COMPUTATIONAL STUDY OF A VERTICAL-AXIS LOW-POWER WIND TURBINE IN ANSYS FLUENT

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Abstract

In mathematical modeling of wind turbine aerodynamics within the ANSYS Fluent software package, the main problem is the choice of a turbulence model.

As part of the work, to describe the turbulent flow, the standard and modified $k-\varepsilon$ models were tested, Spalart-Allmaras model, $k-\omega$ model and RNG model for mixing description. The calculations used the control volume method embedded in ANSYS Fluent, where the velocity and pressure fields are linked by the PISO algorithm. Satisfactory agreement between the results of calculation and experiment was obtained when implementing the modified $k-\varepsilon$ model according to the axial distributions of the longitudinal velocity. This model will be further used in determining the values of the tangential flow direction in the blades of the wind generator and the moment of its rotation.

Keywords: wind force, velocity field, Navier-Stokes equations, ANSYS Fluent, control volume method, PISO, turbulence models, computational experiment.

INTRODUCTION

In recent years, Uzbekistan has implemented measures to improve energy efficiency, promote energy-saving technologies, and develop renewable energy. Currently, 85% of the country's electricity comes from natural gas, which contributes to air pollution and the greenhouse effect, raising global temperatures by 1.5–2°C over the past century. This climate change causes glacier melting, extreme weather, and ecological challenges, making the use of alternative energy sources increasingly important [1-5].

Among alternative energy sources, wind power is the most cost-effective and environmentally friendly. Uzbekistan aims to increase its total wind power capacity to 5000 MW by 2030. In addition to large-scale projects, the government supports small-scale generation, including low-power vertical-axis wind turbines.

Vertical-axis turbines are preferred because they operate at low wind speeds, common in Uzbekistan, and can work regardless of wind direction, unlike horizontal-axis turbines that require alignment.

In research and engineering, software tools like ANSYS are widely used for modeling heat and fluid dynamics processes. ANSYS provides a comprehensive simulation environment with modern physical models, multidisciplinary calculations, and a user-friendly interface, allowing engineers to efficiently evaluate designs and optimize performance. Various turbulence models are applied in simulations to accurately describe flow behavior.

The complete system of Navier-Stokes equations with two, one (Spalart-Almars model) or non-linear diffusion equations that take into account fluctuations in the average velocity of turbulent flows is a family of models $k-\varepsilon$ and $k-\omega$, where $k-$ turbulent energy mass density; ε – its dissipation rate; $\omega-$ energy dissipation rate per unit volume and time. A feature of this system is the cascading of its solution, which is most convenient for use in software packages for modeling processes in cylindrical coordinates.

ANSYS CFD has the widest variety of turbulence models available, including the time-tested k-ε, k-ω, and Reynolds Stress Model (RSM) for highly swirling or anisotropic flows. Due to the ever-increasing performance of computers and decreasing their cost, large eddy models (LES) and more economical non-attached eddy models (DES) have become extremely popular in solving industrial problems. New innovative models that allow calculation of the laminar-turbulent transition and a modern model (SAS) that automatically determines the scale of turbulent eddies are usually used in cases where the accuracy of stationary turbulence models is not

enough. Various near-wall functions and the enhanced wall treatment method make it possible to describe the flows bounded by walls as accurately as possible [6].
In the process of solving the problem, five turbulence models can be used to describe turbulence.

METHOD.

Model modified $k-\varepsilon$. In contrast to the well-known works, it is proposed here to describe the turbulent exchange using a modified $k-\varepsilon$ model, which contributes to a more adequate description of the heat and mass transfer process:

$$\begin{cases} \frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-2\rho\varepsilon M_t^2+S_k, \\ \frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho C_1 S\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon. \end{cases}$$

