An empirical model for gas-dynamic characteristics microturbines rotor wheels

Andrey Yu. Fershalov, Mikhail Yu. Fershalov, Lyudmila P. Tsigankova

Abstract: - This study aims to present empirical models of gas-dynamic characteristics of microturbines rotor wheels, namely the ratio of the rotor wheels speed and the angle of exit gas stream from the rotor wheel. The paper was studied rotor wheels with a large angle of rotation flow $\Delta\beta=180°-(\beta_{1к}+\beta_{2к})=151°\ldots164°$. Empirical models of gas-dynamic characteristics of rotor wheels microturbines need to model and analyze the characteristics of the rotor wheels. Empirical models were subjected to regression analysis. Impact of the studied factors on gas dynamic characteristics driving wheels was estimated.

Keywords: - microturbine, speed ratio of the rotor wheel, rotor wheel, turbine stage, nozzle apparatus.

I. Introduction

Improving turbine for different purposes occupies an important place in the global engine industry. In recent years, scientists spending more and more experimental and numerical studies of turbines and their components [1,2,3]. There are investigations under development in the direction of the electrification of remote areas with turbine of different types [4]. The internal combustion engines and turbines are most often used as part of marine power. Besides modern internal combustion engines (ICE) are turbocharged, the latter is ensured by gas generator.

Both turbine and ICE have their advantages and weaknesses. The main advantages of turbines are: high efficiency; high aggregate power with small weight and dimensions; adaptability to automation; high reliability; simplicity of heat and kinematic scheme; simplicity of construction and maintenance; high technological effectiveness; possibility of aggregate repairs; simplicity of transportation and ease of assembly; minimum volumes of hazardous emissions into environment; high maneuverability and rate of load; most turbines have the capacity of short-term overload. Besides, recently there are great achievements both in turbo machinery aerodynamics and in the development of heat-resistant steels and alloys. The successes of aerodynamics and metallurgy allowed increasing turbines’ thermal efficiency to the required level, and creating the conditions for their implementation into the industry.

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Turbine installations are the combinations of a number of elements, in which complex processes take place, the ones which allow converting one form of energy to another. To create such installation it is important to have the complex of scientific knowledge being the result both of theoretical and experimental research in various fields. Therefore it becomes rather clear why modern turbine building is an innovative field with own approaches to the complicated problems solution with the use of theoretical and experimental methodology as well as mathematic methods [5], connected to the construction of mathematic models of real phenomena taking place inside the flow passages of turbines. Due to the complexity of the phenomena happening inside the turbine flow passages, these models, as a rule, are not the universal ones and can be used in calculations of turbine various parameters solely within the definite range of the parameters variations. In multistage turbines the greatest impact on the turbine efficiency has rotor wheels, because wrong assessment of aerodynamic properties of gas behind them can result in wrong profiling of the next stage.

By the information of the Kaluga turbine works the 1% increase of velocity ratio inside the full size turbine lattice increases the stage capacity by 0,73%.

In case of the small sized turbine stage, depending upon the lattice velocity ratio, the capacity increase is more due to the increase in the relative thickness of the boundary layer.

Therefore, reduction of power losses in the rotor wheels allows increase of the turbine stage efficiency, which is important relating to marine turbines, which operate autonomously with time-varying load. So, the issue of the efficiency improvement in case of operational modes variations is of great importance.

II. Experimental studies

The initial data is the material for the subsequent sections of the work were obtained on test stand illustrated in Figure 1 [6]. A distinctive feature of the stand - the ability to determine when the forces generated by the flow of the working fluid at the outlet of the nozzle unit and the rotor wheel during operation stage, due to the design of the nozzle body and the machine wheel with axial output arranged behind the rotor wheel. This solution is possible not only to calculate the characteristics of the gas-dynamic nozzle unit and the rotor wheel, but also to determine the efficiency of the model microturbines, not applying for this load device - brake inductor. It is used only to generate load on the stage of quality control and accuracy of the data on the efficiency of the model stages microturbines.

The pressure of the microturbines stage was regulated by air powered ejector system, which expanded the range of studies regarding πT (πT * = P0 / P2), creating different combinations of their values at the entrance to the nozzle unit and the rotor wheel. In the design of the nozzle apparatus entered the bearing, allowing to measure the rotation moment generated by the reactive power of the flow. The role of the working fluid playing the air, which was supplied to the nozzle assembly radially to eliminate additional rotation moment.

Model rotor wheels have an average diameter - 170 mm, the number of rotor blades - 26, their height - 11.7 mm step - 20.5 mm and a chord - 18.2 mm. Model rotor wheels had a band with three ridges of triangular cross-section and a visor that prevents dynamic leakage of the working fluid over the shroud, which was part of the annular groove of the nozzle unit (forming a closed area between the nozzle assembly and the rotor wheel).

