Investigation of the Spalart-Allmares Turbulence Model for Calculating a Centrifugal Separator

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ABSTRACT

A study of SA turbulence models in application to the calculation of swirling currents inside the separator has been carried out. The paper compared two approaches using vorticity and current functions to eliminate pressure and a semi-implicit method for pressure-binding SIMPLE to solve the Reynolds-averaged Navier-Stokes equations. For the numerical solution of both approaches, an implicit method against the flow was used.

KEYWORDS: *Navier-Stokes equations, SIMPLE, RANS approach, control volume method.Введение*

Introduction

Swirling flows of gases and liquids are often found in modern technological processes [1]. Swirling currents are formed behind the wheels of hydroelectric turbines [2], in the wake of aircraft and propellers, as well as wind turbines, etc. [3]. Cyclones, separators, vortex flowmeters - all these devices use a twist of the working medium flow. The useful properties of swirling currents are widely used in thermal power engineering, for example, with the help of it they achieve flame stabilization in burner devices. However, swirling currents have not only positive features. In strongly swirling flows, the formation of non-stationary structures, such as a precessing vortex core (PVN), often occurs. Low precession frequencies of the vortex core formed, for example, behind the hydro turbine wheel of a hydroelectric power plant, can lead to resonance with the natural frequencies of the hydroelectric unit, which in turn will entail strong vibrations that pose a serious danger to the entire structure of the hydroelectric power plant. The formation of PVR in vortex combustion chambers can be the cause of thermoacoustic resonance [4], which also results in strong vibrations and noise. In addition, it was found that the PVR can affect the efficiency of vortex apparatuses [5]. Large-scale pulsations caused by the precession of the vortex can lead to damage to structures and reduce the reliability of equipment. Despite many years of research on this phenomenon, at the moment there is not enough information to build a theory of PVN and, accordingly, to develop effective methods of managing this phenomenon. Thus, engineering calculations require turbulence models that accurately describe averaged fields and large-scale pulsations of swirling currents. Widely used in engineering calculations $k-\varepsilon$ and $k-\omega$turbulence models do not describe such flows well. In order to improve the adequacy of modeling turbulent swirling flows, they are trying to modify existing RANS models (Reynolds-Averaged Navier-Stokes Equations - Reynolds-averaged Navier-Stokes equations) of turbulence. In [6], the Spalart-Allmaras models were proposed for Spalart and Allmaras. A new model called SA.

PHYSICAL AND MATHEMATICAL FORMULATION OF THE PROBLEM.

It is known that swirling flows are characterized by a strong curvature of the current lines, the appearance of recirculation zones, the location and size of which largely depend on the intensity of the twist and the configuration of the boundaries. In addition, such ceilings are turbulent. Therefore, their research requires the involvement of effective turbulence models. Recently, quite effective turbulence models have appeared

In this paper, we consider a two-dimensional axisymmetric turbulent flow in an air centrifugal separator, which is an important link in the processes of separation and classification of particles, obtaining powders of the required quality. The efficiency of the ongoing processes for separating powders into large and small fractions will depend on how the flow structure is organized inside the working area. The aim of the undertaken numerical study is to clarify the nature of the hydrodynamics of the swirling flow at different geometries. The scheme of the calculated area is shown in Fig. 1.

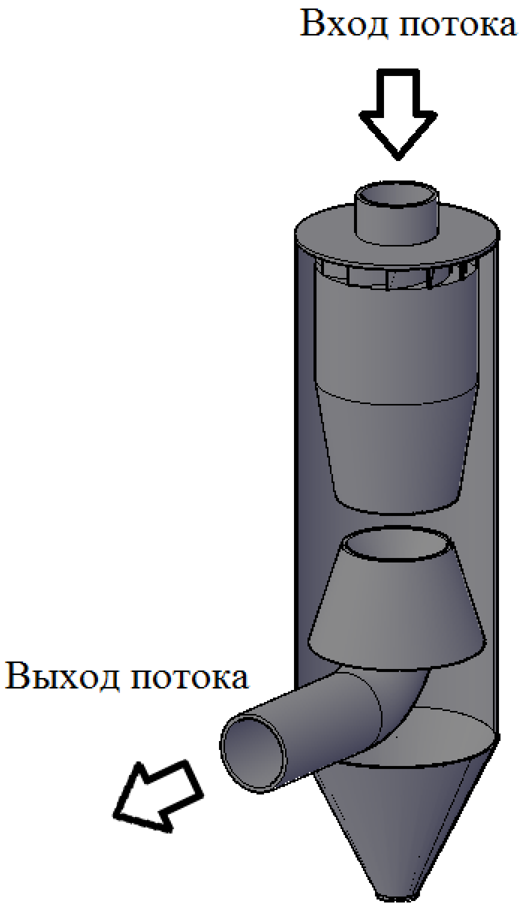


Fig. 1 Diagram of the calculated air-centrifugal separator.

