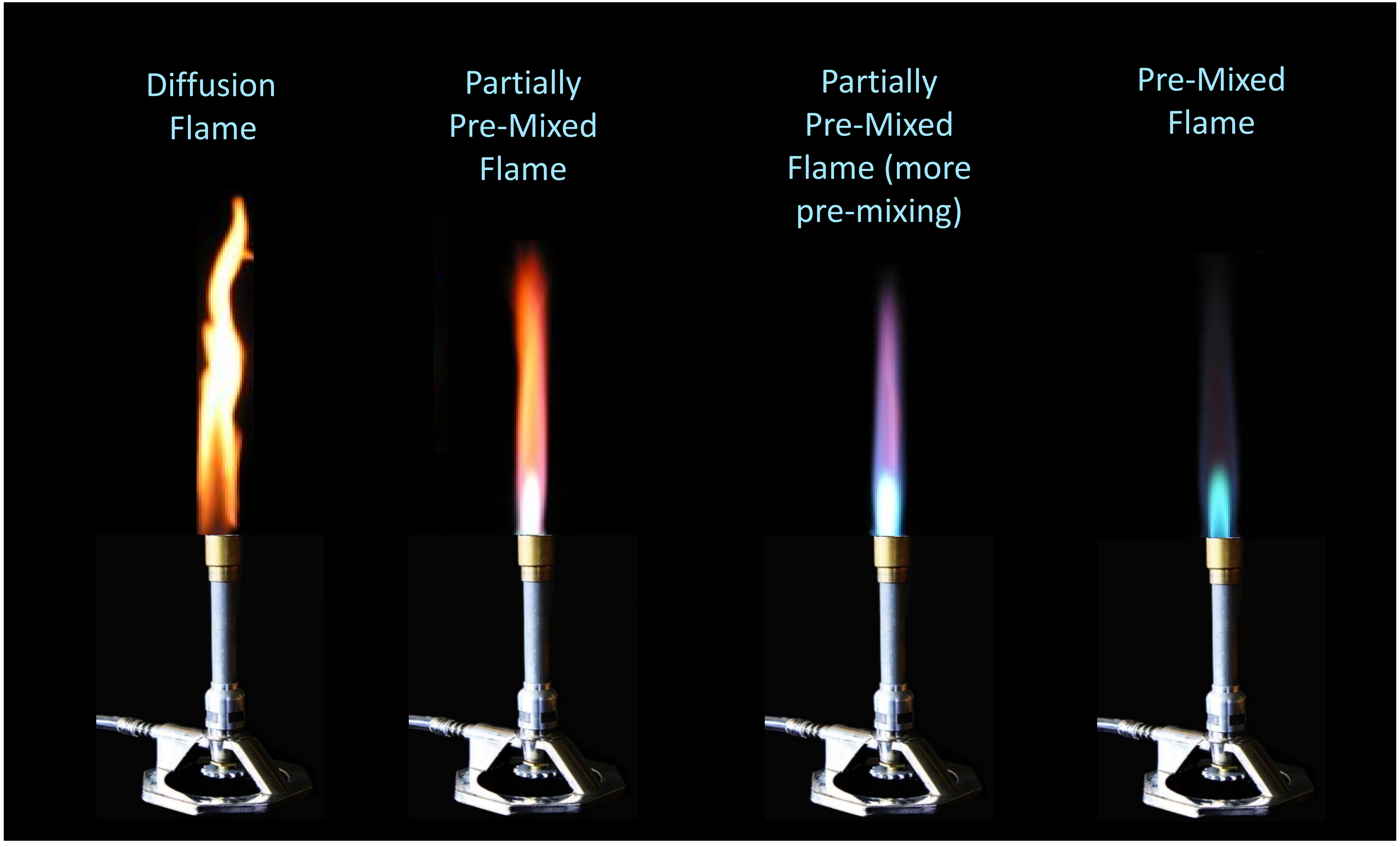
Introduction to Design Considerations and Sizing Methodologies

Gas Turbine Combustion Short Course

Dr Vishal Sethi
Centre for Propulsion and Thermal Power Engineering
School of Aerospace, Transport and Manufacturing
Cranfield University

Contents

Diffusion and Premixed Flames



Diffusion and Premixed Flames

Deflagration Flames

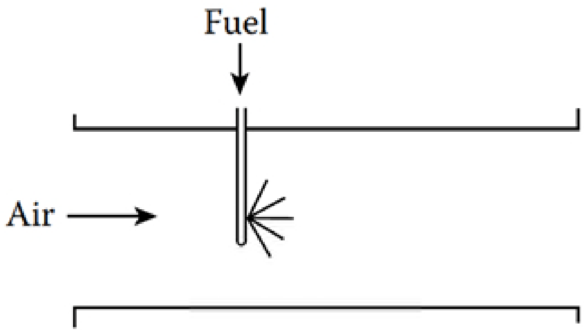
Diffusion Flames

- Lower flame temperatures
- Wider stability limits
- Higher carbon content in flame
- Higher radiation (luminous emissivity)
- Rate of combustion influenced by Fuel/air mixing rate

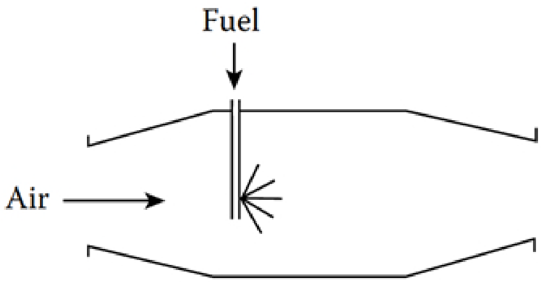
Pre-Mixed Flames

- Higher flame temperatures
- Narrower stability limits
- Lower carbon content in flame
- Lower radiation (luminous emissivity)
- Combustion influenced by chemical kinetic factors

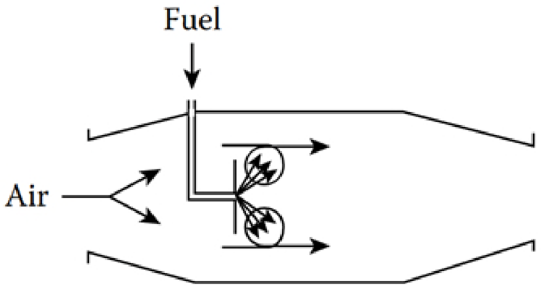
Gas Turbine Combustors:
Basic Design Features