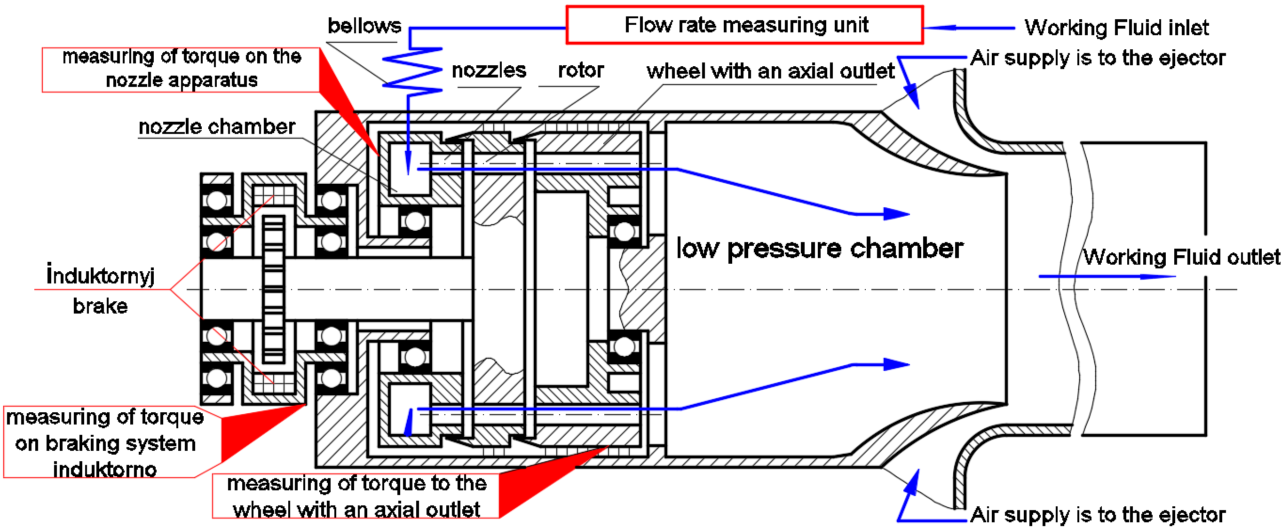

Figure 1 – Scheme of experimental stand

The studies were to determine the relative average error for the rate of speed of the rotor wheel (ψ) and the angle of the output stream from the rotor wheel (β2), which amounted to - ψ - 8,3%; β2 - 20,8%. The absolute value of the average error were ψ - 0,051; β2 - 2,0°.

Speed ratio of the rotor wheel is calculated by the formula:

$$\psi = \frac{w_2}{w_{2t}} \qquad (1)$$

where:

w_2 – the relative speed at the exit of rotor wheel;

w_{2t} – theoretical relative velocity at the exit of rotor wheel.

In the work analyzes the impact of the function on the following factors:

For ψ - $\beta_1 \in$ [3°; 31,5°] - angle of entry of the working body in the rotor wheel $\beta_{1K} \in$ [8°; 14°] - angle of entry into the rotor wheel; $M_{w2t} = \xi_{Mw2t}(P_2/P_1^*) \in$ [0,4; 2,8], where P_1^* – the total pressure behind the nozzles of the nozzle unit, P2 ¬ static pressure behind the rotor wheel;

For β_2 $\beta_{2K} \in$ [8°; 15°] – angle trailing edges of rotor wheel blades, $M_{w2} \in$ [0,2; 2,4] – Mach number calculated by the relative velocity of the working fluid output flow at the exit of the rotor wheel; and $u/c_2 \in$ [0; 0,66] - the ratio of the circumferential speed of rotor wheel to the absolute velocity of the gas at the outlet of the rotor wheel.

After the experiment, correlation analysis confirmed the statistical significance of the influence of the analyzed factors on target functions and the independence of the factors together. As a kind of mathematical model of the following dependence:

$$\psi, \beta_2 = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n}\sum_{j=i}^{n} b_{ji} x_i x_j \,, \qquad (2)$$

where b_i, b_{ji} coefficients (Table 1);

For ψ - n = 3; $x_1 = \bar{\beta}_1$ ($\bar{\beta}_1 = \frac{\beta_1 - 17{,}29}{14{,}43}$); $x_2 = \bar{\beta}_{1k}$ ($\bar{\beta}_{1k} = \frac{\beta_{1k} - 11}{3}$);

$x_3 = \bar{M}_{w2t}$ ($\bar{M}_{w2t} = \frac{M_{w2t} - 1{,}6}{1{,}22}$);

For β_2 - n = 3; $x_1 = \bar{\beta}_{2K}$ ($\bar{\beta}_{2k} = \frac{\beta_{2k} - 11{,}5}{7}$);

$x_2 = \bar{M}_{w2}$ ($\bar{M}_{w2} = \frac{M_{w2} - 1{,}279}{1{,}116}$);

$$x_3 = \bar{u}\ (\bar{u} = \frac{u/c_2 - 0{,}33}{0{,}33}).$$

Dependence arguments were normalized within range $-1 \le x_i \le +1$.

