Journal of Siberian Federal University. Mathematics & Physics 2023, 16(5), 651–660

EDN: QPTSAK
УДК 532.5

Investigation of the Effect of Air Admission on the Vortex Structure of the Flow in a Tangential Chamber

Dmitriy V. Platonov*
Siberian Federal University
Krasnoyarsk, Russian Federation
Andrey V. Sentyabov†
Kutateladze Institute of Thermophysics SB RAS
Novosibirsk, Russian Federation
Andrey V. Minakov‡
Siberian Federal University
Krasnoyarsk, Russian Federation
Sergey I. Shtork§
Kutateladze Institute of Thermophysics SB RAS
Novosibirsk, Russian Federation

Received 10.07.2023, received in revised form 10.08.2023, accepted 11.09.2023

Abstract. In the work, numerical simulations of a turbulent swirling flow in a model tangential chamber were performed. Depending on the swirl number and water flow discharge, various flow regimes are observed: a column vortex, a spiral vortex, a double spiral vortex. In this paper, a study was made of admission air to control the transition between flow regimes. It is shown that when a gas phase is added, a transition from a two-helix structure to a single helical vortex occurs. This phenomenon reproduces the effect observed in the experiment.

Keywords: numerical simulation, swirl number, tangential chamber, multiphase flow, air admission, double-helix vortex structure, mixture model, Euler model.

Citation: D.V. Platonov, A.V. Sentyabov, A.V. Minakov, S.I. Shtork, Investigation of the Effect of Air Admission on the Vortex Structure of the Flow in a Tangential Chamber, J. Sib. Fed. Univ. Math. Phys., 2023, 16(5), 651–660. EDN: QPTSAK.

The tangential vortex chamber is one of the convenient objects for studying various vortex structures. In a rectangular chamber, various flow regimes were observed, such as a columnar vortex, a helical vortex, and a double helical vortex [1]. In other experimental works, the transition between a single and a double helical vortex was studied in a similar circular chamber [2, 3]. In addition, methods for controlling transitions between modes, including the effect of the gas phase to the flow structure, were studied in experiment. On the basis of recent experimental studies, in this work, numerical simulation of the effect of air admission on the vortex structure of a turbulent swirling flow in a cylindrical tangential chamber was carried out.

The control of swirling flow by air admission has been studied in many experimental works. In particular, air admission is widely used to reduce pressure fluctuations caused by the precessing

*platonov-08@yandex.ru https://orcid.org/0000-0001-7276-1499
†sentyabov_a_v@mail.ru
‡Aminakov@sfu-kras.ru
§sergei_stork@mail.ru

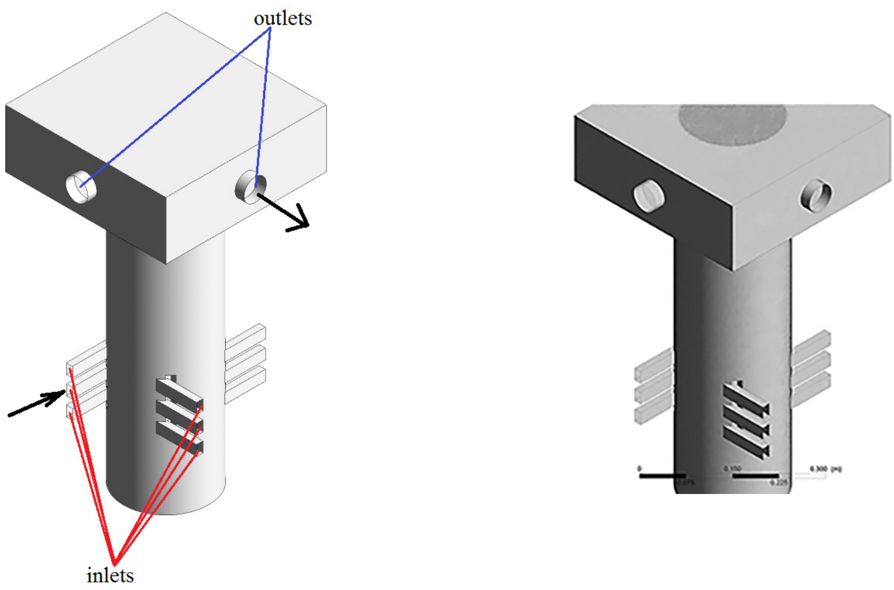
vortex rope behind the runner of a water turbine. This method is used to suppress hydrodynamic pulsations of various origins and frequencies, including noise and vibration reduction [4]. In a two-phase gas-liquid medium, the speed of sound decreases sharply, which leads to a decrease in the frequency of natural oscillations of the flow path. Since the influence of air inlet is associated with acoustic processes, and the precession of the vortex rope is associated with the dynamics of an ideal fluid, it is impossible to fully transfer the results from the scale model to natural conditions [4], which actualizes the need for numerical simulation of this complex of processes.

