Wind Energy Systems

Introduction

The wind blows to the south and goes to the north; round and round goes the wind, and on its circuits the wind returns.

The earths atmosphere can be modeled as a gigantic heat engine.

It extracts energy from one reservoir (the sun) and delivers heat to another reservoir at lower temperature

In the process the work is done on the gases in the atmosphere and on the earths atmospheric boundary.

There will be regions where the air pressure is temporarily higher or lower than average

This difference in air pressure causes atmospheric gases or wind to flow from the region of higher pressure to that of lower pressure.

Solar radiation, evaporation of water, cloud cover all play important roles in determining the conditions of the atmosphere . The study of interactions between these effects is a complex subject called meteorology.

Within the atmosphere ,there are large regions of alternatively high and low pressures

In order for a high pressure region to be maintained while air is leaving it at ground level , there must be air entering the region at the same time

Air flow down inside the high pressure region to maintain the pressure

This descending air will be warmed adiabatically and will tend to become dry and clear.
Inside the low pressure region the rising air is cooled adiabatically which my results in clouds and precipitation.

Background

Wind energy is a large renewable energy source. Global wind power potential is of the order of 11,000 GW.

It is about 5 times the global installed power generation capacity. This excludes offshore potential as it is yet to be properly estimated.

About 25,000 MW is the global installed wind power capacity. It is about 1% of global installed power generation capacity. Wind produces about 50 billion kWh per year globally with the average utilization factor of 2000 hours per year.

History of Wind-Mills

The wind is a by-product of solar energy. Approximately 2% of the sun's energy reaching the earth is converted into wind energy.

The surface of the earth heats and cools unevenly, creating atmospheric pressure zones that make air flow from high-to low-pressure areas.

The wind has played an important role in the history of human civilization .

The first known use of wind dates back 5,000 years to Egypt, where boats used sails to travel from shore to shore.

The first true windmill, a machine with vanes attached to an axis to produce circular motion, may have been built as early as 2000 B.C.

B.C.

In ancien … with wind-
catching … eight were
grinding

- Early in 3,500 BC, The Egyptians were the first known people to use the power of the wind. They created sails for their boats to propel them down the Nile.

The earlies … world date
from the 1…

These too… w hundred
years late… d reclaim
much of Holland from the sea.

The multi-vane "farm windmill" of the American Midwest and West was invented in the United States during the latter half ofthe l9th century.

In 1889 there were 77 windmill factories in the United States, and by the turn of the century, windmills had become a major American export.

Until the diesel engine came along, many transcontinental rail routes in the U.S. depended on large multi-vane windmills to pump water for steam locomotives.

Farm windmills are still being produced and used, though in reduced numbers.

They are best suited for pumping ground water in small quantities to livestock water tanks

In the 1930s a ... bines were built
in the U.S.

They had two ... l generators.

By the early 1 ... ery American
household, via ... r these machines.
Wind turbine c

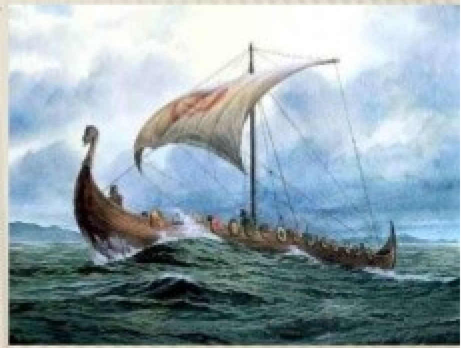
1887 – 1900s

- 1887: The first known wind turbine used to produce electricity is built in Scotland. The wind turbine is created by Prof James Blyth of Anderson's College
- 1888: The first known US wind turbine created for electricity production is built by Charles Brush in Ohio. (Pictured)
- By 1900: Approximately 2,500 windmills with a combined peak power capacity of 30 megawatts are being used across Denmark for mechanical purposes

HISTORY OF WIND USE

Man's harnessing of the wind goes back thousands of years

- Sail Boats
- Wind Mills
- Wind Turbines



The wind turbine captures the wind’s kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator.

The turbine is mounted on a tall tower to enhance the energy capture. Numerous wind turbines are installed at one site to build a wind farm of the desired power generation capacity.

Obviously, sites with steady high wind produce more energy over the year.

Classification of Wind-mills

Wind turbines are classified into two general types: Horizontal axis and Vertical axis

