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ME4020 Turbomachinery

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Lecture 1

Syllabus, Text book & evaluation criteria

Introductory videos explaining constructional architecture and working principle.

Course Plan

This course is intended to give a detailed introduction to various axial and radial flow turbomachines.

Both thermodynamics and fluid mechanics of the turbomachines will be covered in this course.

Basic Principles; Dimensional Analysis; Axial flow turbines; Axial flow compressors and ducted fans; Centrifugal pumps. Fans, compressors; Radial flow gas turbines; Hydraulic turbines

- *We would stick with Grant Ingram's book*
- *If time permits we would see 2D Cascade From S L Dixon's book.*

Reference Book

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Text Book to refer

Basic Concept in Turbomachinery

- by Grant Ingram

Evaluation

Attendance	10%
Homework Assignments	20% **(Evaluated for completeness & plagiarism)**
MidSem	35% **(Avoid Plagiarism)**
Final Exam	35%

Introduction

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Prerequisite

- *Basic knowledge of fluid mechanics and thermodynamics is essential.*

What is a turbomachine?

- *A device that exchanges energy with a fluid using continuously flowing fluid and rotating blades.*
  - E.g. aircraft engine, wind turbines etc.
- *If a device extract energy from working fluid it is called as turbine*
- *If the device delivers energy to fluid, it is called as compressor, fan, blower, and pump.*

Turbomachinery is generalized name for all these machines.

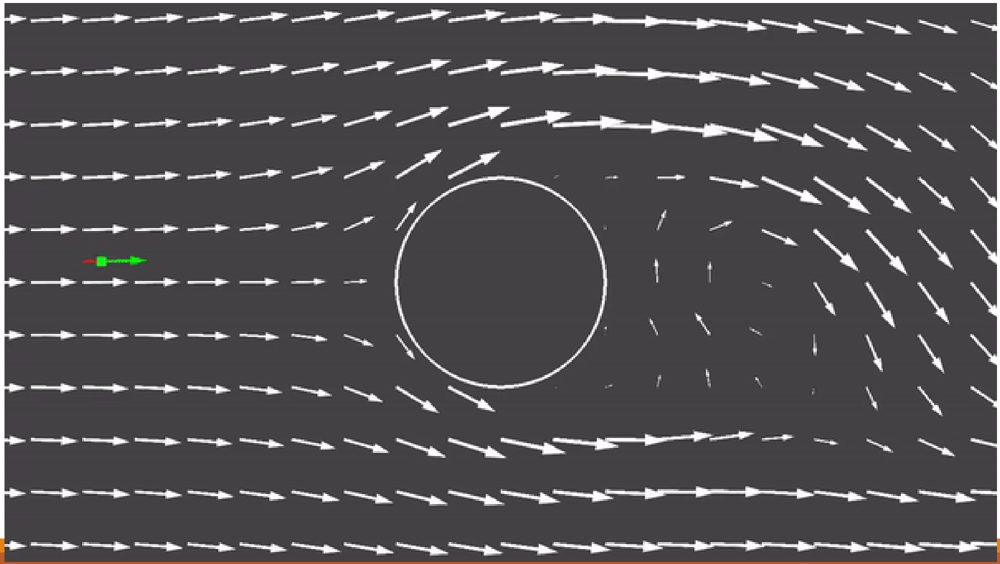
Flow Visualization: A tool to Characterize Flow Field

Lagrangian description of flow field

- *In this approach fluid motion is described by tracing each and every individual particle*
- *Position of particle at any instant of time become function of its identity and time*

Eulerian description of flow field

- *In this approach we fix attention on fixed region or control volume and study what happens in that CV.*



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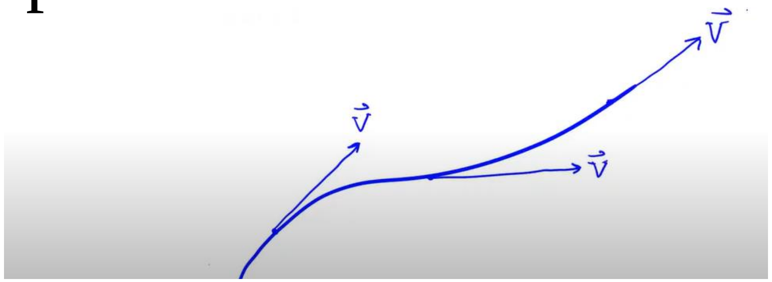
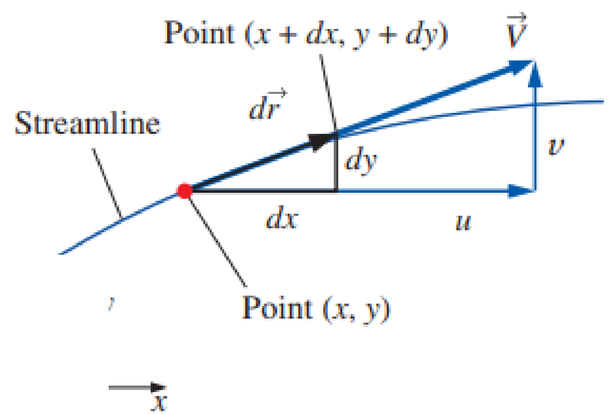
Streamlines

Streamlines are imaginary lines in flow fields such that tangent to those lines at a given point at a given instant represents the direction of velocity vector.





Streamline in the xy-plane: $$\left(\frac{dy}{dx}\right)_{\text{along a streamline}} = \frac{v}{u}$$

Equation for a streamline: $$\frac{dr}{V} = \frac{dx}{u} = \frac{dy}{v} = \frac{dz}{w}$$

$\vec{V}$ is instantaneous velocity vector

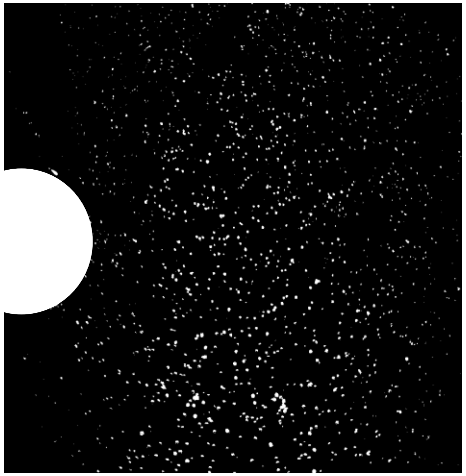
$d\vec{r}$ is infinitesimal line segment along streamline

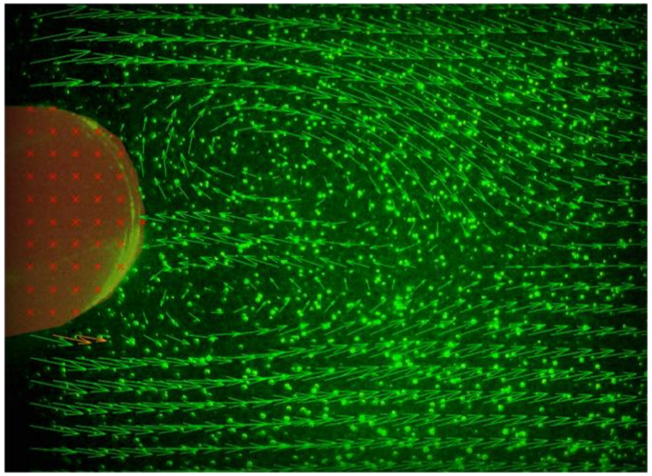
Experiments

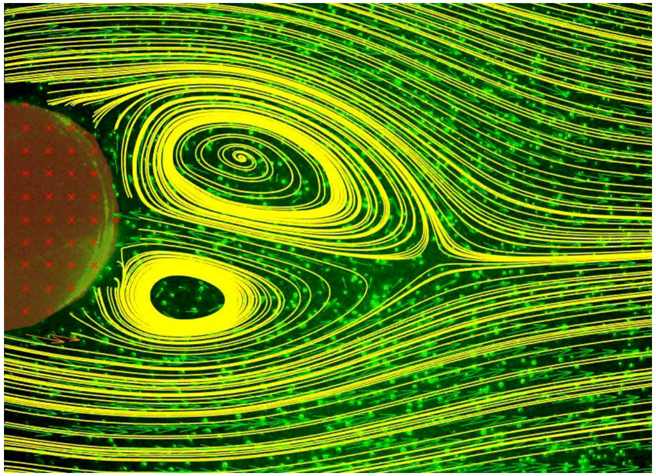
Flow

Velocity in unsteady flow (postprocessing)

Streamlines in unsteady flow (postprocessing)





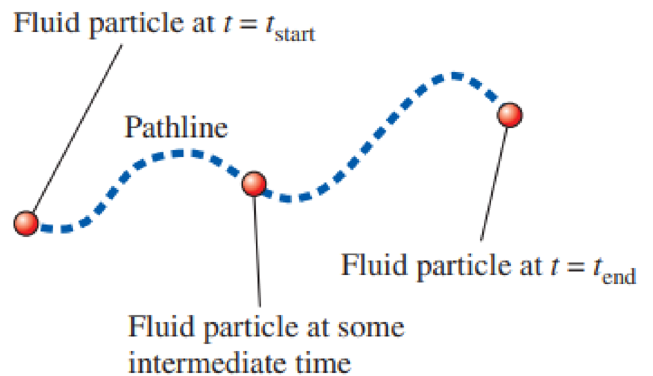


Pathlines

A pathline is the actual path traveled by an individual fluid particle over some time period. It represent the history of particle motion over that time period.

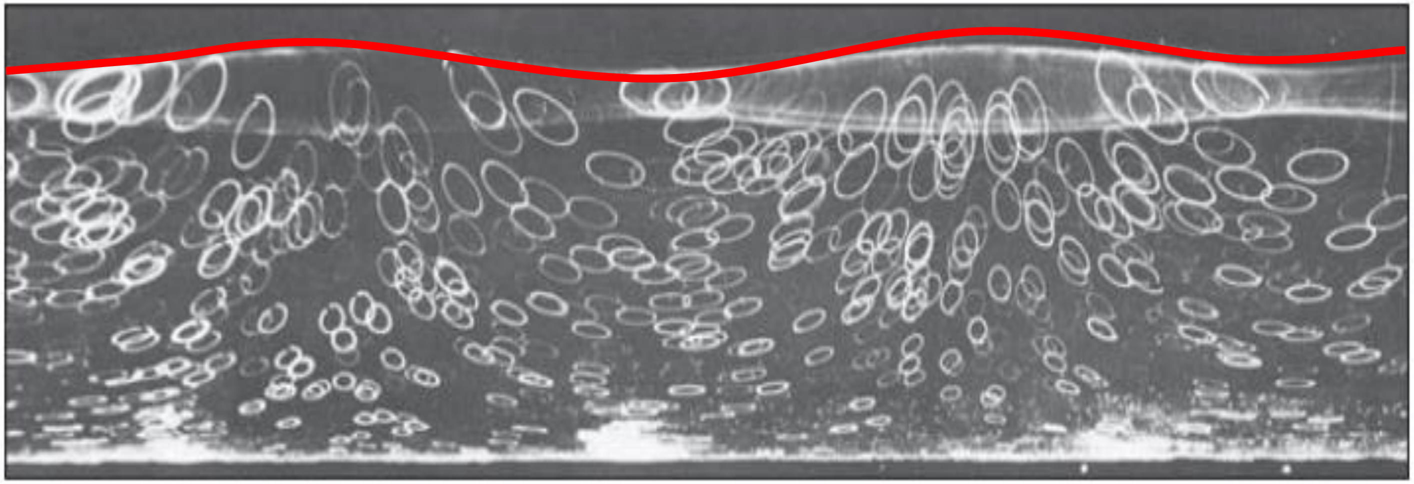
Open the shutter of camera for longer time (time exposure photography)

Pathlines can also be calculated numerically for a known velocity field.



