Development of autonomous energy supply system using a sail type wind turbine

A. Jakovics, S. Sakipova, K. Kussaiynov, Zh. Kambarova, Ye. Kussaiynov

Abstract**—** The paper discusses the problem of creating autonomous power supply system based on renewable resources according to climatic conditions. The authors studied the characteristics of climate and wind energy potential in Kazakhstan and Latvia and considered the possibilities of creation of a device to convert wind energy at low speed wind. A model of a wind turbine, working effectively at low wind speeds, was developed. Initial tests of a sail type wind turbine model with dynamically changeable blade shape were made at a wind tunnel. The results of experimental study of aerodynamic characteristics of wind turbine models are presented. The dependencies of the drag force and traction force at various speeds and directions of airflow were obtained.

Keywords**—** renewable resource, wind energy potential, sail type wind turbine, changeable blade shape, drag force, traction force.

I. INTRODUCTION

High level of development and technology concepts in the field of alternative energy systems make it possible to provide energy for the normal functioning of human life and activities from renewable energy sources (RES). And most accessible ones and promising are technologies and devices for converting wind energy.

In recent years the power growth rate of wind-driven power plants (WDPP) in the world has averaged 26%, which is much higher than the power growth rate of all other types of power plants. Experts claim that every five years, this figure will be doubled, and by 2020 to 18-20% of the entire energy in the world will be produced by the wind [1]. However, currently generated by WDPP energy provides only 2.5% of global electricity consumption in the world.

It is known that every produced by wind GW of energy reduces 780 kg of CO^2 emissions discharged into the atmosphere [2]. In addition, unlike fossil fuels, wind energy is virtually inexhaustible and available everywhere.

Indeed, energy production using wind power cannot be regular. However, it is easier to predict weather conditions than a sudden blackout of thermal power plants. Alterability and inconstancy of wind don’t bring any negative consequences for the environment, and are much "safer" than the radiation leak under depressurization of power generating units at nuclear power plants or nitrogen oxide emissions from coal combustion.

As a member of the European Union, Latvia has an obligation to implement 23% RES of the total energy consumption by 2020 [3]. And in Kazakhstan national objectives were posed; according to them, in 2024 it is planned to produce 5 TWh of energy from renewable energy sources [4]. This tendency to use RES is caused by rise in prices for traditional energy sources such as oil, coal and gas. Moreover, besides environmental safety and reduction of pollutant emissions into the environment, wind power engineering potential is based on socio-economic factors such as development of new technologies, providing employment, increase in taxes, etc.

Electrical energy supplying Enefit company reported that in Latvia the amount of energy produced by the wind, almost doubled to 72 GW in 2012 [5]. These facts indicate that the energy consumption in cities and large enterprises increasingly use RES, including wind power. At the same time detached small household buildings and homes outlying the central power transmission lines are neglected. Today, Kazakhstan has about 200000 farms, of which 90 % have no access to centralized power supply [6]. Actually, at long range electrical power networks maintenance, electric power losses of electricity amount to almost 30%. This makes centralized power supply to remote consumers unprofitable.

President of the Republic of Kazakhstan N. Nazarbayev in the "National programme for the development of wind power engineering in Kazakhstan until 2015 with a view to 2024" notes that the potential of renewable energy sources in Kazakhstan is not still adequately used [7]. He emphasizes that the development of renewable energy sources "would be particularly effective for power generation at the local level, as well as for small distributed loads."

Thus, the development and creation of small wind-driven power plants operating at low wind speeds and adapted to the climatic conditions, are relevant both in Latvia and Kazakhstan.

This research is done with financial support of ESF, project realized by University of Latvia, No. 2013/0027/1DP/1.1.1.2.0/13/APIA/VIAA/007 and by Kazakhstan Republic Ministry of Education and Science, project no. 523, realized by E.A.Buketov Karaganda State University.

Andris Jakovics is professor of University of Latvia, Head of Laboratory for mathematical modelling of technological and environmental processes at Faculty of Physics and Mathematics, University of Latvia, manager of ESF project.

Saule Sakipova is associate professor of E.A.Buketov Karaganda State University, Kazakhstan; visiting researcher of ESF project, mob.phone: +371-224-170-81; +7-777-999-3037, fax: +371-337-81; (e-mail: sesaule@mail.ru)

Kappas Kussaiynov is professor, Head of Engineering Thermophysics Chair, E.A.Buketov Karaganda State University, manager of project no.523.

