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NUMERICAL SIMULATION OF THE FLOW WITH DISPERSE PHASE IN A TANGENTIAL VORTEX CHAMBER

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Abstract The flow with a disperse phase in a tangential vortex chamber at high swirl numbers was studied using a numerical methods. The swirling flow is created using nozzles directed at an angle to the chamber axis. The numerical flow model was based on computational fluid dynamics methods and described the turbulent flow of water. Turbulence was simulated using the large eddy simulation method. Based on the results of single-phase flow simulation, particle motion was calculated using the Lagrange approach. The results of the single-phase flow simulation are consistent with the data from the corresponding experimental studies. The movement of particles depends significantly on their density. For massless particles, the average residence time of the particles is noticeably lower for a higher swirl number. The residence time of heavy particles is 1.5 - 2 times higher than the similar residence time of massless particles. At the same time, most of the heavy particles do not leave the tangential chamber and are deposited.

Key words: swirl flow, tangential chamber, CFD, particles.

AMS Mathematics Subject Classification: 76-10.

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1 Introduction

Swirling flows are widespread in industrial applications, therefore their dynamics are of considerable interest for research [1, 2]. Swirling flows play an important role in many energy devices, in particular, burners and furnaces [3], as well as in cyclone separators, chemical reactors [4] and wind turbines [5], water turbines [6], etc. Vortex structures arising in the flow have a significant effect on heat and mass transfer, and also intensively interact with structures [7].

An important problem is to study the patterns of swirling flow and the movement of disperse phase with various parameters. One of the convenient objects for studying such flows is a tangential vortex chamber in which the flow is swirled using nozzles directed at an angle to the axis of the chamber [8, 9]. Experiments have shown that the vortex flow in such a tangential chamber is strongly influenced by the swirl number. In a number of experimental papers [10, 11] with a tangential vortex chamber, a single or double spiral vortex was observed in the flow, depending on the flow regime. In [12], a numerical simulation of a single-phase turbulent flow in a vortex tangential chamber

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was carried out. The numerical simulation has also shown the appearance of unsteady vortex structures in the form of a single or double spiral vortex.

2 The problem description and numerical model

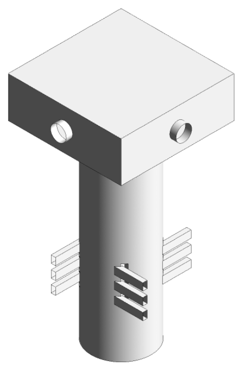

Figure 1: Computational domain.

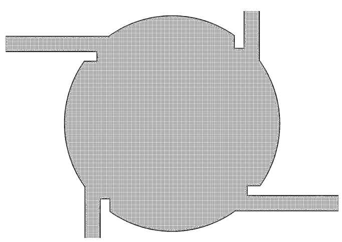

Figure 2: Computational mesh.

The numerical simulation was based on experimental work carried out on a cylindrical tangential vortex chamber with a diameter of $D = 190$ mm and a height of 0.6 m. In total, 12 nozzles were mounted in the cylindrical part, three in each of four symmetrically arranged blocks, the flow through which can be blocked independently. Computational domain of the numerical model is shown in Fig. 1. To form a swirling flow, a uniformly distributed water flow with density and viscosity $\rho = 998\,\mathrm{kg/m^3}$ and $\mu = 10^{-3}\,\mathrm{Pa\,s}$ was supplied to the cylindrical chamber. The flow was discharged through the upper tank of rectangular cross-section using four round nozzles under the condition of constant and equal pressure at the outlets of the nozzles. The water flow rate was $Q = 14\,\mathrm{m^3/h} = 0.00389\,\mathrm{m^3/s}$, which corresponded to the Reynolds number $\mathrm{Re} = 25800$, determined by the diameter of the chamber and the average longitudinal velocity. The swirl number was determined by the geometric parameters of the chamber in accordance with an approximate formula assuming a uniform profile of the axial component of the swirl velocity of the flow [2]: $S = (\pi D d)/(2n\sigma)$, where D is the diameter of the cylindrical section of the vortex chamber, d is the diameter of the reference circle associated with the angle of the nozzle, n is the number of open nozzles, σ is the cross-sectional area of each nozzle. The angle of the nozzles relative to the vortex chamber axis was chosen as maximum as possible and corresponded to the swirl number $S = 6$ (with all nozzles open). The swirl number in the tangential chamber was regulated by the number of open nozzles. When closing one or two rows of nozzles while maintaining the flow rate, the flow velocity in them increases and, accordingly, the angular momentum flux increases. The swirl number, according to the approximate formula for a tangential chamber, will be inversely proportional to the number of the open nozzles (i.e., the total area of the inlets). Thus, for one closed row of nozzles, the swirl number will be equal to $S = (3/2) \cdot 6 = 9$, and for two closed rows $S = 3 \cdot 6 = 18$.