Here we use the notation

$$C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right],\ \eta=S\frac{k}{\varepsilon},\ S=\sqrt{2S_{ij}S_{ij}},\ \mu_t=\rho C_\mu\frac{k^2}{\varepsilon},\ C_\mu=\frac{1}{A_0+A_S\frac{kU^*}{\varepsilon}},\ U^*\equiv\sqrt{S_{ij}S_{ij}+\tilde{\Omega}_{ij}\tilde{\Omega}_{ij}},$$

$$\Omega_{ij}=\overline{\Omega_{ij}}-2\varepsilon_{ijk}\omega_k,\quad A_S=\sqrt{6}\cos\phi,\quad \phi=\frac{1}{3}\cos^{-1}\left(\sqrt{6}W\right),\quad W=\frac{S_{ij}S_{jk}S_{ki}}{\tilde{S}^3},\quad \tilde{S}=\sqrt{S_{ij}S_{ij}},$$

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right),\quad G_k=-\rho\overline{u_i'u_j'}\frac{\partial u_j}{\partial u_i},\quad S\equiv\sqrt{2S_{ij}S_{ij}},\quad G_b=\beta g_i\frac{\mu_t\partial T}{\Pr_t\partial x_i},\quad \Pr_t=1/a_t,$$

$$a_0=1/\Pr=k/\mu c_p,\ \beta=-\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p,\ G_b=-g_i\frac{\mu_t}{\rho\Pr_t}\frac{\partial\rho}{\partial x_i},\ M_t=\sqrt{\frac{k}{a^2}},\ a=\sqrt{\gamma RT}.$$

Empirical Constants $k-\varepsilon$ models take standard values: $C_{1\varepsilon}=1.44, C_2=1.9$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.2$, $A_0=4.04$.

Spalart-Allmaras model. This model belongs to the class of one-parameter linear turbulence models. Here, only one additional differential equation appears for calculating the kinematic coefficient of eddy viscosity. This low Reynolds turbulence model, which describes the entire flow region, is given by the following equation:

$$\frac{\partial}{\partial t}(\rho\tilde{\nu})+\frac{\partial}{\partial x_i}(\rho\tilde{\nu}u_i)=$$

$$G_\nu+\frac{1}{\sigma_{\tilde{\nu}}}\left[\frac{\partial}{\partial x_j}\left\{(\mu+\rho\tilde{\nu})\frac{\partial\tilde{\nu}}{\partial x_j}\right\}+C_{b2\rho}\left(\frac{\partial\tilde{\nu}}{\partial x_j}\right)^2\right]-C_{w1\rho}f_w\left(\frac{\tilde{\nu}}{d}\right)^2+S_{\tilde{\nu}}.$$

Turbulent eddy viscosity is calculated by the formule: $\mu_t=\rho\tilde{\nu}f_{\nu 1}$, additional definitions are given by the following dependencies: $f_{\nu 1}=\frac{\chi^3}{\chi^3+C_{\nu 1}^3}$, $\chi=\frac{\tilde{\nu}}{\nu}$ $\tilde{S}\equiv S+\frac{\nu}{\kappa^2 d^2}f_{\nu 2}$, $f_{\nu 2}=1-\frac{\chi}{1+\chi f_{\nu 1}}$, $S\equiv\sqrt{2\Omega_{ij}\Omega_{ij}}$, $\Omega_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right)$, $S_{ij}=\frac{1}{2}\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right)$, $f_w=g\left[\frac{1+C_{w3}^6}{g^6+C_{w3}^6}\right]^{1/6}$, $r=\frac{\tilde{\nu}}{\tilde{S}\kappa^2 d^2}$, and the closure constants for the model: $C_{prod}=2.0$, $C_{b1}=0.1355$ $C_{b2}=0.622$, $\sigma_{\tilde{\nu}}=\frac{2}{3}$, $C_{\nu 1}=7.1$, $C_{w1}=\frac{C_{b1}}{\kappa^2}+\frac{(1+C_{b2})}{\sigma_{\tilde{\nu}}}$, $C_{w2}=0.3$ $C_{w3}=2.0$, $\kappa=0.4187$.

Standard model $k-\varepsilon$.

$$\begin{cases}\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k,\\ \frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\\ +C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon\rho}\frac{\varepsilon^2}{k}+S_\varepsilon.\end{cases}$$

Turbulent eddy viscosity is calculated by the formula: $\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}$, closure constants for standard $k-\varepsilon$ models: $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $C_\mu=0.09$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$.

