

# AIR BREATHING ENGINES

A Free, Open  
Access MOOC



Session -01

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# Overview

- ▶ Course Objective, Syllabus & COs, Text & References
- ▶ Mode of Evaluation
- ▶ Learning materials
- ▶ Course plan, Mode of Delivery

# Course Objective & Syllabus

## ► Course Objective:

- Introduction to diesel engines, use of mathematics analysis of turbo machines as applied to air breathing engines. Enable the students to do vehicle range analysis. Elaborate the details of design of combustion, intake and exhaust of air breathing systems.

## ► Syllabus:

UNIT 1	UNIT 2	UNIT 3
[Only university is provided below. Link given for the complete syllabus]		
Review of propulsion power cycle, fundamentals of turbochargers	Turbo loading & analysis of intake and exhaust	Analysis, components & design of turbochargers.

# Overview of The Course

- ▶ **Steady state**

- ▶
- ▶

- ▶ **Unsteady state**

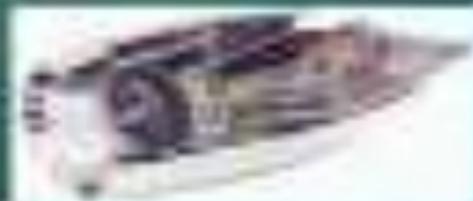
- ▶ Compressors & Turbines
  - ▶ Aerodynamics
  - ▶ Velocity diagrams
  - ▶ Coupling

- ▶ **Inlets**

- ▶ Subsonic
- ▶ Supersonic

- ▶ **Compressors**

- ▶ **Flow through nozzles**



# Text/References

- ▶ Mattingly, Jack, D. "Elements of Propulsion: Gas Turbines and Rockets." AIAA Education Series, 2006.
- ▶ Koch, R. L. "Fundamentals of Jet Propulsion with Applications." Cambridge University Press, 2005.
- ▶ Hill and Peterson, Mechanics and Thermodynamics of Propulsion." Dover, Cambridge, 1992; 5010.





# AIR BREATHING ENGINES



Session-02

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Session -2

**REVIEW OF THE  
THRUST EQUATION &  
BRAYTON CYCLE**



# The Momentum Equation..

- Recalling Momentum equation as applied to a control volume

$$\sum \vec{F} = \frac{d}{dt} \iiint_{CV} \rho u \vec{i} dV + \iint_{CS} \rho u (\vec{u} \cdot \vec{n}) dA$$

- Constituent of  $\rho u$
- Transformation of the equation for a (i) Steady (ii) Uniform flow, and the forces acting the  $x$ -direction...

# Review: Thrust Equation

$$\text{Thrust} = \dot{m}_e V_e - \dot{m}_0 V_0 + A_e (P_e - P_0)$$

► **The Assumptions?**

► **Momentum thrust & Pressure thrust**

$$\dot{m}_e V_e - \dot{m}_0 V_0$$

$$A_e (P_e - P_0)$$

# Review: Thrust Equation

$$\text{THRUST} = \dot{m}_p V_e - \dot{m}_0 V_0 + A_e (P_e - P_a)$$

- ▶ **Achieved by a series of energy conversion processes**
- ▶ Chemical
  - ▶ Thermal
  - ▶ Kinetic

# Review: Thrust Equation

$$F_{\text{thrust}} = \dot{m}_e V_e - \dot{m}_a V_a + A_e (P_e - P_a)$$

- ▶ If "**Pressure thrust**" is absent:
  - ▶ **Correctly Expanded** Nozzle Flow
    - ▶ Subsonic flow achieves **total ambient thrust**

$$F_{\text{thrust}} = \dot{m}_e V_e = \dot{m}_a V_a$$

Over expanded:  
 $P_e > P_a$

Under expanded:  
 $P_e < P_a$

# AIR BREATHING ENGINES



Session:  
Review of  
Brayton Cycle

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Session -3

## **REVIEW OF BRAYTON CYCLE ANALYSIS**



THE PROCESSES, THE COCHLEA AND THE

# Cycle Analysis

- **study of the variation in properties of the working fluid as it moves through the engine**
  - Does not consider the mechanical forces that cause the flow of the fluid
  - Also compares a control device with the effects that they produce and takes into account – “Rubber Analysis”
  - What value this gives for the amount of work done
- **OBJECTIVE:** Determine which conditions for choice for components of an engine to best satisfy a particular performance requirement
  - Relate  $T_1, \gamma, L_{opt}, T_{EPC}$  to the pertinent design parameters

# Brayton Cycle



1-2

Isentropic  
Compression

2-3

Heat addition  
at constant  
pressure

3-4

Isentropic  
Expansion

4-1

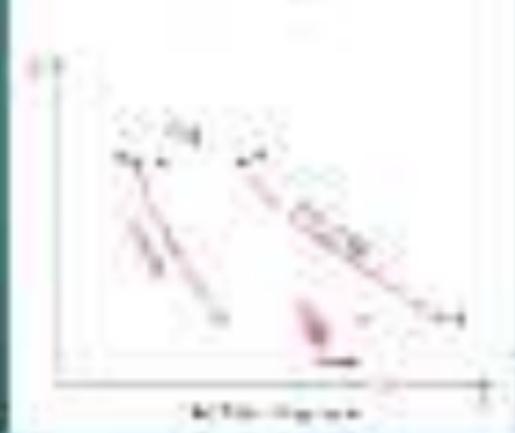
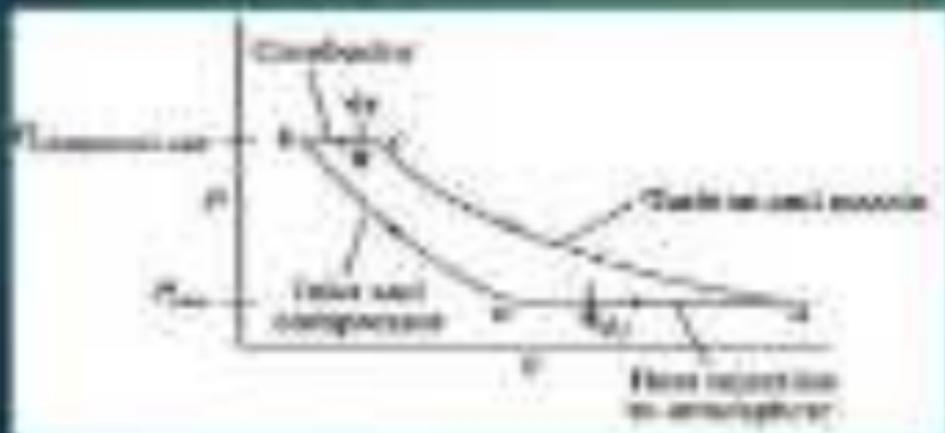
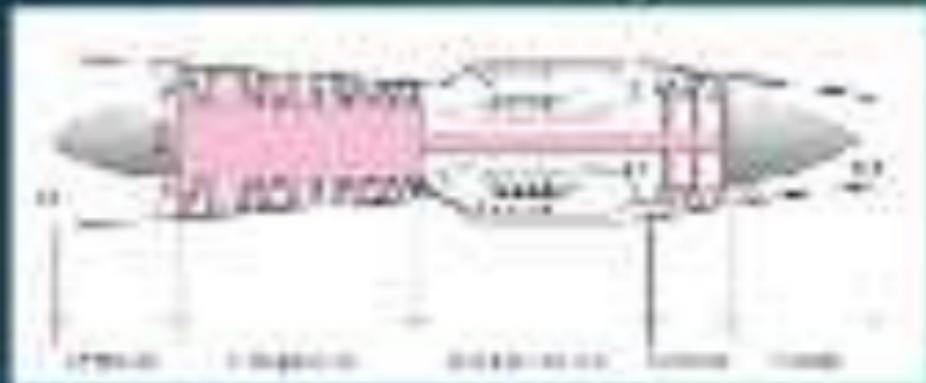
Heat rejection  
at constant  
pressure



1-2 isentropic compression  
2-3 heat addition  
3-4 isentropic expansion  
4-1 heat rejection



# The Ideal Cycle Processes



# Efficiency of The

- **Air-Standard Cycle Efficiency** = Net work output/heat energy transfer into the fluid

Equating Efficiencies of Otto Cycle and Diesel Cycle

$$\eta_{\text{Otto}} = \frac{W_{\text{net}}}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_4(T_4 - T_1)^{\gamma-1}}{T_3(T_3 - T_2)^{\gamma-1}}$$



# Ideal Efficiency

▶ **Ideal Cycle Efficiency**  $\eta = 1 - \frac{T_{02}}{T_{01}}$

▶ since 1-2 is isentropic:  $\frac{T_{02}}{T_{01}} = \left(\frac{P_{02}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}}$

▶ **Ideal Cycle Efficiency**  $= 1 - 1/\pi_c^{\frac{\gamma-1}{\gamma}}$   
( $\pi_c = \left[\frac{P_{02}}{P_{01}}\right]$ )

▶ **Implications...**

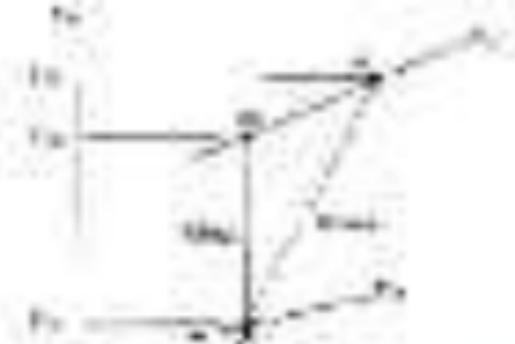
- ▶ The importance of higher compression pressure ratio
- ▶ Required for higher efficiency

## Real Cycle: Losses & Component Efficiencies

- The compression & expansion are NOT isentropic
- Combustion entails pressure loss
- Losses accounted by component efficiencies,  $\eta$

# Real Cycle:

COMPRESSION EFFICIENCY



$\eta = \frac{\text{Ideal Power (Assumed)}}{\text{Actual Power (Measured)}}$  Let us define an efficiency  $\eta$  for a real process in terms of  $q_{12}$

$$\eta = \frac{W_{12} = Q_{12}}{Q_{12} = Q_{12}}$$

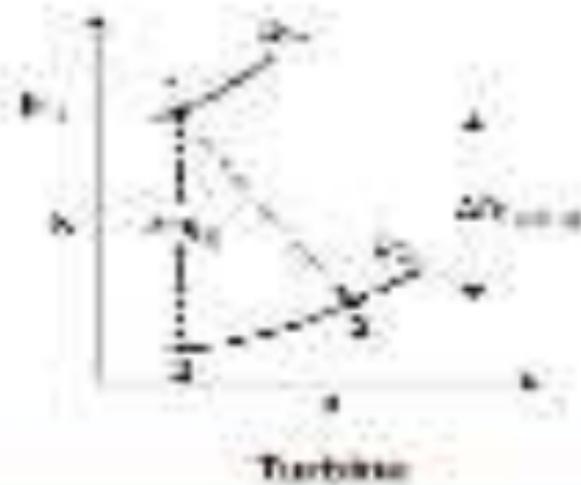
Let us define an efficiency  $\eta$  in terms of temperature process

If Specific heat is assumed to be constant,

$$\text{Isentropic Efficiency} = \frac{T_{12} - T_{2c}}{T_{12} - T_{2s}}$$

$$\eta = \frac{r^{(\gamma-1)/\gamma} - 1}{r - 1}$$

# Real Compression & Expansion



# Isentropic Efficiency, turbine

→ On similar level as for the compressor,

$$\eta = \frac{\text{Actual Power Output}}{\text{Ideal Power Output}} \quad \text{For expansion with a constant stagnation pressure ratio } P_{01}/P_{02}$$

$$\eta = \frac{h_{01} - h_{02}}{h_{01} - h_{02s}} = \frac{T_{01} - T_{02}}{T_{01} - T_{02s}}$$

$$\eta = \frac{1 - \tau}{1 - \tau^{1/\gamma}}$$

# Polytropic Efficiency

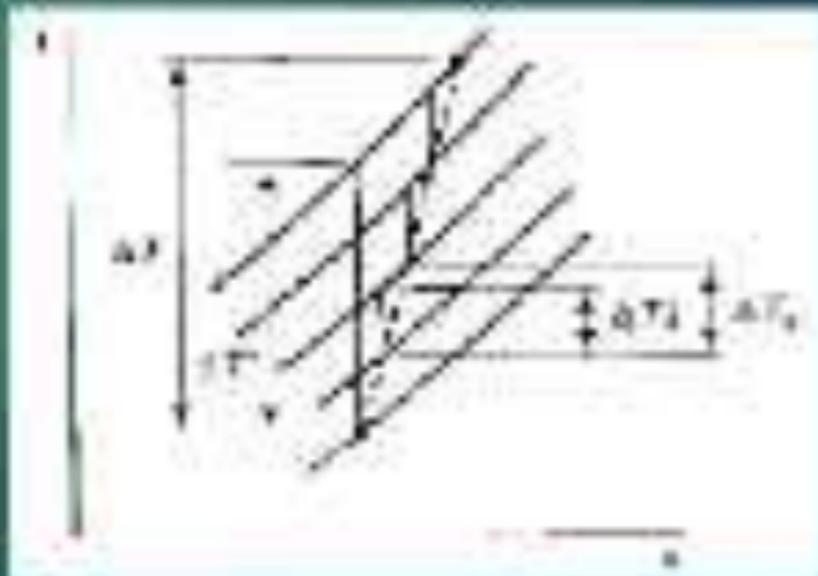
- Definition: the isentropic efficiency of an elemental stage in the pressure ratio that it is considered. Nevertheless the whole process

- $\eta_{p, tot}$  then definition?

- Isentropic efficiency of isentropic compression

Ratio

- $\eta_{p, tot}$  is equal pressure ratio across the compressor



# Polynomial Division

**1.4.6** Example 1 Divide  $2x^3 + 3x^2 - 5x + 7$  by  $x - 2$  using long division. Express the result in the form  $q(x)r(x) + r(x)$ .

**Example**  
Illustration

$$\begin{array}{r} 2x^2 + 7x + 9 \\ x - 2 \overline{) 2x^3 + 3x^2 - 5x + 7} \\ \underline{2x^2 - 4x + 14} \phantom{0} \\ 7x - 7 \\ \underline{7x - 14} \\ 7 \end{array}$$

# Polytropic Efficiency, Turbine

- Defining polytropic efficiency for isentropic expansion. For turbine:

Then

$$\eta_p = \frac{h_1 - h_2}{h_1 - h_2^*}$$

- Deriving the following from the isentropic condition

$$\eta_p = \frac{h_1 - h_2}{h_1 - h_2^*} = \frac{\gamma - 1}{\gamma} \frac{1 - r_p^{1/\gamma}}{1 - r_p^{1/\gamma^*}}$$

$$\eta_p = \frac{1 - r_p^{1/\gamma}}{1 - r_p^{1/\gamma^*}}$$

# AIR BREATHING ENGINES



Session -03-04:  
Introduction to  
Turbomachines

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# Turbomachinery



- Steady interaction between a rotating solid surface and a fluid flowing over it
- Compressor: to pump the fluid, transfer power from the solid surface to the fluid
- Turbine: to extract power from the fluid, transfer power to the solid surface
- Direction of flow
  - axial
  - radial (free vortex)



# Types of Turbo-machines

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➤ Classification based on the direction of energy transfer

- Compressors
- Turbines



➤ Classification based on the direction of flow

- Axial flow
- Centrifugal
- Mixed flow



# Videos - Turbomachines

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<https://www.youtube.com/watch?v=LA0W796Y130>

# Videos – Turbomachines – ctd.

<http://www.youtube.com/watch?v=qWUjPcrtf8>  
crtf8.

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# What is Common to all these ?

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Energy transfer  
between a solid  
chip surface and a  
fluid flowing  
through it

**How to  
quantify this ?**

**How to  
analyze the  
aerodynamics  
of this  
interaction ?**

# The force that causes rotation

- Consider a force acting at a point on the rim of the disc, causing it to rotate
- Can be considered to be behaving in a radial and tangential components
- Radial component passes through the Centre - has no moment about it
- Axial component acts parallel to the axis of rotation - born by the bearings - does not contribute to the rotation
- Rotation is caused only by the **TANGENTIAL COMPONENT** of the force







# Linear Vs Angular Motion

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Linear Motion	Angular Motion
Linear Velocity $V$	Angular Velocity $\omega$
Force $F$	Torque $T$
Linear Displacement $s$ $\propto V$	Angular Displacement $\theta$ $\propto \omega$
Work done $w$ $\propto F \cdot s$	Work done $w$ $\propto T \cdot \theta$
Power $P = F \cdot V$	<b>Power = <math>T \cdot \omega</math></b>

# Angular Motion: Force, Torque, Angular Momentum

A force (or set of forces) causing rotation

Torque = **Moment of the Force**

As applied to a force, it is the **product of Force  $\times$  B Perpendicular Distance** for the point

$$\tau = r \times F$$

Force  $\times$  Moment Arm = Torque = **angular acceleration  $\times$  Moment of Inertia**

$$\tau = I \alpha$$



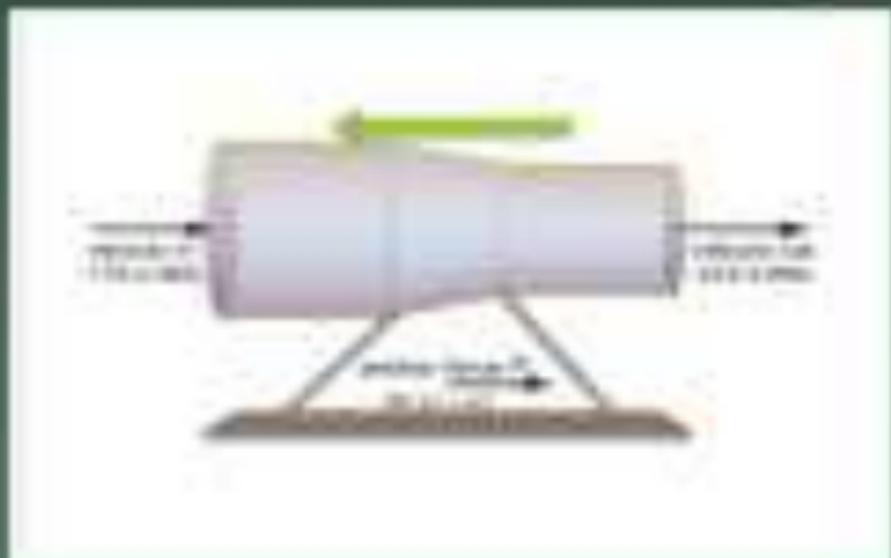
# Force & Linear Momentum

\* Recall that Net force = rate of change of linear momentum

$$\frac{d}{dt} \int_{\text{control volume}} \rho \mathbf{v} dV = \sum \mathbf{F}_{\text{ext}}$$



$$\int_{\text{control volume}} \rho \mathbf{v} dV = \sum \mathbf{F}_{\text{ext}}$$

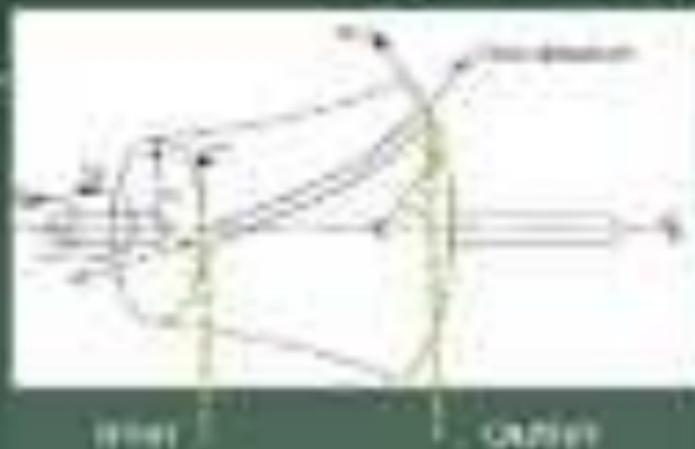


## Torque $\rightarrow$ Angular Momentum

is a vector. An equals the derivative of change of angular momentum to a magnitude that flows through the object.

Example: unattached volute stage tangential flow turbine through a turbomachine passage

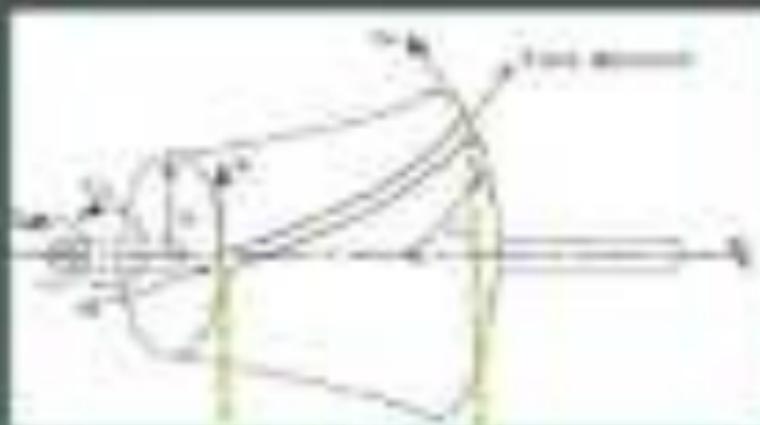
We then do not extract all angular momentum!



$$\left( \begin{array}{l} \text{The sum of all} \\ \text{external moments} \\ \text{acting on a CV} \end{array} \right) = \left( \begin{array}{l} \text{The time rate of change} \\ \text{of the angular momentum} \\ \text{of the contents of the CV} \end{array} \right) + \left( \begin{array}{l} \text{The net flow rate of} \\ \text{angular momentum} \\ \text{out of the control} \\ \text{surface by mass flow} \end{array} \right)$$

# Angular Momentum Equation

$$\left( \begin{array}{l} \text{The sum of all} \\ \text{external moments} \\ \text{acting on a CV} \end{array} \right) = \left( \begin{array}{l} \text{The time rate of change} \\ \text{of the angular momentum} \\ \text{of the contents of the CV} \end{array} \right) + \left( \begin{array}{l} \text{The net flow rate of} \\ \text{angular momentum} \\ \text{out of the control} \\ \text{surface by mass flow} \end{array} \right)$$



Inlet

Outlet

# The Equation..



$$\sum \vec{M} = \frac{d}{dt} \int_{CV} \vec{r} \times \vec{V} \rho \, dV + \int_{CS} \vec{r} \times \vec{V} \rho \vec{V} \cdot d\vec{A}$$

For the specific case of a CV with well defined inlet & outlet (and which allows us to treat the control surface as being averaged), surface integrals can be re-written:

$$\sum \vec{M} = \frac{d}{dt} \int_{CV} \vec{r} \times \vec{V} \rho \, dV + \sum_{in} \vec{r} \times \rho \vec{V} - \sum_{out} \vec{r} \times \rho \vec{V}$$

## Net Torque, in Steady flow

$$\sum \vec{M} = \sum \vec{r} \times m \vec{V} - \sum \vec{r} \times m \vec{V}$$

$$\sum \vec{M} = \sum \vec{r} m \vec{V} - \sum \vec{r} m \vec{V}$$

Net torque acting on the control volume equals the outflow and inflow of angular momentum.

Net torque acting on the control volume during steady flow is equal to the difference between the outgoing and incoming angular momentum flow rates.

Rotation, *Tangential Component* of the Force,..





# Euler's Turbomachinery Equation..

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- For a steady flow through a turbomachine
  - Rate of Change in angular momentum = Total torque exerted on the fluid
- Assume a flow with an axial velocity component
  - A difference in angular momentum across the turbo machine
  - The only velocity component which changes the original momentums of the rotor is the tangential component ( $V_{\theta}$ )

$$\text{Torque, } T = m(V_{\theta 2}r_2 - V_{\theta 1}r_1)$$

$$\text{Power } P = T\omega = m\omega(V_{\theta 2}r_2 - V_{\theta 1}r_1)$$

$$\text{Power } P = T\omega = \dot{m}r(V_{\theta 2}r_2 - V_{\theta 1}r_1)$$

## Direction of Energy Transfer & Euler's Equation

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- ✓ Applied to both compressors & turbines
- ✓ The difference in headwork that fluid systems will be that for compressors
  - ✓ Energy transferred to the fluid
- ✓ For turbines
  - ✓ Energy transferred from the fluid

## Euler's Statement

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Torque exerted by flow on blade row =

$$\dot{m}(r_2 v_{t2} - r_1 v_{t1}) =$$

Rate of change of  
Angular momentum of fluid

## Torque = Angular Momentum

Illustration of the Eulerian table of change of angular momentum as a stream of fluid flows through the stream.

Law of the conservation of angular momentum in the fluid flow through a turbomachine passage.

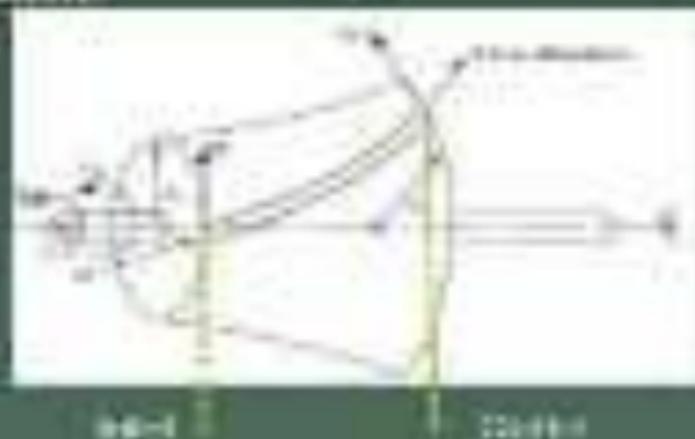
By the conservation of angular momentum:

Net torque = rate of change of angular momentum across CR. (Steady state)

Angular momentum at exit:

Angular momentum at inlet:

$$m_2 v_2 r_2 - m_1 v_1 r_1$$



# Comprehending Euler's Equation..



$$\text{Power } P = T\omega = m\omega(V_{02}r_2 - V_{01}r_1)$$





# AIR BREATHING ENGINES



Session -5/6: Stage of  
An Axial Flow  
Compressor

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# "Staging" of Compressors & Turbines

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## Need for staging

- Requirement of high pressure ratios
- Gradual compression/expansion

## Mechanically what constitutes a "stage"

- **Rotor** – rotating component attached to the shaft that connects compressor & turbine
- **Stator** – Stationary component, attached to the casing





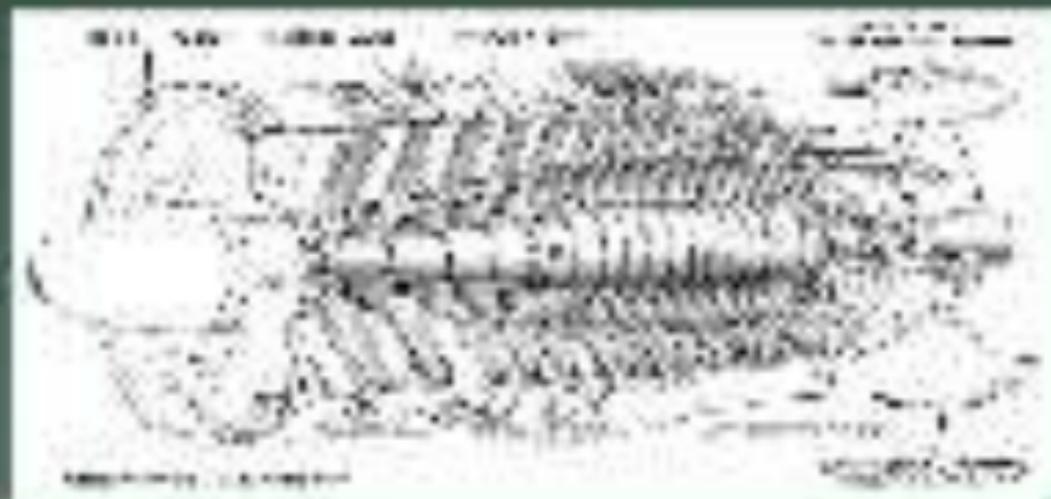
## Number of Stages

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- **Number of stages: Compressor Vs Turbine**
  - For the same pressure ratio, turbine operates with significantly lower number of stages than compressor
  - Difference stems from the fundamental difference between expansion and compression.

## Acute Inflammation

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# A compressor Stage



# Rotor Vs Stator: The Functions

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## The Rotor

- A row of moving blades
- It spins to convert kinetic energy to the fluid and increases the angular momentum: increases the kinetic energy

## The Stator

- A stationary row of blades
- Directs the flow of the fluid around each set of rotor blades
- Increases the fluid's kinetic energy by increasing the fluid velocity that it takes through it
- static pressure increases as the fluid flows through the rotor
- as the energy increases in the rotor, velocity, static pressure, and density also increase



Cut-away view...