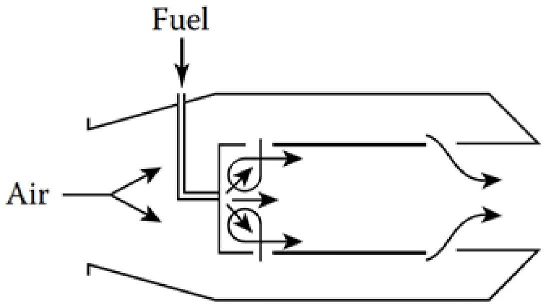
X High $V_3 \Rightarrow \Delta P$ unacceptable



X Flame not satisfactorily anchored $\Rightarrow$ Poor stability & Low η_c



X FAR outside stability limits
X T_4 too high (turbine material limitations)



✓ Gas turbine combustor GA (variations depending on application)

Images courtesy of: Lefebvre. A. H., 2010, "Gas Turbine Combustion", 3rd Edition, McGraw Hill

Gas Turbine Combustors:
Performance and Operability Requirements

- High combustion efficiency
- Good combustion stability
- Ease of Ignition
- Low pressure loss
- Clean exhaust
- Good temperature traverse quality
- Low emissions
- Design for minimum cost and ease of maintenance
- Size and shape compatible with engine envelope
- Durability
- Multi-fuel capability (particularly for land based applications)
- Low size and weight (aero)

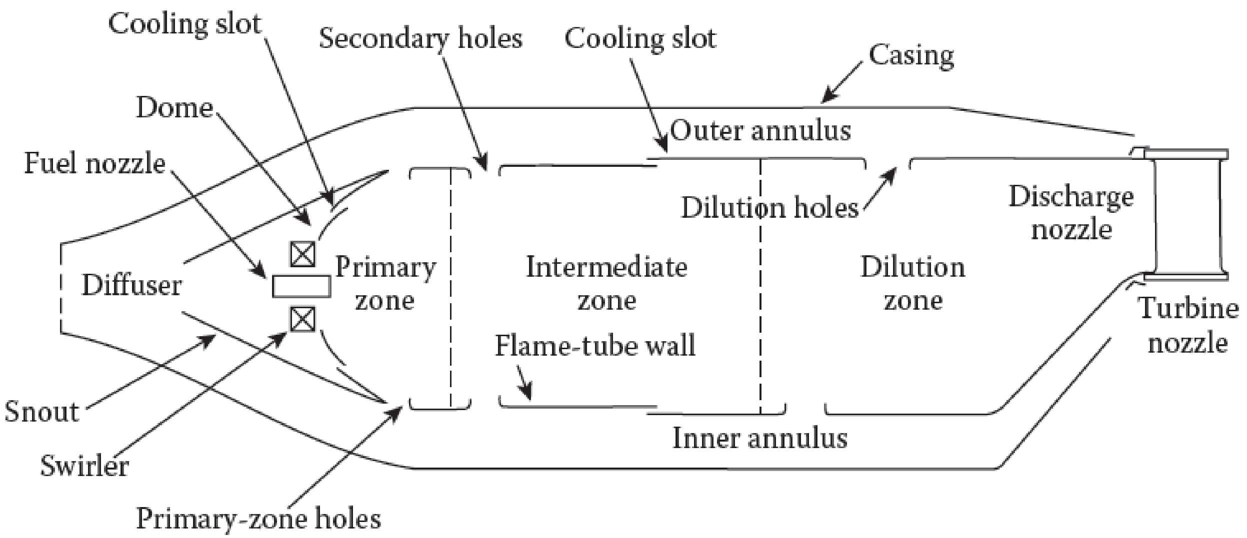


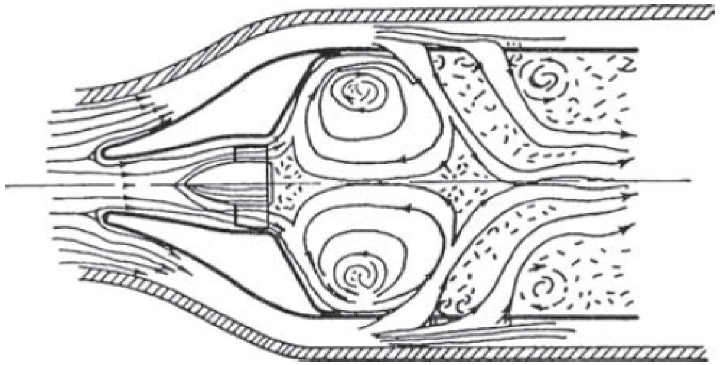
Image courtesy of: Lefebvre. A. H., 2010, “Gas Turbine Combustion”, 3rd Edition, McGraw Hill

Design Considerations:
Primary Zone

- Main Function: To anchor the flame and to provide sufficient time, temperature and turbulence to essentially achieve complete combustion of the incoming F/A mixture

- Primary zone air flow pattern is extremely important to the attainment of these goals

- Important to create a “toroidal” flow reversal that entrains and recirculates a portion of the hot combustion gases to provide continuous ignition to the incoming F/A mixture



Toroidal Flow Reversal via Swirlers & Primary Hole Jets

Image courtesy of: Lefebvre. A. H., 2010, “Gas Turbine Combustion”, 3rd Edition, McGraw Hill

- Good design of swirler vane angle, size & number and location of primary holes will allow the two modes of recirculation to complement and strengthen each other ⇒
    - wide stability limits
    - good ignition performance
    - less susceptibility to combustion pulsations and noise

Design Considerations:

Intermediate Zone

- Main Functions:
  - Allows imperfectly mixed fuel rich pockets to undergo complete combustion
  - Reduces dissociation losses by allowing recombination of dissociated species before the dilution zone

