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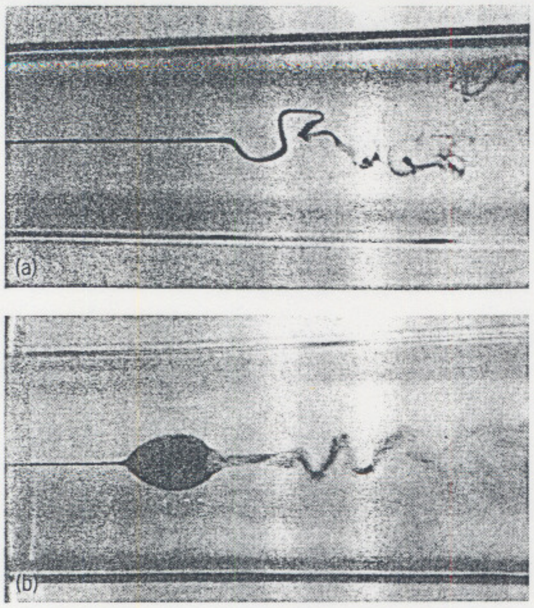

Fig. 2. Vortex breakdowns in a divergent channel. (*a*) Spiral form. (*b*) Bubble form followed by a spiral. (*From S. Leibovich, The structure of vortex breakdown, Annu. Rev. Fluid Mech., 10:221–246, 1978*)

tion or on the aerodynamic surface, often quite dramatically.

Some of the seemingly different postulated physical mechanisms of vortex breakdown are equivalent or related, leading to the same or similar criteria for breakdown. To the extent that the various theories predict a criterion for vortex breakdown, the predictions are quite similar, namely, that the onset of breakdown occurs when the ratio of the swirl to the axial velocity is approximately 1.5. Therefore, this criterion cannot be used to distinguish between the theories.

Numerical simulations. Full numerical simulations of breakdown are usually based on the complete Navier-Stokes equations, appropriate for viscous, rotational flows (flows with vorticity), or the Euler equations, for inviscid, rotational flows. Until recently, because of computer limitations, it was necessary to assume that the flow was both axisymmetric and steady, but more recent calculations solve the unsteady, three-dimensional, full viscous Navier-Stokes equations. Common characteristics of many of the earlier and more recent numerical simulations, as well as many of the experiments, are: (1) extreme sensitivity to flow parameters (such as swirl velocity ratio, external axial velocity variation, or pressure gradient); (2) suddenness of breakdown (that is, breakdown with no evidence of the prior growth of an instability of the basic swirling flow); and (3) a tendency for the breakdowns to migrate upstream to the initial station, that is, the upstream boundary of the computational domain or test section (unless some means is employed to prevent this). This tendency of breakdowns to move to the initial station has caused the validity of such numerical simulations to be questioned. Some of these issues are particularly troubling because, to some extent, the difficulties with the numerical simulations, including the slow rates of convergence to final steady states often encountered, may be intrinsic aspects of the physics of breakdown and not numerical artifacts.

Upstream migration of the vortex breakdown occurs mainly for unbounded, or unconfined, flows, such as aerodynamic flows and flows in diverging channels. Numerically simulated breakdowns, usually in the form of steady axisymmetric bubbles, that occur in bounded or confined swirling flows, for example, in finite closed cylinders with one end wall rotating, or flow in the gap between rotating spheres, do not exhibit this behavior, nor do experiments on these flows. Because of the robustness of the breakdown of the swirling flow in such cylinders, with respect to both the type of breakdown (invariably a symmetric steady bubble) and its location (unmoving and far from the end walls), this configuration has been the focus of much experimental and numerical work. The newest breakdown criterion, based on azimuthal vorticity considerations, was advanced with some success in connection with this problem, and has been applied to other physical situations as well.

Universality. It is not known whether there is a single underlying mechanism of vortex breakdown with universal application, although this is implicitly assumed in much of the above discussion. There may be, also, no fundamental etiological difference between bubble, helical, and spiral breakdowns, or combinations thereof, the particular form being perhaps dependent upon initial and boundary conditions. It is not known whether the same is true for swirling flows in geometries as different as those discussed above.

For background information *SEE BOUNDARY-LAYER FLOW; FLOW MEASUREMENT; FLUID FLOW; FLUID-FLOW PRINCIPLES; HYDRAULIC JUMP; SIMULATION; TURBULENT FLOW; VORTEX* in the McGraw-Hill Encyclopedia of Science & Technology.

Stanley A. Berger

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Wind power

Recent developments involving generation of electricity with machines utilizing wind energy have provided a new potential for pumping water in remote areas. For example, lack of an adequate year-round water supply is still a major impediment to livestock grazing in many arid regions. Cattle tend to graze up to about 1 km (0.6 mi) from a water supply; therefore, several water supplies are needed in most large pastures. Ranchers have found that if sufficient watering places are not provided, livestock do not move to areas of the pasture where grass may be abundant. For this reason, many ranchers continue to haul water for livestock in remote areas.