Zhanar Kambarova is PhD, senior lecturer of the E.A.Buketov Karaganda State University, senior researcher of project no.523.

Yerlan Kussaiynov is Master program student, Kazakhstan, researcher of project no.523.

II. ANALYSIS OF DATA ON WIND ENERGY POTENTIAL IN LATVIA AND KAZAKHSTAN

The proportion of wind power engineering in total energy consumption in Kazakhstan, as well as in Latvia is less than 1%. Introduction of technologies for converting wind energy still remains a problem, since, despite the different geographical location, in most parts of these countries there are areas with values of an average annual wind speed of about (3-4) m/s. Latvia has a high potential of wind energy only along the coast of the Baltic Sea. Areas with the greatest wind speeds are only in the coastal zone of the Baltic Sea and in the northern part of the eastern coast of the Gulf of Riga, Fig.1. Wind speed in these areas reaches 5.1-6.8 m/s and more [8, 9]. Width of the area with strong winds on the coast of the Baltic Sea is 15-20 km, and in the area of the Gulf of Riga is about 10-15km.

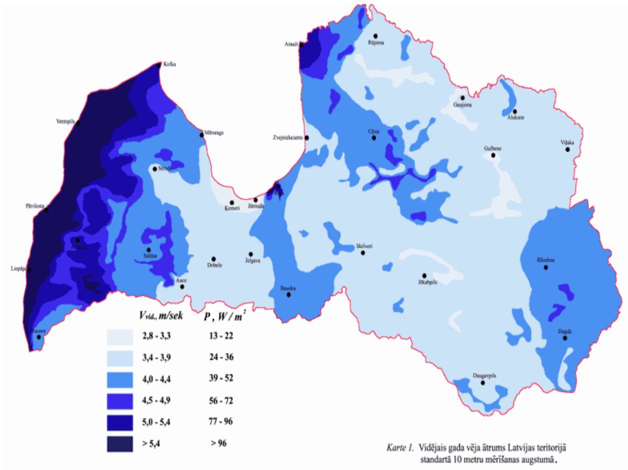
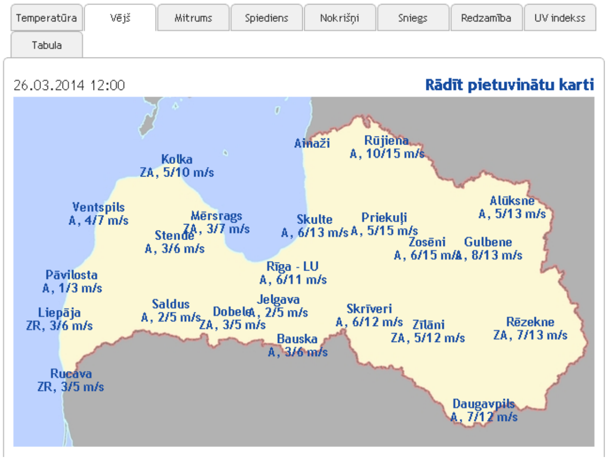


Fig. 1 Map of Latvia winds [8].

This picture of wind potential is confirmed by regular wind speed measurements performed by the office workers of the Latvian Center for Environment, Geology and Meteorology at the meteorological station located near the international airport of Riga [9]. Figure 2 shows an example of wind speed data obtained on-line.



26.03.2014 12:00

Ainaži

Rūjiena
A, 10/15 m/s

Kolka
ZA, 5/10 m/s

Ventspils
A, 4/7 m/s

Mērsrags
ZA, 3/7 m/s

Stende
A, 3/6 m/s

Skulte
A, 6/13 m/s

Priekuļi
A, 5/15 m/s

Alūksne
A, 5/13 m/s

Zosēni
A, 6/15 m/s

Gulbene
A, 8/13 m/s

Rīga - LU
A, 6/11 m/s

Pāvilosta
A, 1/3 m/s

Liepāja
ZR, 3/6 m/s

Saldus
A, 2/5 m/s

Dobele
ZA, 3/5 m/s

Jelgava
A, 2/5 m/s

Bauska
A, 3/6 m/s

Skrīveri
A, 6/12 m/s

Zīlāni
ZA, 5/12 m/s

Rēzekne
ZA, 7/13 m/s

Rucava
ZR, 3/5 m/s

Daugavpils
A, 7/12 m/s

Fig. 2 Example of on-line data on wind speed.