- Intermediate zone length is a compromise between chamber length (weight) & η_c

- Typical length $\approx$ 1/2 times flame tube width

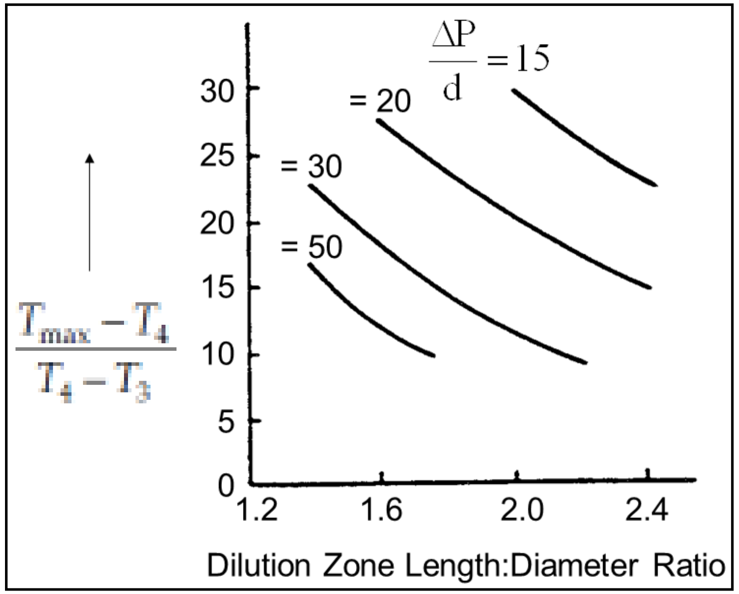
- Length ideally dictated partly by:
  - Minimum length needed to mix the intermediate air with gas flow and
  - Minimum residence time needed for complete combustion

Design Considerations:

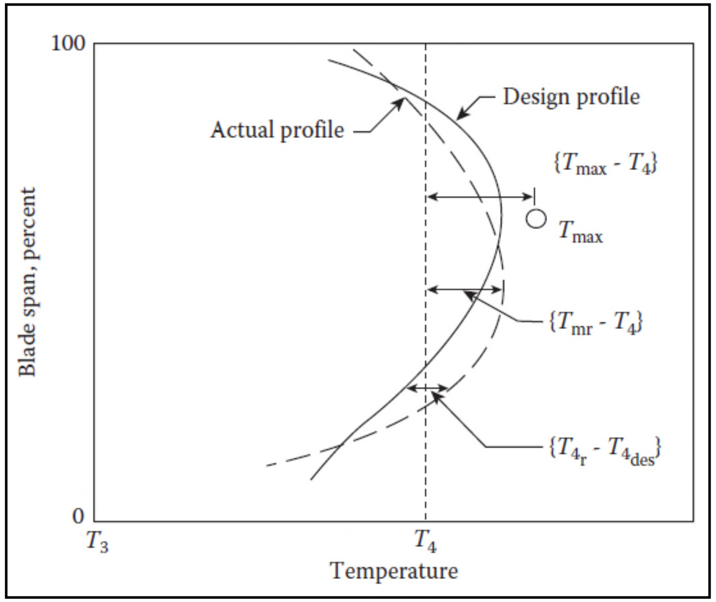
Dilution Zone

- Typical length ≈ 1.5 - 2 times flame tube width

- Main Functions:
  - Dilute combustion gases with substantial amount of air
  - Provide an outlet stream of uniform temperature (Low value of TTQ)
  - Provide a suitable radial temperature distribution (NGV and Turbine Blade Life)



$$\text{Pattern factor} = \frac{T_{max} - T_4}{T_4 - T_3}$$



$$\text{Turbine profile factor} = \frac{(T_{4.r} - T_{4.des})_{max}}{T_4 - T_3}$$

Images courtesy of: Lefebvre. A. H., 2010, “Gas Turbine Combustion”, 3rd Edition, McGraw Hill

Fundamental Aspects of the Ignition Process:
The Three Phases of Ignition

Phase 1: Formation of a flame kernel

- Sufficient size and temperature to be able to propagate
- Success or failure of this phase governed by:
  - Energy and duration of the spark
  - Local turbulence level
  - FAR in the vicinity of the spark plug
  - Spark plug location

Phase 2: Propagation of the flame formed in Phase 1 to all parts of the Primary Zone (PZ)