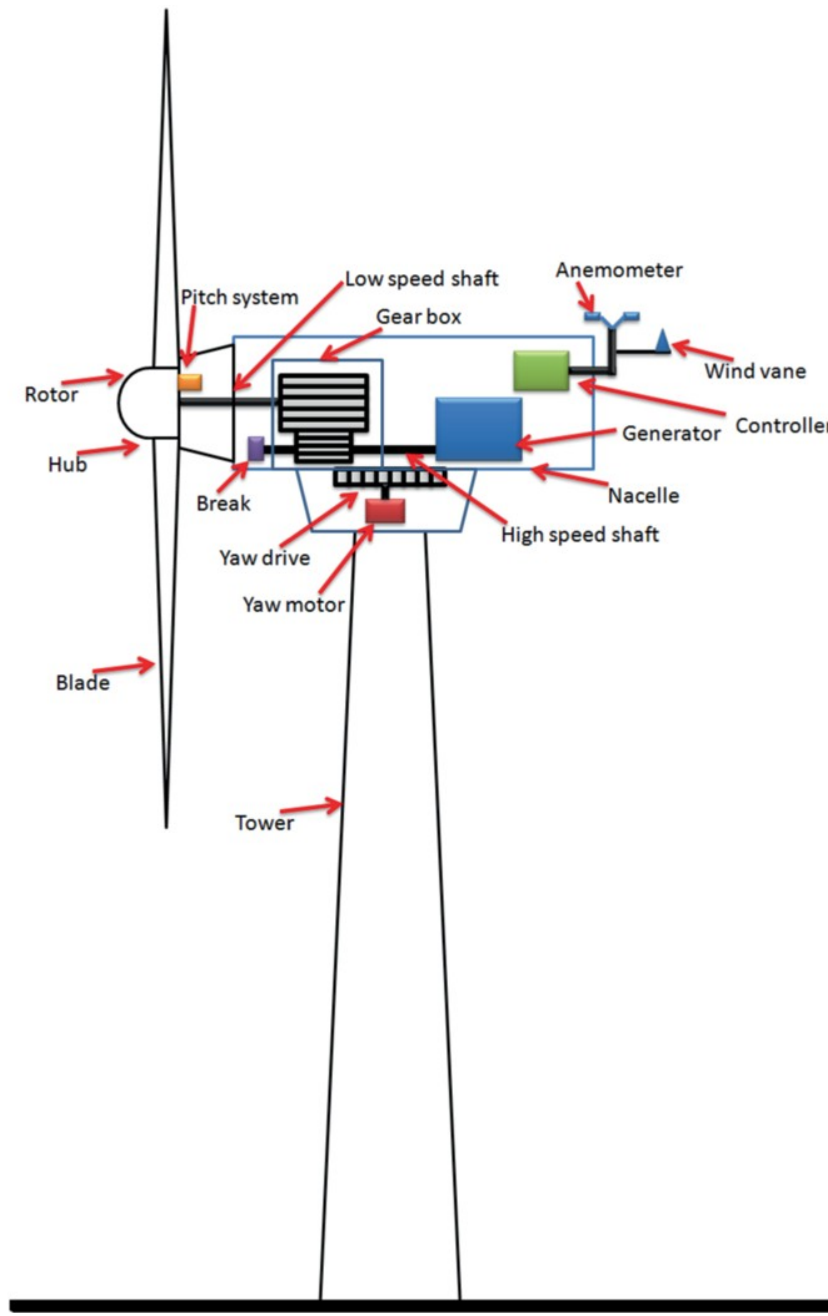
Horizontal Axis

A horizontal axis machine has its blades rotating on an axis parallel to the ground as shown in the above figure.

This is the most common wind turbine design. In addition to being parallel to the ground, the axis of blade rotation is parallel to the wind flow

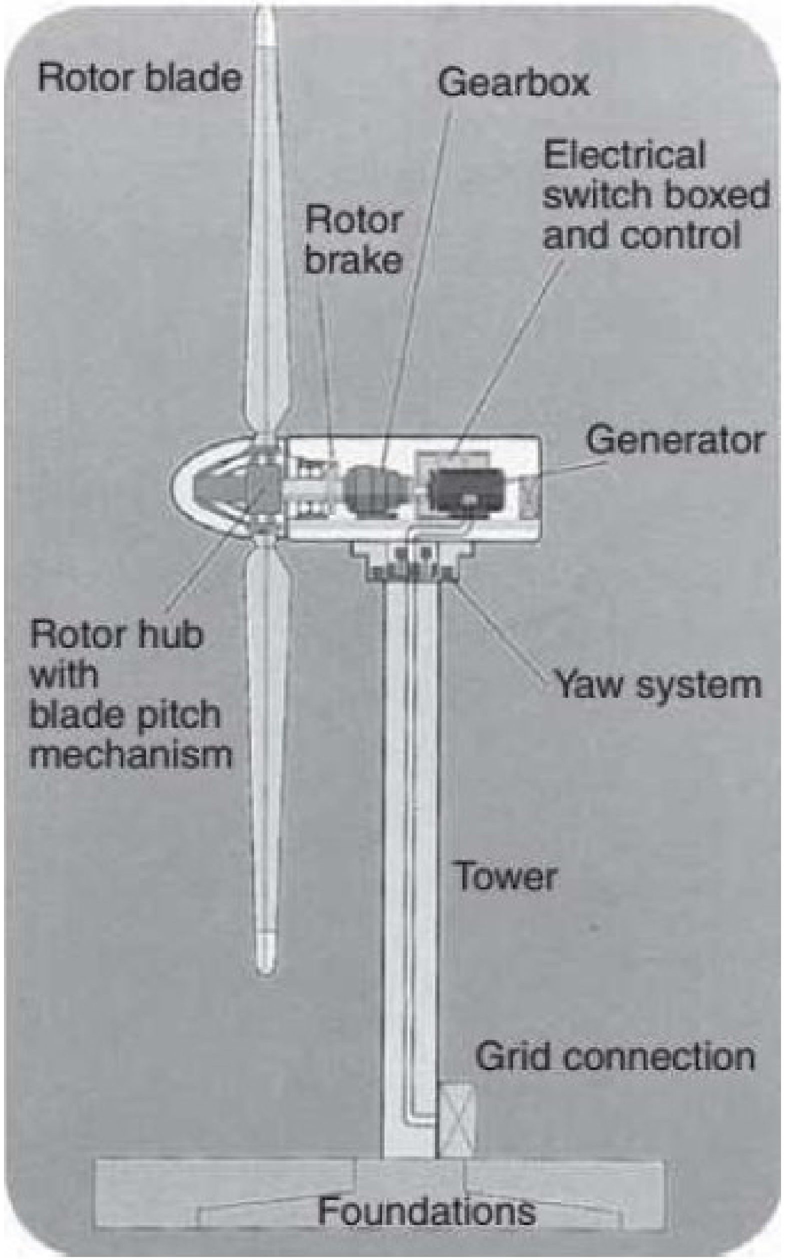
Vertical Axis

Although vertical axis wind turbines have existed for centuries, they are not as common as their horizontal counterparts. The main reason for this is that they do not take advantage of the higher wind speeds at higher elevations above the ground as well as horizontal axis turbines. The basic vertical axis designs are the Darrieus, which has curved blades and efficiency of 35%,



Low speed shaft
Anemometer
Pitch system
Gear box
Wind vane
Rotor
Controller
Generator
Hub
Nacelle
Break
High speed shaft
Yaw drive
Yaw motor
Blade
Tower

Main Components of a wind-mill



The wind power system comprises one or more wind turbine units operating electrically in parallel. Each turbine is made of the following basic components:

- Tower structure
- Rotor with two or three blades attached to the hub
- Shaft with mechanical gear
- Electrical generator
- Yaw mechanism, such as the tail vane
- Sensors and control

Rotor

The portion of the wind turbine that collects energy from the wind is called the rotor. The rotor usually consists of two or more wooden, fiberglass or metal blades which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades. The blades are attached to the hub, which in turn is attached to the main shaft

