AIR BREATHING ENGINES

A Free, Open Access MOOC

Session -01

DEPARTMENT OF AEROSPACE ENGINEERING

AMRITA

Overview

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

Course Objective & Syllabus

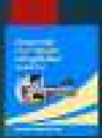
- **Course Objective:**
  - [illegible]
- **Syllabus:**

UNIT 1	UNIT 2	UNIT 3
[illegible]		
Review of propulsion, [illegible] Fundamentals of [illegible]	Turbine cooling & Analysis of inlets and nozzles	Analysis, Components & Design of combustors

Overview of The Course

- Review of
  - [illegible]
  - [illegible]
- Turbomachinery
  - Compressors & Turbines
    - Aerodynamics
    - Velocity diagrams
    - Cooling
- Inlets
  - Subsonic
  - Supersonic
- Combustors
- Flow through nozzles

Text/References



- Mattingly, Jack, D. "Elements of Propulsion: Gas Turbines and Rockets," AIAA Education Series, 2006
- Flack, R. D. "Fundamentals of Jet Propulsion with Applications," Cambridge University Press, 2005
- Hill and Peterson, "Mechanics and Thermodynamics of Propulsion," Dorling Kindersley (India), 2010

APPENDIX

SYLLABUS 1

AIR BREATHIING ENGINES

Session -02

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Session -2

REVIEW OF THE THRUST EQUATION & BRAYTON CYCLE

Recalling Derivation of the THRUST EQUATION

- The Control Volume considered...

The Momentum Equation…

- Recalling Momentum equation as applied to a control volume:

$$\sum F = \frac{d}{dt}\iiint_{cv} \rho u \, dV + \iint_{cs} \rho u (u \cdot n) \, dA$$

- Constituents of it
- Transformation of the equation for a (i) Steady (ii) Uniform flow, and for forces along the x-direction…

Review: Thrust Equation

$$Thrust = \dot{m}_e V_e - \dot{m}_o V_o + A_e(P_e - P_o)$$

- **The Assumptions ?**

- Momentum thrust & Pressure thrust

$$\dot{m}_e V_e - \dot{m}_o V_o$$

$$A_e(P_e - P_o)$$

Review: Thrust Equation

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

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

Review: Thrust Equation

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

- If "**Pressure thrust**" is absent:
  - *Perfectly Expanded* Nozzle Flow
    - Subsonic flow always has zero pressure thrust!

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

Pe > Pa

Overexpanded

Pe < Pa

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Session:
Review of
Brayton Cycle

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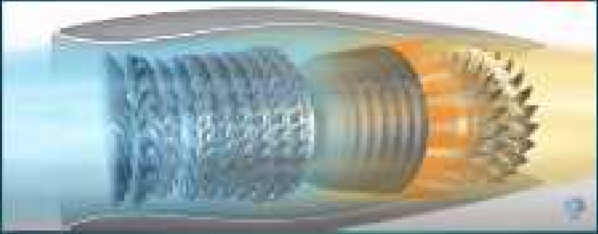
Session -3

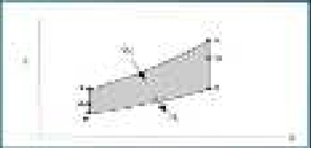
REVIEW OF BRAYTON CYCLE ANALYSIS



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 drives the flow of the fluid
  - The components are treated as [illegible], the effects that they produce are taken into account → "[illegible] Analysis"
  - What does this mean for an aircraft engine analysis ?
- **OBJECTIVE**: Determine which characteristics to choose for components of an engine to best satisfy a particular set of requirements
  - Relate T, [illegible] 15°C to the pertinent design parameters

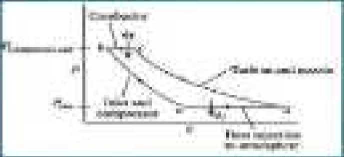
Brayton Cycle



Brayton Cycle

courtesy:
[illegible]

The Ideal Cycle Processes



Efficiency of The [illegible]

- Ideal Cycle Efficiency = Net work output/Net thermal energy transfer into the fluid

Equating P. Ratios of Compression & Expn

$$\eta_{Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

Ideal Efficiency

- **Ideal Cycle Efficiency** $1 - \frac{T_{01}}{T_{02}}$
  - Since 1-2 is isentropic: $\frac{T_{02}}{T_{01}} = \left(\frac{P_{02}}{P_{01}}\right)^{(\gamma-1)/\gamma}$
- **Ideal Cycle Efficiency** $= 1 - 1/\pi_c^{(\gamma-1)/\gamma}$

  $\left(\pi_c = \left(\frac{P_{02}}{P_{01}}\right)\right)$

- 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, <1

Real Cycle:
Compressor Efficiency

$= \frac{\text{Ideal Power Required}}{\text{Actual Power Required}}$

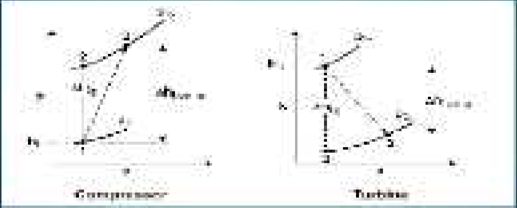
$= \frac{h_{02s} - h_{01}}{h_{02} - h_{01}}$

If Specific heat is assumed to be constant,

Isentropic Efficiency $= \frac{T_{02s} - T_{01}}{T_{02} - T_{01}}$

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

Real Compression & Expansion



Isentropic Efficiency, turbine

- On similar lines as for the compressor,

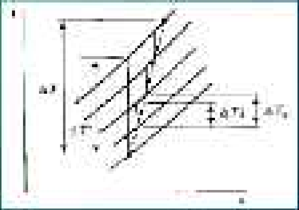
$\eta_t = \dfrac{\text{Actual Power Output}}{\text{Ideal Power Output}}$ For expansion with a specified expansion pressure ratio π_t

$$\eta_t = \frac{h_{03} - h_{04}}{h_{03} - h_{04s}} = \frac{T_{03} - T_{04}}{T_{03} - T_{04s}}$$

$$\eta_t = \frac{1 - \tau}{1 - \pi_t^{(\gamma-1)/\gamma}}$$

Polytropic Efficiency

- Defined as the isentropic efficiency of an elemental stage in the process such that it is constant throughout the whole process
- Why this definition?



Polytropic efficiency

Isentropic efficiency

Polytropic Efficiency, Turbine

- Defining polytropic efficiency for incremental expansion for turbine:

η_{poly}

$$\tau_t = \pi_t^{\frac{\eta_{poly}(\gamma-1)}{\gamma}}$$

$$\eta_t = \frac{1-\tau_t}{1-\tau_t^{1/\eta_{poly}}}$$

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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 (or pump): the fluid absorbs power from the solid surface
- Turbine: the fluid transfers power to the solid surface
- Direction of flow
  - Axial
  - Radial (centrifugal)

Types of Turbo-machines

- Classification based on the direction of energy transfer
  - Compressors
  - Turbines

- Classification based on the direction of flow
  - Axial flow
  - Centrifugal
  - Mixed flow

Videos - Turbomachines

https://www.youtube.com/watch?v=[illegible]

Videos – Turbomachines – ctd.

https://www.youtube.com/watch?v=[illegible]

What is Common to all these ?