The grid consisted of cubic cells in the core and a prismatic boundary layer with a transition region. The numerical mesh contained 37.6 millions cells and was detailed in the input channels and in the wall layer (Fig. 2), $y_+ < 3$ in the entire computational domain.

The turbulent flow was modeled using the LES method with the WALE subgrid model [13]. The time step was $1.3 \cdot 10^{-4}$ s, which corresponds to the Courant number $C_{CFL} < 0.3$ in the entire computational domain. The discretization of the transfer equations was based on the finite volume method [14, 15]. The SIMPLEC procedure [14, 15] was used to link the velocity and pressure fields. The convective terms were approximated using a central difference scheme. A second-order scheme was used for the time approximation.

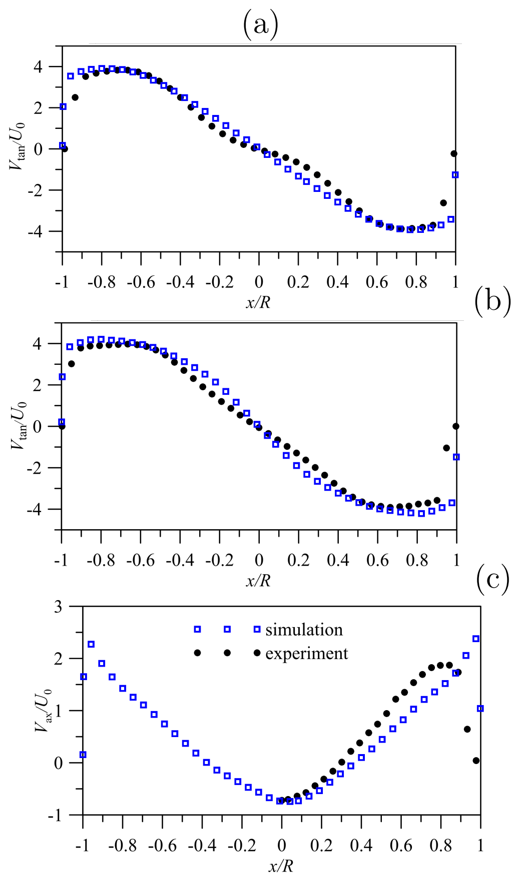

Figure 3: Comparison with experimental data: a) tangential component of average velocity in section $z = 470$ mm, b) tangential component of average velocity in section $z = 320$ mm; c) axial component of average velocity in section $z = 320$ mm

Based on single-phase calculations, the mixing processes and residence time of particles under conditions of swirling flow of a tangential chamber were simulated using the Lagrange approach. Lagrange approach is used for flows with a relatively small concentration of particles in the flow. In these methods, a particle is a point with zero geometric dimensions and the motion of particles is resolved directly and described by the motion equations of a solid body. The carrier fluid is modeled as a continuous medium. This approach allows for a visual assessment of the parameters of the path lines and the time of particle motion.

3 Results of the simulation

Preliminarily, the carrier fluid flow was calculated in various modes. Fig. 3 shows comparison of calculated average velocity components with the experimental data in two horizontal sections z = 320 mm and z = 470 mm from the lower end of the chamber. As can be seen from the Figs., the tangential velocity profile is close to the experimental one in the flow core. The plot of the axial velocity component also reproduces the experimental data in the flow core well, including the recirculation zone. At the same time, in the near-wall region, the experiment shows a significantly larger boundary layer thickness.

Averaging the transient flow shows several regions of backward flow (Fig. 4). In particular, several conjugate recirculation zones are formed in the center of the chamber. Near the upper end of the chamber, there is a toroidal recirculation zone. Below the nozzles, an additional recirculation zone is formed, adjacent to the wall of the chamber from its bottom to the lower row of nozzles. At the same time, transient data show the formation of single or double spiral vortices precessing around the chamber axis.

