Numerical investigation of two-phase media separation in the hydrodynamic filter

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Abstract. Today lots of industries require filtration of two-phase flows with high viscosity non-Newtonian dispersion medium and solid dispersion phase in order to reduce energy consumption for cleaning applications. Specific feature of the separation process for such flows is the limited service life of the filtering equipment. These problems can be solved by modernized tangential filtration with complex flow organization. In the working convergent annular channel are implemented two mechanisms of purification: centrifugal separation and filtration. This work investigates the behavior of solids in non-Newtonian fluids in a context of complex force impacts on flow, as implemented in hydrodynamic filters. The numerical investigation of the flow structure in the convergent annular channel with rotating inner permeable wall was performed. The optimal ratios of the operating parameters are obtained, which ensure steady flow and minimum separation load on the permeable baffle. The obtained results can be used in the design of systems that have high requirements for the purity of the liquid.

1. Introduction

Today lots of industrial applications require separation of two-phase flows with high viscosity non-Newtonian dispersion medium and solid dispersion phase. The fineness of fluid filtration depends on the reliability of technical systems, the probability of occurrence of accidents in production lines, the degree of environmental pollution. The special importance of the mechanical impurities removal is in the systems of waste liquids regeneration, in particular, of waste oils. Hydraulic systems of hydraulic machines and mechanisms often use oils. Hydraulic oils can be contaminated with solid particles when the equipment is worn out. Conversion and recycling of used oil is economically justified and contributes to reducing the anthropogenic load on the environment.

Physical methods for cleaning liquids from solid impurities are widely used, based on the processing of oil in a force field under the action of gravitational, centrifugal force, as well as the method of filtration. Filtration allows guaranteeing the required fineness of purification in contrast to the other methods.

A large number of liquid media used in the industry, exhibit non-Newtonian pseudoplastic properties. These mediums include polymer solutions, heavily polluted waste water, mineral and synthetic oils. For these media can be applied rheological equation of non-Newtonian fluid state, written in the form of a power-law de Waele-Ostwald within the certain range of shear rates \cite{1-3}. Such liquids are characterized by an inverse relationship between the effective viscosity and deformation rate.
Specific feature of the separation process of such flows by the method of filtration is the limited service life of the filtering equipment due to the need for frequent regeneration of the filtering material because of the clogging of its pores by solid particles and plugging of pore channels because of obliteration processes [4]. The high viscosity of dispersion medium results in the necessity of creating a large pressure drop across the filtering baffle, which requires considerable energy costs. To solve these problems, it is advisable to use combined action devices connecting filtration and other physical separation methods. This allows to provide the required fineness of purification, to increase cleaning efficiency, to reduce the size of production areas, and decrease cleansing process costs by reducing the effective viscosity of the liquid to be cleaned with the appearance of additional shear rates [5, 6].

Among the combined action devices can be distinguished the self-cleaning hydrodynamic filter (figure 1), which allows to considerably reduce energy costs in comparison with traditional filtration [7-10]. The principle of hydrodynamic filtering is that the liquid is passed through rotating porous baffle, wherein a portion of the fluid flow to be cleansed (10–15% of total volume) is bypassed along the filtering baffle [11, 12].

![Figure 1. Hydrodynamic filter.](image)

The hydrodynamic force acting on the suspended solids from the pumped flow, contributes to their washout from the baffle surface. This ensures constant cleaning of the filtering surface. By rotating the filtering baffle, it becomes possible to separate under the influence of centrifugal force the solids, having a higher density than the liquid phase. Convergent annular gap between the housing wall and the filtering baffle provides uniform degree of self-cleaning of the baffle over its entire length because of the constancy of the longitudinal fluid flow rate. Reducing the load on the filtering material can be achieved by increasing the proportion of solids separated by the action of centrifugal forces from the total amount of contaminants trapped in the filter by all cleaning mechanisms. This can be achieved by increasing the rotation of the flow, namely the presence of a tangential inlet flow and the rotation of the filtering baffle.

Hydrodynamic filter combines a tangential filtration and centrifugal separation in one device. This allows to increase service life (time between regenerations) and the energy costs of cleaning highly viscous media.

