Government College of Engineering Pune ,

Expert session
ON

“ **BASIC PRINCIPLES OF WIND ENERGY CONVERSION** ”

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Session 1

22-January 2022

10.00 to 12.00 noon

- **The Nature of Wind**
- **History of Wind Power**
- **The Power in Wind & standerd terms**
- **Wind Physics Basics**
- **Wind Power Fundamentals**
- **Technology Overview**
- **Beyond the Science and Technology**
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BASIC PRINCIPLES OF WIND ENERGY CONVERSION

The rising concerns over global warming, environmental pollution, and energy security have increased interest in developing renewable and environmentally friendly energy sources such as wind, solar, hydropower, geothermal, hydrogen, and biomass as the replacements for fossil fuels.

Wind energy can provide suitable solutions to the global climate change and energy crisis. The utilization of wind power essentially eliminates emissions of CO_2 , SO_2 ,

NO_x and other harmful wastes as in traditional coal-fuel power plants or radioactive wastes in nuclear power plants.

By further diversifying the energy supply, wind energy dramatically reduces the dependence on fossil fuels that are subject to price and supply instability, thus strengthening global energy security. During the recent three decades, tremendous growth in wind power has been seen all over the world. In 2009, the global annual installed wind generation capacity reached a record-breaking 37 GW, bringing the world total wind capacity to 158 GW. As the most promising renewable, clean, and reliable energy source, wind power is highly expected to take a much higher portion in power generation in the coming decades.

1. The Nature of Wind

- Wind energy is a converted form of solar energy which is produced by the nuclear fusion of hydrogen (H) into helium (He) in its core.
- The H → He fusion process creates heat and electromagnetic radiation streams out from the sun into space in all directions. Though only a small portion of solar radiation is intercepted by the earth, it provides almost all of earth's energy needs.

Wind energy represents a mainstream energy source of new power generation and an important player in the world's energy market. As a leading energy technology, wind power's technical maturity and speed of deployment is acknowledged, along with the fact that there is no practical upper limit to the percentage of wind that can be integrated into the electricity system [1].

Compared with traditional energy sources, wind energy has a number of benefi ts and advantages.

- Unlike fossil fuels that emit harmful gases and nuclear power that generates radioactive wastes, wind power is a clean and environmentally friendly energy source.
- As an inexhaustible and free energy source, it is available and plentiful in most regions of the earth.
- In addition, more extensive use of wind power would help reduce the demands for fossil fuels, which may run out sometime in this century, according to their present consumptions.

Wind generation

The circulation of air in the atmosphere is caused by the non-uniform heating of the earth's surface by the sun. The air immediately above a warm area expands, it is forced upward by cool, denser air which flows in from surrounding areas causing wind.

The nature of the terrain, the degree of cloud and the angle of the sun in the sky are all factors which influences this process.

- In general, during the day the air above the land mass tends to heat up more rapidly than the air over water. In coastal regions this manifests itself in a strong onshore wind. At night the process is reversed because the air cools down more rapidly over the land and the breeze therefore blows off shore.
- Despite the wind's intermittent nature, wind patterns at any particular site remain remarkably constant year by year. Average wind speeds are greater in hilly and costal area than they are well inland. The winds also tend to blow more consistently and with greater strength over the surface of the water where there is a less surface drag.