Model RNG $k-\varepsilon$ [10-12].

$$\begin{cases} \frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\varepsilon-Y_M+S_k, \\ \frac{\partial}{\partial t}(\rho \varepsilon)+\frac{\partial}{\partial x_i}(\rho \varepsilon u_i)=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon \mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right)+ \\ +C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon\rho}\frac{\varepsilon^2}{k}-R_\varepsilon+S_\varepsilon. \end{cases}$$

Turbulent eddy viscosity is calculated by the formula: $\mu_t=\rho C_\mu \frac{k^2}{\varepsilon}$, closure constants for RNG $k-\varepsilon$ models: $C_\mu=0.0845$, $R_\varepsilon=\frac{C_\mu\rho\eta^3(1-\eta/\eta_0)}{1+\beta\eta^3}\frac{\varepsilon^2}{k}$, $\eta\equiv Sk/\varepsilon$, $\eta_0=4.38$, $\beta=0.012$, $\eta\approx3.0$, $C^*_{2\varepsilon}\approx2.0$, $C_{1\varepsilon}=1.42$, $C_{2\varepsilon}=1.68$.

Model $k-\omega$ - historically the very first High Reynolds model with two differential equations [12-14]:

$$\begin{cases} \frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\Gamma_k\frac{\partial k}{\partial x_j}\right]+G_k-\rho\beta^* f_{\beta^*}k\omega+S_k, \\ \frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega u_i)=\frac{\partial}{\partial x_j}\left[\Gamma_\omega\frac{\partial \omega}{\partial x_j}\right]+G_\omega-\rho\beta f_\beta\omega^2+S_\omega. \end{cases}$$

Does not contain terms reflecting the effect of molecular viscosity on turbulence. Now rarely used.

Turbulent eddy viscosity is calculated by the formula: $\mu_t=\alpha^*\frac{\rho k}{\omega}$, model inserts are defined as a function $\Gamma_k=\mu+\frac{\mu_t}{\sigma_k}$, $\Gamma_\omega=\mu+\frac{\mu_t}{\sigma_\omega}$, $\alpha^*=\alpha^*_\infty\left(\frac{\alpha^*_0+\mathrm{Re}_t/R_k}{1+\mathrm{Re}_t/R_k}\right)$, $\mathrm{Re}_t=\frac{\rho k}{\mu\omega}$, $G_k=-\rho\overline{u'_i u'_j}\frac{\partial u_j}{\partial x_i}$, $\Omega_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right)$, $G_\omega=\alpha\frac{\omega}{k}G_k$, $\alpha=\frac{\alpha_\infty}{\alpha^*}\left(\frac{\alpha_0+\mathrm{Re}_t/R_\omega}{1+\mathrm{Re}_t/R_\omega}\right)$, $\chi_k\equiv\frac{1}{\omega^3}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}$, $\beta^*=\beta^*_i\left[1+\zeta^* F(M_t)\right]$, closure constants for model $k-\omega$: $\alpha^*_0=\frac{\beta_i}{3}$, $\mathrm{R}_k=6$,

$\beta_i = 0.072$, $\alpha^* = \alpha_\infty^* = 1$, $R_\omega = 2.95$, $\alpha = \alpha_\infty = 1$, $\beta_i^* = \beta_\infty^* \left(\frac{4/15 + \left(\mathrm{Re}_t / R_\beta\right)^4}{1 + \left(\mathrm{Re}_t / R_\beta\right)^4} \right)$, $\zeta^* = 1.5$

, $R_\beta = 8$, $\beta_\infty^* = 0.09$, $\chi_\omega = \left| \frac{\Omega_{ij}\Omega_{ij}S_{ij}}{\left(\beta_\infty^* \omega\right)^3} \right|$, $\beta = \beta_i \left[1 - \frac{\beta_i^*}{\beta_i} \zeta^* F(M_t) \right]$, $M_t^2 \equiv \frac{2k}{a^2}$, $M_{t0} = 0.25$,

$a = \sqrt{\gamma R T}$, $\alpha_\infty^* = 1$, $\alpha_\infty = 0.52$, $\alpha_0 = \frac{1}{9}$, $\beta_\infty^* = 0.09$, $\beta_i = 0.072$, $R_\beta = 8$, $R_k = 6$,

$R_\omega = 2.95$, $\zeta^* = 1.5$, $M_{t0} = 0.25$, $\sigma_k = 2.0$, $\sigma_\omega = 2.0$.