2. Problem statement
The pattern of medium flow in the hydrodynamic filter is rather complex. It is therefore advisable to successively consider the individual components of the separation process, driven by the influence of main force factors occurring in its working area. The working area is an annular channel formed by the stationary outer conical surface and the inner rotating cylinder. For the purpose of this study, let’s
consider the three component of fluid flow in the working area. The first velocity component of the flow \( u_r \) (radial velocity component at coordinate \( r \), m s\(^{-1}\)) is caused by filtration through the permeable inner cylinder, determined by the velocity \( u_R \) (radial velocity component at filtering baffle at \( r = R \), m s\(^{-1}\), where \( R \) – radius of filtering baffle) of the fluid suction through its surface (figure 2). The second component is connected with the bypassing of the portion of liquid flow at the velocity \( r_w \), axial velocity component, by means of which hydrodynamic flush of solids from the surface of the permeable cylinder is provided. The third component is caused by the rotation of the permeable cylinder with radius \( R \) and the tangential inlet, which ensures centrifugal separation of solid particles, thereby reducing the load on the filtering material. The defining parameters of separation process are tangential velocity \( v_r \) and initial swirl velocity, described by the average velocity in the inlet pipe \( u_{in} \).

Figure 2. Flow diagram.

And the last component of the flow \( v_r \) is a special case of a known flow between two coaxial cylinders, where the outer one is fixed and the inner one is rotating. It is known, that in case of such flow, unstable liquid separation may occur due to the fact, which the liquid particles in the vicinity of the rotating cylinder tend to move to the outer cylinder. Thereby, starting from a certain Taylor number, regularly alternating leftward and rightward rotating toroidal vortices, called Taylor vortexes, appear between the cylinders [13, 14]. However, known conditions for the appearances of Taylor vortexes are not the flow stability condition in the hydrodynamic filter, since the outer surface is conical and because there are certain factors, that has a stabilizing effect. In the flow being studied, these factors are the viscosity of the fluid and the suction of the fluid through the permeable baffle [15-20]. When filtering high-viscosity media, buckling will occur at a higher rotation speed, as well as by reducing the thickness of the boundary layer due to the suction of the liquid through the rotating cylinder. Therefore, for proper selection of filtering operating parameters ensuring effective separation of particles by the centrifugal mechanism, it is necessary to know the boundaries of appearance vortex structures in view of the aforementioned factors.

Thus, the objective of this study is to determine the effect of the vortexes, which occur between the stationary outer conical wall and the inner permeable rotating cylinder, on the efficiency of separation of solid particles using centrifugal mechanism.

3. Method of research
The system of equations for hydrodynamics two-phase medium is the system of equations, based on the Euler model and Navier-Stokes equations [21], and can be expressed as follows:
- the law of conservation of momentum for a solid phase
\[
\frac{\partial}{\partial t} \left( \alpha_f \rho_f V_{f,j} \right) + \frac{\partial}{\partial x_j} \left( \alpha_s \rho_s V_{s,i} \right) = -\alpha_s \frac{\partial P}{\partial x_i} + \frac{\partial\tau_{\alpha,s}}{\partial x_j} + \alpha_f \rho_f g_i + K_{sf} (V_{i,f} - V_{i,s});
\]

- the law of conservation of momentum for fluid phase

\[
\frac{\partial}{\partial t} \left( \alpha_f \rho_f w_{j,f} \right) + \frac{\partial}{\partial x_j} \left( \alpha_f \rho_f V_{i,f} \right) = -\alpha_f \frac{\partial P}{\partial x_j} + \frac{\partial\tau_{\alpha,f}}{\partial x_j} + \alpha_f \rho_f g_i + K_{sf} (V_{i,x} - V_{i,f});
\]

- continuity equation for solid phase

\[
\frac{\partial}{\partial t} (\alpha_s \rho_s) + \nabla \left( \alpha_s \rho_s V_{s} \right) = 0;
\]

- continuity equation for fluid phase

\[
\frac{\partial}{\partial t} (\alpha_f \rho_f) + \nabla \left( \alpha_f \rho_f V_{f} \right) = 0;
\]

- the volume fractions of the phases

\[
\alpha_f + \alpha_s = 1;
\]

where

\(\alpha_f, \alpha_s\) – relative volumetric concentrations of fluid and solid phase;

\(\rho_f, \rho_s\) – density of fluid phase and solid phase;

\(V_f, V_s\) – velocity of fluid phase and solid phase;

\(P\) – pressure within the medium;

\(x\) – coordinate;

\(g\) – mass forces;

\(K_{sf}\) – phase interaction factor;

\(i\) – index numbers of the coordinate axis, \(i = 1, 2, 3\).