1. Numerical model

1.1. Computational Domain, Mesh Resolution and Boundary Conditions

The vortex flow in the cylindrical tangential chamber shown in Fig. 1a is considered. A water flow with density $\rho = 998$ kg/m^3 and viscosity $\mu = 10^{-3}$ Pa·s was supplied through 12 rectangular nozzles to form a swirling flow. The flow was released through the upper tank of rectangular cross section by means of four round nozzles. The internal diameter of the chamber was 0.19 m, and its height was 0.6 m. Each nozzle had a rectangular cross-section of 14x23 mm, and they were located in four blocks in 3 rows.The same flow rate was set at each inlet nozzles. Zero pressure was set at the outlets.

The grid consisted of cubic cells in the volume and a prismatic boundary layer with a transition region (Fig. 1b). A boundary layer of prismatic cells was refined near the walls. The computational grid contained 37.6 million cells, with $y_+ < 3$ on the wall.



a *b*

Fig. 1. Computational domain (*a*) and computational mesh (*b*)

The turbulent flow was calculated using the LES method with the WALE subgrid model [5]. The time step was 10^{-4} s which at a flow rate of 14 m^3/h corresponds to the Courant number

$C_{\text{CFL}} < 0.3$ in the entire computational domain. The numerical simulation was based on the control volume method and the incompressible flow approximation. The SIMPLEC procedure was used to connect the velocity and pressure fields. The convective terms was approximated by means of the central difference scheme, and the second-order scheme was used to approximate the unsteady term.

There are two approaches to modeling the multiphase flow. One of them is based on the continuum representation of both the carrier and the dispersed phase (Euler's approach), the second is based on the simulation of the motion of individual particles with a calculated velocity field of the carrier phase (Lagrange's approach). In turn, the Euler approach is subdivided into several models, of which the Mixture model and the Eulerian model are of interest for the purposes of this study.

1.2. Mixture model equations

The Mixture model is based on the shared equations of continuity and momentum transfer for a homogeneous mixture, the properties of which are determined in accordance with the local fractures of the phases. A two-phase medium is considered as consisting of two components: liquid and gas and having a continuous density distribution. The local properties of a two-phase medium depend on the local value of the gas volume fraction, which is (Fig. 2):

$$\alpha_g = \frac{V_{\text{gas}}}{V_{\text{cell}}}, \tag{1}$$

where V_{gas} is a total volume of gas bubbles in the cell, V_{cell} is the mesh cell volume.

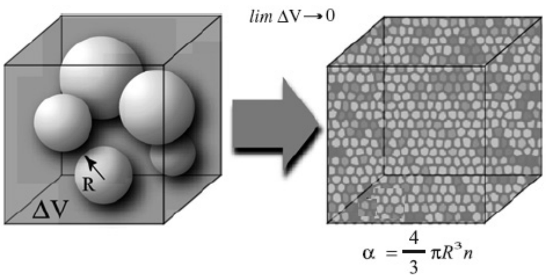


Fig. 2. Mixture model approximation

The density of the mixture (two-phase medium) is defined as the density of a multicomponent medium in terms of the densities of the individual phases:

$$\rho = \alpha_g \rho_g + (1 - \alpha_g)\,\rho_L, \tag{2}$$

molecular viscosity of the mixture, respectively:

$$\mu = \mu_g \alpha_g + (1 - \alpha_g)\,\mu_L. \tag{3}$$

The mathematical model of the flow within the framework of the continuum approximation is based on the conservation laws for a multicomponent incompressible flow.
Continuity equation (law of conservation of mass):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0. \tag{4}$$

Momentum equation (momentum conservation law):

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla p + \nabla(\tau), \tag{5}$$

where the stress tensor is

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right). \tag{6}$$

A feature of the Mixture model is the shared partial differential equations for pressure and velocity of the mixture. Thus, in comparison with the single-phase flow model, only one differential equation is added which is the gas fraction transfer equation:

$$\frac{\partial (\rho_g \alpha_g)}{\partial t} + \nabla \cdot (\rho_g v\, \alpha_g) = -\nabla \cdot (\alpha_g \rho_g \mathrm{v}_{dr}), \tag{7}$$

where the parameter v_{dr} is determined by the velocity of the gas bubbles relative to the liquid, which, in turn, is calculated from the condition of the balance of forces acting on the bubble.

