Journal of Engineering Physics and Thermophysics, Vol. 74, No. 5, 2001

SCREW-TYPE WINDMILLS AND THEIR PARTICULAR FEATURES

I. I. Smul'skii

UDC 621.311.24+621.548

A new type of windmill based on a screw-type wind receiver has appeared recently. In the present article, the principles of operation of screw-type windmills and their geometric characteristics are discussed. Attention is given to the design and technology of manufacture of a screw-type rotor; possible arrangements of wind-power plants with a screw-type rotor are shown. The procedure of calculation of the power characteristics is substantiated. Screw-type windmills are noiseless and environmentally safe; they show promise as the least expensive ones.

Introduction. In the late 80s, due to the exhaustion of the supply of organic fuel and to the accidents at nuclear power stations and also for various environmental reasons, a rather rapid development of wind-power engineering became evident; this development is expected to continue in the future [9]. On the one hand, substantial wind-power resources are available; for instance, only the winds of the Arctic coast can easily satisfy all the power needs of Russia and of the CIS countries [10]. On the other hand, electric power supply to hard-to-reach regions is associated with great economic expenditures. Thus, on individual farms of the Taimyr peninsula the cost of one kilowatt hour of electric power is 25-fold higher than that in the European part of the country [11]. However, at present, cheap wind-power assemblies of small power for use on individual farms are required. Screw-type windmills with thin propeller blades can meet these requirements.

Geometric Characteristics of a Screw-Type Windmill. Figure 1 shows a three-start screw-type rotor [2] of length L equal to the pitch of a helical line S. Blades 1, 2, and 3 are connected to hub 4. The hub is hollow. The blades and the hub are manufactured from thin metal sheets. The rotor can rotate in bearings 5. The power takeoff is accomplished by an electric generator 7 via a driven gear or pulley 6.

The helical surface of the blade in the radial direction consists of a number of helical lines. A helical line is the shortest line that connects two points on a cylindrical surface. Any lateral deformation of the blade is accompanied by an increase in the lengths of the helical lines, i.e., by their tension. Therefore, the screw blade under wind load will operate for tension and it can be manufactured thin.

With the axial direction of wind the rotor operates as a conventional windwheel. The wind pressure acting on blades 1, 2, and 3 inclined at an angle α to the wind creates a torque. Owing to the multiple overlap $k = nL/S$ of the swept surface, the wind energy not utilized on the initial portion of the rotor is utilized on the subsequent portions.

With the side wind directed at a mean angle of $\varphi = \pm\alpha_m$ (see Fig. 2a), the upper parts of blades 1 turn edgewise to the wind and the wind load is received only by some parts of blades 2. As a consequence, a permanent torque exists, which makes the rotor rotate. At an angle of $\varphi < \alpha_m$ a torque is also created by blades 1. At $\varphi > \alpha_m$ blades 1 will create a counter-torque, and at $\varphi = 90^o$ the counter-torque of blades 1 will balance the torque of blades 2. Therefore, only the position at $\varphi = \pm 90^o$ is an off position, while the remaining directions are operating. However, the operating efficiency falls with increase in φ from α_m to 90^o; there-

Institute of the Cryosphere of the Earth, Siberian Branch of the Russian Academy of Sciences, Tyumen', Russia; email: smulski@ikz.tmn.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 74, No. 5, pp. 187–195, September–October, 2001. Original article submitted February 1, 2000; revision submitted February 4, 2001.

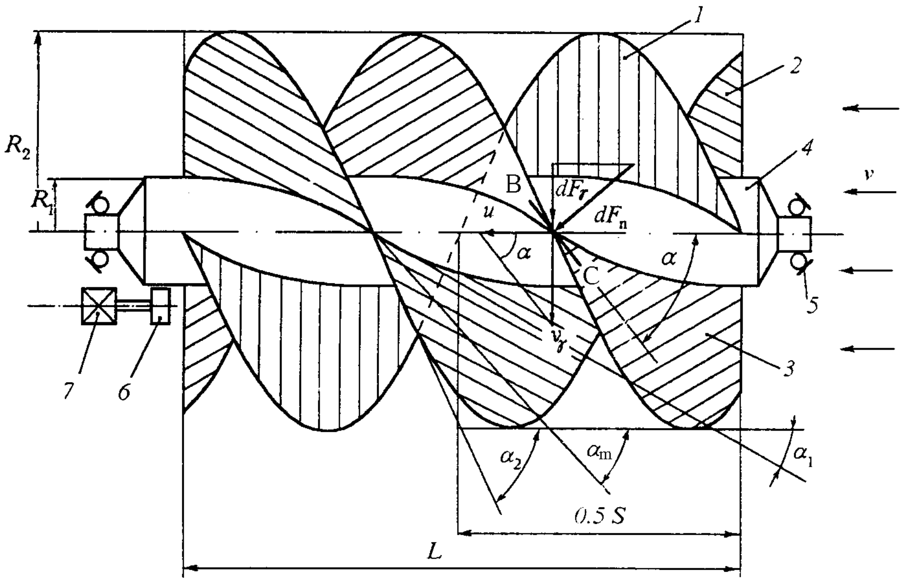

Fig. 1. Schematic of a three-start screw-type windmill: 1, 2, 3) screw blades; 4) hub; 5) bearing supports; 6) gear; 7) electric generator.

fore, the optimum operation of the rotor will be within the range $0 \le \varphi \le \alpha_m$. With the side wind, the power of the rotor increases in proportion to its length. For a certain length the rotor power will change slightly in a wide range of variation of the wind direction. Therefore, in the territories with the prevailing direction of winds the rotor with screw blades can be manufactured unoriented.