More accurate wind speed values in Riga can be obtained from the results of automated measurements performed continuously at a weather station based in Botanical Garden of the University of Latvia, Fig.3, 4.

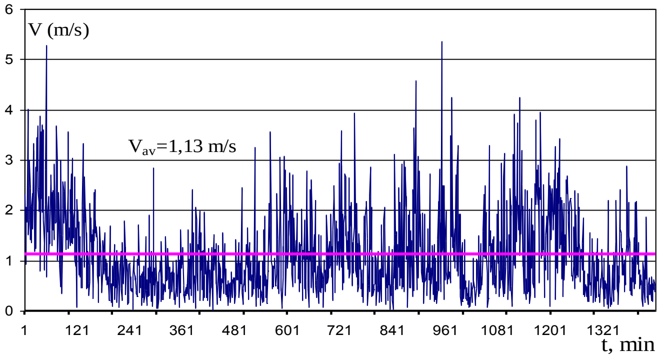


Fig. 3 Diagram of every minute change of wind speed during a day, 12.02.2014.

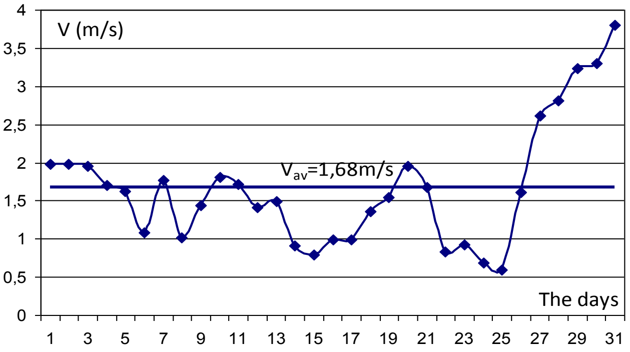


Fig. 4 Diagram of daily change of wind speed in January 2013, Riga.

Data analysis showed that in Latvia in 2013, the value of an average annual wind speed is V=2,37 m/s. Measurements show that in the central part of Latvia, an average wind speed is (3-4) m/s; in Riga the wind speed is even smaller and varies from 1.9m/s to 2.8m/s.

A similar picture of the wind potential can also be seen on the map of winds in Kazakhstan, Figure 5. Due to its geographical position, the Republic of Kazakhstan is in a wind zone of the northern hemisphere and in some regions of Kazakhstan there are sufficiently strong air currents [10 , 11].

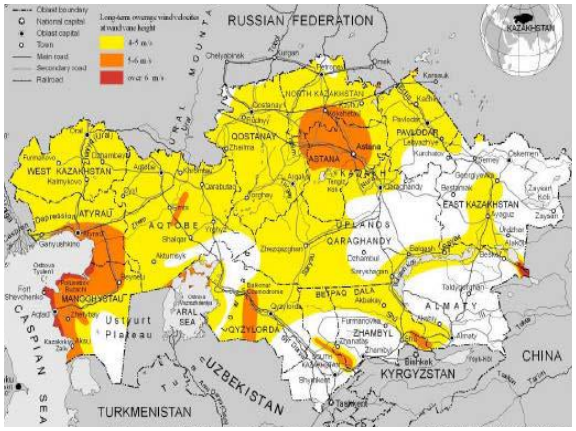


Fig. 5 Map of winds in Kazakhstan [4]

For example, according to the data of weather stations in Karaganda region in 2013, in the central part of Kazakhstan the average annual wind speed measured at a height of 10m, is equal to 3.8 m/s, and in Karaganda city it is less, Fig. 6.

