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Numerical study of the screw rotors for small scale hydropower

D V Platonov[1,2], A V Minakov[1,2], D A Dekterev[1,2], A A Dekterev[1,2], Ar A Dekterev[1] and A S Lobasov[1]

[1]Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia
[2]Siberian Federal University, Krasnoyarsk, Russia

E-mail: platonov-08@yandex.ru

Abstract. This paper reports on the investigation of screw rotors with different geometric parameters by numerical simulation. The study was performed for the free flow around a fully submerged system. The effect of the inner shaft diameter, the rotor screw pitch and running frequency on the energy characteristics, as well as the torque on a shaft and generated power are shown. Following up upon the conducted research of the screw rotor the geometric parameters and operating modes, which allow achieving maximum effectiveness at the same initial parameters, were determined.

1. Introduction

From ancient times due to their geometric features Archimedes screws are widely used in water supply systems, for example in the irrigation systems. However, currently they are used in different industrial applications. In the 1922 in America, W. Mercer patented hydrodynamic screw turbine [1]. This date can be considered as the starting date of using an Archimedes screws as turbines for hydropower plants (HPP). The problem was further elaborated only in the 1990s when the engineer Karel-August Radlik and Professor Karel Brada developed the idea of using the Archimedes screw as a hydraulic turbine and brought it to practical implementation [2]. In 1995-1996 in Prague, the first turbine model was tested. In 1997, the Czech company SIGMA under the guidance of engineer Radlik and Professor Brada presented the first prototype of the Archimedes screw. This prototype was later installed in the HPP in Germany. In the future, it is expected to install a large number of the screw turbines in small-scale hydropower plants in Europe. By now, 11 hydropower plants with Archimedes screw were built only in the UK from 2008 to 2010. Their capacities ranged from 1.4 up to 70 kW. In the USA, the first hydroelectric power plant with a screw turbine (capacity on 105 kW) was built as late as in 2017.

Typically, screw turbines are used on rivers or in channels with a relatively low water level head (from 1 to 10 m) and low water flow rate (about 10 m3/s per turbine). A significant advantage of screw turbines over other types of turbines is that they generate a relatively large torque on the shaft at a low running frequency of the blades. This parameter is extremely important in terms for aquatic fauna safety and allows operating screw HPPs in places with high environmental requirements.

The high pace of construction of small-scale hydropower plants in pursuit of safe methods of electricity production has led to the fact that the subject of study, optimization, and modernization of screw turbines has gained great scientific interest around the world. To date, there are a lot of scientific papers aimed at studying and improving the efficiency of screw turbines depending on geometric parameters, such as the angle of installation, length, the ratio of the radii of the shaft and blades, the

number of blades, their shape and slope, the pitch of the screw, the screw filling coefficient with water, etc. [3-7]. However, almost all works consider options for using a screw turbine in stationary pressure head HPPs with full or partial overlap of the riverbed or channel. Only in some works at the level of abstracts, it is proposed to use screw turbines in floating (free-flow) micro-hydroelectric power plants (micro-HHP) [8, 9]. So currently, this area is the least studied.

The goal of this work is the investigation of the possibilities of using screws as turbines in free-flow floating and submerged micro-HHPs.

2. Numerical technique

Engineering calculations require turbulence models, which describe averaged fields and large-scale pulsations of swirling flows with sufficient accuracy.

The k-ε and k-ω turbulence models, widely used in engineering calculations, poorly describe such flows. In order to improve the simulation of turbulent swirling flows, attempts are made both to modify the existing RANS turbulence models, and to use methods, in which large-scale turbulent vortices (LES, DES) are resolved.

To simulate a vortex swirling flow, it is necessary to apply non-stationary, in particular, vortex-resolving methods, such as, for example, the Large Eddy Simulation (LES) method. However, its application requires a very detailed grid, especially near the walls. At the same time, RANS models are quite economical and describe the boundary layers well. To combine the advantages of these approaches, a method of Detached Eddy Simulation (DES) is proposed. The first version of the DES was based on the Spalart-Allmaras Turbulence Model. In the future, the DES method was used with other models of turbulence, transforming into various modifications.

The basic numerical method, in this case, was the Navier-Stokes equations averaged over Reynolds. This numerical method is described in more detail in [10, 11].

In this case, the flow is complicated by the need to take into account the rotation of the rotor and its interaction with the oncoming flow. There are many approaches for modeling flows with rotating bodies, which include dynamic grids, sliding grid approach, and the method based on the rotating reference frame.

Using a rotating coordinate system is the most common and simple way to simulate the rotation of the impeller. The transition to a rotating coordinate system allows simulating the flow in the approximation, in which the impeller is motionless, while the swirling liquid flows onto it. This approach is often called "frozen rotor".