In the territories with a symmetric wind rose, the wind-oriented rotor can be installed (see Fig. 2b). As the wind direction changes, the moment of forces develops owing to the windage of the rotor; as a result, the rotor orients itself with the wind via its rotation in the upper support relative to the vertical axis.

The rotor with screw blades can also be used in hydraulic power engineering. Since the hollow hub provides buoyancy of the rotor, the latter can be on the water surface, and due to the action of water only on the lower parts of the blades it will rotate even in the case of flow perpendicular to the axis. In this way the energy of mountain rivers, sea streams, tides, and waves can be utilized.

The screw rotor generates acoustic oscillations to a lesser extent, as a consequence of the continuity of the blades within one revolution, and rotates smoothly. Moreover, such a rotor will modulate electromagnetic radiation also to a lesser extent. Therefore, as compared to conventional windmills, it will create noise and tele- and radiointerferences to a lesser extent.

The angle α (see Fig. 1) between the helical line and the generatrix of the cylinder of radius r, determined from the relation

$$\tan \alpha = 2\pi r / S, \tag{1}$$

changes over the blade radius from α_1 on the hub to α_2 on the swept surface. Therefore, the mean angle of inclination α_m determined from the expression $\tan \alpha_m = 2\pi R_m / S$, where $R_m = (R_1 + R_2)/2$, can be chosen as a characteristic of the inclination of the blade.

In cutting screw blades from a flat sheet, the radius of curvature of the helical line turns out to be an important characteristic. To determine it, we write the equation of the helical line in the Cartesian coordinate system x, y, z in the following form:

$$x = r \cos \psi, \quad y = r \sin \psi, \quad z = \psi S / 2\pi, \tag{2}$$

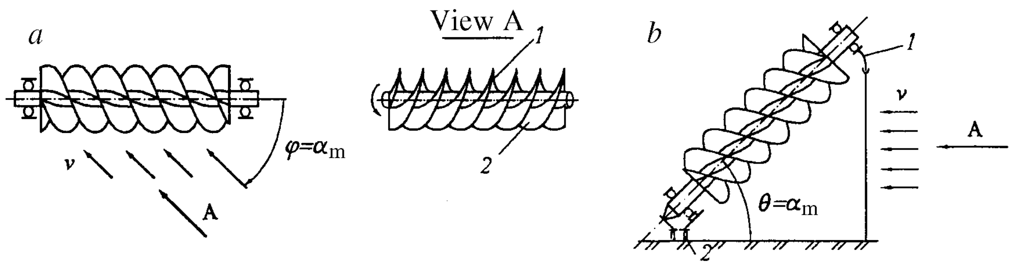

Fig. 2. Screw-type wind rotor in the case of a side wind: a) unoriented (the blade portions are developed [1) edgewise to the wind; 2) planewise to the wind]); b) oriented [1) upper support; 2) lower support].

where the z axis is directed along the screw axis, while ψ is the polar angle in the plane x, y. The radius of curvature of the spatial curve is determined as follows [12]:

$$\rho_{cu} = \left|\frac{d\mathbf{r}}{d\psi}\right|^3 \bigg/ \left|\frac{d\mathbf{r}}{d\psi} \cdot \frac{d^2\mathbf{r}}{d\psi^2}\right| . \tag{3}$$

According to (2), the derivatives will be written as

$$\frac{d\mathbf{r}}{d\psi} = -\,\mathbf{i}r\sin\psi + \mathbf{j}r\cos\psi + \mathbf{k}S/2\pi\,, \quad \frac{d^2\mathbf{r}}{d\psi^2} = -\,\mathbf{i}r\cos\psi - \mathbf{j}r\sin\psi\,,$$

After substituting them into (3), we obtain the radius of curvature of the helical line in the form

$$\rho_{cu} = (S^2 + 4\pi r^2)/(4\pi^2 r)\,. \tag{4}$$

Problems of the Design and Technology of Screw-Type Rotors. The existing designs and technologies of manufacture of screw-type wind rotors [1] and screws for other purposes [13] make it impossible to obtain a lightweight and strong screw. Therefore, various designs of screw-type rotors are under development. For instance, a rotor can consist of a cylindrical shell which is reinforced inside with longitudinal stringers and transverse frames [3]. At the rotor ends the subassemblies of bearings are connected to the last two frames. To the outer shell surface angle pieces are attached. The blades consist of segments connected to the angle pieces and to each other and forming the helical surface. The segments are manufactured from a flat sheet. Its internal and external arcs are made with radii ρ_{cu1} and ρ_{cu2}, which are determined by the radius of curvature of the helical line (4) for $r_1 = 0.5D_1$ and $r_2 = 0.5D_2$ respectively. The segment height of a blank is equal to the height of the screw blade:

$$h = 0.5\,(D_2 - D_1)\,. \tag{5}$$

The length of chords is $2b$. The quantity b on different radii is determined by the following relations: $b = \rho_{cu}\sin 0.5\varphi_b$ where $\varphi_b = 4\pi^2 r/(n_s\sqrt{S^2 + 4\pi^2 r^2})$.