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*What if there is no stator...*



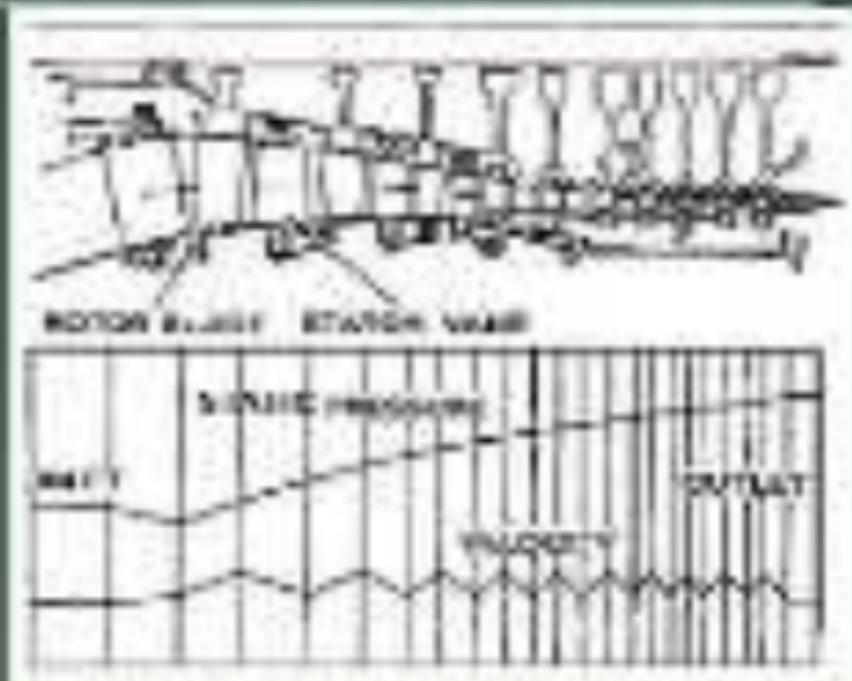
# As Fluid Passes through a Multistage Turbomachine

Image: KJTL, Nasa

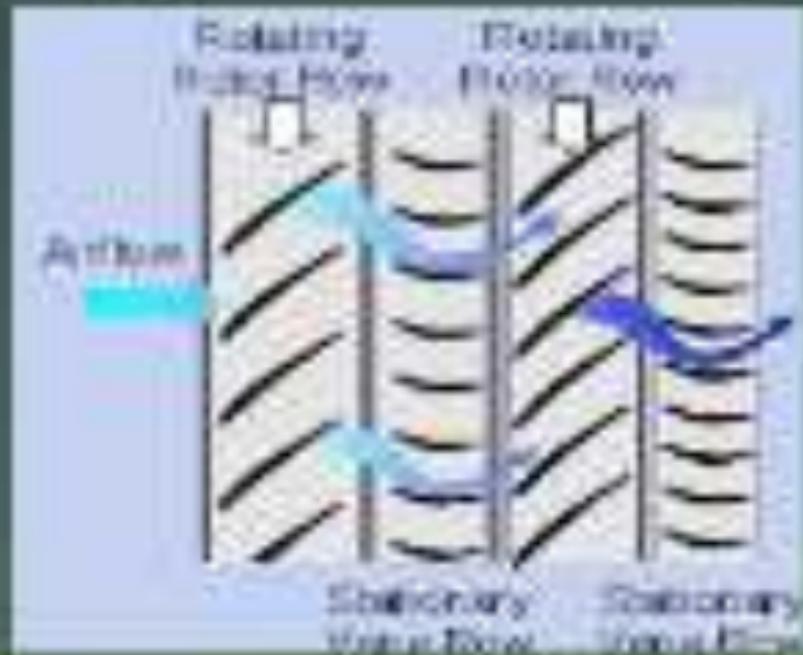
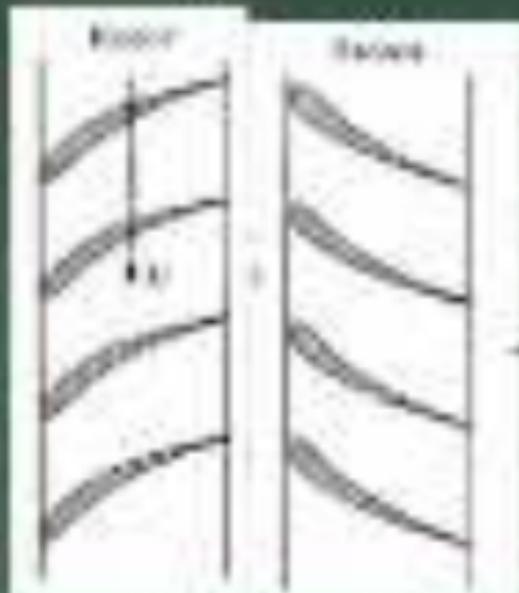
Principles of Turbomachinery

1. Introduction

2. Compressor



# A Compressor Stage...



# A Compressor Stage: Summary of Variation of Flow Properties

Property	Static	Dynamic
Static pressure	Increases	Increases
Stagnation pressure	Remains Constant	Increases
Static temperature	Increases	Increases
Stagnation temperature	Increases	Increases
Velocity	Decreases	Increases

# Trent 1000

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Compressor

Turbine

IP - Single stage

IP - 6 stage

OP - 8 stage

OP - single stage

HP - 8 stage

HP - single stage









# AIR BREATHING ENGINES

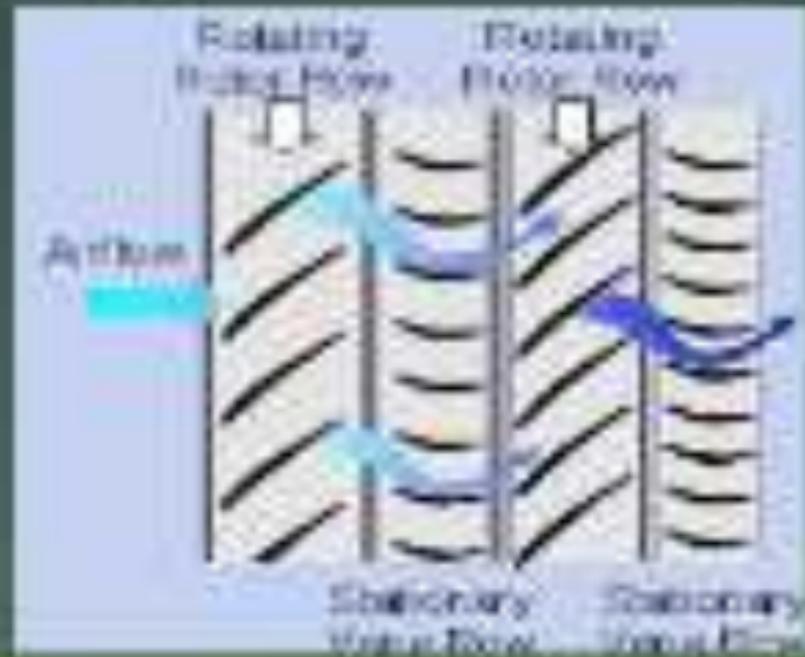
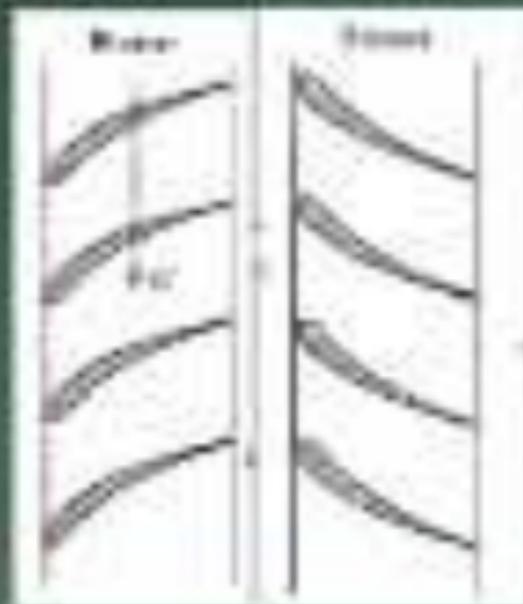


## Session -07: Velocity Triangles

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# A Compressor Stage...



## Torque, Power, Work

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$$\text{Torque, } T = m\omega(V_{\theta_2}r_2 - V_{\theta_1}r_1)$$

$$\text{Specific work} = \frac{T\omega}{m} = \omega(V_{\theta_2}r_2 - V_{\theta_1}r_1)$$

$$\begin{aligned}\text{At a given radius: } w &= \omega r(V_{\theta_2} - V_{\theta_1}) \\ &= U(V_{\theta_2} - V_{\theta_1})\end{aligned}$$

## CASCADE Analysis



➤ Analysing flow in the 2-dimensional plane involving axial and tangential directions.

➤ No variations in the radial direction.

➤ As though the passage is unwrapped.

➤ Known as cascade analysis.











# Velocity Triangle: *The Components*

> Absolute velocity vector

>  $V_{rel}$  The relative velocity

> The rotational velocity ( $\omega r$ )

> The relative velocity

>  $V_{ax}$  The tangential component of velocity

> Angles that the absolute and relative velocities make with the axial direction



# Numerical Problem

An infinitely ductile (no large elastic component of  $\sigma$ ) thin set of rectangular strips, with a velocity of 1.20 m/s. The roller rotates at 5000 rpm. Calculate the reduction in width of a strip which is 0.2% in.

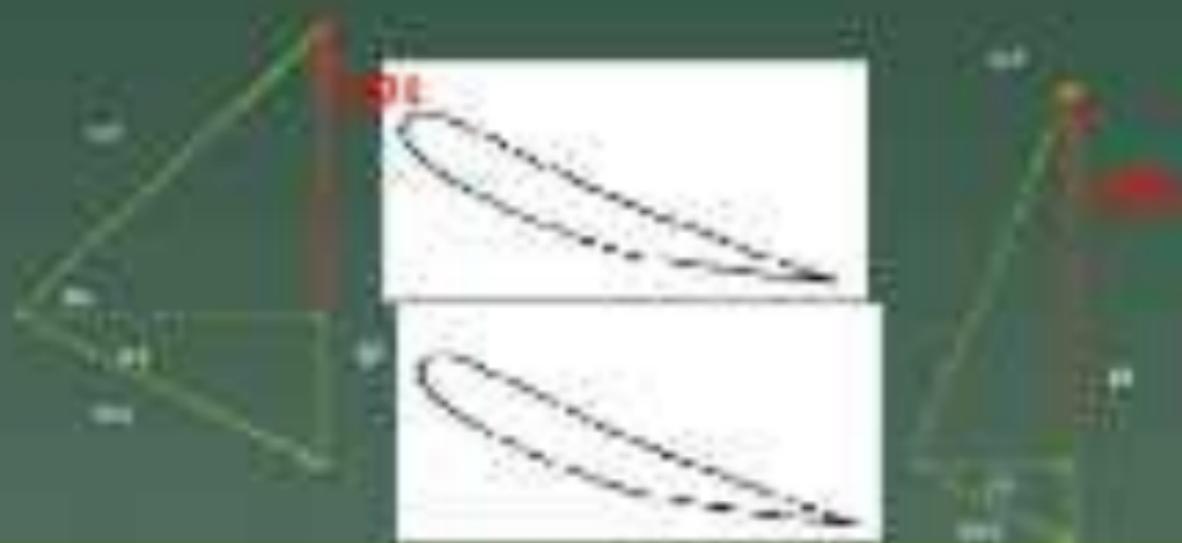


Property	Value	Unit	Value	Unit	Value	Unit
Width	100	mm	100	mm	100	mm
Thickness	0.2	mm	0.2	mm	0.2	mm
Velocity	1.20	m/s	1.20	m/s	1.20	m/s
Roller Speed	5000	rpm	5000	rpm	5000	rpm

# Velocity Triangle

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Slide 87 to 91 at  
end of unit V6  
Relative flow  
angles



# Vectors – Addition & Subtraction



$A, B$



$A+B$



$A-B$

# AIR BREATHING ENGINES



Session 16 – Solidity & Forces on Blades

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## Blade Solidity

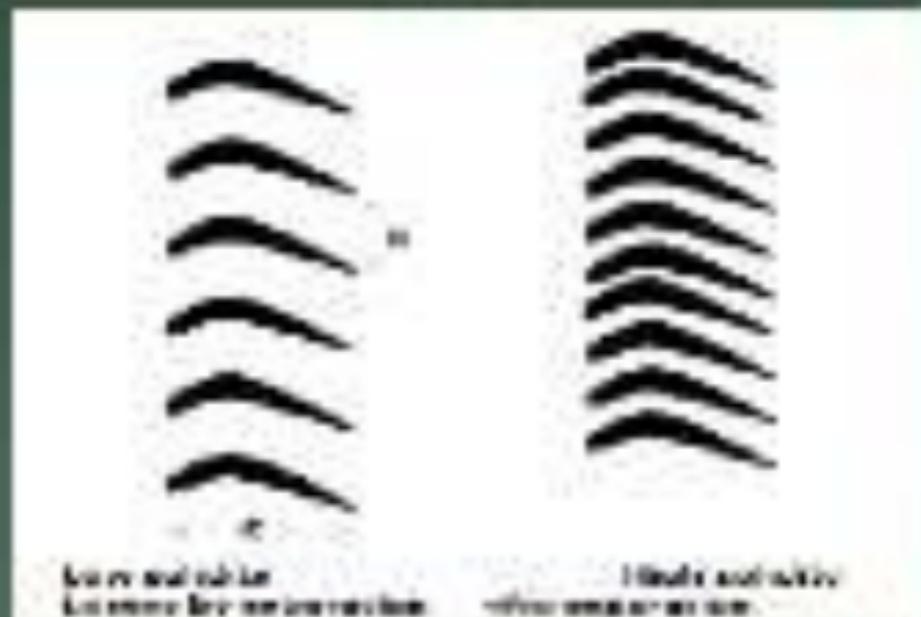
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- ▶ **Solidity** of blades in a compressor is the ratio of the aerodynamic chord over the peripheral distance between two blades
  - ▶  $\sigma = c / \pi r$  where  $c$  = chord length of the blades &  $r$  = spacing between the blades
  - ▶  $\sigma = \frac{z c}{\pi D}$  where  $r = \frac{D}{2}$  is the mean radius &  $z$  is the number of blades
- ▶ **An important geometry parameter that influences the design and the performance**

# Cascade View: Low & High Solidity

✓ suitable for turbomachinery – easy for summarization and WW

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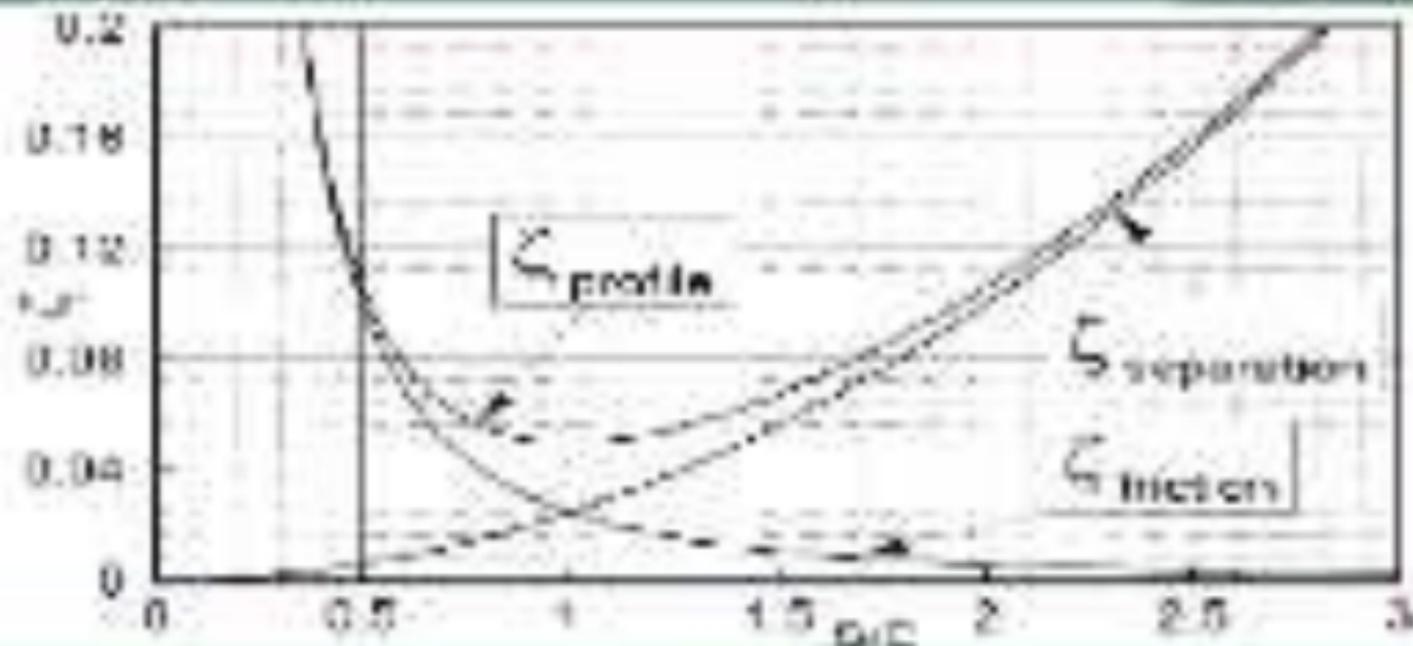


$$\alpha = \frac{zN_B}{2\pi r_{in}}$$

## Solidity & Losses

- > If the spacing between the blades is too small:
  - > implies design with large number of blades
  - > High friction losses
- > Too little spacing:
  - > Reduced number of blades
  - > Less friction but increased separation losses due to less flow guidance in the passage spacing (due to less number of blades)
- > Profile Losses =  $\zeta_0 - \zeta_{0,ideal} = \zeta_{separation}$

# Optimum Solidity



# A Semi-Empirical Relation

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Upstream stability calculated from  
Cowell, Christiani

$$\text{Upstream stability} = \frac{2.5 \cos \beta_2 \bar{y}_2}{\cos \beta_1} \sin(\beta_1 - \beta_2)$$

## Lift & Drag on Blades

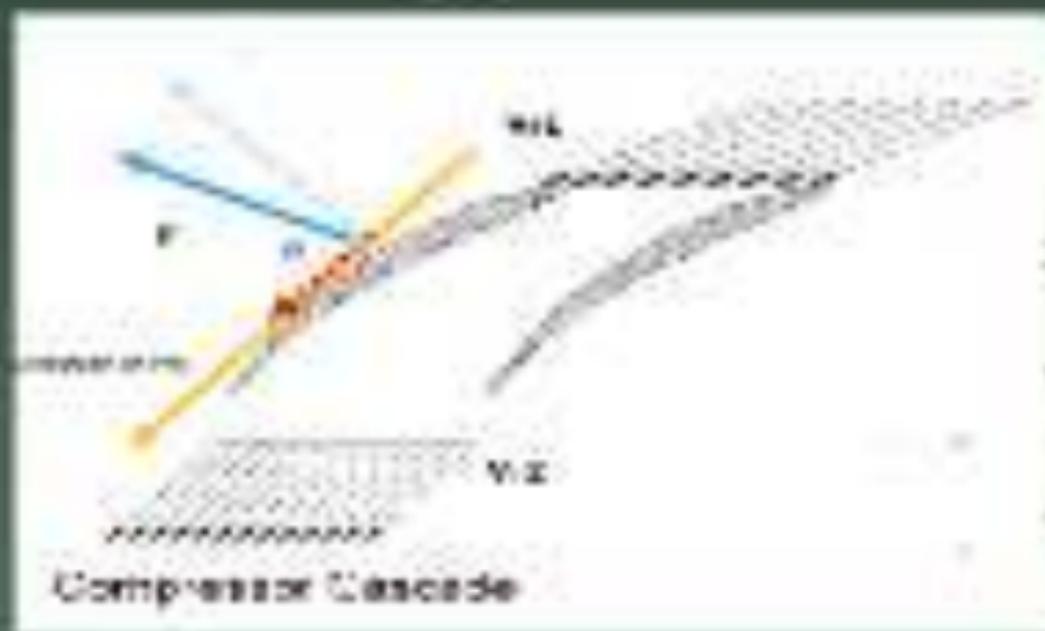
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## Forces Acting on the Blades

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# Forces & Power

The resultant force on each blade  $F = f(L, D)$

Net Torque due to this force,  $T = n a r F$

Power required to rotate,  $P = T \omega = n_D r F \omega$

Note that this is related to the Hines/Dynalene relation:

— "Fig 5.10" 1980



LTerd: 5,20 (m)

Spacing: 1,5 (m)

→ Solibty: 0,25/0,5 - 1,0



# AIR BREATHING ENGINES



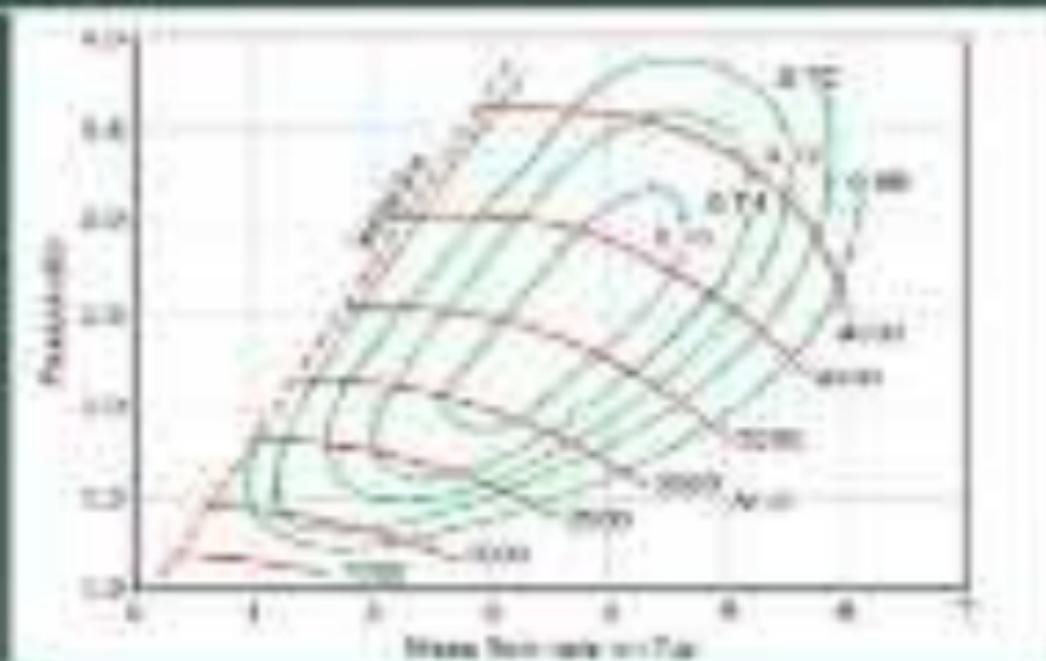
Session 17 – Performance  
Parameters & Mapping

DR. A.R. SRIKISHNAN



**AMRITA**  
UNIVERSITY

# Performance **MAPPING**



# Compressor Performance Evaluation & Mapping

- Quantification of the performance
- Comparison of performance
- Identification of operating conditions as the performance of a given compressor
- Comparison of different compressors at similar operating conditions

All these require:

Identification of parameters that influence the performance

Relationship with other parameters

Mapping of performance as a function of operating conditions

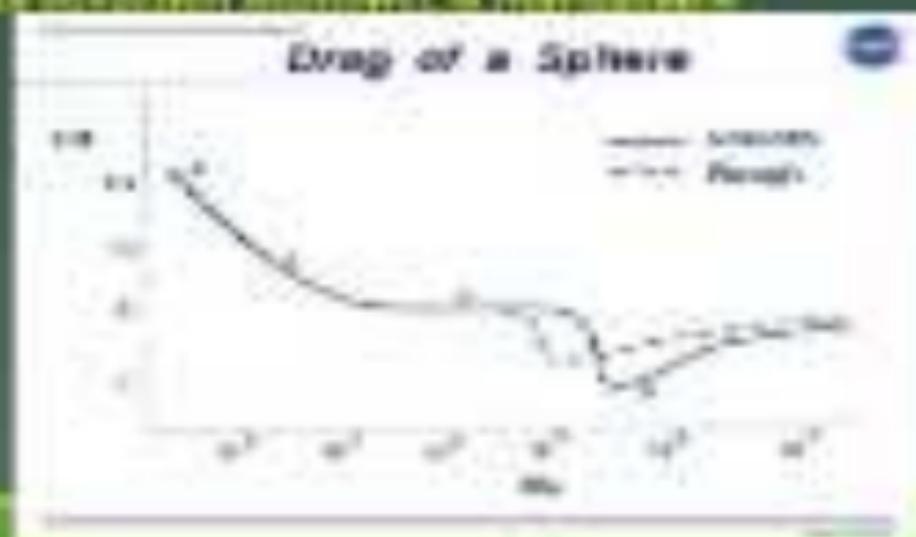
# Performance Characterization

---

- Focussed on quantifying the influence of a set of parameters that are identified as key variables on the desired performance parameters
  - Operating conditions
  - Geometric parameters
- Identify the set of parameters
- Reduce them to preferably dimensionless amount
- Determine the influence of functional groups on key performance parameters

## Dimensional Analysis

- The initial procedure by which a group of variables impacting a physical process is reduced to a smaller number of independent variables.
- Enables experimental data on different systems to be compared.
- Applied successfully for 1000s of years.



# Compressor Performance

Flow coefficient  
 $\dot{m} \sqrt{v_1}$   
Pressure coefficient  
 $\frac{P_2 - P_1}{\rho v_1^2}$

Fluid  
viscosity

Fluid  
Density

Fluid  
Compressibility  
→ ~~compressibility~~

Speed of  
Rotation

Mass flow  
rate

Ratio of  
specific heats

# Performance parameters of Interest ?

---



# Non-Dimensional Functional Relations

---

$$\frac{P_{10}}{P_{00}} = f \left\{ \frac{nr\sqrt{RT_{00}}}{D^2 \rho_{00}} = \frac{ND}{\sqrt{RT_{00}}} = \text{Re. } r \right\}$$

Dimensional analysis indicates that the functional relation between the two variables is independent of  $r$  at high flow rates,  $r \gg 1$ , i.e.  $\text{Re. } r \gg 1$ .

$$\frac{\eta_{0,1}}{\eta_{0,2}} = f\left(\frac{\rho_1 \sqrt{C_p T_{01}}}{D^2 \rho_{01}}, \frac{\eta_{01}}{\sqrt{\gamma R T_{01}}}\right)$$

- For a given engine:  $D$  is constant
- For a given working fluid (air):  $C_p$ ,  $R$  is  $\gamma$  are constant
- Hence:

$$\frac{\eta_{0,1}}{\eta_{0,2}} = f\left(\frac{\rho_1 \sqrt{T_{01}}}{D^2}, \frac{\eta_{01}}{\sqrt{T_{01}}}\right)$$

# Compressor Testing & Atmospheric Conditions

- Dependence of the Mass Flow on Atmospheric Conditions of Pressure & Temperature

Both the mass flow  $\dot{m}$  and the compressor speed  $n$  are dependent on the atmospheric conditions of pressure  $p_a$  and temperature  $T_a$ .

Both these parameters to remain the same:

That is,  $\left(\frac{\dot{m}}{\sqrt{T_a}}$  and  $n \sqrt{T_a}$  are constant) is obtained by speed by  $\left(\frac{\dot{m}}{\sqrt{T_a}}$  are constant variables of any compressor.

Similarly, for the mass flow parameter to be used

## Corrected Mass & Speed

- In industry, usually the thrust coefficient (for a given weight) is expressed in terms of

thrust **corrected** mass flow:

$$\frac{d\sqrt{\theta}}{t}$$

thrust **corrected** speed:

$$\frac{a}{\sqrt{\theta}}$$

$$\dot{m} = \frac{T_{\text{net}}}{Y_a} \quad \text{and} \quad a = \frac{C_{y_2}}{C_{x_2}}$$

$$\frac{C_{y_2}}{C_{x_2}} = \sqrt{\left( \frac{d\sqrt{\theta}}{t} \right)^2 + \left( \frac{a}{\sqrt{\theta}} \right)^2}$$

# Numerical Problem

During a compressor test in the laboratory, the compressor runs at 100% design speed and ingests air at the rate of 52 kg/s. The compressor pressure ratio (compression ratio) that may vary is specified as 2.00:1.0 and 2.80:1.0, respectively. Determine the corrected mass flow and the corrected RPM corresponding to standard atmospheric conditions of pressure = 101.325 kPa, & temperature = 288 K.

$$\theta = \frac{T_{ref}}{T} \quad \text{and} \quad \phi = \frac{P}{P_{ref}}$$

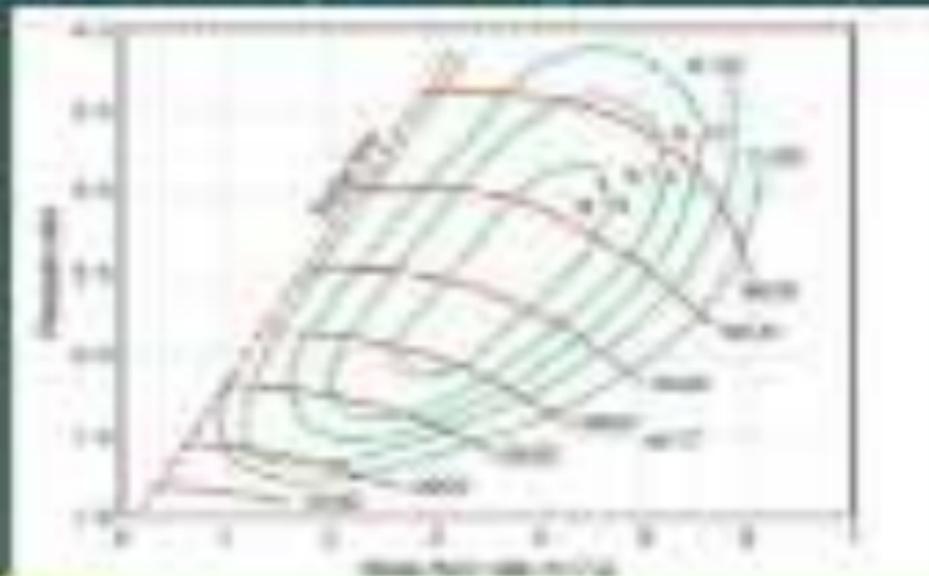
$$\frac{\dot{m} \sqrt{\theta}}{\phi}$$

$$\frac{N}{\sqrt{\theta}}$$

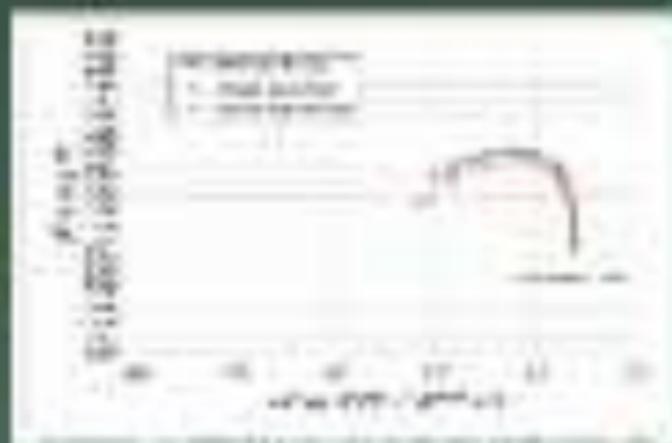
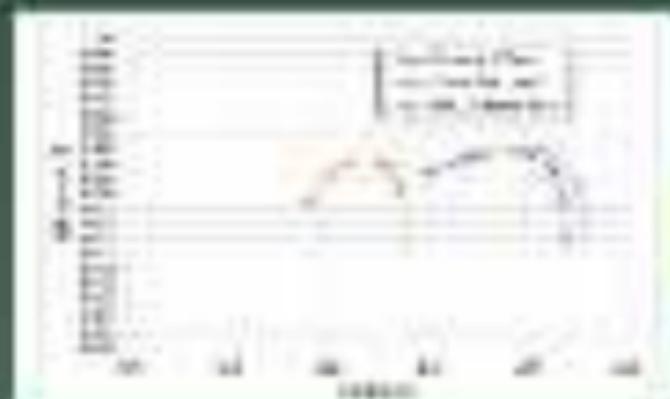
Face	Radius (mm)	Area cm <sup>2</sup>	Flow Direction	P (kPa)	T (K)	$\rho$ (kg/m <sup>3</sup> )	Velocity (m/s)
Inlet	100	3141.59	Inlet	101.325	288	1.225	120

# Compressor Performance Map

The pressure ratio of a compressor is plotted against its corrected mass flow rate and rotational speed.