In this paper, the simulation of rotor rotation was carried out in the framework of the frozen rotor approach. Numerous test calculations show the correctness of this approach, in terms of description of both the integral and pulsation characteristics of the flow.

The discretization of the transfer equations was carried out by the control volume method on an unstructured grid. The coupling of the velocity and pressure fields for an incompressible fluid was implemented using the SIMPLEC procedure. To approximate the convective terms of the equation to the momentum components, the Quick scheme (Leonardo scheme) was used. To approximate convective terms of the equation on turbulent characteristics, the scheme of the first order was used. Non-stationary terms were approximated by an implicit scheme of the 2nd order of accuracy. Diffusion terms were approximated by the scheme of the 2nd order. This numerical technique was tested and verified on a number of test problems and a lot of experimental data. According to the results of testing, we can say that the technique adequately describes three-dimensional turbulent swirling flows [12].

3. Simulation results

In the course of the work, a series of numerical experiments for screw rotors of different geometric parameters and running frequency was carried out. As mentioned above, the main disadvantage of using screw rotors for free-flow HPPs is their rather low energy power. Therefore, the main purpose of the work was to consider various options and define parameters which have influence on generated power.

The boundary conditions at the inlet were set in the form of a flow with a constant velocity of 1.5 m/s that roughly corresponds to the average flow velocity of the river. At the flow outlet, the conditions of free exit, as well as zero friction were set on the side walls that served to simulate an infinite open space in the flow.

A screw rotor with an outer diameter of D = 1 m, a length of L = 2 m, an internal shaft diameter of d = 0.2 m, and a pitch S1 = 0.5 m was chosen for experiments (Fig. 1). At the first stage of the study the diameter of the inner shaft varied taking values of 0.2 m, 0.3 m, and 0.4 m. In this case, in all experimental options, the rotor rotated at a speed of 20 rpm.
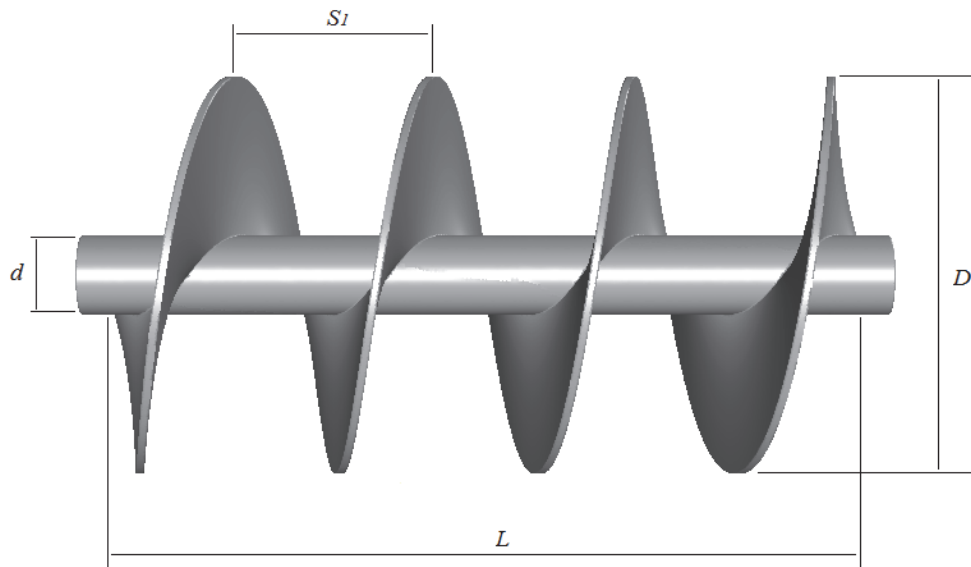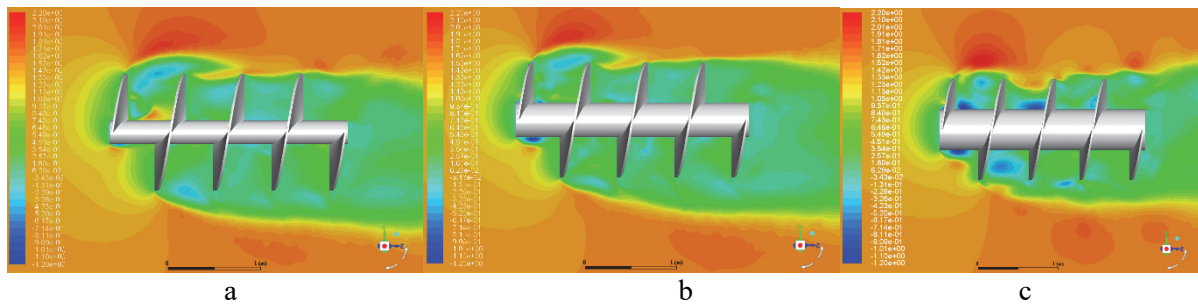

Figure 1. Configuration of the screw rotor.