Generator

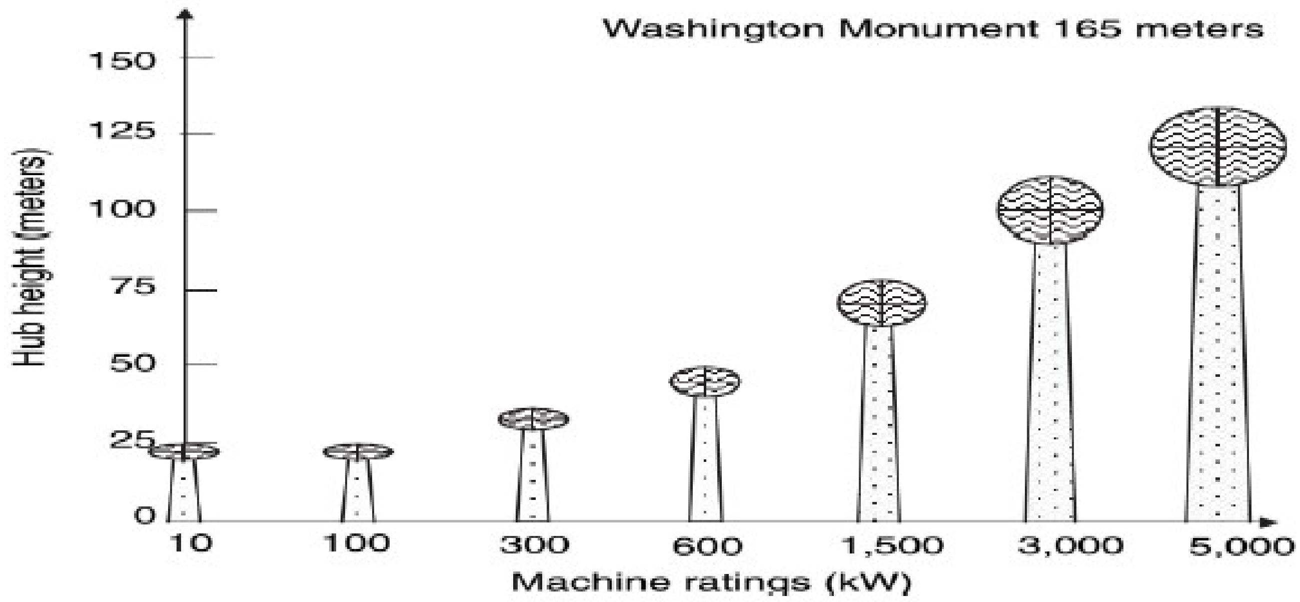
The generator is what converts the turning motion of a wind turbine's blades into electricity. Inside this component, coils of wire are rotated in a magnetic field to produce electricity. Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings.

Transmission (Gear Box)

The number of revolutions per minute (rpm) of a wind turbine rotor can range between 40 rpm and 400 rpm, depending on the model and the wind speed. Generators typically require rpm's of 1,200 to 1,800. As a result, most wind turbines require a gear-box transmission to increase the rotation of the generator to the speeds necessary for efficient electricity production.

Tower

The tower on which a wind turbine is mounted is not just a support structure. It also raises the wind turbine so that its blades safely clear the ground and so it can reach the stronger winds at higher elevations. Maximum tower height is optional in most cases, except where zoning restrictions apply

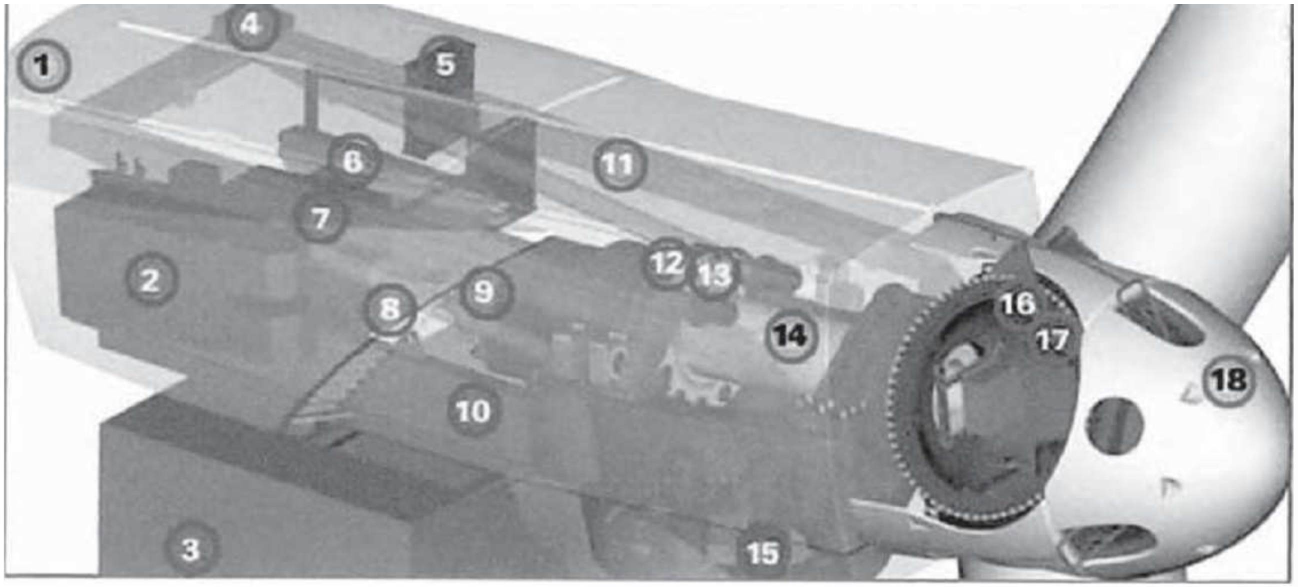


Tower heights of various capacity wind turbines.

Yaw drive: It keeps the upwind turbine facing into the wind as the wind direction changes. A yaw motor powers the yaw drive. Downwind turbines do not require a yaw drive, as the wind blows the rotor downwind.

Nacelle

A nacelle is a cover housing that houses all of the generating components in a wind turbine, including the generator, gearbox, drive train, and brake assembly



1. Nacelle
2. Heat Exchanger
3. Offshore Container
4. Small Gantry Crane
5. Oil Cooler
6. Control Pane
7. Generator
8. Impact Noise Reduction
9. Hydraulic Parking Brake
10. Main Frame
11. Swiveling Crane
12. Gearbox
13. Rotor Lock
14. Rotor Shaft
15. Yaw Drive
16. Rotor Hub
17. Pitch Drive
18. Nose Cone

Operating Characteristics of wind mills

All wind machines share certain operating characteristics, such as cut-in, rated and cut-out wind speeds.

Cut-in Speed

Cut-in speed is the minimum wind speed at which the blades will turn and generate usable power. This wind speed is typically between 10 and 16 kmph.