1.3. Eulerian model equations

In contrast to the Mixture model, in the Eulerian model, the mass conservation equations and the momentum conservation equations are solved for each phase separately, taking into account the interaction between the phases, while maintaining the same pressure for all phases.

Transfer equation for the fraction of phase k:

$$\frac{\partial (\rho_k \alpha_k)}{\partial t} + \nabla \cdot (\rho_k v_k\, \alpha_k) = \sum_{l=1}^{n} (\dot{m}_{lk} - \dot{m}_{kl}), \tag{8}$$

where $\dot{m}_{lk}$ is the phase exchange rate.

Momentum transfer equation for phase k:

$$\frac{\partial (\alpha_k \rho_k v_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k v_k v_k) = -\alpha_k \nabla p + \nabla(\tau_k) + \sum_{l=1}^{n} (\mathbf{R}_{lk} + v_{lk}\dot{m}_{lk} - v_{kl}\dot{m}_{kl}) + \mathbf{F}_{\mathrm{lift},k}, \tag{9}$$

where $\mathbf{R}_{lk}$ is an interaction force between phases, and $\mathbf{F}_{\mathrm{lift},k}$ is a lift force acting on the gas bubbles from the carrier liquid.

This approach makes it possible to simulate the motion of gas bubbles relative to liquid for various ratios of the bubble relaxation time to the characteristic time of the problem.

2. Results of single-phase simulations

Single-phase flow calculations were carried out for two swirl numbers. The swirl number, according to the approximate formula for a tangential chamber, is inversely proportional to the number of the open nozzles (i.e., the total area of the inlets):

$$S = \frac{\pi D d}{2 n \sigma}, \tag{10}$$

where D is the chamber diameter, d is the nominal circle diameter associated with the nozzle rotation angle, n is the number of open nozzles, σ is the cross-sectional area of each nozzle.

When all 12 inputs are open, the swirl number $S = 6.6$. With one row of nozzles closed, the swirl number will be equal to $S = 3/2 \cdot 6.6 = 9.9$.

The flow rate was 14 m^3/h, which corresponds to the Reynolds number Re $= 25800$. The Reynolds number is based on the average axial velocity in the tangential chamber:

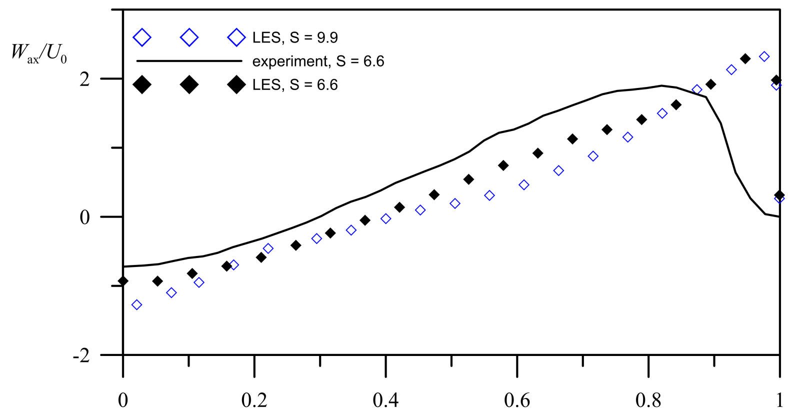
$$\mathrm{Re} = \frac{U_0 2R\rho}{\mu}, \quad U_0 = \frac{Q}{\pi R^2}, \tag{11}$$

where R is the radius of the tangential chamber. The Strouhal number is based on the same velocity:

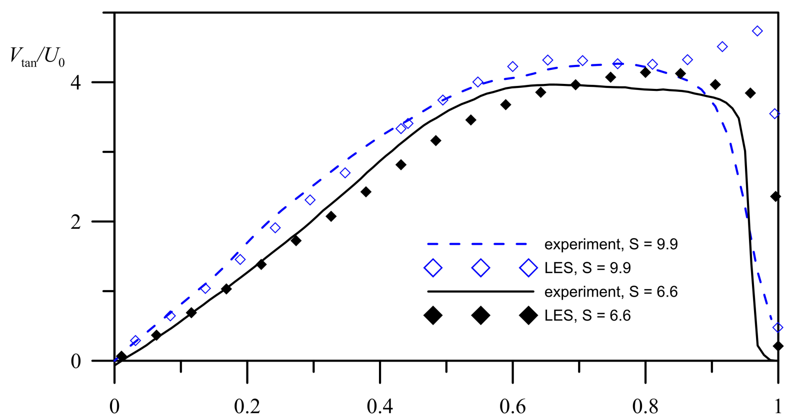
$$\mathrm{St} = \frac{2Rf}{U_0}, \tag{12}$$

where f is the dominant frequency of the pressure pulsations.

For comparison, graphs of the average velocity components in horizontal sections $z = 320$ mm and $z = 470$ mm were plotted (Fig. 3). The mean velocity profiles show close agreement with



(*a*)

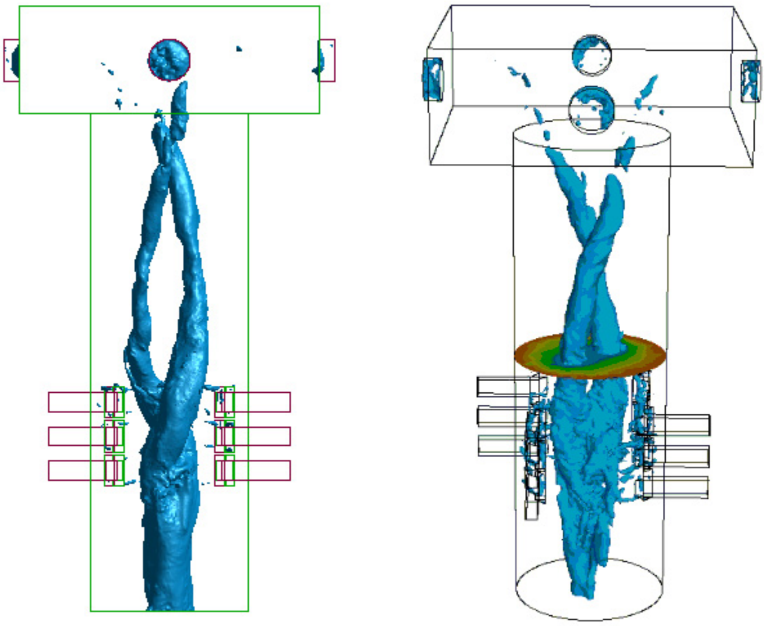


(*b*)

Fig. 3. Axial (*a*) and tangential (*b*) components of the average velocity in the section $z = 320$ mm for different swirl numbers

experiment for both flow regimes. As can be seen from the graphs, the tangential velocity profile almost completely tracks the experimental results. The graph of the axial velocity component is also close to the experimental data, except for the near-wall region, in which the experiment shows a significantly greater thickness of the boundary layer.

Calculations for the swirl mode $S = 9.9$ showed that there is a well-defined and stable two-vortex structure in the flow, which is depicted using the pressure isosurface in Fig. 4. In the mode $S = 6.6$, a double-helix structure also appears (Fig. 4), however, it is unstable and disappears with time.



a) *b*)

Fig. 4. Vortices visualized by pressure isosurface: $a)S = 6.6, b)S = 9.9$

In both modes, the spectrum of pressure fluctuations on the wall contains a dominant harmonic (Fig. 5), which corresponds to the Strouhal number $\mathrm{St} = 1.8$ in the mode $S = 6.6$ and the Strouhal number $\mathrm{St} = 3.7$ in the mode $S = 9.9$ (Tab. 1). The spectrum of pressure fluctuations was built using the fast Fourier transform of the pressure signal on the wall with a window of 8.5 s, which gives a frequency step of 0.11 Hz ($\Delta\mathrm{St} = 0.16$). In the mode $S = 6.6$, the spectrum also contains a lower harmonic $\mathrm{St} = 0.8$, and in the mode $S = 9.9$ it contains the harmonic $\mathrm{St} = 1.3$. The last harmonic approximately corresponds to the rotation speed of the two-helix vortex structure as a whole. During one revolution, the centers of the vortices of the double-helix structure pass the monitoring point twice, thus generating pulsations with a frequency twice as high as the frequency of rotation of the double-helix structure itself.

