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Analysis of Aerodynamic Characteristics of Rotating Porous Cylinders

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Abstract—We report on the results of experiments on determining the head resistance and lift force for a rotating cylinder with a porous surface in the air flow velocity range 5–13 m/s (Re = 40000—105000) at a constant rotation number of the cylinder about its own axis. We also give the results of measurement of the head resistance and the lift force for a single rotating cylinder in the range of cylinder revolution numbers 400–1400 rpm at a constant air flow velocity. It is shown that the drag coefficient and the lift coefficient depend on the Reynolds number and on the number of revolutions of the cylinder. The dependence of the coefficients of aerodynamic characteristics on the degree of porosity of the rotating cylinder surface is established.

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INTRODUCTION

Renewable energy sources are being developed for fuel and energy saving, for reducing the negative effect on the environment, and for electric energy supply to far regions. The Kazakhstan Republic has a huge potential of renewable energy sources. For example, the average annual wind velocity is 3–5 m/s; therefore, the development of wind-power engines is topical. Of special interest are the windmills based on rotating cylinders with constant and variable cross sections, which can effectively operate at low wind velocities. To increase the effectiveness of operation of such a windmill, it is necessary to analyze the aerodynamic characteristics of the windmill element—rotating cylinder. Thus, this problem is important both from the theoretical point of view and for applications.

The aerodynamic characteristics for a transverse flow past stationary individual cylinders in the infinite flow were studied in detail by Isataev [1]. The effect of blocking of the flow on the regularities of the flow past an infinitely long cylinder (aerodynamic and hydraulic drags) were analyzed and systematized by Akylbaev [2, 3]. The aerodynamics of short cylinders that are often encountered in elements of power aggregates and units was studied experimentally by Zhangunov [4].

However, the number of publications devoted to analysis of aerodynamics of the complex flows past a single rotating cylinder and systems of such cylinders, which are elements of the windmill developed in this study and are accompanied with a turbulent flow of a group of interacting vortices, is scarce. The well-known articles by Bychkov [5, 6] deal with the determination of aerodynamic parameters of single rotating cylinders in an air flow.

The contemporary level of engineering and high technologies makes it possible to use a rotating cylinder as a special element for obtaining an additional lift force directed across the flow. During rotary motion of the cylinder in the air flow, the velocity of the flow in the upper part and the velocity of the surface coincide, are added, and give rise to acceleration of the flow and an increase in the velocity [7].

In the lower part of the cylinder, the velocities of the flow and of the rotating surface have opposite directions and are subtracted, which causes deceleration of the flow and a decrease in its velocity. The emergence of such a difference gives rise to a transverse pressure difference and a transverse lift force known as the Magnus effect (Fig. 1). This phenomenon was used here in the development of a windmill.

The novelty of this design is that in contrast to available simple helical windmills with the blades reflecting the air flow through small angles, cylindrical elements in our windmill entrain the wind flow much more effectively due to rotation of cylinders themselves. This ensures the high efficiency of the windmill operation at low wind velocities.

To explain physical effects accompanying a complex turbulent flow past a rotating cylinder and to obtain qualitative and quantitative dependences of aerodynamic characteristics on the geometrical and regime parameters of the flow, fundamental studies are required.

Analysis of the available data called for experimental study of the effect of porosity on the aerodynamic characteristics of a rotating cylinder, which is an element of the windmill based on the Magnus effect.

The Magnus effect has been used for studying a cylinder rotating in a flow for a long time; however, the possibility of its practical application as a driving force of new-generation windmills for low velocities of the flow has been studied systematically only in recent years.

This study aims at analysis of the effect of porosity of the surface on the aerodynamic characteristics of a single rotating cylinder, which is the main element of the windmill operating at low wind velocities on the basis of the Magnus effect.

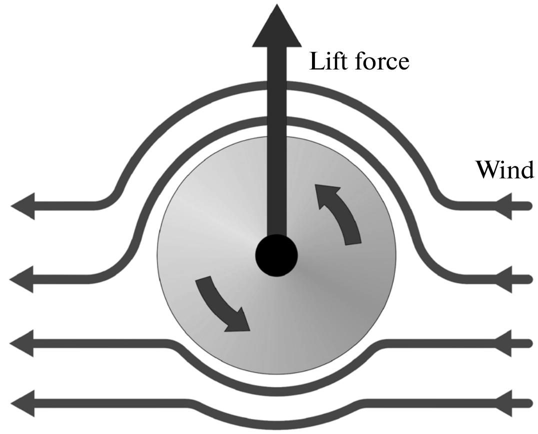

Fig. 1. Diagram of the flow past a rotating cylinder.

1. EXPERIMENTAL TECHNIQUE

The experimental setup contained a closed-type wind tunnel with an open working part with a metal frame suspended from a three-component aerodynamic balance. The diameter of the working part was 0.5 m and its length was 0.8 m.

Our experiments were carried out in the air flow velocity range 5–13 m/s (Re = 40 000–105 000) at a constant number of revolutions of the cylinder about its own axis. The head drag and the lift force of the rotating cylinder were measured using the three-component wind-tunnel balance. This balance makes it possible to measure the head drag and the lift force to a high degree of accuracy.