It is easy to understand that the efficiency of such a separator strongly depends on its geometry. Therefore, in order to find optimal geometric parameters, the task of modeling the kinematics of particles inside the installation arises. It is clear that the kinematics of particles depends on the dynamics of the air flow. Therefore, two tasks arise here: 1) to investigate the dynamics of the air flow; 2) on the basis of the obtained hydrodynamic parameters of the air flow to investigate the trajectories of the separated particles.

A system of equations averaged by Reynolds Navier-Stokes equations in a cylindrical coordinate system is used for numerical investigation of the problem [7]:

$$\begin{cases} \frac{\partial U}{\partial z}+\frac{\partial rV}{r\partial r}=0, \\ \frac{\partial U}{\partial t}+U\frac{\partial U}{\partial z}+V\frac{\partial U}{\partial r}+\frac{1}{\rho}\frac{\partial P}{\partial z}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\nu_{eff}\frac{\partial U}{\partial r}\right], \\ \frac{\partial V}{\partial t}+U\frac{\partial V}{\partial z}+V\frac{\partial V}{\partial r}-\frac{G^2}{r^3}+\frac{1}{\rho}\frac{\partial P}{\partial r}=\frac{1}{r}\frac{\partial}{\partial r}\left[r\nu_{eff}\frac{\partial V}{\partial r}\right]-\frac{\mu}{r^2}V, \\ \frac{\partial G}{\partial t}+U\frac{\partial G}{\partial z}+V\frac{\partial G}{\partial r}=\frac{\partial}{r\partial r}\left(\nu_{eff}\frac{\partial G}{\partial r}\right)-\frac{\partial}{r^2\partial r}\left(2\nu_{eff}G\right)+\frac{2\nu_{eff}G}{r^3}; \\ G=W\times r;\ \nu_{eff}=\nu+\nu_t \end{cases} \quad (1)$$

here ν,ν_t are molecular and turbulent viscosity, U,V,W are dimensionless averaged velocity vectors; r,z-are dimensionless coordinates; Initial and boundary conditions for the system of equations (1) are set in a standard way [8].

When $z=0: U=U_0,\ V=0, W=W_0$. On the walls: $U=V=W=0$. On the axis $r=0$: $\frac{\partial \Phi}{\partial r}=0$ for $\Phi=U$ and $W,V=0$.

To calculate equation (1) of complex shapes, we change the coordinate system. Let's write the system (1) in the Mises variables [9] *(z, r)* to *-(ξ, n),* where $\xi=z/L$. In the new variables, the derivatives are determined by the well-known formula:

$$\frac{\partial}{\partial z}=\frac{\partial \xi}{\partial z}\frac{\partial}{\partial \xi}+\frac{\partial \eta}{\partial z}\frac{\partial}{\partial \eta}=\frac{\partial}{\partial \xi}+\eta'\frac{\partial}{\partial \eta}, \quad \frac{\partial}{\partial r}=\frac{\partial \xi}{\partial r}\frac{\partial}{\partial \xi}+\frac{\partial \eta}{\partial r}\frac{\partial}{\partial \eta}=F(z)\frac{\partial}{\partial \eta}.$$

In the new variables, the system of equations (1) takes the form

$$\begin{cases} \frac{\partial U}{\partial \xi}+\eta'\frac{\partial U}{\partial \eta}+F(z)\frac{\partial rV}{r\partial \eta}=0, \\ \frac{\partial U}{\partial t}+U\frac{\partial U}{\partial \xi}+U\eta'\frac{\partial U}{\partial \eta}+V\times F(z)\frac{\partial U}{\partial \eta}+\frac{\partial P}{\partial \xi}+\eta'\frac{\partial P}{\partial \eta}=\frac{F(z)}{r}\frac{\partial}{\partial \eta}\left[r\nu_{eff}F(z)\frac{\partial U}{\partial \eta}\right], \\ \frac{\partial V}{\partial t}+U\frac{\partial V}{\partial \xi}+U\eta'\frac{\partial V}{\partial \eta}+V\times F(z)\frac{\partial V}{\partial \eta}-\frac{G^2}{r^3}+F(z)\frac{\partial P}{\partial \eta}=\frac{F(z)}{r}\frac{\partial}{\partial \eta}\left[r\nu_{eff}F(z)\frac{\partial V}{\partial \eta}\right]-\frac{\nu_{eff}}{r^2}V, \\ \frac{\partial G}{\partial t}+U\frac{\partial G}{\partial \xi}+U\eta'\frac{\partial G}{\partial \eta}+V\times F(z)\frac{\partial G}{\partial \eta}=\frac{F(z)}{r}\frac{\partial}{\partial \eta}\left(\nu_{eff}F(z)\frac{\partial G}{\partial \eta}\right)-\frac{F(z)}{r^2}\frac{\partial}{\partial \eta}\left(2\nu_{eff}G\right)+\frac{2\nu_{eff}G}{r^3}, \\ \nu_{eff}=\nu+\nu_t \end{cases} \quad (2)$$

On the system equation (2) $F(z)$ is a function that depends on the calculated area $\eta_0=0.6\eta$

The Reynolds-averaged Navier-Stokes equations were closed using the turbulence model: Spalart-Allmaras.