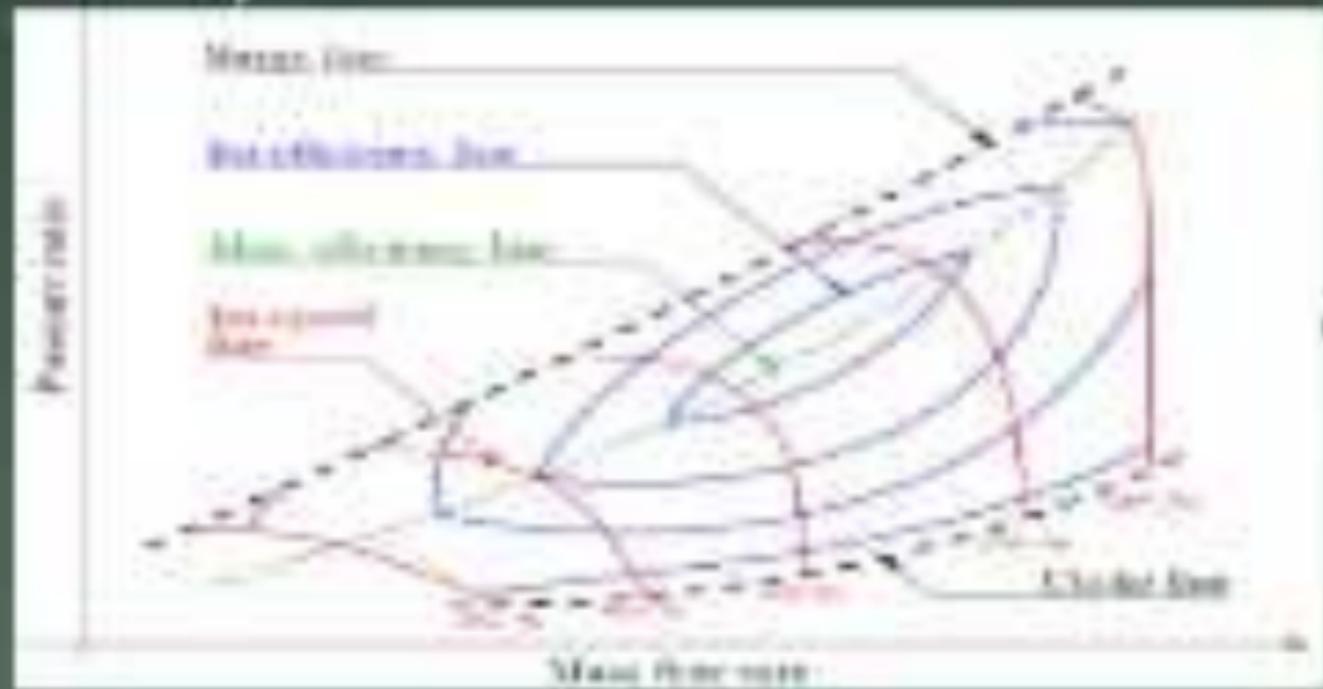


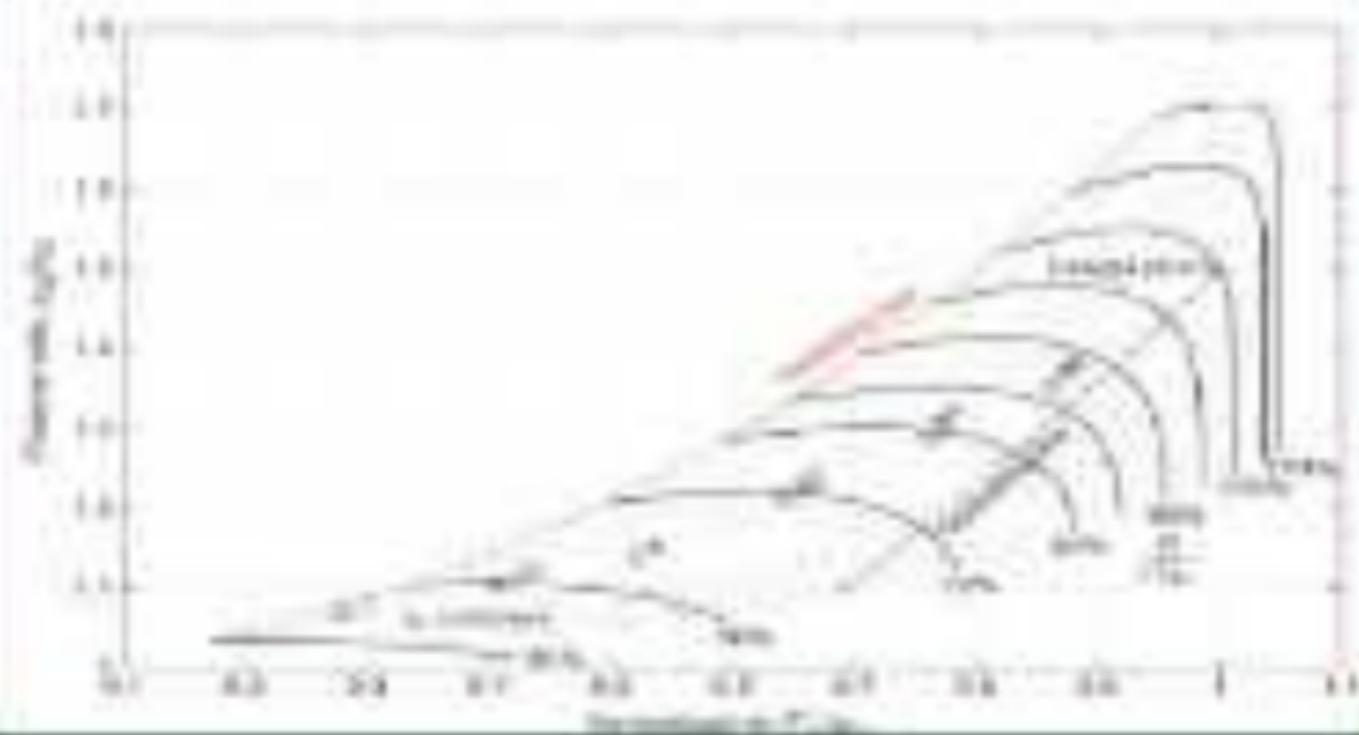
# The Utility of *Corrected* Parameters: Comparison Across Diverse Operating Conditions



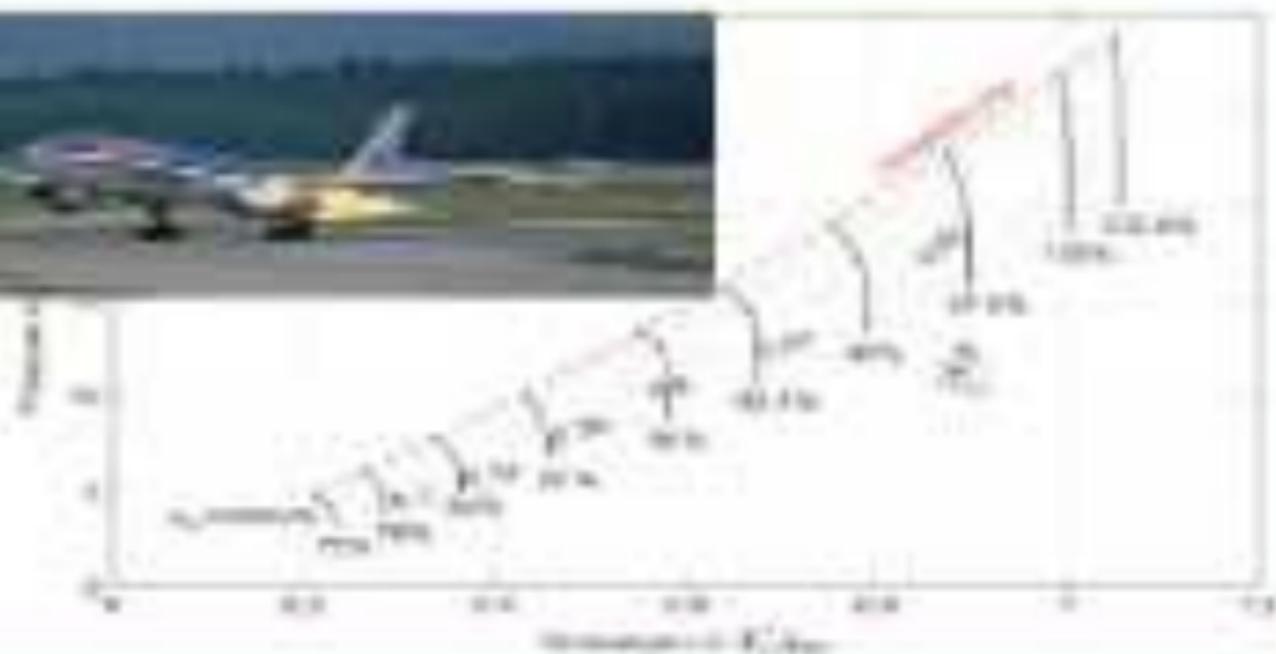
Christof Meiß, J. Neftci

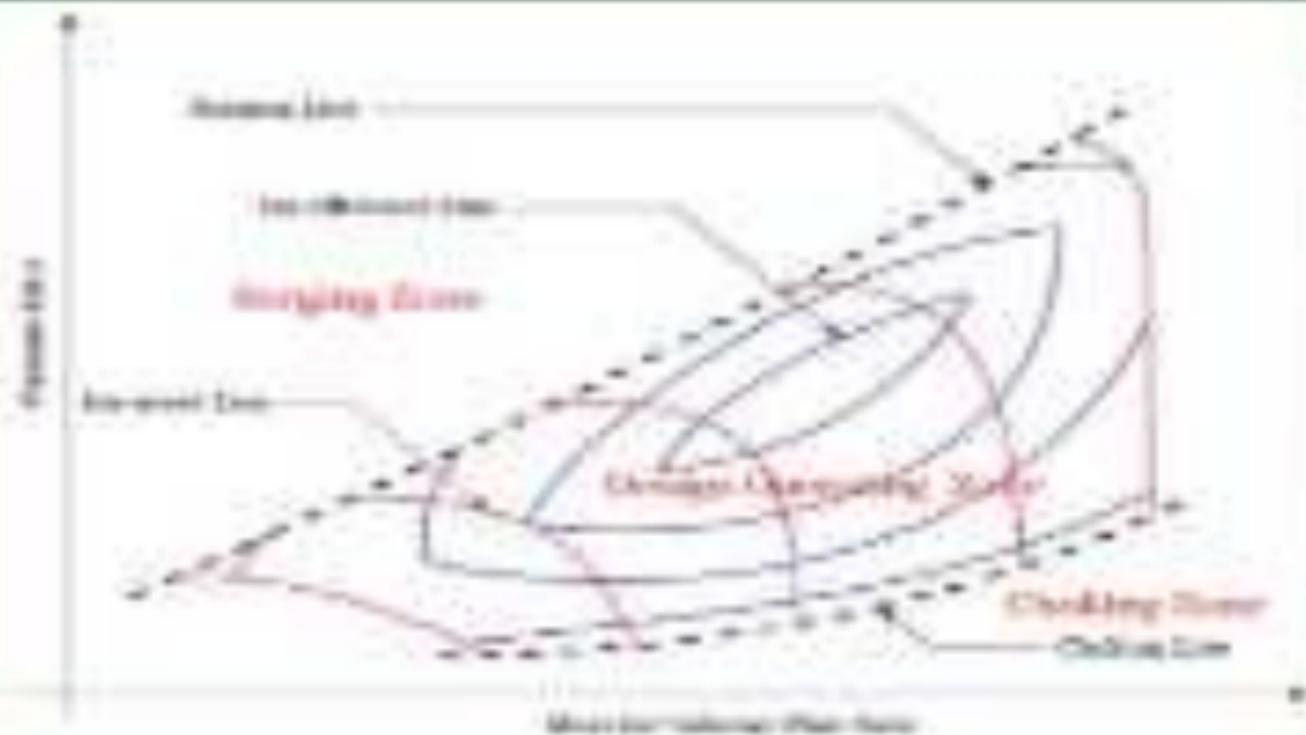
# Compressor Performance Map





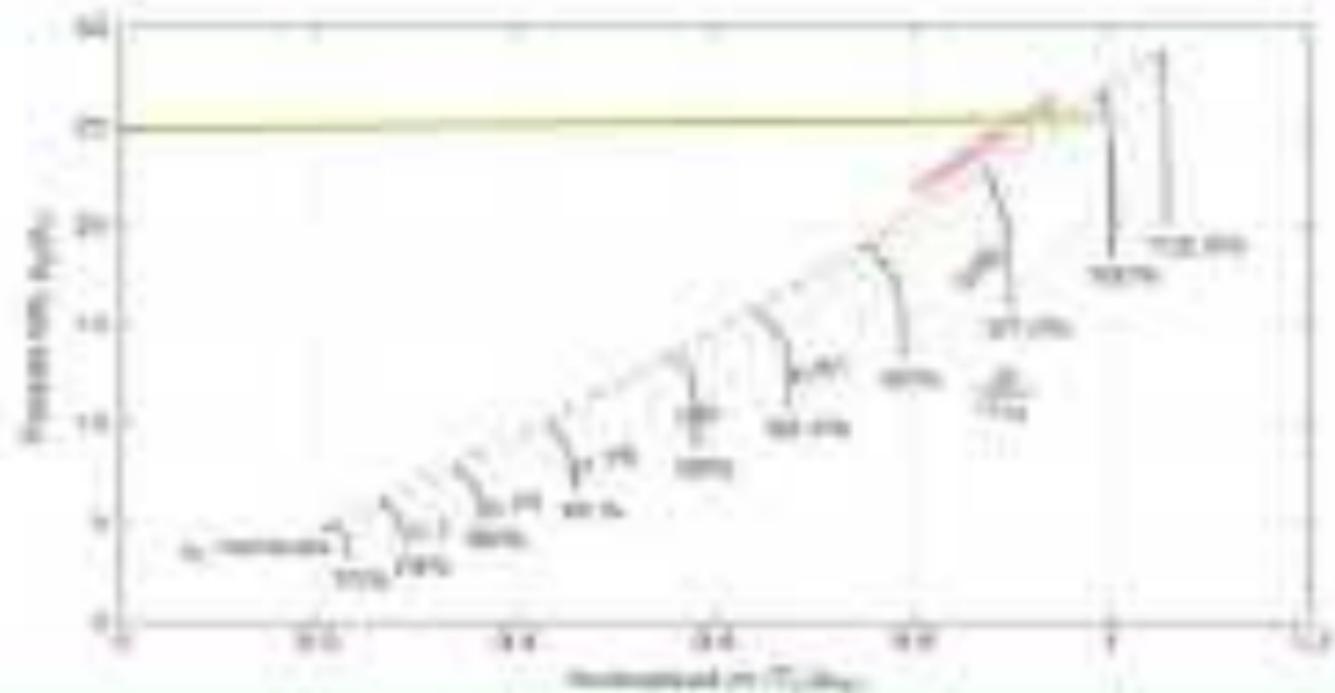
## Surge/Dynamic Instability











# AIR BREATHING ENGINES



Session 1B:  
Off-design  
Performance

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## The Off-design Challenges

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- > The Design is made to suit a specific flow rate, specific speed, specific density etc.
- > but during an entire cycle of operation, the engine should go through several operating conditions
- > And should perform reliably and with fairly good efficiency
- > off-design: How they work when **All Is not well...**

## "Isolated Stage" Vs Multi-stage

---

The variation from design performance progressively increases

- A minor variation at the first stage may gradually get enhanced as the air flows through subsequent stages
  - Successive improvements at the flow are added for each stage. Next stage repeat the work done by the stage
  - Lesser the work, lesser the delay at the inlet to the next stage. The less repeats the theoretical flow design value
  - This continues...
- How this affects the flow field and overall performance?

# Compressor Stall ...



Stall: Flow separation caused by the failure of flow over the outer blade

- An inherently unstable phenomenon
- Leads to drop in efficiency

Flow becomes turbulent near leading edge when air starts

- backflow. When it happens there is a  $\beta$  value
- depends on the nature of the turbulence. When it is known, stall always occurs before the maximum efficiency





a) Separation of wall cells, boundary layer separation, due to an increase of positive incidence angle



b) Separation of wall cells, reflection of velocity direction caused by wall cells

# Stall Propagation & Development of **Surge**

---



Onset of stall cells to surge

## Surge Line/Instability line

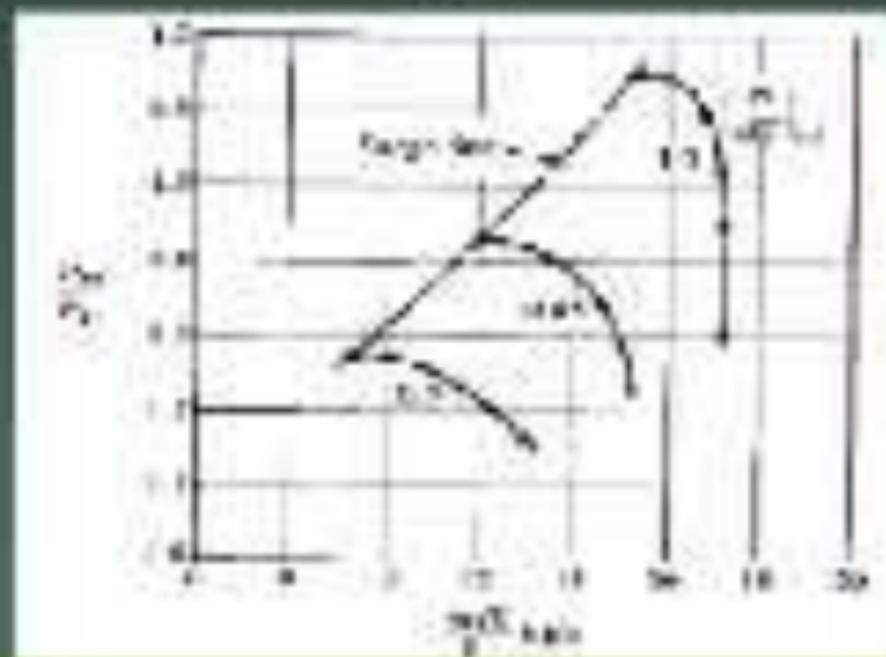


## Compressor Surge

---

- Surge is a condition of instability in the operation of compressor stages resulting reversal of flow in the compressor and even in the engine
- Surging takes place when the flow rate being handled is reduced to a point where insufficient pressure is being generated to maintain flow
- Can lead to strong vibrations, reversal of flow from the combustor through the compressor etc.
- Can be hazardous if left uncontrolled

# Compressor Surge



# Surge Videos

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[https://www.youtube.com/watch?v=UW11E1111111](#)



[https://www.youtube.com/watch?v=UW11E1111111](#)



[https://www.youtube.com/watch?v=UW11E1111111](#)



# AIR BREATHING ENGINES

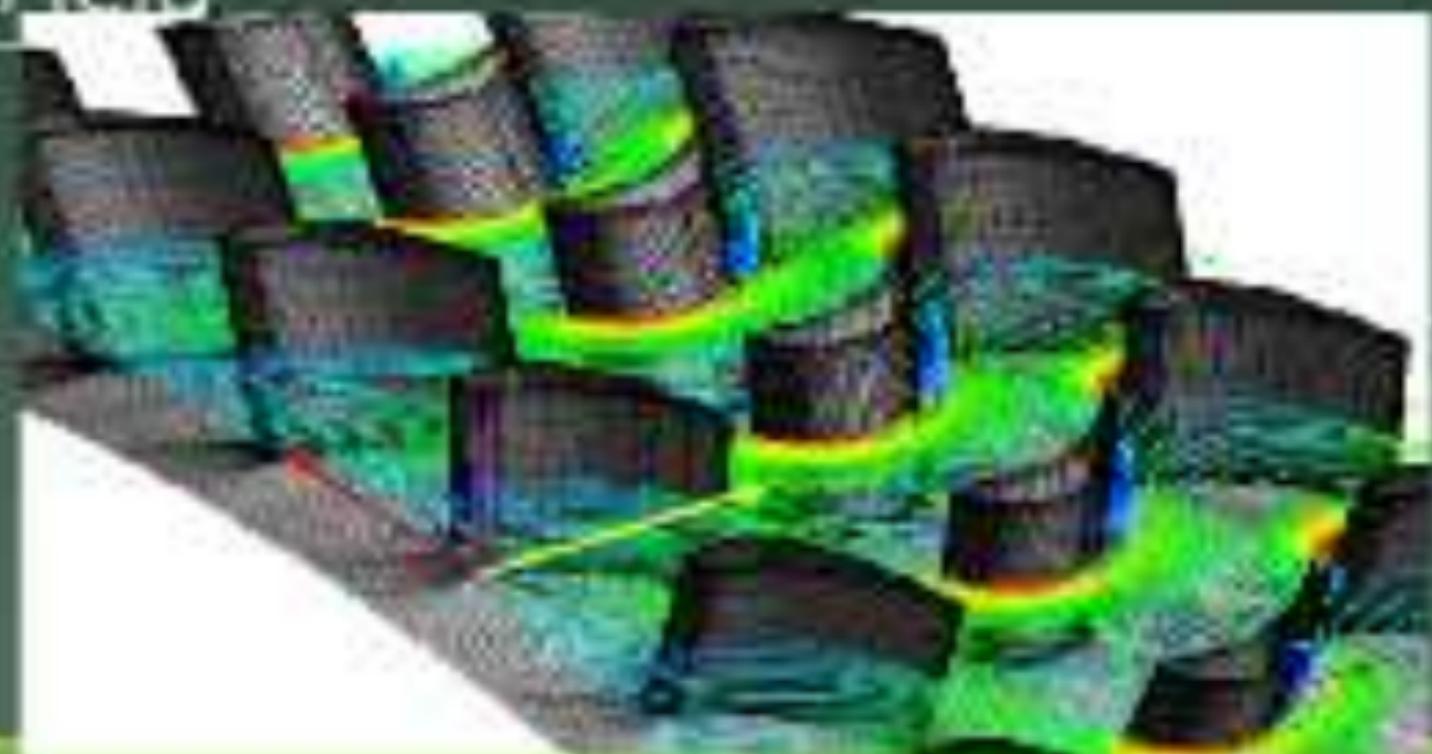


Sessions – Radial  
Equilibrium

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# Three Dimensionality of Flow Field

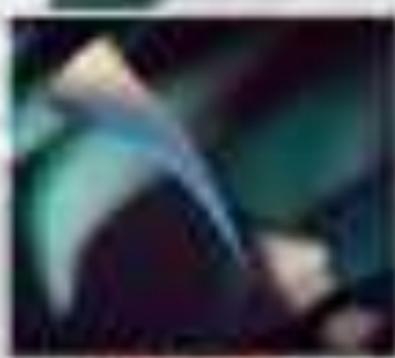




00001 0 0 000



00004 0 000



00007 0 000



00010 0 000

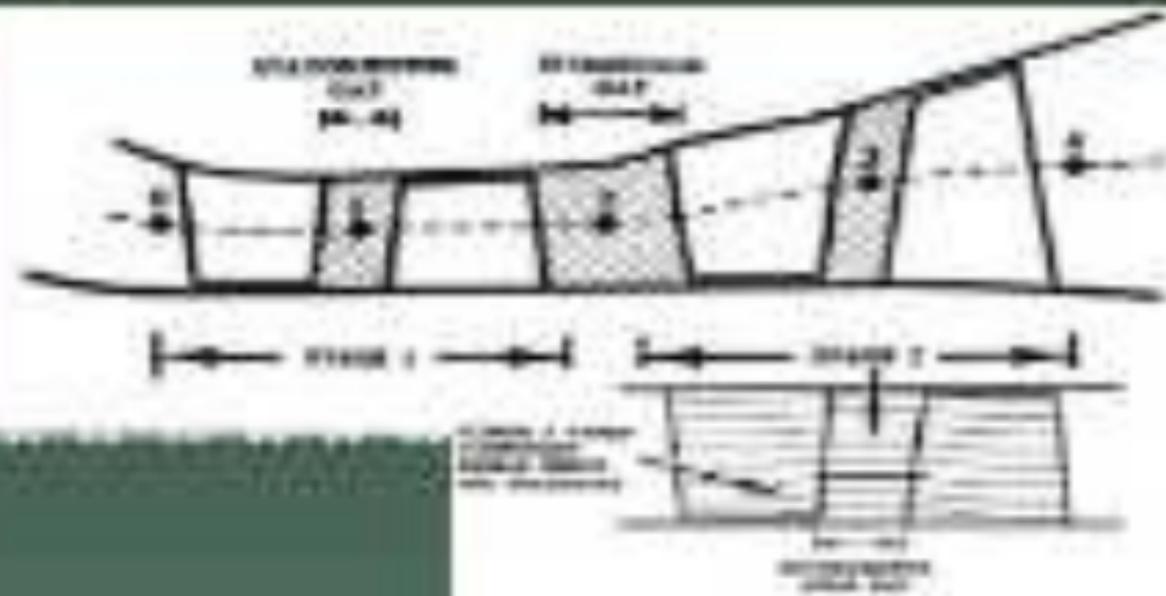
Courtesy of Walter Meyer

## Radial Direction: Hub Radius ( $R_H$ ) and Tip Radius ( $R_T$ )

---



# Flow Across the Blades



# Flow Velocity Direction

---

- ◆ **Flow Velocity Direction**
- ◆ **Axial flow: Main direction**
- ◆ Tangential Velocity: Related to momentum exchange
- ◆ **Radial Flow: Normal to axial & Tangential velocity**
  - ◆ To be minimized/avoided for good performance
  - ◆ Flow along blade height

## Flow in Radial Direction

---

- ✓ We are already familiar with the variation of blade velocity ( $U$ ) in radial direction
  - ✓  $U = r\omega$
  - ✓ So far we did calculations at a given radius – So for a given  $U$ 
    - ✓ No consideration of flow deflection varies at different radii...
- ✓ How other properties vary along radial direction ?

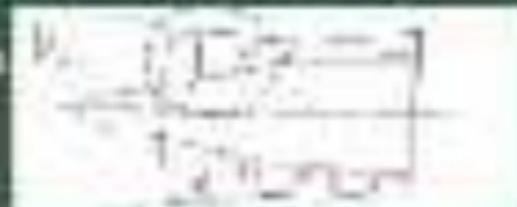


# Hub-to-Tip Variation

---

- ✓ **Radial flow:**

- ✓ In the direction of centrifugal forces



- ✓ **Not critical if  $D_{tip}$  radius/hub-radius is low**

- ✓ **Of significant concern otherwise**

- ✓ The centrifugal field distorts the flow velocity profiles considerably.
  - ✓ Fluid particles tend to move outwards rather than passing along cylindrical stream surfaces.

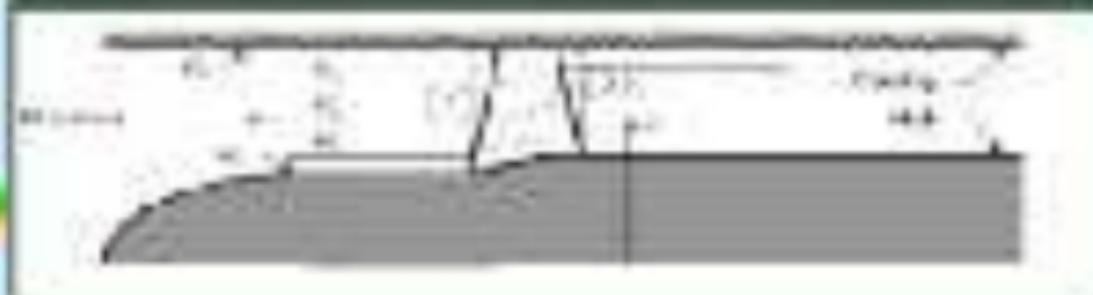
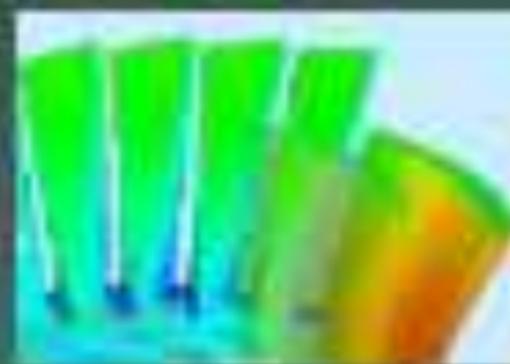


Dorsal fin

Pectoral fin

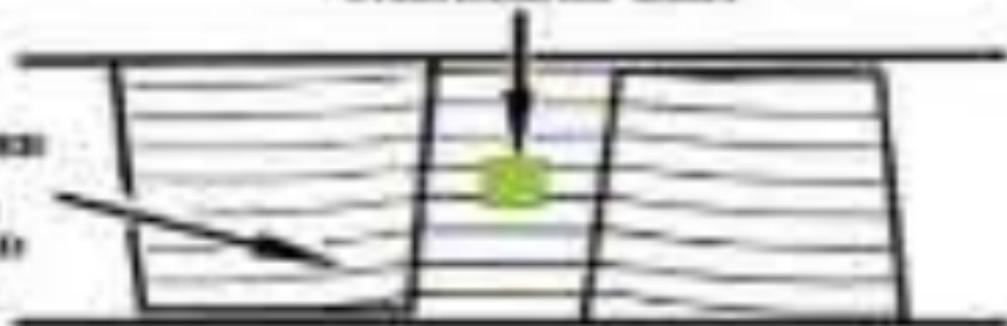
# The Assumption of Radial Shift

500047p, 11005011L, 14007011101160, 1401111411p



# Radial Septs

ASSUMPTION  
ACROSS THE CAP  
NO RADIAL SEPTS  
IN THE MERIDIONAL  
STREAMLINES EXIST



ACROSS A VARIOUS  
COMPONENT  
RADIAL SEPTS  
ARE TOLERATED

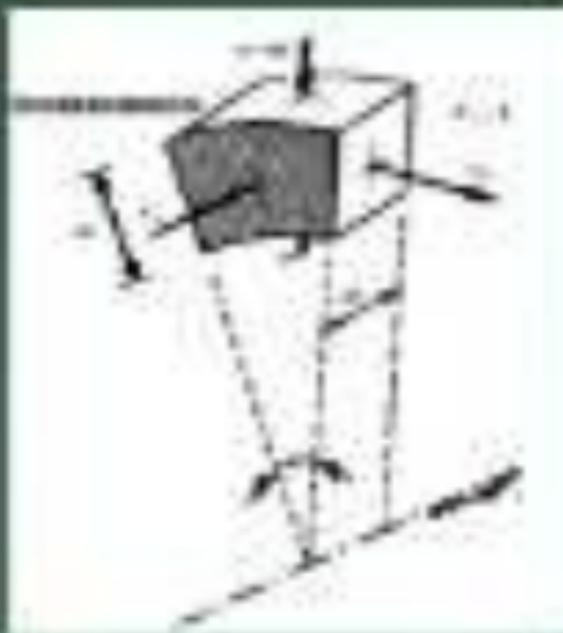
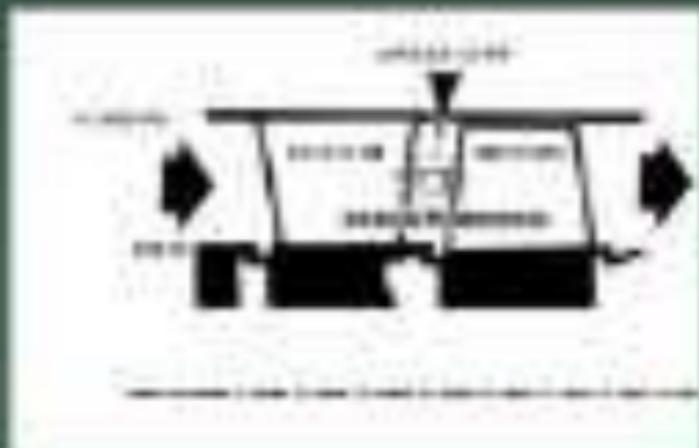
STATOR ROTOR  
AXIAL CAP

# Force Balance in the Radial Direction

- In axial flow compressors or turbines, the working fluid has a rotational and translational motion.
  - The rotating fluid is subjected to centrifugal forces that must be balanced by the pressure gradient in order to maintain their radial equilibrium.
    - A radial pressure gradient is necessary to be maintained.
  - Balance of pressure gradient and the centrifugal force on a rotating fluid element.