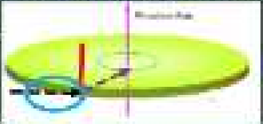
Energy transfer between a rotating blade surface and a fluid passing through

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 behaving an axial, radial and tangential components
- Radial components passes through the Centre – has no moment about it
- Axial component acts parallel to the axis 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

Linear Motion	Angular Motion
Linear Velocity V	Angular Velocity ω
Force F	Torque T
Linear Momentum [illegible]	Angular Momentum [illegible]
Work done = F * S	Work done = T * θ
Power P = F * V	**Power = T * ω**

Angular Motion: Force, Torque, Angular Momentum

A force (or set of forces) causing rotation

Torque = Moment of the Force

[illegible]

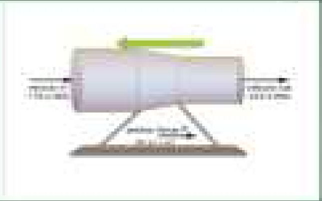
$$\tau = r \times F$$

[illegible]

[illegible]

Force & Linear Momentum

- Recall that force = rate of change of linear momentum



Torque → Angular Momentum

[illegible]

[illegible] through a turbo machine passage

[illegible]

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

Angular Momentum Equation

(The sum of all external moments acting on a CV) = (The time rate of change of the angular momentum of the contents of the CV) + (The net flow rate of angular momentum out of the control surface by mass flow)

Inlet Outlet

The Equation…

$$\sum \vec{M} = \frac{d}{dt}\int_{CV} (r \times \vec{V})\rho \, dV + \int_{CS} (r \times \vec{V})\rho(\vec{V} \cdot \hat{n}) \, dA$$

For the specific case of a CV with well defined inlet & outlet over which velocities across the control surfaces can be averaged, surface integrals can be simplified

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

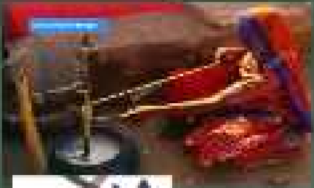
Net Torque, in Steady flow

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

$$\sum M = \sum_{out} rmV - \sum_{in} rmV$$

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…

- For a steady flow through a turbomachine
  Rate of Change in angular momentum = [illegible]
  [illegible]
- [illegible]
  - = Difference in angular momentum across the turbomachine
  - The only velocity component which changes the angular momentum of the rotor is the tangential component (V_θ)

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

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

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

Direction of Energy Transfer & Euler's Equation

- Applicable to both compressors & turbines
- The difference between out & in [illegible] will be [illegible] in compressors
  - Energy transferred to the fluid
- [illegible] in turbines
  - Energy transferred from the fluid

Euler's Statement

Torque exerted by flow on blade row =

[illegible] =

Rate of change of Angular momentum of fluid

Torque = Angular Momentum

Consider a control volume enclosing fluid motion through a turbomachine passage

By the conservation of angular momentum:

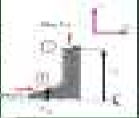
Net torque = rate of change of angular momentum across CV (steady state)

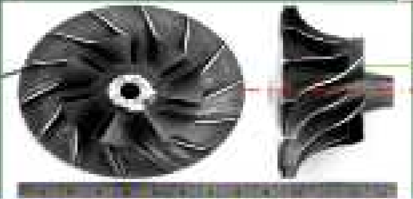
= Angular momentum at exit - Angular momentum at inlet

= $m_2 v_2 r_2 - m_1 v_1 r_1$

Inlet Outlet

Comprehending Euler's Equation…



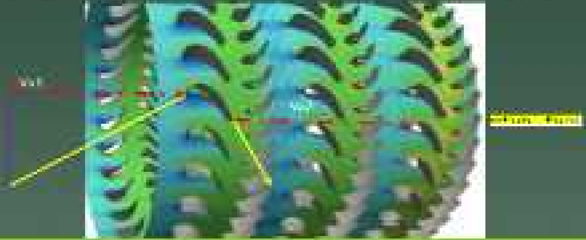


$$Power\ P = T\omega = \dot{m}\omega(V_{\theta2}r_2 - V_{\theta1}r_1)$$

Numerical Problem - 1

[illegible]
3000 rpm. The fluid enters the stage making an angle of 60 deg (with
[illegible]

[illegible]



AIR BREATHING ENGINES

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

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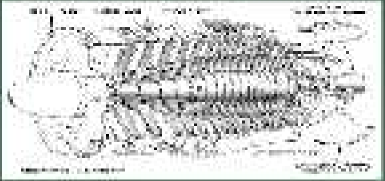
"Stages" of Compressors & Turbines

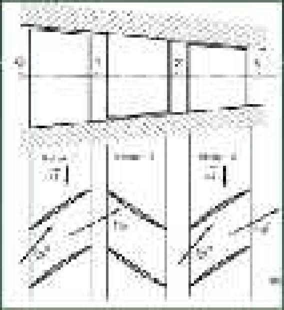
- Need for staging:
  - Requirement of high pressure ratios
  - Gradual compression/expansion
- Mechanically what constitutes a "stage"
  - Rotor – Rotating component attached to the shaft that connects compressor & turbine
  - Stator – Stationary component, attached to the casing


Number of Stages

- 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.



A compressor Stage



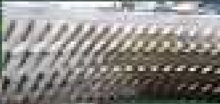
Rotor Vs Stator: The Functions

The Rotor

- A row of moving blades
- [illegible] momentum: increases the Kinetic Energy

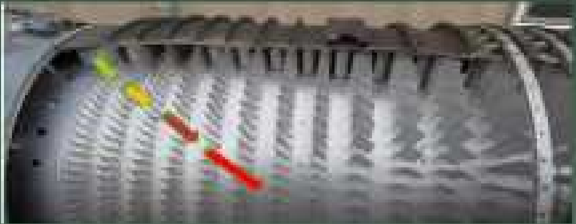
The Stator

- A stationary row of vanes
- [illegible]
- [illegible] Pressure
  - [illegible]
  - [illegible]

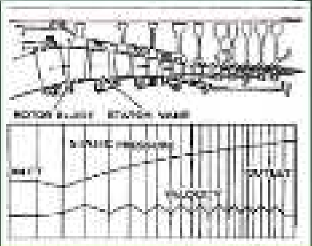


Cut-away view….

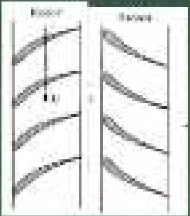
What if there is no stator...

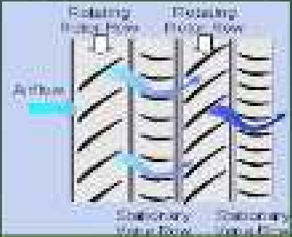


As Fluid Passes through a Multistage Turbomachine



A Compressor Stage...





A Compressor Stage: Summary of Variation of Flow Properties

Property	Stator	Rotor
Static pressure	Increases	Increases
Stagnation pressure	Remains Constant	Increases
Static temperature	Increases	Increases
Stagnation temperature	Remains constant	Increases
Velocity	Decreases	Increases

Trent 1000

Compressors	Turbines
LP – Single stage	LP – 6 stage
IP – 8 stage	IP – single stage
HP – 6 stage	HP – single stage

AIR BREATHING ENGINES

Session -07: Velocity Triangles

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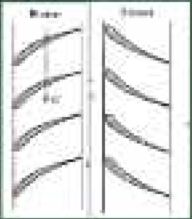
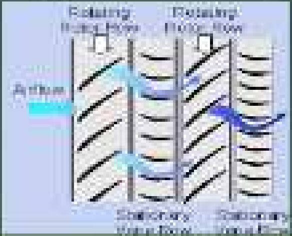
A Compressor Stage…





Torque, Power, Work

$Torque: T = \dot{m}(V_{\theta_2} r_2 - V_{\theta_1} r_1)$

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

At a given radius: $w = \omega r(V_{\theta_2} - V_{\theta_1})$

$= U(V_{\theta_2} - V_{\theta_1})$

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

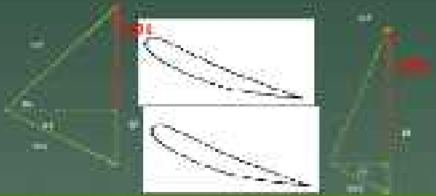
Velocity Triangle: *The Components*

- Absolute velocity vector
- [illegible]
- [illegible]
- [illegible]
- V_u, The tangential component of velocity
- Angles that the absolute and relative velocities make with the axial direction

Numerical Problem

Air enters axially (no tangential component) into an axial compressor stage, with a velocity of 120m/s. The rotor rotates at 5000 rpm. Calculate the relative velocity at a mean radius of 0.25 m.