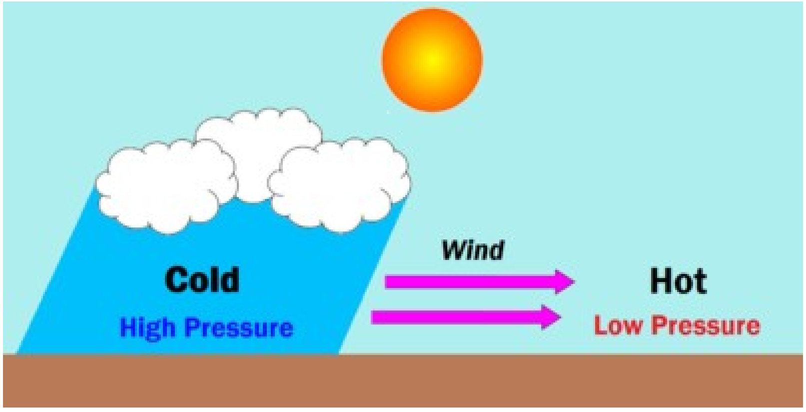


Fig. Wind formation due to uneven heating of the Earth's surface

The generation and movement of wind are complicated due to a number of factors. Among them, the most important factors are uneven solar heating, the Coriolis effect due to the earth's self-rotation, and local geographical conditions.

It can be briefly discussed as under:

- Wind is formed due to uneven heating of the Earth's surface.[2] These surfaces absorb heat at different rates; for example sand on a beach can be too hot to walk on while nearby grass feels cool.
- As these surfaces absorb heat at different rates, the air just above the surface warms and begins to rise. The rising hot air creates a change in pressure in the area.[1] Air naturally moves from the areas of high pressure to low pressure, which causes the horizontal movement of air.

A practical example is the ocean breeze. The air above land warms faster than air over water. As the hot air over land rises, the cool air over the ocean rushes in to fill thespace. The result is a cool ocean breeze.

The earth's self-rotation is another important factor to affect wind direction and speed. The Coriolis force, which is generated from the earth's self-rotation, deflects the direction of atmospheric movements.

- In the north atmosphere wind is deflected to the right and in the south atmosphere to the left. The Coriolis force depends on the earth's latitude; it is zero at the equator and reaches maximum values at the poles.
- In addition, the amount of deflection on wind also depends on the wind speed; slowly blowing wind is deflected only a small amount, while stronger wind deflected more.

In large-scale atmospheric movements, the combination of the pressure gradient due to the uneven solar radiation and the Coriolis force due to the earth's self rotation causes the single meridional cell to break up into three convectional cells in each hemisphere: the Hadley cell, the Ferrel cell, and the Polar cell (Fig. 1). Each cell has its own characteristic circulation pattern.