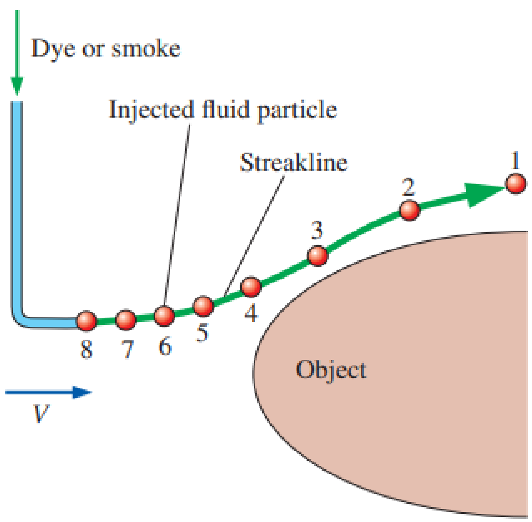
Experiments

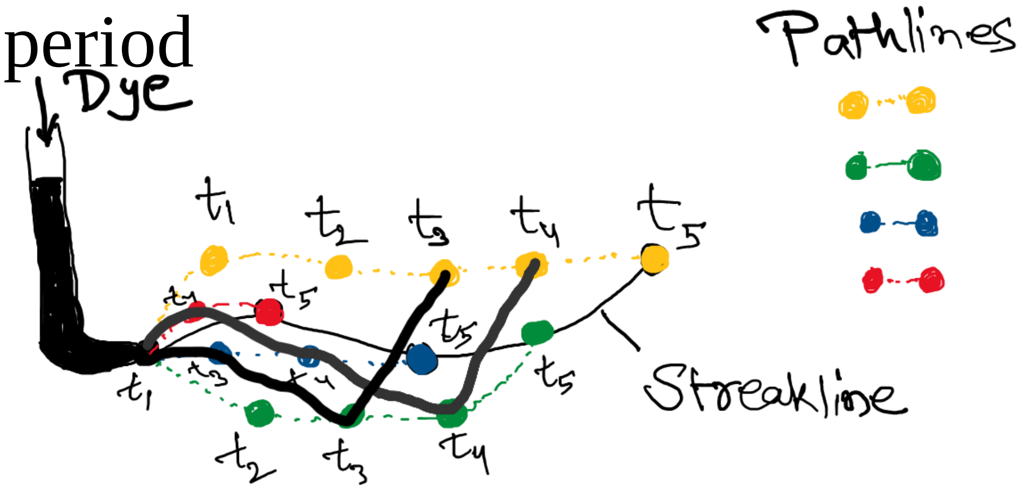
Pathlines produced by white tracer particles suspended in water and captured by time-exposure photography; as waves pass horizontally, each particle moves in an elliptical path during one wave period



Streakline

- Streakline is the curve produced by fluid particles that have pased through a prescribed point
- It is defined over some time period so It represents the history of flow over that period





Labeled tracer particles (1 through 8) were introduced sequentially

Streaklines

In experiments streakines are obtained by isokinetic (same velocity as flow) injection of Smoke into gas or dye into fluid

In steady flow streak line is same as stream line and pathline so it is very helpful for validation of CFD results of steady flows.

Wind tunnel experiment of air flow over the spinning ball (630 rpm)

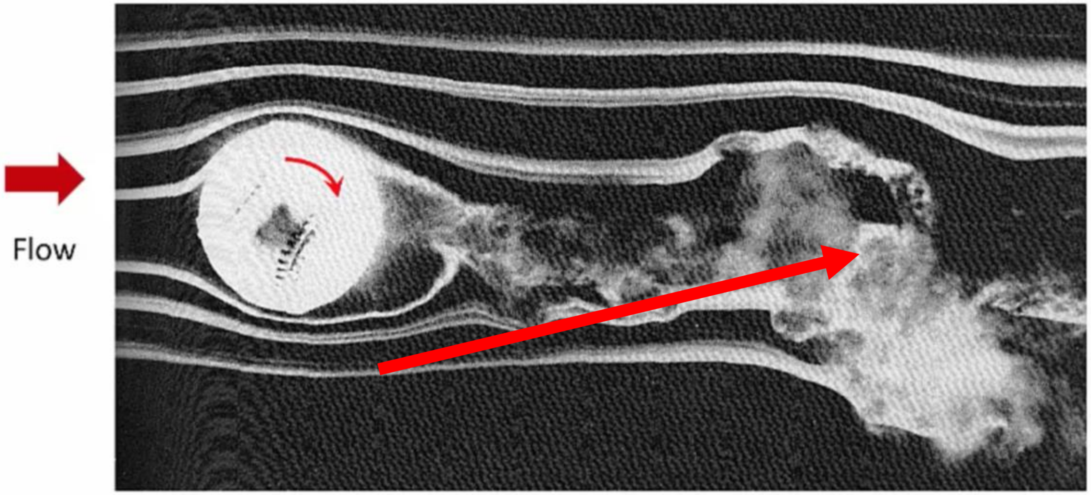


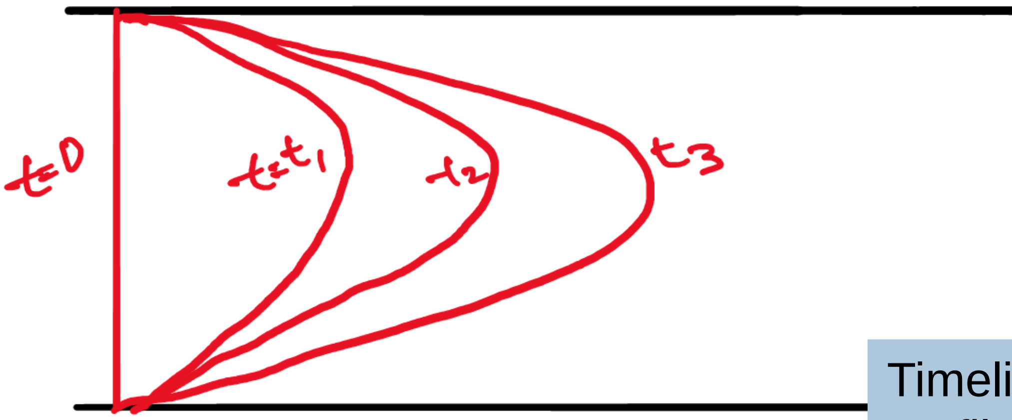
Photo Credit: Album of Fluid Motion (Van Dyke 1988)

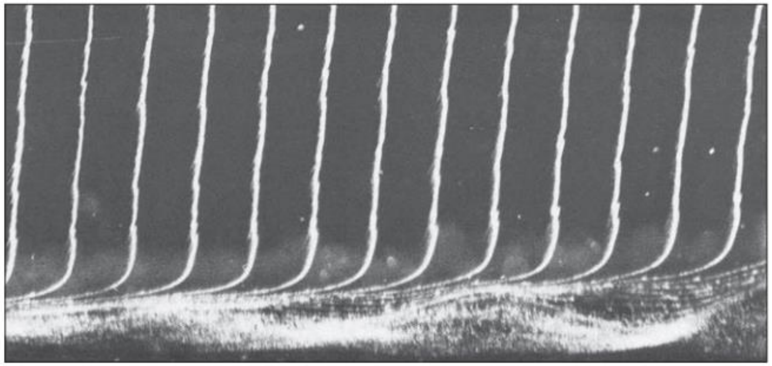
Smoke is moving downward

Timelines

A timeline is a set of adjacent fluid particles that were marked at the same (earlier) instant in time

Timelines are formed by marking a line of fluid particles, and then watching that line move (and deform) through the flow field





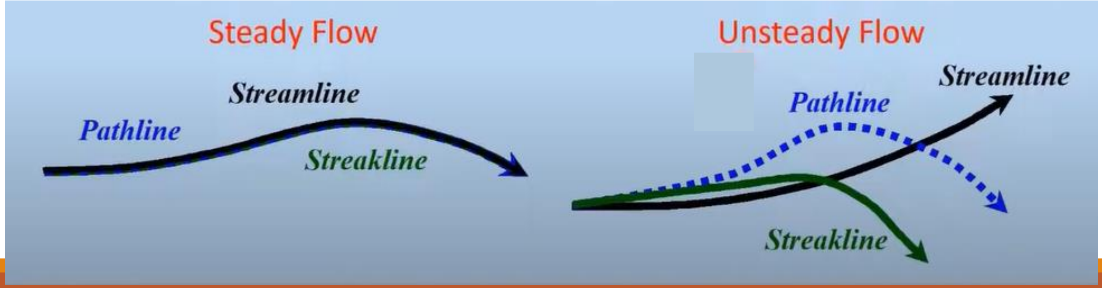
Timelines produced to visualize the velocity profile shape along a flat plate.

Timelines never coincide with streamline, streakline or pathline even in steady flow

Streamlines represent the instantaneous flow field but streaklines and pathlines represent history of flow

Streamline, pathlines and streaklines overlap in steady flow

Streamlines, pathlines and streaklines differ in unsteady flow



Flow Visualization: A tool to Characterize Flow Field

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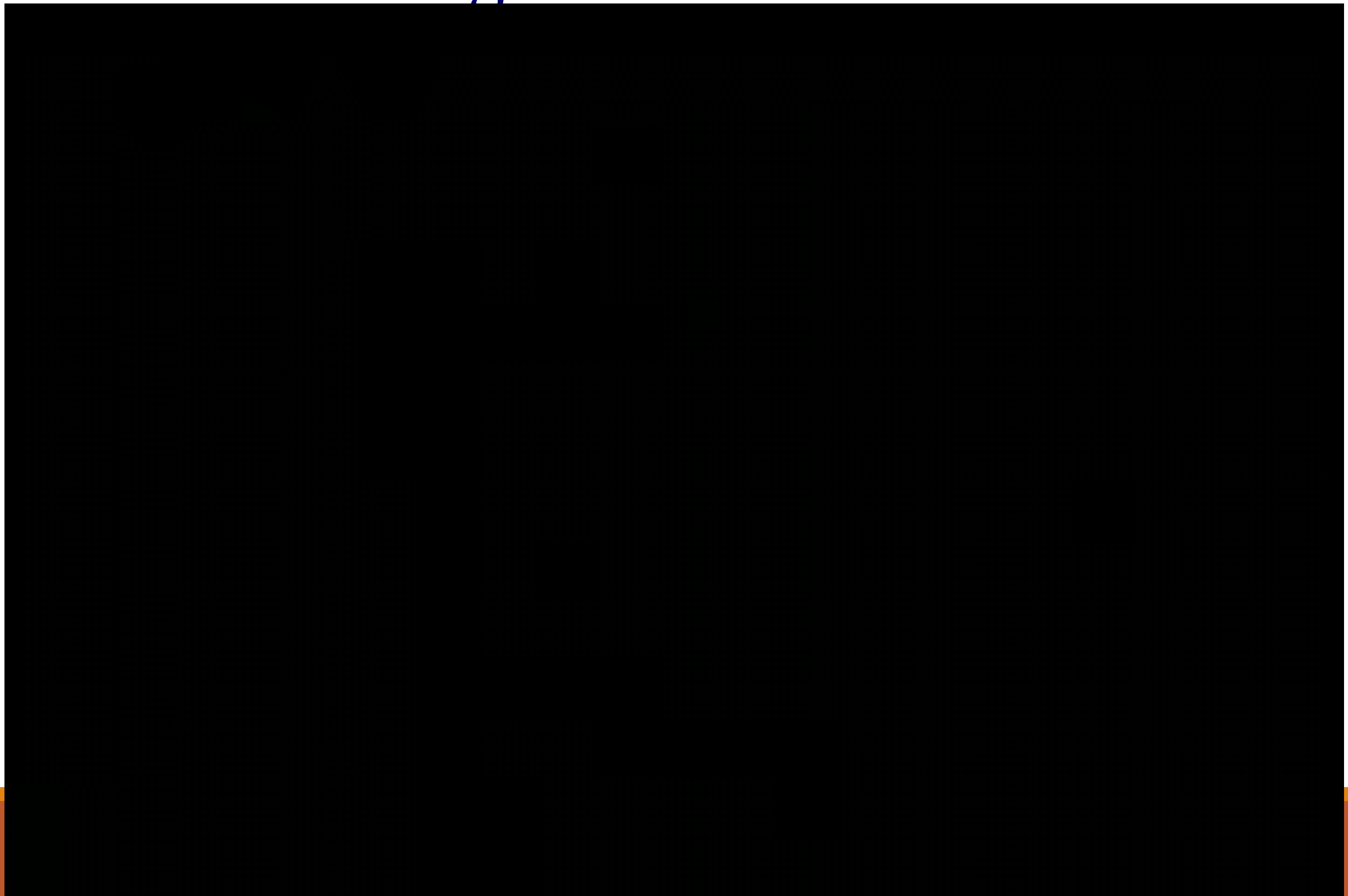
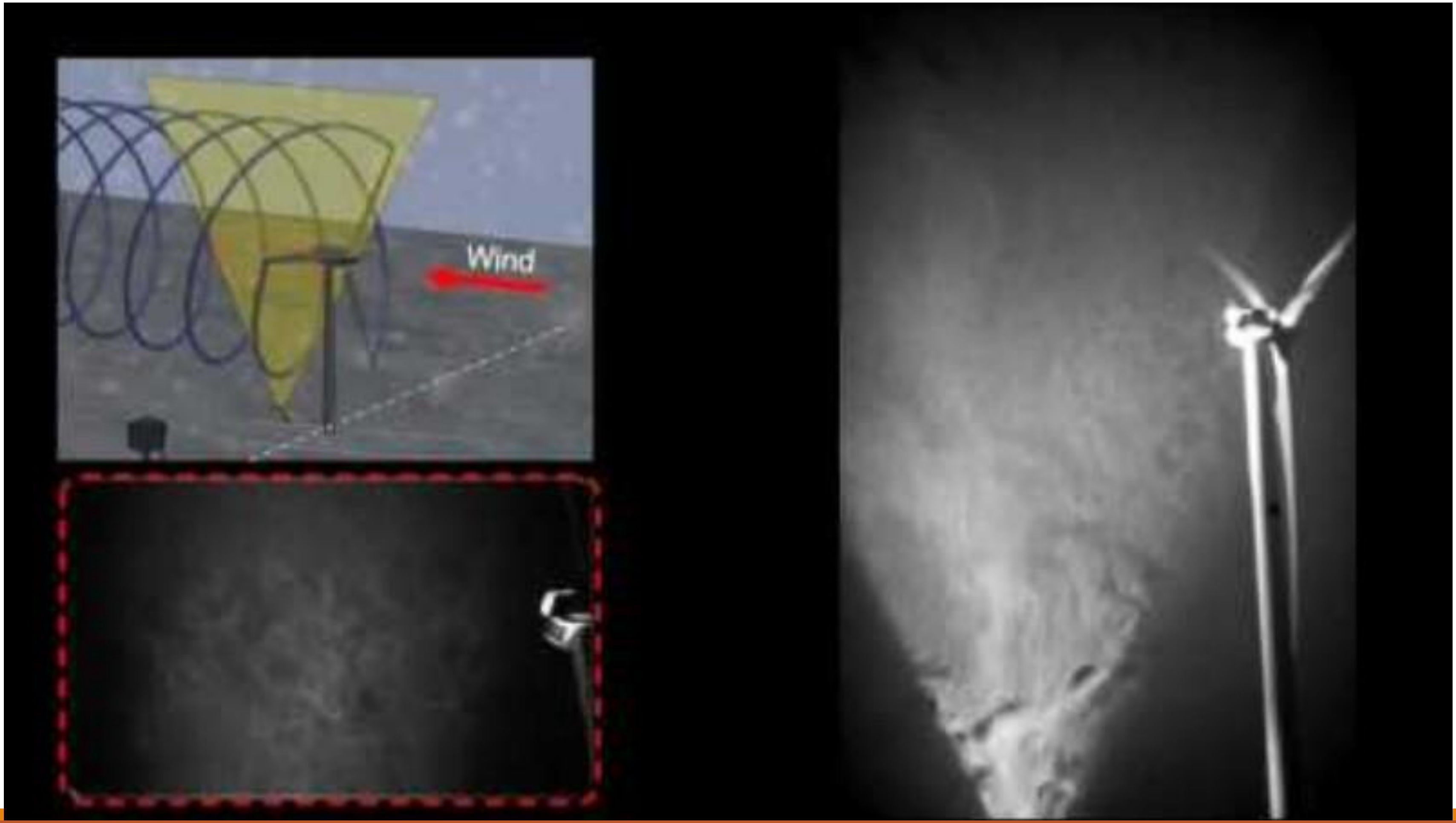
Very good video available on Youtube showing pathline, streaklines, streamlines using bubble visualization.

