Filtering highly viscous and severely polluted media using integrated power effect on the liquid flow under cleaning

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Abstract. Filtering is a stage in purification of liquids and is included in most technological processes; therefore, design and development of advanced filtering devices is required in order to increase the useful life aiming at energy and resource saving. The given work demonstrates that a hydrodynamic filter that combines filtering and centrifugal separation in a single implementation could become such a device. Numerical method was used to solve the system of hydrodynamic equations describing the medium flow in a hydrodynamic filter. Efficiency of solid particles separation by a centrifugal mechanism was calculated. As a result of the study, it was found out that motion trajectories of the particles up to 20 μm in size coincide with the liquid phase flow. Proposed integrated power effect on the flow under cleaning makes it possible to reduce the load on the filtering material and, as a result, to increase the filter service life. Satisfactory compliance between the experimental study results and the calculated values confirms adequacy of the mathematical model to the real flow pattern and possibility of its use in practical calculations of hydrodynamic and separation processes in a hydrodynamic filter. Using a hydrodynamic filter to remove solid contaminants from a liquid would provide a possibility to solve ecological problems that are acute for many industrial sectors.

1. Introduction and Background

Intensification and improvement of efficiency in the filtering processes in regard to highly viscous and severely contaminated media are of great interest in many industrial sectors, such as oil production, oil refining, chemical, medical and food industries [1-3]. Besides, filtering of highly viscous media is connected to high costs required to create a driving force for the process, ensure fast clogging of the filtering material pores and the need for frequent regeneration of the filtering material [4-6]. Therefore, there appears a necessity to replace the filtering material with a new one. Design, development and study of devices that make it possible to increase the filtering material useful life before regeneration, to reduce energy consumption in creating the required differential pressure, while maintaining the device compactness and the required fineness of filtration are remaining relevant.

The authors suggest using filtering in combination with cleaning in centrifugal fields and vibration fields [7-9]. Centrifugal forces field in a hydrodynamic filter (Figure 1) is generated due to the tangential fluid introduction into the device apparatus and to the rotation of a cylindrical filtering partition. The difference between the presented method from other technologies lies in creating a potential flow in the device annular zone within the field of centrifugal forces. Such flow organization makes it possible to remove up to 80% of contaminants with the filtrate bypass fluid flow bypassing the filtering partition, which would reduce the load on the filtering material and increase the service life. Vibration of the filter membrane provided for in the design makes it possible to destroy the
sediment layer on it and to direct the sediment into the filtrate stream. Thus, the proposed hydrodynamic filter possesses the ability of self-regeneration. This leads to an additional increase in the functionality characteristics of the filtering partition and the efficiency of the entire device operation in general [1-4].

2. Materials and Methods

There is a limited number of works devoted to description of separate mechanisms implemented in a hydrodynamic filter. Most of them are related directly to filtering without taking into account the influence of all the cleaning mechanisms or the other schemes of the liquid flow [6, 7]. Therefore, studying the mechanisms and modes of cleaning, design and development of an analytical apparatus that describes hydrodynamic processes in a hydrodynamic filter are remaining relevant and practically important tasks [10-16].

The given work is devoted to studying the flow of contaminated liquid in the filter working channel using the method of mathematical modeling, the Navier–Stokes equations and the confirmation of results obtained after a full-scale experiment. Considered scheme of the liquid flow in a hydrodynamic filter is presented in Figure 2.

Device consists of a conical housing (2), where a cylindrical filtering partition (1) is installed. Suspension is fed into the annular gap from above. Exposed to the differential pressure, the liquid under cleaning is filtered through partition (1) having the velocity $v_\phi$ circumferential, $v_r$ radial and $v_z$ longitudinal component values. Part of liquid is bypassing along the partition and leaves through the lower annular gap. Determination of the flow hydrodynamic characteristics in the annular gap is of greatest interest; therefore, only this area will be considered below.

Mathematical model of the non-Newtonian fluid flow in the filter confusor area appears to be a combination of Navier – Stokes equations, continuity equations, medium rheological equation, liquid uniformity consumption through the filtering partition and boundary conditions [17-20].

We believe that velocity distribution does not depend on the angular coordinate, the flow mode is turbulent, and the liquid is incompressible.
Figure 2. Flow pattern in a hydrodynamic filter: 1 – filtering partition; 2 – filter housing.

In order to carry out experimental studies, a bench was created on the basis of a model hydrodynamic filter (Figure 3). Experimental bench makes it possible to conduct studies of filtration and filtering processes at various filter operation modes: filtering partition is motionless; it rotates; vibrates; rotates and vibrates. Filter operation in the given modes is ensured by the bench control module, which provides for variations in such parameters as liquid consumption and filter partition rate of rotation. Various suspensions that differ in the liquid physical and chemical properties and in the presence of contaminant particles could also be used in the experiment.

Figure 3. Experimental bench.

3. Results and Discussion
Figure 4 presents flow lines constructed on the basis of velocity calculations using the Navier – Stokes equation and the continuity equation supplemented by the turbulence model and the boundary conditions, as well as by the intermediate positions of particles with a diameter of 8 μm with the ratio
of the $\rho_f$ liquid phase density and the $\rho_p$, solid particles density of $\rho_f/\rho_p = 0.4$ obtained using the ANSYS software package.

![Flow pattern in a hydrodynamic filter](image)

**Figure 4.** Flow pattern in a hydrodynamic filter: 1 – filtering partition; 2 – filter housing; 3 – liquid flow lines; 4 – particle trajectories.

Analysis of numerous calculations demonstrated that it was possible to assume with reasonable certainty that trajectories of particles of up to 20 microns in size were coinciding with the liquid phase flow line. Obtained flow lines could be used to determine trajectories of the solid particles and concentration fields in the filter narrowing ring channel under an assumption that particles were moving along the flow lines of the suspension liquid phase. The given assumption is valid for steady flow and for small particle diameters.

Results of the hydrodynamic vibration filter experimental study confirmed with a satisfying degree of coincidence (15-20%) separation and hydraulic parameters of the filter predicted by mathematical modeling, which demonstrated its efficiency and prospects for implementing the hydrodynamic vibration filtering technique.

Estimation of the centrifugal separation contribution to the total cleaning efficiency was carried out as the ratio between the number of particles separated by the centrifugal mechanism and the total number of particles in the liquid being cleaned at the input to the device. Figure 5 presents dependences of the $\eta$ centrifugal mechanism cleaning efficiency on the $d_{50}$ median average particle size for the polydisperse composition of contaminants, which fractional composition complies with the logarithmic normal law. Dependencies were obtained with similar consumption characteristics, properties of dispersed phase and dispersion medium, as during the full-scale experiment. This made it possible to acknowledge correctness and accuracy of the mathematical model used. As could be seen from the graph, at the angular rotation speed of $\omega = 210$ rad/s 60% of particles with diameter of 200 $\mu$m and density of 2,250 kg/m$^3$ are removed from the industrial oil with a density of 900 kg/m$^3$. 
4. Summary and Conclusion
Thus, rotation of the filter partition appears to be a factor that improves separation of the solid phase from the high-viscosity non-Newtonian liquids due to intensification of the particles’ separation process using the centrifugal cleaning mechanism in the filter annular gap.

Satisfactory agreement of the results of experimental studies on the efficiency of solid particles’ separation in a hydrodynamic filter with calculated values obtained using the equations of the Newtonian fluids’ hydrodynamics confirms their adequacy to the real flow pattern and possibility of using them in practical calculations of hydrodynamic and separation processes in a hydrodynamic filter.

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