This technology was employed to manufacture a rotor with a diameter of 1 m from a 0.5-mm-thick Duralumin sheet that represented a rather lightweight and strong structure. The more improved technology allowed manufacture of 0.5-m-diam. rotors from a 0.3-mm-thick aluminum sheet. On its basis a process line of continuous manufacture of a screw from a metal sheet can be created.

Screw-type rotors can also be manufactured from nonmetal materials. A technology of manufacturing of small-diameter (150 mm) screw-type wind rotors from the glass epoxide material was developed. Such wind rotors were tested in a wind tunnel and operated under different wind conditions. Of interest is the

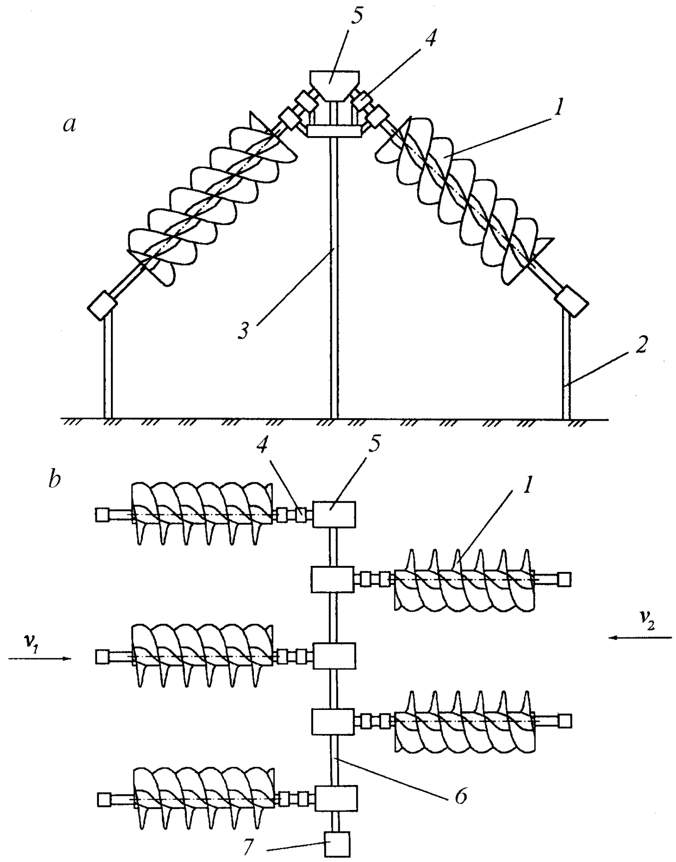

Fig. 3. Multirotor plant: a) frontal view; b) top view: 1) screw-type rotor; 2) and 3) lower and upper supports; 4) unit with overrunning clutches connected in opposition; 5) conic reducer; 6) transmission shaft; 7) electric generator.

manufacture of a continuous-operation screw from thermoplastic materials by the extrusion method. According to our estimates, the continuous technology of manufacturing screw-type rotors can lead to a threefold reduction in the cost of wind-power plants.

Arrangements of Screw-Type Wind Rotors. Owing to their strength properties, a screw-type rotor can be used as a structural member. This allows one to arrange different designs of wind-power plants. One of the simplest arrangements is a one-rotor self-oriented wind-power plant [8] made according to the scheme of Fig. 2b but elevated slightly above the ground on a mast. Two versions of the self-oriented wind-power plant-pump, namely, with screw-type rotors 200 and 500 mm in diameter, respectively, were made. Also, a version of the 2 kW self-oriented wind-power plant with a 2 m diameter of the screw-type rotor and with the reducer and the electric generator positioned on top was worked out structurally. Self-oriented wind-power plants can rather efficiently be used at small powers (e.g., up to several kW) when the overall dimensions of the rotors are small. Their installation on a mast in the region of high wind speeds increases the power as compared to the ground disposition.

Figure 3 schematically shows a multirotor wind-power plant [4]. The rotation of all rotors in it is transferred to one outlet shaft. The plant contains screw-type wind rotors 1 inclined to the horizontal plane. At the bottom the wind rotors are joint connected via the subassembly of bearings to supports 2, while at the top they are connected to support 3. Rotation of the wind rotors, via the unit with overrunning clutches 4 connected in opposition, is transferred to conic reducer 5 from which common transmission shaft 6 transfers the rotation to electric generator 7.