Table 1. Strouhal number of the dominant harmonics of the pressure fluctuations

	calculations	experiment
S = 6.6	1.8	1.7
S = 9.9	3.7	4.0

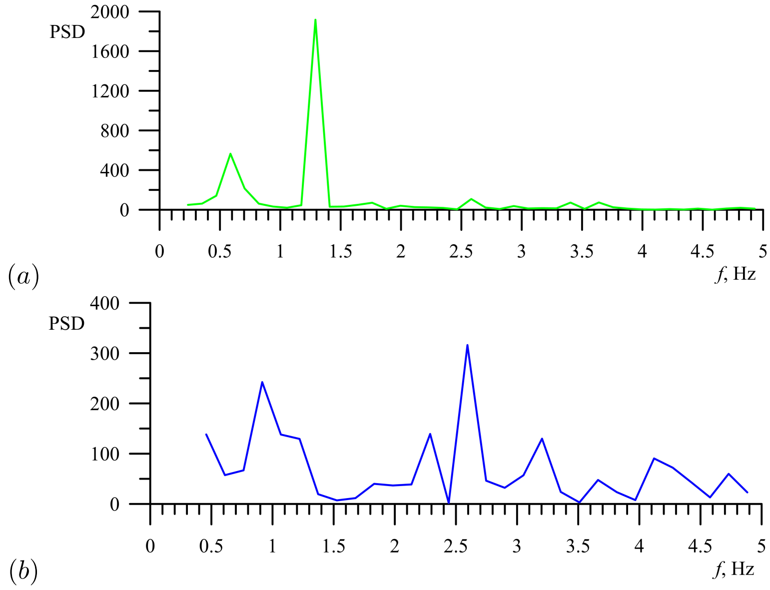
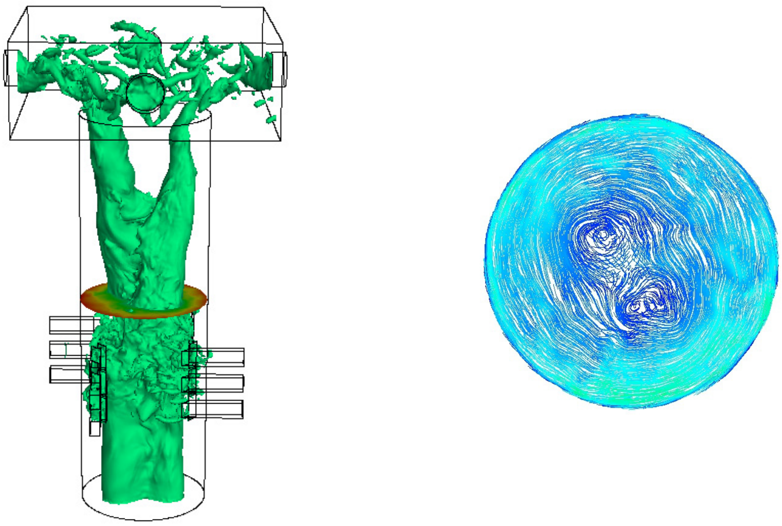


Fig. 5. Power spectral density of pressure fluctuations on the wall: $(a) S = 6.6$, $(b) S = 9.9$

3. Results of two-phase simulations

When calculating the flow with air admission, the water flow rate was 14 m^3/h and the air flow rate was 0.7 m^3/h, so the air volume fraction at the inlet was 5%. The density of water was 998 kg/m^3, and the density of air was 1.225 kg/m^3. The size of air bubbles (dispersion) was 2 mm. The swirl number of the flow was $S = 9.9$, which corresponds to the formation of the two-helix vortex structure.



a *b*

Fig. 6. Mode $S = 9.9$, calculations with air (Mixture model, concentration 5%, dispersion 2 mm): *a*) vortex visualized by pressure isosurface, *b*) streamlines at $z = 320$ mm

Calculations of the two-phase flow in the vortex chamber using the Mixture model in this mode did not show the influence of the gas phase on the flow patterns. In this calculation, a stable two-helix vortex structure was formed in the tangential chamber (Fig. 6). At the same time, the gas phase in these calculations was not concentrated at the centers of the vortices (as happens in the experiment), which shows that the slip velocity approximation in the Mixture model is limited for the conditions of this tangential vortex chamber.