Based on single-phase simulation, calculations of particle motion were performed for different swirl numbers. Tab. 1 presents the parameters of massless particle motion from the inlet to the outlet, which were launched at the nozzle inlets. The particle residence time is related to the chamber turnover time T_{ref}, which at a flow rate of Q = 14 m^3/h = 0.00389 m^3/s is $T_{ref} = (4Q)/(\pi D^2 H)$, where Q is the volumetric flow rate, $D = 0.19$ m is the diameter of the tangential chamber, $H = 0.6$ m is the height of the tangential chamber.

As can be seen from Tab. 1, the residence time of particles decreases noticeably for the swirl number $S = 18$. This can be explained by the fact that high swirl leads to an increase in the volume of recirculation zones in the tangential chamber. Massless particles, as follows from this assumption, follow the carrier fluid streamlines and, accordingly, almost never enter the stagnation zones. The stagnation zones, in turn, reduce the effective volume of the tangential chamber available for the passage of the fluid, which leads to a decrease in the average residence time of massless particles.

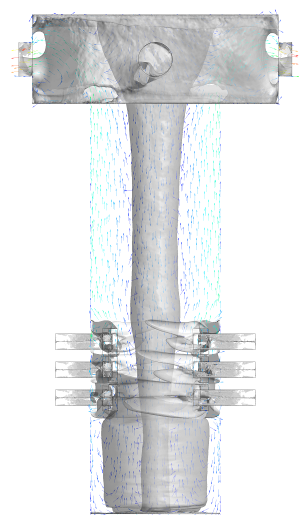

Figure 4: Axial component of average velocity in longitudinal section and recirculation zone visualized by zero iso-surface of axial velocity under the swirl number $S = 6$

In the calculations, particles were released from the upper inlets for different flow modes. Particles mainly move along the periphery of the chamber, but massless particles pervade in different parts of the tangential chamber, including its lower part near

Table 1: Dependence of the residence time of massless particles on the swirl number

Swirl number	residence time, s	relative residence time, T/T_{ref}	rms residence time, s	rms relative residence time, T/T_{ref}
$S = 6$	9.27	40.5	5.5	24.0
$S = 9$	9.18	40.1	6.2	27.1
$S = 18$	7.26	31.7	5.1	22.3

Table 2: Dependence of the residence time of heavy particles on the swirl number, without gravity

Swirl number	residence time, s	relative residence time, T/T_{ref}	rms residence time, s	rms relative residence time, T/T_{ref}
$S = 6$	14.6	63.8	7.5	32.8
$S = 18$	19.8	86.5	2.0	143.2

the bottom end (Fig. 5). It can also be seen that longer residence time is typical for those particles that move closer to the center.

As an example of heavy particles, we used anthracite particles with a diameter of 1 mm and a density of 1550 kg/m^3. Since the movement of such particles is affected by gravity, two series of calculations were carried out: with and without gravity. In this case, the gravitational acceleration was directed along the chamber axis towards the bottom end (similar to the experimental conditions), which corresponds to the downward direction.

The motion of heavy particles differs significantly from that of massless particles. As can be seen from Tabs. 2 - 7, in most cases the residence time of heavy particles is 1.5-2 times longer than that of massless particles. At the same time, most of the heavy particles do not leave the tangential chamber and are apparently deposited. As can be seen from Tab. 8, the proportion of particles that leave the tangential chamber is 60-90% for massless particles and only 0.1-4% for heavy particles.

The path lines of heavy particles without taking gravity into account show that their motion occurs closer to the wall of the tangential chamber (Fig. 6a). Despite zero gravity, particles in large quantities pervade into the chamber space below the nozzles. An interesting effect occurs when gravity is taken into account: the path lines of most particles achieve limited height (approximately the same for all swirl numbers), and particles with a long residence time are concentrated in this horizontal layer (Fig. 6b).