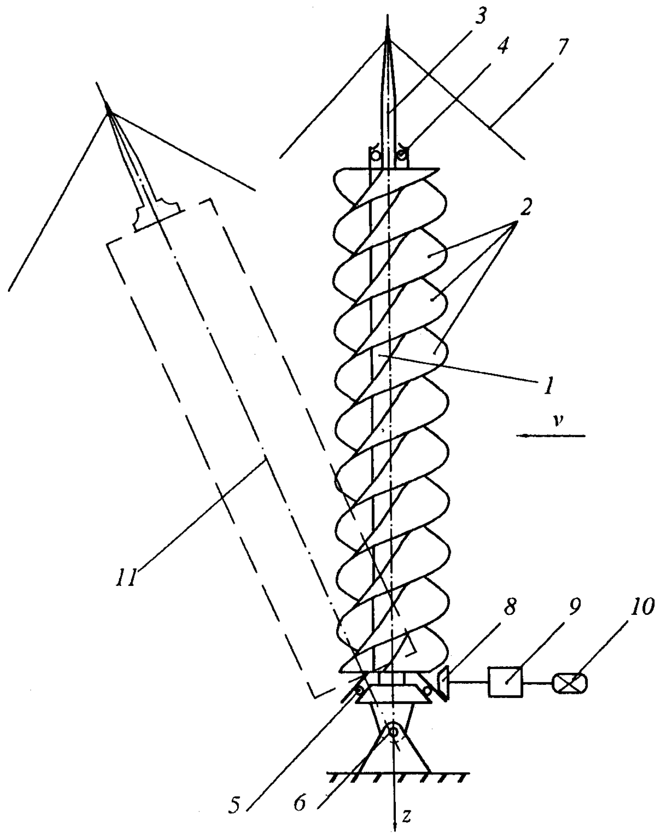

Fig. 4. Funnel-like screw-type windmill: 1) hub; 2) funnel-like screw blades; 3) mast; 4, 5) upper and lower bearing supports; 6) hinge; 7) tension members; 8) transmission; 9) step-up gear; 10) electric generator; 11) wind rotor in the inclined position.

With the wind direction v_1 the windward rotors rotate in one direction, while the leeward rotors rotate in the other direction. With the wind direction v_2, the rotors rotate in the opposite direction. The mechanism with overrunning clutches connected in opposition contains two such clutches, which provide the rotation of outlet shaft 6 in one direction for different directions of rotation of the rotors. It is expedient to manufacture multirotor wind-power plants with a power of tens of kilowatts or more. They can be installed in the form of wind-power dams along coasts or across mountain valleys. In the territories with a symmetric wind rose, a wind-power plant can be assembled of three or more rotors installed in a circle. In this case, the common transmission shaft can be installed vertically at the center of the wind-power plant. Such a three-rotor wind-power plant with a power of 1 kW was designed and manufactured [5].

Of interest is an overhanging wind-power assembly [7] in which a screw-type rotor, similarly to a wind vane, follows the wind in two planes. With change in the direction of the wind, the screw-type rotor turns in the rotation unit relative to the vertical axis and orients itself with the wind. With change in the speed, the rotor turns in the hinge relative to the horizontal axis.

When the wind is absent, the overhanging rotor is exposed to the largest bending loads due to its weight. With a certain speed the rotor gets suspended and the bending loads disappear. Since the inclination of the rotor to the horizon decreases, the number of revolutions (rotational speed) stabilizes as well. Overhanging wind-power assemblies can attain a power of several tens of kilowatts. It is expedient to install them in territories with variable and gusty winds.

The wind-power plants considered are inclined with respect to the wind. Figure 4 shows a screw-type wind rotor with funnel-like screw blades [6] which can operate in the vertical position and is independent of the wind direction. Unlike the right helicoid (2), the coordinate z of the funnel-like helical surface can be described as $z = \frac{S}{2\pi}\psi + f(r)$, where $f(r)$ is a monotonous function of the radius. With the wind direction v, the larger load is received by the concave portions of the blades located to the left of the axis and, as a consequence, a torque directed to the left occurs. A vertical screw-type rotor stably rotates in the case of variable gusty winds. Its power can attain several hundred kilowatts. Such wind-power plants can be installed in different regions, including cities, for instance, on roofs of buildings.

As compared to high-speed wind rotors of the Darier type [14], in which the initial torque is small, a vertical screw-type rotor produces energy in great amounts at small speeds and has smaller bending and centrifugal loads. As compared to the Savonius rotor [15], it has a larger factor of utilization of the wind energy.

Interaction of a Screw-Type Rotor with an Axial Flow. Works by N. E. Zhukovskii, N. Krasovskii, and G. Kh. Sabinin are known (for instance, [16, 17]) in which calculations of the interaction of a flow with the wind based on the theory of vortices or the theorem of pulse receivers are given. However, the results obtained depend on a number of theoretical constants, and they do not allow determination of the optimum parameters of a screw-type rotor. We investigate the aerodynamic properties of the rotor on the basis of the force of action of the flow on a small plane area.

Let us consider an area element of length BC = dl along the helical line on the radius r, with the width dr and the total area $df = dldr$ (see Fig. 1) which is located at the angle α to the wind direction v. In rotation of the rotor with the angular speed ω, the small area has the tangential speed $v_\tau = \omega r$. As the rotor turns, the remaining portions located along the screw blade will be positioned at the same angle α. Therefore, in a fixed coordinate system the small area df moves along the rotor axis with the axial velocity

$$u = v_\tau / \tan\alpha = \omega S / 2\pi \,. \tag{6}$$

When the axial velocity u of the small area df is equal to the wind velocity v, the area does not interact with the wind. If $u > v$, the small area enhances the wind head and the rotor operates as a fan. If $u < v$, the wind acts on the small area and the rotor operates as a windmill. From expression (6) it is seen that for the screw blade the velocity u is independent of the radius. Therefore, if a certain small area operates in an optimum regime, then all the rotor parts operate in the optimum regime. Thus, the helical surface of the blades is the optimum one for utilization of the wind energy.

On the plane small area df, which moves with the velocity u in the wind direction and which is perpendicular to the flow, the force $dF = C\frac{\rho w^2}{2}df$ acts, where $w = v - u$ is the wind velocity relative to the small area. We will consider the interaction of the flow with the small area for large Reynolds numbers when C is independent of Re. For these velocities the frictional force of the flow can also be neglected. Therefore, we disregard the force that is tangential to the small area. Since the small area df (see Fig. 1) is inclined and the normal to it makes an angle of $(90^{\circ} - \alpha)$ with the wind direction, the flow acts on the small area with a force normal to d, i.e., $dF_{\text{n}} = C_\alpha\frac{\rho w^2}{2}df\cos(90^{\circ} - \alpha) = C_\alpha\frac{\rho w^2}{2}df\sin\alpha$. Here C_α is the aerodynamic coefficient that can depend on the small angle of inclination of the small area to the flow.