Rated Speed

The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power

Cut-out Speed

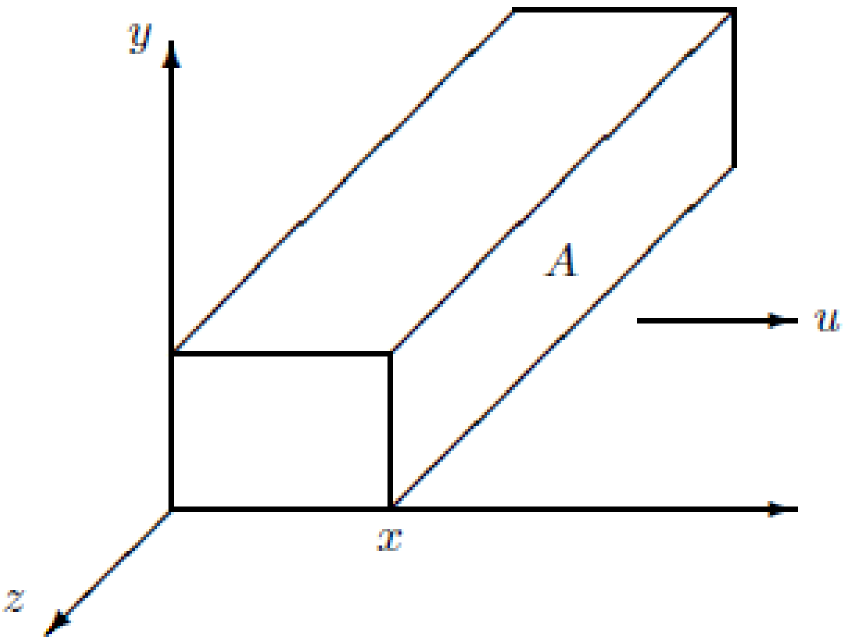
At very high wind speeds, typically between 72 and 128 kmph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut-out speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage.

POWER OUTPUT FROM AN IDEAL TURBINE

The kinetic energy in a parcel of air of mass m, flowing at speed u in the x direction is

$$U = \frac{1}{2} m u^2 = \frac{1}{2} (\rho A x) u^2 \qquad \text{Joules}$$

where A is the cross-sectional area in m^2, is the air density in kg/m^3, and x is the thickness of the parcel in m.



Packet of air moving with speed *u*

Power in the wind is derivative of kinetic energy

$$P_w = \frac{dU}{dt} = \frac{1}{2}\rho A u^2 \frac{dx}{dt} = \frac{1}{2}\rho A u^3 \qquad \mathrm{W}$$

An expression for air density is given by

$$\rho = 3.485 \frac{p}{T} \qquad \mathrm{kg/m^3}$$

In this equation, p is the pressure in kPa and T is the temperature in kelvin. The power in the wind is then

$$P_w = \frac{1}{2}\rho A u^3 = \frac{1.742 p A u^3}{T} \qquad \mathrm{W}$$

where A is area in square meters and u is wind speed in meters per second. For air at standard conditions, 101.3 kPa and 273 K, this reduces to

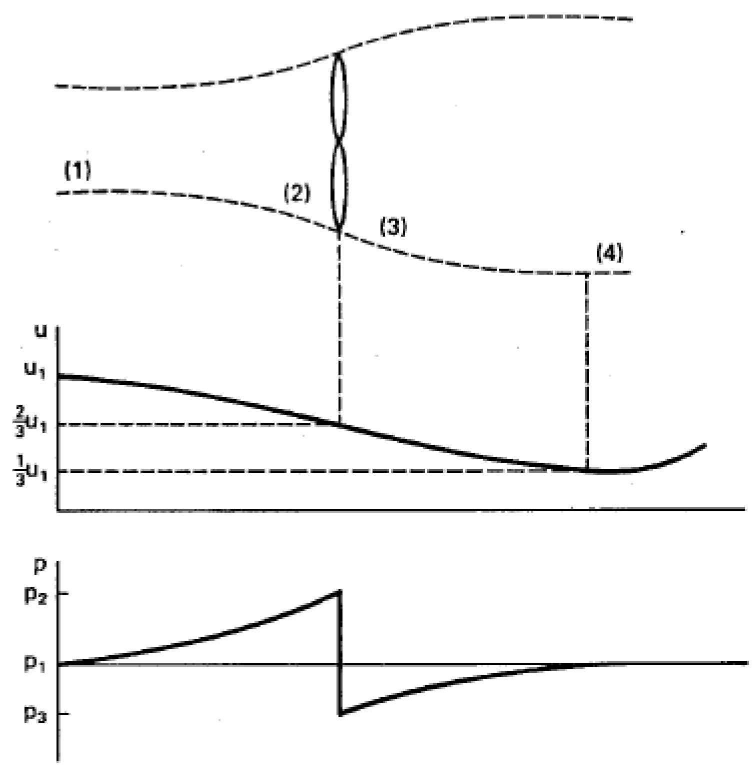
$$P_w = 0.647 A u^3 \qquad \mathrm{W}$$

- At standard conditions, the power in 1 m^2 of wind with a speed of 5 m/s is $0.647(5)^3 = 81$ W.
- The power in the same 1 m^2 of area when the wind speed is 10 m/s is 647 W.

This illustrates two basic features of wind power.

- One is that wind power is rather diffuse. It requires a substantial area of wind turbine to capture a significant amount of power.
- The other feature is that wind power varies rapidly with wind speed. Over speed protection devices are therefore required to protect both the turbine and the load at high wind speeds

The physical presence of a wind turbine in a large moving air mass modifies the local air speed and pressure as shown below.



- Consider a tube of moving air with initial or undisturbed diameter d1, speed u1, and pressure p1 as it approaches the turbine.
- The speed of the air decreases as the turbine is approached, causing the tube of air to enlarge to the turbine diameter d2.
- The air pressure will rise to a maximum just in front of the turbine and will drop below atmospheric pressure behind the turbine.
- Part of the kinetic energy in the air is converted to potential energy in order to produce this increase in pressure.

- Still more kinetic energy will be converted to potential energy after the turbine, in order to raise the air pressure back to atmospheric.

- This causes the wind speed to continue to decrease until the pressure is in equilibrium. Once the low point of wind speed is reached,

- The speed of the tube of air will increase back to u1 as it receives kinetic energy from the surrounding air

It can be shown[Dwinell .J.H] that under optimum conditions, when maximum power is being transferred from the tube of air to the turbine, the following relationships hold:

$$\begin{aligned} u_2 &= u_3 = \frac{2}{3} u_1 \\ u_4 &= \frac{1}{3} u_1 \\ A_2 &= A_3 = \frac{3}{2} A_1 \\ A_4 &= 3 A_1 \end{aligned}$$

The mechanical power extracted is then the difference between the input and output power in the wind:

$$P_{m,\text{ideal}} = P_1 - P_4 = \frac{1}{2}\rho(A_1 u_1^3 - A_4 u_4^3) = \frac{1}{2}\rho(\frac{8}{9}A_1 u_1^3) \qquad \text{W}$$

This states that 8/9 of the power in the original tube of air is extracted by an *ideal turbine*.

