Improving the efficiency of carousel wind turbine using aerodynamic shield

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Abstract. The problem of increasing the efficiency of using the oncoming air flow for a wind wheel with a vertical axis of rotation, which is a mechanical drive of the wind heat generator, is considered. It is proposed to increase the efficiency of the device by installing an aerodynamic shield for the air flow oncoming the wind wheel. Such a shield is a cylindrical body in which a heat generator is placed. The shield creates an effect of confuser, leading to an increase in the speed and, consequently, in the kinetic energy of the air flow acting on the rotor blades. It is shown experimentally that the presence of an aerodynamic shield under the conditions of the experiments carried out at an incoming air flow velocity of ~ 1 m/s leads to a practical doubling of the wind wheel torque.

1. Introduction

The task of creating an efficient and easy-to-use source of thermal energy based on a wind generator is classical and has a long history. Currently, there are many different conceptual designs of wind power plants (WPP), which, according to the type of wind wheels (rotors, turbines, propellers), can be divided into two main types. The first type includes wind turbines with a horizontal axis of rotation (vaned) and the second one includes turbines with the vertical axis of rotation (rotary or carousel) [1-3].

Currently, more than 90% of all used wind turbines in the world are installations with horizontal-axial propeller rotors. More than 100 companies are engaged in their serial production.

Vertical-axis wind turbines began to be intensively developed thanks to the successful experience of VAWT (Great Britain), which put into commercial operation a wind turbine with a rotor diameter of 25 m and a power of 130 kW. The main advantage of vertical-axis wind turbines is operation at low wind speeds (4–5 m/s) and the absence of the need to orient them to the wind; they use the wind coming from any direction.

The main unit of any WPP is a wind turbine (WT), which is a device that converts wind energy into mechanical energy of a windwheel (WW) rotation. It is customary to characterize the efficiency of WT by a specific power parameter $C_p$ (coefficient of wind energy usage), which is the ratio of a part of the air flow energy used by the WW to the total kinetic energy of the air flow acting on the windwheel.

The wind turbine power formula is as follows [2]:

$$ N = 0.5 \cdot \rho \cdot V^3 \cdot \eta \cdot C_p \cdot F $$

(1)
where $\rho$ is the air density under standard conditions, kg/m$^3$; $V$ is the wind speed, m/s; $\eta$ is the efficiency of the generator (mechanical transmission system between the WW and the generator), $C_p$ is the power coefficient, depending on the wind wheel design and other operating parameters, $F$ is the area of the surface swept by the wind wheel, m$^2$.

The theoretical maximum value of $C_p$ for ideal vaned windwheel (spiral WW) is $C_p \sim 0.6$, the real coefficient is $C_p = (0.42-0.46)$. For low-speed carousel turbines, this coefficient is $C_p = (0.27–0.33)$ [2].

The authors have patented a design of an opposed wind heat generator [3], in which two vertical carousel-rotary wind turbines drive two coaxial rotors of the heat generator into counter-rotation. Structurally, the working part of the heat generator consists of two multi-cylinder rotors nested into each other and forming a system of annular coaxial channels. In such a device, heat is released in the volume of liquid located in narrow annular gaps between coaxial cylinders rotating towards each other (circular Couette-Taylor flow), which allows creation of effective heat sources [4-7]. The investigations carried out by the authors have shown that the specific thermal power released in a heat generator of such a design can reach values of the order of 1 MW/m$^3$, which indicates the competitiveness of such devices among devices based on renewable energy sources.

In this paper, the issue of increasing the efficiency of using the incoming air flow for a wind wheel having a design described in the patent [3] of an opposed wind heat generator is considered. It is proposed to increase the efficiency by using a special aerodynamic shield.

2. Experimental setup design and technique

Figure 1(a) shows a design diagram of a wind heat generator described in the patent [3], figure 1(b) shows the proposed design diagram of a wind heat generator with an aerodynamic shield.

![Figure 1](image_url)

**Figure 1.** Design diagrams of the wind heat generator: (a) heat generator body is located between the upper and lower WW (there is no aerodynamic shield); (b) heat generator body is located inside the upper and lower WW and forms an aerodynamic shield. 1 – WW blades, 2 – blade rotation axis, 3
- blade stops, 4 – heat generator body, 5 - cylindrical rings of the upper heat rotor, 6 - cylindrical rings of the lower heat rotor, 7 – working fluid, 8 - upper WW, 9 - lower WW, 10 - element of the supporting structure.

The scheme of a wind heat generator with two counter-rotating WW provides doubling of the relative rotational speed of the rotors and, accordingly, an increase in generation of thermal power at the given values of the wind speed and the area of the swept surface. Due to the design, the windwheel rotates horizontally in any wind direction. Freely rotating vertical flat blades 1 are installed on axes 2 (see figure 1). These blades in the upper part of WW, under the influence of the flow, stand at "sail" position and create a torque. In the second opposite half of the WW, under the influence of the flow, the blades 1 are deployed to the “weathervane” position and at the same time they create a minimum resistance to the air flow. Under the influence of the resulting torque, the WW rotates and drives the rotor of the heat generator located with it on the same axis.

In this work, the authors propose to supplement the design of the wind heat generator (see figure 1a) with installation of an aerodynamic shield for the air flow approaching the WW. Such a screen is a cylindrical body in which a heat generator is placed (see figure 1b). The aerodynamic shield increases the amount of the incoming air flow falling on the working blades of the WW. A kind of confuser effect arises, leading to an increase in the speed, and, consequently, in the kinetic energy of the air flow. Ultimately, this confuser effect leads to an increase in the power of the heat generator.