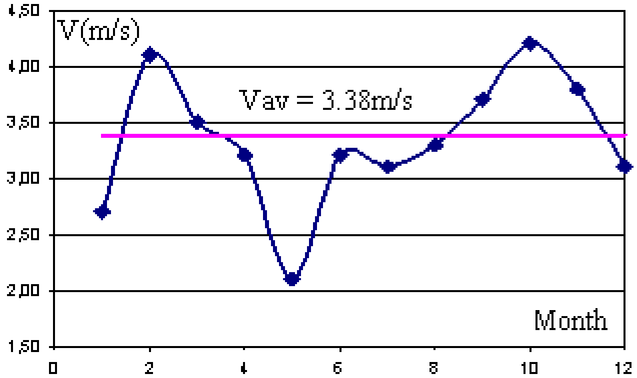


Fig.6. Diagram of the monthly change in the average wind speed in Karaganda city, 2013.

Use of manufactured in production scale small or medium power WDPP are economically unprofitable, since at these wind speeds, they do not work. But during its running time, an adequate wind turbine produces energy, which costs almost 80 times more than it is spent on its production. For this purpose, it is necessary to take into account specific features of the climate in the area, in this case, the wind speed and its direction. In fact, the owner of an autonomous power plant becomes quite independent of traditional energy producers.

III. DEVELOPMENT OF SAIL TYPE WIND TURBINE. EXPERIMENTAL CONDITIONS.

When choosing a wind turbine for energy supplying autonomous system, priorities are determined by many factors that depend on the demands of a particular customer, the quality and price of products. Known various methods and devices of convert wind energy into electrical energy are given in [6, 12, 13]. Efficiency of the use of wind turbines at small wind speeds was described in [6]. Wind turbine analogs designed for operation at low average wind speeds, are given in [14-19]. Articles of Bychkov N.M., N. Murakami (Japan) [11, 15], Nobuhiro M. [17] were shown a wind turbines for small wind speeds based on the Magnus effect. Characteristics analysis of various WDPP showed that sail type wind turbines are suitable for low wind speeds. The advantage of sail type wind turbines is that they can generate electrical energy at low wind, less than 3m/s. Previously authors of this paper also were engaged in the development of wind turbines using the Magnus effect and oriented for low wind speeds also, the results are given in [18,19].

The closest analogue for given sail type turbine is described in works [20, 21]. But weakness of this design is the absence the dynamically changeable surface shape of the blades, which does not allow to optimize the aerodynamic characteristics of a wind turbine in the work process. Moreover, the change of wind direction to the opposite direction leads to a change in the rotation axis of the wind turbine that is inconvenient in practice.

Now the authors for the first time are developing sailing wind turbine type with dynamically changeable blade shape. The dependence of the traction force and lift force were studied for the wind turbine prototype with five a triangular shaped sailing blades. In [22] studies are the results of real testing experiments for a wind turbine with six blades and 1.6 meters diameter.

For sample studies, a sail type wind turbine model was designed to be used in creating an autonomous wind power system. The model consists of a wind wheel made of metal frame rods with six sail blades of triangular shape fixed on them. The sail blades are made of lightweight and durable material, one end of the blade is attached to the top of the frame by strong thread. The diameter of the sail wheel is 0,4m. The model is fixedly attached to the mount by support rods.

This model of wind turbine differs from known analogues in that as load bearing elements, triangular blades of dynamically variable surface shape with a movable end are used. It provides continuous rotation of the wind wheel during a rapid change in the direction of airflow. To supply with electrical power, the model of sail wind turbine is coupled to a low power generator through a sheave and a belt drive. Initial tests of the model of a sail type wind turbine were carried out at T-I-M wind tunnel with an open test section in the laboratory of E.A.Buketov Karaganda State University (Fig.7).

Main characteristics of the working part of the wind tunnel are follows: the diameter is 500mm; the length is 500mm; turbulence level is 3%; the range of variation of airflow speed is (1 ÷ 25) m/s. Rotational speed of the sail type wind turbine is 50-100 rev/min, the minimum threshold of airflow operating speed is 3 m/s. Measurement errors of airflow speed in the test section using a built-in sensor do not exceed 3-5%.