The block diagram of the main elements of the setup in the working part of the wind tunnel is shown in Fig. 2.

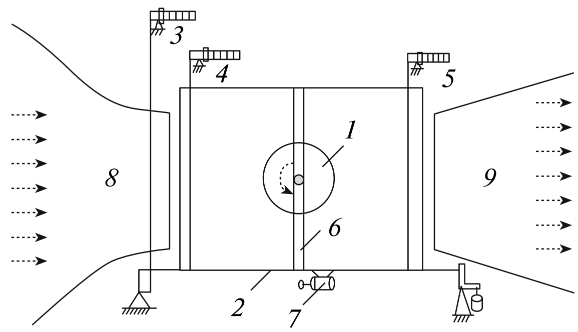

Fig. 2. Diagram of the experimental setup for studying the aerodynamic characteristics of the cylinder: (*1*) cylinder under investigation; (*2*) frame for fixation of the model with an aerodynamic balance; (*3*) balance measuring the aerodynamic drag; (*4*, *5*) balance measuring the lift force; (*6*) stand for fixing the cylinders; (*7*) motor driving the cylinders; (*8*, *9*) diffuser and confusor of the wind tunnel.

The experimental model was blown by a transverse air flow generated in the working part of the wind tunnel. The cylinder was driven by an electric motor. The air flow incoming to the head part of the cylinder exerts the force detected by all balances (Fig. 3).

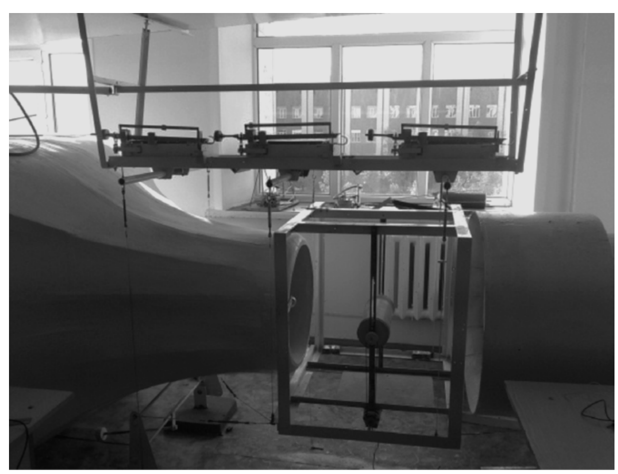

Fig. 3. Photograph of the cylinder installed in the working part of the T-1-M wind tunnel.

The Reynolds number and the coefficients of the aerodynamic parameters were calculated as follows.

The expression defining the Reynolds number has the form

$$\mathrm{Re} = (ud)/\nu, \quad (1)$$

where u is the velocity of the air flow incoming on the cylinder, d is the outer diameter of the cylinder under investigation, and ν is the kinematic viscosity of air.

The drag coefficient is defined by the formula

$$C_x = F_{\mathrm{a.d}}/((\rho u^2/2)S), \quad (2)$$

where $F_{\mathrm{a.d}}$ is the aerodynamic drag, u is the velocity of the air flow, ρ is the density of air, and S is the midsection area of the cylinder under investigation.

The lift force coefficient is defined as

$$C_y = F_{\mathrm{l.f.}}/((\rho u^2/2)S), \quad (3)$$

where $F_{\mathrm{l.f.}}$ is the lift force.

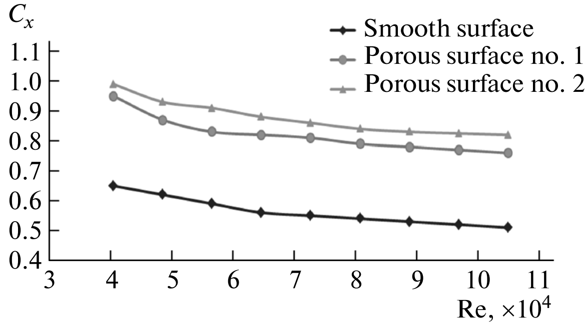

Fig. 4. Dependence of the aerodynamic drag coefficient on the Reynolds number.

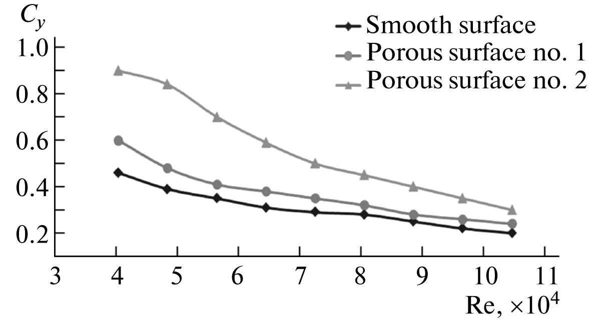

Fig. 5. Dependence of the lift force coefficient on the Reynolds number.