According to the calculation results, it can be seen that the maximum effectiveness was obtained when using the screw rotor with the smallest diameter of the inner shaft (Table 1), which for given geometric parameters amounted to 169.9 W. Figure 2 shows the axial velocity component in the central longitudinal section. It can be concluded from the figures that with increasing diameter of the inner shaft, the screws of the rotor are less efficient since more areas with flow recirculation appear.

Table 1. Dependence of energy characteristics on the inner shaft diameter (S1=0.5 m, ω=20 rpm)

	Torque, N*m	Power, W
d = 0.2 m	80.7	169.9
d = 0.3 m	72.2	151.6
d = 0.4 m	58.3	122.1

Figure 2. Field of the axial velocity component in the central section.

When conducting calculations for previous geometric parameters, it was revealed that just the first pitch of the screw rotor was operating most efficiently. Therefore, the next stage of the research consisted in changing the pitch of the screw rotor with the diameter of the inner shaft d = 0.2 m. Figure 3 shows a selection of three different geometric parameter: S1= 0.5 m; S2= 1 m; and S3= 2 m. The running frequency, in this case, was also 20 rpm.

Simulation of the screw rotor with different screw pitch has shown that the maximum effect was achieved using the rotor with a pitch of S2 = 1 m, at a speed of 20 rpm, and a torque of 170.3 N*m, at that, the resulting power was 358.5 Watts.

**Table 2.** Dependence of energy characteristics on screw rotor pitch (d= 0.2 m, ω=20 rpm)

	Torque, N*m	Power, W
S1 = 0.5 m	80.7	169.9
S2 = 1 m	170.3	358.5
S3 = 2 m	167.1	351.8

Figure 3 shows the axial velocity fields in the central longitudinal section for rotors with different screw pitch. Analyzing the flow patterns, one can note that by increasing the pitch of the screw and maintaining the original length, the flow at the test section is much more efficient (Fig. 3b). In turn, this leads to a significant increase in energy performance. Thus, the rotor with a pitch S2 = 1 m at a running frequency of 20 rpm generates torque equal to 170.3 N*m that allows obtaining power of 358.5 W. However, with a further increase in the pitch (Fig. 3c), a decrease in both the torque and the generated power was noted.
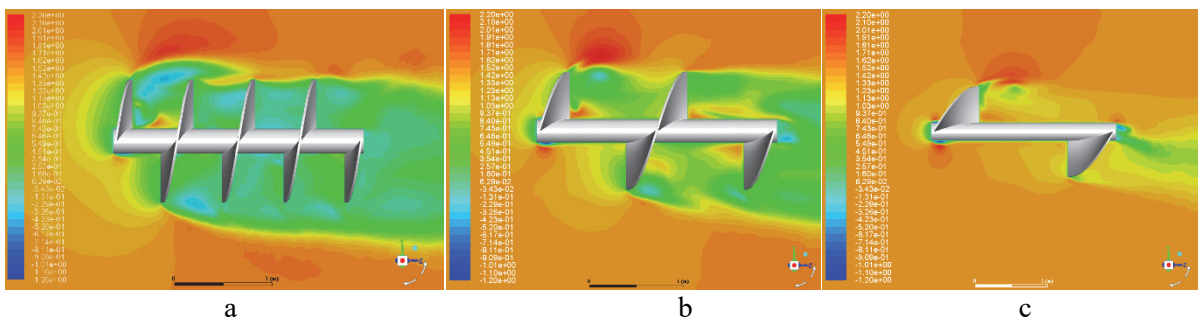
Figure 3. Field of the axial velocity component in the central section.