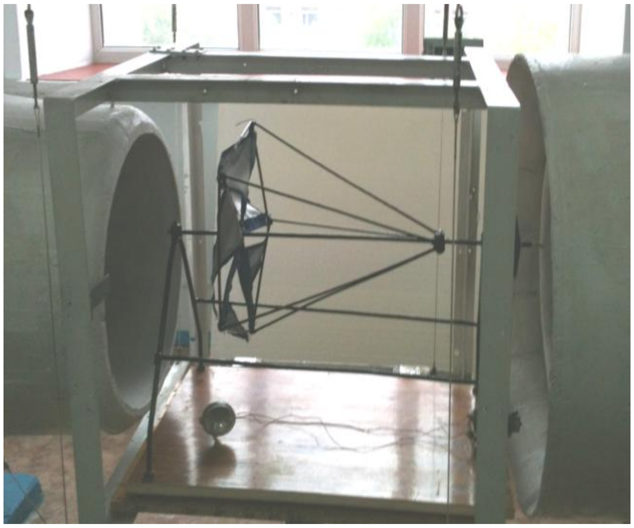


Fig. 7 The model of a sail type wind turbine in the test section of the T-1-M wind tunnel

The traction force was measured using a spring dynamometer, which was rigidly attached to the sheave of the wind turbine model. The model of the wind turbine in the test section is fixed to the cubic frame of an aerodynamic balance using thin metal braces to minimize the resistance of auxiliary elements. Aerodynamic characteristics of the wind turbine model at various speeds and directions of airflow were measured using a three-component aerodynamic balance.

IV. DISCUSSION OF THE EXPERIMENTAL RESULTS

As a result of the experiments we obtained dependences of changes in the drag force, lifting force and traction force at various air flow rates and different angles of attack.

The dimensionless drag coefficient C_x, traction force coefficient C_M and Re is similarity criterion - Reynolds numbers were calculated from measurements by next formulas:

$$C_x = \frac{2F_x}{\rho u^2 \cdot S} \tag{1}$$

$$C_M = \frac{2M}{\rho u^2 \cdot S \cdot l} \tag{2}$$

$$\mathrm{Re} = \frac{u \cdot L}{\nu} \tag{3}$$

where F_x is the drag force, M is the thrust moment, ρ, ν are the air density and viscosity, u is the flow rate, S is the characteristic area of midship section, l is the length of the lever arm, L is the characteristic size of the wind turbine model.

Figure 8 shows the dependence of the drag coefficient on the Reynolds number. A sharp fall of the drag coefficient is observed up to the Reynolds value that is equal to $1{,}5 \cdot 10^4$, at further increase in the flow rate this decrease becomes less intense, and then virtually remains constant.

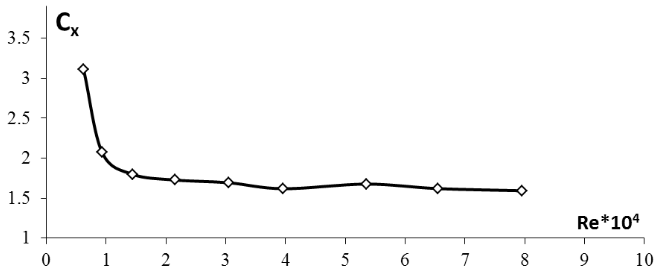


Fig. 8 Dependence of the drag coefficient of the wind turbine model on the Reynolds number

Figure 9 shows the variation of the drag coefficient C_x of the wind turbine model by changing the dimensionless attack angle β of flow at two different airflow rates: of 3m/s and 5 m/s. It is evident that the types of dependences of drag force on the dimensionless angle of attack for these rates are practically the same.

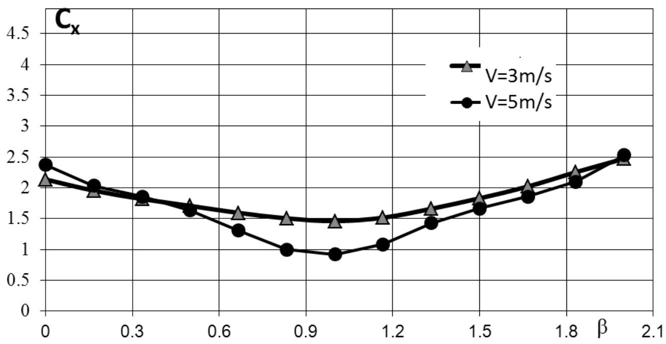


Fig. 9 The dependence of the drag coefficient of the wind turbine model on the dimensionless angle of attack

It can be seen that when the attack angle of airflow increases up to 90°, the drag force coefficient diminishes and then rises. This is due to the fact that when the attack angle of the wind flow increases up to 90°, the square of midship section of the wind wheel decreases, and at further increase in angle of attack up to 180° it grows.