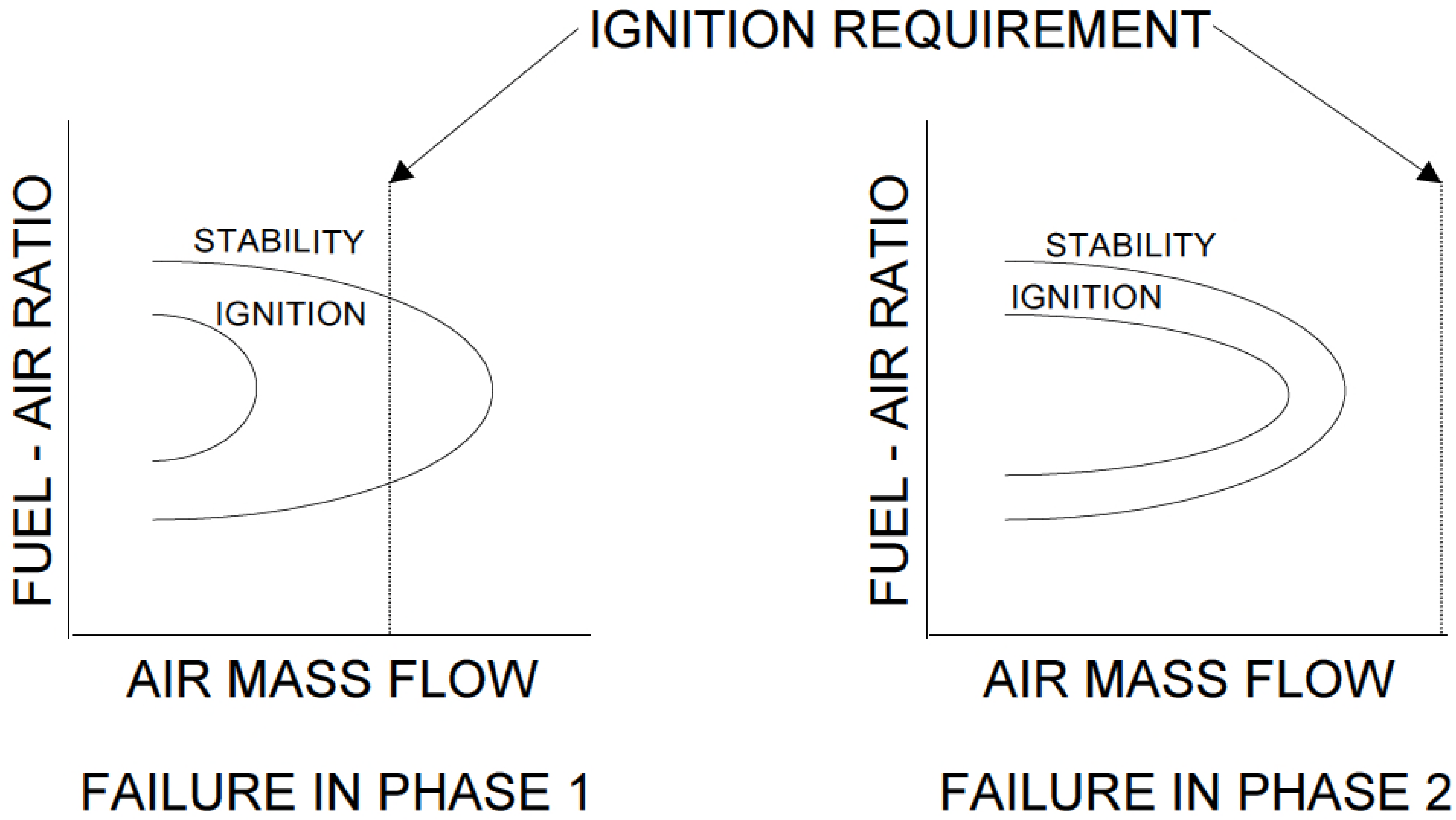
- Success or failure of this phase governed by:
  - Overall PZ FAR must be within flammability limits
  - Plug location
  - General air flow and fuel distribution patterns
  - PZ turbulence level

Phase 3: Light Around (annular and tubo-annular combustors)

- Success or failure of this phase governed by:
  - Design of interconnector tubes (short & large diameter)

Fundamental Aspects of the Ignition Process:

Stability and Ignition Loops



Sources of Combustor Pressure Loss

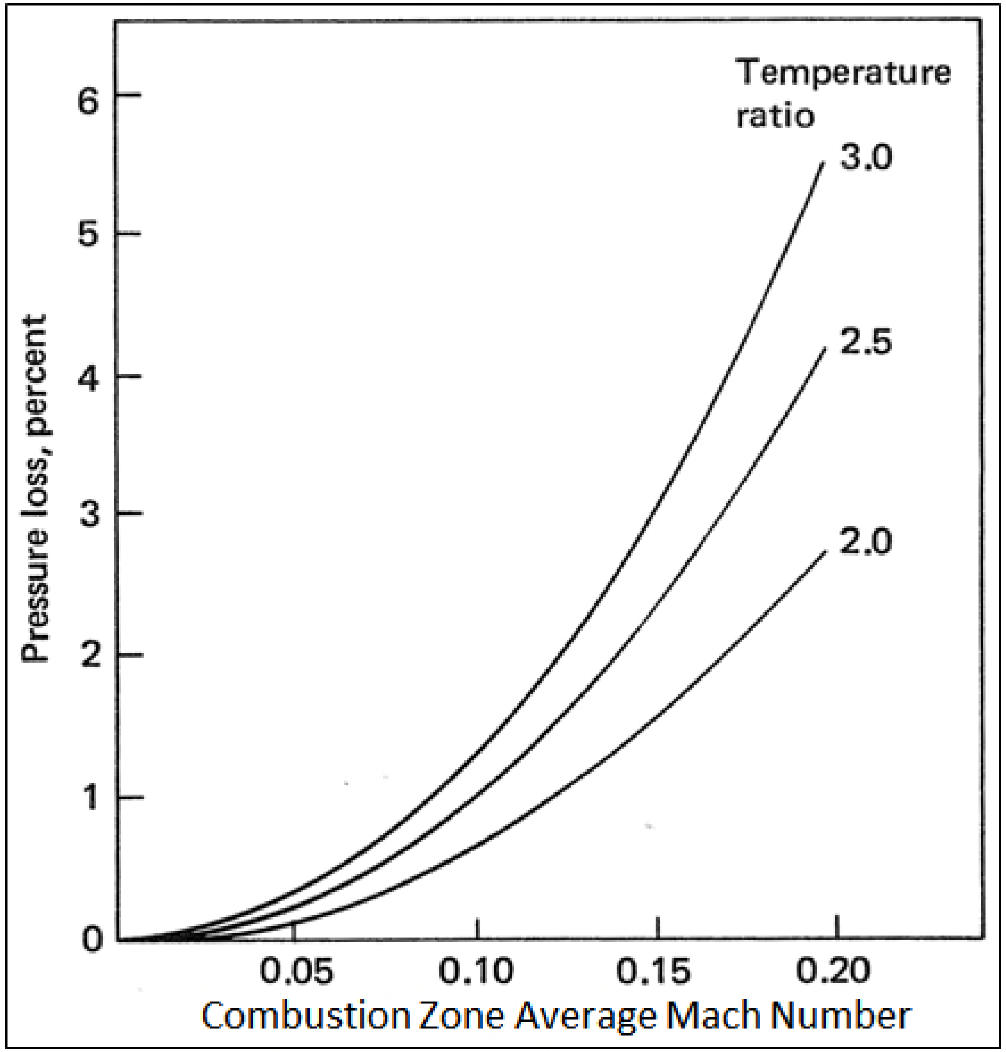
- Cold loss
  - Pre-combustor diffuser (reduces Mach number of flow from ≈ M 0.3)
  - Liner losses - Introduction of air in secondary and dilution zones
    - Provide mixing energy through jet penetration and turbulence
    - Require 3% loss across NGV leading edge for film cooling

