The Methodology of Numerical Simulations of Separation Process in SPR-Separator

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Abstract. The article describes the methodology of hydrocyclone SPR separator numerical simulation, which is used for oil lubricant and liquid impurities separation on technological lines of circulation lubrication of metallurgical machines. The methodology of hydrocyclone SPR separator numerical simulation was developed with taking into account up-to-date articles about the study of hydrocyclone equipment. It was done for determining the relation between the main structural dimensions of the device and the flow parameters, as well as the separation efficiency of the heterogeneous inlet mixture. Numerical simulations were performed by using ANSYS namely its module Fluent Flow. The methodology of the finite volume computational grid building was described. This methodology takes into account the geometry features of the model, such as the presence of surfaces curvature and small gaps compared to other linear dimensions. Settings of the Fluent module was described with design features of the SPR-separator and its working parameters. Eulerian multiphase flow model, k-ε RNG turbulence model with Swirl Dominated Flow settings was chosen. According to the results of the numerical simulation was determined the main hydrodynamic characteristics of the flow which presented as isolines in the middle section of the separator and value of the separation efficiency of the heterogeneous mixture. New design of a spiral nozzle was proposed for expansion of the range of effective work.

Keywords: Hydrocyclone, Heterogeneous Mixture, Research Methodology, Numerical Experiment, CFD.

1 Introduction

Nowadays, circulating oil lubrication systems are widespread in the metallurgical equipment. According to this method, the liquid lubricant moves through oil pipes, which form a closed ring circuit, lubricates the units and cools of the friction pairs. It should be noted that the lubricant insignificant amount loose during its movement. Therefore, the main advantage of the circulating oil lubrication systems is their economic efficiency. One of the required element of the circulating oil lubrication systems is separation devices since oil lubricant become contaminated with liquid and solid particles after passing the circuit oil pipes. For this purpose, hydrocyclones are widely used.

By one of the highly efficient hydrocyclones are considered to be SPR-separators with the spiral nozzle (turbo-spiral), which is designed for the incoming flow directing in a radial way and as a result creating of centrifugal forces. The main advantage of the SPR-separator is the high fluid speed in the enclosure of the centrifugal element, which provides a high-intensity separation process. On the other hand, we can observe that high fluid speed may cause a negative influence on the separation process, such as re-mixing of the dispersed and the continuous phase. Therefore, technological regimes causing the above phenomena must be eliminated at the design stage to ensure reliable and efficient operation of this unit.

The main aim of this work is relations determining between the main structural dimensions of the SPR-separator (Fig. 1) and the flow parameters, as well as the separation efficiency of the heterogeneous inlet mixture.

Fig. 1. The scheme of the SPR-separator with the main flows [1].

2 Literature Review

It should be noted that hydrocyclones have commonly used equipment in various technological lines of chemical and food industries [1–3], at oil production from wells [4–6], for gas purification in titanium dioxide productions [7, 8], etc. Thus, first and foremost, the equipment characteristics are determined depending on its purpose. At the same time, the development of new hydrocyclone designs continue by creating favorable hydrodynamic regimes for separating [1–5], adding new propelling power of the process in addition to centrifugal [7] and methods of them manufacturing [5, 7–10], as well as their new appointments opening [11].

In each of the above works, the flow parameters were determined by experimental [3, 5, 8, 10–14] and numerical methods [1, 2, 4, 7–10, 15, 16]. Herewith, separation efficiency is determined by flow parameters. A significant advantage of the numerical methods is the ability to studying of a large number of hydrocyclone designs as a consequence determining of the basic design parameters, which effect on the separation efficiency of the input heterogeneous mixture, without significant capital expenditures associated with the creation of experimental samples. In works [1, 2, 4, 7–10, 15, 16] various software packages were used for carrying out numerical calculations among which ANSYS, OPENFoam, etc. They are based on the finite volume method.