Further, based on the geometric parameters of the rotor with maximum effectiveness (S2 = 1 m, d = 0.2 m), the dependence of the torque (M) and power (P) on the running frequency was studied (Fig. 4).
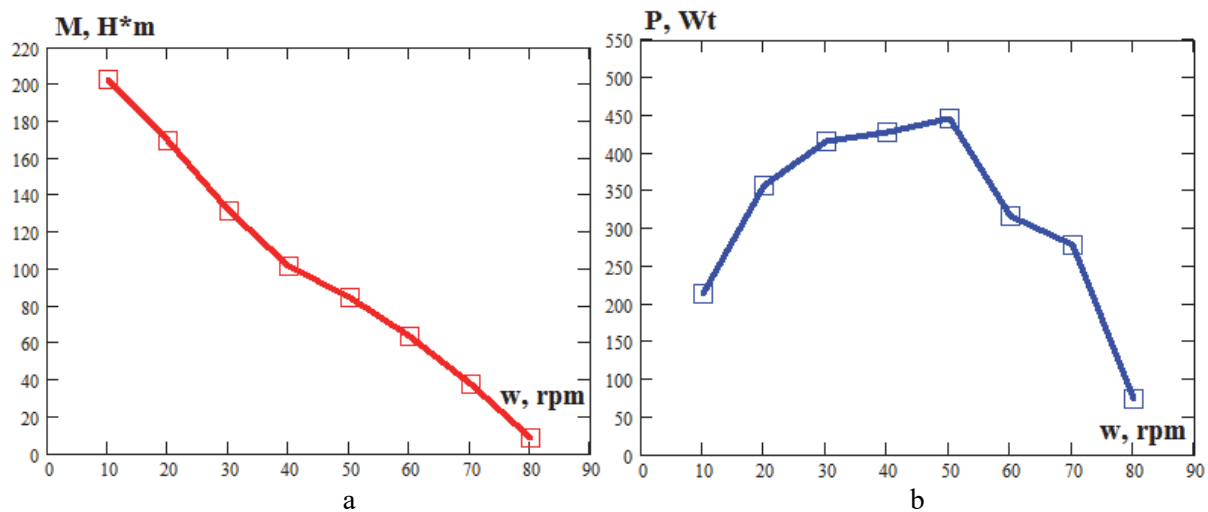
Figure 4. The dependence of the torque (a) and power (b) generated on the shaft
at different running frequencies.

From Fig. 4a it is seen that with an increase in the running frequency, the torque on the shaft is reduced quite essentially and almost linearly. At a running frequency of 10 rpm, it is 202.8 N*m, while at a running frequency of 80 rpm it amounts to 8.76 N*m. At the same time, the power, as one can see in Fig. 4b initially grows from 213.5 W at $\omega = 10$ rpm to 446.8 W at 50 rpm, and then falls quite sharply with a further increase in the running frequency.

Conclusion

In the course of the work, screw rotors were numerically studied as potential propellers for use in free-flow mini-hydroelectric power plants. The rotor with a diameter of one meter and a length of two meters was adopted as the basic one. A study was conducted to figure out the effect of the diameter of the inner shaft, which showed that in the case of using screw rotor, increase in shaft diameter leads to a decrease in generated torque and the resulting power on the shaft.

The screw pitch effect on energy performance was studied as well. It is shown that under the condition of full immersion of the rotor and its streamline by the flow, there is no reason to do more than 2-3 pitches of the screw, because they start operating inefficiently, creating stagnant areas and recirculation zones. The small pitch of the screw gives also a negative effect on the torque on the shaft since the local resistance increases and the flow does not effectively rotate the rotor.

The conducted research allowed identifying the most effective screw rotor and revealing the effect of its running frequency on the resulting torque on the shaft, as well as the output power. It is shown that depending on the running frequency, the generated power can vary quite essentially.

Acknowledgment

References

[1]   Kantert P J 2008 *Praxishandbuch Schneckenpumpe* (Hirthammer Verlag) ISBN 978-3-88721-202-5 William Moerscher *Patent US* 1434138

[2]   Brada K, Radlik K-A 1998 *Water Screw Motor to Micro Power Plant – First Experiences of Construction and Operation*

[3]   Passamonti A 2018 *Investigation of energy losses in the laboratory and full-scale Archimedes screw generators*

[4]   Waters S 2015 *Analysing the performance of the Archimedes Screw Turbine within tidal range technologies* (Lancaster University)

[5]   Saroinsong T et al. 2016 *Journal of Engineering Science & Technology Review* **9** (2)

[6]   Songin K 2017 *Experimental analysis of Archimedes screw turbines* Ph.D. thesis

[7]   Kraybill Z 2013 *Structural Analysis of an Archimedes Screw and a Kinetic Hydro Turbine*

[8]   Stergiopoulou A V et al. *Two Innovative Experimental Archimedean Screw Energy Models In The Shadow Of Archimedes III* // 5th International Conference on Experiments/Process/ System Modeling/Simulation/Optimization

[9]   Stergiopoulou A, Stergiopoulos V, Kalkani E 2015 *International Journal of Energy and Environment* **6** (5) 471

[10]   Minakov A V, Platonov D V, Dekterev A A, Sentyabov A V, Zakharov A V 2015 *Computers & Fluids* **111** 197–205

[11]   Minakov A V, Platonov D V, Dekterev A A, Sentyabov A V, Zakharov A V 2015 *International Journal of Heat and Fluid Flow* **53** 183–194

[12]   Minakov A V, Platonov D V, Litvinov I V, Shtork S I, Hanjalić K 2017 *Journal of Hydraulic Research* **55** (5) 668–85