- Fundamental (hot) loss
  - Fundamental thermodynamics dictate that there is always a pressure loss associated with heat release
  - With addition of heat there is a reduction in density which results in an increase in velocity (mass flow continuity) and this results in a pressure loss (conservation of momentum)

$$\Delta P_{fund} = \frac{1}{2}\rho U^2 \times \left[\frac{T_{out}}{T_{in}} - 1\right]$$

Magnitude of Pressure Losses
Diffuser pressure loss (cold) ≈ 1%
Fundamental hot loss ≈ 0.2%
Liner losses (mixing) (cold) ≈ 3% – 4%
Overall ≈ 4% – 5%

Pressure Loss Due to Heat Addition



Pressure Loss Due to Heat Addition

Image courtesy of: Lefebvre. A. H., 2010, “Gas Turbine Combustion”, 2nd Edition, McGraw Hill

Fundamental Challenge:

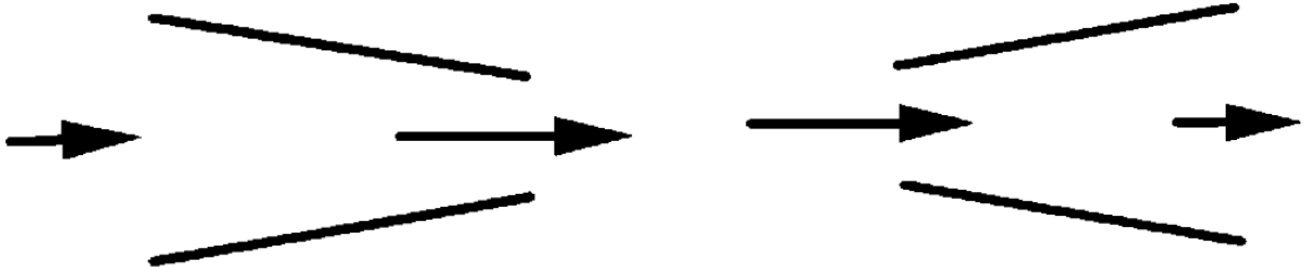
- Compressor outlet velocity: >150m/s (~M 0.25)
- Flame speed (Jet A-1 in air):

  ~20 – 100 cm/s (laminar)

  ~5 – 9 m/s (turbulent)

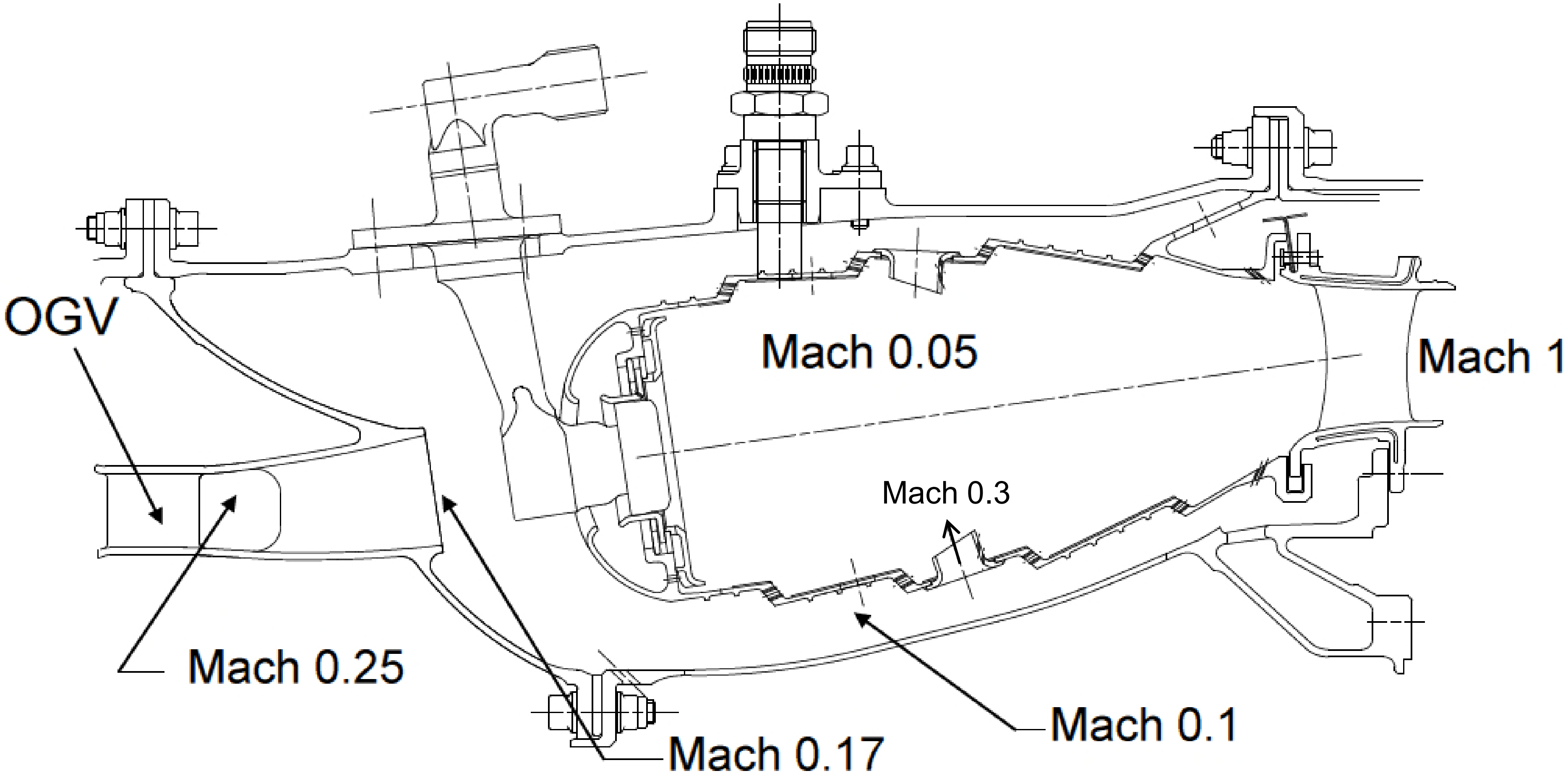
British Airways spent ~€3.2b on fuel in FY2019. 1% pressure loss would have cost them ~ €15m pa!