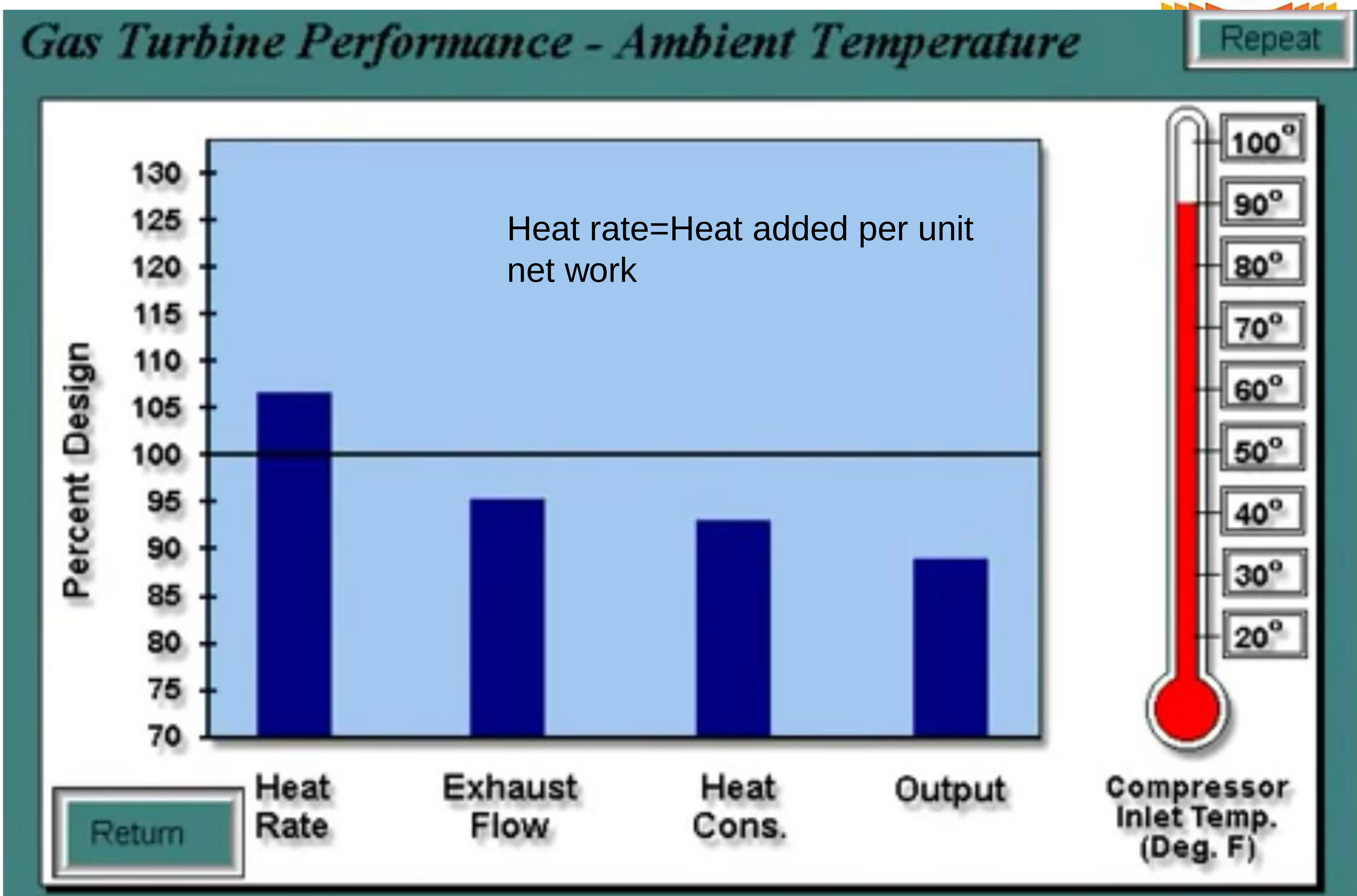
US national committee for fluid mechanics film (1963)
In real experiments visualization of these lines
Watch: **https://youtu.be/mh4hZbNMEfo**



Flow visualization in wind turbine




Theory of Operation - Gas Turbine Cycle
Repeat
Click on Right Arrow
Ref
Text
Prev Menu
Main Menu



Heat rate=Heat added per unit net work

3D Animation of Gas Turbine Engine

Axial Flow Compressor Constructional Architecture

Lecture 2

Introduction

Turbine Architecture & Working

Cascade View

Co-ordinate System & Meridional Velocity

Classification of Turbomachines

Introduction

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What is a machine?

- *A machine is a tool containing one or more parts that uses energy to perform an intended action.*
    - Machines are usually powered by mechanical, chemical, thermal, or electrical means, and are often motorized.

What is fluid machine?

- *A fluid machine is a device which converts the energy stored by a fluid into mechanical energy or vice versa .*
    - The energy stored by a fluid mass appears in the form of potential, kinetic and intermolecular energy.
    - The mechanical energy, on the other hand, is usually transmitted by a rotating shaft.

Introduction

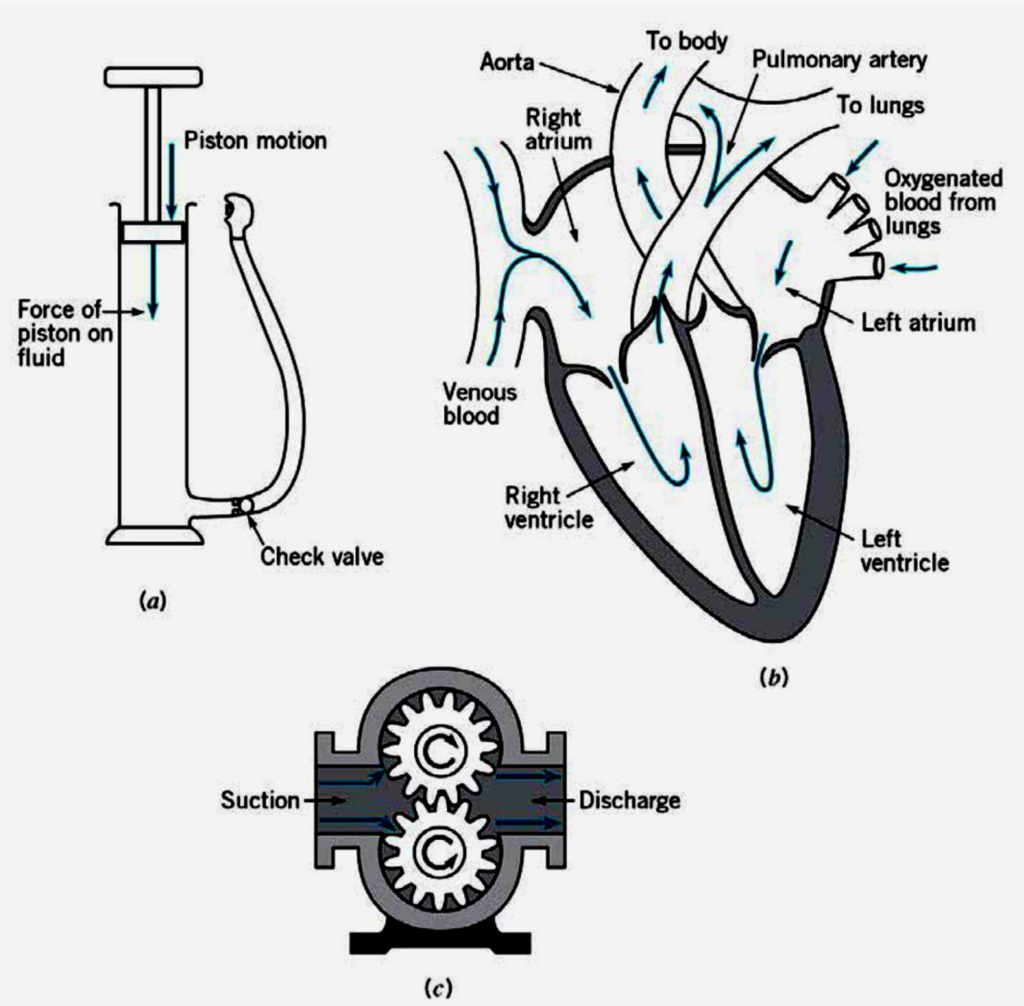
What is a turbomachine?

- *Machines that transfer energy between a rotor and a fluid, including both turbines and compressors. While a turbine transfers energy from a fluid to a rotor, a compressor transfers energy from a rotor to a fluid.*

What is distinguishing parameter for turbomachines from all general fluid machines involving fluid and energy interaction?