The normal method of expressing this extracted power is in terms of the undisturbed wind speed u1 and the turbine area A2. This method yields

$$P_{m,\text{ideal}} = \frac{1}{2}\rho[\frac{8}{9}(\frac{2}{3}A_2)u_1^3] = \frac{1}{2}\rho(\frac{16}{27}A_2u_1^3) \qquad \text{W}$$

- The factor 16/27 = 0.593 is called the *Betz coefficient*. It shows that an actual turbine cannot extract more than 59.3 percent of the power in an undisturbed tube of air of the same area.
- In practice, the fraction of power extracted will always be less because of mechanical imperfections.
- A good fraction is 35-40 percent of the power in the wind under optimum conditions, although fractions as high as 50 percent have been claimed.

- A turbine which extracts 40 percent of the power in the wind is extracting about two-thirds of the amount that would be extracted by an ideal turbine.
- This is rather good, considering the aerodynamic problems of constantly changing wind speed and direction as well as the frictional loss due to blade surface roughness.

- The ideal frictionless efficiency of propeller wind mill was given by A. Betz in 1920

- The propeller is represented by an actuator disk

- Which creates across the propeller vane a pressure discontinuity of area A and local velocity V

- The wind is represented by stream tube of velocity V1

- And a lower down stream velocity V2

- The pressure rises to Pb before the disc and drops to Pa Just after

The maximum possible efficiency of an ideal frictionless wind turbine is usually stated in terms of the power coefficient

$$C_p = \frac{P}{\frac{1}{2}\rho A V_1^3}$$

The fraction of power extracted from the power in the wind by a practical wind turbine is usually given the symbol Cp, standing for the coefficient of performance.

Total power coefficient is

$$C_{p,\max} = \frac{16}{27} = 0.593$$

This is called the Betz number and serves as an ideal with which to compare the actual performance of real wind mill

Wind speed variation with height

Many a times the wind speed data are not available and some estimate must be made from wind speeds measured at about 10m.

This requires an equation that predicts the wind speeds measured at one height in terms of the measured speed at the lower height

$$u(z) = \frac{U_f}{K}\left[\ln\frac{z}{z_o} - \xi\left(\frac{z}{L}\right)\right]$$

Uf= friction velocity
K= Von Karmans constant(0.4)
Zo= surface roughness length
L= is a scale factor called the Monin Obukov length

$\xi\left(\frac{z}{L}\right)$ Is determined by net solar radiation at the site

The surface roughness length Zo will depend on both the size and the spacing of roughness elements such as grass, crops or buidings.
Zo=0.01cm for water or snow surfaces
= 1cm for short grass,25 cm for tall grass or crops,1-4m for forest and city

Power law:

$$\frac{u(z_1)}{u(z_2)} = \left(\frac{z_2}{z_1}\right)^{\alpha}$$

$$\alpha = a - b \log u(z_1)$$

Z1 is taken at the height of measurement at 10 m
Z2 height at which wind speed estimate is required
The average value of α has been determined by many measurements as (1/7)

The values of a and b are o.11 and 0.061 in the day time and 0.38 and 0.209 at night

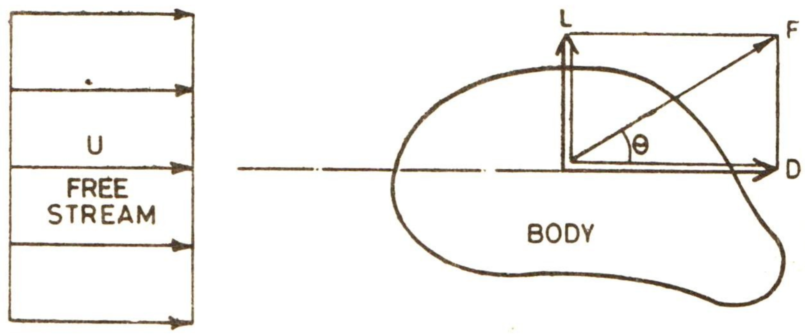
Lift and Drag

- Consider a body placed in the free stream of a real fluid
- The fluid exerts a force F on the body
- Let the force acts at an angle θ with the free stream
- The component of the force acting in the direction of the free stream is called Drag force

D=F cos θ

- The component of the force in a direction at right angles to the direction of the free stream is called lift fore

L=Fsin θ



Lift and drag on a body placed in a free stream

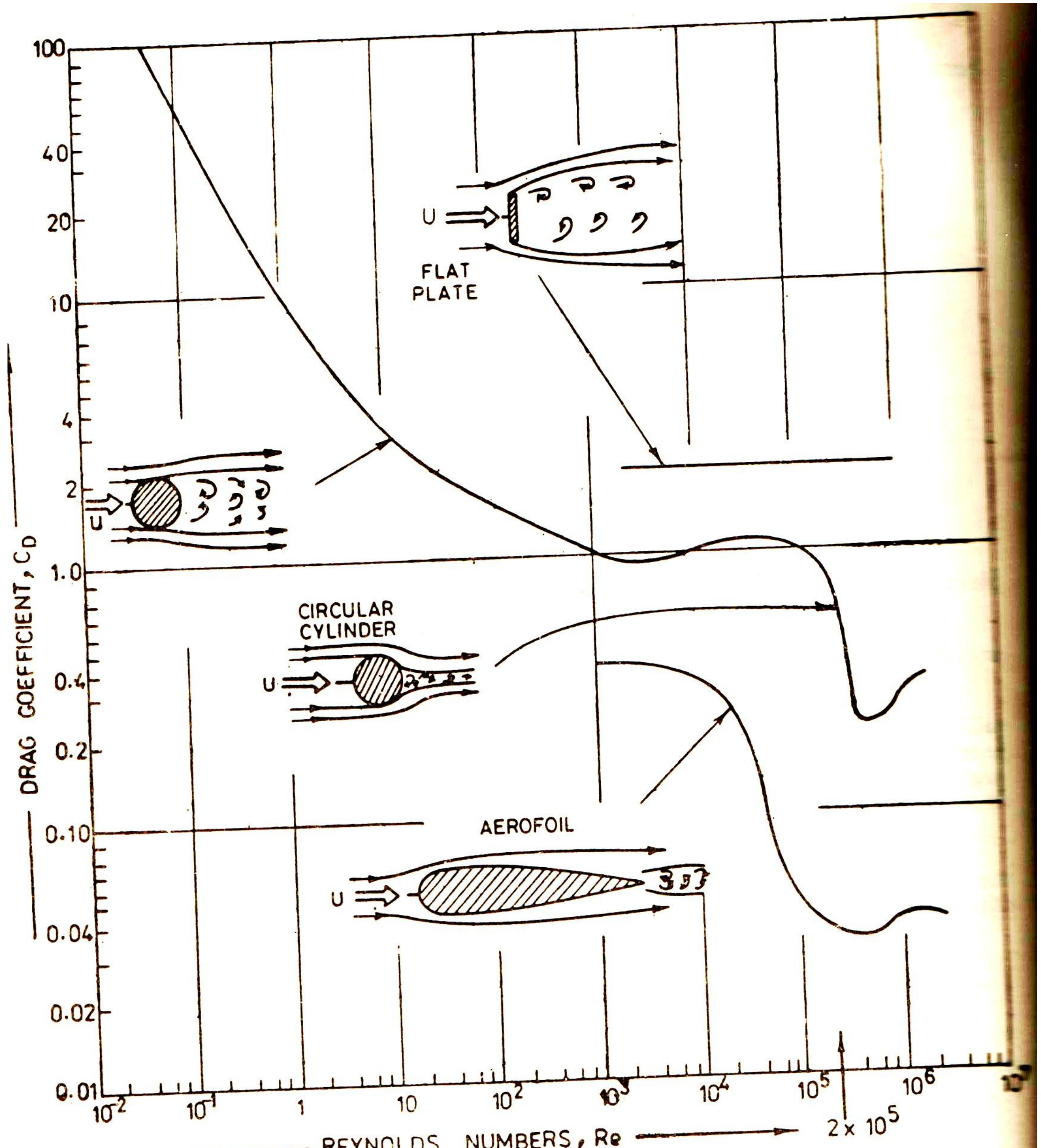
- The drag and lift forces are expressed in terms of coefficient of drag and lift