For example, in works [1, 4, 7, 10, 15, 16] the ANSYS software package namely its module Fluent Flow was chosen for simulation. Wherein, various models of multiphase mixtures were defined depending on the medium under study. The Mixture model was selected as the model of a multiphase flow in [6] for caring out numerical studies of magnetic hydrocyclon. In other cases [1, 15–17], the VOF model was chosen. Its feature is the solution of the momentum equation and temperatures determining for each phase separately.

Most scientists for describing of turbulent flows in hydrocyclone enclosure prefer the Reynolds Stress Model (RSM) since this model gives the best correlation with experiment for swirling flows. Thus, in works [6, 9, 15, 17] this model was chosen. Herewith, it is resource-intensive, so in [4] the Swirl model RNG k-ε turbulence was used as an alternative.

In summary, the ANSYS Workbench software package, namely its module Fluent Flow was chosen for caring out numerical calculations on flow parameters in the SPR separator since it has different models for describing both the multiphase flow and the turbulence.

3 Research Methodology

As mentioned above, the ANSYS Workbench software package, namely its Fluent Flow module was chosen to determine the flow characteristics in the SPR-separator under study. The first stage of calculations in this module is the building of a three-dimensional design geometry, which is used for determining the boundary conditions as shown in Fig. 2.

As can be seen from Fig. 2, the boundary condition of the “wall” type was not specified since the Fluent Flow module automatically assigns it to surfaces, which aren`t defined as other boundary conditions.

The second stage of the calculation was the building of the finite volume grid, which takes into account the features of the model, such as the presence of surfaces curvature and small gaps comparatively to other linear dimensions. To that end, the global setting Proximity and Curvature was chosen for considering the above model features. The number of elements in the gap 5 was additionally specified by the Proximity Size Function – Face and Edges. According to the above function, 5 elements are built always, even as the main specified element sizes deny building a required number of elements on the surfaces/faces. The boundary layer was built on the surfaces, which aren`t specified as inlet and outlet, for ensuring a qualitative description of the flow near the wall. The Inflation Option – Last Aspect Ratio was used for reducing the height of subsequent layers as appropriate (for example, in the gap), with First Layer Heights equivalent to 50 μm. The Advanced Options namely Collision Avoidance – Layer Compression were also used. It allows reducing the height of the first layer in the gaps and prevents Stair Stepping. A volumetric computational grid with 1.5 million elements was obtained as a result of the above settings using. This grid has following quality indicators: the maximum Skewness value is 0.93, which is not exceed the permissible value 0.95; the minimum Orthogonal Quality value is 0.13, which does not less than the permissible value 0.1; Aspect Ratio – 809, which is satisfactory when using Double Precision. Last indicated setting is necessary for multiphase flow calculations. The computational grid that was obtained is shown in Fig. 3.

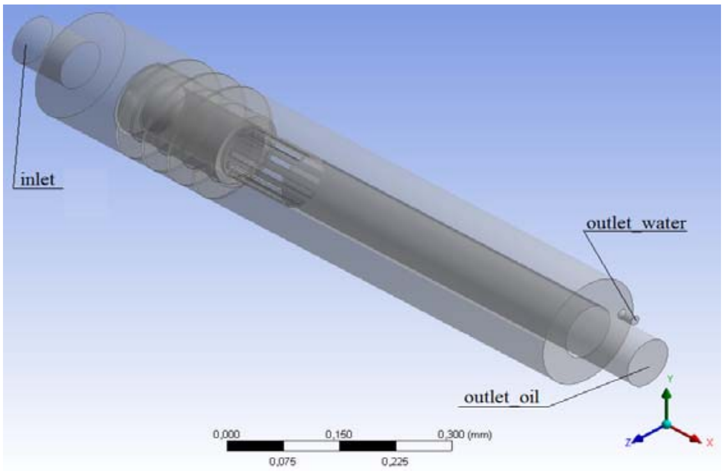

Fig. 2. Three-dimensional design model, with surfaces for specifying boundary conditions.

