Fluid Mechanics

Chapter-8

Basics of Wind Energy Conversion

8.1 Principles of Wind Energy Conversion

The primary component of a wind turbine is the energy converter which transforms the Kinetic energy contained in the moving air, into mechanical energy. For the initial discussions of principles, the exact nature of the energy converter is irrelevant. The extraction of mechanical energy from a stream of moving air with the help of a disk-shaped, rotating wind energy converter follows its own basic rules. The credit for having recognized this principle is owed to Albert Betz. Between 1922 and 1925, Betz published writings in which he was able to show that, by applying elementary physical laws, the mechanical energy extractable from an air stream passing through a given cross-sectional area is restricted to a certain fixed proportion of the energy or power contained in the air stream [1]. Moreover, he found that optimal power extraction could only be realized at a certain ratio between the flow velocity of air in front of the energy converter and the flow velocity behind the converter. Although Betz's "momentum theory", which assumes an energy converter working without losses in a frictionless air flow, contains simplifications, its results are quite usable for performing rough calculations in practical engineering. But its true significance is founded in the fact that it provides a common physical basis for the understanding and operation of wind energy converters of various designs. For this reason, the following sections will provide a summarized mathematical derivation of the elementary "momentum theory" by Betz.

8.1.1 Betz's Elementary Momentum Theory

The kinetic energy of an air mass *m* moving at a velocity *v* can be expressed as:

$$E = \left(\frac{1}{2}\right) m v^2 \; Nm$$

Considering a certain cross-sectional area *A*, through which the air passes at velocity *v*, the volume $V^{|}$ flowing through during a certain time unit, the so-called volume flow, is:

$$V^{|} = v\,A \; (m^3/s)$$

8.1.2 Turbine design and construction

Most wind turbines have upwind rotors that are actively yawed to preserve alignment with wind direction. The three-bladed rotor is the most popular and, typically, has a separate front bearing with a low speed shaft connected to a gearbox which provides an output speed suitable for a four-pole generator (see Figure 8.1). Commonly, with the largest wind turbines, the blade pitch will be varied continuously under active control to regulate power at the higher operational wind speeds (furling). Support structures are most commonly tubular steel towers tapering in some way, both in metal wall thickness and in diameter from tower base to tower top. Epoxy based resin systems dominate the market in blade manufacture and carbon fibre reinforcement is increasingly used in big blades. In 2006, the focus of attention is on technology around and above the 2 MW rating and commercial turbines now exist with heights over 100 m and rotor diameters up to 100 m. Designs with *variable pitch* and *variable speed* dominate the market while *direct drive* generators are becoming more prevalent.