Velocity Triangle



Vectors – Addition & Subtraction

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Session 16 – Solidity & Forces on Blades

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Blade Solidity

- Solidity of blades in a compressor is the ratio of the aerodynamic chord over the peripheral distance between two blades
  - $\sigma = c/s$ where c = chord length of the blade & s = spacing between the blades
  - $s = 2\pi r_m/Z_B$ where r_m is the mean radius & Z_B is the number of blades
- An important geometry parameter that influences the design and the performance

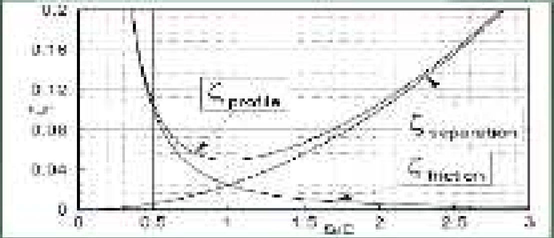
Cascade View: Low & High Solidity

Solidity & Losses

$$\sigma = \frac{z l_b}{2\pi r_m}$$

- If the spacing between the blades is too small:
  - Implies design with large number of blades
    - High friction losses
- [illegible]
  - 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** = $\zeta = \zeta_{friction} + \zeta_{separation}$

Optimum Solidity

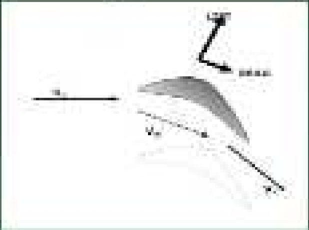


A Semi-Empirical Relation

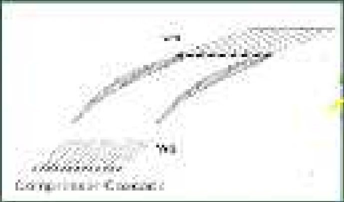
Optimum salinity calculated from:
[illegible]

$$\text{Optimum Salinity} = \frac{1.8 \cos \beta_2}{\cos \beta_1} \sin(\beta_1 - \beta_2)$$

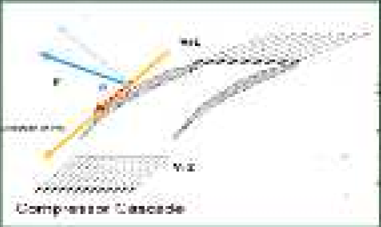
Lift & Drag on Blades



Forces Acting on the Blades



Forces Acting on the Blades



Forces & Power

The resultant force on each blade $F = f(\xi, \theta)$

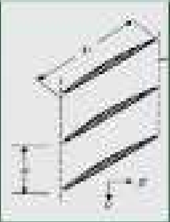
Net Torque due to this force, $T = n_B r F$

Power required to drive, $P = T\omega = n_B F r \omega$

Chord: 5.25 cm

Spacing: 3.5 cm

→ Solidity: 5.25/3.5 = 1.5



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Session 17 – Performance Parameters & Mapping

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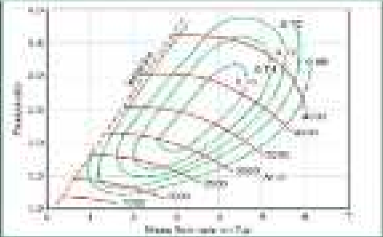
Performance MAPPING



Compressor Performance Evaluation & Mapping

- Quantification of the performance
- Comparison of performance
- Influence of operating conditions on the performance of a given compressor
- Comparison of different compressors at similar operating conditions

All these require:

Identification of parameters that influence the performance

Grouping of these parameters

Mapping of performance as a function of operating conditions

Performance Characterization

- Focused 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 groups
- Determine the influence of functional groups on key performance parameters

Dimensional Analysis

- The formal procedure by which a group of variables impacting a physical process is reduced to a smaller number of independent variables
- Enables experimental data collection economical & manageable
- Applied extensively for turbo machines

Compressor Performance

- Fluid Viscosity
- Fluid Density
- Fluid compressibility
- Speed of Rotation
- Mass flow rate
- Ratio of specific heats

Performance parameters of Interest ?

Non-Dimensional Functional Relations

$$\frac{p_{02}}{p_{01}},\ \eta = f\left\{\frac{\dot{m}\sqrt{\gamma R T_{01}}}{D^2 p_{01}},\ \frac{ND}{\sqrt{\gamma R T_{01}}},\ Re,\ \gamma\right\}$$

$$\frac{p_{02}}{p_{01}}, \eta = f\left(\frac{\dot{m}\sqrt{C_p T_{01}}}{D^2 p_{01}}, \frac{ND}{\sqrt{C_p T_{01}}}\right)$$

- For a given engine: D is constant
- For a given working fluid (air): C_p, R & γ are constant
- Hence:

$$\frac{p_{02}}{p_{01}}, \eta = f\left(\frac{\dot{m}\sqrt{T_{01}}}{p_{01}}, \frac{N}{\sqrt{T_{01}}}\right)$$

Compressor Testing & Atmospheric Conditions

- Dependence of the mass flow on atmospheric conditions of Pressure & Temperature

[illegible] Both these parameters to remain the same.

[illegible]

[illegible]

Corrected Mass & Speed

- In industry, usually the functional relation that a given engine is expressed in terms of

Mass flow: $\dfrac{\dot{m}\sqrt{\theta}}{\delta}$

and Speed: $\dfrac{N}{\sqrt{\theta}}$

$$\theta = \frac{T_{02}}{T_a} \quad \text{and} \quad \delta = \frac{p_{02}}{p_a}$$

$$\frac{p_{03}}{p_{01}},\eta \;=\; f\left(\frac{\dot{m}\sqrt{\theta}}{\delta}, \frac{N}{\sqrt{\theta}}\right)$$

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 atmospheric pressure and temperature on the day are recorded as 55060 Pa and 250 K respectively. Determine the corrected mass flow and the corrected RPM corresponding to standard atmospheric conditions of pressure = 101.325 kPa (1 atm) & temperature = 288 K.

$$\theta = \frac{T_{t1}}{T_0} \quad \text{and} \quad \delta = \frac{p_{t1}}{p_0}$$

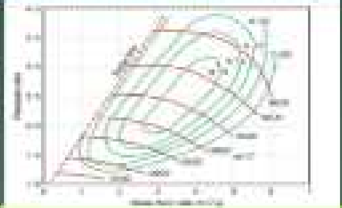
$$\frac{\dot{m}\sqrt{\theta}}{\delta}$$

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

[illegible]	[illegible]	Corrected Mass… [illegible]		[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

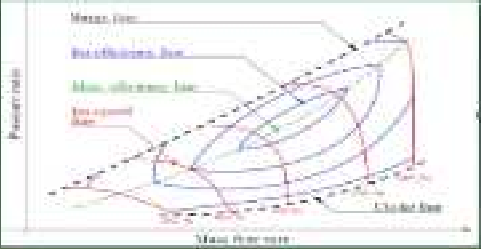
Compressor Performance Map

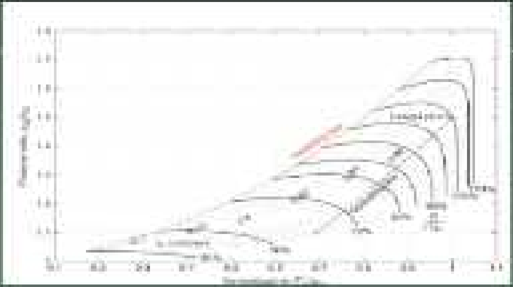
The pressure ratio of a compressor is plotted versus corrected mass flow rate and rotational speed



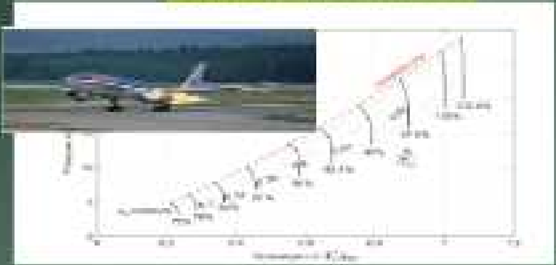
The Utility of *Corrected* Parameters: Comparison Across Diverse Operating Conditions