Spalart-Allmaras models [6]. This model belongs to the class of one-parameter turbulence models. Here there is only one additional equation for calculating the kinematic coefficient of vortex viscosity

$$\frac{\partial \rho\tilde{\nu}}{\partial t}+\nabla(\rho\tilde{\nu}U)=\rho(P_v-D_v)+\frac{1}{\sigma_v}\nabla\left[(\nu+\nu_t)\nabla\tilde{\nu}\right]+\frac{C_{b2}}{\sigma_v}\rho(\nabla\tilde{\nu})^2-\frac{1}{\sigma_v\rho}(\mu+\rho\tilde{\nu})\nabla\rho\nabla\tilde{\nu}. \quad (3)$$

The turbulent vortex viscosity is calculated from: $\nu_t = \tilde{\nu} f_{v1}$

Initial and boundary conditions. The parameters of the undisturbed flow in the entire computational domain were set as initial conditions. Non-reflective boundary conditions were applied at the outer boundary. A condition of adhesion was set on the surface of a solid. In the turbulence model SA, the value of the working variable on the body was set to zero *vt = 0*, at the input boundary *vt = 3*, the Neumann condition was set at the output boundary.

SOLUTION METHODS

Using vorticity and current function [13]

To facilitate numerical implementation, partial parabolization was carried out in system (1), i.e. terms with derivatives in z were neglected in the right parts. The current function ψ is introduced, for which the continuity condition is satisfied:

$$V = -\frac{1}{r}\frac{\partial \psi}{\partial z}, \quad U = \frac{1}{r}\frac{\partial \psi}{\partial r}. \qquad (4)$$

Vorticity is also introduced ζ

$$\zeta = \frac{\partial U}{\partial r} - \frac{\partial V}{\partial z}. \qquad (5)$$

Next, we exclude pressure from the first two equations of system (1) and, substituting expressions (4) into (5), we obtain a system with respect to new variables.

$$\begin{cases} \dfrac{\partial \zeta}{\partial t} + U\dfrac{1}{L}\dfrac{\partial \zeta}{\partial \xi} + U\eta'\dfrac{\partial \zeta}{\partial \eta} + F(z)V\dfrac{\partial \zeta}{\partial \eta} - \zeta\dfrac{V}{r} + \dfrac{1}{r^2}\dfrac{1}{L}\dfrac{\partial G^2}{\partial \xi} + \dfrac{\eta'}{r^2}\dfrac{\partial G^2}{\partial \eta} = -\dfrac{F(z)}{r^2}\dfrac{\partial\left(r(\nu_{eff})\zeta\right)}{\partial \eta} + \dfrac{F(z)^2}{r}\dfrac{\partial^2\left(r(\nu_{eff})\zeta\right)}{\partial \eta^2}, \\ \dfrac{\partial G}{\partial t} + \dfrac{U}{L}\dfrac{\partial G}{\partial \xi} + U\eta'\dfrac{\partial G}{\partial \eta} + F(z)V\dfrac{\partial G}{\partial \eta} = F(z)\dfrac{\partial}{\partial \eta}\left((\nu_{eff})\left(F(z)\dfrac{\partial G}{\partial \eta} - \dfrac{G}{r}\right)\right) - \dfrac{\mu}{r^2}G, \\ \dfrac{F(z)^2}{r}\dfrac{\partial^2 \psi}{\partial \eta^2} - \dfrac{F(z)}{r^2}\dfrac{\partial \psi}{\partial \eta} + \dfrac{1}{rL^2}\dfrac{\partial^2 \psi}{\partial \xi^2} + 2\dfrac{\eta'}{rL}\dfrac{\partial^2 \psi}{\partial \xi \partial \eta} + (\eta')^2\dfrac{\partial^2 \psi}{r\partial \eta^2} + \eta''\dfrac{\partial \psi}{r\partial \eta} = \zeta, \\ \psi = -\dfrac{1}{L}\dfrac{\partial V}{\partial \xi} + \eta'\dfrac{\partial V}{\partial \eta}, \quad \psi = F(z)\dfrac{\partial U}{\partial \eta}, \\ \dfrac{\partial \tilde{\nu}}{\partial t} + U\dfrac{\partial \tilde{\nu}}{\partial \xi} + U\eta'\dfrac{\partial \tilde{\nu}}{\partial \eta} + F(z)V\dfrac{\partial \tilde{\nu}}{\partial \eta} = (P\nu - D\nu) + \dfrac{F(z)}{r\sigma_\nu}\dfrac{\partial}{\partial \eta}\left[r(\nu + \tilde{\nu})F(z)\dfrac{\partial \tilde{\nu}}{\partial \eta}\right] + \dfrac{C_{b2}}{\sigma_\nu}\left(F(z)\dfrac{\partial \tilde{\nu}}{\partial \eta}\right)^2. \end{cases} \qquad (6)$$