In the direction of rotation of the rotor, the component, tangential to the rotor, of the force $dF_\tau = dF_{\text{n}}\cos\alpha$ will act on the small area; this component does the work $dA = dF_\tau\omega rdt$ in the direction of the rotary motion of the small area df. Then the power transferred to the small area by the flow is $dN = dA/dt = \omega r dF_\tau$. After substituting the values of dF_τ, w, and u, we obtain

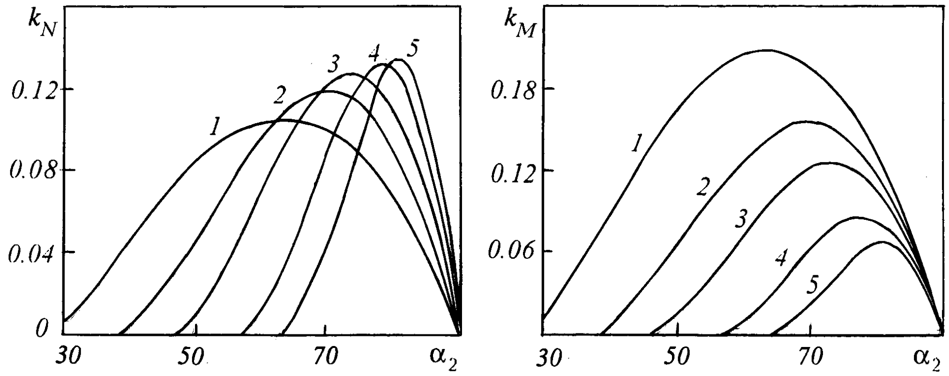

Fig. 5. Coefficients of the power and the torque versus angle of inclination of the blade for $\bar{R}_1 = 0.265$ and different high speeds z_v: 1) 0.5; 2) 0.75; 3) 1; 4) 1.5; 5) 2. α_2, deg.

$$dN = 0.5C_\alpha \rho \left(v - \frac{\omega S}{2\pi}\right)^2 \omega r \sin\alpha \cos\alpha \, df. \tag{7}$$

The product $df \sin\alpha$ (see Fig. 1) is a projection of the small area onto the plane of rotation; therefore, it can be written in the form $df \sin\alpha = rd\psi dr$. Then, after integration of (7) with respect to the angle ψ, on which the parameters, except for C_α, do not depend, we obtain the following expression for the wind-rotor power:

$$N = C_m \rho v^3 f_{p.d.a} z_v \operatorname{ctan}^3 \alpha_2 (1 - z_v \operatorname{ctan}\alpha_2)^2 \int_{x_1}^{x_2} \frac{x^2}{\sqrt{1+x^2}} dx, \tag{8}$$

where $f_{p.d.a} = \pi R_a^2$, $z_v = \omega R_2/v$, $x = \tan\alpha$, $x_1 = \tan\alpha_1$, $x_2 = \tan\alpha_2$, and C_m is the aerodynamic coefficient for the small area inclined at a mean angle of α_m.

Expression (8) holds for the portions of the blades onto which the flow not disturbed by the other blades is incident, i.e., at the rotor length up to the first overlap of the blades $L_1 = S/n$. After integration of expression (8) and substitution of the integration limits, the rotor power N with a single overlap and the torque M with the wind being directed along its axis will be written as follows:

$$N = C_m \frac{\rho v^3}{2} f_{p.d.a} k_N, \tag{9}$$

$$k_N = (1 - z_v a_2)^2 z_v a_2 \left(\sqrt{1 + a_2^2} - \bar{R}_1 \sqrt{\bar{R}_1^2 + a_2^2} - a_2^2 \ln \frac{\sqrt{1 + a_2^2} + 1}{\sqrt{\bar{R}_1^2 + a_2^2} + \bar{R}_1} \right), \tag{10}$$

$$M = N/\omega = C_m \frac{\rho v^2}{2} f_{p.d.a} k_M R_2, \tag{11}$$

where $a_2 = \operatorname{ctan}\alpha_2 = S/2\pi R_2$, $\bar{R}_1 = R_1/R_2$, and $k_M = k_N/z_v$.

As is seen from formulas (9), (10), and (11), the geometric (a_2, $\bar{R}_1$) and dynamic (z_v) parameters exert an influence on the power and torque of the rotor in terms of the parametric coefficients k_N and k_M. Figure 5 presents the plots of these coefficients versus the external angle of the blade α_2 for different high speeds (specific speeds) z_v. The coefficient k_N and, consequently, the power N for a fixed z_v has a maximum in α_2. With increase in the high speed, the values of the maxima increase and their position is displaced toward large angles α_2. However, with increase in α_2 and z_v the torque tends to zero. Since, for small wind velocities, the rotor with a small torque will not operate, one must restrict oneself to the values of the angle α_2 and of the high speed z_v, proceeding from actual capabilities of the rotor design. In experiments with the rotor model, the maximum electric power was obtained for $z_v = 1$. As is seen from Fig. 5, for this high speed the optimum of the power is attained at $\alpha_2 = 73^o$.