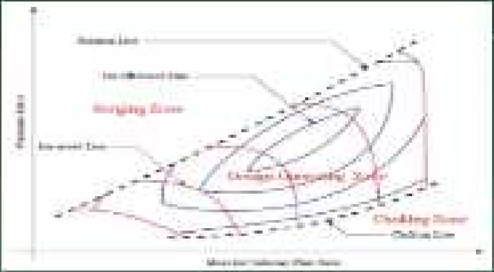
Compressor Performance Map

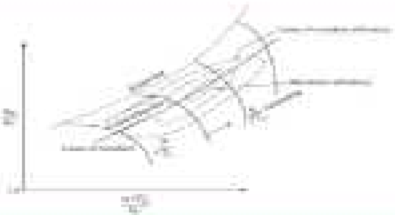




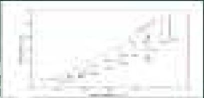
Surge/Dynamic Instability

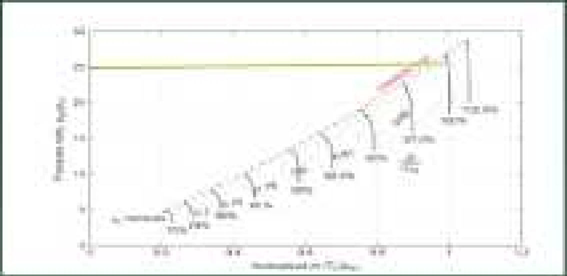



Surging Zone
Design Operating Zone
Choking Zone



Numerical Problem





AIR BREATHING ENGINES

Session 18:
Off-design
Performance

DR. A.R. SRIKRISHNAN

AMRITA

The Off-design Challenges

- The Design is made to suit a specific flow rate, specific speed, specific density etc.
- [illegible]
- 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

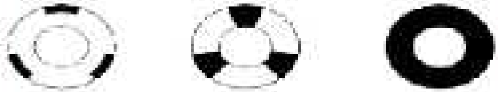
- A minor variation at the first stage may gradually get enhanced as the air flows through subsequent stages.
  - [illegible]
  - [illegible]
  - This continues.
- How this affects the flow field and overall performance?

Compressor Stall…

a) Inception of stall cells; boundary layer separation due to an increase of positive incidence angle

b) Manifestation of stall cells; deflection of velocity streamlines caused by stall cells

Stall Propagation & Development of Surge



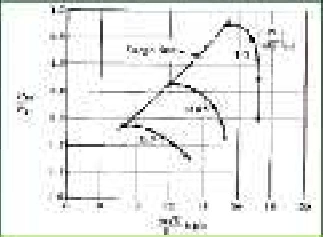
Growth of stall cells to surge

Surge Line/Instability line

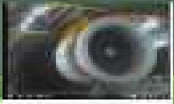
Compressor Surge

- Surge is a condition of instability in the operation of compressors 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



AIR BREATHING ENGINES

Sessions – Radial Equilibrium

DR. A.R. SRIKRISHNAN

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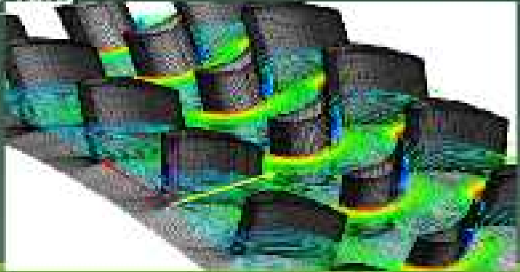
Three Dimensionality of Flow Field



Radial Direction: Hub Radius (R_h) and Tip Radius (R_t)

Flow Across the Blades

Flow Velocity Direction

- [illegible]
- 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 <u>along</u> blade height

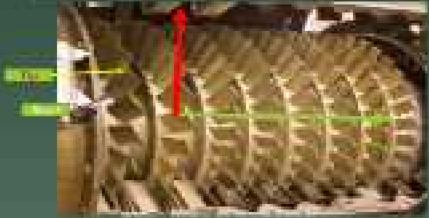
Flow in Radial Direction

- 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 how flow deflection varies at different radii*
- How other properties vary along radial direction ?

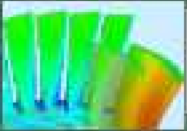
Hub-to-Tip Variation

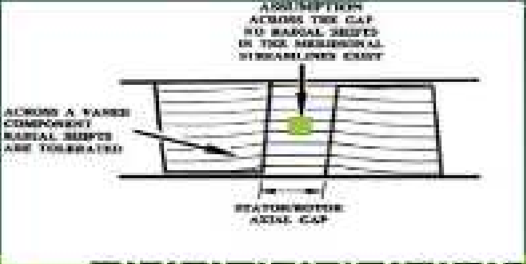
- Radial flow:
  - In the direction of centrifugal forces

- Not critical if 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.



The Assumption of Radial Shift

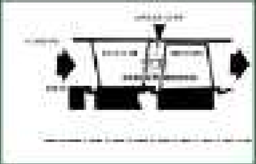


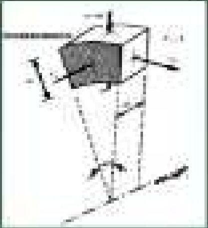

ASSUMPTION
ACROSS THE GAP
NO RADIAL SHIFTS
IN THE MERIDIONAL
STREAMLINES EXIST
ACROSS A BLADE
COMPONENT
RADIAL SHIFTS
ARE TOLERATED
STATOR/ROTOR
AXIAL GAP

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 the radial equilibrium.
    - [illegible]
  - *Balance of pressure gradient and the centrifugal force on a swirling fluid element*

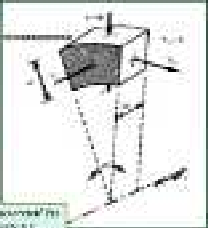
Fluid element



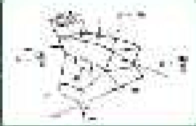


Radial Equilibrium of The Fluid Element

$$F_R = r\,dp\,d\theta$$



The Centrifugal Force



The centrifugal force

$V_\theta = r\omega$

$$F_{centrifugal} = \rho V_\theta^2 dr d\theta$$

Equilibrium

the element will move along constant radius r

$$F_{pressure} = F_{centrifugal}$$

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

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

Uniform work distribution along radial direction

Stagnation enthalpy at any section:

V_x … (axial section)

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

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

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

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

$$\frac{dh_0}{dr} = \frac{V_\theta^2}{r} + V_x\,\frac{dV_x}{dr} + V_r\,\frac{dV_r}{dr} + V_\theta\,\frac{dV_\theta}{dr} = 0$$

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

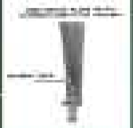
$$\frac{d}{dr}(rV_\theta) = 0$$

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

$$\frac{d}{dr}(rV_\theta) = 0 \Rightarrow V_\theta\, r = \text{Constant}$$

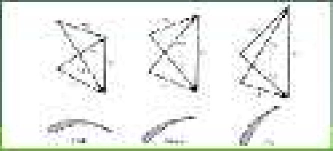
[illegible] to the velocity profile & the design

Experimental data on radial distribution of To



Free Vortex Design

- One of the popular methods in blade design
- But results in highly twisted blades: blade angle varies significantly from the root to the tip
- Velocity triangles vary in shape across the radial direction



AIR BREATHING ENGINES

Sessions:
Centrifugal
Compressors

DR. A.R. SRIKRISHNAN

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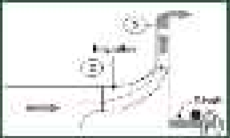
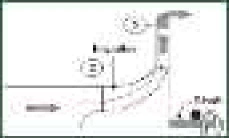
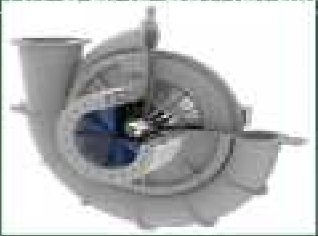
Centrifugal/RADIAL Compressors