The next (third) stage of the numerical calculations is the setting of the Fluent Flow module, which begins with the introduction of General Setting, namely Double Precision and Gravity. First activated setting is needed for multiphase flows, second - for taking into account the gravity force, which is necessary for consideration draining of the separated liquid film directed vertically downwards (from the inlet to the outlet) along the X-axis. It makes sense to use the Eulerian approach for description of multiphase flow since we consider water particles with an average size of 100 μm, their volume fraction of dispersed phase is 0.1. Thus, the Eulerian model with Formulation – Implicit was chosen. The k-ε RNG turbulence model was chosen with the following settings: Swirl Dominated Flow, Curvature Correction and Near Wall Treatment – Enhanced Wall Treatment. It was done accordingly to the value of the Reynolds number $2.9 \cdot 10^4$ and from the viewpoint of reducing the computation resource-intensiveness.

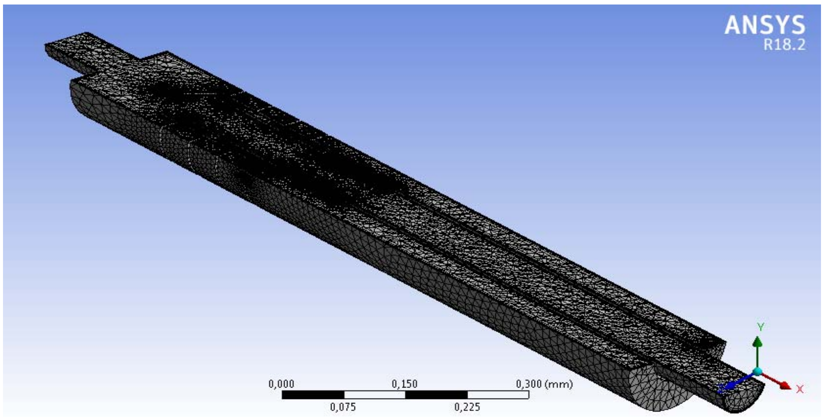

Fig. 3. The obtained finite-volume computational grid

The necessary stage was materials definition for the phases from the library:

- primary phase – kerosene-liquid, with properties: density ρ = 780 kg/m^3, dynamic viscosity μ = 0.0024 Pa·s;
- secondary phase – water liquid, with properties: density ρ = 998 kg/m^3, dynamic viscosity μ = 0.001003 Pa·s.

The following boundary conditions are specified at the inlet:

- for the mixture – a gauge pressure of 0.4 MPa, turbulence parameters such as hydraulic diameter 76 mm and the average value of turbulence intensity – 5 %;
- for the main phase (kerosene-liquid) - inlet speed 1.18 m/s;
- for the dispersed phase (water) - volume fraction 0.1.

The following boundary conditions are specified at the lubricant outlet:

- for the mixture – a gauge pressure of 0.4 MPa, turbulence parameters such as hydraulic diameter 76 mm and the average value of turbulence intensity – 5 %;
- for the dispersed phase (water) - volume fraction in the possible reverse flow 0.1.

As the boundary conditions at the water outlet are given:

- for the mixture – a gauge pressure of 0.4 MPa, turbulence parameters such as hydraulic diameter 15 mm and the average value of turbulence intensity – 5 %;
- for the dispersed phase (water) - volume fraction in the possible reverse flow 1.

Standard initialization was used for calculations. Firstly, the problem was solved by the Method-Velocity Coupling - Simple method with the following Spatial Discretization parameters: Gradient – Least Square Cell Based; Momentum – First Order

Upwind; Volume Fraction – First Order Upwind; Turbulent Kinetic Energy – First Order Upwind; Turbulent Dissipation Rate – First Order Upwind. The Pressure-Velocity Coupling-Coupled method was used after problem convergence for the improvement of the results accuracy, wherein following Spatial Discretization parameters were used: Gradient-Least Square Cell Based; Momentum – Second Order Upwind; Volume Fraction – Second Order Upwind; Turbulent Kinetic Energy – First Order Upwind; Turbulent Dissipation Rate – First Order Upwind.

4 Results

The isolines of a dispersed phase in the cross-section of the unit (Fig. 4), the isolines of gauge pressure (Fig. 5) and the velocity vectors of water (Fig. 6) were obtained as a result of the calculations.