- *Energy interaction based on*
    - Static forces (positive displacement machines)
    - Dynamic forces (turbomachines)

Introduction



Positive Displacement Machines

- *Force fluid into or out of a chamber by changing the volume of the chamber*
- *The pressure developed and the work done are a <u>result of essentially static forces rather than dynamic effects</u>.*

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Turbomachines

- *Turbomachines involve a collection of blades, buckets, flow channels, or passages arranged around an axis of rotation to form a rotor.*
- *Turbomachines are mechanical devices that either extract energy from a fluid (turbine) or add energy to a fluid (pump) as a result of dynamic interactions between the device and the fluid.*
- *The fluid used can be either a gas or a liquid. (viz. steam or gas turbines and hydraulic turbines)*

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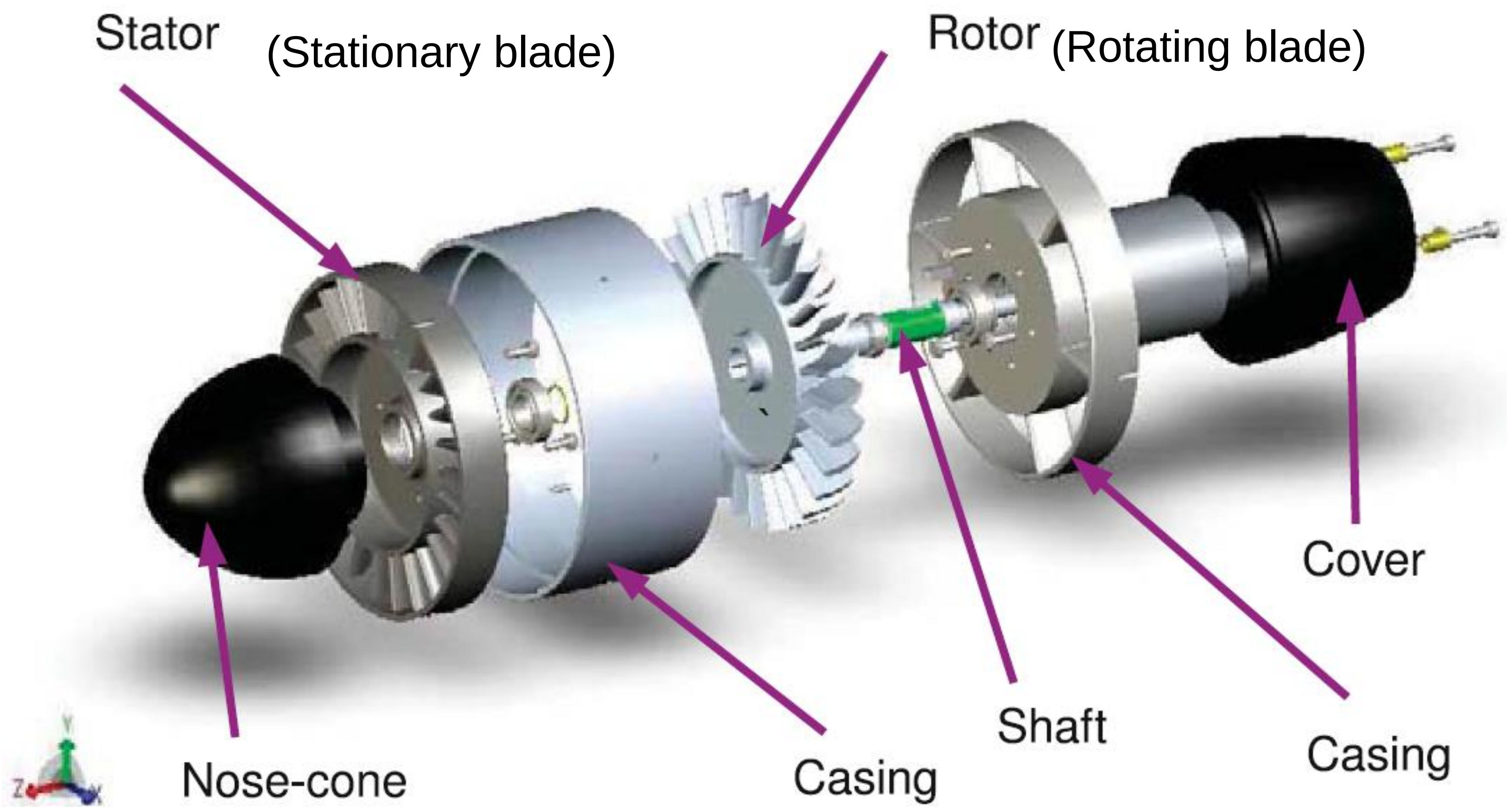
Why Study Turbomachinery?

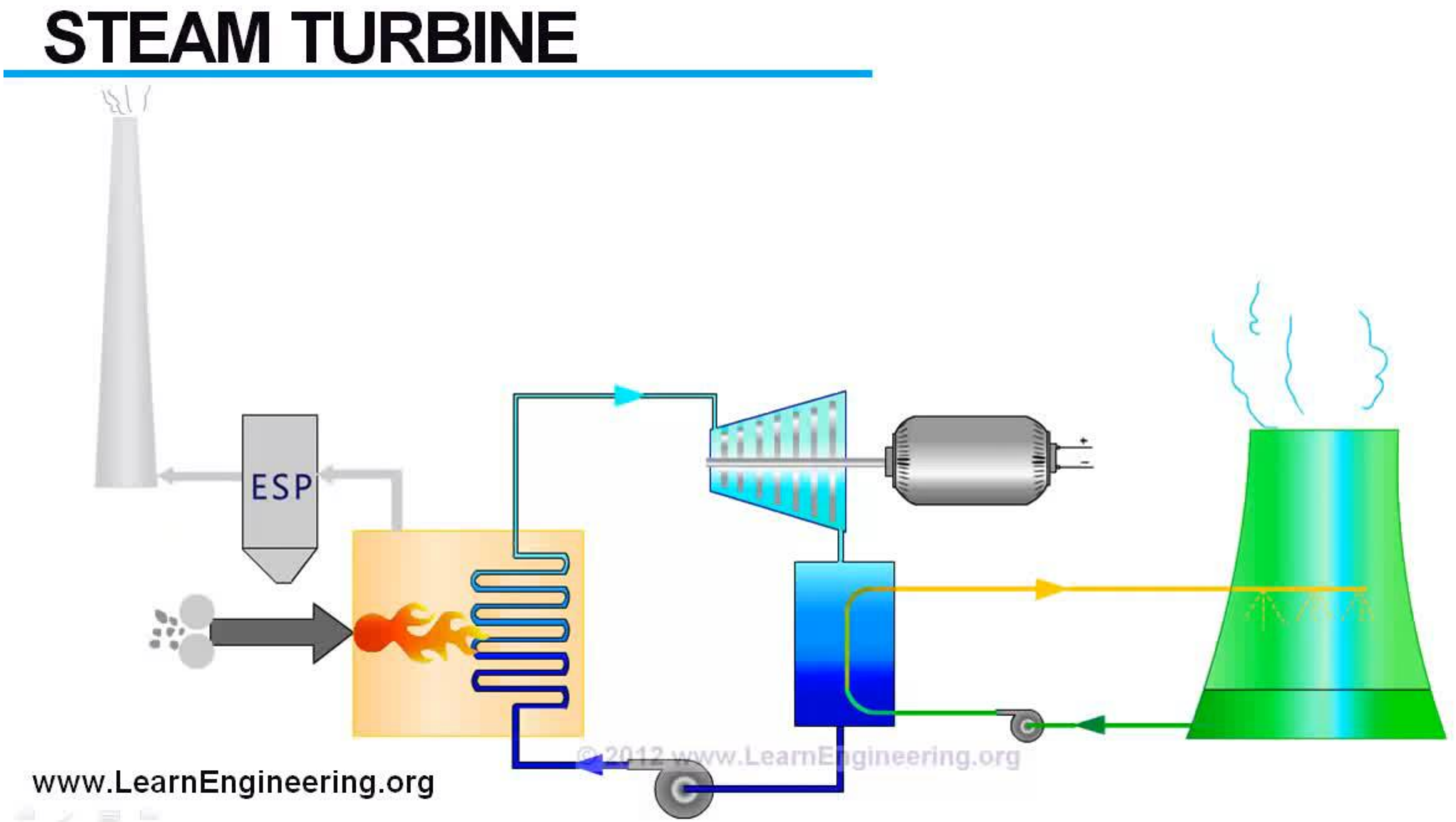
- *It is important to the operation of modern world.*
  - Turbines are used in all significant electricity production in the world. Viz. steam power plant, gas turbine power plant, wind turbine power plant, hydroelectric power plant.
- *Pumps are around to transport water, oil etc.*

In short turbomachinery is all around you and worthy of further study

Let's Look at Turbine Architecture



How a steam turbine works



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What to study?

- *There are only three difficult ideas to be understood based on broad overview of turbomachinery design development and performance rating.*
  - Concept of reaction.
  - Velocity triangles.
  - Cascade view.

Energy absorption/delivery by working fluid

- *Pressure and velocity changes (reaction concept)*
- *Velocity changes alone (impulse concept)*

Introduction

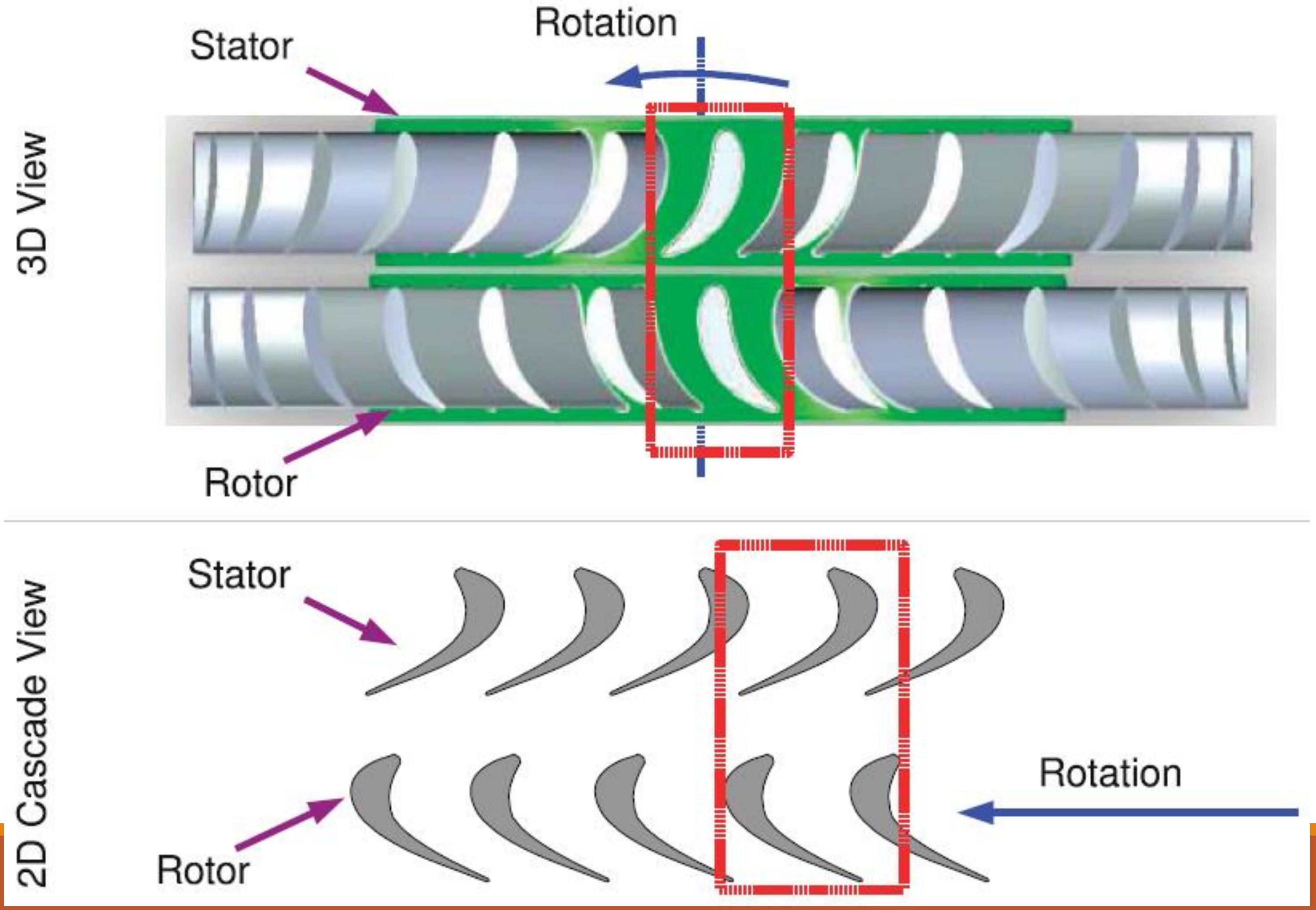
Velocity Triangles

- *Turbomachinery involves rotating device called as rotor/impeller/wheel/turbine*
- *Working fluid entry and exit to turbomachine and direction of fluid flow and rotation of wheel makes one to look into relative motion between the working fluid and rotor.*
- *Velocity triangle concept looks into relative motion change and energy transfer to/from working fluid.*

Cascading involves rotor and stator/guide vanes.

- *In order to reduce the energy transfer loss, smooth operation guide vanes are used to direct the flow onto rotor.*
- *Rotor and stator set can be stacked in sequence to create multiple stages for energy exchange to/from working fluid.*

Cascade View



Co-ordinate System (Cylindrical polar)

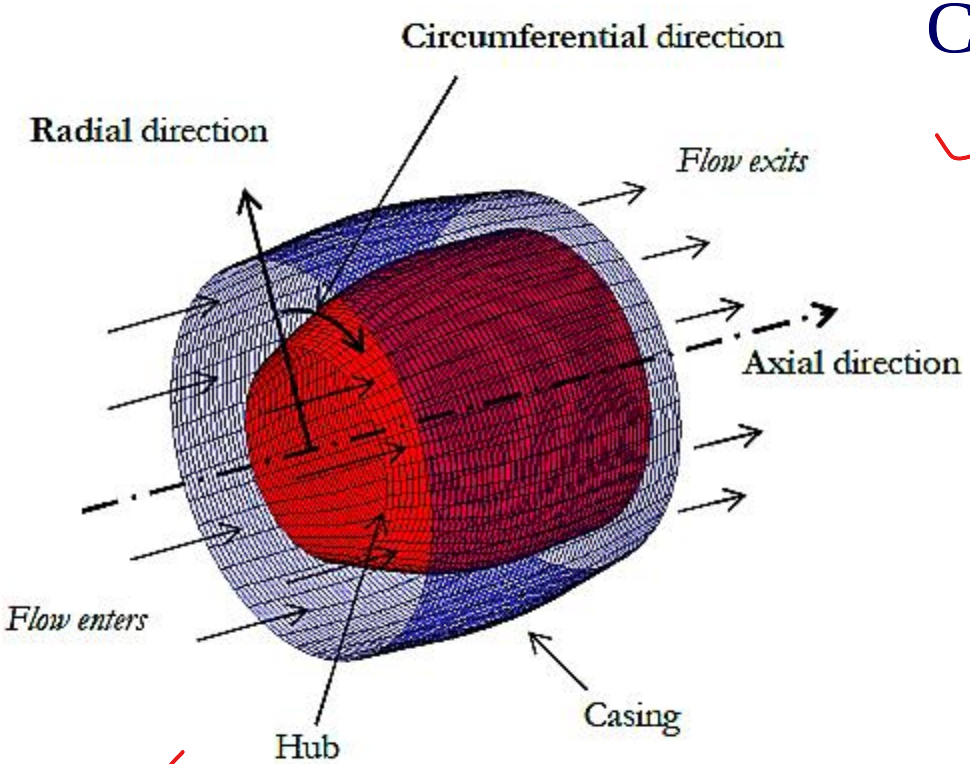


Figure Schematic turbomachine showing the turbomachinery coordinate system

Co-ordinate System

- *Structure of turbomachines shows that they tend to have some form of cylindrical shape.*
  - **Cylindrical polar co-ordinate system would be best for their description & analysis.**

Co-ordinate System

A turbomachine can be considered as a tube in which you have an inner and an outer wall.