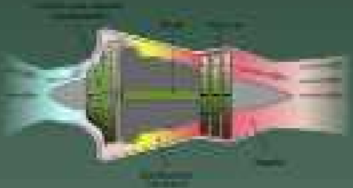


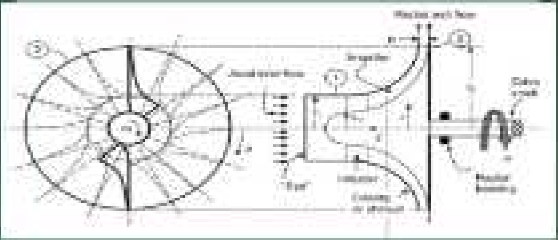
Centrifugal/RADIAL Compressors



CENTRIFUGAL Compressors

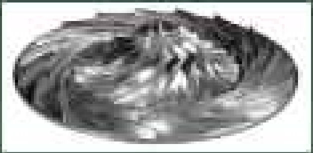


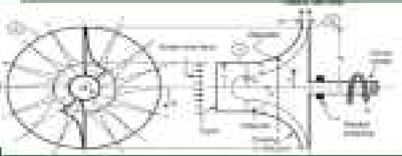


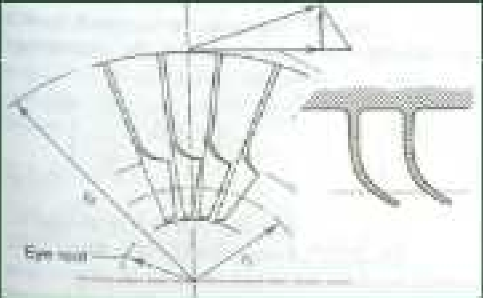


Components

- Inducer
  - [illegible]
- Impeller
  - Transfers energy
  - Increases the stagnation pressure, stagnation temperature as well as the static properties
- Diffuser
  - Increases static pressure by decelerating the flow






Eye

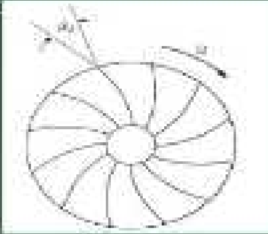
Work transfer in Radial Compression

[illegible]

[illegible]

Since $r_2 > r_1$, even a small increment in V_u can lead to high difference in h.

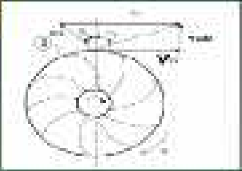
Hence typically centrifugal compressors support higher stagnation pressure ratio per stage



Backward-leaning blades

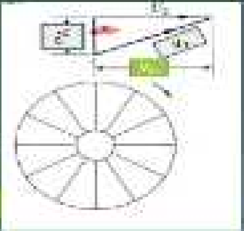
Backward-swept impeller has passages that direct the relative flow in a direction opposite that of the rotor rotation

The blades are [illegible] from radial direction

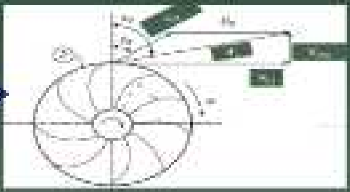


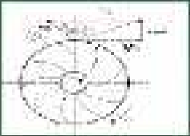
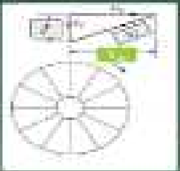
Straight/Radial Blades

The blades are designed in such a way that the flow leaves radially outwards – flowing along the radius all through the passage

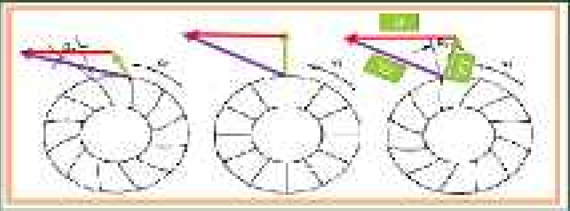


Forward-leaning blades




Exit Velocity Triangles

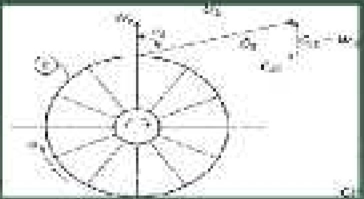


Tangential Velocity *[Ideal]*

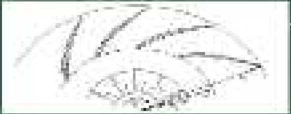
[illegible]

[illegible]

[illegible]



Diffuser



- **The swirl component in diffuser reduces as a result of:**
  - Angular momentum conservation: as Vtheta*r = constant
  - Viscous forces as the fluid moves out

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
- Frontal area for a given mass flow is higher for centrifugal compressors

GATE 2019

GATE 2018

GATE 2007

GATE 2014

[illegible]

Specific work = [illegible] as the flow enters axially

[illegible] (definition of slip factor)

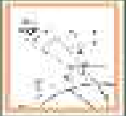
[illegible]

[illegible]

Efficiency = **74.8%**

Numerical Problem

Calculate the shaft power required for a centrifugal compressor for which: Flow enters axially, blade tip velocity = 520m/s, radial velocity at outlet [illegible] m/s, [illegible] of 30°. Mass flow rate of air = 5 kg/s



Vwhirl2 = U-Vrad2*tan(30) = 433.4 m/s

Power = m*U*Vwhirl2 = **[illegible] mW**

Numerical Problem

Air leaves the impeller of a backward-swept compressor with a radial velocity of 110 m/s, at a relative angle of 25.5 deg. The speed of the impeller is 475 m/s. The compressor operates with a [illegible]. Calculate the power required to drive the compressor

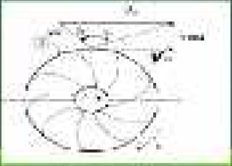
- $\tan(\beta_2) = (U - V_{\theta 2})/V_{rad2}$

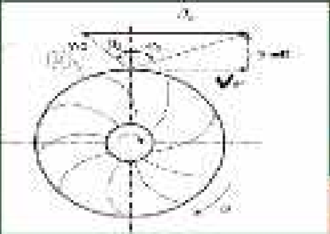
- → Power required = $U \cdot V_{\theta 2}$

$\tan(25.5) = (475 - V_{\theta 2})/110$

⇒ $V_{\theta 2} = 422$ m/s

= [illegible]





AIR BREATHING ENGINES

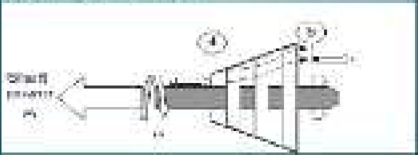
Sessions:
Axial Flow Turbines

DR. A.R. SRIKRISHNAN

AMRITA

The Direction of Work Transfer

- Turbines absorb energy from the fluid
  - Expansion process
  - Drop in stagnation enthalpy



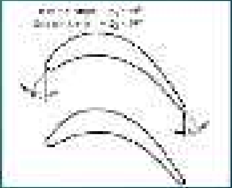
Expansion Vs Compression

- Flow expands through the turbine
  - Favourable pressure gradient
  - Less chances of separation
  - Aerodynamically simpler
- [illegible]
  - Hot combustion gases are the working fluid
  - Erosion → Thermal stresses
  - Needs continuous cooling
  - Thermally complex

Stator, Rotor – The Turbine stage

- Stator\"Nozzle"

Rotor

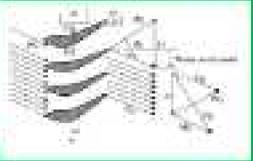


Compressor Vs Turbine

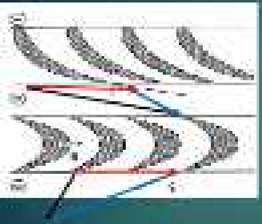
- Blade Passage: Diverging in compressors, Converging in turbines

Turbine Stage

Conventionally [illegible] first & [illegible] second in turbine stage considerations



Velocity Triangles



Torque, Power

- $T = \dot{m}(r_1 V_{u1} - r_2 V_{u2})$
- $P = \dot{m}(U_1 V_{u1} - U_2 V_{u2})$ (work is done by the fluid)
- $\quad = \dot{m} c_p (T_{01} - T_{02})$

- In the above equations 1 and 2 denote the inlet and exit sections of the rotor

Note that by convention we use 2 & 3 respectively for the above locations for the turbine

Degree of Reaction

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

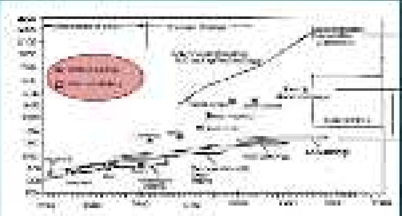
$$R = \frac{\text{Enthalpy drop in the moving blades}}{\text{Enthalpy drop in the stage}}$$

$$= \frac{h_2 - h_3}{h_1 - h_3} = \frac{\mathbf{V}a}{2U}\left(\tan\beta_1 - \tan\beta_2\right)$$

Turbine Blade Cooling

Higher turbine inlet temperatures: The Progress..