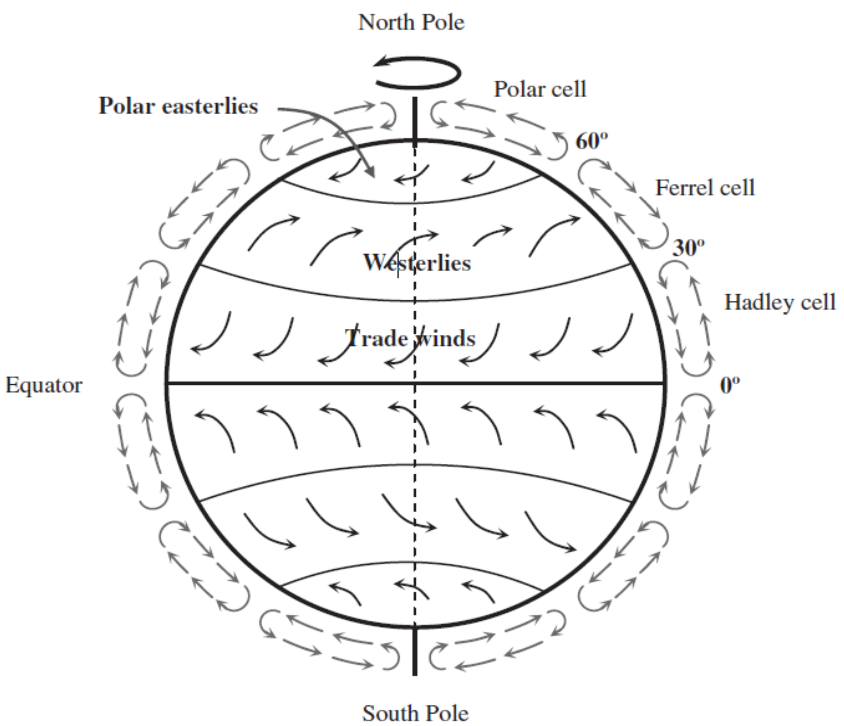


Figure 1: Idealized atmospheric circulations

Brief History – Early Systems

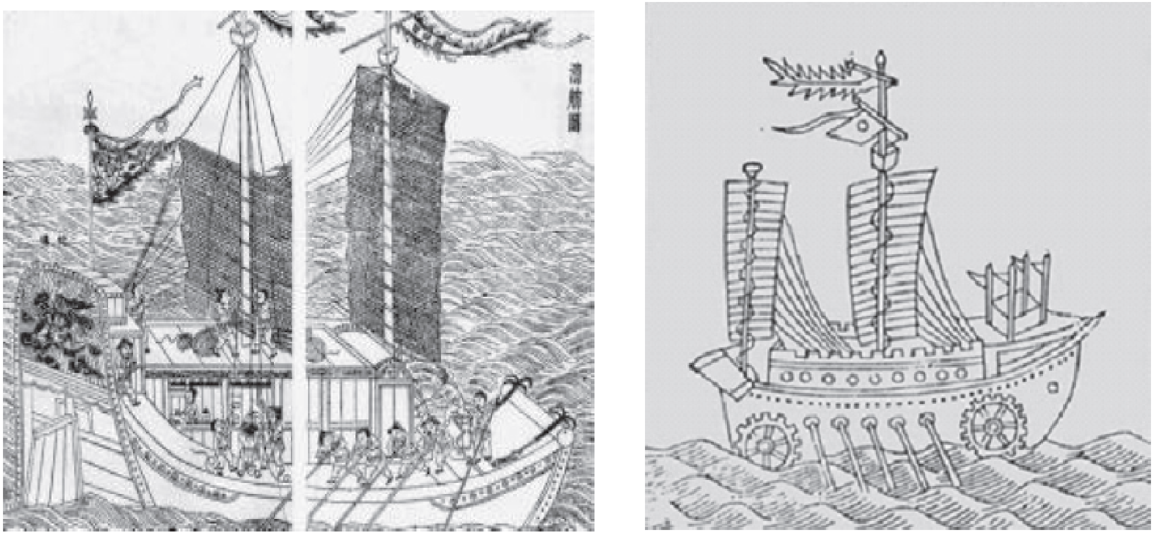
1st Wind Energy Systems

Ancient Civilization in the Near East / Persia, Vertical-Axis Wind-Mill: sails connected to a vertical shaft connected to a grinding stone for milling

Wind in the Middle Ages

Post Mill Introduced in Northern Europe

Horizontal-Axis Wind-Mill: sails connected to a horizontal shaft on a tower encasing gears and axles for translating horizontal into rotational motion



(a) (b)

Figure 2: Ancient Chinese junks (ships): (a) two-mast junk ship [7]; (b) wheel boat [8] .

Wind in 19th century US

Wind-rose horizontal-axis water-pumping wind-mills found throughout rural America

Key attributes of this period:

- Scale increase
- Commercialization
- Competitiveness
- Grid integration

Catalyst for progress: OPEC Crisis (1970s)

- Economics
- Energy independence
- Environmental benefits

Turbine Standardization:

- 3-blade Upwind Horizontal-Axis on a monopole

2. The Power in Wind

Wind energy is a special form of kinetic energy in air as it fl ows. Wind energy can be either converted into electrical energy by power converting machines or directly used for pumping water, sailing ships, or grinding gain.

- Therefore Wind possesses energy by virtue of its motion. Any device capable of slowing down the mass of moving air, like a sail or propeller, can extract part of the energy and convert it into useful work.

There are three factors determine the output power generated from the wind mill, they are;

(1) The wind speed

(2) The cross section of wind swept by rotor, and

(3) The overall conversion efficiency of rotor, transmission system and generator or pump.