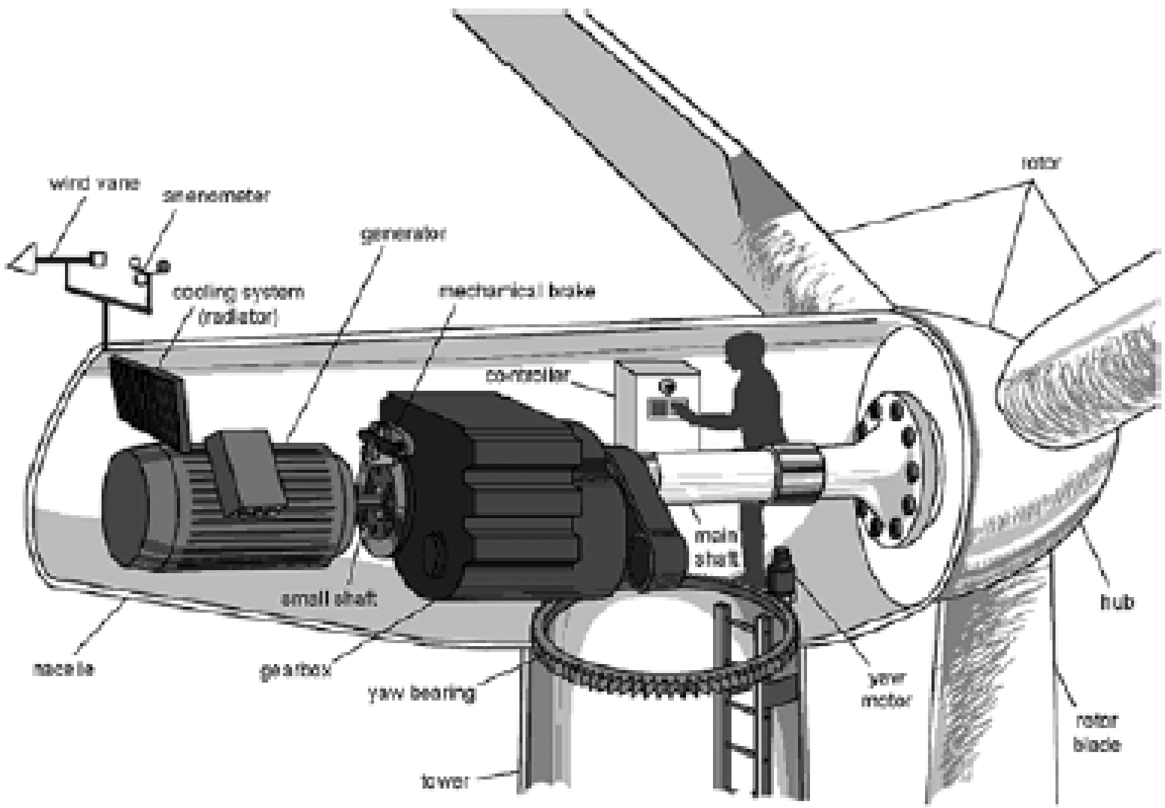

Fig 8.1 Construction of Wind Turbine

8.2 Tip Speed Ratio

In reference to a wind energy conversion device's blades, the ratio between the rotational speed of the tip of the blade and the actual velocity of the wind. High efficiency 3-blade-turbines have tip speed ratios of 6-7. On the whole, a high tip speed ratio is better, but not to the point where the machine becomes noisy and highly stressed. The tip speed ratio determines how fast the wind turbine will want to turn and so has implications for the alternator that can be used.

Modern wind turbines are designed to spin at varying speeds. Use of aluminum and composites in their blades has contributed to low rotational inertia, which means that newer wind turbines can accelerate quickly if the winds pick up, keeping the tip speed ratio more nearly constant. Operating closer to their optimal tip speed ratio during energetic gusts of wind allows wind turbines to improve energy capture from sudden gusts that are typical in urban settings.

In contrast, older style wind turbines were designed with heavier steel blades, which have higher inertia, and rotated at speeds governed by the AC frequency of the power lines. The high inertia buffered the changes in rotation speed and thus made power output more stable.

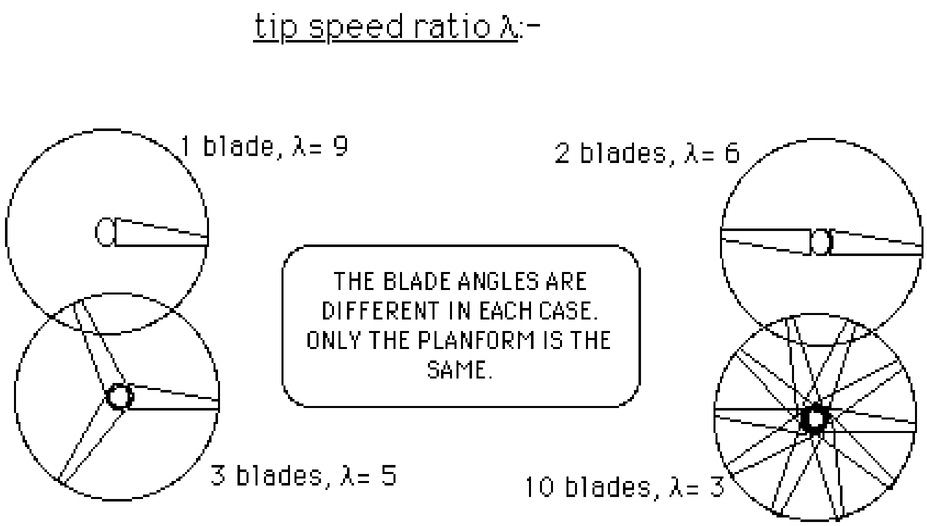

Fig 8.2 Tip Speed Ratio

8.3 Wind Direction Changes

Wind is the roughly horizontal movement of air (as opposed to an air current) caused by uneven heating of the Earth's surface. It occurs at all scales, from local breezes generated by heating of land surfaces and lasting tens of minutes to global winds resulting from solar heating of the Earth. The two major influences on the atmospheric circulation are the differential heating between the equator and the poles, and the rotation of the planet (Coriolis effect).

Given a difference in barometric pressure between two air masses, a wind will arise between the two which tends to flow from the area of high pressure to the area of low pressure until the two air masses are at the same pressure, although these flows will be modified by the Coriolis effect in the extratropics.

Some local winds blow only under certain circumstances, i.e. they require a certain temperature distribution.

Differential heating is the motive force behind land breezes and sea breezes (or, in the case of larger lakes, lake breezes), also known as on- or off-shore winds. Land is a rapid absorber/radiator of heat, whereas water absorbs heat more slowly but also releases it over a greater period of time. The result is that, in locations where sea and land meet, heat absorbed over the day will be radiated more quickly by the land at night, cooling the air. Over the sea, heat is still being released into the air at night, which rises. This convective motion draws the cool land air in to replace the rising air, resulting in a land breeze in the late night and early morning. During the day, the roles are reversed. Warm air over the land rises, pulling cool air in from the sea to replace it, giving a sea breeze during the afternoon and evening.