- Higher pressure ratios
- Higher cycle efficiency



Turbine Blade Cooling

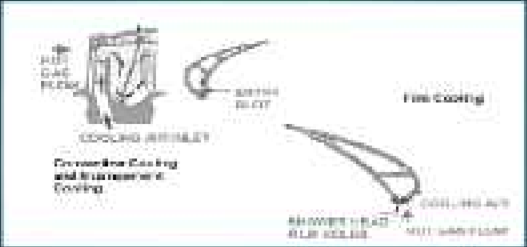
Blade Cooling:The standard procedure are to bleed air from some stage of the compressor, bypass the combustion chamber and inject it as cooling air in the turbine.

Blade Cooling Methods

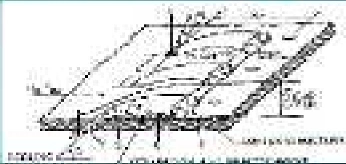
$$\eta = \frac{T_g - T_b}{T_g - T_c}$$

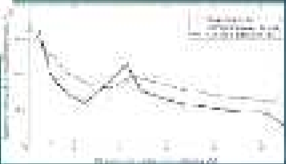
Impingement cooling: a concentrated air jet is made to impinge on the inner surface of the blade through small holes

Film Cooling: The air after being used for internal cooling is ejected out through some holes or slots to the external surface to create a protecting "air film" acting as a barrier from the hot combustion gases


Convection Cooling
and Impingement
Cooling
Film Cooling

FILM COOLING BEHAVIOR

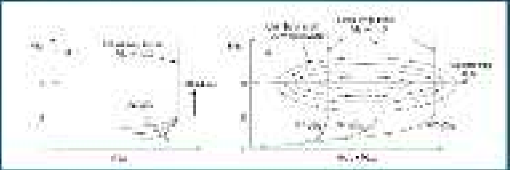




Designing the Blade Cooling System

- Steps in setting up the requirements:
  - Estimate the heat flux at the blade wall (q_w) for given wall temperature (T_w)
  - Calculate the thermal stresses
  - Determine the reduction in q_w required to limit stresses within permissible values
  - Calculate the effectiveness required
  - Determine the arrangement of cooling holes and cooling airflow for film cooling to provide the required effectiveness
  - Calculate the flow rate required for interior cooling airflow to obtain reduced q_w

Turbine Characteristics



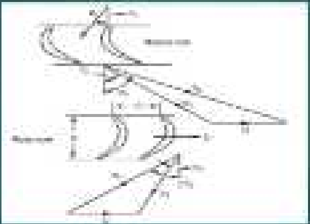
Numerical Problem

Consider a single-stage axial flow gas turbine. The gas enters at stagnation temperature of [illegible] K. Axial velocity is constant through the stage and equal to [illegible] m/s. Mean blade speed is [illegible] m/s. Mass flow rate of gas is [illegible] kg/s and assume equal inlet and outlet velocities. Nozzle exit angle is [illegible] deg, stage exit swirl angle equal to [illegible] deg. Determine the rotor blade angles, degree of reaction, and power output.

Power = mU(V[illegible] + V[illegible])

Tan(alfa2) = (U+V[illegible] tan(beta2))/V[illegible] = beta3

U+V[illegible] tan(alfa3) = V[illegible] tan(beta3) → beta3



Solution

[illegible]

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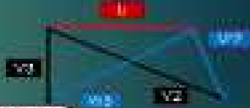
[illegible]

Note the following:

1. Axial exit velocity means [illegible]
2. "Nozzle exit" refers to rotor inlet -> [illegible]

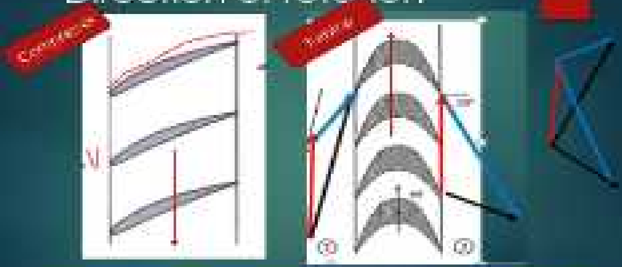


Solution: Sp. Work: w = U*(Vw2-Vw3) = U*Vw2 as Vw3 = 0.

→ Vw2 = w/U = 518.2 m/s

V2 = Vw2/sin(70) = 551.45 m/s

Direction of rotation

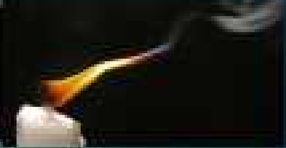


AIR BREATHING ENGINES

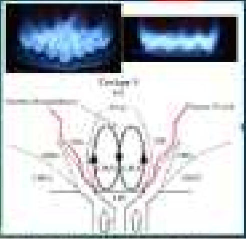
Flame Stabilization & Combustor Sizing

DR. A.R. SRIKRISHNAN

Flame Stabilization



The Approach



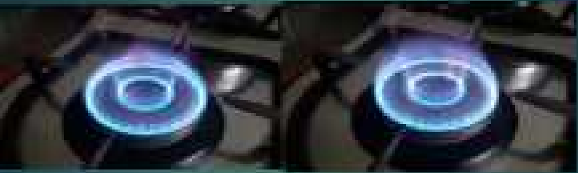
- Create a sheltered zone of low ... upstream

and of the liner, where flame speeds are greatly enhanced by imparting a turbulence to the airflow.

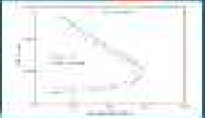
... jets and by ... of the products

to recirculate and mix

with the incoming air and fuel



Stability Loop – Determi
Stability performance



- After ignition the fuel flow is gradually reduced until flame extinction occurs
- Combustion is reestablished and the fuel flow slowly
- The complete stability performance of an engine combustor is
- obtained by carrying out sufficient tests to allow a number of
- stability loops to be drawn at different levels of pressure

Flammability Limits

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

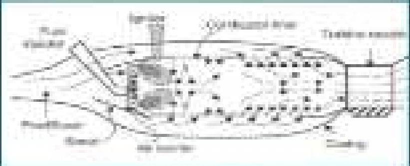
Broader on the rich side of fuel-air ratios

Bluff Body Flame Holders

- Typically flame extinction occurs when the time available for chemical reaction becomes less than

Stabilization In Aircraft

[illegible]



Flame Stabilization in Afterburners

- The necessary recirculation … premixed flame

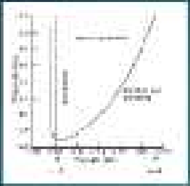
… relatively sep…
- … tube.com/wa…
https://www.youtube.com/wa…

Influence of Various Parameters on Flame Stability

[illegible] flame stability can be extended by the following parametric changes:

- 1. A reduction in approach stream velocity
- 2. An increase in approach stream temperature
-
- 4. Any change in equivalence ratio toward unity
- 5. An increase in [illegible]
- 6. A reduction in flameholder blockage (for a constant [illegible])

Problem...