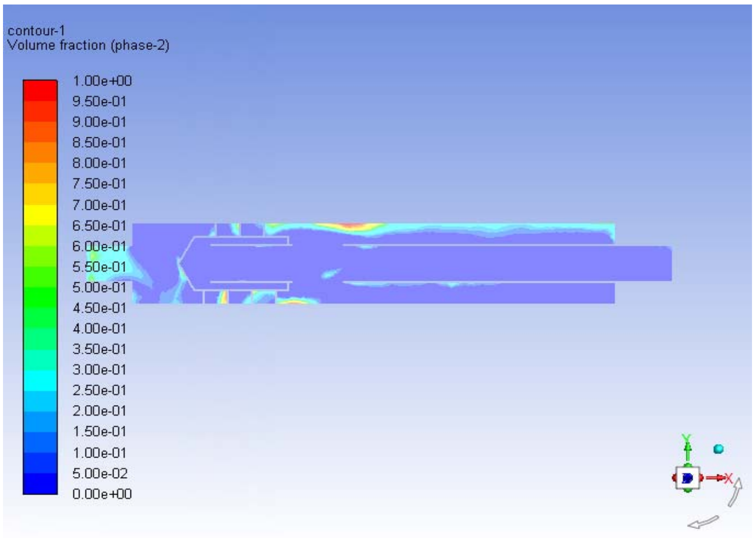

Fig. 4. The isolines of the water volume fraction in the middle section of the SPR-separator.

Based on the results of the SPR-separator hydrodynamics numerical simulation, namely isolines and velocity vectors of the dispersed phase, it can be argued, that the proposed modeling methodology corresponds to the theoretical concepts of the separation of two-component streams in the centrifugal field. Fig. 4 shows that the component with a large value of density (water) is located near to the walls and is absent in the central part of the apparatus. Fig. 6 shows the velocity vectors of the dispersed phase, which are directed from the axis to the periphery and along to the walls of the SPR-separator. This indicates that the separation process is efficient. The value of the separation efficiency (η = 95 %) was calculated according to the equation:

$$\eta = \left(1 - \frac{c}{c_0}\right) \cdot 100\%, \tag{1}$$

c_0 – volume fraction of the secondary phase at the inlet; c – volume fraction of the secondary phase at the outlet of the SPR-separator.

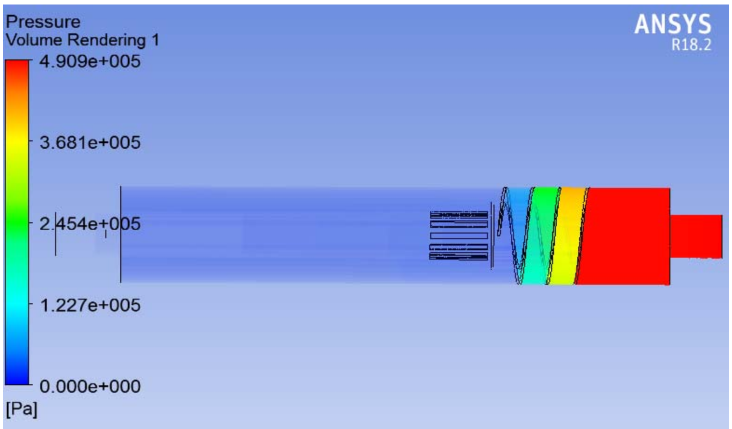

Fig. 5. Isolines of the gauge pressure.