Thus, the new variables make it possible to bring all the equations of the system to a parabolic form and this system can be written in vector form

$$\frac{\partial \Phi}{\partial t} + U\frac{\partial \Phi}{\partial \xi} + U\eta'\frac{\partial \Phi}{\partial \eta} + V\eta\frac{\partial \Phi}{\partial \eta} = F(z)^2\frac{\partial}{\partial \eta}\left(a^{(\Phi)}\frac{\partial \Phi}{\partial \eta}\right) + \Pi^{(\Phi)} \qquad (7)$$

An implicit scheme was used for the numerical implementation ζ of *G* and *v* in equations (7).

$$\Phi = \begin{bmatrix} \zeta \\ G \\ \tilde{\nu} \end{bmatrix}, \quad \Pi^{(\Phi)} = \begin{bmatrix} F(z)V\dfrac{\partial \zeta}{\partial \eta} - \zeta\dfrac{V}{r} + \dfrac{1}{Lr^2}\dfrac{\partial G^2}{\partial \xi} + \dfrac{\eta'}{r^2}\dfrac{\partial G^2}{\partial \eta} \\ 0 \\ (P\nu - D\nu) + \dfrac{C_{b2}}{\sigma_\nu}\left(F(z)\dfrac{\partial \tilde{\nu}}{\partial \eta}\right)^2 \end{bmatrix}, \quad a^{(\Phi)} = \begin{bmatrix} r(\nu_{eff}) \\ 1 \\ r(\nu + \tilde{\nu})F(z) \end{bmatrix}.$$

The scheme against the flow has the form

$U = U_{i,j}^n,\;\; V = \left(U_{i,j}^n \eta' + V_{i,j}^n F(z)\right),$

$$\frac{\Phi_{i,j}^{n+1} - \Phi_{i,j}^n}{\Delta t} + \frac{0.5\left(U_{i,j} + \left|U_{i,j}\right|\right)}{L}\frac{\Phi_{i,j}^n - \Phi_{i-1,j}^n}{\Delta \xi} + \frac{0.5\left(U_{i,j} - \left|U_{i,j}\right|\right)}{L}\frac{\Phi_{i+1,j}^n - \Phi_{i,j}^n}{\Delta \xi} + 0.5\eta'\left(U_{i,j} + \left|U_{i,j}\right|\right)\frac{\Phi_{i,j}^n - \Phi_{i,j-1}^n}{\Delta \eta} +$$

$$+ 0.5\eta'\left(U_{i,j} - \left|U_{i,j}\right|\right)\frac{\Phi_{i,j+1}^n - \Phi_{i,j}^n}{\Delta \eta} + 0.5F(z)\left(V_{i,j} + \left|V_{i,j}\right|\right)\frac{\Phi_{i,j}^n - \Phi_{i,j-1}^n}{\Delta \eta} + 0.5F(z)\left(V_{i,j} - \left|V_{i,j}\right|\right)\frac{\Phi_{i,j+1}^n - \Phi_{i,j}^n}{\Delta \eta} = \quad (8)$$

$$= F(z)\frac{\Phi_{i,j+1}^{n+1}(a_{i,j+1}^{(\Phi)} + a_{i,j}^{(\Phi)}) - \Phi_{i,j}^{n+1}(a_{i,j+1}^{(\Phi)} + 2a_{i,j}^{(\Phi)} + a_{i,j-1}^{(\Phi)}) + \Phi_{i,j-1}^{n+1}(a_{i,j}^{(\Phi)} + a_{i,j-1}^{(\Phi)})}{2r_j \Delta \eta^2} + \Pi^{(\Phi)}.$$

It is absolutely stable and the unknowns on the new layer were found by the run-through method. The integration steps were $\Delta\xi = 0.05, \Delta\eta = 0.02.$ The number of calculated points in the transverse direction was 50, in the longitudinal direction 100. The Poisson equation for the current function was also approximated by the central difference and the upper relaxation iteration method was used to resolve it

$$\frac{\psi^k{}_{i+1,j} - 2\psi^{k+1}{}_{i,j} + \psi^k{}_{i-1,j}}{\Delta\xi^2} + \frac{\psi^k{}_{i,j+1} - \psi^k{}_{i,j-1}}{2\Delta\eta} + \frac{\psi^k{}_{i+1,j+1} - \psi^k{}_{i-1,j+1} + \psi^k{}_{i+1,j-1} - \psi^k{}_{i-1,j-1}}{2\Delta\xi\Delta\eta} + \frac{\psi^k{}_{i,j+1} - 2\psi^{k+1}{}_{i,j} + \psi^k{}_{i,j-1}}{\Delta\eta^2} = r_j \zeta^k_{i,j}. \quad (9)$$