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 are combined into the Combustor Loading Parameter (CLP), defined as

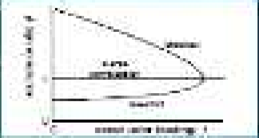
$$CLP = \frac{\dot{m}}{p^n \times \text{Combustion Volume}}$$

$$CLP = \frac{\dot{m}}{p^n \times \text{Combustion Volume}}$$

Stability of Combustion & Combustor Volume

- [illegible] process to sustain itself
- If too lean or too rich
    - [illegible]
    - [illegible]
- CLP (Combustion Loading Parameter)
    - [illegible]

$$CLP = \frac{\dot{m}}{[illegible]}$$



Combustor Size

- Cross-sectional Area determined by mass-flow rate and velocity requirements at 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

Combustor Length & Cycle Parameters

A similar argument can be made regarding the cycle thermal

Combustion Intensity

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

- lower the combustion intensity easier to design a system with desired requirements

Typically Aircraft Engines have combustors with CI in the range of 2×10^5 to 5×10^5 kW/m³·atm

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AIR BREATHING ENGINES

Fuels & Emissions

DR. A.R. SRIKRISHNAN

AMRITA

Aviation Fuels: Properties/Attributes of Inter

- Combustion
- handling

- Density, Viscosity, Calorific value, Thermal stability etc
- Availability, cost

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...

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

A Correlation for Calorific Value

Typical Jet Fuels & Their Properties

Nature of Compone[illegible]

Paraffins

Aromatics

Naphthenes

[illegible] large number of hydrogen atoms, they are very active [illegible]

[illegible] hydrogen and, in consequence, their specific [illegible]

- The disadvantages of aromatic compounds in [illegible] is marked tendency to [illegible] and a high [illegible] precipitation of [illegible] [illegible] temperature

[illegible] oil had [illegible] an average composition of [illegible]% paraffins, [illegible]% naphthenes, [illegible]% aromatics and contains about [illegible]

Alternative Fuels

- Conventional aircraft engine exhaust produces a range of hazardous compounds:
  - CO, NOx, SOx, unburned hydrocarbons (UHC)
  - Particulate matter (soot)
  - Greenhouse gases, most notably CO_2
- Future evolution of the aviation sector requires reliable, diverse, cost-effective and environmentally sustainable energy sources

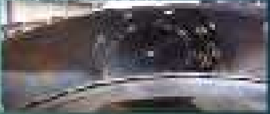
What is an Alternative Fuel ?

- A fuel that either augments or replace the conventional fuel on a [illegible] basis with no adverse effects on engine performance, maintenance or operational life may be defined as an alternative fuel.
  - Range from highest quality fuels such as hydrogen and methane, to low-grade liquid and gaseous fuels that [illegible]
  - [illegible]

Fuel-Future…

- The future of the alternative fuel industry depends on the following key factors:
  - End-use [illegible] of the engines and infrastructure already in place.
  - [illegible]
  - CO2 life-cycle analysis and carbon footprint issues.
  - [illegible]

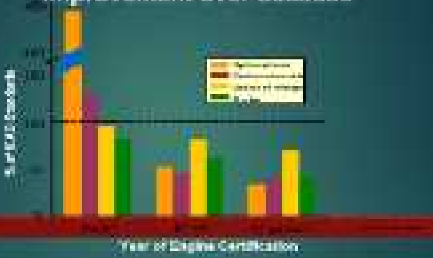
Closer Look at Aircraft Combustors



Emission Issues

Issue	Key Emission	Mitigation
Climate Change	- Carbon Dioxide (CO_2) - Water Vapor - NOx	- Fuel Efficiency - Operational Measures - Combustion Design
Local Air Quality	- NOx - Carbon Monoxide (CO) - Unburned Hydrocarbons (HC) - Smoke/Soot	- Combustion Design - Operational Measures

Local Air Quality: Continuous Improvement over decades



CO_2/NOx Trade

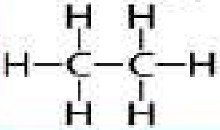
Conflicting Design Requirements: CO_2/Nox Control

CO_2/NOx Trade

APPENDIX

Saturated Hydrocarbons

Ethane C_2H_6

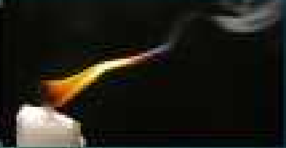


AIR BREATHING ENGINES

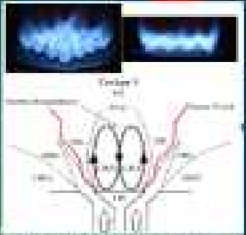
Flame Stabilization & Combustor Sizing

DR. A.R. SRIKRISHNAN

Flame Stabilization



The Approa



- Create a sheltered zone of low ... upstream
end of the liner, where flame speeds
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... jets and by entraining ... products
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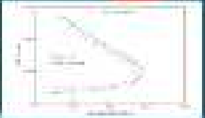
Stability Loop – Determi
Stability performance



- Combustion is reestablished and the fuel flow down
- The
- The complete stability performance of an aero engine combustor is
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Flammability Limits

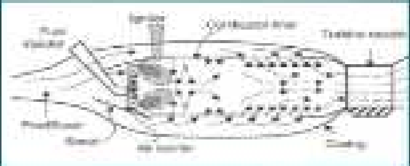
Broader on the rich side of fuel-air ratios

Bluff Body Flame Holders

- Typically flame extinction occurs when the time available for chemical reaction becomes less than

Stabilization In Aircraft

Disadvantages



Flame Stabilization in Afterburners

- The necessary recirculation ... premixed flame

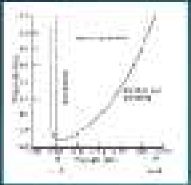
- ... massively sep...
- ...tube.com/wa...
https://www.youtube.com/wa...

Influence of Various Parameters on Flame Stability

[illegible] flame stability can be enhanced by the following parametric variations.

- 1. A reduction in approach stream velocity
- 2. An increase in approach stream temperature
-
- 4. A reduction in turbulence intensity
- 5. Any change in [illegible]
- 6. An increase in flameholder size [illegible]
- 8. A reduction in [illegible] blockage (for a constant flameholder size)

Problem...



Combustor Sizing

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The effect of mass flow rate, combustion volume and pressure on the stability of the combustion process ... are combined into the Combustor Loading Parameter (CLP), defined as

$$CLP = \frac{\dot{m}}{p^n \times \text{Combustion Volume}}$$

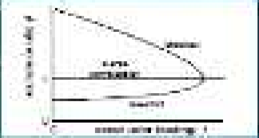
(n ~ 1.8)

$$CLP = \frac{\dot{m}}{p^n \times \text{Combustion Volume}}$$

Stability of Combustion & Combustor Volume

- Combustor volume also impacts the ability of the combustion process to sustain itself
- If too lean or too rich
  - Temp & reaction rates drop below the levels required to heat and vaporize the fuel/air
  - Will require larger volume
- CLP (Combustion Loading Parameter)
  - Indication of stability based on mass flow, pressure (n ≈ 1.8 for typical fuels), and combustor volume

$$CLP = \frac{\dot{m}}{P^n (V_c)}$$



Combustor Size

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Combustor Length

- [illegible]
- [illegible]

[illegible]

Combustor Length & Cycle Parameters

A similar argument can be made regarding the cycle thermal

Combustion Intensity

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

- lower the combustion intensity easier to design a system with desired requirements

Typically Aircraft Engines have combustors with CI in the range of 2×10^5 to 5×10^5 kW/m^3-atm

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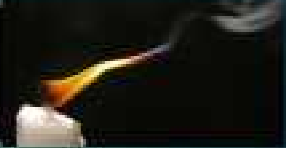
AIR BREATHING ENGINES