- No device, however well-designed, can extract all of the wind's energy because the wind would have to be brought to a halt and this would prevent the passage of more air through the rotor.
- The most that is possible is for the rotor to decelerate to whole horizontal column of intercepted air to about one-third of its free velocity.
- A 100% efficient aerogenerator would therefore only be able to convert up to a maximum of around 60% of the available energy in wind into mechanical energy.
- A well-designed blades will typically extract 70% of the theoretical maximum, but losses incurred in the gear box, transmission system and generator or pump could decrease overall wind tubine efficiency to 35% or less.

2.1 Calculation of Power in the Wind:

- The power in the wind can be computed by using of Kinetics (Kinetic means relating to or resulting from motion). The wind mill works on the principle of converting Kinetic energy of the wind to mechanical energy.

We know that power is equal to energy per unit time. The energy available is the kinetic energy of the wind. The kinetic energy of any particle is equal to one half its mass times the square of its velocity. Lets consider a typcal **wind turbine as in fig3 below**

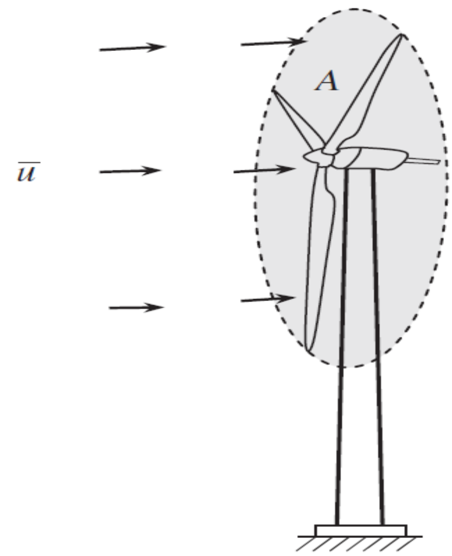


Figure 3: Swept area of wind turbine blades

Kinetic Energy of particle = ½ mv^2

Where;

M : Mass of particle (kg)

V : Velocity of particle (m/s)

The amount of air passing in unit time, through an area 'A', with velocity 'V' is AxV, and its mass 'm' is equal to its volume multiplied by its density 'ρ' of air.

Air density

Another important parameter that directly affects the wind power generation is the density of air, which can be calculated from the equation of state:

$$\rho = \frac{p}{RT}$$

where p is the local air pressure, R is the gas constant (287 J/kg-K for air), and T is the local air temperature in K.

Therefore;

i.e., Kinetic Energy of particle $= \frac{1}{2} mv^2$ ... (5.1)

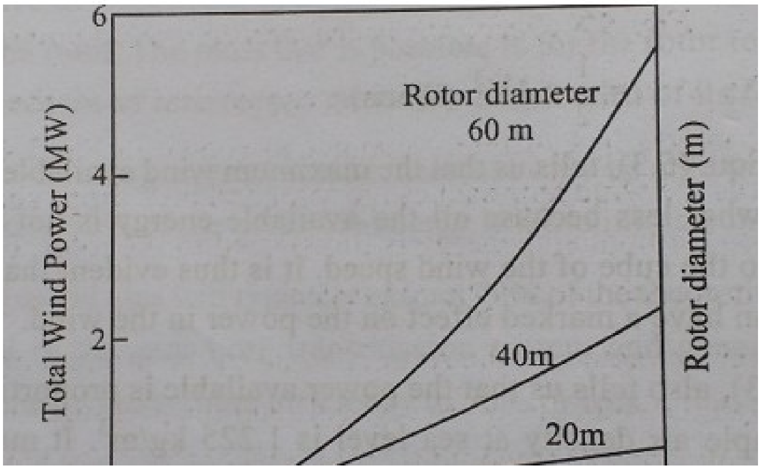
Where, m is the mass of air transversing the area 'A' swept by the rotating blades of a wind mill type generator.