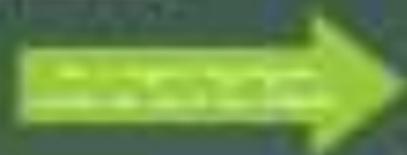
# Fluid element



# Radial Equilibrium of The Fluid Element

$$F_r = (p + \Delta p) \sin \theta - p \cos \theta - 2 \left( p + \frac{\Delta p}{2} \right) dr \sin \left( \frac{\theta}{2} \right)$$

$$\rightarrow \left( \frac{\partial p}{\partial r} \right) = \frac{\rho v^2}{r}$$



$$F_p = r \rho v^2 \sin \theta$$

$\sin \theta = 1$  (just like we've assumed in the case of the skis)



# The Centrifugal Force



As a result of the rotation, the fluid element is displaced from its original position.

The centrifugal force  $F_c = m\omega^2 r$

$V = r\omega$

$$F_{centrifugal} = \rho V \omega^2 r dr d\theta$$

# Equilibrium

When the forces are in equilibrium, the element will move along constant radius if

$$F_{\text{pressure}} = F_{\text{centrifugal}}$$

$$r dp d\theta = \rho V_{\theta}^2 dr d\theta$$

$$dp = \rho V_{\theta}^2 \frac{dr}{r}$$

For  
conditions  
see notes at  
[www.ewb.co.uk](http://www.ewb.co.uk)

# Uniform work distribution along radial direction



Stagnation enthalpy at any section:

$h_0 = h + \frac{V^2}{2}$  (total enthalpy)

$$h_0 = h + \frac{V^2}{2}$$

$$dh = \frac{dp}{\rho}$$



$$dh = V_{\theta}^2 \frac{dr}{r}$$

$$dh_0 = V_{\theta}^2 \frac{dr}{r} + d\left(\frac{V_x^2}{2} + \frac{V_r^2}{2} + \frac{V_{\theta}^2}{2}\right) = 0$$

$$\frac{dh_0}{dr} = \frac{V_\theta^2}{r} + \frac{d}{dr} \left( \frac{V_r^2}{2} + \frac{V_z^2}{2} + \frac{V_\theta^2}{2} \right) = 0$$

$$\frac{dh_0}{dr} = \frac{V_\theta^2}{r} + V_r \frac{dV_r}{dr} + V_z \frac{dV_z}{dr} + V_\theta \frac{dV_\theta}{dr} = 0$$

Wiederholung  
unveränd.  
Impuls

$$\frac{dh_{\theta}}{dr} = \frac{V_{\theta}^2}{r} + V_{\theta} \frac{dV_{\theta}}{dr} + V_{\theta} \frac{dV_{\theta}}{dr} = 0$$

Cancel  
the  
terms

$$\frac{d}{dr}(rV_{\theta}) = 0$$

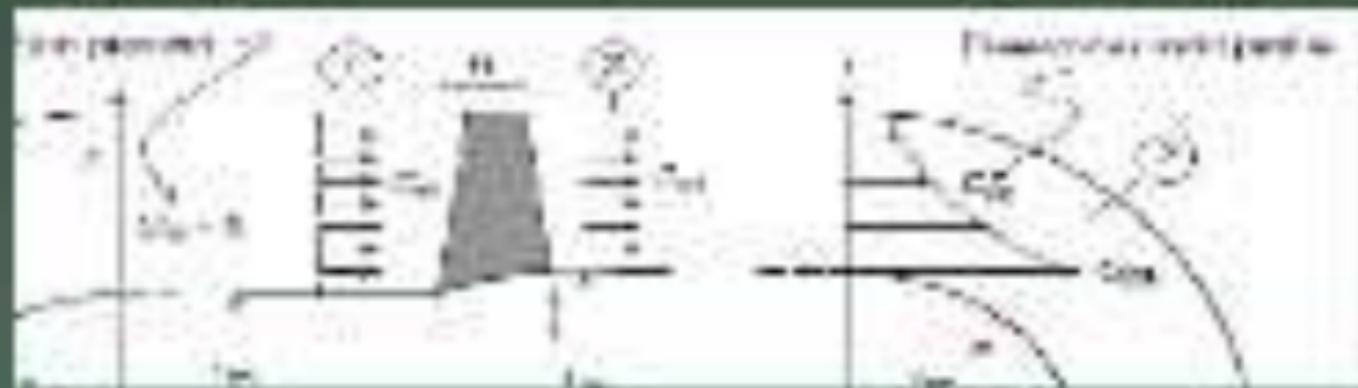
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$V_{\theta} r = \text{Constant}$

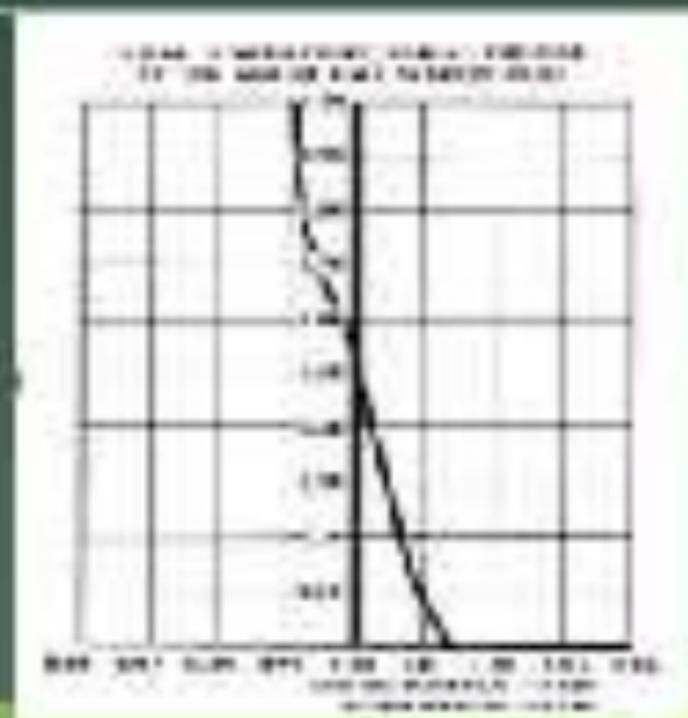
$$\frac{d}{dr}(rV_{\theta}) = 0$$

$$V_{\theta} r = \text{Constant}$$

Implication: how fluid properties & the force supported by rotating vanes relate to the velocity profile & the design



# Experimental data on radial distribution of $T_o$ <

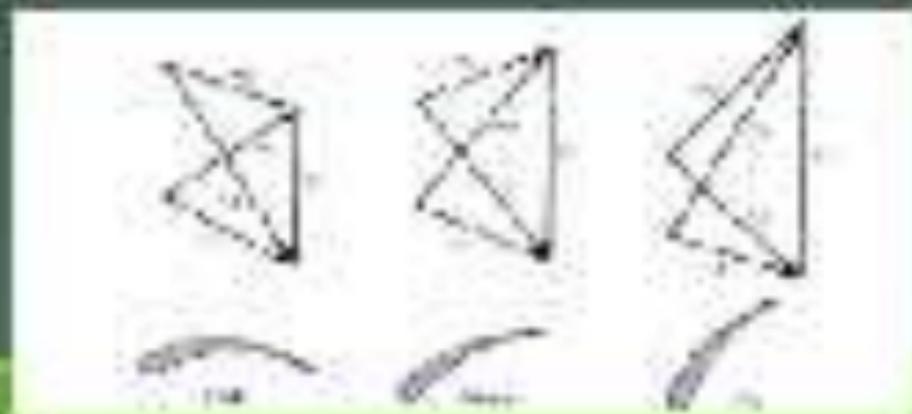


# Free Vortex Design

- One of the popular methods in tidal energy
- An **axial** flow turbine associated to vertical flow
- But results in highly twisted blades: blade angle varies significantly from the root to the tip
- Velocity triangles vary in shape across the radial span



• Results in highly twisted blades



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1888-1889

# AIR BREATHING ENGINES



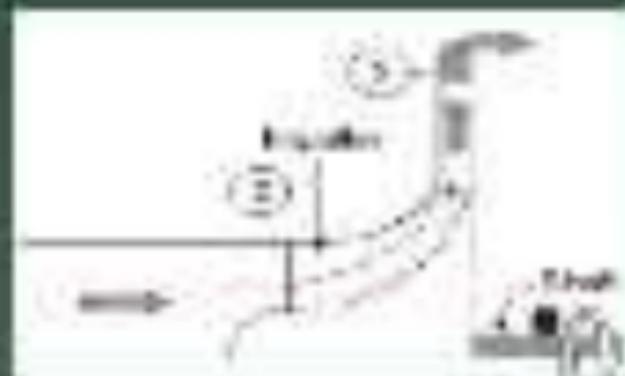
Sessions:  
Centrifugal  
Compressors

DR. A.R. SRIKISHNAN

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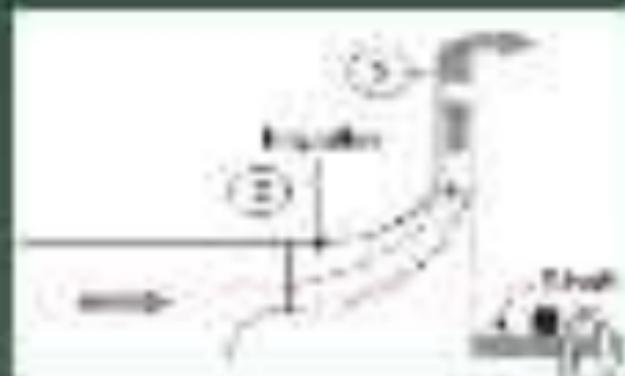
# Centrifugal/RADIAL Compressors

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# Centrifugal/RADIAL Compressors

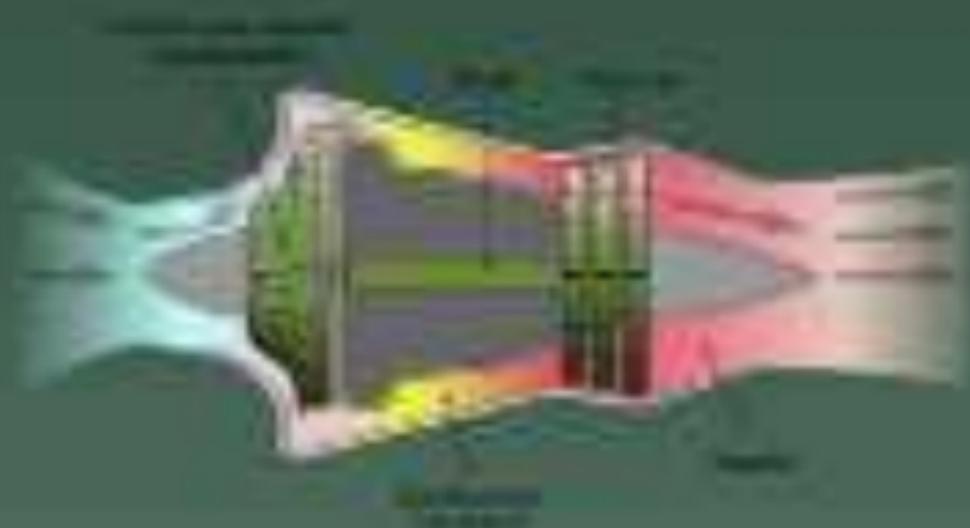
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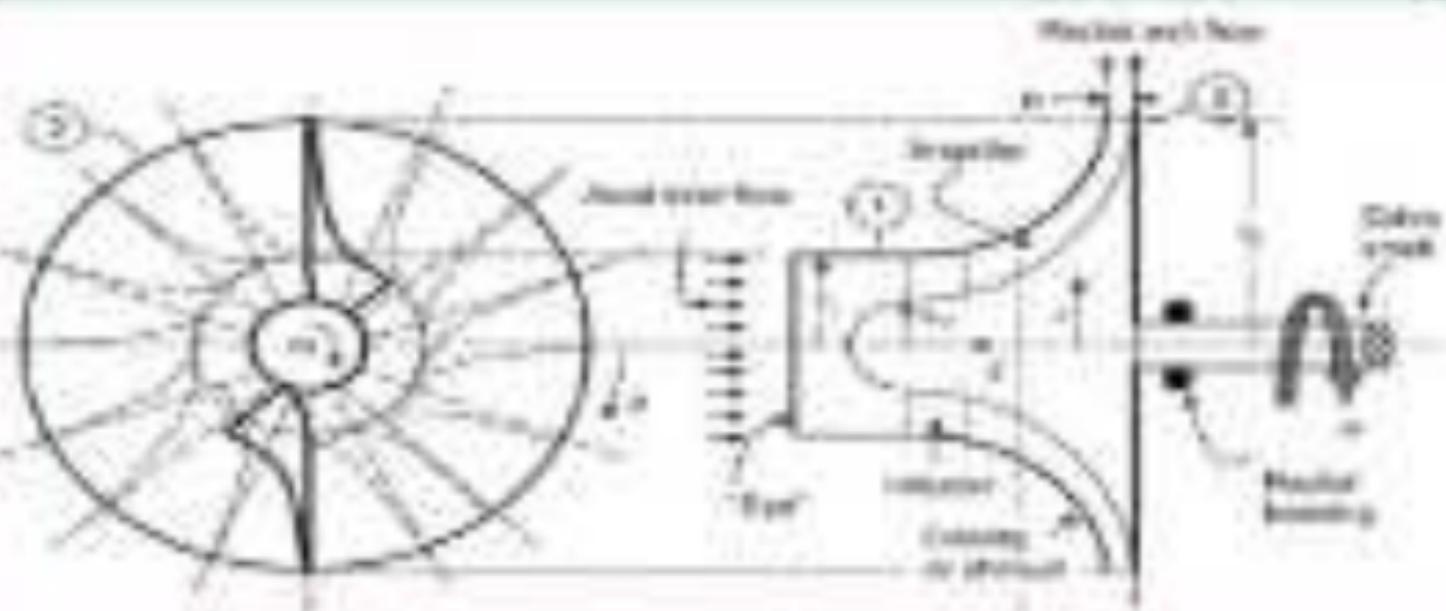


# CENTRIFUGAL Compressors

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# Components

---

## Translator

- Processes a sketch, the usual flow for a computer language, and sends it to the compiler

## Compiler

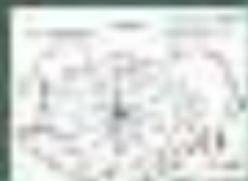
- Analyzed strings  
- It reports the violations and issues, if any, of the temperature, as well as the static properties

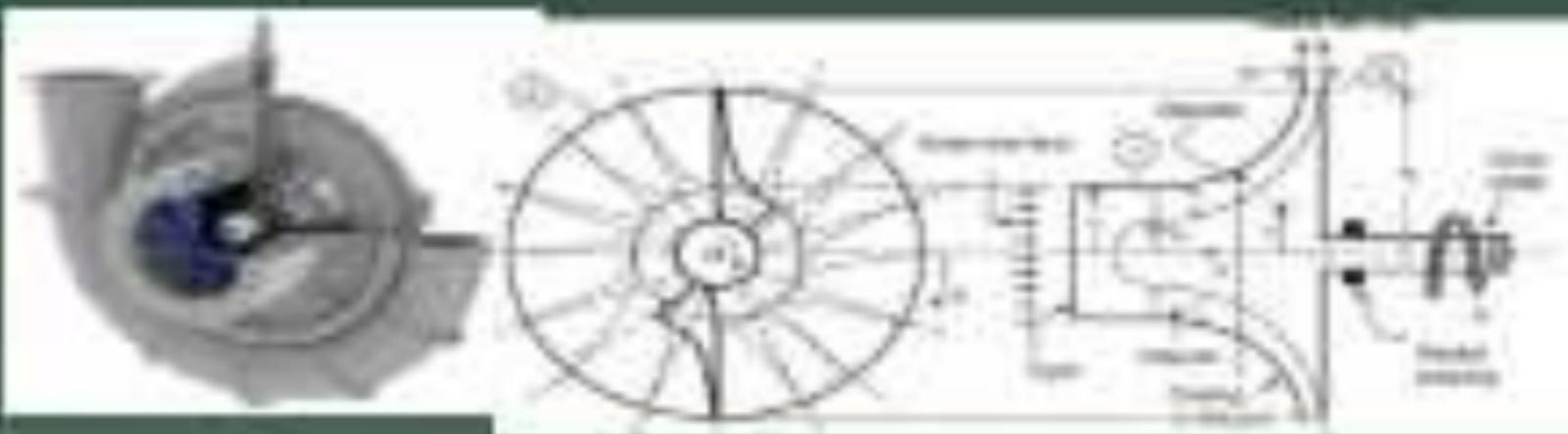
## Optimizer

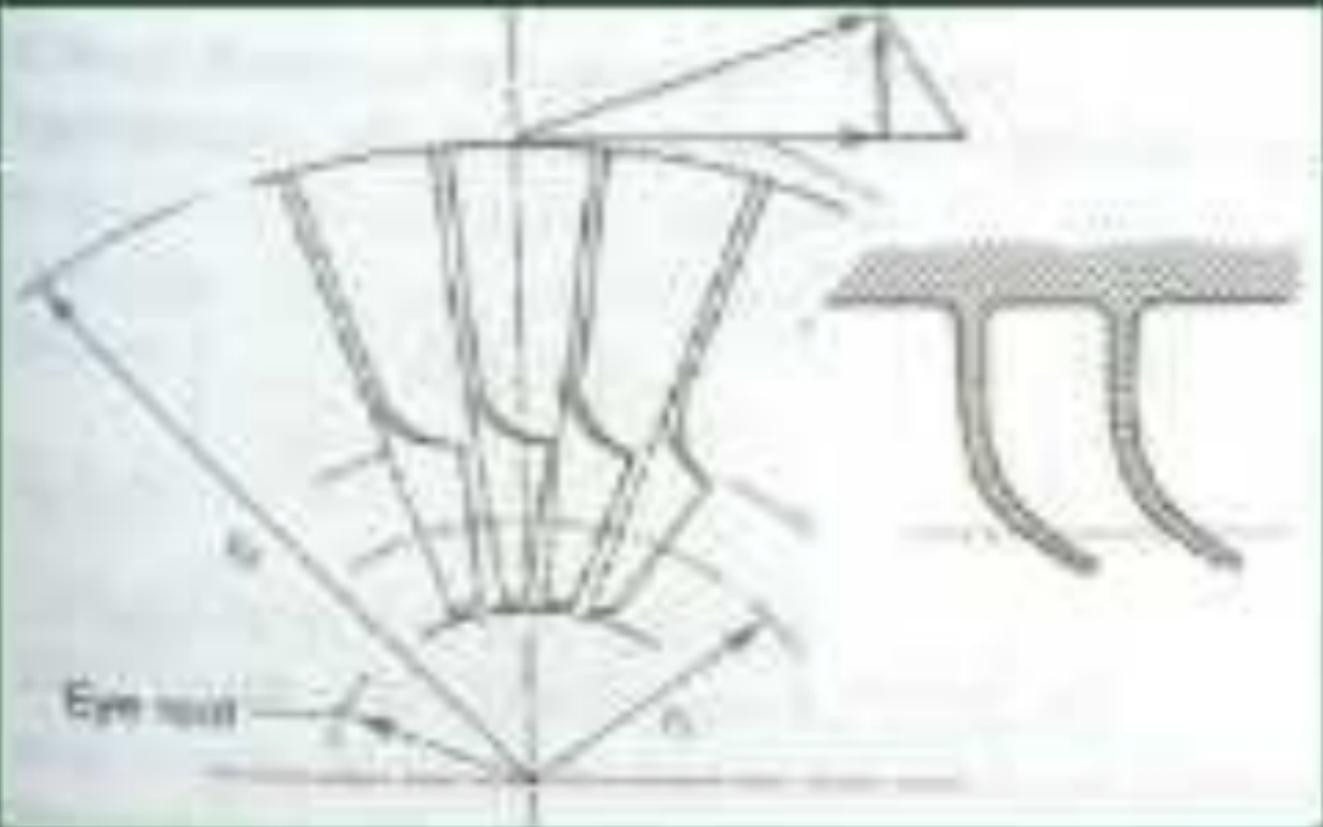
- It removes static properties by identifying the flow

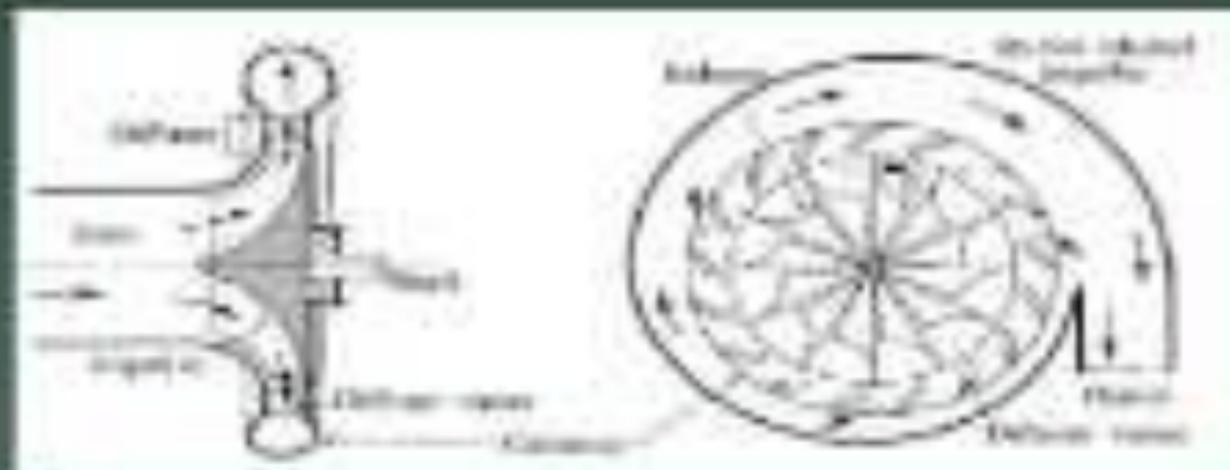












# Work transfer in Radial Compression

$$\text{Work Transfer} = \dot{m} C_p (T_{02} - T_{01}) \\ = \dot{m} (h_{02} - h_{01})$$



Since  $r_2 = r_1$ , even a small increment in  $V_2$  can lead to high difference in  $T_2$ .

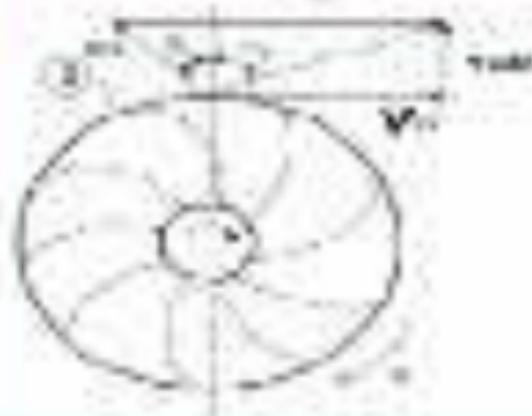
Hence typically centrifugal compressors support higher stagnation pressure ratio per stage



# Backward-leaning blades

Backward swept impeller has passages that direct the relative flow in a direction opposite that of the rotor rotation.

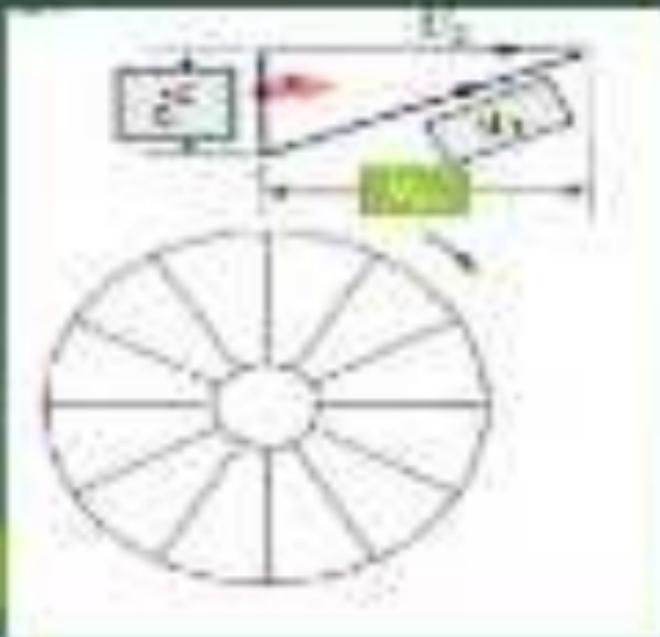
The blades are mounted from roots  
outward.



# Straight/Radial Blades

The turbine is designed in such a way that the flow leaves radially outwards - Remains along the radius all through the passage

At the inlet, the flow is radial



Flow is  
radial

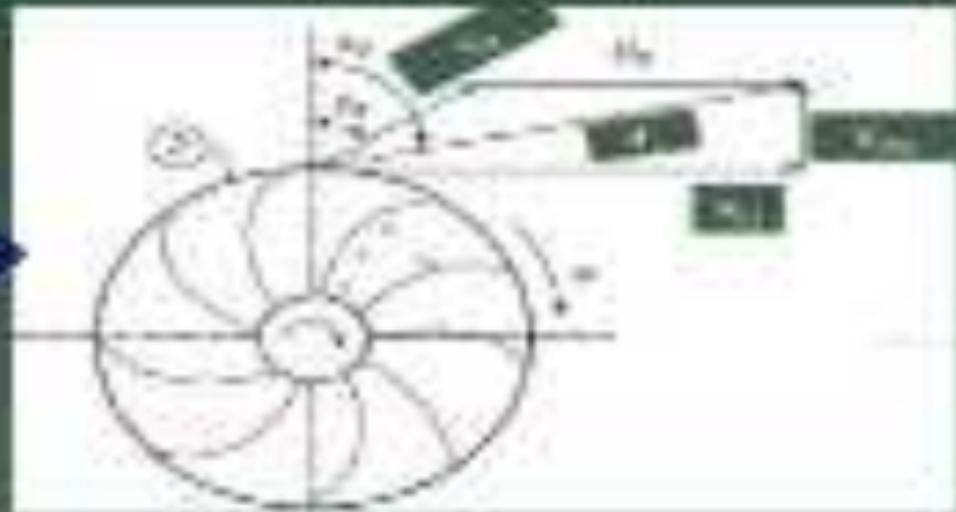
Flow is  
radial

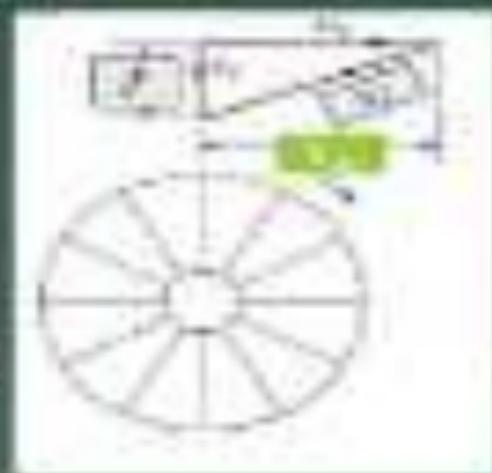
Flow is  
radial

Flow is  
radial

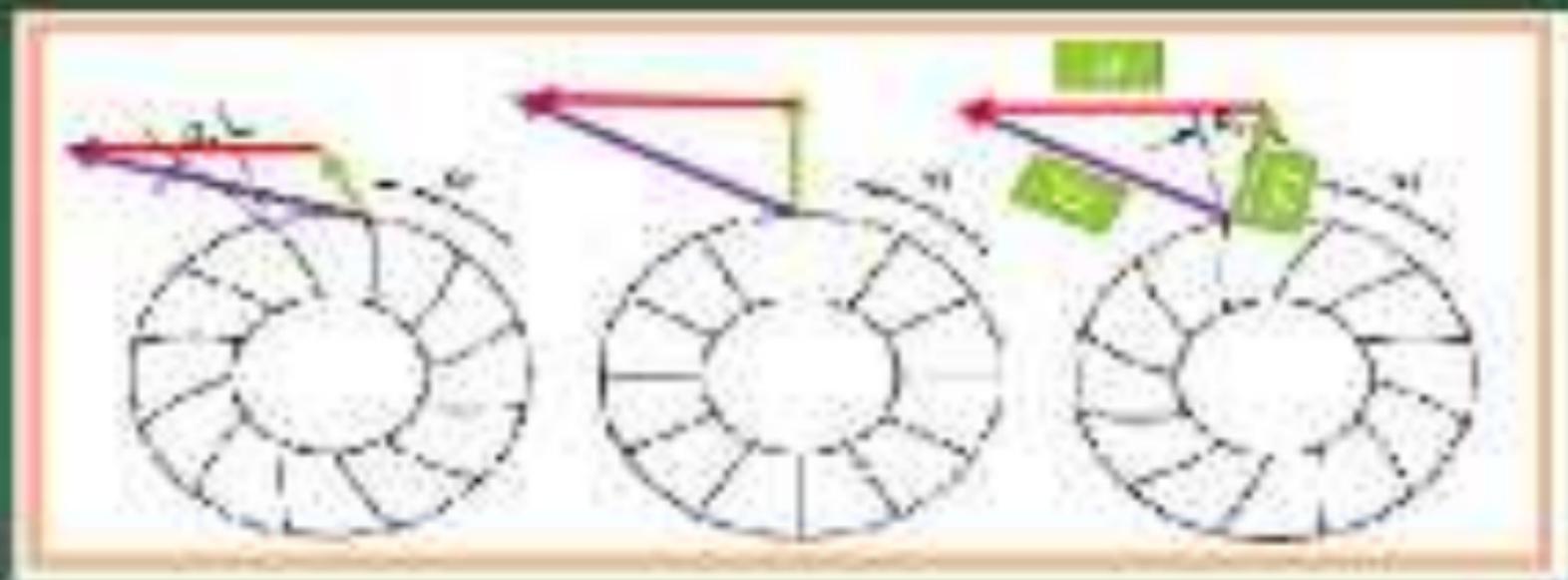
## Forward-leaning blades

The forward leaning geometry  
increases the axial passage  
length in the direction of  
the rotor rotation.