Subsonic Flow in a Duct



	Converging Duct	Diffuser (Diverging Duct)
Area	↓	↑
Velocity	↑	↓
Mach Number	↑	↓
Total Temperature	-	-
Static Temperature	↓	↑
Total Pressure	↓	↓
Static Pressure	↓	↑
Density	↓	↑

GT Combustor: Typical Flow Mach Numbers



RRD BR Series Combustor

Image courtesy of Bryn Jones – Kausis Consultancy

"Ideal" Diffuser Requirements

- Achieves required velocity reduction
- Minimum length
- Minimum pressure loss
- Uniform and stable flow at outlet
  - Difficult to achieve with aircraft engines as compressor outlet velocity profiles are peaked and asymmetric >> subject to variation with changes in altitude and speed
  - Non uniformity / instability mean temperature traverse quality and radial temperature distribution are harder to control

Diffuser Design Choices

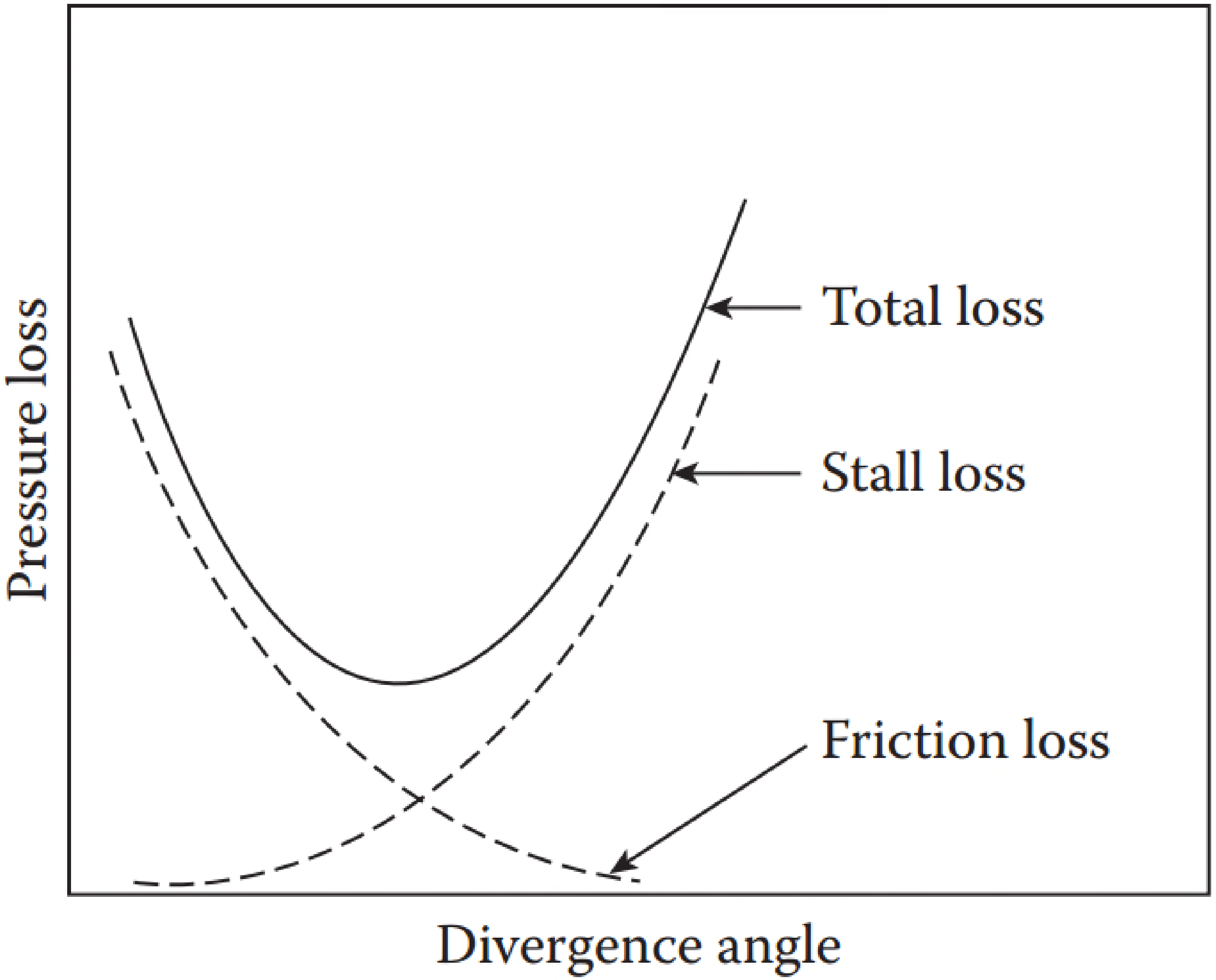


Image courtesy of: Lefebvre. A. H. & Ballal, D.R., 2010, “Gas Turbine Combustion”, 3rd Edition, CRC Press

Diffuser Design Choices:
Faired Diffuser

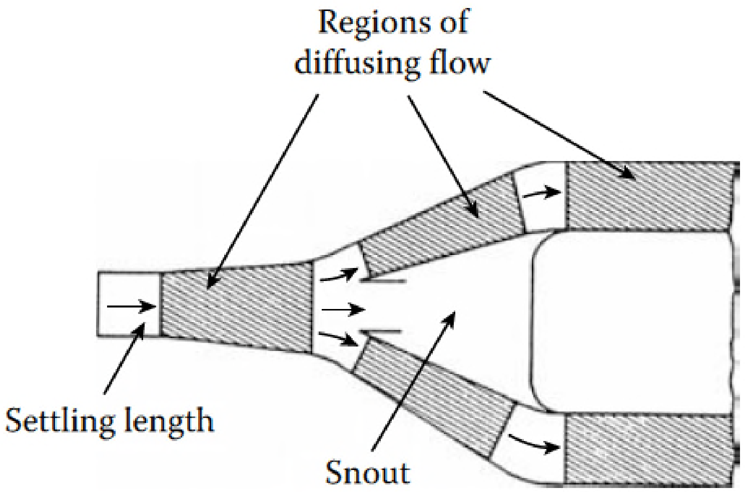


Image courtesy of: Lefebvre. A. H. & Ballal, D.R., 2010, “Gas Turbine Combustion”, 3rd Edition, CRC Press