A semi-implicit method for binding pressure is SIMPLE

The numerical solution of the presented system of equations was carried out in the physical variables velocity - pressure by physically splitting the velocity and pressure fields [10]. The numerical solution of the transfer equation is carried out on a hybrid, staggered difference grid by the control volume method. According to this method, the solution of the Reynolds equations written in the cylindrical coordinate of the new variables includes two stages:

$$\begin{cases} \frac{\tilde{U} - U^n}{\Delta t} + U^n \frac{\partial U^n}{\partial \xi} + U^n \eta' \frac{\partial U^n}{\partial \eta} + V^n \times F(z)\frac{\partial U^n}{\partial \eta} + \frac{\partial P}{\partial \xi} + \eta' \frac{\partial P}{\partial \eta} = \frac{F(z)}{r}\frac{\partial}{\partial \eta}\left[r\nu_{eff}F(z)\frac{\partial \tilde{U}}{\partial \eta}\right], \\ \frac{\tilde{V} - V^n}{\Delta t} + U^n \frac{\partial V^n}{\partial \xi} + U^n \eta' \frac{\partial V^n}{\partial \eta} + V^n \times F(z)\frac{\partial V^n}{\partial \eta} - \frac{G^2}{r^3} + F(z)\frac{\partial P}{\partial \eta} = \frac{F(z)}{r}\frac{\partial}{\partial \eta}\left[r\nu_{eff}F(z)\frac{\partial \tilde{V}}{\partial \eta}\right] - \frac{\nu_{eff}}{r^2}\tilde{V}, \quad (10) \\ \frac{\tilde{G} - G^n}{\Delta t} + U^n \frac{\partial G^n}{\partial \xi} + U^n \eta' \frac{\partial G^n}{\partial \eta} + V^n \times F(z)\frac{\partial G^n}{\partial \eta} = \frac{F(z)}{r}\frac{\partial}{\partial \eta}\left(r\nu_{eff}F(z)\frac{\partial \tilde{G}}{\partial \eta}\right) - \frac{F(z)}{r^2}\frac{\partial}{\partial \eta}\left(2\nu_{eff}\tilde{G}\right) + \frac{2\nu_{eff}}{r^2}\tilde{G}, \\ \frac{\partial \tilde{\nu}}{\partial t} + U\frac{\partial \tilde{\nu}}{\partial \xi} + U\eta' \frac{\partial \tilde{\nu}}{\partial \eta} + F(z)V\frac{\partial \tilde{\nu}}{\partial \eta} = (P\nu - D\nu) + \frac{F(z)}{r\sigma_\nu}\frac{\partial}{\partial \eta}\left[r(\nu_{eff})F(z)\frac{\partial \tilde{\nu}}{\partial \eta}\right] + \frac{C_{b2}}{\sigma_\nu}\left(F(z)\frac{\partial \tilde{\nu}}{\partial \eta}\right)^2, \\ \nu_{eff} = \frac{1}{\mathrm{Re}} + \nu_t \end{cases}$$

$$\begin{cases} U^{n+1} = \tilde{U} - \Delta t \frac{\partial \delta p}{\partial z} \\ V^{n+1} = \tilde{V} - \Delta t \frac{\partial \delta p}{\partial r} \end{cases} \quad (11)$$

Equation (10) is a system of RANS equations written in the cylindrical coordinate of the new variables. The superscript "$\tilde{U}$" denotes an intermediate grid function for the velocity vector; pressure correction. Multiplying equation (11) by the gradient and taking into account the solenoids of the velocity $\delta p = p^{n+1} - p^n$ vector on the (n+1)th time layer, we obtain the Poisson equation for determining the pressure correction:

$$\Delta t\left(\frac{\partial^2 \delta p}{\partial z^2} + \frac{\partial^2 \delta p}{\partial r^2} + \frac{\partial \delta p}{r \partial r}\right) = \frac{\partial U^n}{\partial z} + \frac{\partial r V^n}{r \partial r}; \quad (12)$$

Equations (12) of the new variables have the form:

$$\Delta t\left(\frac{\partial^2 \delta p}{\partial \xi^2}+2\eta'\frac{\partial^2 \delta p}{\partial \xi \partial \eta}+(\eta')^2\frac{\partial^2 \delta p}{\partial \eta^2}+\eta''\frac{\partial \delta p}{\partial \eta}+A^2\frac{\partial^2 \delta p}{\partial \eta^2}+A\frac{\partial \delta p}{r\partial \eta}\right)=\frac{\partial U^n}{\partial \xi}+\eta'\frac{\partial U^n}{\partial \eta}+A\frac{\partial rV^n}{r\partial \eta}. \quad (13)$$

The solution of the stationary problem is carried out by the method of time determination, therefore the dependence (13) is written in the form of a non-stationary differential equation

$$\frac{\partial \delta p}{\partial t_0}-\Delta t\left(\frac{\partial^2 \delta p}{\partial \xi^2}+2\eta'\frac{\partial^2 \delta p}{\partial \xi \partial \eta}+(\eta')^2\frac{\partial^2 \delta p}{\partial \eta^2}+\eta''\frac{\partial \delta p}{\partial \eta}+A^2\frac{\partial^2 \delta p}{\partial \eta^2}+A\frac{\partial \delta p}{r\partial \eta}\right)=\frac{\partial U^n}{\partial \xi}+\eta'\frac{\partial U^n}{\partial \eta}+A\frac{\partial rV^n}{r\partial \eta}. \quad (14)$$

where the dummy time *t0* is an iterative parameter. When solving equation (14) for a time step, it is possible to write $\Delta t_0 = a_1 \Delta t$, while the value of the constant a_1, as a rule, is less than one and is selected from the condition of rapid convergence of the numerical process. The Neumann condition is used as a boundary condition for pressure correction, $\tilde{U}$ which is fulfilled if the exact value is used for the boundary U^{n+1} [11-15]:

For the numerical solution of the transfer equation of the system (10), a finite-difference scheme against the flow is used, which has a second-order accuracy, i.e. $O(\Delta t, \Delta\xi^2, \Delta\eta^2)$.

$$\begin{cases}
\frac{\tilde{U}-U^n}{\Delta t}+U^n\frac{\partial U^n}{\partial \xi}+U^n\eta'\frac{\partial U^n}{\partial \eta}+V^n\times F(z)\frac{\partial U^n}{\partial \eta}+\frac{\partial P}{\partial \xi}+\eta'\frac{\partial P}{\partial \eta}=\frac{F(z)}{r}\frac{\partial}{\partial \eta}\left[r\nu_{eff}F(z)\frac{\partial \tilde{U}}{\partial \eta}\right],\\
\frac{\tilde{V}-V^n}{\Delta t}+U^n\frac{\partial V^n}{\partial \xi}+U^n\eta'\frac{\partial V^n}{\partial \eta}+V^n\times F(z)\frac{\partial V^n}{\partial \eta}-\frac{G^2}{r^3}+F(z)\frac{\partial P}{\partial \eta}=\frac{F(z)}{r}\frac{\partial}{\partial \eta}\left[r\nu_{eff}F(z)\frac{\partial \tilde{V}}{\partial \eta}\right]-\frac{\nu_{eff}}{r^2}\tilde{V},\\
\frac{\tilde{G}-G^n}{\Delta t}+U^n\frac{\partial G^n}{\partial \xi}+U^n\eta'\frac{\partial G^n}{\partial \eta}+V^n\times F(z)\frac{\partial G^n}{\partial \eta}=\frac{F(z)}{r}\frac{\partial}{\partial \eta}\left(r\nu_{eff}F(z)\frac{\partial \tilde{G}}{\partial \eta}\right)-\frac{F(z)}{r^2}\frac{\partial}{\partial \eta}\left(2\nu_{eff}\tilde{G}\right)+\frac{2\nu_{eff}}{r^2}\tilde{G},\\
\frac{\partial \tilde{\nu}}{\partial t}+U\frac{\partial \tilde{\nu}}{\partial \xi}+U\eta'\frac{\partial \tilde{\nu}}{\partial \eta}+F(z)V\frac{\partial \tilde{\nu}}{\partial \eta}=(P\nu-D\nu)+\frac{F(z)}{r\sigma_\nu}\frac{\partial}{\partial \eta}\left[r(\nu_{eff})F(z)\frac{\partial \tilde{\nu}}{\partial \eta}\right]+\frac{C_{b2}}{\sigma_\nu}\left(F(z)\frac{\partial \tilde{\nu}}{\partial \eta}\right)^2,\\
\nu_{eff}=\frac{1}{\mathrm{Re}}+\nu_t
\end{cases} \quad (15)$$

$$\Phi=\begin{bmatrix}U\\V\\G\\\tilde{\nu}\end{bmatrix},\ \Pi^{(\Phi)}=\begin{bmatrix}-\left(\frac{\partial P}{\partial \xi}+\eta'\frac{\partial P}{\partial \eta}\right)\\ \frac{G^2}{r^3}-F(z)\frac{\partial P}{\partial \eta}-\frac{\nu_{eff}}{r^2}\tilde{V}\\ -\frac{F(z)}{r^2}\frac{\partial}{\partial \eta}\left(2\nu_{eff}\tilde{G}\right)+\frac{2\nu_{eff}}{r^2}\tilde{G},\\ (P\nu-D\nu)+\frac{C_{b2}}{\sigma_\nu}\left(F(z)\frac{\partial \tilde{\nu}}{\partial \eta}\right)^2\end{bmatrix},\ a^{(\Phi)}=\begin{bmatrix}r\nu_{eff}F(z)\\r\nu_{eff}F(z)\\r\nu_{eff}F(z)\\r(\nu+\tilde{\nu})F(z)\end{bmatrix}.$$

The scheme against the flow has the form

$$U_{i,j}=U^n_{i,j},\quad V_{i,j}=\left(U^n_{i,j}\eta'+V^n_{i,j}F(z)\right),$$

$$\frac{\Phi^{n+1}_{i,j}-\Phi^n_{i,j}}{\Delta t}+\frac{0.5\left(U_{i,j}+\left|U_{i,j}\right|\right)}{L}\frac{\Phi^n_{i,j}-\Phi^n_{i-1,j}}{\Delta\xi}+\frac{0.5\left(U_{i,j}-\left|U_{i,j}\right|\right)}{L}\frac{\Phi^n_{i+1,j}-\Phi^n_{i,j}}{\Delta\xi}+0.5\eta'\left(U_{i,j}+\left|U_{i,j}\right|\right)\frac{\Phi^n_{i,j}-\Phi^n_{i,j-1}}{\Delta\eta}+ \quad (16)$$