All statistical calculations used 95% confidence level (p = 0.05).

Checking the significance of coefficients performed by t -criterion.

The adequacy of the results of the investigated characteristics obtained on the developed model by the results of the experiment confirmed the calculated values of the Fischer’s criteria, which is less than the critical values (Table 1).

Comparison of the results of the experiment with the values calculated from the regression model showed that the module is the average displacement in the whole study area was 0.04 for ψ and 1,6 ° for β2. Shifting is acceptable for the practice of values, and further analysis of factors influence the performance of microturbines was conducted on the basis of the developed regression model.

Table 1 Coefficient values (b_i, b_{ji}), coefficient of determination (R^2) and Fisher criteria values for ψ и β_2.

	j \ i	0	1	2	3	R^2	F_{table} (p=0,05)	$F_{calculated}$
Ψ	0	0,80	0,112	–	0,109	0,83	1,225	1,202
	1		–	0,002	–			
	2			–	–			
	3				–			
β_2	0	14,5	3,665	0,329	1,622	0,66	1,224	1,211
	1		0,140	3,110	1,077			
	2			–	–			
	3				–			

Note: the coefficients b_i, b_{ji} estimated by least squares method.

III. Results of Research

The research of the rotor wheels with large flow turning angle were based on the results of the turbine stage nozzle apparatus’ operational mode simulation. Regression models, specifically designed for this purpose, were obtained in the simulation experiment results processing [6-8].

Optimization by one factor. Methodology of the analysis by this method is based on the determination of maximum and minimum values of the function under the study relative to each factor in its variations. Other factors take three values in turn: minimum, average and maximum. The discrepancies between maximum and minimum values, for each factor at every level, are ranked in ascending order. The positions (defined earlier) by the degree of the influence of each factor at each level are summarized, and the smaller this amount is, the stronger the effect on the tested model has a factor.

The degree of factors impact on the rotor wheel velocity ration is ranked in the following way: β_1, M_{w2t} and β_{1K}.

By the sum of difference values (ψ_{max}-ψ_{min}) the degree of factors impact on the rotor wheels velocity ratio is ranked in similar order. The degree of factors impact on the exit angle of flow from the rotor wheel passage is ranked in the following way: β_{2K}; M_{w2} and u/c_2. By the sum of difference values (β_{2max}-β_{2min}) the degree of factors impact on β_2 is ranked in similar order.

To increase the reliability of the fact that by the degree of impact on the target function factors are placed in the mentioned order, there were applied methods given below.

Four-dimensional optimization. The aim of the analysis by this method was limited to finding maximum and minimum values of the functions under consideration by means of solving the task of the functions optimization with the fixed value of one factor being limited by the boundaries of the experiment done. Each factor takes in turn three values, i.e. minimum, maximum and average. Then the difference between maximum and minimum values of functions of each factor at every level is calculated. Then these values are ranked in descending order. The stronger the factor impact on function – the more the difference. The analysis done by this methodology hasn’t statistically revealed (with the account of errors) various degree of impact on the studied factors’ regression models.

Visual analysis of the factors’ impact. Visual analysis implies the sensitivity analysis of the result obtained by calculations and showing its value alteration with the factors’ values variation within the studied limitations. It can help to check the correctness of decisions and conclusions made concerning the connection between the function under research and variables studied. The numerical experiment has been done for the sake of the above with the use of the models of simulation based on the developed regression models. The results are shown as graph dependence.

Fig.1 shows that in case of minimum values of factors the most important impact on ψ has β_1, which determines with the rotor wheel inlet edge angle of installation the angle of incidence and Mw2t.