Another application of wind-powered systems is to provide a safe and dependable source of water to about one-third of the world's population. Many people depend on surface waters that are polluted and harmful to their health. Water cannot be pumped, because energy and labor for servicing engine-driven pumps are usually unavailable. Thousands of mechanical water pumping systems have been installed over the years to meet the water requirements of people and livestock. However, because of high maintenance requirements and aging equipment, many water users must seek other energy sources to power their pumps. The availability and cost for new electrical grid service are often prohibitive.

System equipment. A wind-electric water pumping system consists of a wind turbine that produces alternating-current electric power at variable voltage, variable frequency; a pump controller; and a standard utility-grade electric motor and pump. The wind-electric water pumping system allows the wind turbine to operate at variable speed, thus producing a variable-voltage, variable-frequency system that can supply electric power directly to a standard electric motor. The direct-drive, permanent-magnet alternators nominally produce three-phase, 240-V alternating-current power at 60 Hz at 325 revolutions per minute (rpm). The frequency varies between 0 and 90 Hz, and the corresponding voltage varies between 0 and 330 V. At a wind speed of 6 m/s (13 mi/h), the system stabilizes, and the voltage and frequency increase rapidly together until the rotor furls (turns out of the wind) at a wind speed of 13.5 m/s (30 mi/h). The benefit of this type of system is seen in **Fig. 1**, which shows the voltage-frequency ratio. The voltage-frequency ratio exceeds 3 at a wind speed of 6 m/s (13 mi/h) and remains almost constant until furling at 13.5 m/s (30 mi/h). The electric motor, rated at 240 V and 60 Hz, will operate best at a voltage-frequency ratio near 4. Although the voltage-frequency ratio varies from 3 to 4, this range is acceptable for most motors. When the voltage-frequency ratio is constant or nearly constant, the current draw to the motor is proportional to the power provided, and it is always equal or below the design current. Motor overheating will not occur as long as design current is not exceeded.

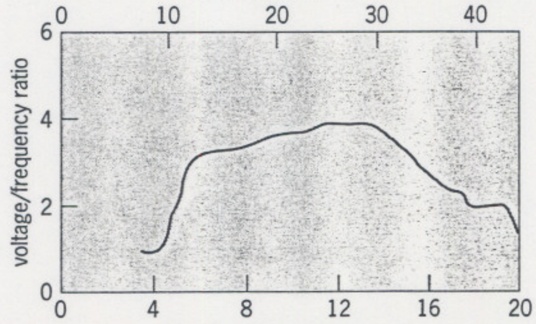

Fig. 1. Voltage-frequency ratio for a 1500-W wind turbine pumping from a depth of 45 m (150 ft).

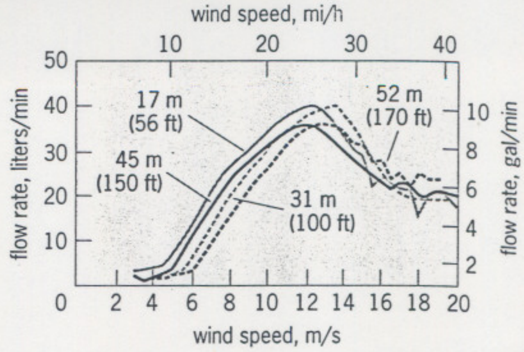

Fig. 2. Water-flow rates for four pumping depths, using a submersible pump and a 1500-W wind turbine.

Operation. Each wind turbine system has a mechanical rotor overspeed control, which allows the unit to run unloaded. The units furl and slow the rotor by turning sideways out of the wind flow. The rotor blades are usually constructed of fiber-reinforced plastic or epoxy-coated wood, and they operate at rotor speeds between 100 and 500 rpm. Rotor diameters for small water pumping systems range from 2 to 7 m (7 to 23 ft).

The wind pumping system is controlled by an electronic circuit that senses the frequency output of the wind turbine generator; when a preset cut-in frequency is reached, a standard motor solenoid connects the electric power from the wind turbine to the standard electric pump motor. The controller performs four control functions by starting the electric pump motor at the low-speed cut-in, stopping the motor at a low-speed cut-out, stopping the motor at a high-speed cut-out, and restarting the motor after a high-speed cut-out.

The pumps used in wind-electric systems are multistage submersible pumps powered by three-phase, 240-V standard submersible electric pump motors. Pumps and motors operate at 3450 rpm when powered at a constant 60 Hz (utility power). Systems have been tested at several pumping heads to determine the effect of pumping head on the wind speed at which pumping is initiated, and to develop the pumping curves under the different pumping heads as a function of wind speed. (Pumping head is the specific energy that is required to move water from a beginning point to a discharge point.)