The influence of such an aerodynamic shield on the developed WW torque was studied experimentally. The experiments were carried out on a specially created aerodynamic setup, the diagram of which is shown in figure 2.

![Figure 2. Diagram of the aerodynamic setup with an automated system for recording experimental data. Temperate sensors 1-3 are platinum thermistors, LC – load cell measuring the WW torque, A - mechanical anemometer, measuring the air flow rate at one point at the fan outlet, TA - hot-wire anemometer, measuring the air flow velocity field in four sections of the aerodynamic stand, MBA8 - microprocessor-based controller.](image-url)
Humidity and atmospheric pressure were recorded by self-contained instruments. The setup consisted of a centrifugal fan with an adjustable diaphragm, a diffuser and two sections. Section No. 1 with a square section of 980x980 mm had a length of 2700 mm and was designed to form a uniform air flow. Section No. 2 of square size of 980x980 mm had a length of 1200 mm.

At the end of the second section, a model of the investigated WW was installed. In front of the model, a flow-leveling mesh lattice with a length of 1000 mm and a mesh size of 60x60 mm was installed. A centrifugal fan with a capacity of 1600 m$^3$/h provided a uniform air flow at the outlet of the leveling lattice with an average speed of (0.5-5.0) m/s.

The setup is equipped with an automated system, which recorded: the velocity and temperature of the air flow in four planes of the flow section, the torque induced by the air flow of the WW model, the current time of the experiment and the time of registration of the measured parameters. To control uniformity of the air flow in the working space of setup, the velocity field was recorded in four sections of the setup (see figure 2). In each section, the velocity was measured with a standard hot wire anemometer with a tungsten filament 100 μm in diameter at 100 points uniformly distributed over the section. At each point, the turbulent flow velocity was measured with averaging over an interval of 180 seconds. The exact installation of the hot-wire anemometer sensor at the point of measurement of the flow velocity was provided using a special coordinate device. According to the results of preliminary measurements, non-uniformity of the air flow velocity field was ~ 4%.

All experiments were carried out on a decelerated WW blown by an air flow. The WW was equipped with a dynamometric system to measure the torque induced by the air flow. Figure 3 shows a photograph of the WW model and a diagram of installation of the dynamometric system. The height of the WW is 400 mm, the diameter of the WW is 300 mm, and the width of the working blades is 75 mm. The used dynamometric system is described in detail in [6,7]. The dynamometer was calibrated in a static mode using exemplary weights. The calibration dependence of the torque on the dynamometer output signal was linear, and uncertainty of the torque measurement was ~ 1% of the upper limit of the dynamometer measurement (2 N·m).

Figure 3. WW model (a) and dynamometer installation diagram (b)
1 - WW model, 2 - strain gauge dynamometer, 3 - dynamometer arm (100 mm), 4 - support structure, 5 - dynamometer thrust, 6 - WW braking position fixation structure.

Figure 4 shows the diagrams of tested WW structures: 4a - WW model without aerodynamic shield, 4b - WW model with aerodynamic shield.
Figure 4. Variants of WW designs (a - without aerodynamic shield; b - with aerodynamic shield).

In version 4a (see figure 4), the space between the WW rotation axis and its inner rim was free for the air flow to pass through it. In version 4b, a stationary cylindrical body (aerodynamic shield) was placed in this space coaxially with the WW axis. The gap between the inner rim of the WW and the aerodynamic shield was 5 mm. The WW had six sectors of 60° each, in each sector a working blade was installed so that the angular distance between the axis of adjacent blades was 60°. The device for recording the WW torque allowed its measurement at seven values of the angle α (see figure 4): 0°, 10°, 20°, 30°, 40°, 50°, and 60°.

3. Results

Figure 5 shows the results of measurements of the dependence of the torque that occurs when a uniform air flow at a speed of 1 m/s acts on a restrained WW in this flow when angle α changes from 0° to 60°.

It follows from Figure 5 that under the conditions of the experiment, the value of the WW torque averaged over the angle of rotation α with an aerodynamic shield is 1.95 times (almost twice) greater than the torque of a wind wheel without a screen, which convincingly proves the effectiveness of using such a shield.

Figure 5. Dependence of the torque on angle α at the WW break restrained in the air flow.
It should be noted that the torque for the restrained WW is greater than for the WW rotating under the action of the air flow. This can be easily shown by considering the surface work under the action of the wind force, but at the same time the relative influence of the presence of an aerodynamic shield remains.

Conclusions
As a result of the experiments, it has been shown that the proposed by the authors arrangement of the opposed wind heat generator with the placement of the heat generator structure inside the cylinder, which, in turn, is an aerodynamic screen for the wind wheels rotating the heat generator rotors, leads to an increase in the torque of the wind engines, and, consequently, the power of the heat generator. The aerodynamic screen increases the volume of the incoming air flow falling on the working blades of the wind engines. A kind of confuser effect arises, leading to an increase in the speed and kinetic energy of the air flow, acting on the working blades of wind engines.

The presence of an aerodynamic screen under the conditions of the experiment at the incoming air flow velocity of ~ 1 m/s led almost to doubling of the wind wheel torque.

The result obtained should be considered as a result that fundamentally indicates the way to increase the efficiency of vertical-axis wind power plants (WPP) with opposed wind engines. It is necessary to carry out systematic studies of the use of aerodynamic screens for such WPP in order to generalize investigation results in a wide range of working parameters of WPP and issue practical recommendations for the design of such units.

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