- The coefficients are defined as the ratios of corresponding forces to the dynamic force on the projected area
- The coefficient of drag and lift ,C_D and C_L is given by

$$C_D = \frac{D}{\frac{1}{2}\rho U^2 A}$$

$$C_L = \frac{L}{\frac{1}{2}\rho U^2 A}$$

$$\frac{C_L}{C_D} = \frac{L}{D}$$

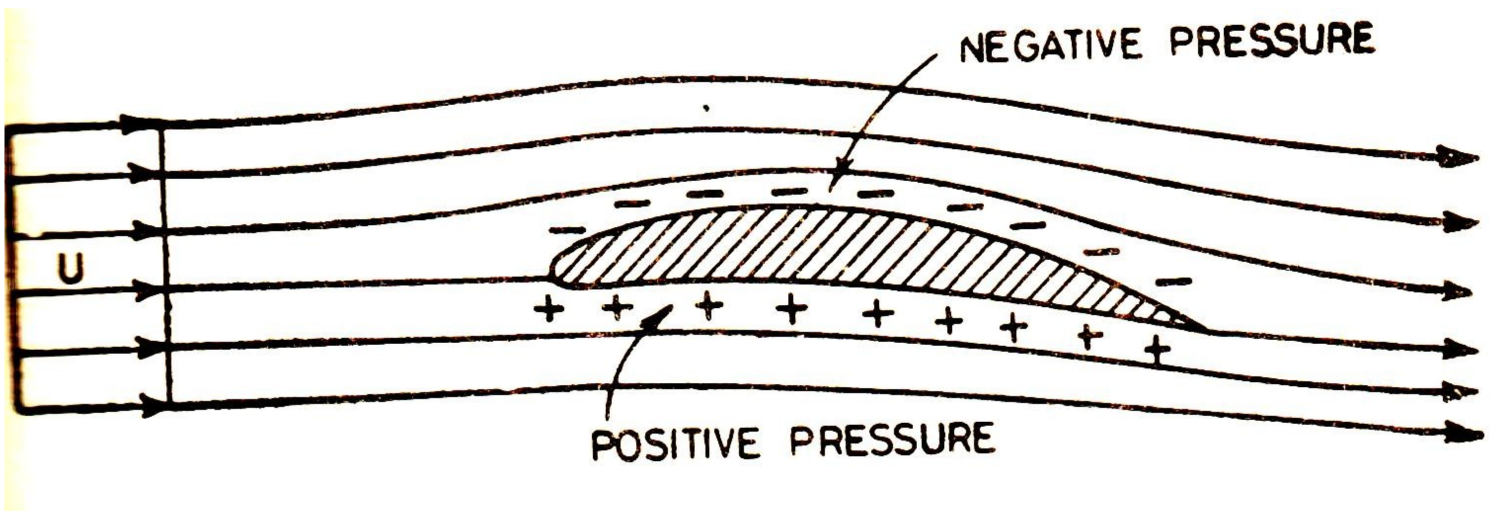


DIMENSIONAL BODIES

Streamlined body:

- A body is said to be stream lined if when placed in a flow , the surfaces of the body tend to coincide with the stream surface
- The stream lines therefore conform with the boundaries of the body
- The boundary layer may commence at the leading edge but the layer grows from laminar to turbulent and does not separate until the trailing edge on a streamlined body
- Consequently there is none or little eddying zone and wake formation behind the stream line body
- A body may be stream line at one velocity and at some particular angle of attack

- A streamlined body experiences drag mainly due to skin- friction drag at its surface
- Stream lined bodies are employed to provide high lift and low drag