## Exit Velocity Triangles



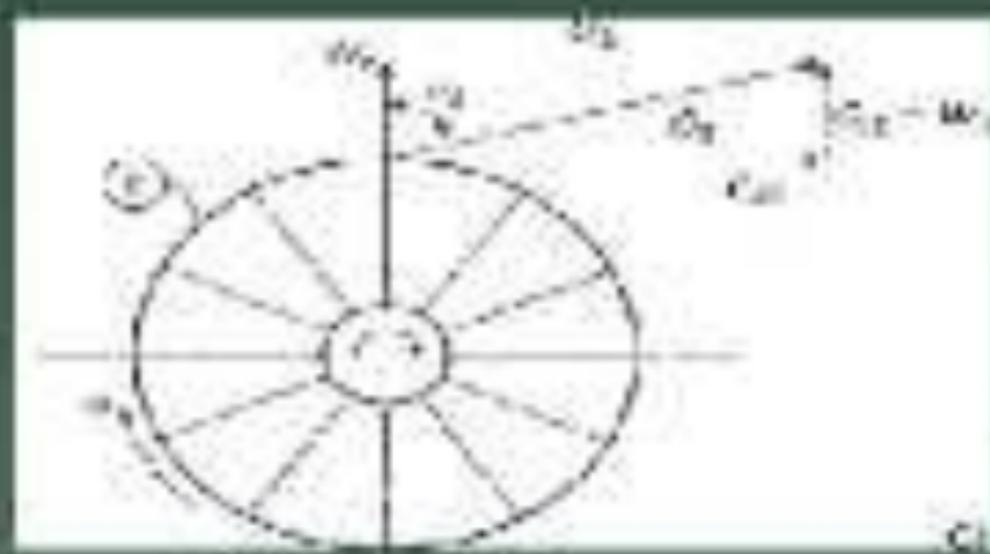
# Tangential Velocity *[Ideal]*

Ideal Blade:  $V_{tip} = M \cdot C$

Maximum energy transfer:  $V_{tip} = 1.17 C$

Freezing Speed Limit:  $V_{tip} > 1.17 C$





# Diffuser



- The **stoma** (st) is a pore, surrounded by two kidney-shaped guard cells, which is used for **photosynthesis**.
- The **stomatal type** of leaf is dependent on the **climate** that it grows in. A **sun loving** plant diffuses a lot of its leaves.



- The swirl component in diffuser reduces as a result of:

- Angular momentum conservation: as  $V_{\theta} r = \text{constant}$
- Viscous forces as the fluid moves out

$$\frac{r_1 C_{\theta 1}}{r_2} = \frac{r_2 C_{\theta 2}}{r_1}$$



# Axial Flow Compressors Vs Centrifugal Flow Compressors

---

- Centrifugal compressors can provide higher stagnation pressure ratio per stage
- Multi staging is more difficult in centrifugal compressors
  - Ideally suited if the total pressure ratio required is 3-5
- Axial flow compressors are slightly more efficient than centrifugal compressors
- Control area for a given mass flow is higher for centrifugal compressors

# GATE 2019

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QUESTION

Discrete Structures

- Q.11. Let  $S$  be a set and  $f$  be a function from  $S$  to  $S$ . Let  $f^0(x) = x$  and  $f^k(x) = f(f^{k-1}(x))$  for  $k > 0$ . Let  $f^k(x) = x$  for all  $x \in S$  and  $k > 0$ . Let  $f^k(x) = x$  for all  $x \in S$  and  $k > 0$ . Let  $f^k(x) = x$  for all  $x \in S$  and  $k > 0$ . Let  $f^k(x) = x$  for all  $x \in S$  and  $k > 0$ .

# GATE 2018

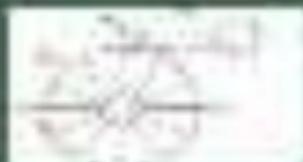
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QUESTION

QUESTION NUMBER

Q.14 In a PMOS common source amplifier, a PMOS transistor is operated at a constant gate overdrive of  $V_{GS} - V_{GS,th} = 0.25$  V. The drain current is given by  $I_D = 100 \mu A (V_{GS} - V_{GS,th})^2$ . The drain voltage is  $V_D = 1.5$  V. The drain current is  $I_D = 100 \mu A$ . The drain voltage is  $V_D = 1.5$  V. The drain current is  $I_D = 100 \mu A$ .

$$V_D = 1.5 \text{ V} \Rightarrow V_{GS} - V_{GS,th} = 0.25 \text{ V} \Rightarrow I_D = 100 \mu A$$



ANSWER CHOICE

## GATE 2007

- Q.44. An engine is to be run on a constant pressure combustion with a compression ratio of 15. The maximum temperature is limited to 2500 K. Assuming the compression ratio to be 15, the maximum temperature is 2500 K. If the isentropic efficiency of the compressor is 0.85, the work input to the compressor per kg of the working gas is (rounded off to 1 decimal place) \_\_\_\_\_ kJ/kg. Give the pressure ratio across the compressor as

0.75233

1.11300

1.17500

1.17200

1.17200

# GATE 2014

Q10) The cost of producing a quantity  $x$  of a commodity is given by  $C(x) = 0.001x^3 + 0.002x^2 + 0.003x + 1000$ . The marginal cost is  $C'(x) = 0.003x^2 + 0.004x + 0.003$ . The marginal cost is equal to the average cost when the quantity produced is  $x = 1000$ . The average cost is  $C(x)/x = 0.001x^2 + 0.002x + 0.003 + 1000/x$ . The marginal cost is  $C'(x) = 0.003x^2 + 0.004x + 0.003$ . The marginal cost is equal to the average cost when  $0.003x^2 + 0.004x + 0.003 = 0.001x^2 + 0.002x + 0.003 + 1000/x$ . Simplifying, we get  $0.002x^2 + 0.002x - 1000/x = 0$ . Multiplying by  $x$ , we get  $0.002x^3 + 0.002x^2 - 1000 = 0$ . Dividing by  $0.002$ , we get  $x^3 + x^2 - 500000 = 0$ . The only positive root is  $x = 1000$ .

$$C(x) = 0.001x^3 + 0.002x^2 + 0.003x + 1000$$

Specific work =  $C(1000) - C(0) = 0.001(1000^3) + 0.002(1000^2) + 0.003(1000) + 1000 = 1000 + 2000 + 3 + 1000 = 4003$

WZ = 4003 (definition of a to factor)

U = 4003  $\Rightarrow$  4003 work

$\Rightarrow$  4003 work  $\Rightarrow$  4003% lab = 4003%  $\Rightarrow$  4003%

Efficiency = **74.8%**

# Numerical Problem

Calculate the shaft power required for a centrifugal compressor for which: Flow enters axially, blade tip velocity = 520 m/s, radial velocity at exit = 1.11 m/s, flow angle at inlet =  $21^\circ$  and flow angle at exit =  $33^\circ$ . Mass flow rate of air = 5 kg/s



$$V_{theta2} = U \sin \alpha \tan \beta = 453.4 \text{ m/s}$$
$$\text{Power} = \dot{m} U V_{theta2} = \mathbf{1.127 \text{ MW}}$$

# Numerical Problem

Air leaves the impeller of a backward-swept compressor with a radial velocity of 310 m/s, at a relative angle of 25.5 deg. Tip speed of the impeller is 475 m/s. The compressor runs at 15000 rpm. Thermal efficiency = 1. Efficiency = 100 percent  
required to drive the compressor

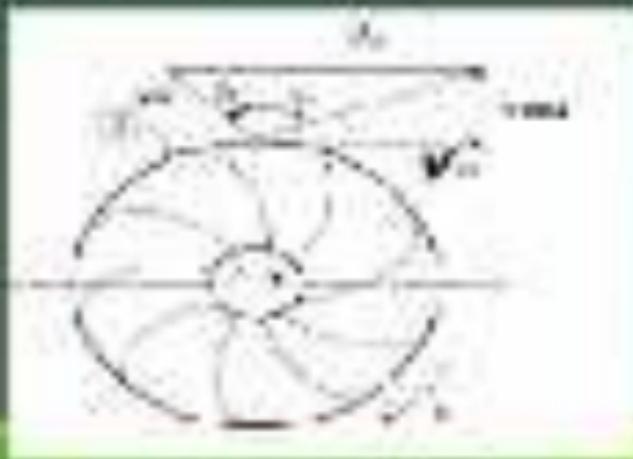
$$\rightarrow \tan(\Delta\alpha_2) = (U - v_{\theta 2})/v_{r2}$$

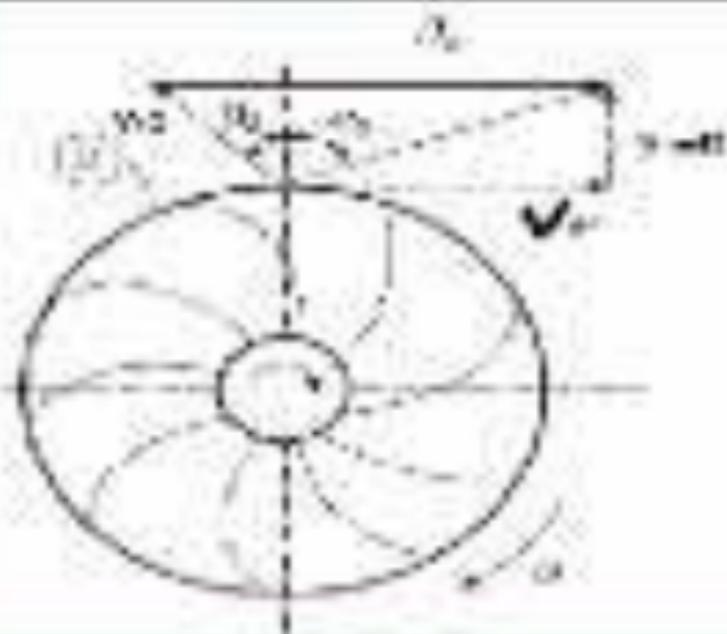
$$\tan 25.5^\circ = (475 - v_{\theta 2})/310$$

$$\rightarrow v_{\theta 2} = 207 \text{ m/s}$$

$$\rightarrow \text{Power required} = U \cdot v_{\theta 2}$$

$$= 98.8 \text{ kW}$$





$\alpha = \arcsin \left( \frac{C}{2R} \right)$  (small angle approx)  
 $\alpha \approx \frac{C}{2R}$

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100.

# AIR BREATHING ENGINES



Sessions:  
Axial Flow Turbines

DR. A. R. SRIKRISHNAN

 **AMRITA**  
UNIVERSITY

# The Direction of Work Transfer

- ▶ **Turbines absorb energy from the fluid**
  - Equal work product
  - Drop in stagnation enthalpy



# Expansion Vs Compression

- **Flow expands through the turbine**
  - Favourable pressure gradient
  - Less chances of separation
  - Aerodynamically simpler
- **Flow compresses through the compressor**
  - Hot combustion gases, due to **the mixing field**
  - **Rotation → Thermal stresses**
  - **Needs continuous cooling**
  - **Thermally complex**

# Stator, Rotor - The Turbine stage

Stator, "Inlet"



Rotor

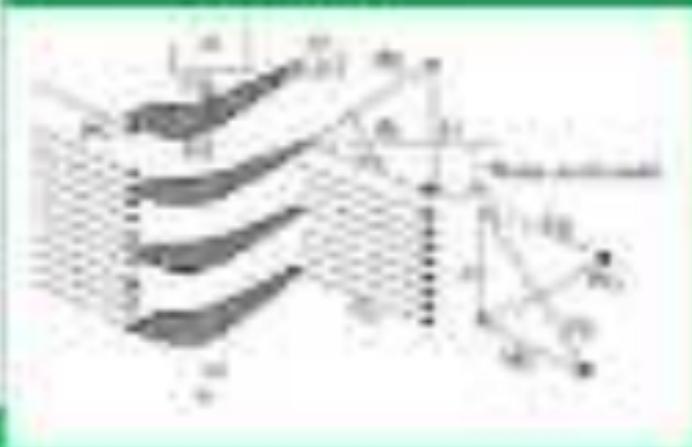


# Compressor Vs Turbine

- ▶ Blade Passage: Diverging in compressors, Converging in turbines.
- ▶ **Flow direction:** In compressor flow is inward, in turbine it is outward.
- ▶ **Flow deflection:** In turbine the flow turning angle is significantly high – Cross axial pressure gradient & narrow leaf tip of compressor.
- ▶ **Temperatures:** Turbines operate typically with temperatures around 1200-1700 K, in compressor rotor surfaces (inward flow) do not go beyond 800K in most designs.
  - ▶ Use the above angles & flow direction with software to design and simulate.
- ▶ **Blade:** If you take Turbine as Helix, Helical, Double Helix for manufacturing purposes.

# Turbine Stage

Conventional Axial Compressor First & Last second  
in turbine stage considerations



# Velocity Triangles



# Torque, Power

$$\Rightarrow T = m(V_{w1} r_1 - V_{w2} r_2)$$

$$\Rightarrow P = mU(V_{w1} - V_{w2}) \quad (\text{work is done by the fluid})$$

$$\Rightarrow \dot{W} = mU(r_1 \omega - r_2 \omega)$$

$r_1$  &  $r_2$  are above and below  $r$ , and  $U$  denotes the inlet and exit positions of the rotor

Note that by convention we use 1 & 2 respectively for the positive locations for the turbine

# Degree of Reaction

- Ratio of static enthalpy drop in stator to that in the rotor

$$R = \frac{\text{Enthalpy drop in the moving blades}}{\text{Enthalpy drop in the stage}}$$
$$= \frac{h_2 - h_3}{h_1 - h_3} = \frac{V_{a2}}{2U} (\tan \beta_1 - \tan \beta_2)$$

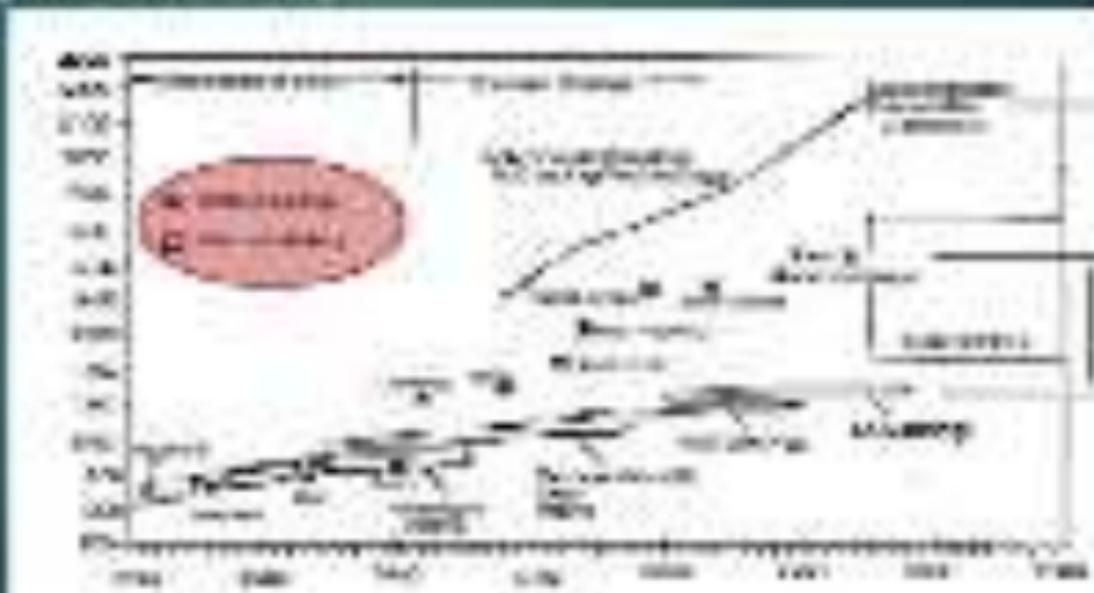
## Turbine Blade Cooling





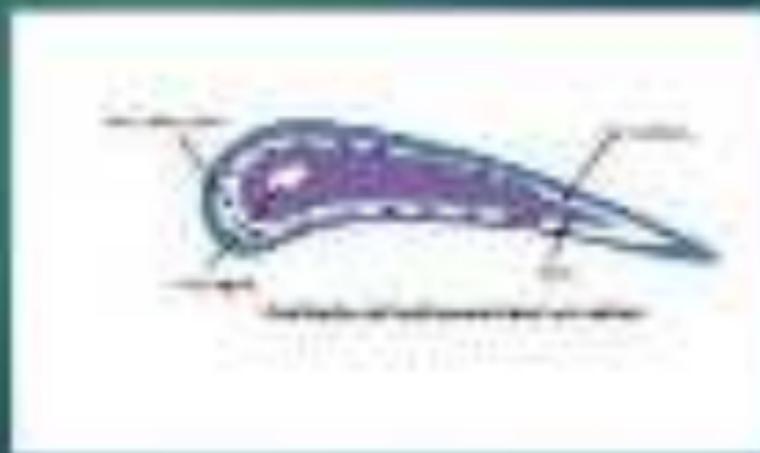
# Higher turbine inlet temperatures: The Progress..

- Higher pressure ratios
- Higher cycle efficiency



# Turbine Blade Cooling

**Blade Cooling:** The standard procedure is to bleed air from some stage of the compressor, bypass the combustion chamber, and inject it as cooling air in the turbine.



# Blade Cooling Methods

$$\eta = \frac{T_3 - T_4}{T_3 - T_2}$$



**Internal Cooling:** A perforated surface is made to impinge on the inner surface of the blade through small holes.

## Film Cooling:

The air after being used for internal cooling is ejected out through some holes on the external surface to create a protective "air film" acting as a barrier from the hot combustion gases.



COOLING CHIMNEY

Cross-Flow Cooling  
and Transverse  
Cooling



SHOWER HEAD  
BLW. COOLING

Film Cooling

COOLING AIR  
FILM COOLING







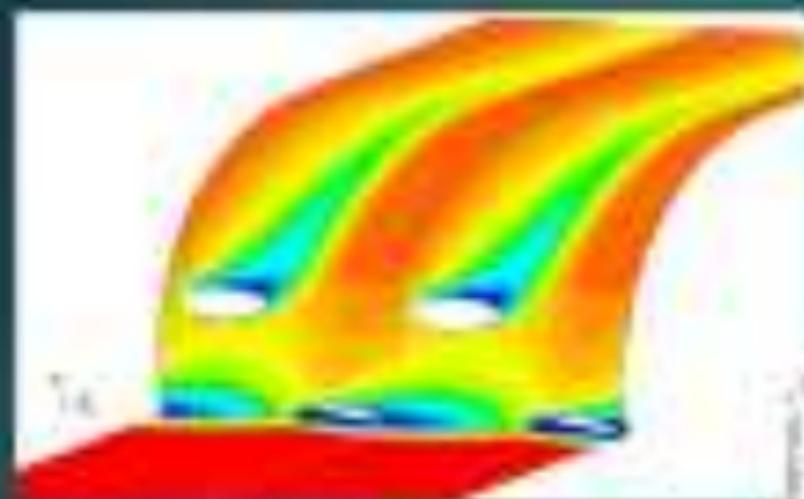
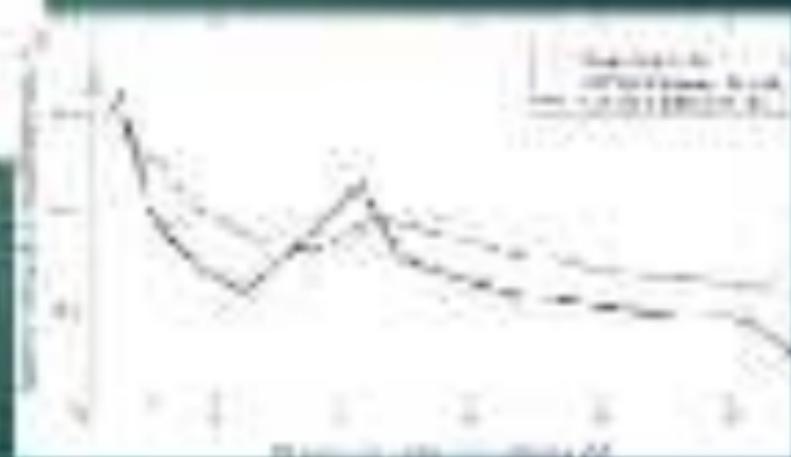


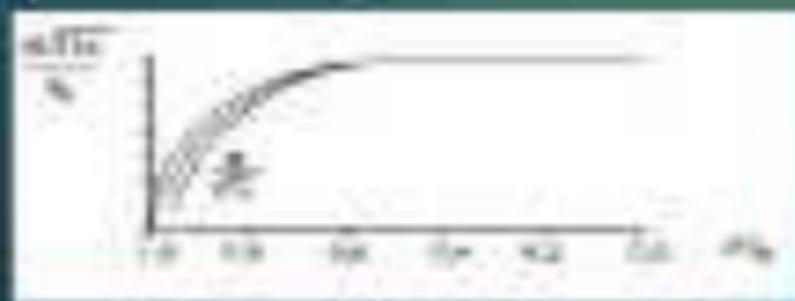
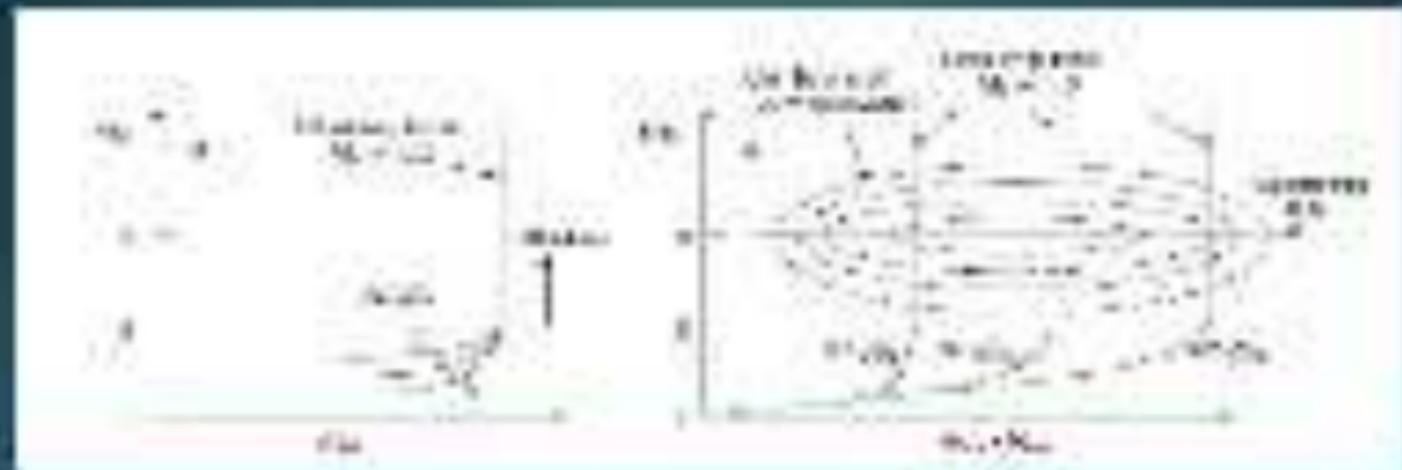
Figure 16: Comparison of the velocity profiles at the inlet and outlet of the duct.



## Designing the Blade Cooling System

- Steps in setting up the requirements:
  - Estimate the heat flux of the blade wall ( $q_w$ ) for given wall temperature ( $T_w$ )
  - Calculate the thermal stress
  - Determine the reduction in  $q_w$  required to limit stress within permissible values
  - Calculate the effectiveness required
  - Determine the department of cooling zone and cooling air flow for film cooling to provide the required effectiveness
  - Calculate the flow rate required for internal cooling air flow to obtain required  $q_w$

# Turbine Characteristics



# Numerical Problem

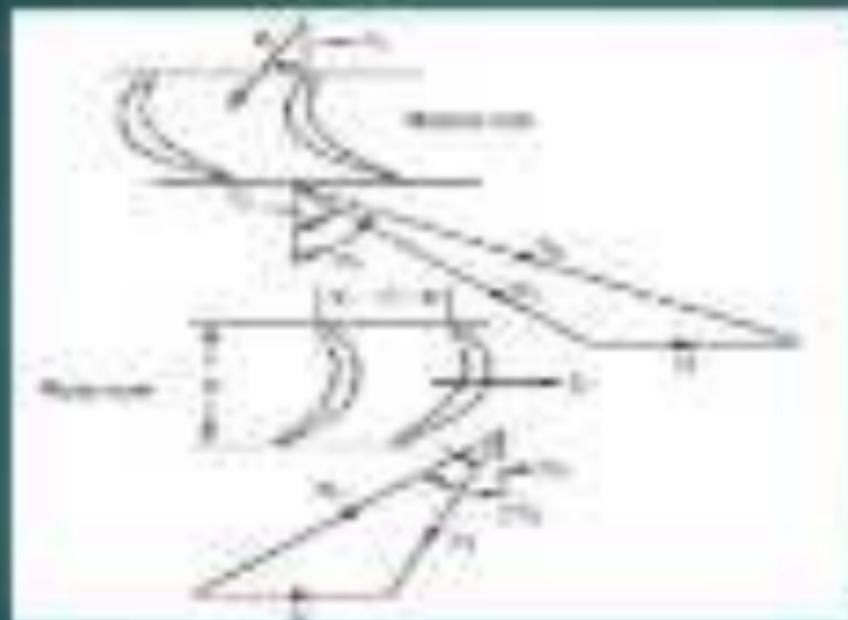
Consider a single stage axial flow gas turbine. The gas enters at stagnation temperature of 1100K. axial velocity is constant through the stage and equal to 250 m/s. Mean blade speed is 350 m/s. Mass flow rate of gas is 15 kg/s and assumes equal inlet and outlet velocities. Blade exit angle is 50deg, stage exit axial angle equal to 9deg. Determine the inlet blade angle, degree of reaction, and power output.