Stress tensors:

- for fluid phase

\[
\tau_{j,f} = \frac{2}{3} \alpha_f \rho_f \kappa_f \delta_{ij} + \alpha_f \mu_f \left[ \frac{\partial V_{i,f}}{\partial x_j} + \frac{\partial V_{j,f}}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial V_{k,f}}{\partial x_k} \right];
\]

- for solid phase

\[
\tau_{j,s} = \alpha_s \mu_s \left( \frac{\partial V_{i,s}}{\partial x_j} + \frac{\partial V_{j,s}}{\partial x_i} \right) + \left( \alpha_s v_s - \frac{2}{3} \alpha_s \mu_s \right) \delta_{ij} \frac{\partial V_{k,s}}{\partial x_k},
\]

where

\(\kappa_f\) – turbulence kinetic energy;

\(\delta_{ij}\) – Kronecker delta;

\(\mu_f\) – effective viscosity of the fluid;

\(\mu_s\) – solids shear viscosity.
The equation of state for non-Newtonian fluid, which is written as power-law de Waele-Ostwald dependence, has the form of [1]:

\[ \tau = m |\dot{\gamma}|^{n-1} \gamma, \]  

(6)

where flow index or the intensity of non-Newtonian properties \( n < 1 \),

\( m \) – consistency index;

\( \gamma \) – shear rate.

As a model of two-phase flow turbulence, we adopted the \( \kappa - \varepsilon \) turbulence model, where the transport equations are written for the turbulence kinetic energy \( \kappa \) and the turbulent energy dissipation rate \( \varepsilon \) for each of the phases separately. In this paper, the system (1) – (5) is solved numerically by finite volume method under stationary conditions.

4. Research results

Calculations have been made for two-phase flow with the following parameters:

1. The continuous fluid. Density \( \rho_f = 900 \text{ kg m}^{-3} \); consistency index \( m = 0.15 \text{ Pa s}^n \), the degree of intensity of non-Newtonian properties \( n \) was varying from 0.8 to 1.0.

2. The solid phase. Density \( \rho_s = 2250 \text{ kg m}^{-3} \). At the first iteration the solid phase monodispersity condition was adopted. Diameter of particles \( d_s \) was varying from 20 to 100 \( \mu \text{m} \).

3. The geometrical parameters. The radius of the filtering baffle \( R = 0.02 \text{ m} \); the length of the channel \( L = 0.1 \text{ m} \); the slant angle of 12°; little radius cone of 0.025 m.

The following are the results of the numerical solution of the system equations (1) – (5) of the analytical model. The effective viscosity in the working area was determined. For this type of complex flow the influence of dispersed phase particle diameters \( d_s \), circumferential rotation velocity of the inner cylindrical surface and the degree of intensity of non-Newtonian properties of particles on efficiency of particle separation using centrifugal separation mechanism were examined.

4.1. The effective viscosity in working zone of the hydrodynamic filter

The rotation of the filtering baffle and the tangential input of the cleaned flow into the working zone makes possible to reduce the effective viscosity of pseudoplastic fluid in the channel by creating additional shear rates. Figures 3a-3b shows the distribution of the relative effective viscosity \( \mu_f^{\text{eff}} \) along the relative radial distance \( \bar{r} \) at \( z/L = 0.1 \) (figure3a), 0.5 (figure3b):

\[ \mu_f^{\text{eff}} = \mu_f^{n=1}; \bar{r} = \frac{r}{R}, \]

where

\( \mu_f^{n=1} \) – effective viscosity of the fluid with \( n = 1 \).

As can be seen from the graphs, the introduction of rotation of the filtering baffle really allows reducing the effective viscosity in the annular channel. For instance, the rotation of the filtering baffle with \( \omega = 100 \text{ rad s}^{-1} \) allows to reduce the effective viscosity by an average of 15% for fluid with the degree \( n = 0.9 \), and with \( n = 0.8 \) by 25%.

However, there is the limit to reducing the effective viscosity. For considered continuous fluid it is not advisable to use rotation more than \( \omega = 400 \text{ rad s}^{-1} \). In this case the decrease in effective viscosity will be less than 1% when rotational speed of filtering baffle increases by 100 rad s\(^{-1}\) (figure 4). This effect is due to the presence of pseudoplastic properties in the liquid phase, which are subordinate to power-law de Waele-Ostwald. In this case the dependence between shear stress and shear rate conventionally has three regions: the first Newtonian region (the viscosity does not depend on the shear rate); region of viscosity decrease due to orientation of molecules or particles; the second
Newtonian region (the viscosity remains constant, independent of the further shear rate growth). Therefore, it is necessary to select the operating parameters so that they correspond to the boundary of the second and third regions of the relationship between the shear stress and the shear rate for the regenerated pseudoplastic liquid.