Performance. A 1500-W wind-electric water pumping system that operates independently of the electric utility was operated at seven different pumping heads ranging from 17 to 59 m (56 to 190 ft). Performance data were collected for more than 700 h at each pumping head. During all these tests, the wind turbine, pump controller, electric submersible motor, and pump required no maintenance. These systems experienced wind speeds in excess of 30 m/s (65 mi/h). The water-flow rates for four pumping heads are given in **Fig. 2**. For the 17-m (56-ft) pumping head, flow was initiated at a wind speed of 3 m/s (7 mi/h), and a peak flow of 40 liters/min (10 gal/min) was recorded at a wind speed of 12 m/s (27 mi/h) when furling occurred. The peak flows varied from 36 to 41 liters/min (9 to 10 gal/min) for all heads tested.

The flow curve for a pumping head of 45 m (150 ft) was selected for conducting a prediction of yearly pumping. Monthly wind-speed histograms from 10 years of wind-speed data collected at a height of 10 m (33 ft) at Bushland, Texas, were used to calculate an average daily pumping volume for each month. **Figure 3** shows the average daily water pumped when the pumping head was 45 m (150 ft). The highest daily average water pumped was in March with a volume of 16,139 liters/day (4264 gal/day), and the lowest was in August with 7349 liters/day (1942 gal/day). The average for the year was 12,534 liters/day (3311 gal/day); all months, except August, exceeded 10,000 liters/day (2642 gal/day). A beef cow requires 40–50 liters/day (10–15 gal/day); therefore, this pumping system would provide for well over 100 head. A rancher should plan for storage of a 5-day supply and size the herd for the lowest daily amount available. However, in this case a rancher might choose to select the average of July, August, and September, or 9680 liters/day (2560 gal/day), as the available water supply.

Since the multibladed windmill has been used for many years to provide water for livestock, its performance was compared to this electrical water pumping system. A month-by-month comparison of the two pumping systems using the average daily water volume is given in Fig. 3. The average daily water volume for the wind-electric system exceeds the wind-mechanical system by almost 4000 liters/day (1050 gal/day), or 45% more water. The wind-electric pump provided more water in all months except August, when the average wind speed is significantly lower than in the other months. These data clearly show that electrical wind pumps operate better than mechanical systems when the average wind speed is above 5 m/s (11 mi/h), and operate about the same as mechanical systems when the wind speed is 4–5 m/s (9–11 mi/h). Comparisons made between mechanical and electrical wind pumps for pumping heads of 17–30 m (56–100 ft) show that the electrical wind pump will pump about twice as much water.

In the two systems the electric wind turbine rotor at 3.05 m (10 ft) is larger than the mechanical windmill rotor at 2.44 m (8 ft). The mechanical windmill starts pumping at a lower wind speed, but the difference is less than 1 m/s (2 mi/h) and is dependent

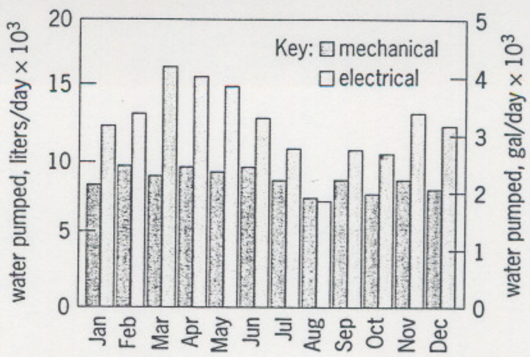

Fig. 3. Comparison of the average daily water pumped by a mechanical windmill and a wind-electric pumping system. The pumping depth was 45 m (150 ft). Wind data are from 1983–1992.

upon the pumping head. Probably the most important comparison is between the costs of the two systems. The turbines and towers cost about the same, but the costs of the controls and pumps differ greatly. The higher cost of steel pipe and the requirement for a pump rod for the mechanical system more than offset the cost of the pump controller for the electrical system. These small-sized submersible pumps are often supported by a hanger wire, and polyethylene pipe is used to transport the water to the surface, thus reducing the cost of the pump installation. The overall costs are almost identical for the two systems.

These machines have proved to be reliable and robust enough to be installed in remote areas where the greatest need for pumping water for livestock and domestic use occurs. This wind-electric water pumping system has consistently performed better than the wind-mechanical system. Although data are presented for one pump and four pumping heads, several pumps using three different wind turbines have been tested, and all perform better than mechanical pumps. Much of the improved performance of wind-electric systems is a result of using submersible pumps that have a low starting torque and a flow that is proportional to the speed of the pump. In contrast, the piston pump used with wind-mechanical water pumping systems has a high starting torque, with flow proportional to the stroke length and stroke speed. Mechanical wind systems furl and reduce the pump speed when the wind speed exceeds 10 m/s (22 mi/h), thus wasting significant amounts of energy.

For background information *SEE ALTERNATING-CURRENT MOTOR; PUMP; WIND POWER* in the McGraw-Hill Encyclopedia of Science & Technology.

R. Nolan Clark

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