700 Btu/lb). (See Section 7 for values.) The blending of ethanol and methanol with gasolines (9± gasoline to 1± alcohol) has been used particularly in Europe since the 1930s as a suitable internal-combustion-engine fuel. The miscibility of the lighter alcohols with water and gasoline introduces corrosion problems for engine parts, and lowers the octane number. Higher carbon alcohols (e.g., butyl) which are immiscible with water are possible blending substitutes, but their availability and cost are not presently attractive. Such properties as flash point would introduce further problems. While these constitute some of the unsolved technical problems, the basic principle of harnessing the sun's energy through vegetation will continue as a provocative challenge not only in the field of power generation but also as a solution for the perennial farm problem.

WIND POWER

by D. K. McLaughlin and W. L. Hughes

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Wind is one of the oldest widely used sources of energy. Although its use is many centuries old, it has not been a dominant factor in the energy picture of developed countries for the past 50 years because of the abundance of fossil fuels. Recently, the realization that fossil fuels are in limited supply has awakened the need to develop wind power with modern technology on a large scale. Consequently, there has been a tremendous resurgence of effort in wind power in just the past few years. The state of knowledge will be rapidly increasing, and the reader must soon look in the current literature for information on the latest technology. There are, however, fundamental principles in wind-power technology which will not change. These fundamentals are discussed in the subsequent paragraphs.

Wind Turbines The essential ingredient in a wind-energy conversion system (WECS) is the wind turbine, traditionally called the windmill. Today, wind-axis and cross-wind-axis turbines are the predominant configurations in use and under study throughout the world. In the performance analysis of wind turbines, the wind-axis devices were studied first, and their analysis set the present-day conventions for the evaluation of all turbines.

General Momentum Theory for Wind-Axis Turbines Conventional analysis of wind-axis turbines begins with an axial-momentum balance originated by Rankine using the control volume depicted in Fig. 1. In this nomenclature, V is wind speed decelerated to $V(1-a)$ at the turbine disk and to $V(1-2a)$ in the wake of the turbine. (a is called the interference factor.) Momentum analysis predicts the axial thrust on the turbine of radius R to be

$$T = 2\pi R^2 \rho V^2 a(1-a) \qquad (1)$$

where ρ, air density, equals 0.00237 lbf·s²/ft⁴ or 1.221 kg/m³ at sea-level standard-atmosphere conditions.

Application of the mechanical-energy equation to the control volume depicted in Fig. 1 yields the prediction of power to the turbine of

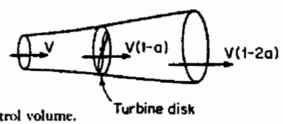

Fig. 1 Control volume.

$$P = 2\pi R^2 \rho V^3 a(1-a)^2 \qquad (2)$$

This power can be nondimensionalized with the energy flux E in the upstream wind covering an area equal to the rotor disk, i.e.,

$$E = \tfrac{1}{2} \rho V^3 \pi R^2 \qquad (3)$$

The resulting power coefficient is

$$C_P = \frac{P}{E} = 4a(1-a)^2 \qquad (4)$$

This power coefficient has a theoretical maximum at $a = \tfrac{1}{3}$ of $C_P = 0.593$. This result was first predicted by Betz.

This derivation includes some important assumptions which limit its accuracy and applicability. First, the turbine must be a wind-axis configuration such that an average stream tube (Fig. 1) can be identified. Second, the portion of kinetic energy in the swirl component of velocity in the wake is neglected. Third, the effect of the radial pressure gradient is excluded. Partial accounting for the rotation in the wake has been included in the analysis of Glauert with the resulting prediction of power coefficient as a function of turbine-tip speed ratio $X = \Omega R/V$ (where Ω is the angular velocity of the turbine) shown in Fig. 2.

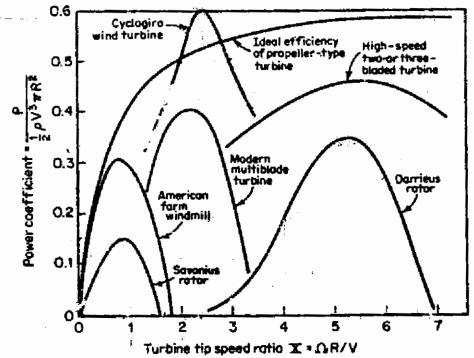

Fig. 2 Performance curves for wind turbines.

Blade-Element Theory for Wind-Axis Turbines Blade-element theory provides the mechanism for analyzing the relationship between the individual airfoil properties and the interference factor a, the power produced P, and the axial thrust T of the turbine. Rather than the stream tube of Fig. 1, the control volume consists of the annular ring bounded by streamlines depicted in Fig. 3. It is assumed that the flow in each annular ring is independent of the flow in all other rings.

