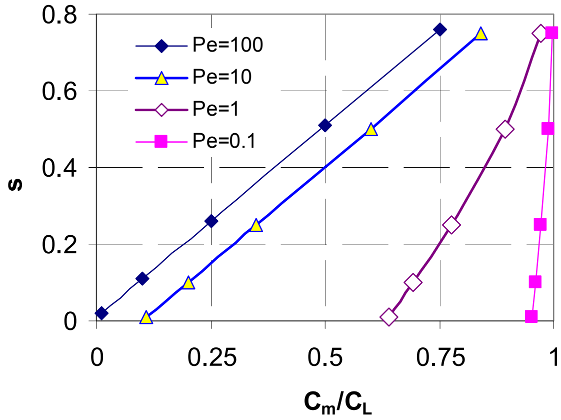

Fig. 6. Sediment thickness as dependence of inlet solid phase concentration C_m / C_L for different Pe - numbers.

4. ADAPTATION TO A HYDROCYCLONE

The flow in hydrocyclone is far more complicated than in the slot-classifier described above. Accordingly, more complex are the processes of particulate transport in the device. Nevertheless, the given above can be applied to analyze the solid phase concentration profiles in a hydrocyclone.

The flow of suspensions in a hydrocyclone $Q = u_{in} \pi d_{in}^2$ depends on the inlet pressure drop Δp, since u_{in} depends on Δp.

To calculate the diffusion coefficient and the centrifugal acceleration in the device (which determines the sedimentation velocity) and the suspension velocity at the device inlet the following formulas can be used, Schubert et al. (1990):

$$u_{in} = 0.52 \frac{d_{of}}{d_{in}} \left(\frac{\Delta p}{\rho_f} \right)^{0.5}, \quad w_{tan} = 3.7 \frac{d_{in}}{d_c} u_{in}, \quad a = \frac{w_{tan}^2}{d_c}, \quad D_t = 16 * 10^{-4} w_{tan} d_c, \tag{10}$$

Here from, for the diffusion coefficient we obtain the formula:

$$D_t = 59.2 * 10^{-4} d_{in} u_{in} \tag{11}$$

With $v_s = \frac{\Delta \rho}{\rho_f} \frac{1}{18 \nu} a d^2$, Pe-number can be calculated:

$$\frac{d_c v_s}{4 \pi D_t} = 2.76 * \frac{\Delta \rho}{\rho_f} d_j^2 \frac{w_{tan}}{\nu \, d_c} \tag{12}$$

Taking into account the relations for u_{in} and w_{tan} from (10), the following is valid:

$$Pe = \frac{d_c v_s}{D_t} = 33.1 * \frac{\Delta\rho}{\rho_f}\left(\frac{d_j}{d_c}\right)^2 \sqrt{\frac{\Delta p}{\rho_f}} \frac{d_{of}}{\nu} \tag{13}$$

Let us consider an illustrative example. Parameters of the considered hydrocyclone are as follows: $d_{of} = 16 * 10^{-3}$ m – diameter of the fine product channel exit, $2h = 50 * 10^{-3}$ m – diameter of the hydrocyclone cylindrical part. Physical properties of components: ρ_s =2650 kg/m^3 – solid material density, ρ_f =1000 kg/m^3 – water density, ν =10^{-6} m^2/s - water viscosity. For particulates with d_j =10^{-5} m and inlet pressure equal to $\Delta p = 10^5$ N/m^2, the Pe-number is equal to 0.7. For these values of parameters, the sediment formation conditions can be expected for feed slurry with concentration about 0.8 C_L, i.e. about 0.5.

5. DISCUSSION AND CONCLUSIONS

Based on equations (7) and (13) we can conclude that the larger are the particulates, the lower must be the concentration of solid phase to avoid the device blocking. The smaller the device, the greater is danger of clogging. Increasing the pressure leads to a much more rapid increase in sedimentation rate as compared to the increase in turbulent diffusion, which promotes the deposition of particulates on the wall.

Let us remark here that sediment deposition on the wall, probably in the first approximation, does not affect the quality of classifying. Indeed, equating the times of particulate settling $t_s = D_c/v_s$ and diffusion $t_D = D_c^2/D_t$ gives for this case $v_s = D_t/D_c$ (which corresponds to a value of $Pe = 1$). Herewith, for cut size of separation follows $d_{50}{}^2 \propto D_t/D_c$. But turbulent diffusion coefficient is proportional to D_c, so the size of channel is not among the influential parameters. The impact of the possible blockage, perhaps, is more important for the hydraulics in the device.

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