**Figure 3.** The effective viscosity in working zone of the hydrodynamic filter at $z/L$ equal 0.1 (a) and 0.5 (b).

**Figure 4.** The average effective viscosity in working zone of the hydrodynamic filter at $z/L = 0.5$.

### 4.2. The efficiency of solid particles separation by the centrifugal mechanism

In general, the efficiency of liquid cleaning in hydrodynamic filter will be determined by the pore size of the filtering material. The simplest version is when the pore size is smaller than the particle size, and the solid particle settles on the surface of the baffle, forming a layer of sediment. If the particle size is commensurate with the pore size, it can penetrate the filtering baffle and get into cleaned flow (filtrate), violating the guarantee of the purity of the liquid. When the sediment layer accumulates on the surface of the filtering baffle, the pressure drop rapidly increases and regeneration is required. To reduce the rate of sediment accumulation in the hydrodynamic filter the rotation of the filtering baffle is implemented, what prevents accumulation of sediment layer. The more particles are separated by centrifugal mechanism and withdrawn from the filter along with the concentrate, the longer the time between regenerations of the filtering material. Therefore, the results of calculating the efficiency of
solid particles separation using centrifugal separation mechanism, the main component that affects the efficiency of the filter, are given below.

The efficiency of solid particles separation using centrifugal separation mechanism was estimated by the relative volume concentration of solid particles $\alpha_{s,\text{out}}$ at the exit of the concentrate branch pipe. For evaluation of convenience let’s convert $\alpha_{s,\text{out}}$ to initial concentration $\alpha_{s,\text{inlet}}$ at the input of the filter to calculate the efficiency of solids separation by the centrifugal mechanism:

$$\eta = \frac{\alpha_{s,\text{out}}}{\alpha_{s,\text{inlet}}}.$$

where

$\alpha_{s,\text{inlet}}$ – relative volume concentrations of solids at the inlet to the computational domain;

$\alpha_{s,\text{out}}$ – relative volume concentrations of solids on concentrate outlet.

Comparison of figures 5, 6 showed that the larger particles are separated better. The explanation of this fact is the increase of the centrifugal force for 100 $\mu$m particles as compared to the particles of 20 $\mu$m.

**Figure 5.** Dependence of solid particles separation efficiency using centrifugal separation mechanism $\eta$ on rotational speed of filtering baffle at $n = 0.8$. 

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**Figure 6.** Comparison of solid particles separation efficiency for different particle sizes at $n = 0.8$. 

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**Figure 7.** Efficiency of solid particles separation using centrifugal mechanism for different rotational speeds of filtering baffle.
Figure 6. Dependence of solid particles separation efficiency using centrifugal separation mechanism $\eta$ on rotational speed of filtering baffle at $n = 0.9$.

As can be seen from the curves on figures 5, 6, particle separation efficiency using centrifugal mechanism increases as the flow index $n$ decreases. This is due to the effect of "liquefaction" of power-law fluid in case of a complex shift, when the effective viscosity decreases with the decreasing of the flow index $n$. Therefore, with the increased $n$ a solid particle is affected by greater drag force that results in a decreasing of separation efficiency using centrifugal mechanism.

Increasing efficiency $\eta$ due to increasing of circumferential speed of the inner permeable cylinder rotation is logical, because centrifugal force, that affects a solid particle, is directly proportional to the square of the circumferential speed. However, this increasing is limited and observed at the steady state for the existence of the circulation vortex in the working zone. Further increase in the speed of rotation leads to a sharp increase in hydraulic resistance.

5. Inference

Based on the deterministic approach, we have developed the model of the medium flow process in the convergent channel formed by the stationary conical outer surface and the inner cylindrical rotating permeable surface. We have examined the process of movement of the two-phase flow containing dispersed phase, consisting of solid particles and liquid disperse medium, the rheological properties of which are described by the power-law de Waele-Ostwald dependence, within an annular channel with rotating permeable inner surface. We have identified key parameters of the solid particles separation process in a complex flow. The results of the study can be used to develop an engineering method for calculating hydrodynamic filters, the principle of operation of which is based on filtering in condition of complex impacts on the flow. The obtained results can be used in the design of systems for cleaning high-viscosity fluids from solid particles.

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