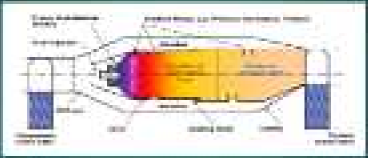
Combustor Components-12 Swirler & Atomizer

DR. A.R. SRIKRISHNAN

Typical Configuration of An Annular Combustor

Need for Flame Stabilization





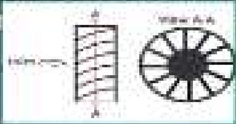
Swirler

- Designed to enhance mixing and enable flame anchoring
- Swirler creates flow reversal that entrains and recirculates a portion of the hot combustion products to mix with the incoming air and fuel.
  - This anchors the flame
  - Also provides the continuous supply of hot radicals, i.e. hot combustion products needed to achieve high heat release rates

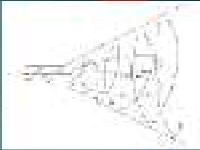
Atomization

- 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 vastly increased surface area
  - The smaller the droplet size, the faster the rate of evaporation

Swirler: Induces Recirculation in Primary Zo



Swirler Flow field



- An effective way of inducing flow recirculation in the primary zone
- Swirl causes recirculation in the core region when the amount of

rotation imparted to the flow is high

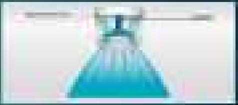
- Swirl components produce strong shear regions: high turbulence.

and rapid mixing rates

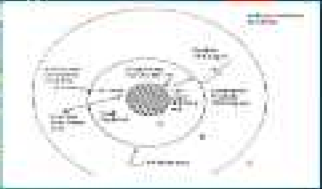
The Recirculation Field

https://www.youtube.com/watch?v=[illegible]

ATOMIZATION



Droplet Combu



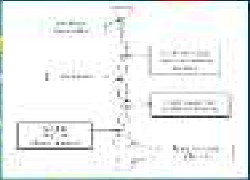
The Process of Atomization

- [illegible]
- [illegible]
  - [illegible]
- [illegible]
- [illegible]
  - [illegible]
- [illegible]
  - [illegible]
  - [illegible]

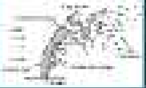
Weber Number

“Classical” Mechan... of Jet break up

- A factor of great ...
- **Primary atomization** ...
- **Secondary atomization** ...



"Prompt" Atomization



- [illegible]
  - [illegible]
  - [illegible]
- [illegible]
  - [illegible]
- [illegible]

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. Freedom from flow instabilities
- 4. Low power requirements
- 5. Capability for scaling, to provide design flexibility

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

Types of Atomizers

- Pre

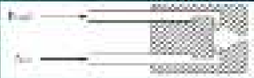
surrounding air or gas.

Simplex Atomizer: […] pressure-swirl atomizer, in which a swirling motion is imparted to the fuel so that, under the action of centrifugal force, it spreads out in the form of a conical sheet as soon as it leaves the orifice.

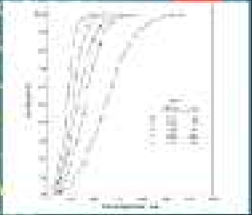
A major drawback of the simplex atomizer is that its flow rate varies as the square root of the injection pressure differential. Doubling the flow rate demands a fourfold increase in injection pressure.

Air-Assisted Atomization

- [illegible]
- [illegible] before exiting from the outlet orifice.
- [illegible] tangential [illegible] to encourage [illegible]



Spray Characterizati
Drop Size & Distribu



- The most important mean diameter … combustion applications is the Sauter Mean Diameter (SM

AIR BREATHING ENGINES

Combustor Fundamentals

DR. A.R. SRIKRISHNAN

The Process of Combustion

The Fundamental Thermodynamic Process – Review

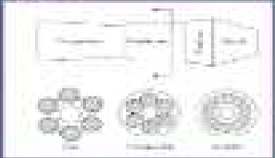
Staged Combustion - Review

Primary Zone:
Anchor the flame & provide time for mixing & combustion

Intermediate Zone: Completion of combustion

Dilution Zone:
Provide an outlet stream with a temperature distribution that is acceptable to the turbine

Types of Combustors – Re



and pressure loss

https://www.youtube.com/watch

Key Performance Requirements

- High combustion efficiency
- Reliable and smooth ignition: At start & in the event of any flame out
- Wide stability limits
  - the flame should stay alight over wide ranges of pressure and air/fuel ratio
- Low pressure loss
- [illegible]
- Low volume & weight
- [illegible]

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AIR BREATHING ENGINES

Session :

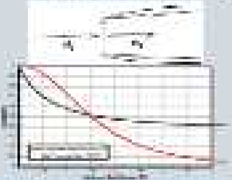
& NOZZLES

R. SRIKRISHNAN

Supersonic-to-Subsonic Diffusion

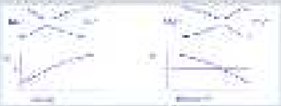
Supersonic Inlets

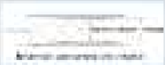
Normal Shock Inlets & Oblique Shock Inlets



Stagnation Pressure Loss Vs Mach Number

Diffuser = Inverse Nozzle ?

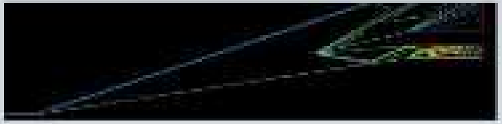




Types of Supersonic Inlets

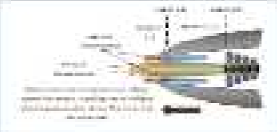
External Compression Inlets

Mixed Compression Inlets

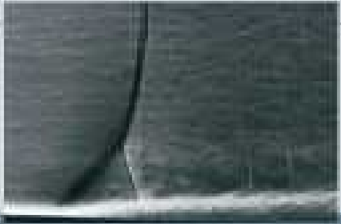


Intake Efficiency

$$\eta_d = \frac{h_{02s} - h_1}{h_{02} - h_1}$$



Shock Boundary Layer Interaction:



Nozzles

Jet Expansion Scenarios

Nozzle Efficiency

Nozzle adiabatic efficiency:

Adiabatic Efficiency

$$\eta_N = \frac{h_{01} - h_2}{h_{01} - h_{2s}} = \frac{V_2^2/2}{V_{2s}^2/2}$$

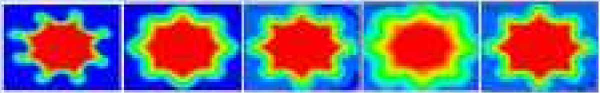
Numerical Problem

[illegible]

Thrust Vectoring

Jet Noise

Chevron Nozzles



GE-Affinity

COURSE COMPLETION

THANK YOU !!

AIR BREATHING ENGINES

Session :

Supersonic Inlets

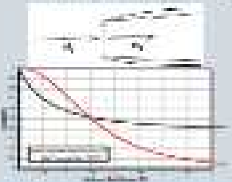
R. SRIKRISHNAN

AMRITA

Supersonic-to-Subsonic Diffusion

Supersonic Inlets

Normal Shock Inlets & Oblique Shock Inlets



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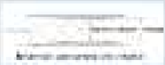

Types of Supersonic Inlets

External Compression Inlets

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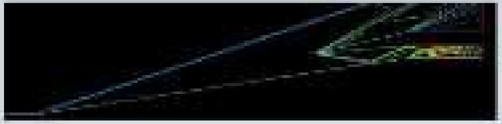
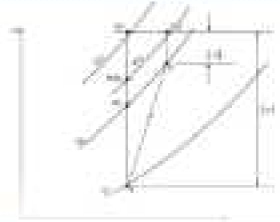


$$\eta_s = \frac{h_{h2,s} - h_1}{h_{h2} - h_1}$$



Shock Boundary Layer Interaction:

Nozzles

Jet Expansion Scenarios

Nozzle Efficiency

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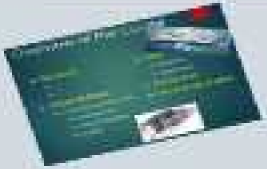
COURSE COMPLETION



THANK YOU

!!