In a number of cases, it is more convenient to use the mean angle α_m; therefore, we express power in terms of α_m. With account for (1) expression (7) can be written in the following form:

$$dN = C_\alpha \frac{\rho v^3}{2} \frac{\omega S}{2\pi v}\left(1 - \frac{\omega S}{2\pi v}\right)^2 \sin^2 \alpha \, df . \qquad (12)$$

Here, integration is carried out over the area element $df = drdl$ of the helical surface. Only one parameter, i.e., the angle of inclination of the small area α, changes. Since α changes monotonically within the small range from α_1 to α_2, this parameter can be replaced by the mean angle α_m. Then integration over all of the small area yields the area of the blades $f_b = \int df$ with their single overlap. Under these conditions, the rotor power with a single overlap expressed in terms of the mean angle α_m will be written as

$$N = C_m \frac{\rho v^3}{2} f_b k_{Nm} , \qquad (13)$$

where

$$k_{Nm} = z_{vm} a_m (1 - z_{vm} a_m)^2 / (1 + a_m^2) ; \quad z_{vm} = 0.5 z_v (1 + \bar{R}_1) ; \quad a_m = \text{ctan}\, \alpha_m = S / 2\pi R_m ; \qquad (14)$$

C_m is the mean aerodynamic coefficient, which can differ from the aerodynamic coefficient in formula (9) due to different averaging algorithms.

The difference of the approximate expression (13) for power from the exact expression (9) is within 5%. The function k_{Nm} for $z_{vm} a_m = 1/3$ has an optimum which corresponds to the maxima of k_N in Fig. 5:

$$k_{Nm\,max} = 0.148 \sin^2 \alpha_m . \qquad (15)$$

From (15) it follows that the maximum value of k_{Nm} and, consequently, of k_N will be when $\alpha_m \to 90$ and is equal to $k_{Nm\,max} = 0.148$, but the high speed z_v tends to infinity in this case.

Since, according to (1), $\tan \alpha_m = 0.5(1 + R_1) \tan \alpha_2$, the optimum power for $\alpha_2 = 73^o$, $\bar{R}_1 = 0.265$, and the high speed $z_v = 1$ corresponds to a mean angle of $\alpha_m \approx 65^o$. Then, in the case of the axial wind direction, the rotor with a single overlap will have a rather large power and torque if the mean angle of the rotor α_m is within 60–70^o and the high speed is $z_v \approx 1$.

Influence of the Overlap of Blades in the Case of an Axial Wind. The area of the screw blade f_b over the length of one pitch S or the area n of the blades over the length of one overlap are determined as a result of integration of df with respect to the blade length S and to the radius r within the limits from R_1 ro R_2:

$$f_b = \int_{R_1}^{R_2} \sqrt{4\pi^2 r^2 + S^2}\, dr = \frac{S^2}{2\pi} \int_{x_1}^{x_2} \sqrt{1 + x^2}\, dx ,$$

where $x = 2\pi r/S$. After integration and substitution of the limits, the area of the screw blade will be written in the form

$$f_b = f_{p.d.a}\left(\sqrt{1+a_2^2} - \bar{R}_1\sqrt{\bar{R}_1^2 + a_2^2} + a_2^2 \ln \frac{\sqrt{1+a_2^2}+1}{\sqrt{\bar{R}_1^2 + a_2^2} + \bar{R}_1}\right). \quad (16)$$

With the wind directed along the axis of the rotor with k overlaps, the wind energy not used on the portion of the first overlap can be extracted on the subsequent portions. We evaluate how efficiently the wind energy is utilized here. For this purpose, we transform the expression for power (13) by substituting the parameters k_{Nm}, z_{vm}, z_v, and the axial velocity of the small area u according to (6) into it. As a result, we obtain

$$N_1 = 0.5C_m \rho f_b \frac{\omega S}{2\pi}(v-u)^2 \sin^2 \alpha_m . \quad (17)$$

Let the wind velocity decrease to v_1 after passing the first overlap of the blades by the flow, to v_2 after the second overlap, and so on. Then the power taken by the second portion of the rotor is determined from formula (17) for $v = v_1$ as

$$N_2 = 0.5C_1 \rho f_b \frac{\omega S}{2\pi}(v_1-u)^2 \sin^2 \alpha_m = N_1\beta^2 , \quad (18)$$

where $\beta = (v_1 - u)/(v - u)$ is the abrupt decrease in the relative wind velocity over the length of one overlap of the rotor. Since all the subsequent portions have the same design, we can assume that the relative wind velocity is the same everywhere, i.e., $\beta = (v_1 - u)/(v - u) = (v_2 - u)/(v_1 - u) = (v_3 - u)/(v_2 - u)$. Since $v_2 - u = \beta(v_1 - u)$, $v_3 - u = \beta(v_1 - u)$, etc., the powers generated on the subsequent portions can be written according to (18) as $N_2 = N_1\beta^2$, $N_3 = N_2\beta^2$. For a long rotor with the number of power overlaps k as a sum of powers on individual portions we have

$$N_{ax} = N_1 + N_2 + N_3 + ... = N_1 \sum_{i=1}^{k} \beta^{2(i-1)} . \quad (19)$$

With a twofold decrease in the relative velocity ($\beta = 0.5$), the power of the long rotor with $k = 4$ experiences, according to (19), a 1.313 increase, i.e., with the axial operation of the screw rotor, it is inefficient to increase its length.