- *These walls are usually referred to as hub and casing respectively.*
  - The hub and casing walls bound the flow channel and give it an annular shape.
  - The flow enters the turbomachine on one side and exits on the other side.
  - As the flow passes through the turbomachine, the cross section of the annular flow channel will most probably vary.

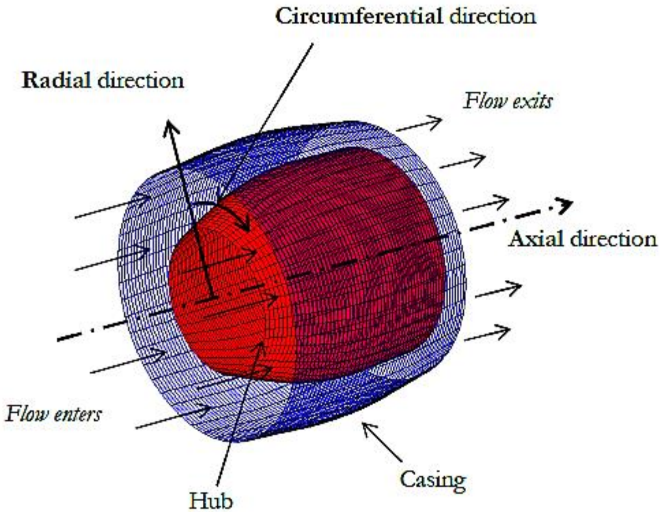


Figure Schematic turbomachine showing the turbomachinery coordinate system

Also, as you will learn in this course, the swirl of the flow is changed such as to add or extract energy from the fluid.

Co-ordinate System

Axial view shows the cross section of annular region formed between casing and hub.

- ***Radial and circumferential or tangential direction can be clearly identified in this view.***

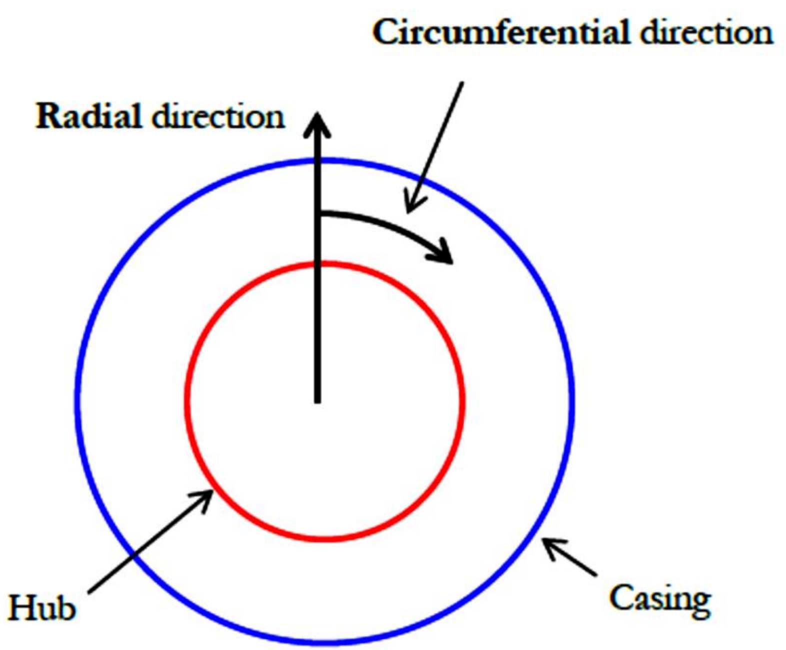
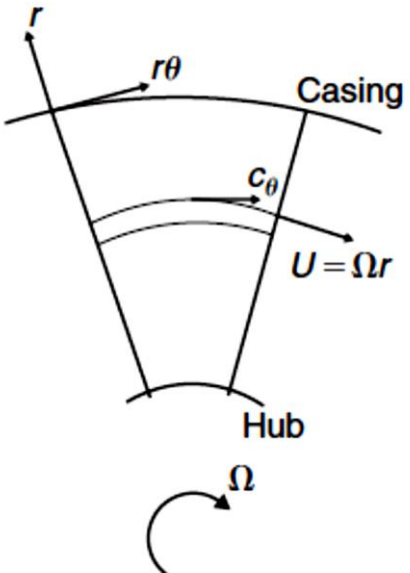
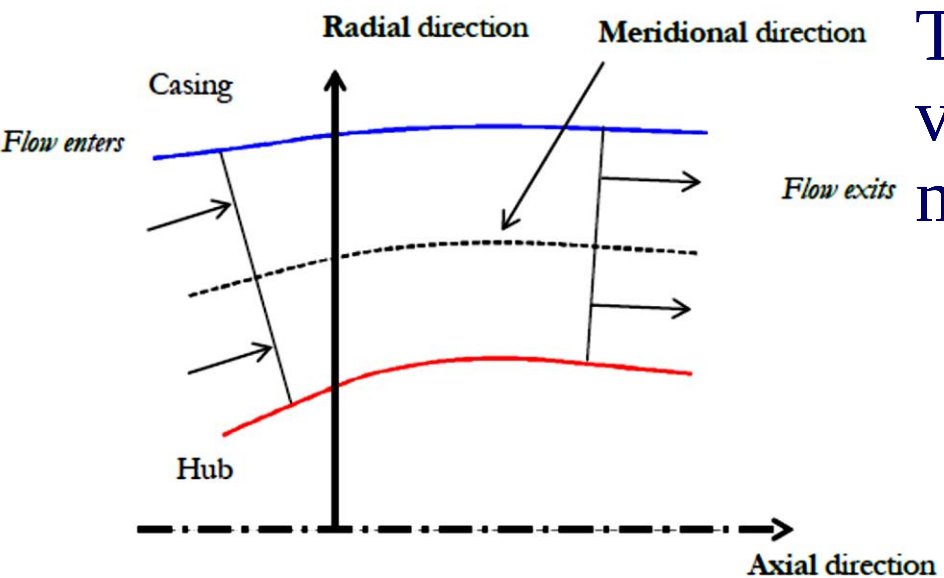


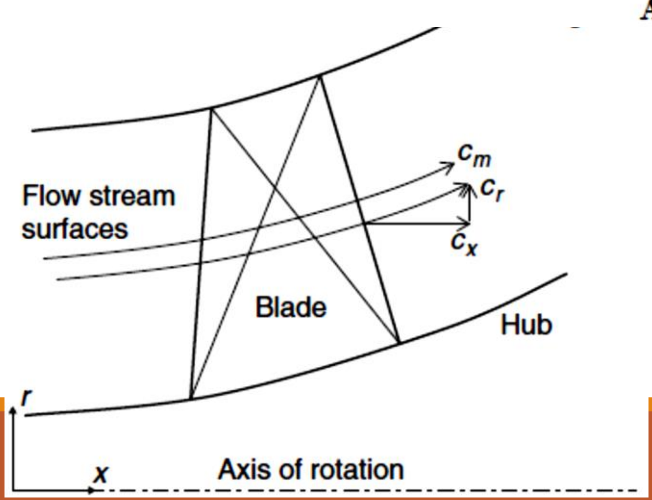
Figure 2. Axial view of a schematic turbomachine



There might be discrepancy in symbols as slides are prepared by referring multiple sources of material on turbomachines Viz. ω or Ω

Co-ordinate System





The side view is defined by viewing a cut through the machine in an axial-radial plane.

- *The cross-section that one would see is referred to as the meridional cross-section.*
- ***The direction of the mean radius** is referred to as the meridional direction.*
- *For constant mean radii, this is then the same as the axial direction.*

$$c_m = \sqrt{c_x^2 + c_r^2}.$$

In order to address the flow in detail inside a turbomachine, an unwrapped view of a stream surface is used.

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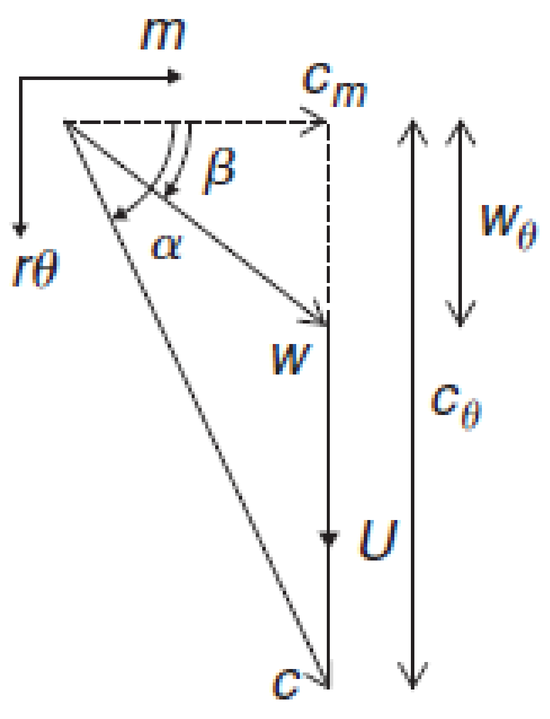
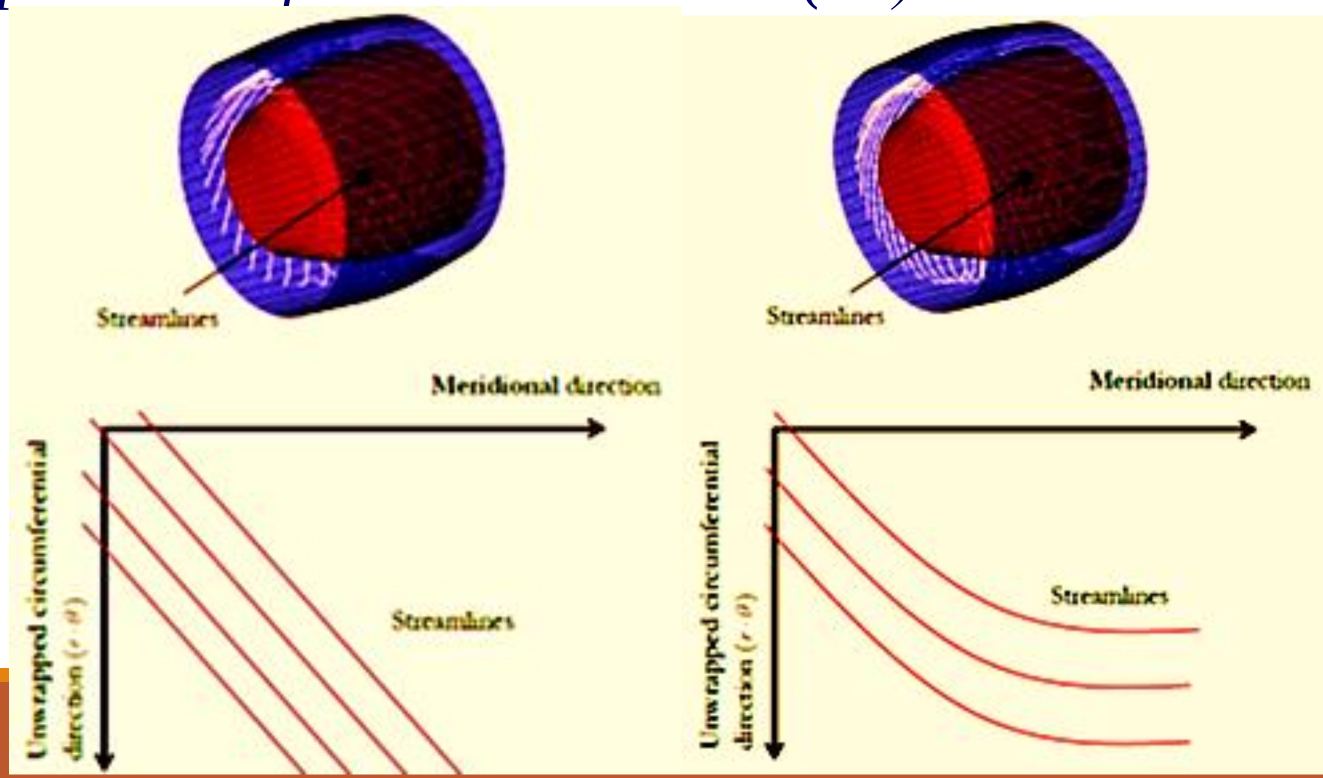
For a 1D analysis, this would be the stream surface on the reference radius.