$$\text{Power} = \dot{m}U(V_{w2} - V_{w1})$$

$$\tan(\alpha_2) = (U + V_a \tan(\beta_2)) / V_a \rightarrow \beta_2$$

$$(U + V_a \tan(\alpha_1)) = V_a \tan(\beta_1) \rightarrow \beta_1$$







100





# GATE 2013

1110. A function  $f(x)$  is defined as  $f(x) = \frac{1}{x^2}$  for  $x > 0$ . The value of  $f(x)$  at  $x = 1$  is  $1$ . The value of  $f(x)$  at  $x = 2$  is  $\frac{1}{4}$ . The value of  $f(x)$  at  $x = 3$  is  $\frac{1}{9}$ . The value of  $f(x)$  at  $x = 4$  is  $\frac{1}{16}$ . The value of  $f(x)$  at  $x = 5$  is  $\frac{1}{25}$ . The value of  $f(x)$  at  $x = 6$  is  $\frac{1}{36}$ . The value of  $f(x)$  at  $x = 7$  is  $\frac{1}{49}$ . The value of  $f(x)$  at  $x = 8$  is  $\frac{1}{64}$ . The value of  $f(x)$  at  $x = 9$  is  $\frac{1}{81}$ . The value of  $f(x)$  at  $x = 10$  is  $\frac{1}{100}$ . The value of  $f(x)$  at  $x = 11$  is  $\frac{1}{121}$ . The value of  $f(x)$  at  $x = 12$  is  $\frac{1}{144}$ . The value of  $f(x)$  at  $x = 13$  is  $\frac{1}{169}$ . The value of  $f(x)$  at  $x = 14$  is  $\frac{1}{196}$ . The value of  $f(x)$  at  $x = 15$  is  $\frac{1}{225}$ . The value of  $f(x)$  at  $x = 16$  is  $\frac{1}{256}$ . The value of  $f(x)$  at  $x = 17$  is  $\frac{1}{289}$ . The value of  $f(x)$  at  $x = 18$  is  $\frac{1}{324}$ . The value of  $f(x)$  at  $x = 19$  is  $\frac{1}{361}$ . The value of  $f(x)$  at  $x = 20$  is  $\frac{1}{400}$ . The value of  $f(x)$  at  $x = 21$  is  $\frac{1}{441}$ . The value of  $f(x)$  at  $x = 22$  is  $\frac{1}{484}$ . The value of  $f(x)$  at  $x = 23$  is  $\frac{1}{529}$ . The value of  $f(x)$  at  $x = 24$  is  $\frac{1}{576}$ . The value of  $f(x)$  at  $x = 25$  is  $\frac{1}{625}$ . The value of  $f(x)$  at  $x = 26$  is  $\frac{1}{676}$ . The value of  $f(x)$  at  $x = 27$  is  $\frac{1}{729}$ . The value of  $f(x)$  at  $x = 28$  is  $\frac{1}{784}$ . The value of  $f(x)$  at  $x = 29$  is  $\frac{1}{841}$ . The value of  $f(x)$  at  $x = 30$  is  $\frac{1}{900}$ . The value of  $f(x)$  at  $x = 31$  is  $\frac{1}{961}$ . The value of  $f(x)$  at  $x = 32$  is  $\frac{1}{1024}$ . The value of  $f(x)$  at  $x = 33$  is  $\frac{1}{1089}$ . The value of  $f(x)$  at  $x = 34$  is  $\frac{1}{1156}$ . The value of  $f(x)$  at  $x = 35$  is  $\frac{1}{1225}$ . The value of  $f(x)$  at  $x = 36$  is  $\frac{1}{1296}$ . The value of  $f(x)$  at  $x = 37$  is  $\frac{1}{1369}$ . The value of  $f(x)$  at  $x = 38$  is  $\frac{1}{1444}$ . The value of  $f(x)$  at  $x = 39$  is  $\frac{1}{1521}$ . The value of  $f(x)$  at  $x = 40$  is  $\frac{1}{1600}$ . The value of  $f(x)$  at  $x = 41$  is  $\frac{1}{1681}$ . The value of  $f(x)$  at  $x = 42$  is  $\frac{1}{1764}$ . The value of  $f(x)$  at  $x = 43$  is  $\frac{1}{1849}$ . The value of  $f(x)$  at  $x = 44$  is  $\frac{1}{1936}$ . The value of  $f(x)$  at  $x = 45$  is  $\frac{1}{2025}$ . The value of  $f(x)$  at  $x = 46$  is  $\frac{1}{2116}$ . The value of  $f(x)$  at  $x = 47$  is  $\frac{1}{2209}$ . The value of  $f(x)$  at  $x = 48$  is  $\frac{1}{2304}$ . The value of  $f(x)$  at  $x = 49$  is  $\frac{1}{2401}$ . The value of  $f(x)$  at  $x = 50$  is  $\frac{1}{2500}$ . The value of  $f(x)$  at  $x = 51$  is  $\frac{1}{2601}$ . The value of  $f(x)$  at  $x = 52$  is  $\frac{1}{2704}$ . The value of  $f(x)$  at  $x = 53$  is  $\frac{1}{2809}$ . The value of  $f(x)$  at  $x = 54$  is  $\frac{1}{2916}$ . The value of  $f(x)$  at  $x = 55$  is  $\frac{1}{3025}$ . The value of  $f(x)$  at  $x = 56$  is  $\frac{1}{3136}$ . The value of  $f(x)$  at  $x = 57$  is  $\frac{1}{3249}$ . The value of  $f(x)$  at  $x = 58$  is  $\frac{1}{3364}$ . The value of  $f(x)$  at  $x = 59$  is  $\frac{1}{3481}$ . The value of  $f(x)$  at  $x = 60$  is  $\frac{1}{3600}$ . The value of  $f(x)$  at  $x = 61$  is  $\frac{1}{3721}$ . The value of  $f(x)$  at  $x = 62$  is  $\frac{1}{3844}$ . The value of  $f(x)$  at  $x = 63$  is  $\frac{1}{3969}$ . The value of  $f(x)$  at  $x = 64$  is  $\frac{1}{4096}$ . The value of  $f(x)$  at  $x = 65$  is  $\frac{1}{4225}$ . The value of  $f(x)$  at  $x = 66$  is  $\frac{1}{4356}$ . The value of  $f(x)$  at  $x = 67$  is  $\frac{1}{4489}$ . The value of  $f(x)$  at  $x = 68$  is  $\frac{1}{4624}$ . The value of  $f(x)$  at  $x = 69$  is  $\frac{1}{4761}$ . The value of  $f(x)$  at  $x = 70$  is  $\frac{1}{4900}$ . The value of  $f(x)$  at  $x = 71$  is  $\frac{1}{5041}$ . The value of  $f(x)$  at  $x = 72$  is  $\frac{1}{5184}$ . The value of  $f(x)$  at  $x = 73$  is  $\frac{1}{5329}$ . The value of  $f(x)$  at  $x = 74$  is  $\frac{1}{5476}$ . The value of  $f(x)$  at  $x = 75$  is  $\frac{1}{5625}$ . The value of  $f(x)$  at  $x = 76$  is  $\frac{1}{5776}$ . The value of  $f(x)$  at  $x = 77$  is  $\frac{1}{5929}$ . The value of  $f(x)$  at  $x = 78$  is  $\frac{1}{6084}$ . The value of  $f(x)$  at  $x = 79$  is  $\frac{1}{6241}$ . The value of  $f(x)$  at  $x = 80$  is  $\frac{1}{6400}$ . The value of  $f(x)$  at  $x = 81$  is  $\frac{1}{6561}$ . The value of  $f(x)$  at  $x = 82$  is  $\frac{1}{6724}$ . The value of  $f(x)$  at  $x = 83$  is  $\frac{1}{6889}$ . The value of  $f(x)$  at  $x = 84$  is  $\frac{1}{7056}$ . The value of  $f(x)$  at  $x = 85$  is  $\frac{1}{7225}$ . The value of  $f(x)$  at  $x = 86$  is  $\frac{1}{7396}$ . The value of  $f(x)$  at  $x = 87$  is  $\frac{1}{7569}$ . The value of  $f(x)$  at  $x = 88$  is  $\frac{1}{7744}$ . The value of  $f(x)$  at  $x = 89$  is  $\frac{1}{7921}$ . The value of  $f(x)$  at  $x = 90$  is  $\frac{1}{8100}$ . The value of  $f(x)$  at  $x = 91$  is  $\frac{1}{8281}$ . The value of  $f(x)$  at  $x = 92$  is  $\frac{1}{8464}$ . The value of  $f(x)$  at  $x = 93$  is  $\frac{1}{8649}$ . The value of  $f(x)$  at  $x = 94$  is  $\frac{1}{8836}$ . The value of  $f(x)$  at  $x = 95$  is  $\frac{1}{9025}$ . The value of  $f(x)$  at  $x = 96$  is  $\frac{1}{9216}$ . The value of  $f(x)$  at  $x = 97$  is  $\frac{1}{9409}$ . The value of  $f(x)$  at  $x = 98$  is  $\frac{1}{9604}$ . The value of  $f(x)$  at  $x = 99$  is  $\frac{1}{9801}$ . The value of  $f(x)$  at  $x = 100$  is  $\frac{1}{10000}$ .

11. The value of  $f(x)$  at  $x = 1$  is  $1$ .

12. The value of  $f(x)$  at  $x = 2$  is  $\frac{1}{4}$ .

13. The value of  $f(x)$  at  $x = 3$  is  $\frac{1}{9}$ .

14. The value of  $f(x)$  at  $x = 4$  is  $\frac{1}{16}$ .

# GATE 2016

A ship is moving with velocity  $u$  in the direction of the wind and with the wind. The absolute direction of the wind is  $70^\circ$ . The relative angle between a velocity vector of  $100 \text{ km/hr}$  and the wind is  $70^\circ$ . The absolute direction of the wind is  $70^\circ$ . The absolute direction of the wind is  $70^\circ$ .

(A)  $100 \text{ km/hr}$

(B)  $200 \text{ km/hr}$

(C)  $150 \text{ km/hr}$

(D)  $100 \text{ km/hr}$

Note the following:

1. Axis and velocity vectors  $v_1$  and  $v_2$  are at  $70^\circ$ .
2. "Winds set" refers to vector  $v_1$ .



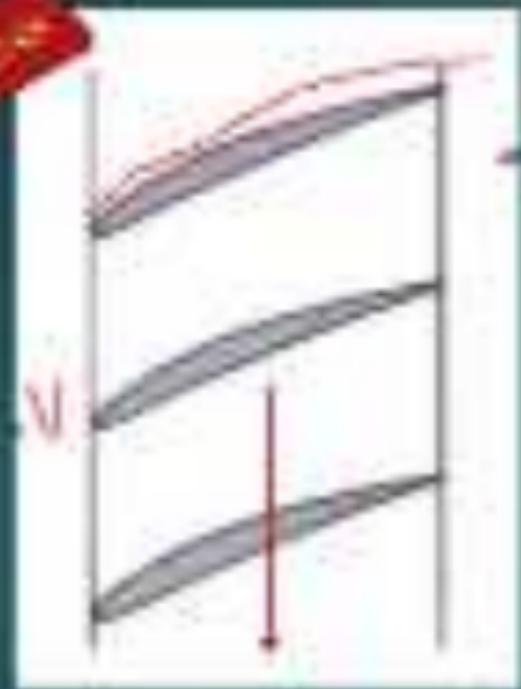
Solution: Sp. Work:  $w = U^2(v_1 - v_2) = U^2 v_1$  as  $v_1$  is  $100$ .

$\Rightarrow v_1 = w/U = 100 \text{ km/hr}$

$v_2 = v_1/\sin(70) = 100/0.9397 = 106.52 \text{ km/hr}$

# Direction of rotation

Counterclockwise



Clockwise



The resulting situation is that the beam will rotate in the direction of the shear force. If the shear force is positive, the beam will rotate clockwise. If the shear force is negative, the beam will rotate counterclockwise.

# AIR BREATHING ENGINES



Flame Stabilization  
& Combustor  
Firing

DR. A.R. SRIKRISHNAN

 AMRITA

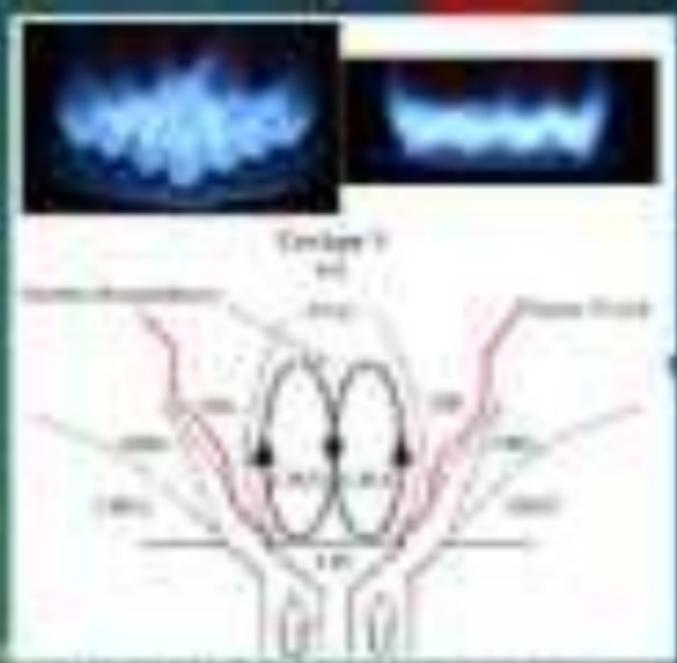
# Flame Stabilization



# The Approach



- Create a shallower zone of low velocity and of the linear, where flume speeds are greatly enhanced by increasing a furrowed to the primary jet and by widening the bed to recede to a level that will the existing (or new) bed



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# Stability Loop – Determining Stability performance



- A stability calculation is conducted, providing levels of fuel flow, temperature, and pressure.
- After ignition, the fuel flow is gradually reduced until flame extinction occurs.
  - Now, the fuel flow is increased until the flame is re-ignited.
- Combustion is re-established and the fuel flow slowly increased until flame extinction occurs.
- This process is repeated at least 100 cycles of re-ignition and flame extinction.
- The complete stability performance of an open engine combustor is obtained by carrying out sufficient calculations to give a low number of stability loops to be drawn at different levels of pressure.

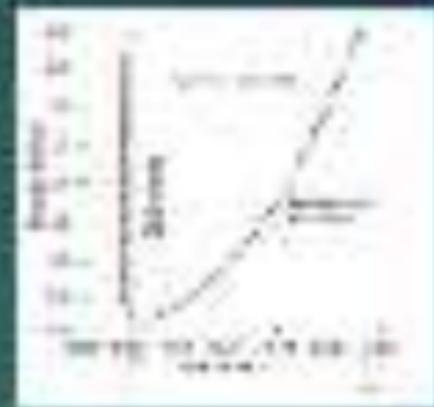


# Flammability Limits

| Flammability Limits of Various Fuels |                 |                 |                     |                     |
|--------------------------------------|-----------------|-----------------|---------------------|---------------------|
| Fuel                                 | Lower Limit (%) | Upper Limit (%) | Ignition Temp. (°C) | Explosion Range (%) |
| Hydrogen                             | 4               | 75              | 500                 | 5-75                |
| Acetylene                            | 2.5             | 82              | 300                 | 3-82                |
| Ethylene                             | 3               | 36              | 490                 | 3-36                |
| Ethane                               | 3               | 14              | 490                 | 3-14                |
| Propane                              | 2.1             | 9.5             | 470                 | 2.1-9.5             |
| Butane                               | 1.8             | 8.4             | 405                 | 1.8-8.4             |
| Pentane                              | 1.4             | 7.8             | 260                 | 1.4-7.8             |
| Hexane                               | 1.2             | 7.5             | 220                 | 1.2-7.5             |
| Heptane                              | 1.0             | 7.0             | 200                 | 1.0-7.0             |
| Octane                               | 0.9             | 6.5             | 180                 | 0.9-6.5             |
| Nonane                               | 0.8             | 6.0             | 160                 | 0.8-6.0             |
| Decane                               | 0.7             | 5.5             | 150                 | 0.7-5.5             |
| Gasoline                             | 0.6             | 5.0             | 140                 | 0.6-5.0             |
| Gasoline vapor                       | 0.5             | 4.5             | 130                 | 0.5-4.5             |
| Gasoline vapor + air                 | 0.4             | 4.0             | 120                 | 0.4-4.0             |
| Gasoline vapor + oxygen              | 0.3             | 3.5             | 110                 | 0.3-3.5             |
| Gasoline vapor + nitrogen            | 0.2             | 3.0             | 100                 | 0.2-3.0             |
| Gasoline vapor + carbon dioxide      | 0.1             | 2.5             | 90                  | 0.1-2.5             |
| Gasoline vapor + sulfur dioxide      | 0.05            | 2.0             | 80                  | 0.05-2.0            |
| Gasoline vapor + hydrogen sulfide    | 0.02            | 1.5             | 70                  | 0.02-1.5            |
| Gasoline vapor + water vapor         | 0.01            | 1.0             | 60                  | 0.01-1.0            |
| Gasoline vapor + steam               | 0.005           | 0.5             | 50                  | 0.005-0.5           |
| Gasoline vapor + carbon monoxide     | 0.002           | 0.2             | 40                  | 0.002-0.2           |
| Gasoline vapor + hydrogen cyanide    | 0.001           | 0.1             | 30                  | 0.001-0.1           |
| Gasoline vapor + ammonia             | 0.0005          | 0.05            | 20                  | 0.0005-0.05         |
| Gasoline vapor + hydrogen chloride   | 0.0002          | 0.02            | 15                  | 0.0002-0.02         |
| Gasoline vapor + hydrogen fluoride   | 0.0001          | 0.01            | 10                  | 0.0001-0.01         |
| Gasoline vapor + hydrogen bromide    | 0.00005         | 0.005           | 5                   | 0.00005-0.005       |
| Gasoline vapor + hydrogen iodide     | 0.00002         | 0.002           | 2                   | 0.00002-0.002       |

Border on the rich side of fuel/air ratio

Lower limit of flammability is the minimum concentration of fuel in air that will support combustion



# Bluff Body Flame Holders

- Typically flame will blow out when the time available for chemical reaction becomes less than

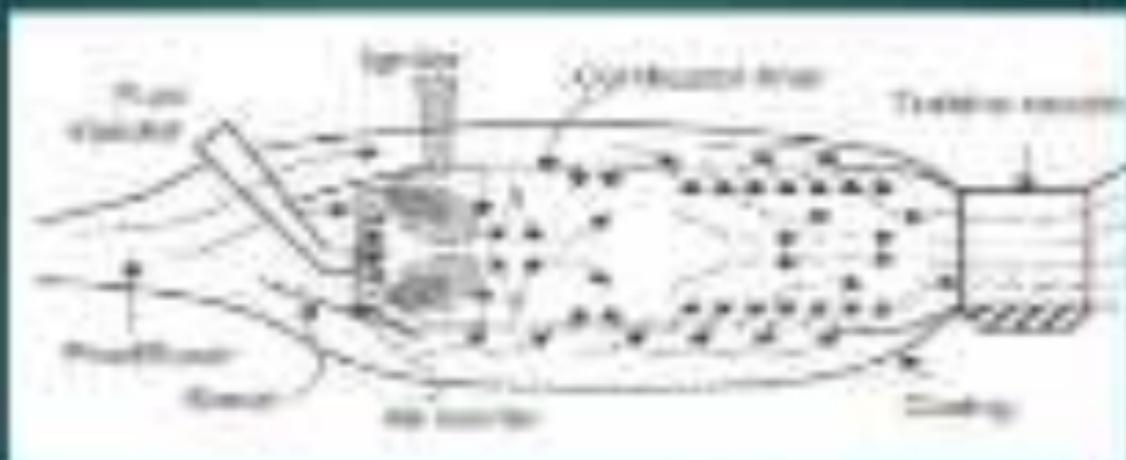


some of the burning mixture is blown away and the unburned gas is not entrained in the recirculatory flow, which conveys it upstream to mix with the gas for the next burn. A flame will blow out if the duct is through contraction of the system.

# Stabilization in Aircraft

- The attitude (yaw, roll and pitch) is controlled and maintained by air entering through inlet vanes mounted around the last intake duct through an engine inlet duct as the result of bleed air.
- In addition to air bleed flow in the main duct, bleed air in the secondary air passages are also provided and having access to air with the incoming air mass flow.
- As the engine is used for a lot of applications such as a turbofan, turbojet, turbo-propeller, etc. as well as other types of gas-turbines, and turbo-shaft.





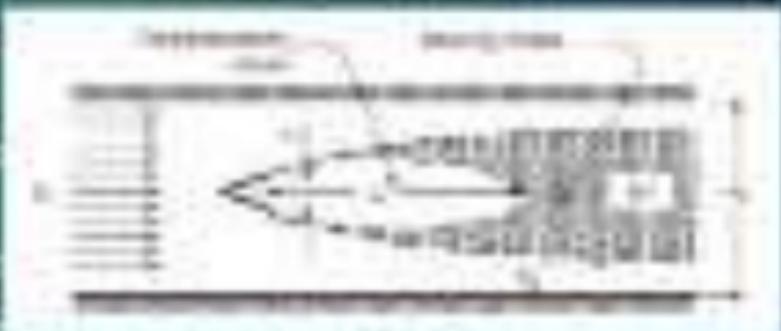
# Flame Stabilization in Afterburners

- The necessary reaction with a preheated flame.



relatively expensive

the density of



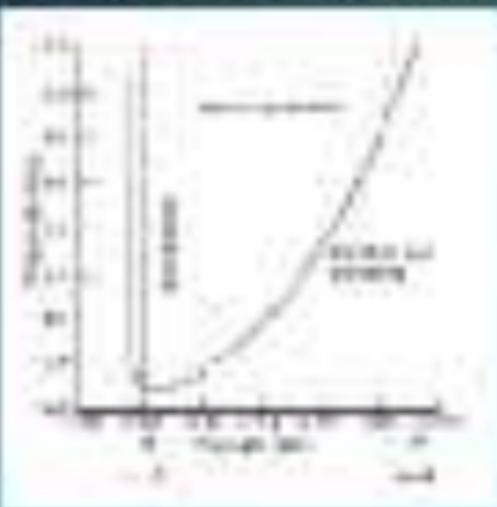
<https://www.youtube.com/watch?v=...>

# Influence of Various Parameters on Flame Stability

The extent of flame stability can be influenced by the following parameters/substitutions:

- 1. A reduction in approach stream velocity
- 2. An increase in approach stream turbulence
- 3.
- 4. Any change in equivalence ratio towards unity
- 5. An increase in flame height due to blockage
- 6. A reduction in flame holder blockage (that is constant flame height due to)

# Problem...



→ **Number of Resources:** Both resources are essential to the production of output, and the production process is strictly concave. → **Input:** Input is the amount of resources. → **Output:** Output is the amount of output produced. → **Cost:** Cost is the amount of resources used to produce the output.

# Combustor Sizing

---

## Combustor Volume: The effect of parameters

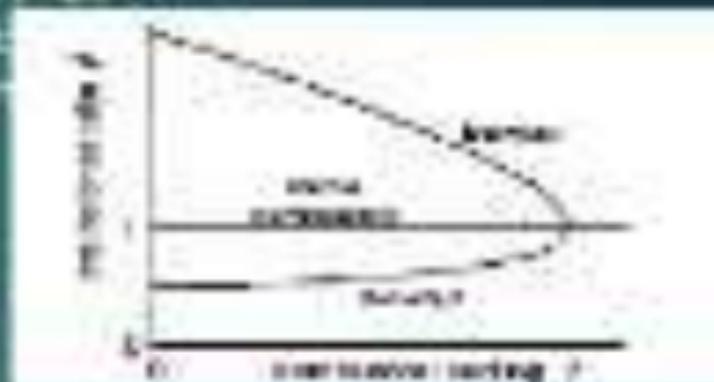
The effect of mass flow rate, combustion volume and pressure on the stability of the combustion process. The combustion process is described by the Combustion Loading Parameter (CLP), defined as:

$$CLP = \frac{\dot{m}_{fuel}}{V^*} \quad (1)$$

$\dot{m}$  = Mass flow rate

$$CLP = \frac{\dot{m}_{fuel}}{V^*} \quad (2)$$

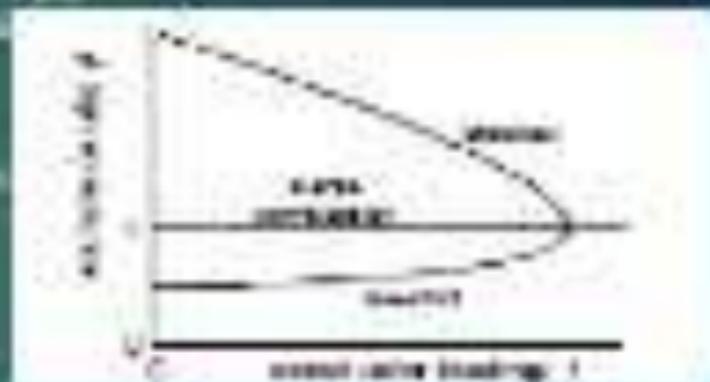
$V^*$  = Combustion Volume



## Stability of Combustion & Combustor Volume

- Combustor required able to tolerate fluctuations of the combustion process to sustain itself
- If Too lean or too rich
  - flame & reaction rates drop below the levels required to heat and evaporate the fuel/oxidizer
  - will require longer analysis
- CLP (Combustion Loading Parameter)
  - Indication of stability based on Mach flow pressure ( $M = 1.5$  for typical fuels), and combustor volume

$$CLP = \frac{1}{\gamma^2 (1 + \gamma)}$$



## Combustor Size

- Cross-sectional Area determined by mass-flow rate and velocity requirements of the inlet to the turbine
- Length: Completion of Combustion and Flame stabilization requirements
  - $L/D$  typically around 3-6
- Volumetric heat release rate: Depends on pressure



# Combustor Length & Cycle Parameters

- Also within the combustor, the maximum flame is limited by the distance from the injection location of the oxidizer and the temperature
- $T_{max} \propto T_{in}$

$$\frac{L_{max}}{D} \propto \frac{P_{in} \sqrt{D}}{T_{in}}$$

- Similarly, this leads to
- A large pressure ratio engine cycle will have a high combustion temperature, but a low flame speed, which can be made up for by a longer combustor length. In a turbojet engine with a lower pressure ratio, a similar argument can be made regarding the cycle thermal loading constraint of

Financial Statement for the Month Ended 31/12/2019

| Particulars        | 2019   | 2018   | 2017   | 2016   | 2015   |
|--------------------|--------|--------|--------|--------|--------|
| Revenue            | 10000  | 9500   | 9000   | 8500   | 8000   |
| Cost of Sales      | (4000) | (3800) | (3600) | (3400) | (3200) |
| Gross Profit       | 6000   | 5700   | 5400   | 5100   | 4800   |
| Operating Expenses | (2000) | (1900) | (1800) | (1700) | (1600) |
| Operating Profit   | 4000   | 3800   | 3600   | 3400   | 3200   |
| Finance Income     | 500    | 450    | 400    | 350    | 300    |
| Finance Expenses   | (1000) | (950)  | (900)  | (850)  | (800)  |
| Profit Before Tax  | 3500   | 3300   | 3100   | 2900   | 2700   |
| Tax Expense        | (800)  | (750)  | (700)  | (650)  | (600)  |
| Profit After Tax   | 2700   | 2550   | 2400   | 2250   | 2100   |
| Dividend Paid      | (1000) | (950)  | (900)  | (850)  | (800)  |
| Retained Profit    | 1700   | 1600   | 1500   | 1400   | 1300   |

Notes to the financial statements are provided on pages 10 to 15.

Approved by the directors



# Combustion Intensity

$$\text{combustion intensity} = \frac{\text{heat release rate}}{\text{cubic vol.} \times \text{pressure}} \quad \text{kW/m}^3 \text{ atm}$$

- ↳ Lower the combustion intensity needed for design or system safety related requirements.

Typically, Aircraft Engines have combustion with  $\square$   
at 100 atm and 25 MPa to 50 MPa (kW/m<sup>3</sup>-atm)

- Q.37 A gas is flowing in a pipe with a constant cross-sectional area. The velocity of the gas is 10 m/s at a pressure of 100 kPa. The pressure is 80 kPa at another section of the pipe. The velocity of the gas at this section is

(A) 10 m/s (B) 8 m/s (C) 12.5 m/s (D) 11.18 m/s

# AIR BREATHING ENGINES



Principles & Applications

DR. A.R. SRIKRISHNAN

**AMRITA**  
AMRITA UNIVERSITY

# Aviation Fuels: Properties/Attributes of International

Operation,  
Availability,  
Combustion  
efficiency.

Density, viscosity,  
Calorific value,  
Thermal stability etc.

Storage,  
handling

Storage, handling,  
fire risk

Flexibility,  
compatibility

Availability, cost  
of production

# Calorific Value

- Hydrocarbon fuels typically have calorific value in the range of 42 MJ/kg-48 MJ/kg
- The percentage of hydrogen in the compound favourably influences the calorific value

# Typical Values...



Table 1: Typical Values for the Parameters of the Lognormal Distribution

| Parameter          | Value | Unit | Value | Unit |
|--------------------|-------|------|-------|------|
| Mean               | 1.0   | mm   | 1.0   | mm   |
| Standard Deviation | 0.1   | mm   | 0.1   | mm   |
| Minimum            | 0.5   | mm   | 0.5   | mm   |
| Maximum            | 2.0   | mm   | 2.0   | mm   |



# Typical Jet Fuels & Their Properties

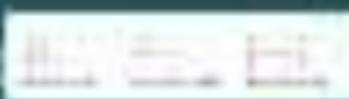
of different hydrocarbons with different molecular weights

| Property                         | JP-1             |                 | JP-8             |                 | JP-7             |                 |
|----------------------------------|------------------|-----------------|------------------|-----------------|------------------|-----------------|
|                                  | Specific Gravity | Weight (lb/gal) | Specific Gravity | Weight (lb/gal) | Specific Gravity | Weight (lb/gal) |
| Upper limit of 10% water content | 0.0001           | 0.00            | —                | 0.00            | —                | 0.00            |
| Water tolerance (ppm)            | —                | 20              | —                | 20              | —                | 20              |
| Aluminum (ppm)                   | —                | 20              | 1.00             | 20              | 1.00             | 20              |
| Iron (ppm)                       | —                | 20              | 1.00             | 20              | 1.00             | 20              |
| Vanadium (ppm)                   | —                | 1.0             | 1.00             | 1.0             | 1.00             | 1.0             |
| Fluorine (ppm)                   | —                | 1.0             | 1.00             | 1.0             | 1.00             | 1.0             |
| Lead (ppm)                       | —                | 1.0             | 1.00             | 1.0             | 1.00             | 1.0             |
| Upper limit of 10% water content | 0.0001           | 0.00            | 0.0001           | 0.00            | 0.0001           | 0.00            |
| Water tolerance (ppm)            | —                | 20              | —                | 20              | —                | 20              |
| Aluminum (ppm)                   | —                | 20              | —                | 20              | —                | 20              |
| Iron (ppm)                       | —                | 20              | —                | 20              | —                | 20              |
| Vanadium (ppm)                   | —                | 1.0             | —                | 1.0             | —                | 1.0             |
| Fluorine (ppm)                   | —                | 1.0             | —                | 1.0             | —                | 1.0             |
| Lead (ppm)                       | —                | 1.0             | —                | 1.0             | —                | 1.0             |

Of course, **weight**

is **critical**

# Nature of Components



Coal tar

The distillate (1) - Heavy metal rich, contains low boiling hydrocarbons

Aromatics

As a whole, the number of hydrocarbons present, there are more aromatic hydrocarbons than hydrocarbons, in consequence, their specific gravity is greater than hydrocarbons

Hydrocarbons

The characteristics of aromatic compounds include a marked tendency to adsorb and hold on a high hydrocarbon that can lead to precipitation of low boiling or high boiling hydrocarbons

It had 50% an average composition of 40% paraffins, 30% naphthenes, 20% aromatics and contains about 500

components

# Alternative Fuels

- Conventional jet aircraft engine exhaust produces a range of hazardous trace compounds:
  - CO, NO<sub>x</sub>, SO<sub>x</sub> - returned by reabsorption (UFC)
  - Particulate matter (PM)
  - Greenhouse gases, most notably CO<sub>2</sub>
- Future developments will focus on fuel and/or engine related technologies, which are effective, simple, and economically viable, available and change quickly

# What is an Alternative Fuel

- A fuel that either supplements or replaces the conventional fuel on a substantially permanent basis with no adverse effects on engine performance, maintenance, or operational life may be defined as an alternative fuel.
- Ranges from highest quality fuels such as hydrogen and methanol, to low-grade liquid and gaseous fuels that require different in-cylinder designs, then other alternative fuels.
- [Alternative Fuels: A Guide to the Fuel of the Future](#)

# Fuel-Future..

- The future of the alternative fuel industry depends on the following key factors:
  - **Short-term** capacity and flexibility for the refinery and infrastructure **ability to price**
  - The **external** impact that includes competition with food, water, and land
  - CO2 life-cycle analysis and carbon footprint issues;
  - **Energy** and **environmental** benefits **flexibility**, **efficiency**, **durability**

# Closer Look at Aircraft Combustors

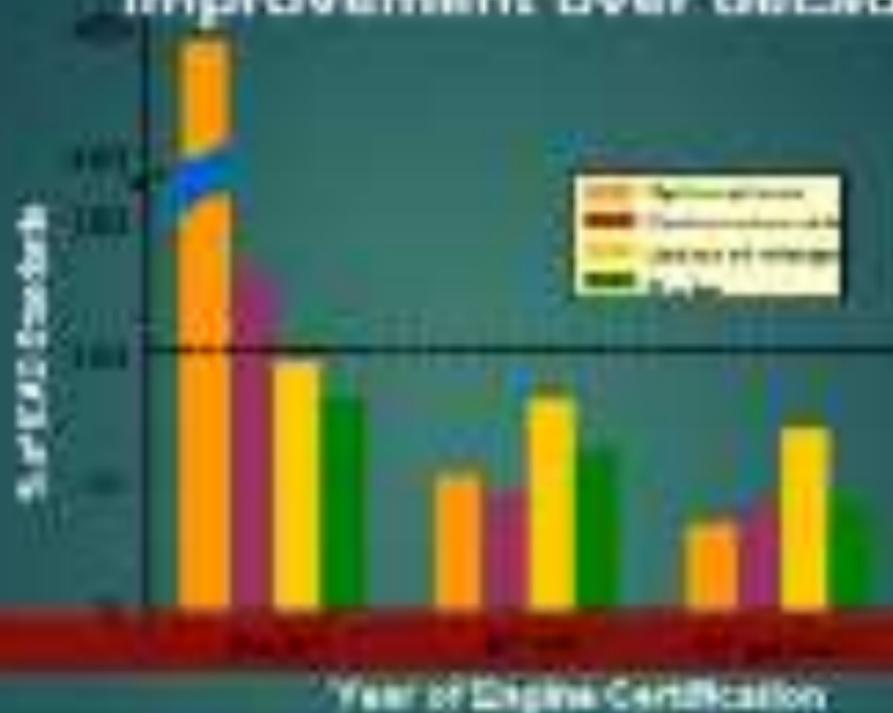
▶ [http://www.youtube.com/watch?v=09C\\_gkbaT](http://www.youtube.com/watch?v=09C_gkbaT)



# Emission Issues

- | Source  | Key Regulations   | Mitigation  |
|---|---|---|
| <ul style="list-style-type: none"><li>- Climate Change</li></ul>    | <ul style="list-style-type: none"><li>- Carbon Dioxide (CO<sub>2</sub>)</li><li>- Methane</li><li>- HFCs</li></ul>  | <ul style="list-style-type: none"><li>- Fuel Efficiency</li><li>- Green Buildings</li><li>- Emission Trading</li><li>- Carbon Footprint</li></ul> |
| <ul style="list-style-type: none"><li>- Local Air Quality</li></ul> | <ul style="list-style-type: none"><li>- PM<sub>2.5</sub></li><li>- Ozone Depleting Substances (ODS)</li><li>- Chlorofluorocarbons (CFCs)</li><li>- Smoke Part</li></ul> | <ul style="list-style-type: none"><li>- Low VOC Paints</li><li>- Green Building</li><li>- Mitigation</li></ul>                                    |

# Local Air Quality: Continuous Improvement over decades



## CO<sub>2</sub>/NO<sub>x</sub> Trade

- A full set of tradable permits will be available to all countries, so the resulting ΔCO<sub>2</sub> emissions from abatement by (A, B) will be equal due to identical abatement



## Conflicting Design Requirements: CO<sub>2</sub>/Nox Control

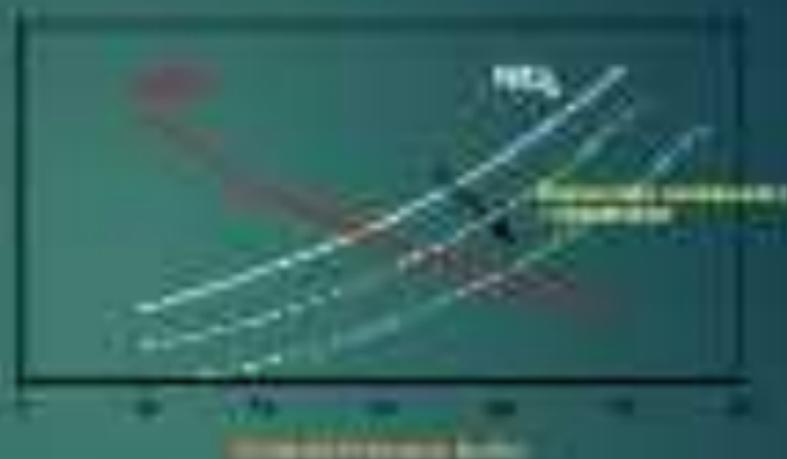
- Hydrocarbon emissions increase with increase in NOx emissions due to increasing gas inlet temperature. Lower inlet temperature reduces NOx emissions.
- Hydrocarbon emissions after catalyst increase. Lower inlet temperature increases conversion of HC emissions.