Figure 10 shows the dependencies of the traction force coefficient C_M of the wind turbine model on the Reynolds number at various attack angles of airflow. The highest value of the coefficient of traction force of a model are observed in the forward direction of the wind flow. For various angles of attack of the flow when Reynolds number increases, the traction force coefficient gradually rises.

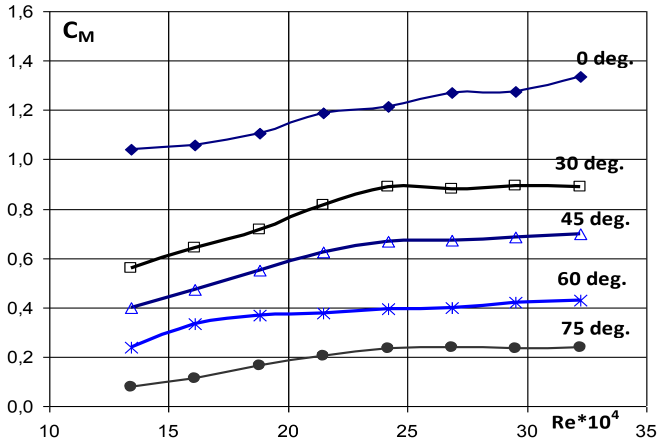


Fig. 10 Dependences of traction force coefficient of the wind turbine model on Reynolds number at various angles of attack of wind flow

Figure 11 presents dependencies of the traction force coefficient C_M of the wind turbine model on the Reynolds number when the direction of the airflow is reversed. The graphs show that the thrust moment varies virtually in the same way. The experiments showed that the designed model of the sail type wind turbine has optimum aerodynamic characteristics due to a self-regulating surface shape of blades. The wind turbine in the air flow acts as self-organized device, efficiently converting wind energy into the energy of rotational motion.

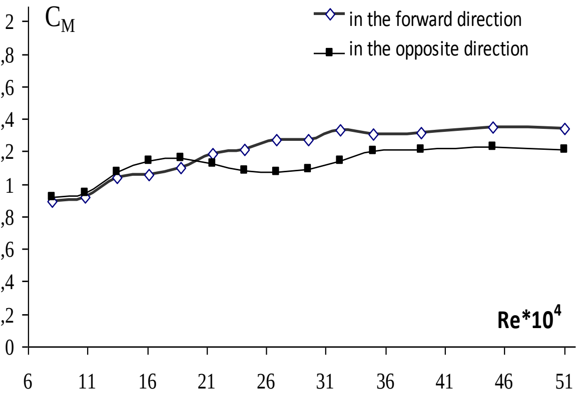


Fig. 11 Dependence of the traction force coefficient of the wind turbine model on Reynolds number at different flow directions.

The design flexibility with dynamically variable surface shape of blades provides the minimum aerodynamic resistance, and increases the utilization ratio of the wind. The comparison of experimental data on changes in drag forces another wind turbine is showing qualitative agreement. The wind turbine maintains operability in a wide range of changes of wind direction that is a positive factor in operation. It was experimentally found that even when the direction of the airflow is reversed, the wind turbine continues to rotate in the previous direction. All experimental measurements were repeated under the same conditions 5 -7 times for credibility.

Sail type WDPP matches a wind direction and practically does not originate noise and vibration [13, 22]. Power generated by a sail type wind turbine is proportional to the third power of wind speed, i.e. when wind speed doubles, the power is increased by eight times.

V. CONCLUSION

A pilot model of a sail type wind turbine with dynamically changeable surface shape of the blades was designed and developed.

The dependences of the thrust moment of the laboratory model and that of the drag force on the airflow rate at different angles of attack were studied by experiments. As the result of research we developed a measuring technique of aerodynamic characteristics of a sail type wind turbine. It was demonstrated that due to the self-regulated surface shape of blades of a sail type wind turbine, the latter can efficiently convert the energy of airflow even when the direction of airflow is reversed.

The results obtained will be used for engineering calculations in the development of sail type WDPP, adapted to specific climatic conditions, i.e. operating at low wind speeds and generating a targeted amount of electricity.