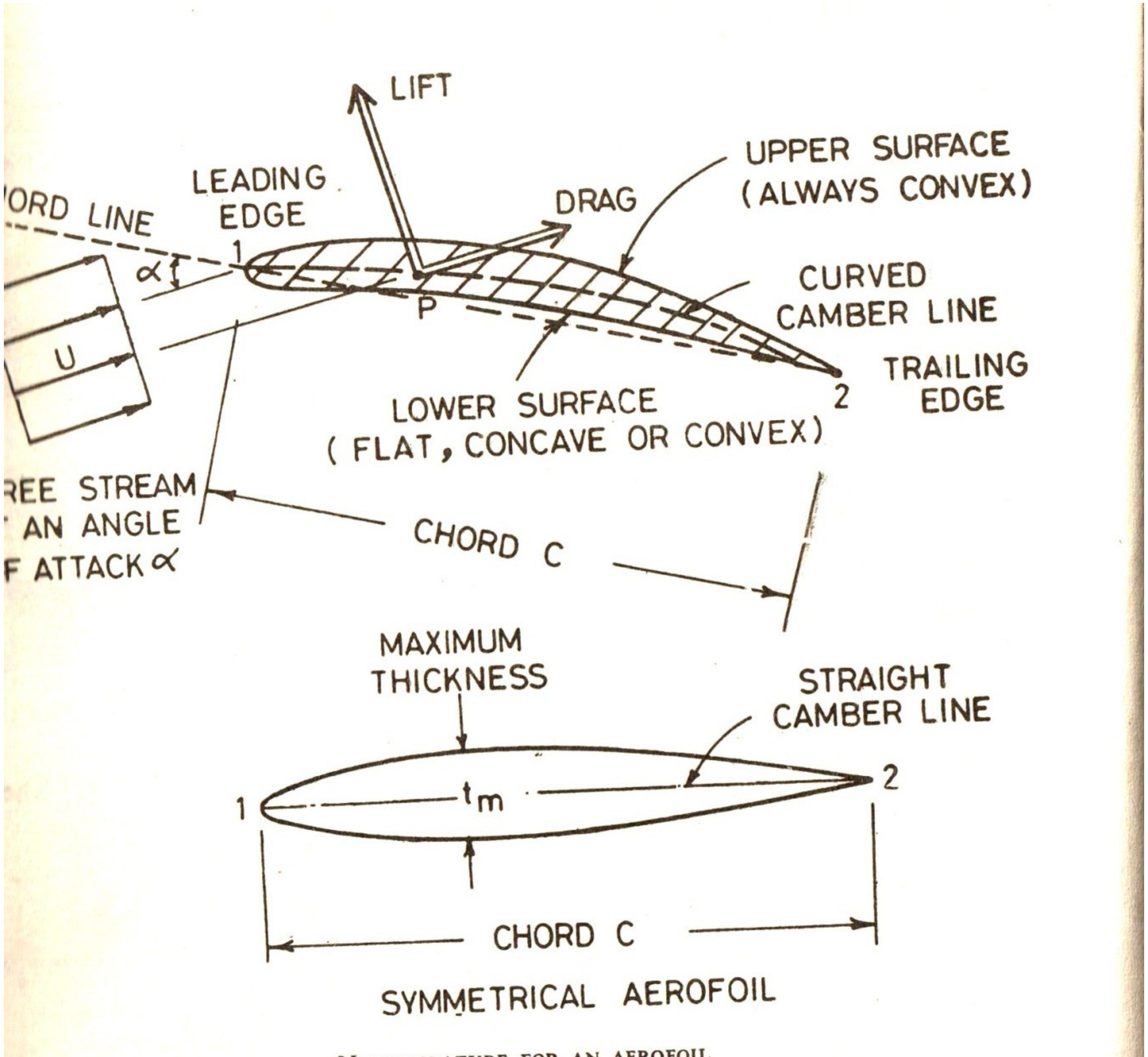
FLOW AROUND AN AEROFOIL

- An aero foil is a stream lined body designed to produce a streamlined flow pattern when placed in a free stream

- Aero foils may be symmetrical or unsymmetrical about the chord line
- The camber line is straight and coincides with the chord line for a symmetrical aero foil
- Where as it is curved for an unsymmetrical aero foil

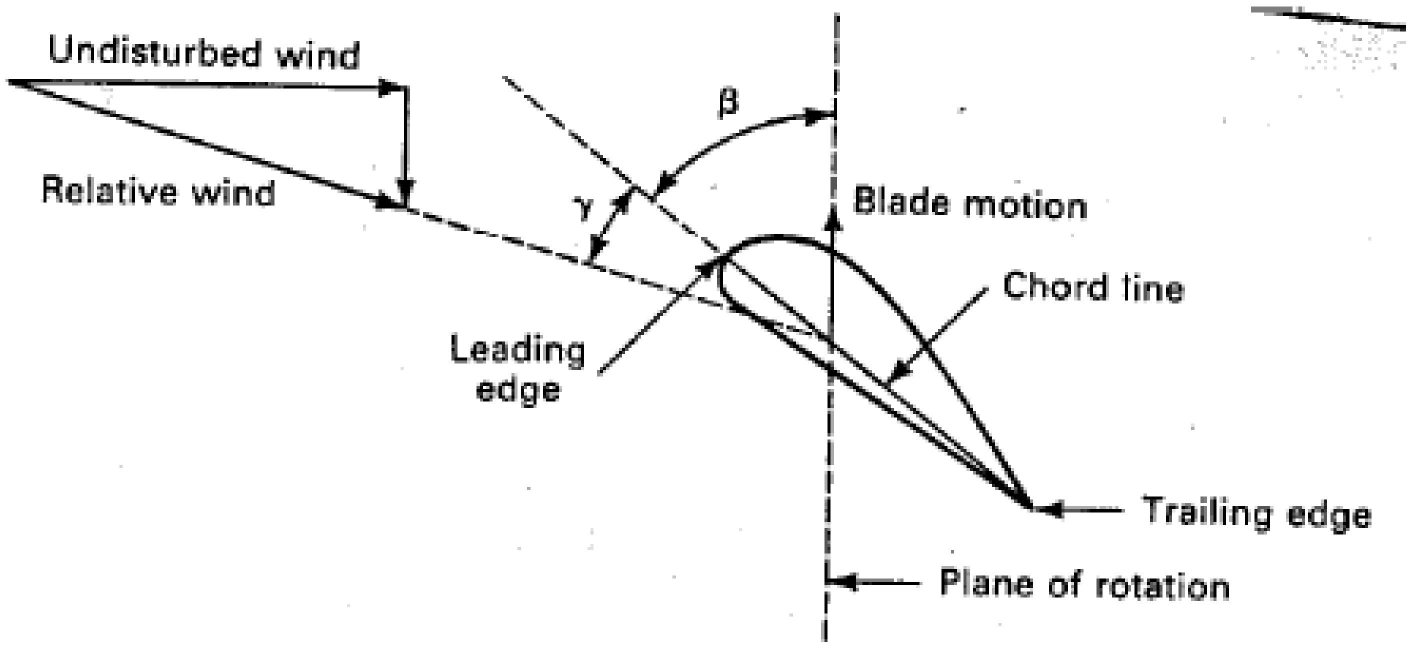
- The flow around an aero foil placed in the free stream of a fluid varies with the angle of attack, The angle between free stream and chord
- The pressure distribution accordingly changes
- At a certain angle of attack i.e zero for symmetrical aero foil the pressure distribution is such that the lift is zero
- The angle of attack at which the lift is maximum is called the critical angle denoted by αc

Nomenclature of an aero foil



NOMENCLATURE FOR AN AEROFOIL

- These forces and the overall performance of a wind turbine depend on the construction and orientation of the blades.
- One important parameter of a blade is the *pitch angle*, which is the angle between the chord line of the blade and the plane of rotation
- The *chord line* is the straight line connecting the leading and trailing edges of an airfoil. The *plane of rotation* is the plane in which the blade tips lie as they rotate.
- The pitch angle is a static angle, depending only on the orientation of the blade.



Pitch angle and angle of attack

Angle of attack, which is the angle between the chord line of the blade and the relative wind or the effective direction of air flow.