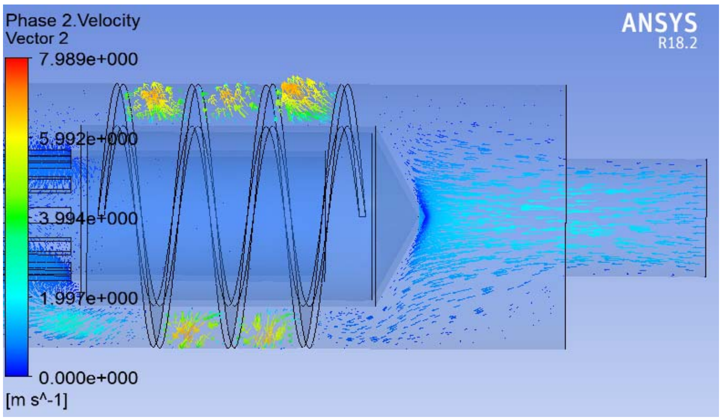

Fig. 6. Water velocity vectors.

As mentioned above, the separation efficiency value is 0.95. However, this value was determined for the following working parameters: velocity at the inlet – 1.18 m/s, gauge pressure at the inlet and outlet – 0.4 MPa, discrete phase volume fraction at the inlet – 0.1, but high fluid speed may cause a negative influence on the separation process, such as re-mixing of the dispersed and the continuous phase, and on the other hand low fluid speed may cause insufficient centrifugal force for separation. Similar problem takes place at process of a gas-liquid separation, which is based on the usage of inertia of particles (droplets). The main drawback of this method is the secondary splashing, resulting from a possible increasing of the flow velocity to a critical value and disruption of the trapped liquid, with following occurrence of the highly dispersed particles [19]. The avoidance of this problem is realized in dynamic separation elements. The related certificates of the authorship are “The method of capturing highly dispersed dropped liquid from the gas-liquid flow” Sumy State University, Ukraine, bulletin No. 20 with No. u201505124 and No. u201605061. The above elements work as an automatic control system, in which the regulating action is elastic forces, and the object of regulation is the hydraulic resistance.

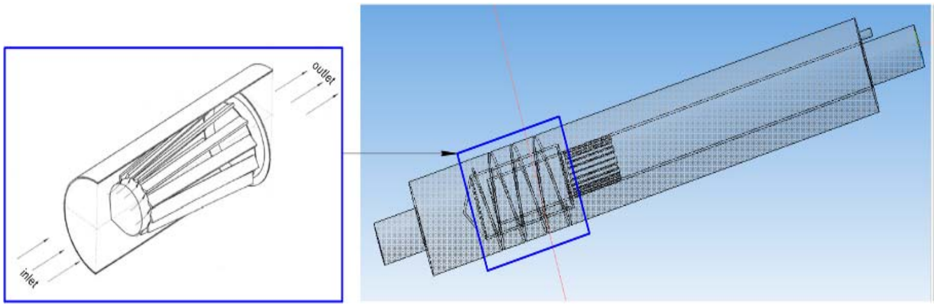

Fig. 6. New design of the spiral nozzle.

New design of the spiral nozzle was proposed and it shown in Fig. 7. This spiral nozzle design was developed accordingly to the results of numerical simulations and based on similar principles of the dynamic separation elements. The related certificate of the authorship is “The device for separation of disperse liquid from gas flow” Sumy State University, Ukraine, bulletin No. 23 with No u 2018 06182.

For future research main aim will be developing of engineering method for calculation of new SPR-separator design. Herewith, main problem is necessarily of solving a complex problem of the hydroaeroelasticity, which analytical solution has been already obtained for similar case in [19]. The articles [20–22] will be used for father improving of SPR-separator, due to creating regularly-structured elements with well-organized liquid drainage [20, 21] and mounting filtering or their thin-layer modules [22].

5 Conclusions

The method of numerical research of the SPR-separator is proposed. This technique allows to determining the main hydrodynamic parameters of the separation processes, the efficiency of separation, hydraulic resistance, value and direction of the velocities of the disperse phase, etc.

The efficiency of separation was calculated, which in turn confirms the adequacy of the proposed methodology and the possibility of using it for future research. Main disadvantages of separation process in SPR-separator are re-mixing of the dispersed and the continuous phase, insufficient centrifugal force for separation. New design of the spiral nozzle was developed accordingly to the results of numerical simulations and based on similar principles of the dynamic separation elements. For future research main aim will be developing of engineering method for calculation of new SPR-separator design.

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