Mountain breezes and valley breezes are due to a combination of differential heating and geometry. When the sun rises, it is the tops of the mountain peaks which receive first light, and as the day progresses, the mountain slopes take on a greater heat load than the valleys. This results in a temperature inequity between the two, and as warm air rises off the slopes, cool air moves up out of the valleys to replace it. This upslope wind is called a valley breeze. The opposite effect takes place in the afternoon, as the valley radiates heat. The peaks, long since cooled, transport air into the valley in a process that is partly gravitational and partly convective and is called a mountain breeze.

Mountain breezes are one example of what is known more generally as a katabatic wind. These are winds driven by cold air flowing down a slope, and occur on the largest scale in Greenland and Antarctica. Most often, this term refers to winds which form when air which has cooled over a high, cold plateau is set in motion and descends under the influence of gravity. Winds of this type are common in regions of Mongolia and in glaciated locations.

Because katabatic refers specifically to the vertical motion of the wind, this group also includes winds which form on the lee side of mountains, and heat as a consequence of compression. Such winds may undergo a temperature increase of 20 °C (36 °F) or more, and many of the world's "named" winds (see list below) belong to this group. Among the most well-known of these winds are the Chinook of Western Canada and the American Northwest, the Swiss föhn, California's infamous Santa Ana wind, and the French Mistral.

The opposite of a katabatic wind is an anabatic wind, or an upward-moving wind. The above-described valley breeze is an anabatic wind.

A widely-used term, though one not formally recognized by meteorologists, is orographic wind. This refers to air which undergoes orographic lifting. Most often, this is in the context of winds such as the Chinook or the föhn, which undergo lifting by mountain ranges before descending and warming on the lee side.

These winds are used in the decomposition and analysis of wind profiles. They are useful for simplifying the atmospheric equations of motion and for making qualitative arguments about the horizontal and vertical distribution of winds. Examples are:

Geostrophic wind (wind that is a result of the balance between Coriolis force and pressure gradient force; flows parallel to isobars and approximates the flow above the atmospheric boundary layer in the midlatitudes if frictional effects are low) Thermal wind (not actually a wind but a wind difference between two levels; only exists in an atmosphere with horizontal temperature gradients, i.e. baroclinicity)

Ageostropic wind (difference between actual and geostrophic wind; the wind component which is responsible for air "filling up" cyclones over time) Gradient wind (like geostrophic wind but also including centrifugal force)

8.4 Types of wind machines

There are two types of wind machines (turbines) used today based on the direction of the rotating shaft (axis)

i. horizontal–axis wind machines
ii. vertical-axis wind machines

The size of wind machines varies widely. Small turbines used to power a single home or business may have a capacity of less than 100 kilowatts. Some large commercial sized turbines may have a capacity of 5 million watts, or 5 megawatts. Larger turbines are often grouped together into **wind farms** that provide power to the electrical grid.

Most wind machines being used today are the horizontal-axis type. Horizontal-axis wind machines have blades like airplane propellers. A typical horizontal wind machine stands as tall as a 20-story building and has three blades that span 200 feet across.

Vertical–axis wind machines have blades that go from top to bottom and the most common type (Darrieus wind turbine) Vertical-axis wind machines make up only a very small percent of the wind machines used today.

8.5 Wind Farm

Wind farm is a collection of windmills or turbines which are used to generate electrical power through their mechanical motions as they are pushed by the wind. Both Europe and the United States have large numbers of wind farms, and the technology is also found on other continents. In Asia, India especially has devoted a great deal of funding to establishing wind farms. The energy generated by a wind farm can be fed directly into the general energy grid after passing through transformers.

As a potentially large source of renewable energy, wind farms are particularly popular in nations which are focusing on alternative energy. Other types of renewable energy include wave power and solar arrays. All of these technologies take advantage of already existing energy, converting it into a usable form. Since a wind farm does not actively deplete resources as it generates power, it is considered a form of "green" energy.

Naturally, some resources must be expended to create a wind farm. The turbines, transformers, and grid system on a wind farm are often made from less than ideal substances, such as metals mined in an unclean way. However, once installed, a wind farm requires no additional energy output other than that required for basic maintenance. This is a marked contrast to a power plant which relies on coal or petroleum products. Consumers who want to support wind farms can buy energy credits which go to developers of wind farms.

Naturally, the best place for a wind farm is a windy location. In some instances, a windy location may also be generally unusable or uninhabitable. In other instances, a wind farm may take up useful real estate which could be used for farming. This has led to some criticism of wind farms, since they take up a great deal more space than a comparable non-renewable energy generating facility. In addition, wind farms pose a severe threat to migratory birds, as has been clearly documented by several scientific organizations.

These issues aside, the technology is generally believed to be environmentally sound and fiscally viable. Especially if wind farms are combined with other renewable energy sources, green energy could make up a bulk of the power grid. This could have a huge impact on the environment and on society in general. Especially at the end of the twentieth century, when a growing number of citizens began to call for energy reforms, wind farms held a great deal of promise.

Fig 8.3 Typical Wind Farm