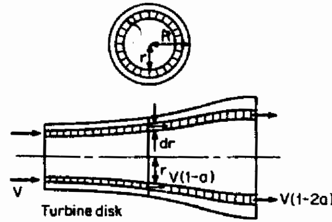

Fig. 3 Annular-ring control volume.

A schematic of the velocity and force-vector diagrams is given in Fig. 4. The elemental torque which acts on all blade elements in an annular ring is

$$dQ = \frac{B}{2} c\, r \rho\, W^2 (C_L \sin\varphi + C_D \cos\varphi)\, dr \qquad (5)$$

The turbine is defined by the number B of its blades, by the variation of the chord c, by the variation in blade angle θ, and by the shape of the blade sections. $a' = \omega/2\Omega$, where ω is the angular velocity of the air just behind the turbine and Ω is the turbine angular velocity. W is the velocity of the wind relative to the airfoil. Equation (5) is derived for the case with no turbine coning, which can be accounted for if appropriate. The sectional lift and drag coefficients C_L and C_D are obtained from empirical airfoil data and are unique functions of the local flow angle of attack $\alpha = \theta - \varphi$, and the local Reynolds number of the flow $Re = Wc/\nu$. Lift and drag coefficients are defined from

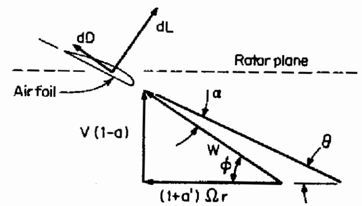

Fig. 4 Velocity and force-vector diagrams.

$$dL = C_L\, (\tfrac{1}{2} \rho W^2)\, c\, dr \qquad (6)$$
$$dD = C_D\, (\tfrac{1}{2} \rho W^2)\, c\, dr \qquad (7)$$

where dL is the lift force on the element of blade and dD is the drag force on the element of blade. In the Reynolds number ν is the kinematic viscosity of air, 160 × 10⁻⁶ ft²/s (14.9 × 10⁻⁶ m²/s).

Power is computed by integrating Eq. (5) after multiplying it by the turbine angular velocity Ω. The result is

$$P = \rho \frac{B\Omega}{2} \int_0^R c r W^2 (C_L \sin\varphi - C_D \cos\varphi) dr \qquad (8)$$

Similarly the total thrust force on the turbine is

$$T = \rho \frac{B}{2} \int_0^R c W^2 (C_L \cos\varphi + C_D \sin\varphi) dr \qquad (9)$$

The relative velocity of the wind with respect to the airfoil section W and the local angle of attack α are computed from the vector diagram of Fig. 3. To do this, the axial interference factor a and the angular-velocity fraction $a' = \omega/2\Omega$ must be calculated by relating the blade-element forces to the momentum and energy equations applied to the annular control volume. The solution cannot be obtained in closed form, and a trial-and-error technique must therefore be used. The idea is that the blade forces are responsible for blocking the wind and for instilling swirl in the wake. However, to compute the blade forces, the amount of blockage a and swirl a' must be known. Hence the trial-and-error requirement.

A typical solution for steady-state operation of a two- or three-bladed wind-axis turbine is shown in Fig. 2. When optimized, these turbines run at high tip-speed ratios and are thus referred to in this manner. The curve showin in Fig. 2 for the two- or three-bladed wind turbine is for constant blade pitch angle. These turbines typically have pitch-change mechanisms which are used to feather the blades in extreme wind conditions. In some instances the blade pitch is continuously controlled to assist the turbine in maintaining constant speed. Turbines with continuous pitch control typically have flatter and hence more desirable operating curves than the one depicted in Fig. 2.

The traditional American farm windmill has a large number of blades with a high solidity ratio σ. (σ is the ratio of area of the blades to swept area of the turbine πR^2.) It typically operates at slower speed with a lower power coefficient than high-speed turbines. However, the lower power coefficients result from poor airfoil lift properties on these turbines, not necessarily from the low-speed operation. Consequently, the power production of a modern multiblade turbine is also shown in Fig. 2 to be comparable with high-speed turbines and much greater than the American farm windmill. The particular turbine whose performance curve is shown is configured much like a bicycle wheel, with an outer rim held in compression with numerous spokes, about half of which are covered with airfoils. The blades of this turbine have a fixed pitch, as do most multiblade turbines.

The curves depicted in Fig. 2 representing the performance of high- and low-speed wind-axis turbines are theoretically predicted performance curves, with accompanying experimental confirmation. Hence they can be regarded as true performance curves.

Cross-Wind-Axis Turbines There are three types of cross-wind-axis turbines of major importance as WECSs. The generally accepted advantage of cross-wind-axis turbines is the elimination of the requirement to drive the axis of the turbine into the wind. The poorest performer of the three is the Savonius rotor composed of two semicylindrical offset cups rotating about a vertical axis. It is a slow-speed turbine with