Rotating machines [8]

ANSYS CFD has been the leading CFD software for modeling rotating machines for many years. It is a leader in the field, where the requirements for accuracy, speed and stability of the calculation are extremely high. ANSYS CFD combines a complete set of models, end-to-end analysis of stationary and rotating turbomachinery components, and specialized add-ons for easy preparation and analysis of mechanical engineering problems. All this makes the complex the most complete and meets the requirements of calculation engineers. The ANSYS family of complexes contains the ANSYS BladeModeler and ANSYS TurboGrid modules for quick and easy creation of a geometric model of a blade wheel and the construction of a high-quality hexahedral computational grid.
The paper considers a variant of the problem of modeling the flow around the developed wind turbine.

Geometry of the object under study

The construction of the CAD model (Fig. 1.) was carried out in the SolidWorks environment, where the main geometric dimensions were specified. Since the task is reduced to modeling a flat task, the 2D design mode was chosen.

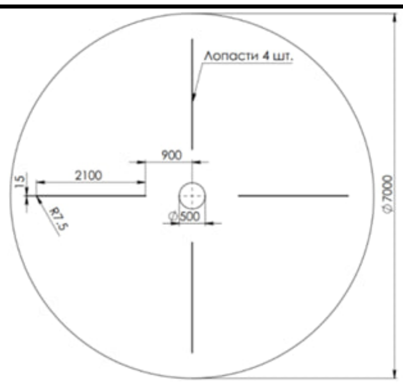


Figure 1. Geometry of a 2D four-bladed wind turbine (top view)

Calculation grid

Next, the CAD model was exported to the Cadence Pointwise program to create a hybrid finite volume mesh (Fig. 2). An O-grid topology type was chosen to define the CFD flow domain. The input velocity boundary condition was specified in the I first quarter of the circular domain and in the remaining parts of the atmospheric pressure output condition. Also, layers of cells were allowed directly at the walls of the blades for accurate modeling of the turbulent viscous layer, where $Y+ < 4$.

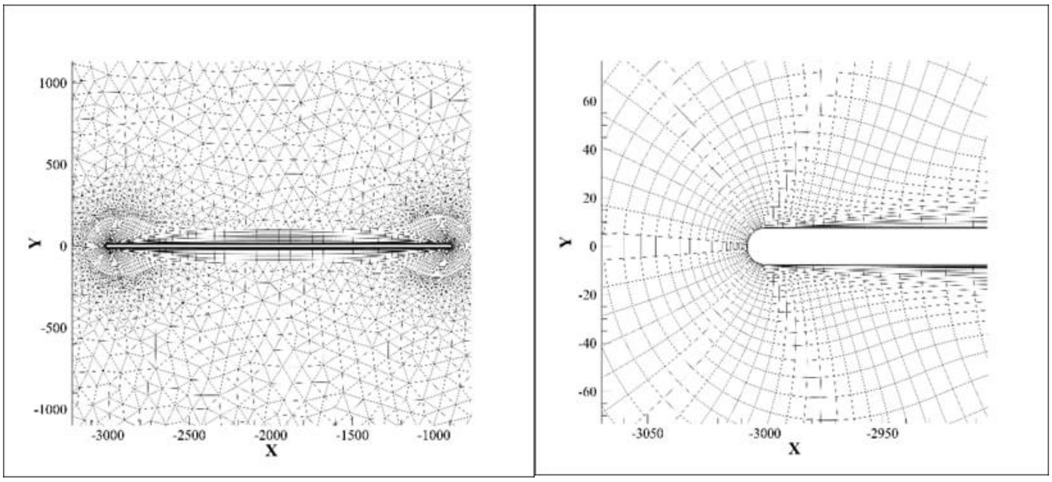


Figure 2. Unstructured computational grid of finite volumes

Ansys Fluent Dynamic Mesh

Ansys Fluent is a general purpose computational fluid dynamics (CFD) software used to simulate fluid flow, heat and mass transfer, chemical reactions, and more.