- *This view is the defined by the meridional (or axial) direction and the unwrapped circumferential coordinate ($r \cdot \theta$)*





Understanding Meridional Velocity

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For mixed flow machines

- *Meridional flow velocity is along the stream surface.*

$$c_m = \sqrt{c_x^2 + c_r^2}.$$

For purely axial flow machines

- *Meridional velocity is axial velocity as radial velocity is zero.*

For purely radial flow machines

- *Meridional velocity is radial velocity as axial velocity is zero*

Understanding Meridional Velocity

The total flow velocity is made up of the meridional and tangential components and can be written as

$$c = \sqrt{c_x^2 + c_r^2 + c_\theta^2} = \sqrt{c_m^2 + c_\theta^2}.$$

The swirl, or tangential, angle is the angle between the flow direction and the meridional direction:

$$\alpha = \tan^{-1}(c_\theta / c_m)$$

Introduction

Structure of turbomachines

- *Many **turbomachines contain** some type of housing or **casing** that surrounds the rotating blades or rotor, thus forming an internal flow passageway through which the fluid flows.*
- *Some turbomachines include stationary blades or vanes in addition to rotor blades. These stationary vanes can be arranged to accelerate the flow and thus serve as an nozzles.*
- *These vanes can be set to diffuse the flow and act as diffusers.*

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Working Fluid (Liquid/Gas) Impact on turbomachines

- *Basic operating principles for turbomachines are the same whether the fluid is liquid or gas.*
- ***Cavitation** may be an important design consideration when liquids are involved if the pressure at any point within the flow is reduced to vapor pressure.*
- ***Compressibility** effects may be important when gases are involved if the Mach number becomes large enough.*
  - Note that Mach number based on relative or absolute velocity whichever is higher is considered.

Introduction

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Generalized classification of Turbomachines

- ***Axial-flow machines***: *The fluid maintains a significant axial-flow direction component from the inlet to outlet of the rotor.*
- ***Mixed-flow machines***: *There may be significant radial and axial-flow velocity components for the flow through the rotor row.*
- ***Radial-flow machines***: *The flow across the blades involves a substantial radial-flow component at the rotor inlet, exit, or both.*

Classification of Turbomachinery

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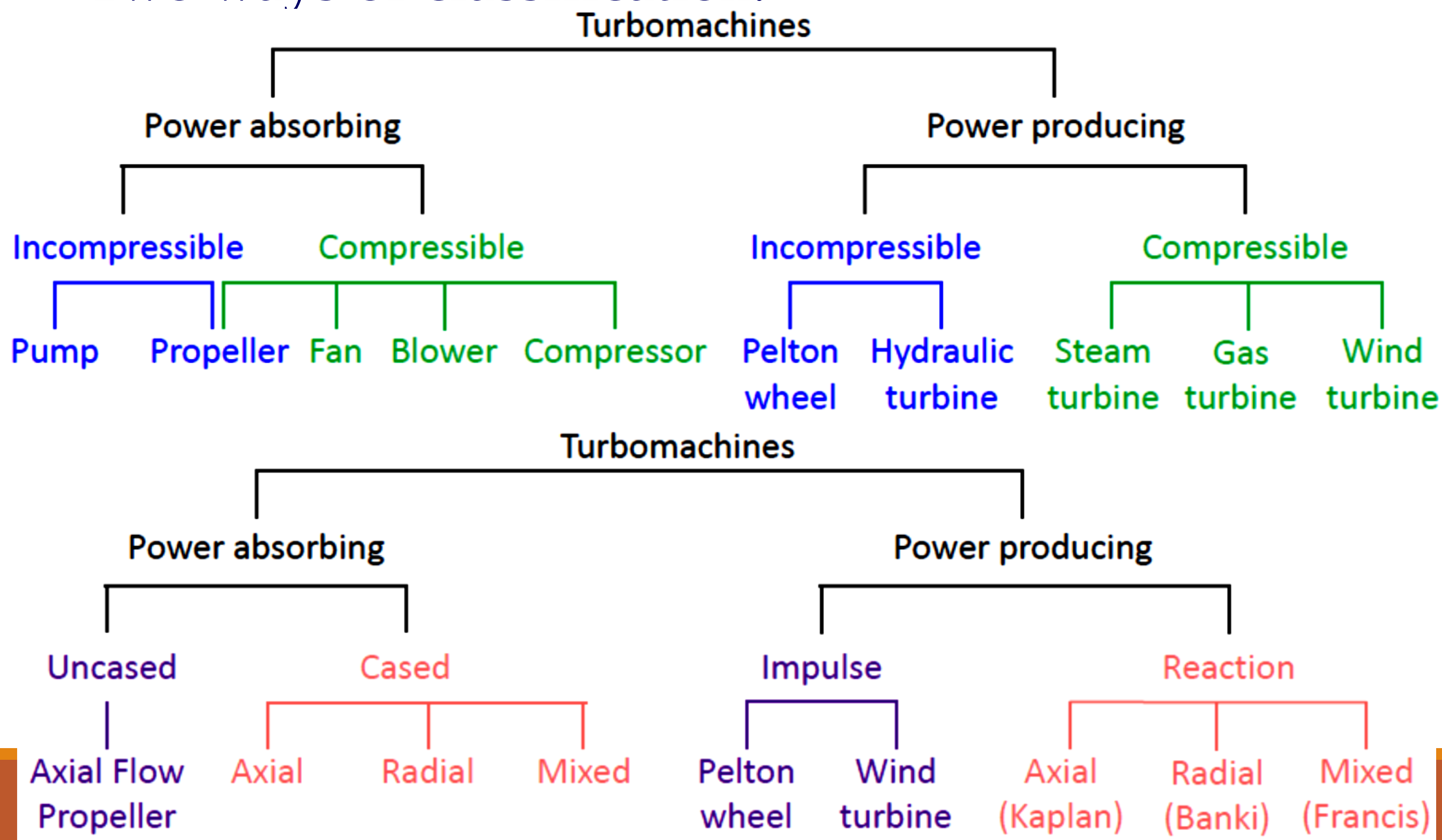
Two ways of classification.



Review of Fluid Mechanics and Thermodynamics

Characteristics of Fluids

- *What's a Fluid ?*
- *What's difference between a solid and a fluid ?*

Definition of Fluid

- *Fluids comprise the liquid and gas (or vapor) phase of the physical forms.*
- *A fluid is a substance that deforms continuously under the application of a shear stress no matter how small the shear stress may be.*
- *A shearing stress is created whenever a tangential force acts on a surface.*

Properties of Fluids

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When a constant shear force is applied:

- *Solid deforms or bends*
- *Fluid continuously deforms.*

Fluid Vs Solid

- *Vague idea*
  - Fluid is soft and easily deformed.
  - Solid is hard and not easily deformed.
- *Molecular structure*
  - Solid has densely spaced molecules with large intermolecular cohesive force allowed to maintain its shape.

Properties of Fluids

Fluid Vs Solid Contd…

- *Liquid has further apart spaced molecules, the intermolecular forces are smaller than for solids, and the molecules have more freedom of movement. At normal temperature and pressure, **the spacing is on the order of 10^{-7} mm**. The **number of molecules** per cubic millimeter is on the order of 10^{21}.*
- *Gases have even greater molecular spacing and freedom of motion with negligible cohesive intermolecular forces and as a consequence are easily deformed. At normal temperature and pressure, **the spacing is on the order of 10^{-6} mm**. The **number of molecules** per cubic millimeter is on the order of 10^{18}*

Fluids? Solids?

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Some materials, such as slurries, tar, putty, toothpaste, and so on, are not easily classified since they will behave as solid if the applied shearing stress is small, but if the stress exceeds some critical value, the substance will flow. The study of such materials is called **rheology**

Fluids

Ideal Fluid

- *It is defined as incompressible fluid having zero viscosity.*

Newtonian Fluid

- *It is defined as fluid in which shear stress is directly proportional to the rate of deformation*

Non-Newtonian Fluid

- *These are the fluids in which shear stress is not directly proportional to shear strain.*

Characteristic Description

Qualitative aspect

- *Qualitative aspect serves to identify the nature, or type, of the characteristics (such as length, time, stress, and velocity) .*
- *Qualitative description is given in terms of certain **primary quantities, such as Length, L, time, T, mass, M, and temperature,** θ. The primary quantities are also referred to as **basic dimensions**.*
- *These primary quantities can then used to provide a qualitative description of any other **secondary quantity:** for example, area* $\doteqdot L^2$,*velocity* $\doteqdot Lt^{-1}$,*density* $\doteqdot ML^{-3}$.

Characteristic Description

Quantitative aspect

- *Provide a numerical measure of the characteristics.*
- *Require both a number and a standard.*
- *A standard for length might be a meter or foot, for time an hour or second, and for mass a slug or kilogram.*
- *Such **standards are called units**.*

Glossary of Turbomachinery terms

Adiabatic Process A process with no heat transfer

Aerofoil An aerodynamic shape designed to produce a lift force with minimal drag (UK spelling)

Airfoil An aerodynamic shape designed to produce a lift force with minimal drag (US spelling)

Blade The name given to the part of the turbine, compressor or fan that guide the flow. Can be stationary or rotating.

Blade Passage The space between two adjacent rotor or stator blades. Essentially this is the empty space that the fluid flows through.

Blade Span The length of the blades in the radial direction

Pump Another name for a device that delivers energy to a liquid. The term compressor isn't appropriate as liquids are almost incompressible.

Rotor Rotating row of blades found after the stator in a turbine and before the stator for a compressor.

Runner Name for the rotating element of a machine, often used in hydraulic turbines

Scroll Casing A casing that resembles a sea shell for a radial turbomachine which aims to ensure an equal distribution of flow around the periphery by reducing the area of the device.

Glossary of Turbomachinery terms

Bucket Another name for Blade

Casing The higher radius where the case of the machine is located

Chord The shortest distance between the leading edge and the trailing edge of an aerofoil

Compressor Device that delivers energy to a fluid, usually used to describe a machine operating on a gas as the output is at a higher density to the inlet

Diaphragm Another word for stator, usually used in steam turbine practise

Enthalpy Formally: A thermodynamic property which is the sum of the internal energy of a substance and the product of the pressure and the specific volume. In more practical terms it is a measure of the energy of a fluid at a given pressure and temperature

Fan Devices that deliver energy to a gas. Usually restricted to a device at has a modest pressure rise over the device.

Gas Turbine The name given to a complete machine including a compressor, combustor and turbine using air as a working fluid. Used to differentiate from a *Steam Turbine* which uses steam as a working fluid or as a generic name for the technology.

Glossary of Turbomachinery terms

SFEE The steady flow energy equation a fundamental equation of Thermodynamics.

Stage A stator and a rotor combined, can be found either in a compressor or in a turbine.

Guide Vane Another name for stator blades, often used with hydraulic turbines

Hub The lower radius at which the blades are attached

Hydraulic Associated with liquids, for example a hydraulic turbine is one that uses liquid (usually water) as a working fluid

Impeller Rotating element of a pump

Isentropic Process A process with constant entropy - that is a perfect process that will have the highest possible efficiency

Isothermal Process A process that takes place at constant temperature

Isobaric Process A process that takes place at constant pressure

Leading Edge The point on an aerofoil that is furthest upstream

Nozzle Another name for a stator

NPSH Net positive suction head - the margin between the saturated pressure vapour and the pressure at inlet

Glossary of Turbomachinery terms

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Stagnation Conditions Conditions (pressure, temperature) that would occur if a fluid is brought to rest in an isentropic manner

Static Conditions Conditions (pressure, temperature etc) which occur in a fluid which is moving

Stator Stationary row of blades found before the rotor in a turbine and after the rotor for a compressor.

Station (Or Analysis Station) A convenient point in a turbomachine where analysis can take place, such as the entry to a blade row or the exit from the machine as a whole.

Steam Turbine A turbine using steam as a working fluid.

Swirl Having a tangential component

Tip The upper radius of rotor blades

Tip Clearance The gap between the moving blades and the stationary casing in a turbomachine. For high performance aeroengines this is around 1% of the blade span.

Tip Leakage The name given to the flow that goes through the tip clearance rather than following the path of the main flow through a turbomachine.