4 Conclusions

Calculations of particle motion under swirling flow conditions in a tangential chamber show a significant difference between the motions of massless and heavy particles. The path lines of massless particles correspond to the flow of the carrier fluid. If diffusion is neglected, this means that the particles do not pervade into the recirculation zones. The stagnation zones reduces the effective volume of the chamber available for the flow. Most of the particles move closer to the periphery of the chamber, but massless particles also pervade into other areas of the tangential chamber. This occurs, apparently, due to the complex system of recirculation zones of the vortex tangential chamber. It can also be seen that a longer residence time is a characteristic of those particles that move

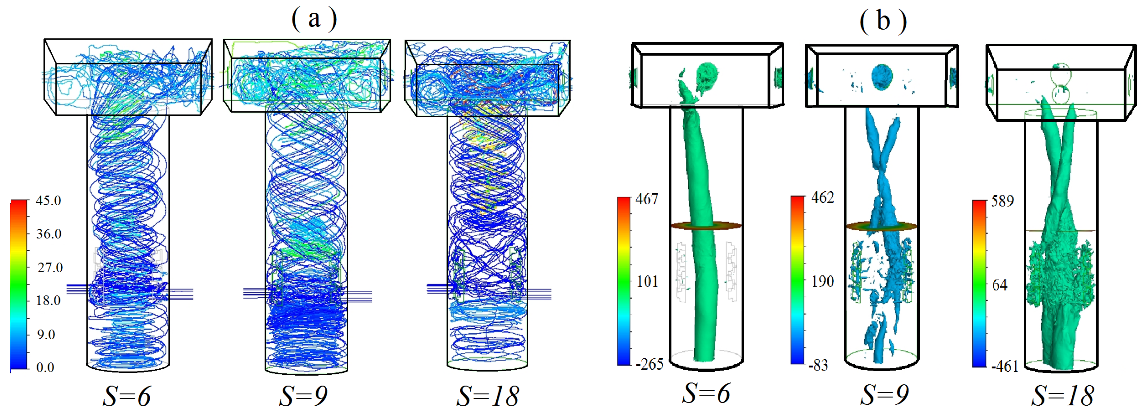

Figure 5: *a*) path lines of massless particles depending on the swirl number, the color indicates the residence time of the particle, [s]; *b*) the corresponding vortex pattern of the flow, visualizion by a pressure iso-surface, [Pa]

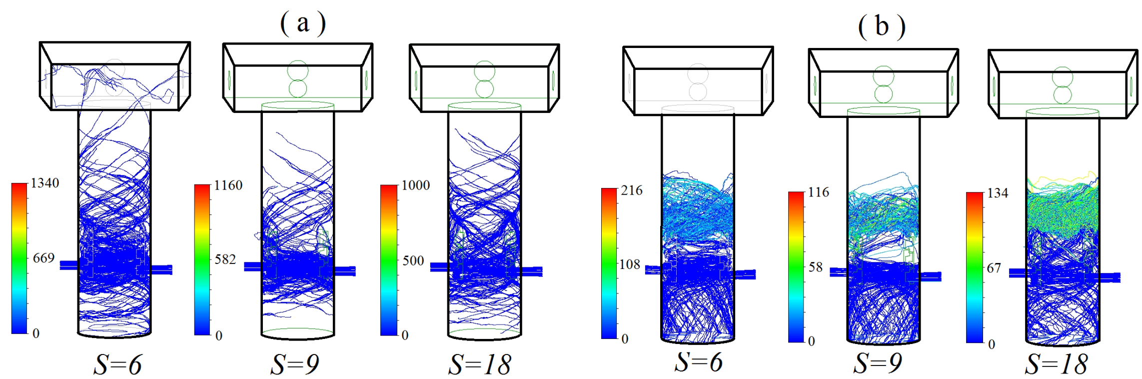

Figure 6: Path lines of heavy particles depending on the swirl number, the color indicates the particles residence time, [s]; *a*) without taking gravity into account, *b*) taking gravity into account

Figure 7: Dependence of the residence time of heavy particles on the swirl number, with gravity

Swirl number	residence time, s	relative residence time, T/T_{ref}	rms residence time, s	rms relative residence time, T/T_{ref}
$S = 6$	2.41	10.5	1.44	6.3
$S = 9$	13.7	59.8	18.1	79.0
$S = 18$	21.7	94.8	7.8	34.1

Figure 8: Fraction of particles leaving the tangential chamber, %

Swirl number	massless particles	heavy particles, without gravity	heavy particles, with gravity
$S = 6$	66	4	2
$S = 9$	89	0	2
$S = 18$	86	0.2	0.1

closer to the center of the chamber, which is probably due to lower axial flow velocities. The residence time of heavy particles is 1.5 - 2 times longer than the similar residence time of massless particles. Moreover, most of the heavy particles do not leave the tangential chamber at all and are deposited.