Evaluation of the Rotor Power in the Case of an Axial Wind. With account for (17), the power of the long rotor (19) in the case of an axial wind can be written in the form $N_{ax} = 0.5C_k\rho f_b \frac{\omega S}{2\pi}(v-u)^2 \sin^2 \alpha_m$, where $C_k = C_m\sum_{i=1}^{k} \beta^{2(i-1)}$. Then, with account for (17) and (16), the power of the long rotor is

$$N_{ax} = 0.5C_k\left(\sqrt{1+a_2^2} - \bar{R}_1\sqrt{\bar{R}_1^2 + a_2^2} + a_2^2 \ln \frac{\sqrt{1+a_2^2}+1}{\sqrt{\bar{R}_1^2 + a_2^2} + \bar{R}_1}\right)\rho\, f_{p.d.a} v^3 k_{Nm} . \quad (20)$$

This expression depends on the unknown coefficient C_k. Using the results for aerodynamic scavengings, we determine this coefficient. We measured the power generated by a three-start screw rotor with the parameters

R_2 = 75 mm, R_1 = 20 mm, S = 212 mm, L = 250 mm, and $\alpha_m = 54.6^o$ which was scavenged in a wind tunnel. In the case of an axial wind with velocity v = 11.4 m/sec, the rotor power was N_{ax} = 6.5 W, while with the wind being at an angle of $\varphi = \alpha_m$ to the rotor axis the power was $N_m = 0.8N_{ax}$. Since, in this case, the overlapping coefficient was k = 3.54, the rotor can be assumed to be long. We will express the power in terms of the swept-surface area $f_{p.d.a}$. After substituting the measurement parameters into (20), we obtain $C_k(\sqrt{1+a_2^2} - \overline{R}_1\sqrt{\overline{R}_1^2 + a_2^2} + a_2^2 \ln \frac{\sqrt{1+a_2^2}+1}{\sqrt{(\overline{R}_1^2 + a_2^2} + \overline{R}_1)}$ = 3.8. Then for the power of the long rotor with the wind directed along the axis we obtain the following estimate:

$$N_{ax} \approx 1.9\rho f_{p.d.a} v^3 k_{Nm} \,. \tag{21}$$

For $z_{vm}a_m$ = 1/3 the quantity k_{Nm}, according to (10), has the maximum $k_{Nm\,max}$ = 0.148. Then the maximum rotor power, with the wind directed along the axis, is $N_{max} = 0.28\rho f_{p.d.a}v^3$; the maximum factor of utilization of the wind energy is $\eta_{max} = \frac{N_{max}}{0.5\rho f_{p.d.a}v^3}\cdot 100\% = 56\%$. This value of η_{max} approaches the limiting value of the utilization factor of the wind energy η_{max} = 59% obtained in [11, 14, 16] for propeller-type wind receivers.

Evaluation of the Power of an Inclined Rotor. With the rotor being inclined relative to the wind direction, its power N_φ will be in proportion to the length L and to the power along the axis N_{ax}. Since the latter power has been reduced to a length multiple to the pitch S, we can write the power of the inclined rotor which is in proportion to the multiplicity of its overlaps k in the form $N_\varphi \approx k_x \frac{nL}{S} N_{ax}$, where k_x is the unknown coefficient. Substituting the parameters of the investigated rotor and the measured powers N_{ax} and N_φ, we obtain k_x = 0.22. Then the power of the rotor installed at an angle $\varphi = \alpha_m$ to the wind is

$$N_\varphi \approx 0.22 \frac{nL}{S} N_{ax} \,, \tag{22}$$

and the utilization factor of the wind energy based on the rotor midsection $2R_2L$ is

$$\eta = \frac{N_\varphi}{0.5\rho 2R_2Lv^3} \cdot 100\% = \frac{0.418\pi n R_2 k_{Nm}}{S} \cdot 100\% \,. \tag{23}$$

Calculation for an inclined rotor with the parameters R_2 = 75 mm, R_1 = 19.5 mm, S = 172.5 mm, and L = 690 mm from this formula gives a maximum utilization factor of the wind energy of η = 19% with the high speed z_v = 1.1. As a result of aerodynamic scavengings, we have obtained η = 20% for this rotor. Thus, relations (13), (22), and (23) allow calculation of the power characteristics of the inclined wind rotor.

It should be noted that a share of the power of the wind flow taken by the wind-power assembly will be higher, since for the inclined rotor its midsection area is larger than the area of the wind flow. With account for the wind-flow area $R_2L \sin\varphi$, the utilization factor of the wind energy of the inclined screw rotor of length L = 690 at $\varphi = 45^o$ is 27%, as follows from the results of the tests.

