Application of computational gas dynamics methods for calculating losses during rotation of solids in low vacuum conditions

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Abstract. On the basis of a mathematical model with distributed parameters, a method for determining aerodynamic losses during high-frequency rotation of a flywheel accumulator is developed. The power of losses due to friction of the rotor against the air is determined as a function of the pressure in the chamber. A comparative analysis of the aerodynamic losses under low vacuum conditions at various pressures of the working medium and the data obtained on the basis of empirical dependences and presented in the scientific literature on this topic is carried out. The maximum difference between the loss power values is no more than 25%. The data deviation decreases as the pressure in the chamber decreases.

1. Introduction
Currently, energy recovery is one of the most promising areas of engineering activity. Recovery systems allow you to store energy without harm to humans and the environment. This energy can be used to accelerate cars and aggregates.

There are a number of developments in which a flywheel battery is used as an energy recuperator. For example, this system was installed in Formula 1 cars to accelerate, as well as in cars to reduce gasoline consumption. The scheme of the flywheel battery is shown in figure 1.

Figure 1. Flywheel accumulator diagram.

The main advantages of the flywheel accumulator are: high energy consumption; durability; high efficiency (up to 98%); low cost, dimensions and weight; operation at any temperature.
2. Aim of the research
The scientific and technical literature on the described topic is reviewed in [1-5]. From the review, it is clear that the use of batteries based on mechanical energy is quite promising, and research is being actively conducted in this direction. One of the most important tasks in the design of flywheel batteries is to ensure their energy efficiency, which is limited, among other things, by the strength of the rotor. Based on the performed calculation described in [6], according to the evaluation of the energy efficiency indicators of the flywheel battery, depending on the shape and material, it is determined that at its manufacturing from alloy steel in the form of a solid cylinder, the maximum permissible angular velocity of rotation is 15290 rad/s (2433 rpm), and the energy intensity is equal to 0.12 MJ/kg.

The main problems when using flywheel batteries, in addition to the occurrence of critical frequencies and imbalances, are large power losses when using mechanical bearings (up to 20% of power in 1 hour) and aerodynamic losses. This problem can be solved by using electromagnetic bearings and a vacuum chamber. The unit is placed in a sealed vacuum chamber. The reduced pressure of the working medium reduces friction and eliminates the effects of oxygen and moisture, which extends the service life of the internal components.

To estimate the aerodynamic losses, there are a number of methods that are mostly based on the experimental data of the studied obsolete rotary machines. In the domestic and foreign literature, the value of the friction power loss is calculated by the formula [7,8] (further, this will be called an empirical method):

\[ N = 0.744 \cdot 10^{-7} \Omega^{2.7} p^{0.7} (1 + 4.4 \frac{l}{D}) D^{4.4} \]  

where \( p \) is the ambient pressure, Pa; \( D \) is the diameter of the flywheel, m; \( \Omega \) is the angular velocity of the flywheel, rad/s; and \( l \) is the length of the section where the losses are determined, m.

However, this technique allows determining only approximate values of the friction power due to the fact that the coefficient of aerodynamic drag is obtained empirically based on experimental data (velocity and size of the rotor, parameters of the gas region around the rotor). In this regard, under conditions different from those at creating this empirical technique, deviations from the calculated value of power losses may be observed. Mathematical models with distributed thermodynamic parameters are widely used in modern scientific and engineering practice. Computational experiments based on such models have proven themselves and allow reducing the cost of product development, as the number of experimental studies decreases. In this paper, we propose to apply a computational method for determining power losses based on numerical modeling for a simplified model of a flywheel accumulator and compare the results obtained with the data based on an empirical method.

The aim of the work is to develop a method for calculating the friction losses of a flywheel on a gas medium based on CFD-modeling using models with distributed thermodynamic parameters.

3. Mathematical modeling
To evaluate the aerodynamic friction and determine the friction power, it is necessary to determine the moment of the friction force on the surface of the rotor in the flywheel accumulator. For this purpose, a mathematical model of the rotation and interaction of the layers of the gas medium is developed. The gas area inside the flywheel accumulator chamber is taken as the computational domain. To compare the effect of discharge in the chamber of the flywheel accumulator on the friction power, several operating conditions of the flywheel accumulator are considered: with absolute air pressures in the chamber equal to 50, 20 and 5 kPa.

The mathematical model of the gas flow in the flywheel accumulator chamber is based on a system of equations: the Navier-Stokes flow of the working medium and the energy and continuity equation, and is supplemented by the equations of the k-ω turbulence model. The following assumptions are made:

- friction in the bearing assemblies is not taken into account;
- all surfaces are assumed to be perfectly smooth;
The flywheel walls are adiabatic; 
- gas is accepted as ideal; 
- the friction between the gas layers is calculated according to Newton's law for viscous friction. 

The initial and boundary conditions are assumed to be: 
- the temperature on the walls of the chamber is 300K; 
- the velocity on fixed walls is 0; 
- the velocity on the rotor wall of the flywheel accumulator is \( v = \Omega \cdot D/2 \); 
- the absolute pressure in the chamber, respectively, is 50 kPa (for solve 1), 20 kPa (for solve 2) and 5 kPa (for solve 3); 
- no mass transfer through the wall.