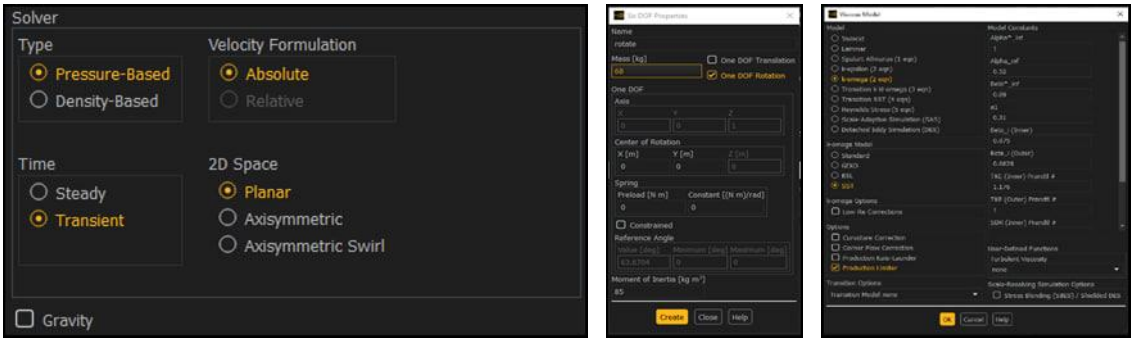
Fluent offers a modern, user-friendly interface that streamlines the CFD process from pre-processing to post-processing in a single-window workflow.

The main advantage of this program is that Fluent allows you to use Dynamic Mesh technology for tasks with a dynamic mesh. The dynamic grid model allows you to move cell zone boundaries relative to other zone boundaries and adjust the grid accordingly. Boundary motion can be rigid, such as pistons moving inside an engine cylinder or flap, deviating on an aircraft wing, or deforming, such as the elastic wall of a balloon during inflation, or the flexible wall of an artery responding to a pressure impulse from the heart. In any case, the nodes that determine that the cells in the domain must be updated based on time, and hence the dynamic grid solutions are inherently non-stationary.

Solver settings and post-processing

Type - unsteady incompressible flow in 2D formulation (Fig. 4.5a). The mass of the installation is 68 kg, the moment of inertia along the Z axis is 85 kg·m^2 (Fig. 3). Input speed – $V = 5\ m/s$.

To describe turbulence in the first version, a two-parameter low-Reynolds Menter model was chosen $k-\omega\ \ SST$ (Fig. 4.5 c). The pressure-velocity coupled scheme was chosen by Coupled, which provides the best time convergence. Spatial discretization is second order for all quantities. Time step $t = 0{,}01\ c$.



(a) (b) (v)

Figure 3. Model settings interface

Calculation algorithm

The equations described above are integrated by the finite volume method in the ANSYS Fluent package. Convective and diffusion flows are calculated with the second order of approximation. Due to the fact that all the problems modeled below are quasi-stationary, the first order of approximation in time is used. The velocity and pressure fields are linked by the PISO algorithm. Solution algorithms, depending on the selected combustion model, have distinctive features.

RESULTS AND DISCUSSION.

The results of modeling the rotation of the wind turbine blades showed a speed of 20-25 rpm at a wind speed of 5 m/s (see Fig. 4). A calculation was also carried out for the case of 8 m/s (see Fig. 5).