REFERENCES

[1] A. S. Vorobyev, On the current state of wind power engineering in the world. *Proc. of the Russian Scientific Technic. Conf. "High Tech in the instrument engineering and machine building and development of innovation activities in a higher educational establishment."* Moscow, 2011, vol.1, pp. 109-110.

[2] D. Glickson, (2014, January) New Test Facility to Improve Wind Turbines Renewable Energy News & Information. http://www.renewableenergyworld.com/

[3] C. Ender, International development of wind energy use – Status 31.12.2008. *DEWI Magazine*, 2009, no. 35, pp. 28–33.

[4] M.M.Kenisarin, K.M.Kenisarina, *Development of wind power engineering in the world and the prospects of its development in the CIS and Baltic countries*. http: // www.bib.convdocs.org

[5] EBRR Renewable Development Initiative - Latvia. http://www.ebrdrenewables.com/sites/renew/countries/

[6] R.S. Abdrakhmanov, F.V. Yakimov, The effectiveness of using wind energy sources with reduced wind speeds. *Izvestiya RAN Energy*. Moscow, 2001, no. 5, pp. 54-57.

[7] N.A. Nazarbayev, *National program for development of wind energy in Kazakhstan until 2015 with a view to 2024*. http:// www.windenergy.kz/files/121379

[8] Sustainable Energy Roadmaps http://www.worldwatch.org/

[9] Operative information of Latvian Center for Environment, Geology and Meteorology http://www.meteo.lv/meteorologijas-operativa-informacija/?nid=459&pid=100

[10] G.Doroshin, About perspectives of wind power development in the Republic of Kazakhstan http://carnegieendowment.org/ files/Presentation - Rus.pdf

[11] A. Orlov, Prospects for the use of wind power engineering in Kazakhstan. *Proc. 8th Rep. Conf. "Seifullin readings."* Astana, 2012, vol. 1, pp.16-17.

[12] Ya.I. Shefter, *The use of wind energy*. Moscow: Energoatomizdat. 1983, 200 p.

[13] O.G. Denisenko, G.A. Kozlovsky, L.P. Fedossenko, A.I. Osadchiy, *Transformation and use of wind energy*. Kiev: Technique, 1992, 176 p.

[14] N.M. Bychkov, Magnus wind turbine. The calculated characteristics of wind wheel. *Thermophysics and Aeromechanics, Novosibirsk,* 2008, vol.15, no. 2, pp.583-596.

[15] N.M. Bychkov, A.M. Sorokin, N. Murakami, "Wind turbine", Russian Patent no. 2118699, September 10, 2009.

[16] N. Nobuhiro, Ito Dzun, "Wind power Magnus", Russian Patent no. 2330988, March 27, 2008.

[17] K. Kusaiynov, S.E. Sakipova, L.N. Nikitina, Aerodynamics of the transversally streamlined rotated barrel. *Proc.12th Int. Cohf. ICMAR "Methods of aerorhysical research",* Novosibirsk, 2004, vol. 4, pp. 195-198.

[18] K. Kusaiynov, S.E. Sakipova et al., Experimental research of aerodynamics of the system of the revolved cylinders in a turbulent stream. *Proc. 7th International Symposium Turbulence, "Heat and Mass Transfer"*, Italy, Palermo, 2012, pp. 577 - 580.

[19] B.V. Voitsekhovskii, Promising energy sources and their comparison. *J. of Applied Mechanics and Theoretical Physics*, 1980, no. 5, pp. 118-125.

[20] B.V. Voitsekhovskii, F.F. Voitsekhovskaya, M.B. Voitsekhovsky, *Micro modular wind energy*. Novosibirsk: Publ. Institute of Hydrodynamics, 1995, 71 p.

[21] S.E. Sakipova, Zh.T. Kambarova, M.M. Turgunov et al. Development of sail type wind turbine for small wind speeds. *Eurasian Physical Technical Journal*, Karaganda, 2013, vol. 10, no. 2(20), pp.20-25.

[22] N.A. Lavrentiev, G.V. Volobueva, et al, Wind energy resources and conditions for construction of wind-driven power plants in Eastern Baltic and the Black Sea area of Europe — Minsk, 2010. — 455 p.