Glossary of Turbomachinery terms

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Trailing Edge The point on an aerofoil which is furthest downstream

Turbine Device for extracting energy from a fluid

Vanes Another word for blades

Vaneless Having no vanes or blades, used often to describe diffusers in pumps

Volute Another word for scroll casing

Wicket Gates Another word for guide vanes

Lecture 3

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Relative & Absolute Motion

Velocity Triangles in Turbomachines

Problems

Relative & Absolute Motion

Turbomachines involve energy interaction through fluid flow motion through the stator and rotor blade passages.

- ***Why frame of reference is necessary when analyzing motions?***
  - Educational movie frames of reference by Dr. Hume & Dr. Ivey

Absolute velocity is sum of frame velocity and relative velocity

Relative & Absolute Motion

Turbomachines involve both stator and rotor.

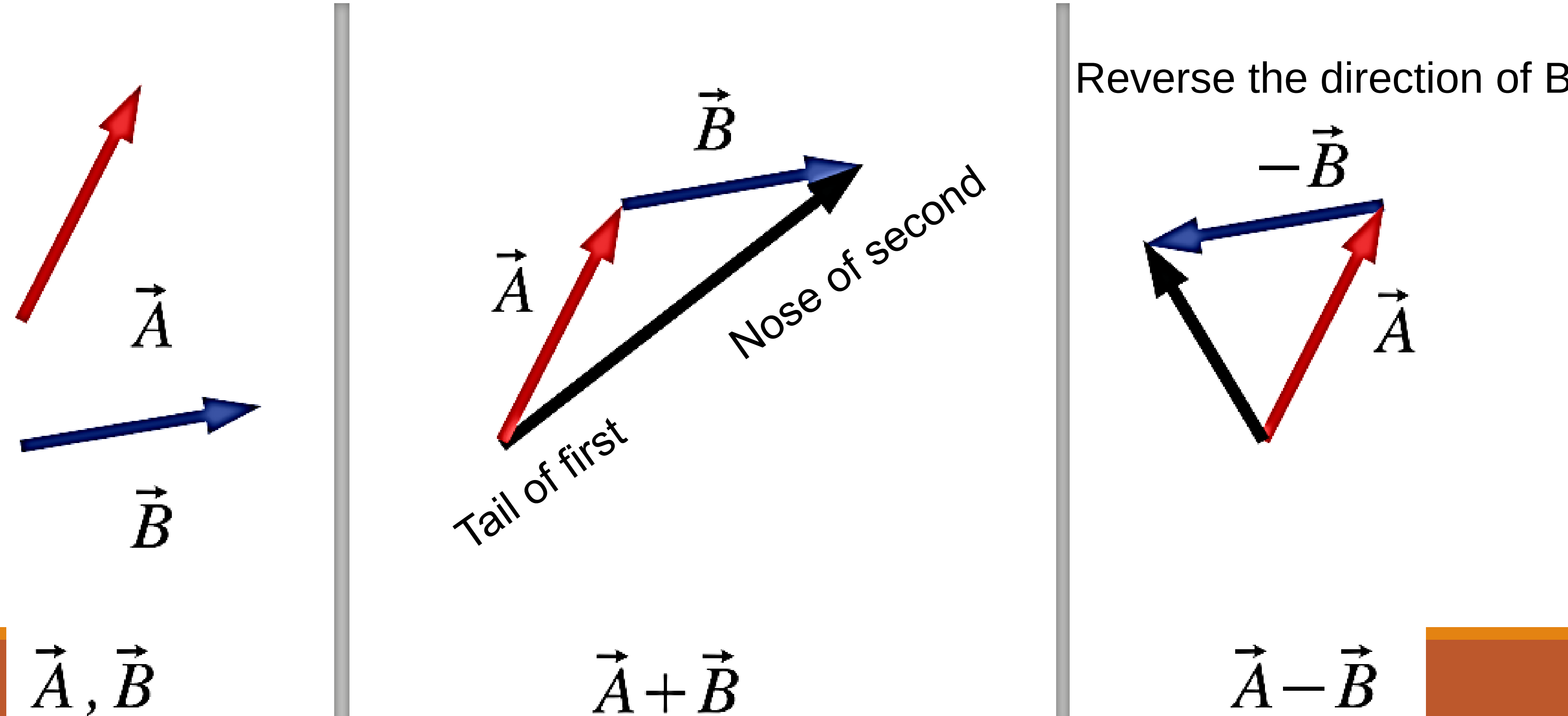
- ***Interaction*** *between* ***fluid flow and stator/rotor*** *blades needs to be understood for getting insight into* ***energy exchange.***
- *Note that rotor blades are moving while stator blades are stationary and guide the flow in designed fashion.*

- Viewing flow from the point of view of a stationary observer is being in absolute frame of reference
- Viewing flow from the point of view of a rotating component observer is being in relative frame of reference
- **First step** in analysis becomes **choosing frame of reference**.
- **Analyzing flow with respect to blades** is good starting point as energy interaction takes place in blade passages.
  - ***For stator blades absolute flow velocities would be considered***
  - ***For rotor blades relative flow velocities would be considered.***

Velocity Triangle

Basic Vector addition and subtraction

- *How did you put together two vectors & how did you draw the resultant (direction)?*



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Velocity Triangle

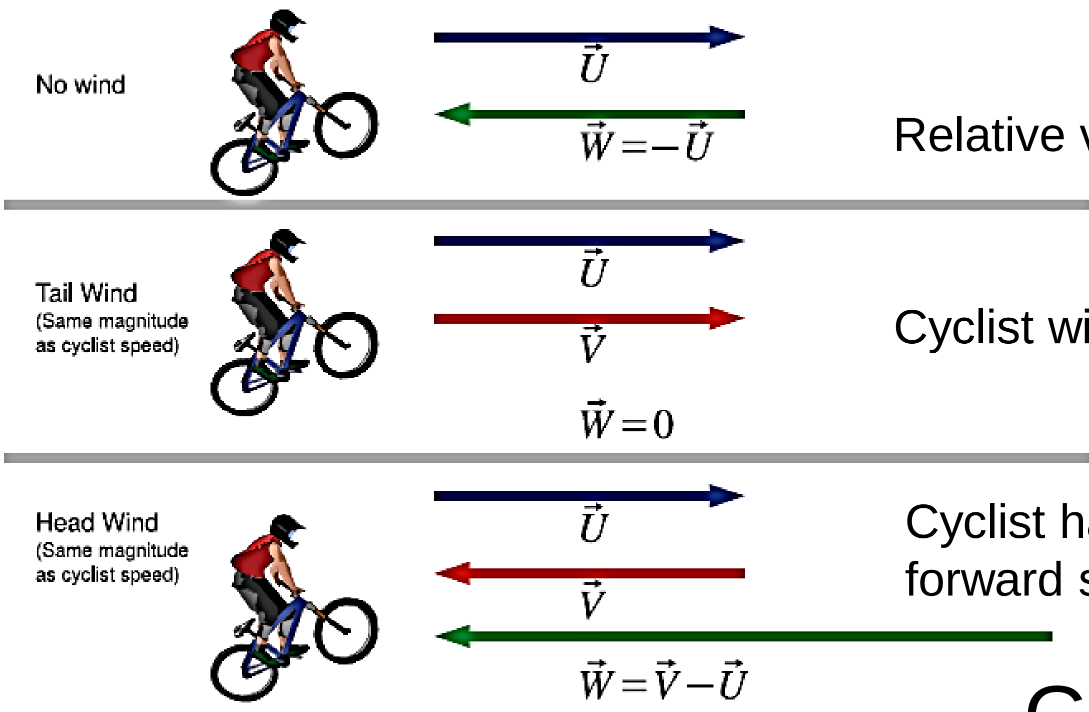

Figure 2.1: Relative and Absolute Velocities for a Cyclist

Relative velocity is $\vec{W} = -\vec{U}$

Cyclist will feel no wind

Cyclist has to work hard to maintain same forward speed

Generalized relation

$$\boldsymbol{\vec{V}} = \boldsymbol{\vec{U}} + \boldsymbol{\vec{W}}$$

*W=relative velocity experienced by cyclist

Velocity Triangle

Velocity triangles at inlet and exit of rotor blade for a turbine stage with rotor blade in rotating frame of reference are shown below.

Always check if absolute velocity is sum of frame velocity and relative velocity

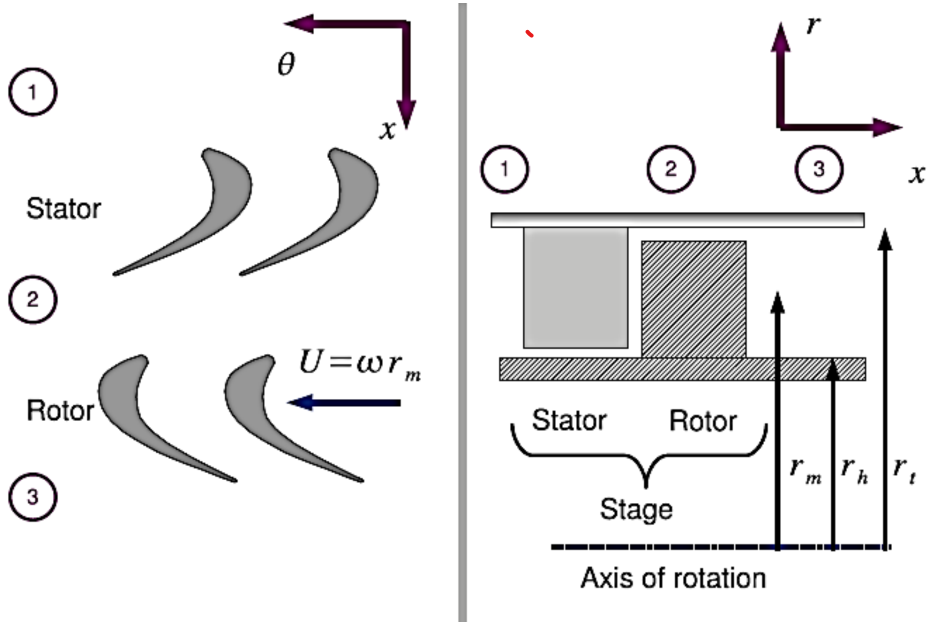

Figure 2.4: Cascade and Meridional Views of a Turbine Stage

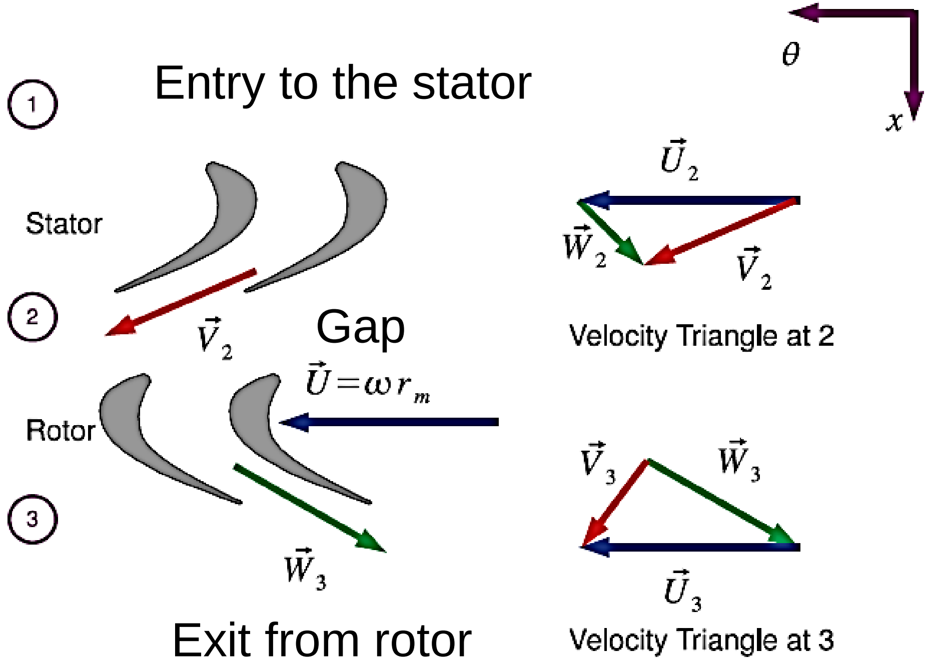

Figure 2.5: Velocity Triangles for a Turbine Stage

Velocity Components

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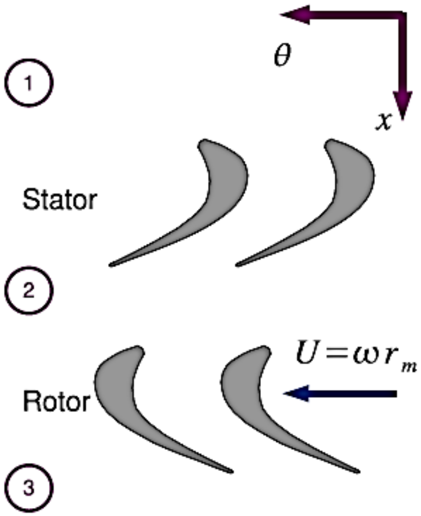
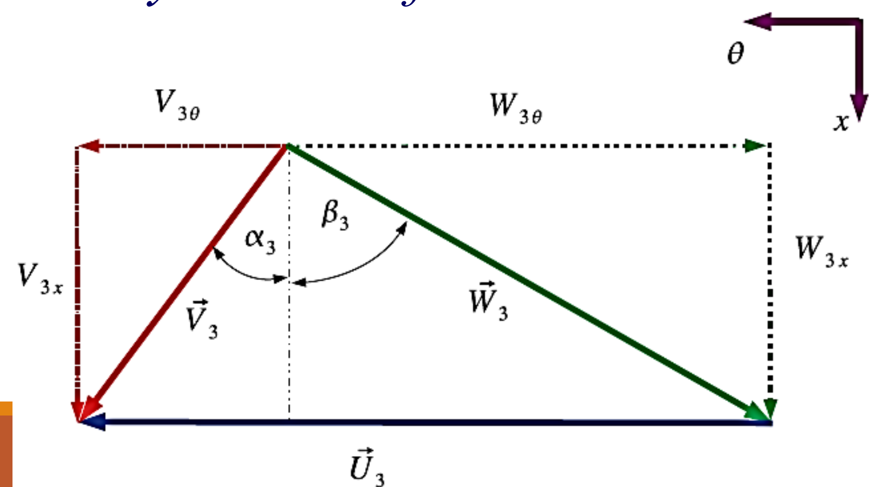
Each velocity in cascade view can be decomposed into axial and tangential component. For axial flow machines, velocity direction are defined with respect to axial direction.