Different wind turbine aerofoil models

NACA(**National Advisory Committee for Aeronautics)** Wing Sections

- The aim of this report is to provide a catalogue of results for a wide range of wind turbine airfoils.
- These results are obtained from numerical simulations with the 2D incompressible Navier-Stokes solver EllipSys2D for a detailed description of the numerical code).
- They are compared with experimental data, when these are available.
- The results are also compared with the XFOIL code, which is based on a panel method combined with a viscous boundary layer formulation

- Three sub-families of NACA wing sections are investigated: NACA 63, NACA 64 and NACA 65.

- They differ from each other by the chord wise position of minimum pressure.

- Among the numerous possibilities in the different families, only the following airfoils are considered:

- NACA 63-215, NACA 63-218, NACA 63-221
- NACA 63-415, NACA 63-418, NACA 63-421
- NACA 64-415, NACA 64-421
- NACA 65-415, NACA 65-421

Method

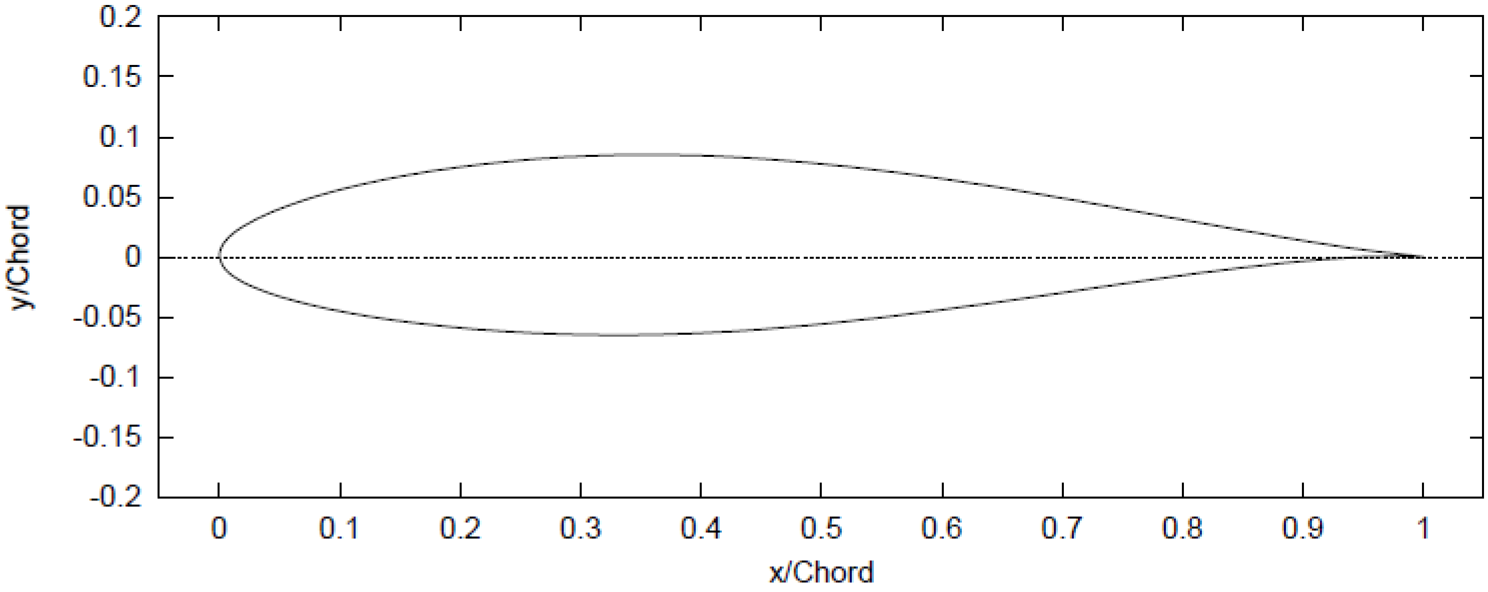
C-meshes were used for all the computations with 384 cells in the direction along the airfoil, 256 of them being on the airfoil, and 64 cells in the direction away from the airfoil.

The non-dimensional height of the cell at the airfoil was $1*10^{-5}$. Further re nements of the grid didn't signicantly improve the results.

The mesh used for the NACA 63-215 airfoil, and details of regions of interest. As it can be seen, the mesh lines were extended in the wake of the trailing edge in order to stabilize the computations.

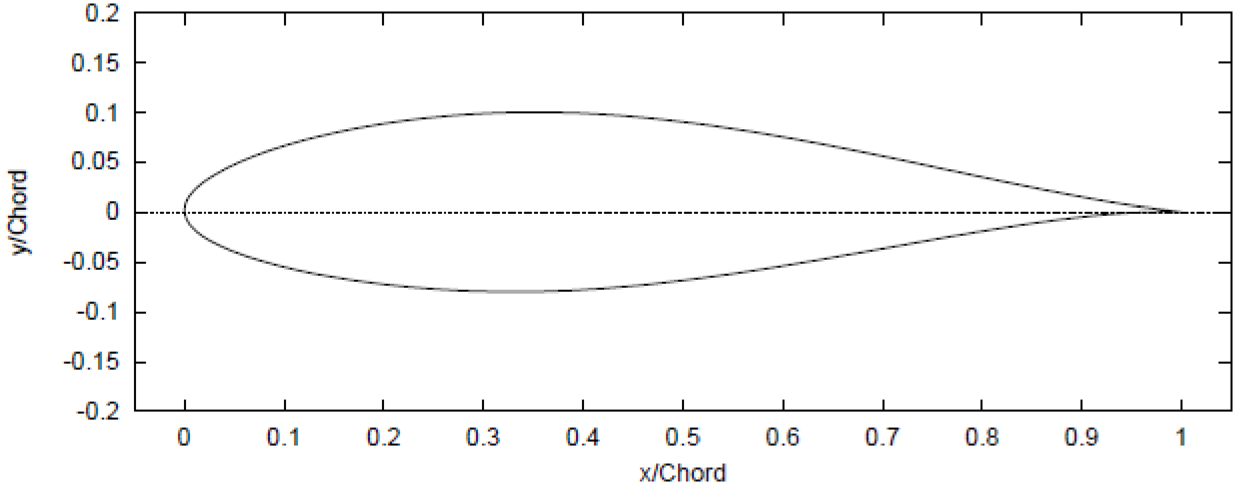
Results are presented as lift, drag and pitching moment coefficient as function of angle of attack, and also pressure and skin friction distributions at various angles are shown.

NACA 63-215



0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
y/Chord
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x/Chord

NACA 63-218



NACA 63-218 Airfoil