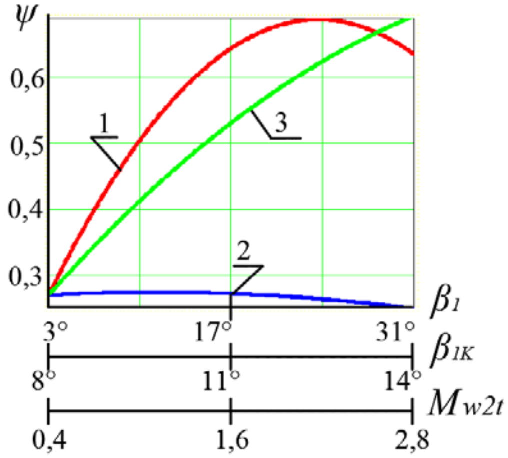

Fig. 1. Dependence of the coefficient ψ with minimum values of factors:
1 – $\psi=\xi\psi(\beta_1)$ when β_{1K}=8°; M_{w2t}=0,4;
2 – $\psi=\xi\psi(\beta_{1K})$ when β_1=3°; M_{w2t}=0,4;
3 – $\psi=\xi\psi(M_{w2t})$ when β_1=3°; β_{1K}=8°

Fig. 2 shows that with the average values of factors the main influence on ψ is exerted by β_1 and M_{w2t}, β_{1K} has less influence.

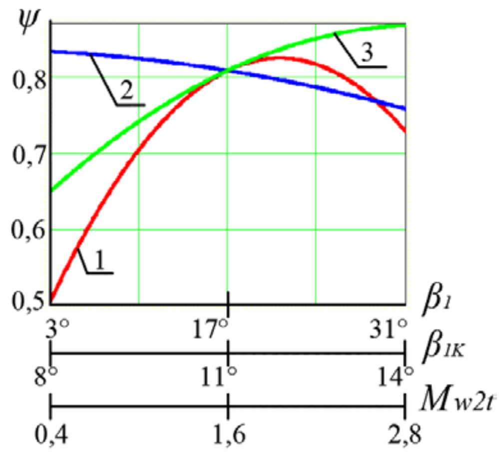

Fig. 2. Dependence of the coefficient ψ with of the average values of factors:
1 – $\psi=\xi\psi(\beta_1)$ when β_{1K}=11°; M_{w2t}=1,6;
2 – $\psi=\xi\psi(\beta_{1K})$ when β_1=17°; M_{w2t}=1,6;
3 – $\psi=\xi\psi(M_{w2t})$ when β_1=17°; β_{1K}=11°

Fig. 3 shows that with maximum values of factors, the main influence on ψ is exerted by β_1 and β_{1K}, M_{w2t} has less influence.

Fig.4 demonstrates that with minimum values of factors main influence on β_2 is exerted by M_{w2} and u/c_2, less influence has β_{2K} despite its guiding impact on the flow. It is connected to the guiding effect of wheels fitted behind the rotor wheel and simulating the guiding apparatus.

Fig.5 shows that with the average values of factors the main influence on β_2 is exerted by M_{w2} and u/c_2, β_{2K} has less impact. The value of Mach number becomes the determining one for the flow deflection angle value at the rotor wheel passages outlet by the analogy with the nozzles of nozzle apparatus. Moreover, u value has an impact on the intensity of vortex, formed in the rotational motion of the working vanes' edges, ventilating gas between rotor wheel and the wheel simulating the guiding apparatus. The latter has also an impact on the flow exit angle value when outgoing from the rotor wheel passages.

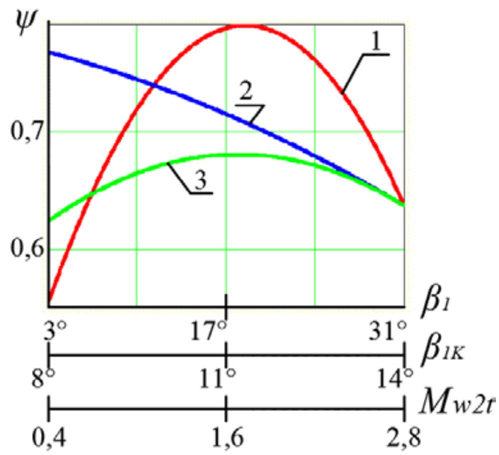

Fig. 3. Dependence of the coefficient ψ with maximum values of factors:
1 – $\psi=\xi\psi(\beta_1)$ when β_{1K}=14°; M_{w2t}=2,8;
2 – $\psi=\xi\psi(\beta_{1K})$ when β_1=32°; M_{w2t}=2,8;
3 – $\psi=\xi\psi(M_{w2t})$ when β_1=32°; β_{1K}=14°