Conclusions. Screw-type wind-power plants are characterized by the high smoothness of operation, the absence of vibration and fatigue load caused by the cyclicity of rotation of the rotor, substantially smaller acoustic and electromagnetic interferences, and decreased environmental impacts. Their various arrangements make it possible to adapt them in the best way to the customer's conditions. The combination of the slow

TABLE 1. Distinctive Features of Propeller- and Screw-Type Wind-Power Assemblies

Parameters	AVÉ-16	WVDSR
Power, kW	16	16
Rotor diameter, m	12.3	5.8
Rotor height, m	–	20.3
Height of the tower (the central rack), m	12.7	25
Weight of the wind-power assembly, kg	4400	4000
Design velocity of the wind for attaining the power, m/sec	10.5	10.5
Rotational speed of the rotor at the rated velocity, r.p.m	98	35
Centrifugal acceleration of the blade end, m/sec^2	647	39
Operating range of the wind velocities, m/sec	5–30	2–40
Annual generation of electric power in relative units	1	2
Cost of 1 kW-h of electric power in relative units	1	0.5
Aerodynamic noise	Yes	No
Teleradiointerferences	Yes	No

speed and the moderate utilization factor of the wind energy provides great amounts of generated energy annually even in the territories with low winds. With the creation of an inexpensive technology of screw manufacture, such a windmill can become available for wide population circles. Finally, in Table 1 we provide a comparison of the evaluated parameters of the wind-power plant with a vertical funnel-like screw rotor (WVFSR) (see Fig. 4) to the parameters of the domestic two-blade wind-power assembly, model AVÉ-16, developed by the "Vetroén" Scientific-Production Association (see Table 1).

NOTATION

A, work; a = ctan α, parameter; b, semichord of the plane segment; C and C_α, aerodynamic coefficients; D_1 and D_2, diameters of the hub and of the rotor, respectively; F, force; df, area element; $f_{\rm p.d.a}$, swept surface; $f_{\rm b}$, area of the blades over the length of one overlap; h, blade height; k, number of overlaps of the swept surface; k_N and k_M, coefficients of the power and of the torque; L, rotor length; M, torque; N, power; $N_{\rm ax}$ and N_φ, power of the long rotor with the axial and inclined position at angle φ to the wind; n, number of blades; n_s, number of segments over the pitch of the helical line; R_1, R_2, and $R_{\rm m}$, radii of the hub and the rotor and the mean radius, respectively; S, pitch of the helical line; u, axial velocity of the small area; v, wind velocity; z_v and $z_{v{\rm m}}$, high speeds based on the outer and mean rotor radii; α, inclination of the helical line with respect to the generatrix of the cylinder; β, coefficient of decrease of the velocity; η, utilization factor of the wind energy; $\rho_{\rm cu}$, radius of curvature of the helical line; ρ, air density; φ, angle formed by the rotor axis and the wind velocity; $\varphi_{\rm b}$, half-angle of the chord of the plane segment; ψ, polar angle in the plane of rotation of the rotor; θ, angle of inclination of the rotor axis to the horizontal surface; ω, angular rotational speed of the rotor. Subscripts: 1, refers to the hub; 2, refers to the diameter of the rotor axis; m, mean value; cu, curvature; k, when the overlapping coefficient is more than unity; N, power; n, normal; M, torque; max, maximum; ax, axial; b, blade; p.d.a, swept area; v, velocity; α, dependent on the angle α; φ, based on the rotor inclined at an angle φ to the wind; τ, tangential.

REFERENCES

1. French Patent No. 2464386, cl. F 03 D 5/00 (1981).

2. I. I. Smul'skii, *Windmill*, Russian Patent No. 1225912, MKI[5] F 03 D 5/00, published 23.04.86, Byull. No. 15.
3. I. I. Smul'skii, *Wind Rotor*, Russian Patent No. 2078250, MKI[6] F 03 D 5/00, 3/06, published 27.04.97, Byull. No. 12.
4. I. I. Smul'skii and M. I. Lipchinskii, *Wind-Power Plant*, Russian Patent No. 2088798, MKI[6] F 03 D 3/02, published 27.08.97, Byull. No. 24.
5. I. I. Smul'skii, *Wind-Power Assembly*, Russian Patent No. 2078993, MKI[6] F 03 D 3/02, 3/06, published 10.05.97, Byull. No. 13.
6. I. I. Smul'skii, V. P. Mel'nikov, and I. N. Kavun, *Screw-Type Wind Rotor*, Russian Patent No. 2101560, MKI[6] F 03 D 5/00, 3/06, published 10.01.98, Byull. No. 1.
7. I. I. Smul'skii, *Overhanging Wind-Power Assembly*, Russian Patent No. 2115826, MKI[6] F 03 D 5/00, published 10.07.98, Byull. No. 20.
8. I. I. Smul'skii, *Self-Oriented Wind-Power Assembly*, Russian Patent No. 2115019, published 10.05.98, Byull. No. 19.
9. P. P. Bezrukikh, *É nergiya: É nergetika, Tekhnika, É kologiya*, No. 8, 24–30 (1995).
10. V. I. Sidorov, V. V. Sidorov, and M. V. Kuznetsov, *Izv. Akad. Nauk SSSR, É nergetika Transport*, No. 3, 73–82 (1980).
11. Ya. I. Shefter, *Studies of Wind Power* [in Russian], Moscow (1983).
12. G. A. Korn and T. M. Korn, *Mathematical Handbook for Scientists and Engineers* [Russian translation], Moscow (1968).
13. A. M. Grigor'ev, *Screw Conveyers* [in Russian], Moscow (1972).
14. D. J. De Renzo (ed.), *Wind Power—Recent Developments* [Russian translation], Moscow (1982).
15. V. V. Zubarev, V. A. Minin, and I. R. Stepanov, *Utilization of Wind Power in the North Regions* [in Russian], Leningrad (1989).
16. N. Krasovskii, in: *Engineering Encyclopedia* [in Russian], Moscow (1928), p. 610.
17. G. Kh. Sabinin, *Tr. TsAGI*, Issue 104, Moscow–Leningrad (1931).