Calculations with the Eulerian model showed that the air bubbles follow the position of the vortex of the two-helix structure well, as that is observed in the experiment. As the transient calculation proceeds, the two-helix vortex structure gradually collapse into a single vortex, and this happens gradually as the branches of the two-helix structure approach and merge from bottom to top (Fig. 7).

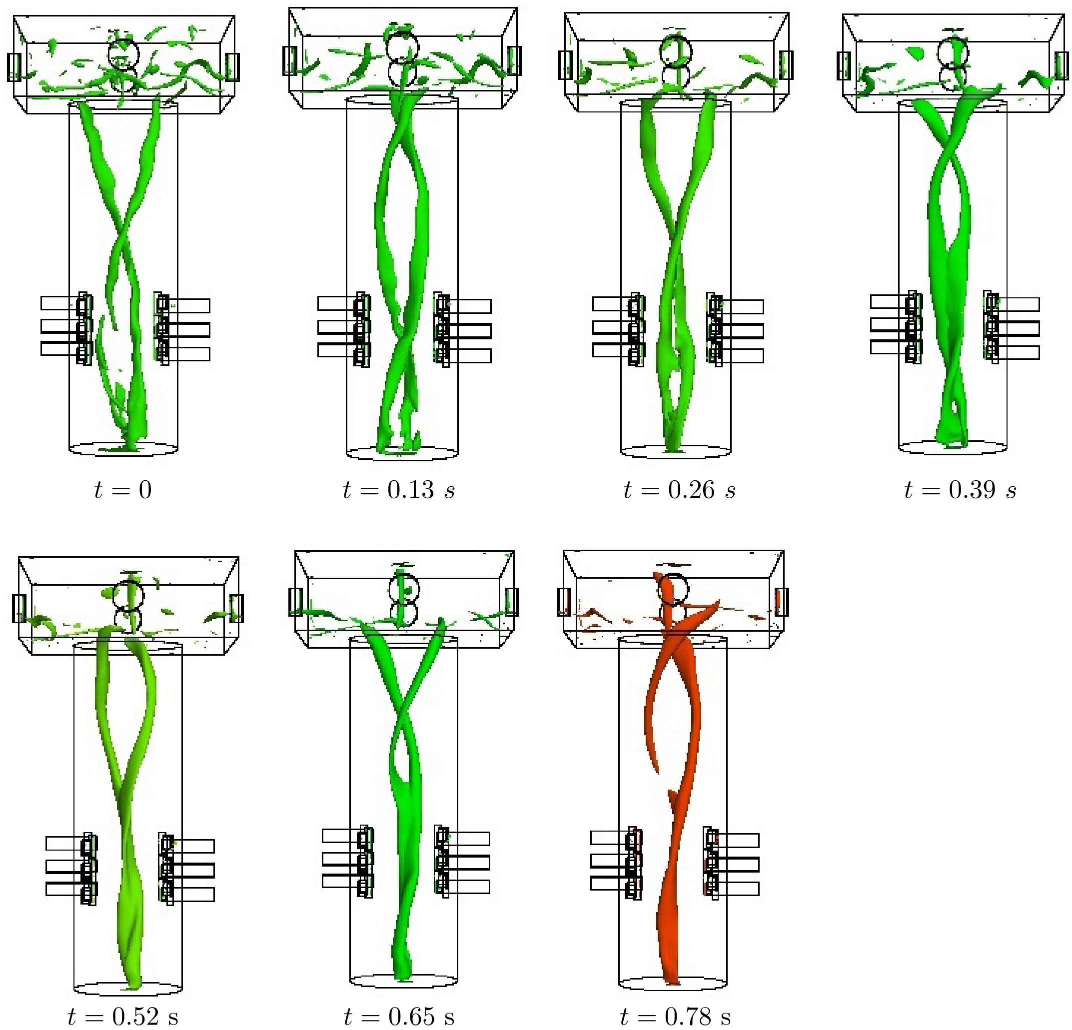


Fig. 7. Mode $S = 9.9$, multiphase calculation (Eulerian model, concentration 5%, bubbles size is 2 mm), isosurface ($f = 0.05$) of the gas volume fraction at different times

As a result of the calculations, it was possible to reproduce the effect of transition from a two-helix structure to a single helical vortex when air is added to the swirling flow. This phenomenon, obtained numerically, fully correlates with the same effect previously obtained by means of the experimental study.