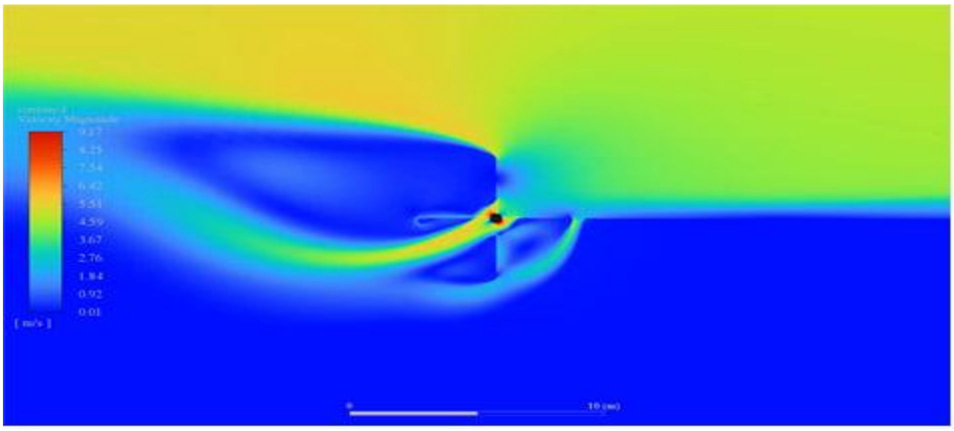


Figure 4. Contour of rotation speed V=5 m/s. K-ω model

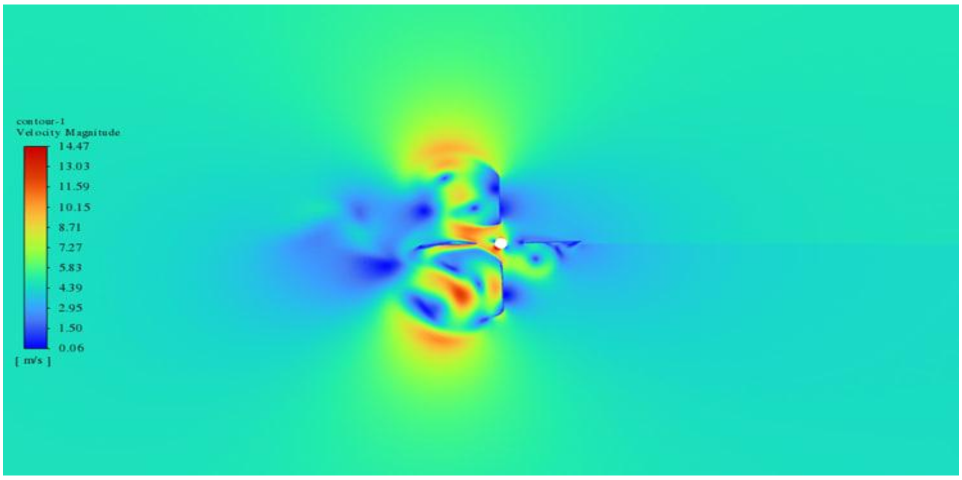


Figure 5. Contour of rotation speed V=8 m/s. K-ω model

Calculations were also carried out using $k-\varepsilon$ turbulence models (Fig. 6) and other turbulence models.

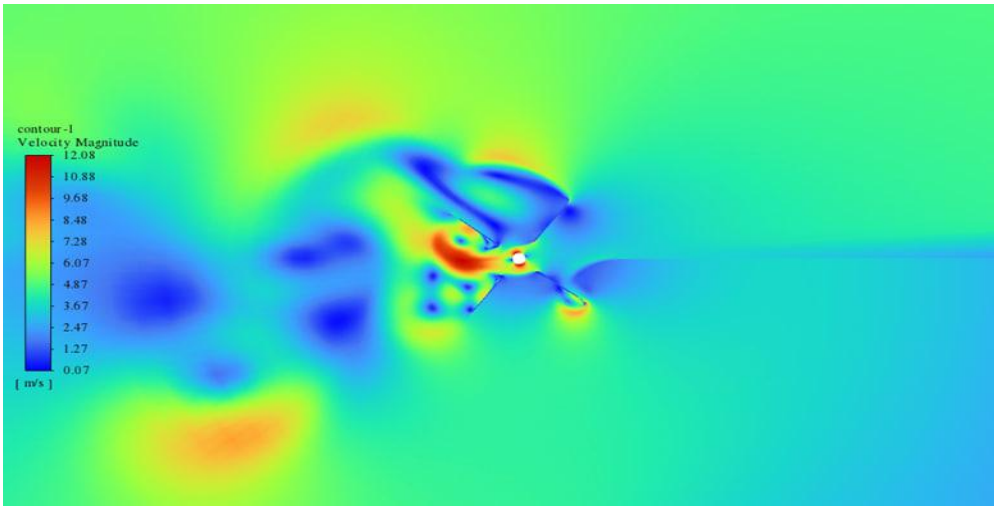


Figure 6. Contour of rotation speed V=5 m/s. $k-\varepsilon$ model

The results of calculating the drag coefficient from the angular position of the first blade using the $k-\varepsilon$ turbulence model are compared with experimental data (Fig. 7).