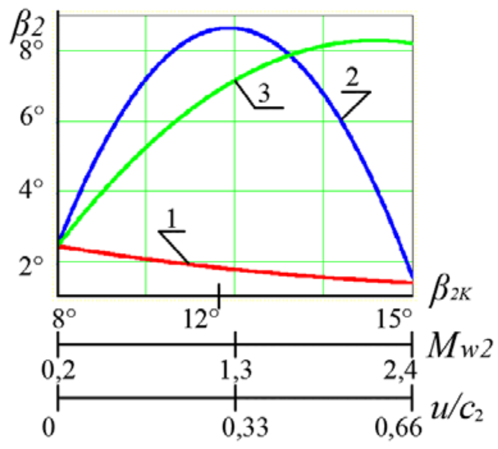

Fig. 4. Dependence angle β_2 with minimum values of factors:
1 – $\beta_2=\xi\beta_2(\beta_{2K})$ when M_{w2}=0,2; u/c_2=0;
2 – $\beta_2=\xi\beta_2(M_{w2})$ when β_{2K}=8°; u/c_2=0;
3 – $\beta_2=\xi\beta_2(u/c_2)$ when β_{2K}=8°; M_{w2}=0,2

Fig. 6 shows that with maximum values of factors main influence on β_2 is exerted by β_{2K}, M_{w2} and u/c_2 have less but not greatly different from each other impact. It is connected to high velocity of gas flow at the rotor wheel passages outlet, which reduces the degree of the opposite action of wheel fitted behind the rotor wheel.

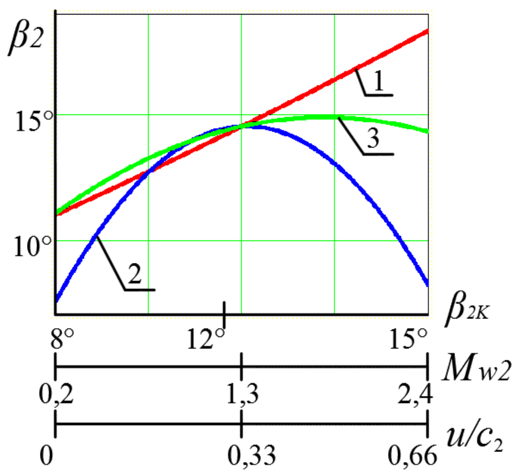

Fig. 5. Dependence angle β_2 with of the average values of factors:
1 – $\beta_2=\xi\beta_2(\beta_{2K})$ when M_{w2}=1,3; u/c_2=0,33;
2 – $\beta_2=\xi\beta_2(M_{w2})$ when β_{2K}=12°; u/c_2=0,33;
3 – $\beta_2=\xi\beta_2(u/c_2)$ when β_{2K}=12°; M_{w2}=1,3

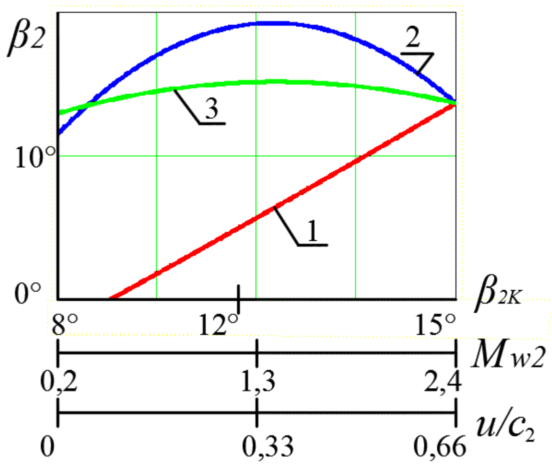

Fig. 6. Dependence angle β_2 with maximum values of factors:
1 – $\beta_2=\xi\beta_2(\beta_{2K})$ when M_{w2}=2,4; u/c_2=0,66;
2 – $\beta_2=\xi\beta_2(M_{w2})$ when β_{2K}=15°; u/c_2=0,66;
3 – $\beta_2=\xi\beta_2(u/c_2)$ when β==15°; M_{w2}=2,4

IV. Conclusion

Rotor wheels of the studied type showed rather high level of their power efficiency under the condition of correct determination of gas-dynamic parameters of flow passage of rotor wheel before them. To determine the values of gas-dynamic parameters of the flow outgoing from the nozzles of nozzle apparatus there has been designed testing beds [9, 10].

To consider gas parameters alterations between rotor wheel and nozzle apparatus it is necessary to use the results of work [11, 12]. Hereinafter, for the similar studies it is assumed to use acoustic methods [13, 14] to get more accurate results.

Developed an empirical model for determining the speed ratio of the rotor wheel and the exit angle of gas flow from the rotor wheel should be used for designing microturbines. Due to the fact that the experiment has been carried out with the rotor wheels, having similar number of vanes of similar size, to transfer the results to the rotor wheel of different sizes or number of vanes it is necessary to use methodology given in work [15].

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