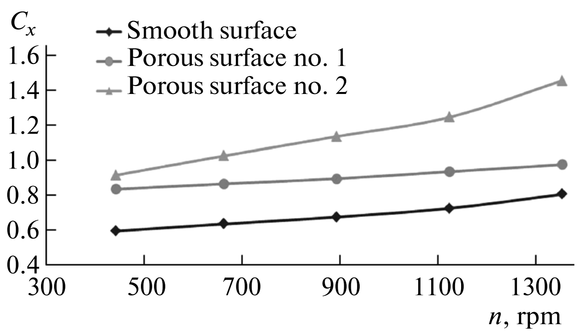

Fig. 6. Dependence of the aerodynamic drag coefficient on the frequency of rotation of the cylinder.

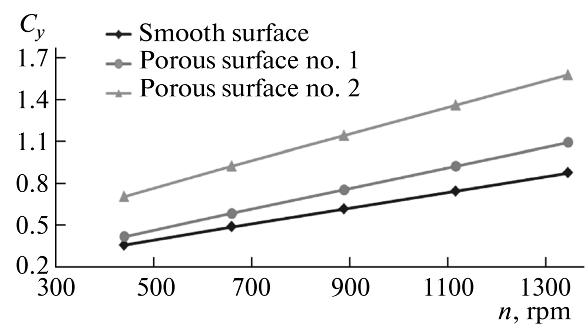

Fig. 7. Dependence of the lift force coefficient on the frequency of rotation.

2. RESULTS OF INVESTIGATION OF AERODYNAMIC CHARACTERISTICS OF A ROTATING CYLINDER WITH A POROUS SURFACE

The tests were carried out with two types of rotating cylinder of diameter 120 mm and length 330 mm (nos. 1 and 2). The difference between the surfaces of the porous cylinders was in the cell size (the cells in no. 1 porous surface were half as large as in no. 2 porous surface). The porosities of cylinder nos. 1 and 2 were 25% and 50%, respectively.

The dependences of the aerodynamic drag and lift force coefficients on the Re number are shown in Figs. 4 and 5.

It can be seen from these figures that the aerodynamic drag and lift force coefficients for the rotating cylinder decrease with increasing flow velocity (Re numbers).

In these experiments, we investigated the dependence of the aerodynamic drag and lift force coefficients on the frequency of cylinder rotation about its own axis at a constant velocity of incoming flow.

Figure 6 shows the dependence of the aerodynamic drag coefficient on the rotational frequency for a constant velocity of the incoming air flow.

It can be seen from the figure that the aerodynamic drag coefficient increases with the rotational frequency. This is due to the fact that vortex flows are formed behind the rotating cylinder at a constant velocity of the flow past it. These vortex flows interact with air particles on the cylinder surface on its rear part and counteract the incoming flow. With increasing frequency of rotation, the force with which the cylinder counteracts the flow increases. Therefore, the aerodynamic drag of the rotating cylinder increases.

Figure 7 shows the dependence of the lift force coefficient on the rotational frequency of the cylinder at a constant velocity of transverse flow past the cylinder.

It can be seen from Figs. 6 and 7 that the lift force coefficient for the rotating cylinder increases with the frequency of its rotation at a constant velocity of the air flow. This is due to the fact that a rotating cylinder generates vortex motion around it. During its rotation, the cylinder entrains the adjacent layers of air; as a result, surrounding air acquires rotation about the cylinder in addition to its translatory motion. In the regions where the velocities of the translatory and rotational motions are added, the resultant velocity exceeds the velocity of the incoming flow. At the same time, the velocities at the opposite end of the cylinder are subtracted, and the resultant velocity is smaller than the velocity of the flow at a large distance from the cylinder. As a result, a difference appears between the pressures at the cylinder surface. This difference affects the coefficients of the aerodynamic characteristics of the rotating cylinder. With increasing frequency of rotation, the pressure difference increases and, hence, the coefficients of the aerodynamic characteristics of the rotating cylinder also increase.

It can be seen from the curves in the above figures that with increasing porosity of the cylinder surface, the coefficients of the aerodynamic characteristics of the rotating cylinder increase numerically. The reason is as follows: when air flows past a rotating cylinder with a porous surface, a boundary layer is formed on the surface of the cylinder, which expands upon an increase in the porosity.

CONCLUSIONS

The results of analysis of the effect of porosity on the coefficients of the aerodynamic characteristics of the rotating cylinder lead to the following conclusions:

(i) the aerodynamic drag and lift force coefficients for a rotating cylinder as an elements of the windmill based on the Magnus effect depend on the Reynolds number; upon an increase in the flow velocity (Re numbers), the coefficients of the lift force and aerodynamic drag decrease by 5–10%;

(ii) upon an increase in the rotation frequency of the cylinder about its own axis, the numerical values of the aerodynamic characteristics of the rotating cylinder increase;

(iii) the aerodynamic characteristics of the rotating cylinder depend on the porosity of the cylinder surface: with increasing porosity, the aerodynamic drag and lift force coefficients numerically increase.

Thus, our results can be used in the designing and constructing windmills for small wind velocities on the basis of the Magnus effect.

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