Thus, for massless particles, the average residence time is determined by the effective volume of the chamber, which apparently decreases with the appearance and growth of recirculation zones. At the same time, the entry of massless particles into the recirculation zones is possible due to diffusion, including the consideration of turbulent diffusion and coherent vortex structures. Particles with a density different from the density of the carrier fluid are subject to the influence of various forces: gravity, buoyancy, inertia, etc. This allows such particles to deviate from the streamlines of the fluid and, potentially, pervade into recirculation zones, increase the residence time and change their concentration in different parts of the chamber. Thus, light particles (such as air bubbles) are concentrated in the centers of the emerging vortices. Heavy particles, on the contrary, move closer to the periphery. A different behavior can be expected if the supply of particles is organized not tangentially, but radially, so that the particles, due to their inertia, fall into stagnant areas in the center of the chamber. Gravity makes heavy particles move upwind, concentrating in a horizontal layer. All the above effects depend significantly on a combination of various parameters, such as the size of the particles, their density and the density of the carrier fluid, the method of supply, the orientation relative to gravity and the structure of the flow. Swirling flow in a tangential chamber is associated with the emergence of a large number of forces and effects acting on various particles in such a medium, which opens possibilities for controlling two-phase flows.

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References

[1] Gupta A.K., Lilley D.G. and Syred N., *Swirl flows.* England, Abacus Press, Tunbridge Wells, 1984.

[2] Alekseenko S.V., Kuibin P.A. and Okulov V.L., *Theory of Concentrated Vortices: an Introduction.* Berlin-Heidelberg-New York, Springer-Verlag, 2007.

[3] Vigueras-Zuniga M.O., Valera-Medina A., Syred N., *Studies of the precessing vortex core in swirling flows.* Journal of applied research and technology, 10.5 (2012), 755-765. DOI: 10.22201/icat.16656423.2012.10.5.368

[4] Kraupl S., Steinfeld A., *Experimental investigation of a vortex-flow solar chemical reactor for the combined ZnO-reduction and CH_4-reforming.* J. Sol. Energy Eng., 123.3 (2001), 237-243. DOI: 10.1115/1.1384569

[5] Hellstrom L.H.O., Hohman T.C., Smits A.J., *POD analysis of the structure of vertical axis wind turbine wakes.* Journal of Wind Engineering and Industrial Aerodynamics, 237.4 (2023), 105403. DOI: 10.1016/j.jweia.2023.105403

[6] Dorfler P., Sick M., Coutu A., *Flow-Induced Pulsation and Vibration in Hydroelectric Machinery.* London, Springer, 2013. DOI: 10.1007/978-1-4471-4252-2

[7] Lupi F., Pieper L., Winkelmann U., Hoeffer R., *Aerodynamic damping functions in vortex-induced vibrations for structures with sharp edges*, Journal of Wind Engineering and Industrial Aerodynamics, 238.1 (2023), 105411. DOI: 10.1016/j.jweia.2023.105411

[8] Alekseenko S.V., Shtork S.I., *Swirling flow large-scale structures in a combustion model.* Russ. J. Eng. Thermophys., 2.4, (1992), 231-266.

[9] Alekseenko S.V., Kuibin P.A., Okulov V.L. and Shtork S.I., *Helical vortices in swirl flow* . J. Fluid Mech., 382 (1999), 195-243. DOI: https://doi.org/10.1017/S0022112098003772

[10] Dremov S.V., Shtork S.I., Skripkin S.G. and Kabardin I.K., *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

[11] Skripkin S.G., Dremov S.V., Shtork S.I., *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

[12] Sentyabov A.V., Platonov D.V., Shtork S.I., Skripkin S.G., Minakov A.V., *Numerical simulation of a double helix vortex structure in a tangential chamber*. International Journal of Heat and Fluid Flow, 107 (2024), 109398. https://doi.org/10.1016/j.ijheatfluidflow.2024.109398

[13] Nicoud F., Ducros F., *Subgrid-scale stress modeling based on the square of the velocity gradient tensor*. Flow Turbul. Combust., 62.3 (1999), 183-200. DOI: 10.1023/A:1009995426001

[14] Ferziger J.H. and Peric M., *Computational Methods for fluid dynamics.* Berlin, Heidelberg, Springer-Verlag, 2002.

[15] Patankar S., *Numerical Heat Transfer and Fluid Flow.* N.Y., Hemisphere, 1980.

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