NOx emissions



# CO<sub>2</sub>/NO<sub>x</sub> Trade

- N<sub>2</sub>O<sub>x</sub> ist ein starkes Treibhausgas  
- relative zu CO<sub>2</sub> ist die Wirkung  
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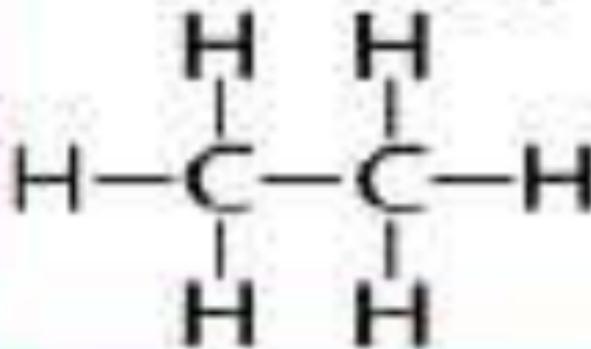
# APPENDIX

## Saturated Hydrocarbons

Saturated hydrocarbons are hydrocarbons that contain a single bond between adjacent carbon atoms. They are the simplest class of hydrocarbons. They are called alkanes and are the most abundant class of hydrocarbons.

Basic

Ethane  $C_2H_6$



# AIR BREATHING ENGINES



Flame  
Stabilisation &  
Combustion Sizing

DR. A.R. SRIKRISHNAN

 AMRITA

# Flame Stabilization



# The Approach



- Create a sheltered zone of low velocity and of the bar, where flume sands are greatly enhanced by increasing turbulence to the primary jet and by arranging the bed to recirculate sand that will then eventually be carried back

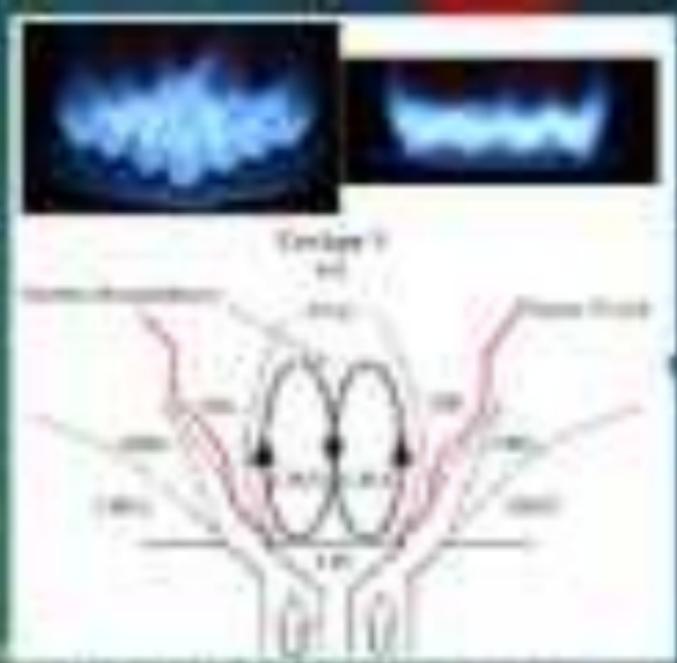


Figure 1. A schematic diagram of a river channel planform. The diagram shows a main channel with several smaller channels branching off. Labels include 'Main Channel', 'Secondary Channel', 'Tributary Channel', and 'Confluence'. Arrows indicate the direction of flow from the tributaries into the main channel.

# Stability Loop – Determining Stability performance



- A series of calculations leads to a combustion product level of fuel air temperature and pressure.
- After ignition the fuel flow is gradually reduced until flame extinction occurs.
  - Now the fuel flow is increased until the flame is re-ignited.
- Combustion is re-ignited and the fuel flow slowly increased until flame extinction occurs.
- This process is repeated at least 100 cycles of re-ignition.
- The complete stability performance of an open engine combustor is obtained by carrying out sufficient calculations to give a low number of stability loops to be drawn at different levels of pressure.

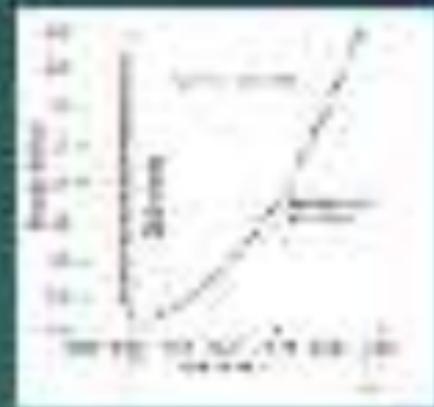


# Flammability Limits

| Flammability Limits of Various Fuels |                 |                 |                     |                     |
|--------------------------------------|-----------------|-----------------|---------------------|---------------------|
| Fuel                                 | Lower Limit (%) | Upper Limit (%) | Ignition Temp. (°C) | Explosion Range (%) |
| Hydrogen                             | 4.0             | 75.0            | 500                 | 4.0 - 75.0          |
| Acetylene                            | 2.5             | 80.0            | 300                 | 2.5 - 80.0          |
| Ethylene                             | 3.0             | 69.0            | 365                 | 3.0 - 69.0          |
| Ethane                               | 3.0             | 12.5            | 490                 | 3.0 - 12.5          |
| Propane                              | 2.1             | 9.5             | 426                 | 2.1 - 9.5           |
| Butane                               | 1.8             | 8.4             | 405                 | 1.8 - 8.4           |
| Pentane                              | 1.4             | 7.8             | 396                 | 1.4 - 7.8           |
| Hexane                               | 1.2             | 7.5             | 392                 | 1.2 - 7.5           |
| Heptane                              | 1.0             | 7.0             | 388                 | 1.0 - 7.0           |
| Octane                               | 0.9             | 6.7             | 385                 | 0.9 - 6.7           |
| Nonane                               | 0.8             | 6.5             | 382                 | 0.8 - 6.5           |
| Decane                               | 0.7             | 6.3             | 380                 | 0.7 - 6.3           |
| Dodecane                             | 0.6             | 6.0             | 375                 | 0.6 - 6.0           |
| Hexadecane                           | 0.5             | 5.7             | 370                 | 0.5 - 5.7           |
| Octadecane                           | 0.4             | 5.4             | 365                 | 0.4 - 5.4           |
| Eicosane                             | 0.3             | 5.1             | 360                 | 0.3 - 5.1           |
| Tricosane                            | 0.2             | 4.8             | 355                 | 0.2 - 4.8           |
| Tridecane                            | 0.2             | 4.5             | 350                 | 0.2 - 4.5           |
| Tridecane                            | 0.1             | 4.2             | 345                 | 0.1 - 4.2           |
| Tridecane                            | 0.1             | 3.9             | 340                 | 0.1 - 3.9           |
| Tridecane                            | 0.1             | 3.6             | 335                 | 0.1 - 3.6           |
| Tridecane                            | 0.1             | 3.3             | 330                 | 0.1 - 3.3           |
| Tridecane                            | 0.1             | 3.0             | 325                 | 0.1 - 3.0           |
| Tridecane                            | 0.1             | 2.7             | 320                 | 0.1 - 2.7           |
| Tridecane                            | 0.1             | 2.4             | 315                 | 0.1 - 2.4           |
| Tridecane                            | 0.1             | 2.1             | 310                 | 0.1 - 2.1           |
| Tridecane                            | 0.1             | 1.8             | 305                 | 0.1 - 1.8           |
| Tridecane                            | 0.1             | 1.5             | 300                 | 0.1 - 1.5           |
| Tridecane                            | 0.1             | 1.2             | 295                 | 0.1 - 1.2           |
| Tridecane                            | 0.1             | 0.9             | 290                 | 0.1 - 0.9           |
| Tridecane                            | 0.1             | 0.6             | 285                 | 0.1 - 0.6           |
| Tridecane                            | 0.1             | 0.3             | 280                 | 0.1 - 0.3           |
| Tridecane                            | 0.1             | 0.0             | 275                 | 0.1 - 0.0           |

Border on the rich side of fuel/air ratio

Lower limit of flammability is the minimum fuel/air ratio that will support a flame. Above this limit, the mixture is too rich to burn.



# Bluff Body Flame Holders

- Typically flame will blow out when the time available for chemical reaction becomes less than



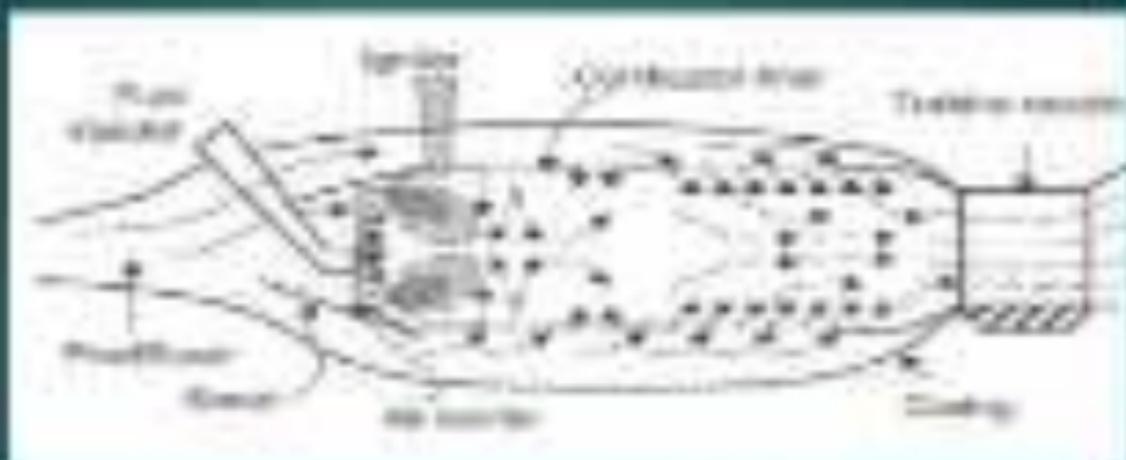
some of the burning mixture is blown off the burner and the rest is not carried into the recirculatory flow, which conveys it upstream to mix with new gas for the next burn. A flame will blow out if the flame through conduction of the system.

# Stabilization in Aircraft

The attitude (nose position) is controlled and maintained by air entering through small holes located in the fuselage and through an adjustable pitot tube in the middle of the fuselage.

As the aircraft is subjected to disturbances, a **Controlled** perturbation may be introduced over a large range of frequencies and amplitudes.





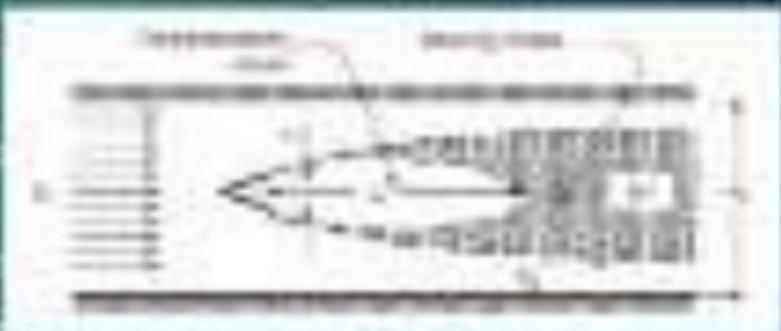
# Flame Stabilization in Afterburners

- The necessary reaction with a preheated flame.



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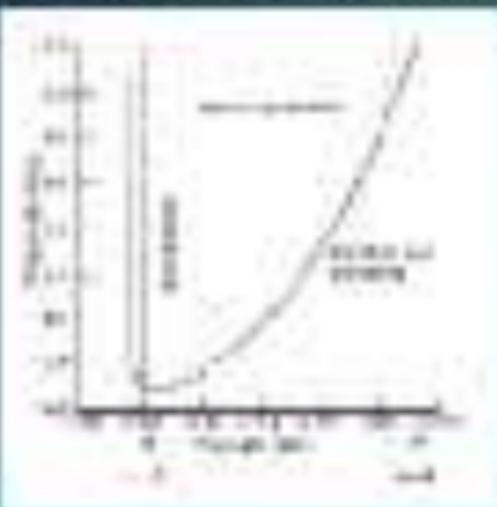
<http://www.youtube.com/watch?v=...>

# Influence of Various Parameters on Flame Stability

The extent of flame stability can be ascertained by the following parameters/conditions:

- 1. A reduction in approach stream velocity
- 2. An increase in approach stream temperature
- 3. A reduction in turbulence intensity
- 4. Any change in tube diameter towards inlet
- 5. An increase in flame holder size & wire rate
- 6. A reduction in diameter of blowdown (for a constant flame holder size)

# Problem...



→ **Number of Resources:** Both resources are essential to the production of output, and the production process is strictly concave. → **Factor prices:** The factors are provided in perfectly elastic supply, and the market price of each factor is equal to the marginal product of that factor. → **Factor Allocation:** The firm chooses the factor allocation that maximizes profit.

# Combustor Sizing

---

## Combustor Volume: The effect of parameters

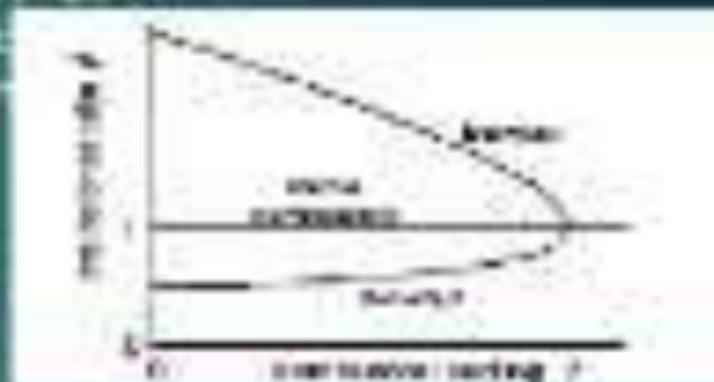
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$V^* = \text{Combustion Volume}$

$$CLP = \frac{\dot{m}_{fuel}}{V^*} \quad (2)$$

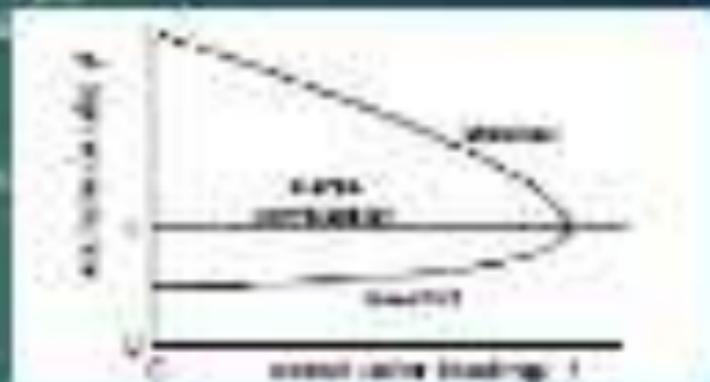
$V^* = \text{Combustion Volume}$



## Stability of Combustion & Combustor Volume

- Combustor required able to tolerate fluctuations of the combustion process to sustain itself
- If Too lean or too rich
  - flame & reaction rates drop below the levels required to heat and evaporate the fuel/oxidizer
  - will require longer analysis
- CLP (Combustion Loading Parameter)
  - Indication of stability based on Mach flow pressure ( $M = 1.5$  for typical flush), and combustor volume

$$CLP = \frac{1}{\gamma^2 (1 + \gamma)}$$



## Combustor Size

- > Cross-sectional Area determined by mass-flow rate and velocity requirements of the inlet to the turbine
- > Length: Completion of Combustion and Flame stabilization requirements
  - >  $L/D$  typically around 3-6
- > Volumetric heat release rate: Depends on pressure

# Combustor Length

- Length for the wave combustion is related to the residence time of the fluid in the burner in the form of the following equation as the combustion
- Parametrically, the length can be related to the residence time of the working fluid with respect to the flow velocity, pressure ratio and the cycle peak temperature.

$$L = \frac{P_{max}}{P_{in}} \frac{V_{max}}{A} \frac{1}{\sqrt{\gamma R T_{max}}} \approx \frac{P_{max}}{P_{in}} \frac{V_{max}}{A} \frac{1}{\sqrt{\gamma R T_{max}}}$$

# Combustor Length & Cycle Parameters

- Also within the combustor, the maximum flame is limited by the distance from the injection location of the oxidizer and the temperature
- $T_{max} \propto T_{inlet}$

$$\frac{L_{max}}{D} \propto \frac{P_{inlet} \sqrt{T_{inlet}}}{\dot{m}}$$

- Similarly, this leads to
- A large pressure ratio engine cycle will have a high combustion temperature, but an engine with a lower pressure ratio  
A similar argument can be made regarding the cycle thermal loading parameter of

Financial Statement Analysis: Income Statement

| Item                        | 2014    | 2013    | 2012    | 2011  | %     |
|-----------------------------|---------|---------|---------|-------|-------|
| Net Income                  | \$1,200 | \$1,100 | \$1,000 | \$900 | 100%  |
| Operating Income            | \$1,000 | \$950   | \$850   | \$750 | 83%   |
| Interest Expense            | (100)   | (100)   | (100)   | (100) | (10%) |
| Income Tax Expense          | (100)   | (100)   | (100)   | (100) | (10%) |
| Other Income                | 200     | 150     | 150     | 150   | 17%   |
| Depreciation                | 500     | 450     | 400     | 350   | 39%   |
| Amortization                | 100     | 100     | 100     | 100   | 11%   |
| Gain on Sale                | 100     | 100     | 100     | 100   | 11%   |
| Loss on Sale                | (50)    | (50)    | (50)    | (50)  | (6%)  |
| Change in Goodwill          | 150     | 150     | 150     | 150   | 17%   |
| Change in Intangible Assets | 100     | 100     | 100     | 100   | 11%   |
| Change in Other Assets      | 100     | 100     | 100     | 100   | 11%   |
| Change in Other Liabilities | (50)    | (50)    | (50)    | (50)  | (6%)  |
| Change in Other Equity      | 100     | 100     | 100     | 100   | 11%   |
| Total                       | \$1,200 | \$1,100 | \$1,000 | \$900 | 100%  |

Source: Financial Statements of ABC Company, 2011-2014.

Assumptions: All amounts in \$ million.

# Combustion Intensity

$$\text{combustion intensity} = \frac{\text{heat release rate}}{\text{cubic vol.} \times \text{pressure}} \quad \text{kW/m}^3 \text{ atm}$$

- ↳ Lower the combustion intensity needed for design or system safety related requirements.

Typically, Aircraft Engines have combustion with  $\square$   
at 100 atm and 25 MPa to 50 MPa (kW/m<sup>3</sup>-atm)

- Q.39 A gas is flowing in a pipe with a constant cross-sectional area. The velocity of the gas is 10 m/s and the pressure is 100 kPa. The temperature of the gas is 300 K. The density of the gas is 1.2 kg/m<sup>3</sup>.

(A) 10 m/s

(B) 8 m/s

(C) 7.7 m/s

(D) 11 m/s

# AIR BREATHING ENGINES



Combustor  
Components-32  
Turbine & Compressor

DR. A.R. SRIKRISHNAN

 AMRITA



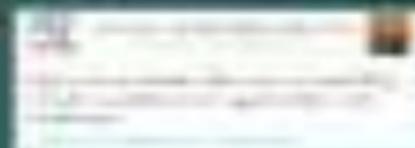
# Need for Flame Stabilization





# Swirler

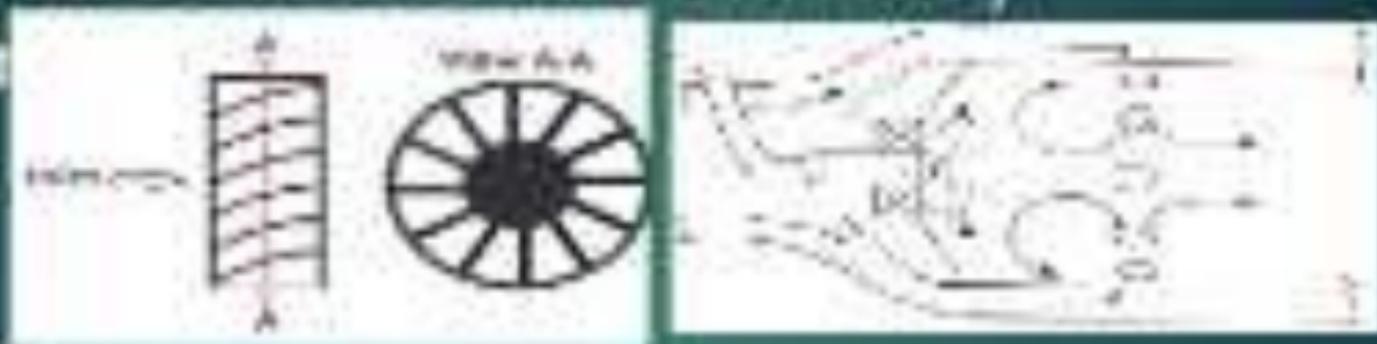
- Designed for wide-angle mixing and stable flame anchoring
- Swirler creates flow reversal that enhances and recirculates a portion of the hot combustion products to mix with the incoming air and fuel.
  - It's used as the flame
  - Also provides the distribution of fuel, air, and oxidant on products needed to achieve high fuel-to-air ratio



# Atomization

- Combustion takes place in gaseous phase
- Typically, liquid fuels are not sufficiently volatile to produce vapor in the amounts required for combustion
  - They need to be atomized into a large number of droplets with a corresponding greatly increased surface area
  - The smaller the droplet size, the faster the rate of evaporation

# Swirler: Induces Recirculation in Primary Zone





## Swirler Flow field

- An effective way of inducing flow recirculation in the primary zone
- Swirl causes recirculation in the core region which the amount of rotation imparted to the flow is high
- Swirl components generate strong shear regions: high turbulence, and rapid mixing rates



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# The Recirculation Field



<https://www.youtube.com/watch?v=6v2D8MV4G0s>

# ATOMIZATION



# Droplet Combustion

- Liquid fuel combustion takes place in gaseous phase
- The droplets evaporate and then reacts with the oxidant
- Rigid convection is responsible for external burning
- $\dot{m} = \pi d^2 \rho \dot{r}$
- $\dot{m} = \pi d^2 \rho \frac{d}{dt} \left( \frac{d}{2} \right)$



# The Process of Atomization

- A fresh surface is being produced by which fresh fresh molecules are lost under small droplets
- **Small droplets that evaporate together**
  - surface tension tends to pull the liquid into the form of a sphere, which has the minimum surface energy
- A fresh surface is continuously being produced, which is not covered by any film or layer of other droplets
- **Large droplets need to be continually removed by strategies**
  - **A hydrophobic surface is formed that repels the droplets**
- **Keep dynamic forces stirring on the liquid surface promoting the disruption process:**
  - **By applying an external disturbing force to the bulk liquid**
  - **Revolving a cylinder or sphere. This means a fluid of the same liquid is moving past the bulk. This causes fluid drag on the surface, causing it to shear**

# Weber Number

- Weber number is the ratio of fluid inertia over dynamic lift due to the interfacial surface tension force

$W = \frac{\rho U^2 L}{\sigma}$

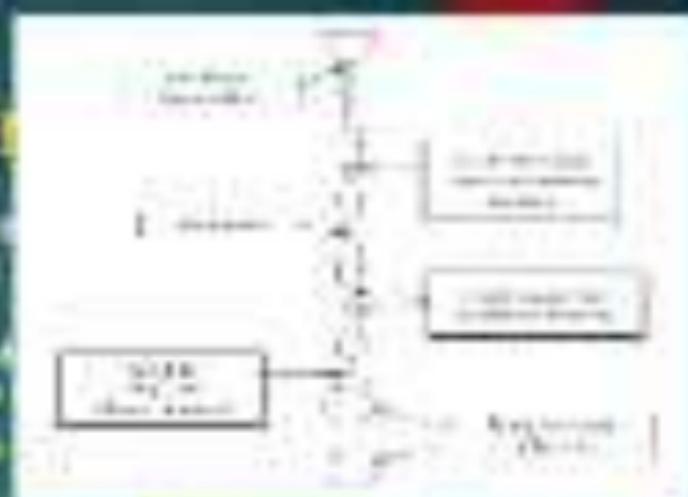
$W = \frac{\rho U^2 R}{\sigma}$

$$W = \frac{\rho U^2 R}{\sigma} = \frac{\rho U^2}{\sigma} R$$

- At small Weber number ( $W \ll 1$ ) the capillary pressure dominates (e.g. small droplets, low velocity, low surface tension)

# "Classical" Mechanisms of Jet Breakup

- **Secondary atomization:** occurs after primary atomization
- A jet of sheet promote the formation of waves that eventually lead to secondary and tertiary atomization
- **Primary atomization:** the jet of sheet is broken into sheets and ligaments
- **Tertiary atomization:** the large drops and ligaments produced by primary atomization further disintegrate into smaller drops





# Atomizer: The Requirements

- 1. Ability to provide good atomization over a wide range of fuel flow
- 2. Rapid response to changes in fuel flow rate
- 3. Proportional fuel flow characteristics
- 4. Low power requirements
- 5. Capability for scaling, to provide design flexibility



- 1. Low cost; light weight, ease of maintenance
- 2. Low susceptibility to breakdown by contaminants in the fuel and to carbon buildup on the nozzle face
- 3. Uniform radial distribution of the fuel
- 4. Substantial radial and circumferential fuel distribution

# Types of Atomizers



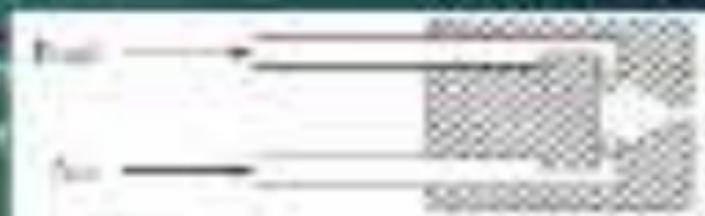
**Pressure-spray atomizer** - when a certain degree of pressure is put in the pressure-spray chamber, in which a swirling motion is imparted to the fuel so that under the pressure it spreads out in the form of a conical sheet as well as it leaves the orifice.

At higher drawback of the simple atomizer, the flow rate varies as the square root of the orifice pressure differential.

As the flow rate demands a flow rate increase in pressure.

# Air-Assisted Atomization

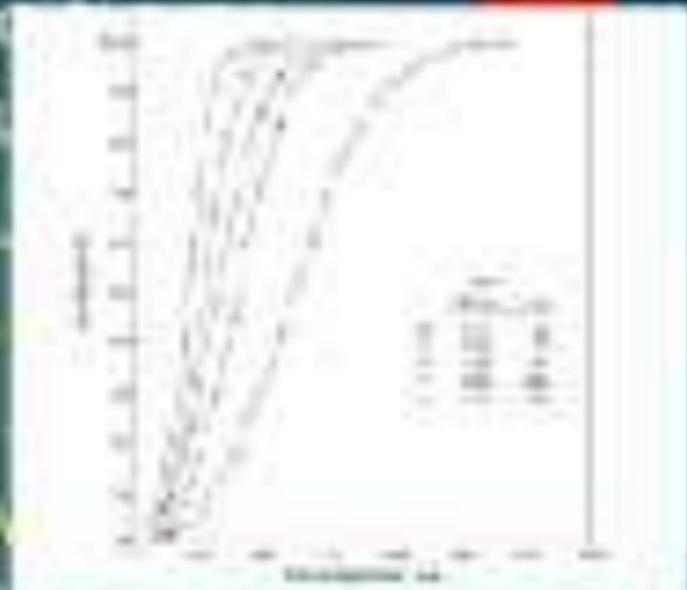
- Reduces the liquid film thickness and the number of primary droplets
- Air and fuel are both in the nozzle before exiting through the outlet orifice.
- The fuel is sometimes added through tangential slots to encourage a conical spray pattern.