Conclusions

By means of the calculations of the flow in the tangential vortex chamber, the two-helix precessing vortex structure observed in the experiment was reproduced. In single-phase calculations, the average velocity profiles in cross sections show close agreement with the experimental data for both considered flow regimes. In both modes, the dominant harmonic is observed. The pressure pulsation frequency increases with the swirl number and corresponds to the Strouhal number $\mathrm{St} = 1.8$ in the mode $S = 6.6$ and the Strouhal number $\mathrm{St} = 3.7$ in the mode $S = 9.9$. In the mode $S = 9.9$, the dominant frequency of pressure fluctuations is approximately two times higher than the rotation velocity of the two-helix vortex structure. Thus, pressure fluctuations on the wall are caused by the passage of one of the two vortices of this structure past the monitoring point. At the same time, the two-helix vortex structure experiences continuous changes, during which the vorticity is redistributed among the vortices, the distance between the centers of the vortices changes, etc.

Under the conditions of a laboratory experiment, the vortex structure of the flow is shown by means of air bubbles that accumulate in the centers of the vortices. With an increase in air discharge, the flow regime changes from a double-helix structure to a single vortex. In the calculation of a multiphase flow using the Mixture model, air bubbles do not accumulate at the centers of vortices, regardless of their dispersion. This shows the limitations of the approximation of the slip velocity for this problem. The calculation using the Eulerian model reproduces well the concentration of air bubbles in the centers of vortices. At the same time, when air is admitted, the double-helix structure gradually disappears. The transition from a two-helix structure to a single vortex occurs gradually as the spiral branches approach and merge from bottom to top.

The work was carried out with the financial support of the Russian Science Foundation (grant no. 21-19-00769, https://rscf.ru/en/project/21-19-00769/).

References

[1] S.V.Alekseenko, P.A.Kuibin, V.L.Okulov, Theory of concentrated vortices. An introduction, Berlin, Heidelberg, New York, Springer, 2007.

[2] S.V.Dremov, S.I. Shtork, S.G.Skripkin, I.K.Kabardin, An experimental investigation of the interaction between a pair of precessing vortices in a tangential vortex chamber, *Journal of Physics: Conference Series* **754**(2016), 022003. DOI: 10.1088/1742-6596/754/2/022003

[3] S.G.Skripkin, S.V.Dremov, S.I.Shtork, Applying phase averaging technique to analysis of unsteady twin vortex structure observed in tangential vortex chamber, *Journal of Physics: Conference Series* , **1382**(2019), 012042. DOI: 10.1088/1742-6596/1382/1/012042

[4] P.Dorfler, M.Sick, A.Coutu, Flow-Induced Pulsation and Vibration in Hydroelectric Machinery, London, Springer, 2013.

[5] F.Nicoud, F.Ducros, Subgrid-scale stress modeling based on the square of the velocity gradient tensor, *Flow, Turbulence and Combustion*, **62**(1999), no 3, 183–200. DOI: 10.1023/A:1009995426001

Исследование влияния подачи воздуха на вихревую структуру течения в тангенциальной камере

Дмитрий В. Платонов
Сибирский федеральный университет
Красноярск, Российская Федерация
Андрей В. Сентябов
Институт теплофизики имени С. С. Кутателадзе СО РАН
Новосибирск, Российская Федерация
Андрей В. Минаков
Сибирский федеральный университет
Красноярск, Российская Федерация
Сергей И. Шторк
Институт теплофизики имени С. С. Кутателадзе СО РАН
Новосибирск, Российская Федерация

Аннотация. В работе выполнено численное моделирование турбулентного вихревого течения в модельной тангенциальной камере. В зависимости от закрутки потока и расхода воды в камере наблюдаются различные режимы течения: колонообразный вихрь, спиральный вихрь, двойной спиральный вихрь. В работе проведено исследование влияния добавления воздуха на переход между режимами течения. Показано, что при добавлении второй фазы происходит переход от двухспиральной структуры к одиночному спиральному вихрю. Данное явление воспроизводит эффект, наблюдаемый в эксперименте.

Ключевые слова: численное моделирование, параметр закрутки, тангенциальная камера, многофазный поток, подвод воздуха, двухспиральная вихревая структура, модель смеси, полная эйлерова модель.