$$0.5\eta'\left(U_{i,j}-\left|U_{i,j}\right|\right)\frac{\Phi^n_{i,j+1}-\Phi^n_{i,j}}{\Delta\eta}+0.5F(z)\left(V_{i,j}+\left|V_{i,j}\right|\right)\frac{\Phi^n_{i,j}-\Phi^n_{i,j-1}}{\Delta\eta}+0.5F(z)\left(V_{i,j}-\left|V_{i,j}\right|\right)\frac{\Phi^n_{i,j+1}-\Phi^n_{i,j}}{\Delta\eta}=$$

$$=F(z)\frac{\Phi^{n+1}_{i,j+1}(a^{(\Phi)}_{i,j+1}+a^{(\Phi)}_{i,j})-\Phi^{n+1}_{i,j}(a^{(\Phi)}_{i,j+1}+2a^{(\Phi)}_{i,j}+a^{(\Phi)}_{i,j-1})+\Phi^{n+1}_{i,j-1}(a^{(\Phi)}_{i,j}+a^{(\Phi)}_{i,j-1})}{2r_j\Delta\eta^2}+\Pi^{(\Phi)}.$$

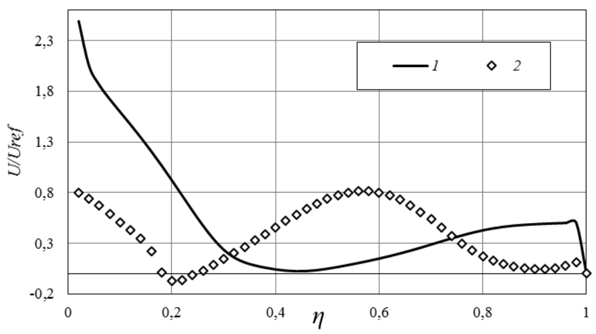
The pressure correction equation in the system (14) has an elliptical form[21-30]. For the numerical solution of such equations, the relaxation method in the direction of □ and the run in ξ is effective and quite simple.

$$\frac{\delta p_{i,j}^{n+1}-\delta p_{i,j}^{n}}{\Delta t_0}-\left(\frac{\delta p_{i+1,j}^{n}-2\delta p_{i,j}^{n+1}+\delta p_{i-1,j}^{n}}{\Delta\xi^2}+\eta'\frac{\delta p_{i+1,j+1}^{n}-\delta p_{i+1,j-1}^{n}-\delta p_{i-1,j+1}^{n}+\delta p_{i-1,j-1}^{n}}{2\Delta\xi\Delta\eta}\right)-$$
$$-\left(\left((\eta')^2+F(z)^2\right)\frac{\delta p_{i,j+1}^{n+1}-2\delta p_{i,j}^{n+1}+\delta p_{i,j-1}^{n+1}}{\Delta\eta^2}+\left(\eta''+\frac{F(z)}{r_j}\right)\frac{\delta p_{i,j+1}^{n+1}-\delta p_{i,j-1}^{n+1}}{2\Delta\eta}\right)= \quad (17)$$
$$=\frac{1}{\Delta t}\left(\frac{U_{i,j}^{n}-U_{i-1,j}^{n}}{\Delta\xi}+\eta'\frac{U_{i,j}^{n}-U_{i,j-1}^{n}}{\Delta\eta}+F(z)\frac{V_{i,j}^{n}r_j-V_{i,j-1}^{n}r_{j-1}}{r_j\Delta\eta}\right).$$

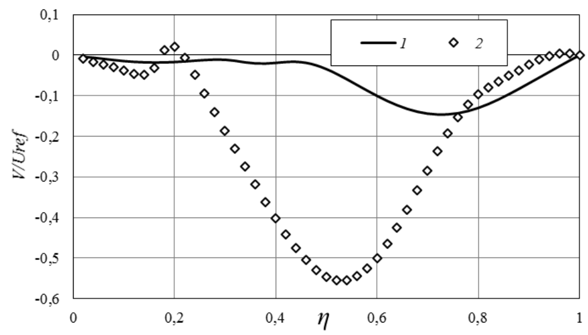
Thus, first, the system of equations (10) is solved by the method of determination, then equation (12) and, in accordance with (11), the velocity vector on the (n+1) th time layer and pressure are determined. $\delta p^{n+1}=p^n+\delta p$

DISCUSSION OF THE RESULTS

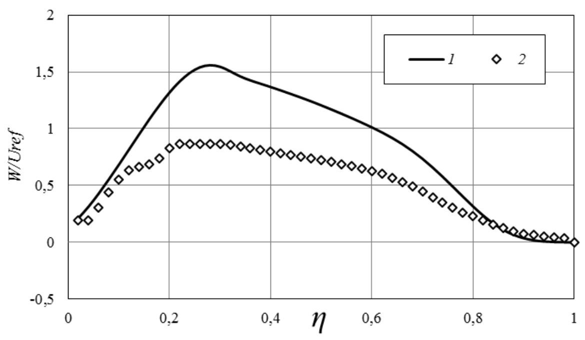
Figure 3 illustrates the profiles of air velocities in the cross section $\xi=0.65$. Here $U/Uref, V/Uref, W/Uref$ - dimensionless speeds. Here $Uref=U_0, Wref/Uref=1$.