Substituting Equ. (5.2) in Equ. (5.1),

We get,

$$\text{Kinetic Energy} = \frac{1}{2} \rho AV \times V^2$$

$$= \frac{1}{2} \rho AV^3 \text{ (Watts)} \qquad \text{... (5.3)}$$



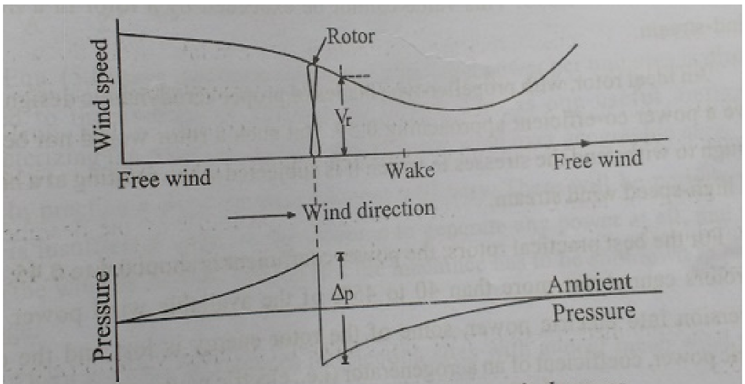


Fig. 5.4 Condition in traversing a wind power.

Power Coefficient

- The conversion of wind energy to electrical energy involves primarily two stages:
- in the first stage, kinetic energy in wind is converted into mechanical energy to drive the shaft of a wind generator. The critical converting devices in this

stage are wind blades. For maximizing the capture of wind energy, wind blades need to be carefully designed.

- The power coefficient *C*p deals with the converting efficiency in the first stage, defined as the ratio of the actually captured mechanical power by blades to the available power in wind:

$$C_{\text{p}} = \frac{P_{\text{me,out}}}{P_{\text{w}}} = \frac{P_{\text{me,out}}}{(1/2)\rho A\overline{u}^3}$$

Because there are various aerodynamic losses in wind turbine systems, for instance, blade-tip, blade-root, profile, and wake rotation losses, etc., the real power coeffi cient *C*p is much lower than its theoretical limit, usually ranging from 30 to 45%.

Therefore the fraction of the free-flow wind power that can be extracted by the rotor is called the power co-efficient; Thus,

Power Coefficient = Power of wind rotor / Power available in the wind

- Where, power available is calculated from the air density, rotor diameter and free wind speed as discussed earlier.
- The maximum theoretical power coefficient is equal to 16/27 or 0.593. This value cannot be exceeded by a rotor in free-flow wind-stream.
- An ideal rotor, with propeller-type blades of proper aerodynamic design, would have a power co-efficient approaching 0.59. But such a rotor would not be strong enough to withstand the stresses to which it is subjected when rotating at a high rate in a high-speed wind stream.

2.3 Total power conversion coefficient and effective power output

- In the second stage, mechanical energy captured by wind blades is further converted into electrical energy via wind generators. In this stage, the converting efficiency is determined by several parameters
  - Gearbox efficiency η gear – The power losses in a gearbox can be classified

as load-dependent and no-load power losses. The load-dependent losses consist of gear tooth friction and bearing losses and no-load losses consist of oil churning, windage, and shaft seal losses. The planetary gearboxes, which are widely used in wind turbines, have higher power transmission efficiencies over traditional gearboxes.

- Generator efficiency η gen – It is related to all electrical and mechanical losses in a wind generator, such as copper, iron, load, windage, friction, and other miscellaneous losses.

- Electric efficiency ηele – It encompasses all combined electric power losses in the converter, switches, controls, and cables.