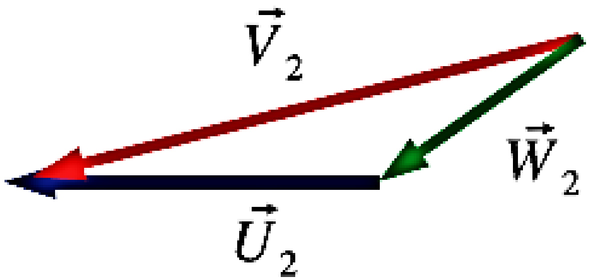


- *Subscript 'x' and 'θ' would be used to denote the axial and tangential components.*
- *Notations 'U' for blade velocity, 'V' for absolute velocity and 'W' for relative velocity are used.*

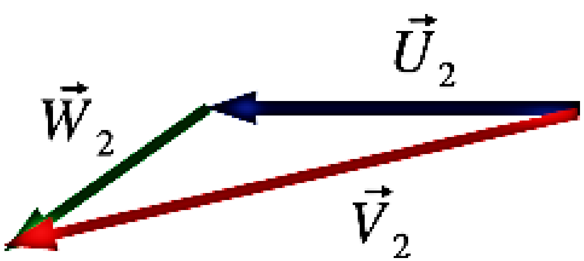


Common Errors in Velocity Triangle

Correct Velocity Triangles

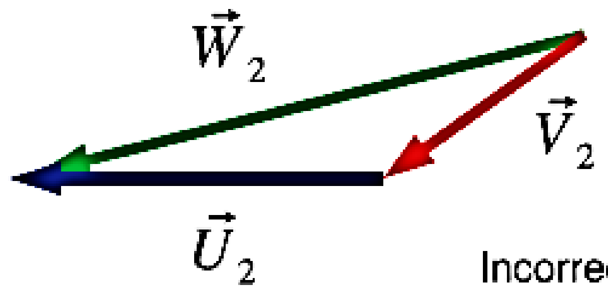


Correct: as earlier examples

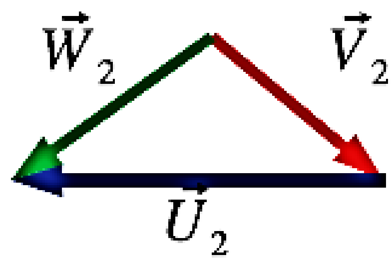


Correct: drawn with U at top

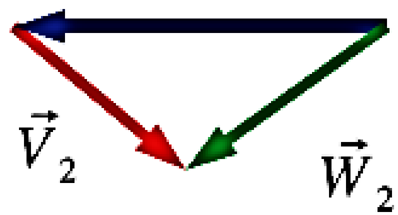
Incorrect Velocity Triangles



Incorrect: V and W interchanged

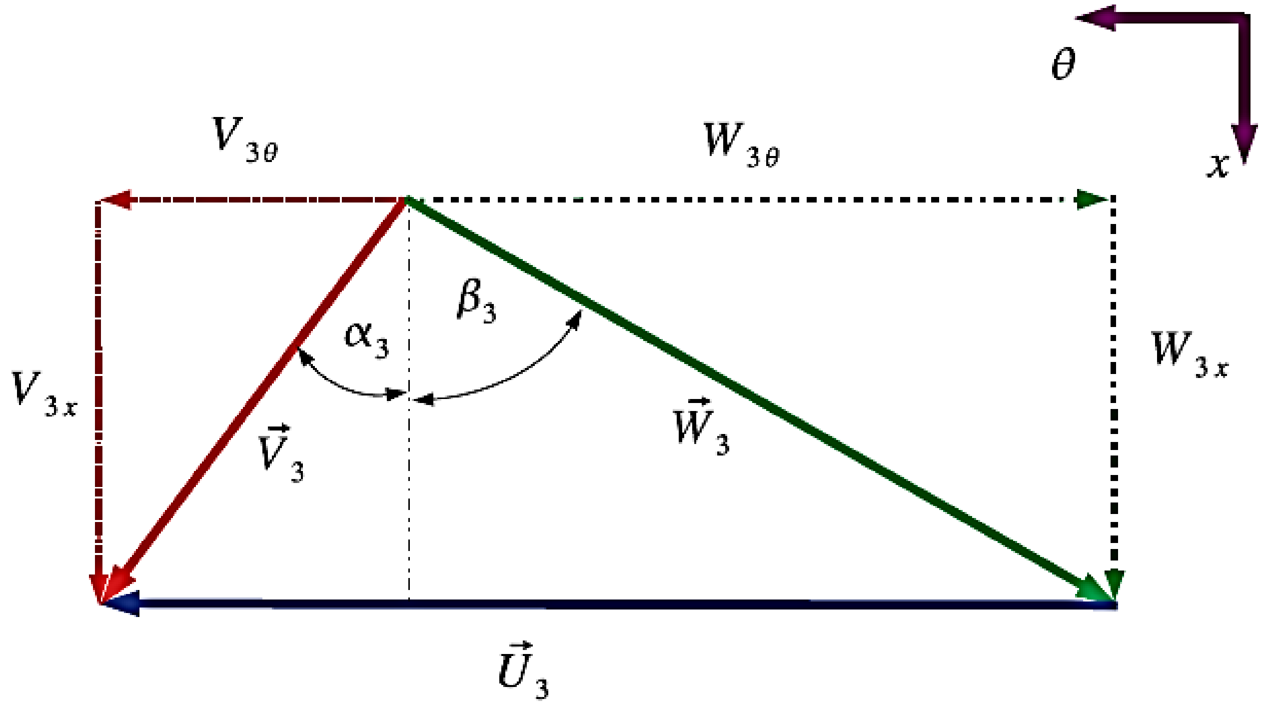


Incorrect: W and U head to head



Incorrect: W and U tail to tail

Relationships Between Velocities

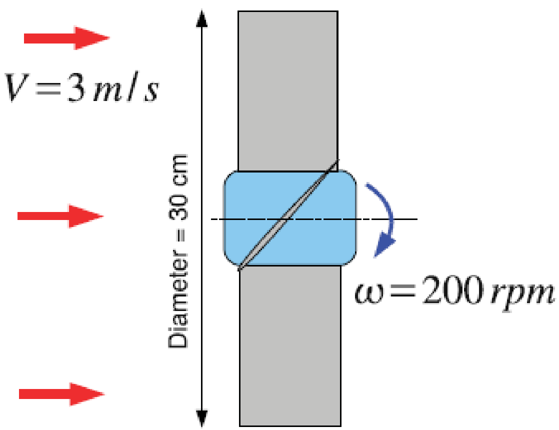


Relative and absolute flow angles

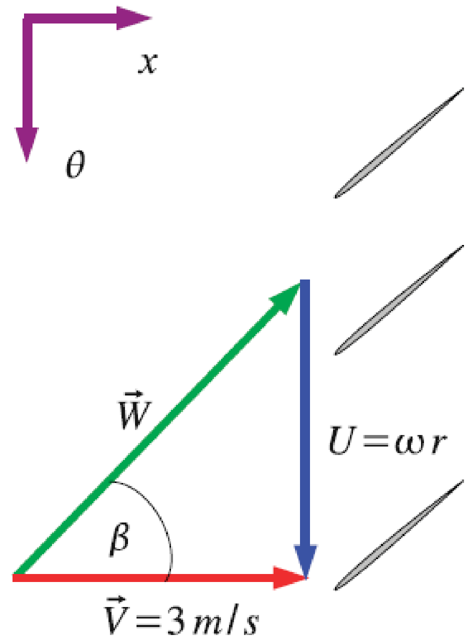
$$
\begin{aligned}
V^2 &= V_\theta^2 + V_x^2 \\
V_x &= V \cos\alpha \\
V_\theta &= V \sin\alpha \\
V_\theta &= V_x \tan\alpha \\
W^2 &= W_\theta^2 + W_x^2 \\
W_x &= W \cos\beta \\
W_\theta &= W \sin\beta \\
W_\theta &= W_x \tan\beta
\end{aligned}
$$

Problem

Example Consider an Office Desk Fan. It rotates at 200 rpm and has a diameter of 30 cm. Air enters the fan at 3 m/s, parallel to the axis of rotation. Calculate the relative velocity ($\vec{W}$) at the tip of the fan.



Side View
(fan support not shown)



Cascade View

- *Frame velocity* $U = r\omega$
- *From velocity triangle*

$$W = \sqrt{U^2 + V^2}$$

- *However direction or angle 'β' needs to be carefully estimated.*

$$\beta = \tan^{-1}\left(\frac{-U}{V}\right)$$

What are the answers for U, W and β?

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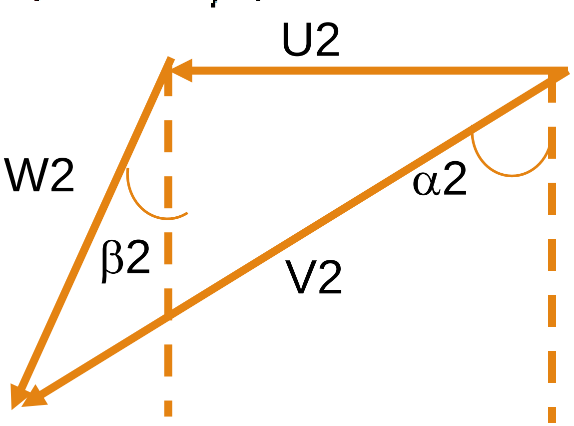
Exercise

The flow at exit from a turbine stator row has a velocity of 100 m/s at an angle (α_2) of 70° to the axial direction. Calculate the tangential and axial velocity components. The rotor row is moving with a velocity of 50 m/s. Calculate the velocity magnitude relative to the rotor blades at inlet and the relative inlet flow angle (β_2). At exit from the rotor row the relative flow angle (β_3) is −60°. Assuming that the axial velocity is constant across the row, what is the absolute exit velocity magnitude and direction? *Answer:* 94.0 m/s, 34.2 m/s; 55.7 m/s, 52.1°; 35.4 m/s, −15.1°



V2 cos(α2), V2sin(α2)

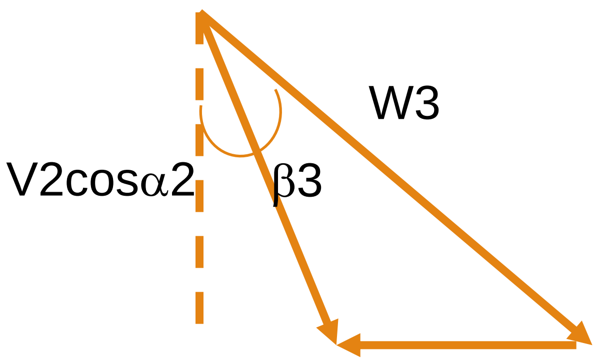
W2=sqrt(----+------)

W2 cos(β2)
= V2 cos(α2)

94,34.2,55.7,52.1

Rotor inlet

The flow at exit from a turbine stator row has a velocity of 100 m/s at an angle (α_2) of 70° to the axial direction. Calculate the tangential and axial velocity components. The rotor row is moving with a velocity of 50 m/s. Calculate the velocity magnitude relative to the rotor blades at inlet and the relative inlet flow angle (β_2). At exit from the rotor row the relative flow angle (β_3) is −60°. Assuming that the axial velocity is constant across the row, what is the absolute exit velocity magnitude and direction? *Answer:* 94.0 m/s, 34.2 m/s; 55.7 m/s, 52.1°; 35.4 m/s, −15.1°



W3 cos (beta3)=V2cosα2

V3=sqrt(V2cosα2^2
+-----)
V3cos(α2)= V2cosα2

35.4, -15.1