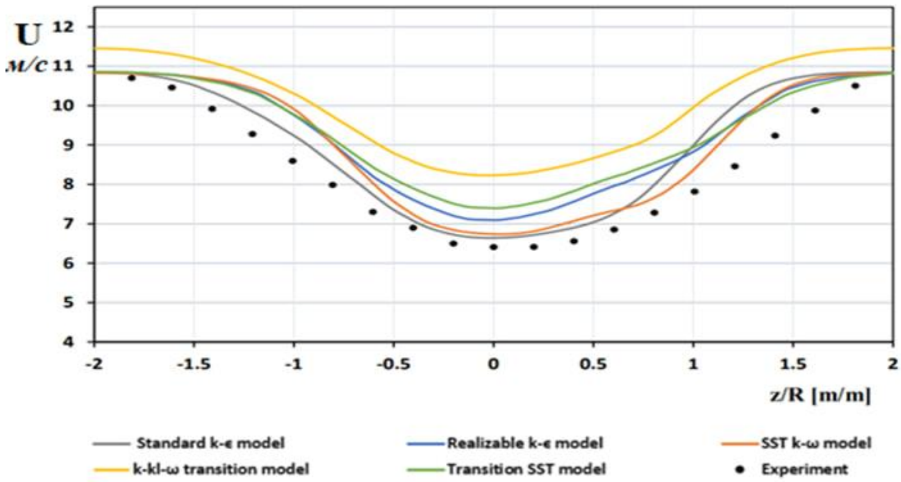


Figure 7 Axial Velocity Profile on a Vertical Line at Hub Height

A comparison of the experimentally determined profile of the axial velocity on a vertical line at the height of the hub with the profiles obtained with different turbulence models showed that it is desirable to use models $k-\omega$ and $k-\varepsilon$ in this regard.

According to the preliminary experimental results, the power curve of the installation was constructed depending on the wind speed (Fig. 8).

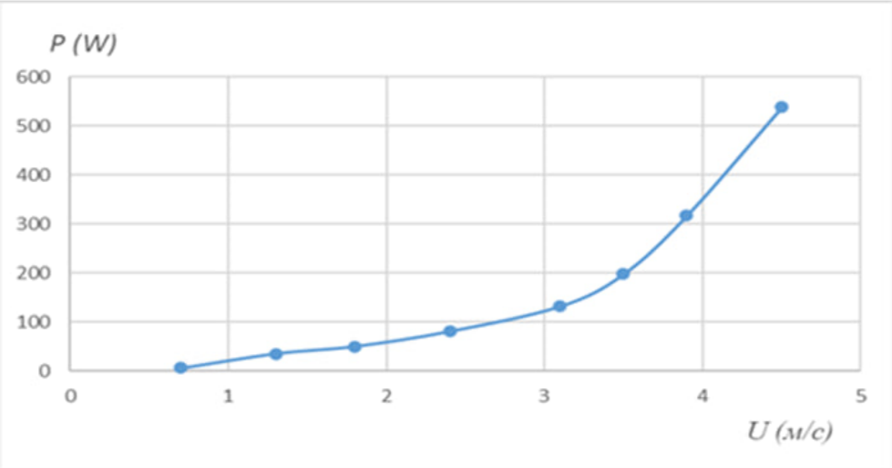


Figure 8. Power Curve

Numerous results on the aerodynamics of a wind turbine with a vertical axis of rotation have been obtained, which should be further processed by statistical methods and analyzed.

CONCLUSIONS

Theoretical calculations in the ANSYS environment have established that when calculating the aerodynamics of the proposed low-power wind generator, turbulence models $k-\omega$ and $k-\varepsilon$ can be used, which more adequately describe the process of flow around a rotating device.

Initial experimental results have been obtained, showing that at wind speeds above 4-5 m/s, the developed device can provide 0.7 kW of energy. The results on wind turbine aerodynamics, which are not included in this report, must be further processed by statistical methods and analyzed.

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