# Spray Characterization

## Drop Size & Distribution

- The drop size is the actual physical distance that makes up the spray pattern
- The spray pattern is a 3D view made off the nozzle
- The most important mean diameter contribution applications is the **Sauter Mean Diameter (SMD)**
  - It is the diameter of a drop with the volume equal to the volume of all the drops in the spray



# AIR BREATHING ENGINES



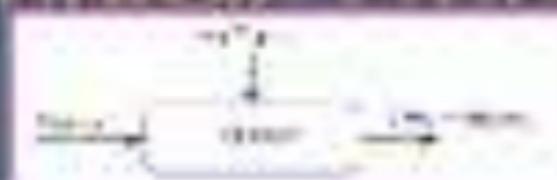
Combustor  
Fundamentals

DR. A.R. SRIKRISHNAN

 AARITA  
ANALYTICAL RESEARCH AND INSTITUTE



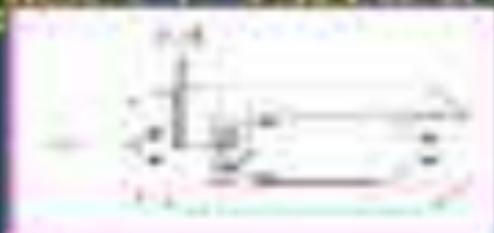
# The Fundamental Thermodynamic Process - Review



$$\dot{m}_f + \dot{m}_a = \dot{m}_p = \dot{m}_f + \dot{m}_a \quad \dot{m}_f = \dot{m}_a \lambda$$

$\dot{m}_a$  = mass flow rate of air  
 $\dot{m}_f$  = mass flow rate of fuel  
 $\dot{m}_p$  = mass flow rate of products  
 $\lambda$  = air-fuel ratio

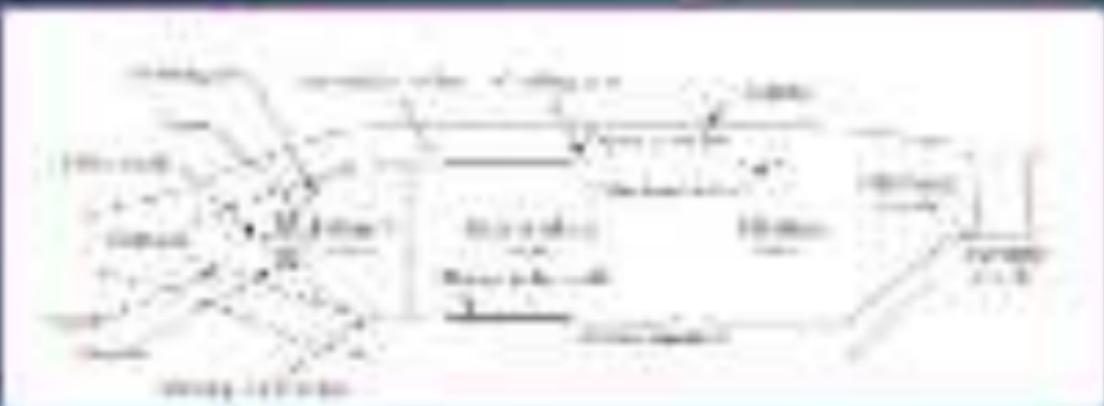
# Staged Combustion - Review



Primary Zone:  
Arrives first flame  
& provides time for  
flaming &  
combustion

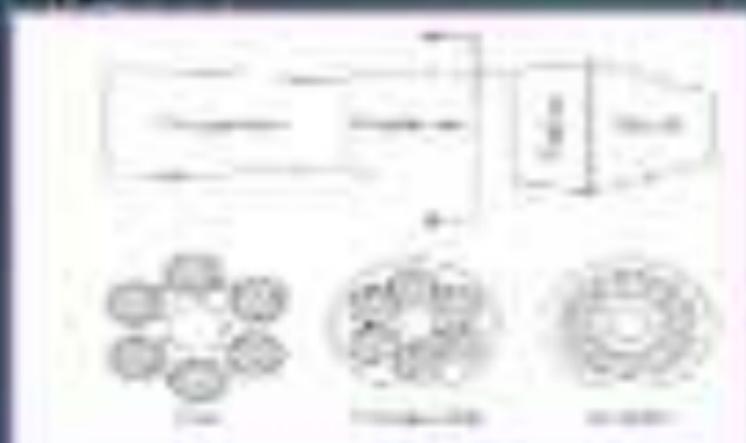
Secondary  
Zone: Completion  
of combustion with  
settling layer on  
diverge plate.

Pressure is reduced  
through with a  
temperature  
distribution that is  
unfavorable to the  
turbine.



# Types of Combustors -

Re



Open Type  
Combustors: Early  
development  
and higher weight  
and pressure loss

Annular  
Combustor:  
Modern design  
and high weight  
and pressure loss

<https://www.youtube.com/watch?v=...>

# Key Performance Requirements

- High combustion efficiency
- Reliable and smooth ignition. At start & in the event of any flame out.
- Wide operating range
  - the flame should stay bright over wide ranges of pressure and air/fuel ratio
- Low pressure loss
- Low heat transfer to the combustion chamber walls
- Low volume & weight
- Low cost, simplicity, ease of manufacture

# GATE 2016

11. A joint venture was formed by two companies, A and B, to develop an oil field in a state in south India of 200 BC. The cost of land in the state is 2000 crore rupees. The cost of development is 2000 crore rupees. The cost of land is 2000 crore rupees. The cost of development is 2000 crore rupees.

Company A contributed 1000 crore rupees  
to  
the joint venture.

What is the cost?

Note  
the  
system  
is  
not  
right  
yet...

|      |      |      |
|------|------|------|
| 1000 | 1000 | 1000 |
| 1000 | 1000 | 1000 |

# GATE 2012

10. The maximum magnitudes of the sine and cosine wave functions  $y = \sin x$  and  $y = \cos x$  respectively, at the same value of  $x$  that is  $\pi/4$  are  $(a)$   $(\sqrt{2}, \sqrt{2})$  and  $(b)$   $(1, 1)$  respectively. The correct answer is
- (A)  $(\sqrt{2}, 1)$   
(B)  $(1, 1)$

$y = \sin x$  and  $y = \cos x$   
at  $x = \pi/4$   
 $\sin(\pi/4) = \frac{1}{\sqrt{2}}$   
 $\cos(\pi/4) = \frac{1}{\sqrt{2}}$

# AIR BREATHING ENGINES

Session :

**NOZZLES**



B. SRIKISHAN

**AMRITA**



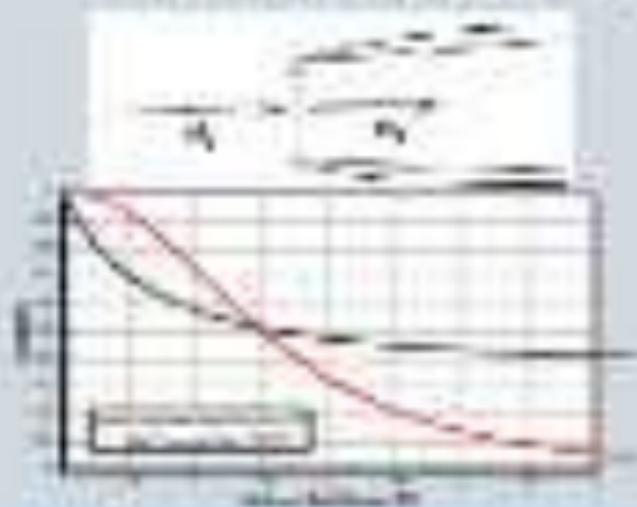
## Supersonic-to-Subsonic Diffusion



# Supersonic Inlets

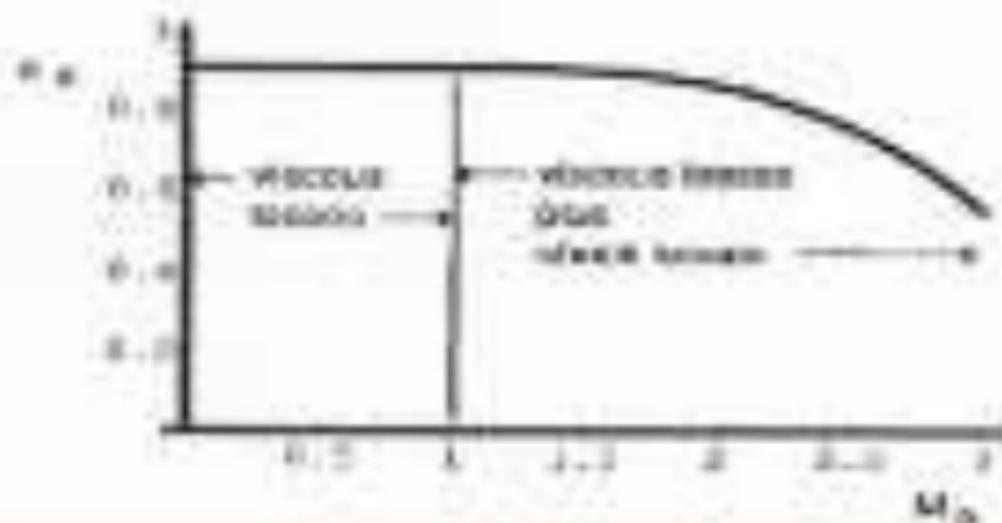
Normal Shock Inlets & Oblique Shock Inlets

Normal Shock & Oblique Shock Inlets: Higher stagnation pressure recovery



$$\frac{p_2}{p_1} = \frac{1 + \gamma M_1^2}{1 + \gamma M_2^2}$$

# Stagnation Pressure Loss Vs Mach Number



# Diffuser = Inverse Nozzle ?



Just a theoretical  
possibility

standard, we need to start with proper units. Converting between the two units of the system. I started  
 thinking about the standard unit of time for the system, which is the daily period of 24 hours.  
 Now, we need to find the standard unit of time for the system, which is the daily period of 24 hours.  
 I think the standard unit of time is 24 hours, so we can convert the time to hours.



## Types of Supersonic Inlets





## Mixed Compression Inlets

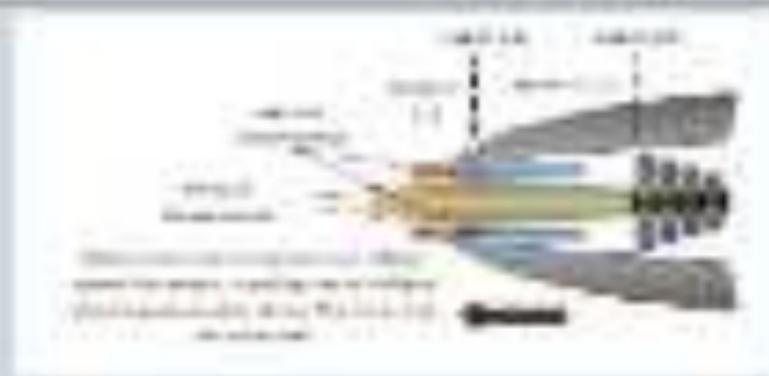
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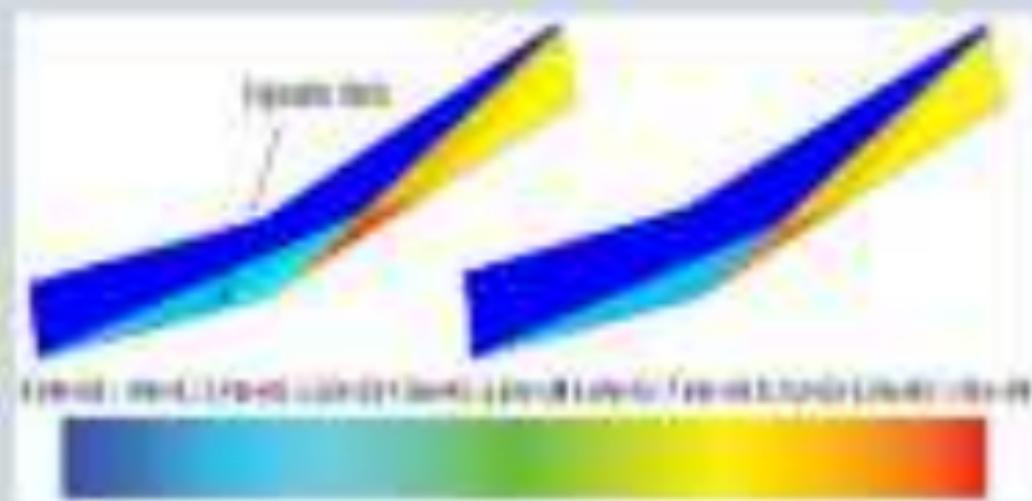






## Shock Boundary Layer Interaction:

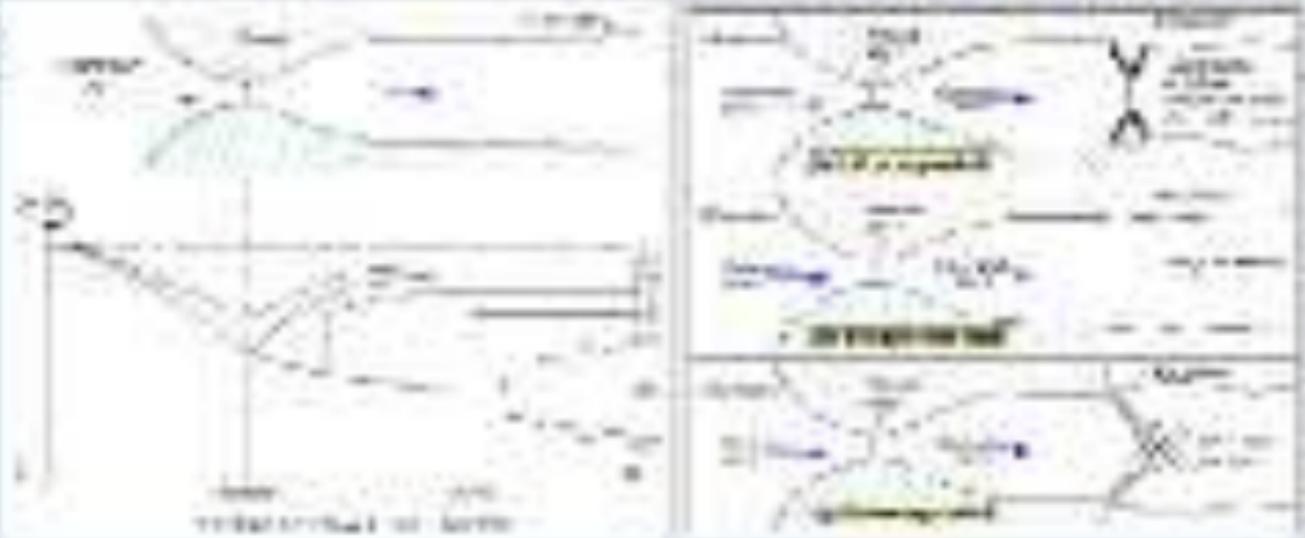






Noddies

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## Jet Expansion Scenarios

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# Nozzle Efficiency

## Nozzle adiabatic efficiency:

The ratio of actual kinetic energy of the fluid jet to the ideal kinetic energy that originates from an isentropic expansion of the nozzle.



Temperature  
A nozzle is  
a nozzle with

ACTUAL EXPANSION: From  $h_0$  to  $h_2$   
→  $h_0 - h_2$  → Kinetic energy

ACTUAL EXPANSION: From  $h_0$  to  $h_2$   
→  $h_0 - h_2$  → Kinetic energy

## Adiabatic Efficiency

---



$$\eta_a = \frac{T_3 - T_4}{T_3 - T_{2s}} = \frac{V_3^2/2}{V_{2s}^2/2}$$

## Numerical Problem

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## Thrust Vectoring

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- A vector is a quantity that has both magnitude and direction
- A vector can be either directed in either direction from a origin or measured in degrees
- It is only a magnitude for a given vector that is used in a calculation

AV-8B Harrier

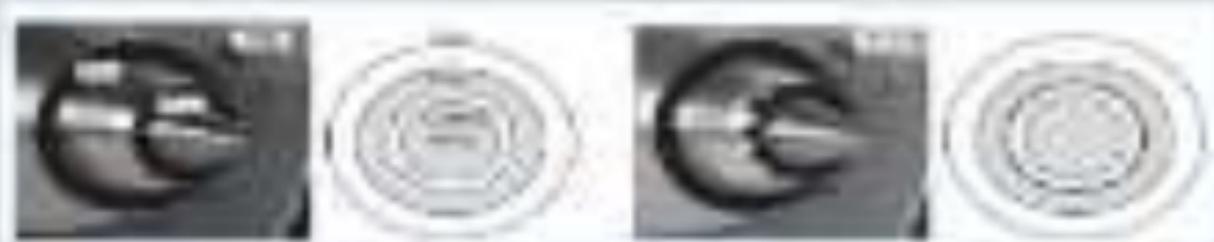


## Jet Noise

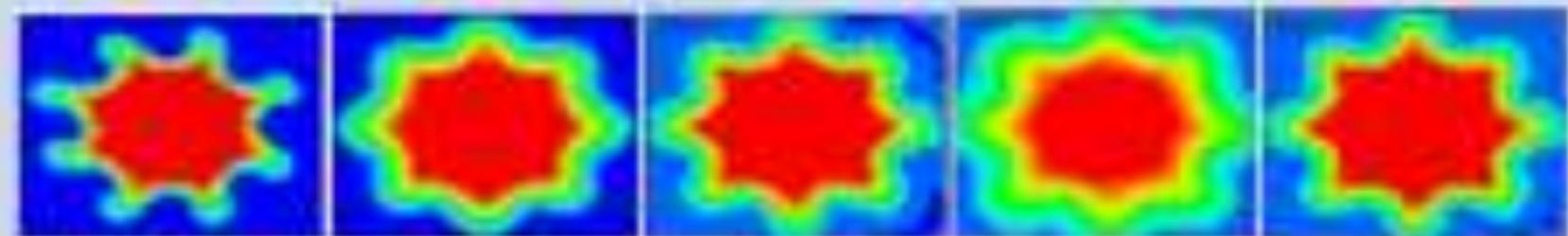
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# Chevron Nozzles



GE-Affinity

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# COURSE COMPLETION

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# AIR BREATHING ENGINES



Session :

**Supersonic Inlets**

B. SRIKRISHNAN

**AMRITA**



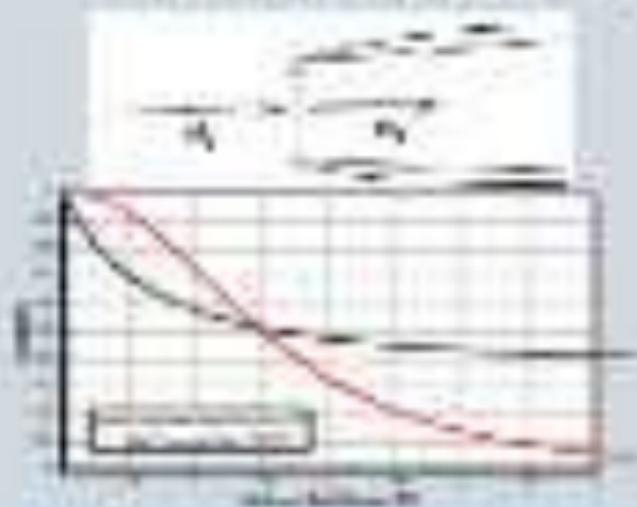
## Supersonic-to-Subsonic Diffusion



# Supersonic Inlets

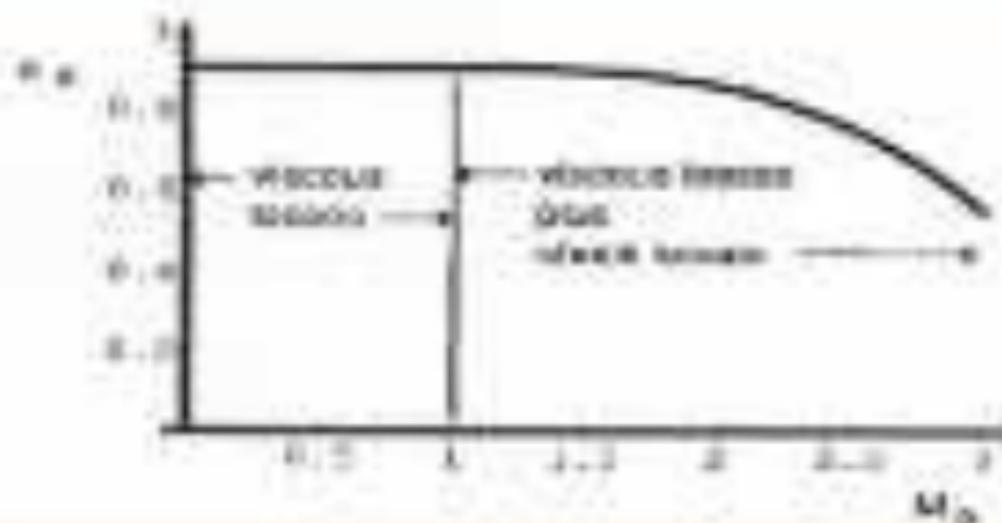
Normal Shock Inlets & Oblique Shock Inlets

Normal Shock & Oblique Shock Inlets: Higher stagnation pressure recovery



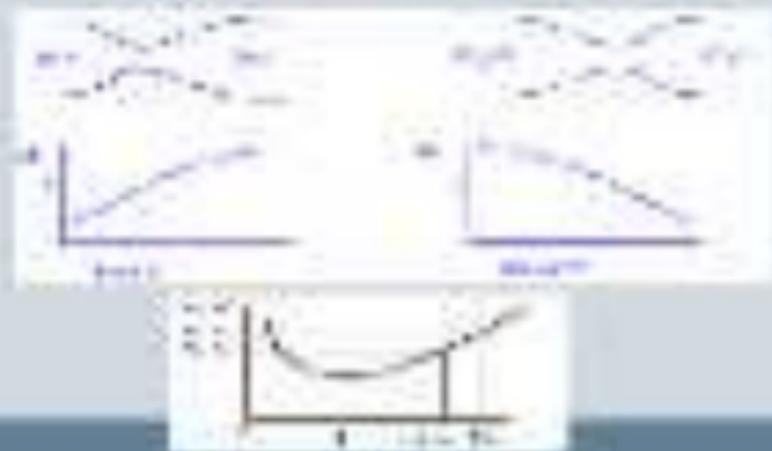
$$\frac{p_2}{p_1} = \frac{1 + \gamma M_1^2}{1 + \gamma M_2^2}$$

# Stagnation Pressure Loss Vs Mach Number



## Diffuser = Inverse Nozzle ?

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standard, we need to start with proper units. Converting between the two units of the system. I started  
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 Now, we need to find the standard unit of time for the system, which is the daily period of 24 hours.  
 I think the standard unit of time is 24 hours, so we can use that.



## Types of Supersonic Inlets



## External Compression Inlets



Low velocity  
flow to the  
compressor  
high velocity  
flow to the  
inlet

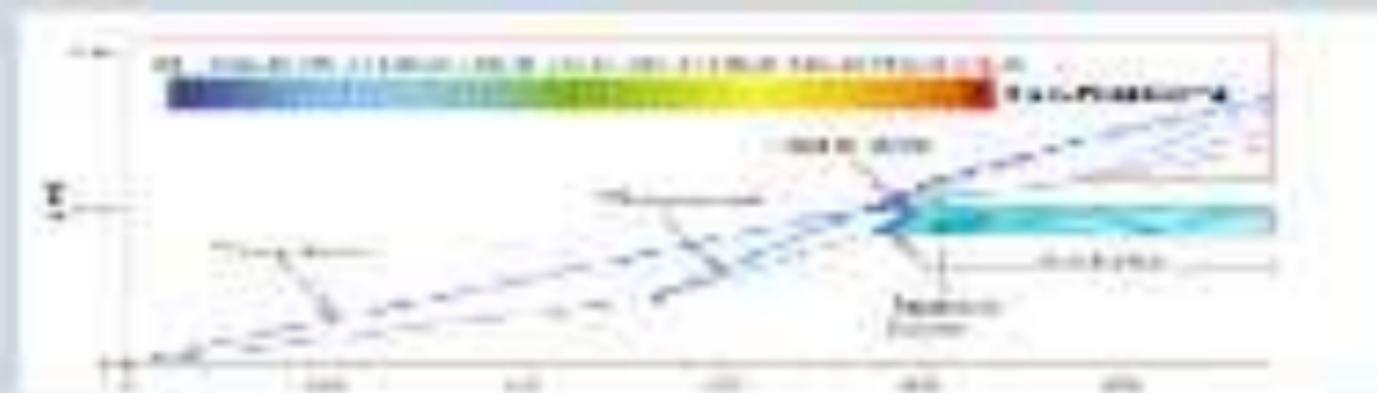


## Mixed Compression Inlets

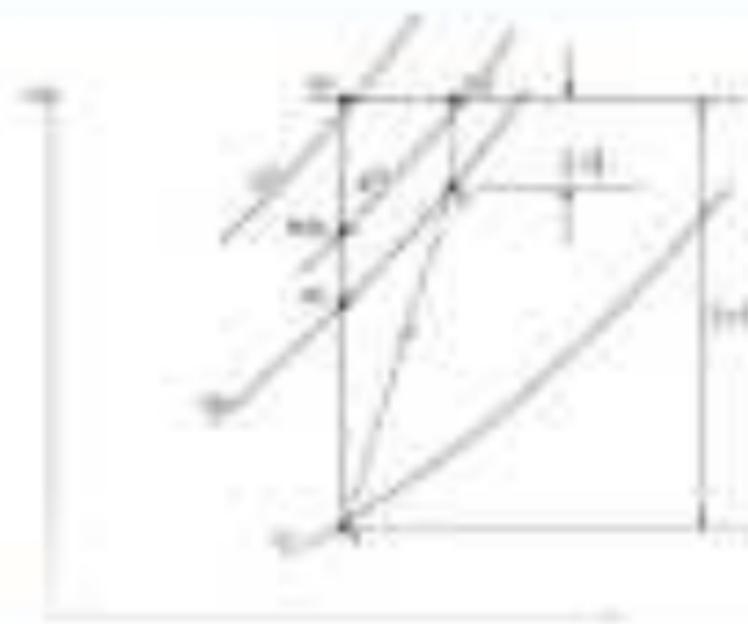
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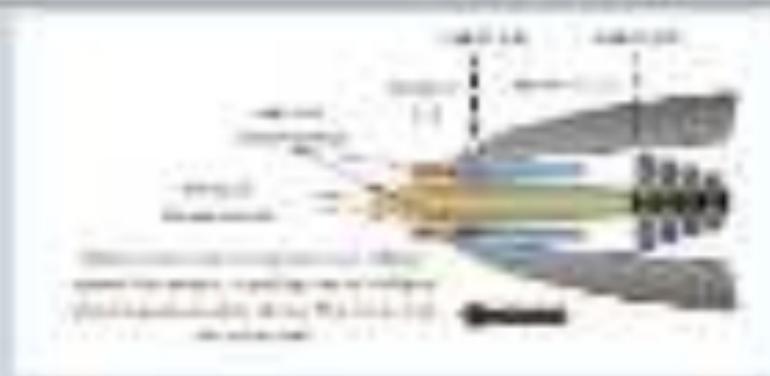






$$\Pi_D = \frac{P_{D2} - P_{D1}}{P_{D2} - P_{D1}}$$





## Shock Boundary Layer Interaction:

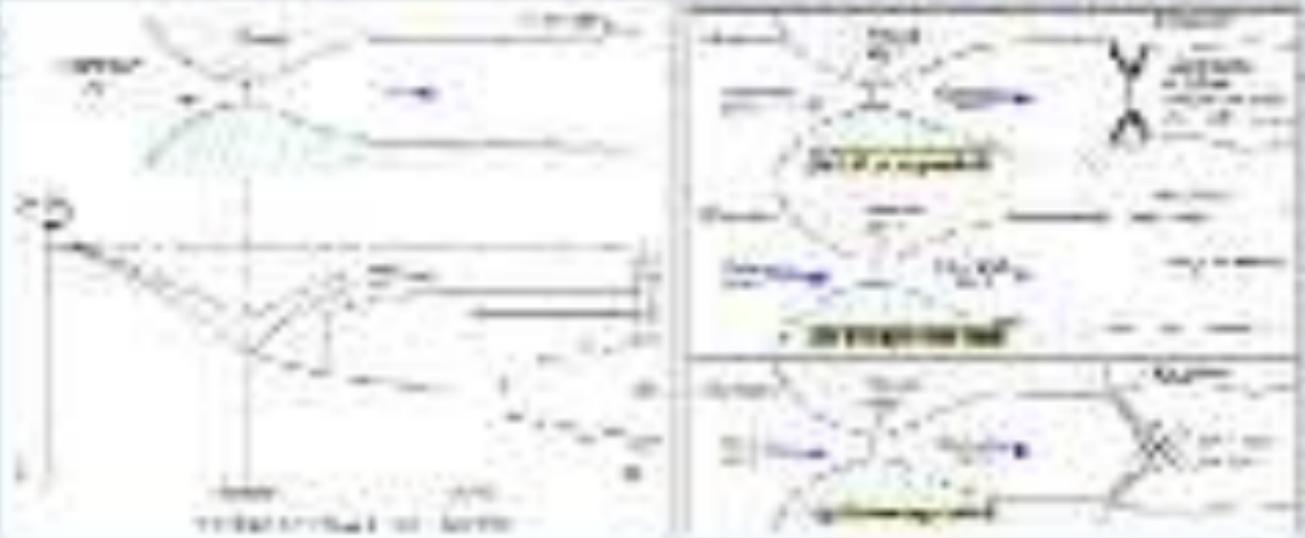






Noddies

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## Jet Expansion Scenarios

---



# Nozzle Efficiency

## Nozzle adiabatic efficiency:

The **adiabatic efficiency** of the nozzle is the ratio of the actual energy that comes from an isentropic expansion to the actual energy that comes from an actual expansion.



**Isentropic expansion**  
A nozzle with  
no losses



**Isentropic expansion** - more is  
made of  $h_1 - h_2$  -  $h_2$  -  $h_3$   
vs.  
**ACTUAL EXPANSION** - more of  $h_1$   
-  $h_3$  -  $h_3$  -  $h_3$

## Adiabatic Efficiency

---



$$\eta_a = \frac{h_{1T} - h_2}{h_{1T} - h_{2s}} = \frac{V_{2s}^2/2}{V_2^2/2}$$

# COURSE COMPLETION

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