Therefore, the total power conversion efficiency from wind to electricity ηt is the production of these parameters, i.e.:

$$\eta t = Cp\ \eta\ gear\ \eta\ gen\ \eta ele \qquad (17)$$

The effective power output from a wind turbine to feed into a grid becomes;

$$Peff = Cp\ \eta\ gear\ \eta\ gen\ \eta ele\ Pw = \eta t\ Pw = 1/2(\eta t\ \rho\ AV^3)$$

2.4 Instantaneous Wind Power

Wind velocity 'V', in actuality, is not constant but is represented by a statically 'Noisy' wind speed time curve, $V_{(t)}$ then the instantaneous power, in the wind would be,

$$P_{w(t)} = \frac{1}{2}\rho A\, V^3_{(t)} \text{ Watts} \qquad \text{(From Equ. 5.3)} \qquad \dots (5.6)$$

Since, we are normally more interested in average power, we must take time average of both sides o Equ. (5.6), signified by the bar, and written as,

$$\bar{P}_{w(t)} = \frac{1}{2}\rho A\, \overline{V^3_{(t)}} \qquad \dots (5.7)$$

the average to find the average wind power available.

It is immediately obvious that this non-steady state case is more complex than the simple steady state case, and it is why for the former case such great emphasis is placed on anemometry data at a proposed Wind Energy Conversion System (WECS) site.

Transposing Equ. (5.7) results in Average wind power density, it is given by,

$$\frac{\overline{P_{w(t)}}}{A} = \frac{1}{2} \rho \overline{V_{(t)}^3} \text{ Watts/m}^2 \quad \ldots (5.8)$$

- Equ. (5.8) says that the average available wind power per unit area is directly related to the average of wind speed cubed. This is one useful method to characterizing the potential specific power in the wind over geographic area.
- In practice a wind turbine's output will vary. There will be periods when there is insufficient wind for the machine to generate any power at all, and times when the wind speeds are so high that the machince has to be shutdown to prevent damage.

2.4. Expression For Maximum Power In Wind

As discussed earlier, that the total power can not converted to mechanical power. Consider a horizontal-axis, propeller-type wind mill, henceforth to be called a wind turbine, which is the, most common type today. Assume that the wheel such a turbine has a thickness 'ab' shown in Fig. 5.5.

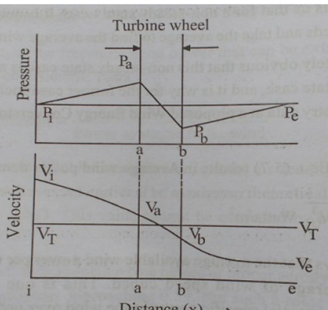


Fig. 5.5 Pressure and velocity profiles of wind moving through a horizontal-axis, propeller-type wind turbine

Let, P_i - Wind pressure at upstream of turbine,

V_i - Velocity at the upstream of turbine,

P_e - Pressure at down stream of the turbine, and

V_e - Velocity at the downstream of the turbine.

V_e is less than V_i, because kinetic energy extracted by the turbine.

2.5. Condition for Maximum Wind Power

For optimum exit velocity '$V_{e,opt}$', that results in maximum power 'P_{max}', which can be obtained by differentiating 'P' with respect to 'V_e', and equating the derivative to zero, i.e.,

$$P_i\, V + \frac{V_i^2}{2g_c} = P_a\, V + \frac{V_a^2}{2g_c} \quad \text{... (5.9)}$$

$$\frac{dP}{dV_e} = \frac{1}{4g_c}\rho A\left[(1+0)\,(V_i^2 - V_e^2) + (V_i + V_e)\,(-2V_e)\right] = 0$$

$$V_i^2 - V_e^2 - 2V_e V_i - 2V_e^2 = 0$$

$$V_i^2 - 2V_e V_i - 3V_e^2 = 0 \text{ (or) } 3V_e^2 + 2V_e V_i - V_i^2 = 0$$

This is solved for a positive 'V_e' to give $V_{e\,opt}$. The quadratic equation has two solution, i.e., $V_e = V_i$ and $V_e = \frac{1}{3}V_i$, only second solution is physically acceptable.