The solution of the equations of the mathematical model, supplemented by the initial and boundary conditions, is carried out using the finite element method. The space of the computational domain is discretized using a computational grid containing up to 500,000 finite elements in the form of a tetrahedron. The boundary layer has a high finite element density to ensure that the \( y+ \) parameter approaches the recommended values of 12-13.

As a result of a series of computational experiments, the values of the moments of forces \( M \) acting on the surface of the rotor, as well as the distribution of pressures, velocities, and temperatures in the calculated region are obtained for different angular velocities of the flywheel accumulator rotor and three values of pressure in the chamber. The temperature distribution in the middle section perpendicular to the axis of rotation of the rotor is shown in figure 2.

![Figure 2. Temperature distribution of the working medium in the cross section of the flywheel accumulator chamber.](image)

The analysis of this distribution shows when the air flows around the rotor in the boundary layer, a sharp increase in temperature is observed due to a sharp change in the velocities. At the same time, due to convective heat exchange, the adjacent air layers are heated, and the temperature of the working medium increases significantly. In the areas most remote from the rotor, at the periphery of the chamber, the temperature gradient is several times lower.

The determination of the friction power is made according to the well-known formula:

\[
N = \Omega \cdot M
\]  \hspace{1cm} (2)

where \( \Omega \) is the angular velocity of the rotor, rad/s; \( M \) is the moment of resistance relative to the axis of rotation of the flywheel, N·m; and \( N \) is the aerodynamic power loss, W.
Based on the data obtained using the empirical method, which shown in formula 1 (method 1, method 2, method 3) and calculated numerically (solution 1, solution 2, solution 3) for chamber pressures of 50 kPa, 20 kPa, and 5 kPa, respectively, the dependences of the friction power $N$ on the rotor velocity of the flywheel accumulator $n$ are constructed, which shown in figure 3.

![Graph of friction power $N$ vs. rotor velocity $n$.]

**Figure 3.** Results of the computational research.

4. Results

A comparative analysis of the aerodynamic losses in low vacuum conditions at different working medium pressures, obtained on the basis of mathematical modeling, and the data obtained on the basis of empirical dependence and presented in the scientific literature on this topic, has been carried out. The analysis shows that when the pressure in the chamber decreases, the data of the empirical method and the numerical calculation agree quite accurately, and the deviation does not exceed 5%. At pressures close to atmospheric pressure, a deviation of more than 25% is observed, which may indicate that the application of the empirical method is not sufficient. The most qualitative verification of the obtained results will be carried out in the future with the help of a series of experimental studies, but the developed model may be used to estimate the friction losses of objects rotating in a gas medium.

**Conclusions**

A mathematical model of gas-dynamic processes occurring in the working cavity of a flywheel accumulator has been developed. When studying the working processes in the chamber of a flywheel accumulator, the developed mathematical model allows determining the power characteristic (moment of resistance) and energy characteristic (power loss), as well as evaluating the distribution of gas-dynamic parameters: velocities, pressures, and temperatures.

On the basis of a mathematical model, a calculated study of the power of friction losses has been carried out during the rotation of bodies in low vacuum conditions. Based on the comparative analysis, it is concluded that at a lower pressure of the working medium, the deviation of the power of the aerodynamic losses obtained by the empirical and numerical methods is insignificant and is less than 5%. As the pressure increases, the deviation of the test parameter increases significantly and reaches 25% at 50 kPa. The analysis of the obtained data shows that when the pressure of the working medium is reduced 10 times, the power of aerodynamic losses is reduced about 6 times.
The scientific novelty of the work is as follows: on the basis of a computational experiment, the dependences of power losses on the rotation frequency of the rotor of a flywheel accumulator under different ambient pressures are obtained for the first time; the deviation of the results when comparing the power values obtained using the numerical method and the empirical formula used to estimate the friction power of rotating bodies is identified, because the values of power losses are reduced and the empirical method does not take into account the influence of the walls of the flywheel battery chamber. The practical significance lies in the fact that the results of this work can be applied to the development of flywheel batteries, which will reduce the time for creating new types of equipment using this type of energy storage devices.

References
[1] Abdullina L, Barbashov N and Leonov I 2019 Lecture Notes in Mechanical Engineering 167–75
[2] Egorova O V and Barbashov N N 2020 Mechanisms and Machine Science 116–25
[3] Barbashov N N, Abdullina L R, Ilyushkov I N and Bolotov I E 2020 IOP Conference Series: Materials Science and Engineering 032047
[4] Abdullina L, Smirnov V, Alimova A, Kaliastrotova A and Kravets A 2021 IOP Conference Series: Earth and Environmental Science 052037
[5] Barbashov N N and Barkova A A 2021 IOP Conference Series: Materials Science and Engineering 012168
[6] Birger I A 1993 Raschet na prochnost detaley machin. [Handbook of calculating the strength of machine parts] (Moscow, Mashinostroenie Publ) 640
[7] Ledovskiy A N 1985 Electricheskiye mashiny s visokocoercitivnymy postoyannymi magnitamy. [Electric machines with high-coercive permanent magnets] (Moscow, Energoatom Publ) 169
[8] Sharov V S 1973 Visokochastotnie e sverchchastotnie electricheskiye mashiny. [High-frequency and ultra-high-frequency electric machines] (Moscow, Energiya Publ) 248