a)



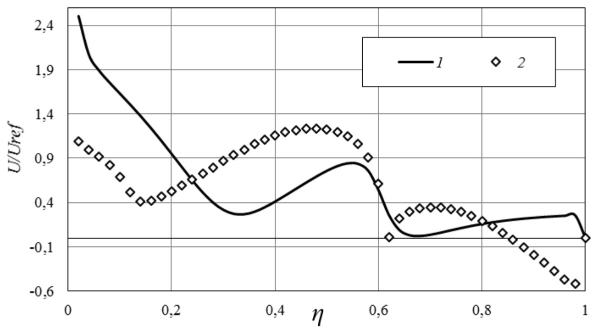
b)



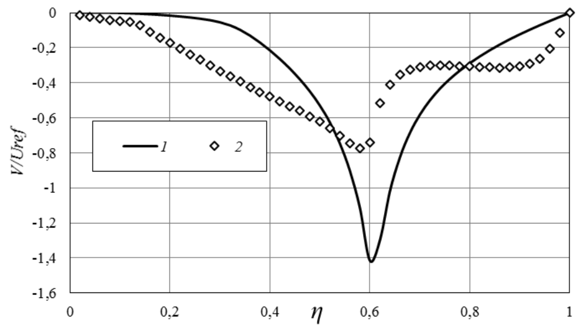
c)

Fig.3. Profiles, a) axial, b) radial and c) tangential air flow velocities in cross section ξ =0.65 at $Wref/Uref$ =1. 1- using vorticity and current function, 2- Semi-implicit method for pressure coupling SIMPLE.

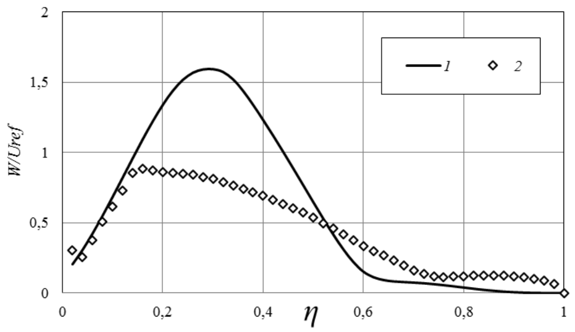
Figure 4 illustrates the profiles of air velocities in the cross section $\xi=0.7$. Here $U/Uref, V/Vref, W/Wref$ - dimensionless speeds. Here $Uref=U_0, Wref/Uref=1$.



a)



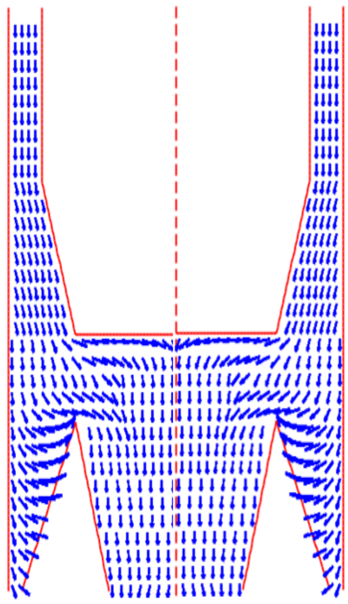
b)



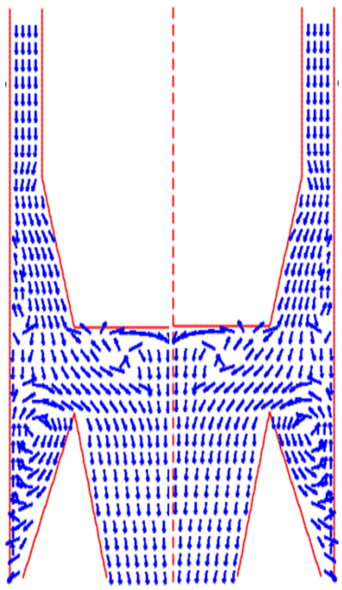
c)

Fig.4. Profiles, a) axial, b) radial and c) tangential air flow velocities in cross section ξ =0.7 at $Wref\ /Uref$ =1. 1- using vorticity and current function, 2- Semi-implicit method for pressure coupling SIMPLE.

Figure 5 shows the velocity vector field in the central section.



a)



b)

Fig. 5. a- using the vorticity and the current function, b- A semi-implicit method for pressure binding SIMPLE.

CONCLUSIONS

It can be seen from the presented figures that the numerical results of the SA and SARC models differ quite significantly. However, it is noted in [2,4] that for swirling flows, the SARC model gives closer results to experimental data. Therefore, it can be assumed that the turbulent SARC model is more suitable for describing the processes occurring inside centrifugal apparatuses.

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