$$\text{Thus, } V_{e,\,opt} = \frac{1}{3}V_i \quad \text{... (5.23)}$$

Using the Equ. (5.22), for an ideal wind machine, with horizontal axis,

$$P_{max} = \frac{8}{27 g_c} \rho A V_i^3 \quad \text{... (5.24)}$$

$$= \frac{16}{27 g_c} \times \left(\frac{1}{2} \rho A V_i^3 \right)$$

$$= 0.593 \times \frac{1}{2} \frac{\rho V_i^3 A}{g_c}$$

$$= 0.593 \, P_{total} \quad \text{... (5.25)}$$

The idea, or maximum theoretical efficiency "μmax" (also called the power Coefficient) of a wind turbine is the ratio of the maximum power obtained from the wind to the total power available in the wind.

The factor 0.593 is known as the Betz coefficient. It is the maximum fraction of the power in a wind stream that can be extract.

$$\text{Power coefficient} = C_p \equiv \frac{\text{Power output from wind machine}}{\text{Power available in wind}}$$

Thus C_p cannot exceed 0.593 for a horizontal axis wind machine.

Lanchester–Betz limit

The theoretical maximum efficiency of an ideal wind turbomachine was derived by Lanchester in 1920. It was revealed that no wind turbomachines could convert more than 16/27 (59.26%) of the kinetic energy of wind into mechanical energy. This is known as Lanchester–Betz limit (or Lanchester–Betz law) today.

As shown in Fig. 8 , let;

- *u*– 1 and *u*– 4 are mean velocities far upstream and downstream from the wind turbine;
- *u*– 2 and *u*– 3 are mean velocities just in front and back of the wind rotating

blades, respectively.

- By assuming that there is no change in the air velocity right across the wind blades (i.e. u– 2 = u– 3) and the pressures far upstream and downstream from the wind turbine are equal to the static pressure of the undisturbed airflow
- (i.e. p 1 = p 4 = p), it can be derived that

$$p_2 - p_3 = \tfrac{1}{2}\rho(\overline{u}_1^2 - \overline{u}_4^2)$$

$$\overline{u}_2 = \overline{u}_3 = \tfrac{1}{2}(\overline{u}_1 + \overline{u}_4)$$

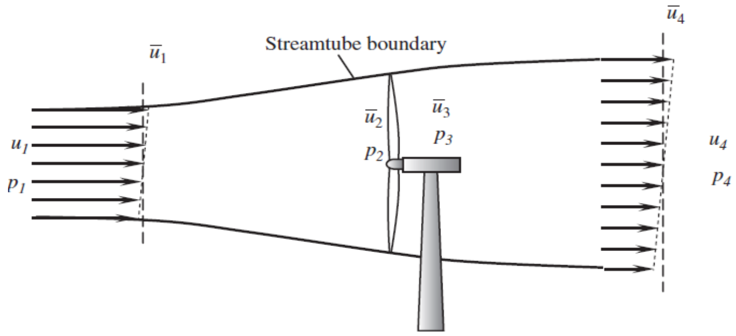


Figure 8: Airflow through a wind turbine

Thus, the power output of mechanical energy captured by wind turbine blades is

$$P_{\text{me,out}} = \tfrac{1}{2}\rho A\overline{u}_2(\overline{u}_1^2 - \overline{u}_4^2) = \tfrac{1}{2}\rho A\overline{u}_1^3 4a(1-a)^2$$

where a is the axial induction factor, defined as

$$a = \frac{\overline{u}_1 - \overline{u}_2}{\overline{u}_1}$$

Substitute eqn (21) into (16) (where u– 1 = u–), yields

$$C_p = 4a(1-a)^2$$

This indicates that the power coeffi cient is only a function of the axial induction factor a . It is easy to derive that the maximum power coefficient reaches its maximum value of 16/27 when a = 1/3 (see Fig. 9).

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