- Gradual reduction in velocity without inducing stall
- Lips of snout rounded to avoid flow separation. Snout typically comprises ~ 10% of total combustor airflow (higher for air blast atomisers and low emission technologies)

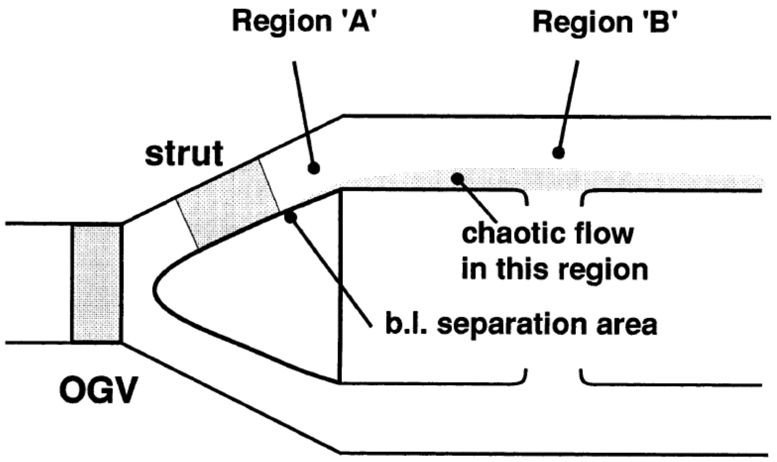


Image courtesy of Bryn Jones – Kausis Consultancy

- Region A: Wake from strut plus diffusion triggers separation. Residual swirl from OGV worsens the situation
- Region B: Increased velocity reduces flame tube hole C_D and produces unpredictable combustor variability – Difficult to balance aerodynamic flow patters in liner

Diffuser Design Choices:

Dump Diffuser

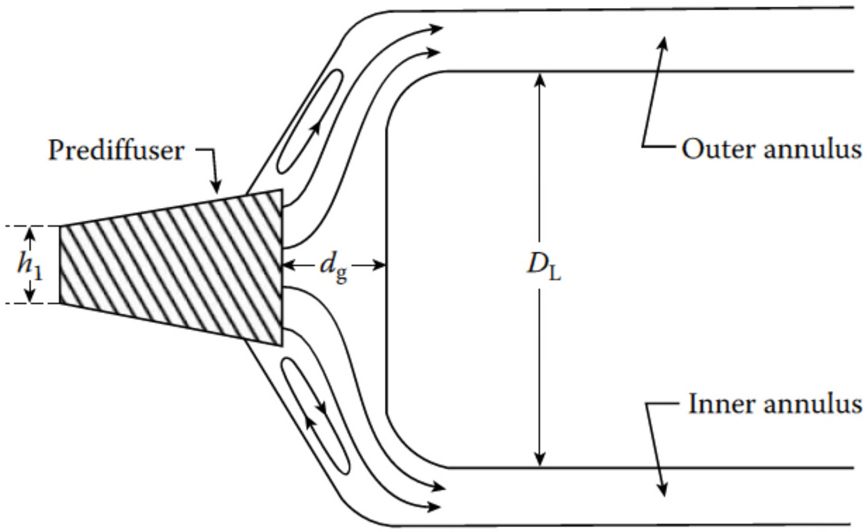


Image courtesy of: Lefebvre. A. H. & Ballal, D.R., 2010, "Gas Turbine Combustion", 3rd Edition, CRC Press

- Short conventional prediffuser reduces velocity by ~60%
- Air subsequently "dumped" and left to divide an flow around liner dome
- Standing vortices help maintain uniform and stable division of flow around the liner
- Sudden expansion results in higher pressure loss than faired diffuser (~50% more)
- Pressure loss penalty more than compensated by substantial savings in length and weight
- Dump diffuser produces stable flow pattern insensitive to manufacturing tolerances & variations in inlet velocity profile
- Optimum performance related to (d_g/h_1) >> the larger the prediffuser angle, the lower the optimum value of (d_g/h_1). Trade-off between prediffuser flow separation loss and dump diffuser pressure loss

Combustor Sizing:
Pressure Loss Approach

$$\frac{\Delta P_{3-4}}{P_3} = \frac{\Delta P_{3-4}}{D} \times \frac{R}{2} \times \left(\frac{W\sqrt{T_3}}{A_{ref} P_3} \right)^2$$

P_3 – Combustor inlet total pressure (Pa)
P_4 – Combustor outlet total pressure (Pa)
D – Dynamic Head (at A_{ref}) (Pa)
W – Combustor inlet mass flow rate (kg/s)
T_3 – Combustor inlet total temperature (K)
A_{ref} – Combustor casing cross sectional area at maximum diameter (m^2)
R – Gas Constant (J/kg.K) (for Dry Air, R = 287J/kg.K)

$\frac{\Delta P_{3-4}}{P_3}$: Ratio of total pressure drop across combustor to inlet total pressure

$\frac{\Delta P_{3-4}}{D}$: Ratio of total pressure drop across combustor to inlet dynamic head $(\frac{1}{2} \times \rho \times V_1{}^2)$

Combustor Sizing:

Pressure Loss Approach

Low Value ⇒ Low SFC

High Value ⇒ Good Mixing

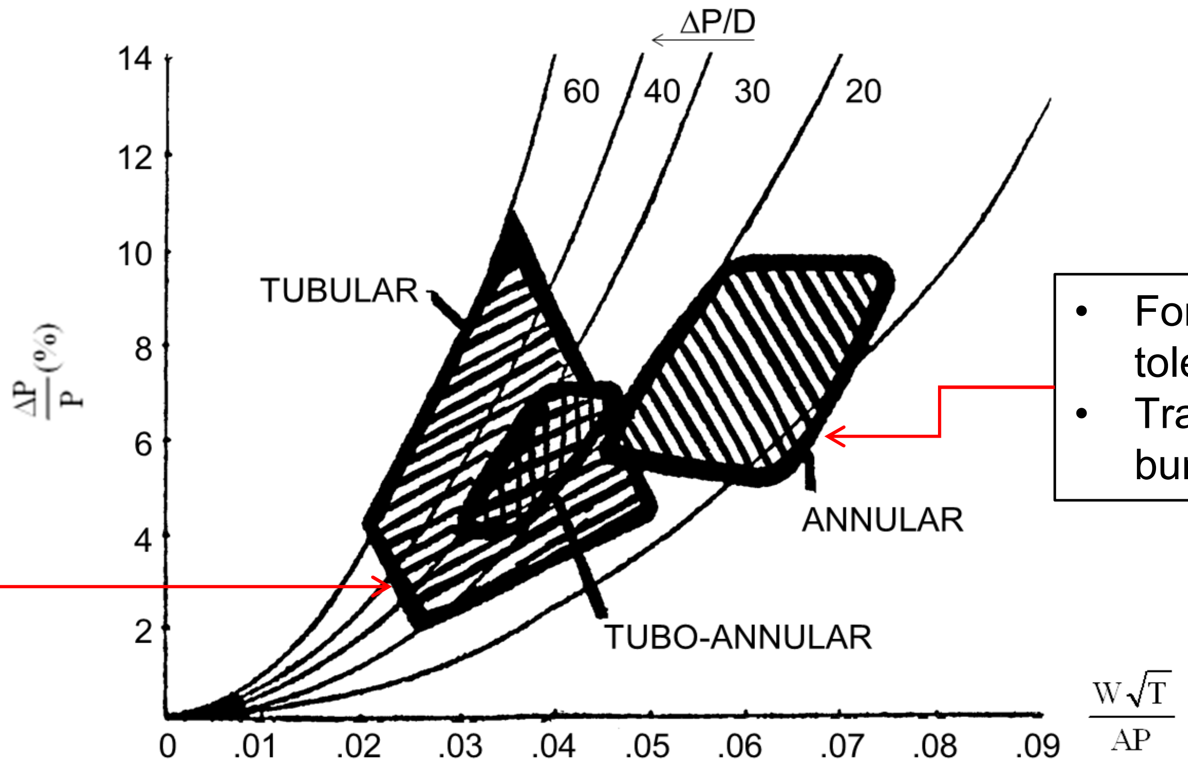
$$\frac{\Delta P_{3-4}}{P_3} = \frac{\Delta P_{3-4}}{D} \times \frac{R}{2} \times \left(\frac{W\sqrt{T_3}}{A_{ref} P_3} \right)^2$$

Low Value ⇒ Smaller Combustor

- Designing combustors which are small in size, have low fractional pressure losses along with good mixing characteristics presents a conflicting situation which can only be optimised in relation to specific engine applications:
  - For a “lift” engine a higher overall pressure loss (↑SFC) may be tolerated in return for a smaller engine (↓A_{ref})
  - For a long distance cruise aircraft engines, a larger diameter combustor is likely to be tolerated in return for a lower pressure loss (↓ SFC)

Combustor Sizing:

Pressure Loss Approach: Design Space



Improvements in technology, increase in risk

- For aero applications, higher pressure loss tolerated for reduced size (& weight) ⇒
- Trade-off between SFC and mission fuel burn

- For stationary applications, size (and weight) constraints are much lower ⇒
- Can design for lowest ΔP/P (consider trade-off between high value of ΔP/D and low value of ΔP/P

Combustor Sizing:
Combustion Efficiency Requirements

$$\eta_C = f(air\ flow\,rate)^{-1}\left(\frac{1}{evaporation\,rate}+\frac{1}{mixing\,rate}+\frac{1}{reaction\ rate}\right)^{-1}$$

Combustion Efficiency - Mixing Rate Controlled Systems

$$\eta_{C\,m} = f\left(\frac{\text{mixing rate}}{\text{air flow rate}}\right) \qquad \eta_{C\,m} = f\left(\frac{P_3 A_{ref}}{m_a T_3^{\ 0.5}}\right)\times\left(\frac{\Delta P_L}{P_3}\right)^{0.5}$$

Combustion Efficiency - Evaporation Rate Controlled Systems

$$\eta_{C\,e} = f\left(\frac{\text{mass of fuel evaporated}}{\text{mass of fuel supplied}}\right) \qquad \eta_{ce} = \frac{8\,\left(k/C_p\right)_g\,\ln\left(1+B\right)\left(1+0.25\,\mathrm{Re}_D^{\ 0.5}\right)t_{res}}{\rho_f D^2}$$

Refer to "Combustion Efficiency" Slides for Derivations

Combustor Sizing:

Altitude Relight Requirements and Considerations for Aero-Engines

- Engine flame out at altitude can occur due to many different reasons e.g.:
  - Engine malfunction
  - Bird ingestion
  - Volcanic ash
  - Deliberate pilot action etc.

- Demonstration of satisfactory altitude relight is an engine certification requirement

- Relighting at altitude is more challenging as combustor pressures, temperatures and velocities are lower relative to SL. This adversely affects combustion sub-processes:
  - Fuel atomisation
  - Droplet evaporation
  - Ignition
  - Reaction rates

- Engine relight involves using high energy igniter plugs suitably positioned to the fuel injector to initiate combustion in a wind milling engine

Combustor Sizing:

Altitude Relight Requirements and Considerations for Aero-Engines

- $\eta_c\downarrow$ due to unsatisfactory fuel preparation (poor SMDs, cone angles etc.) resulting in slow shaft acceleration rates
- Potential for over-fuelling in order to achieve suitable shaft acceleration rates. This could result in:
  - Compressor surge
  - Turbine blades over heating
- Large research activities currently in place to study fuel spray structures (particularly for air blast atomisers) and flame propagation under sub-atmospheric conditions

Combustor Sizing:

Altitude Relight – The θ Parameter

Methodology

- Maximum altitude for operation and minimum acceptable η_c at this altitude (typically 70 – 80%) are selected
- Value of θ is read from "η_c vs. θ" design chart (values of P_3, T_3 and m_A are determined from combination of CFD and experiments)
- Value of (Aref x $Dref^{0.75}$) obtained
- If unacceptable, either a lower η_c must be tolerated or altitude limit lowered

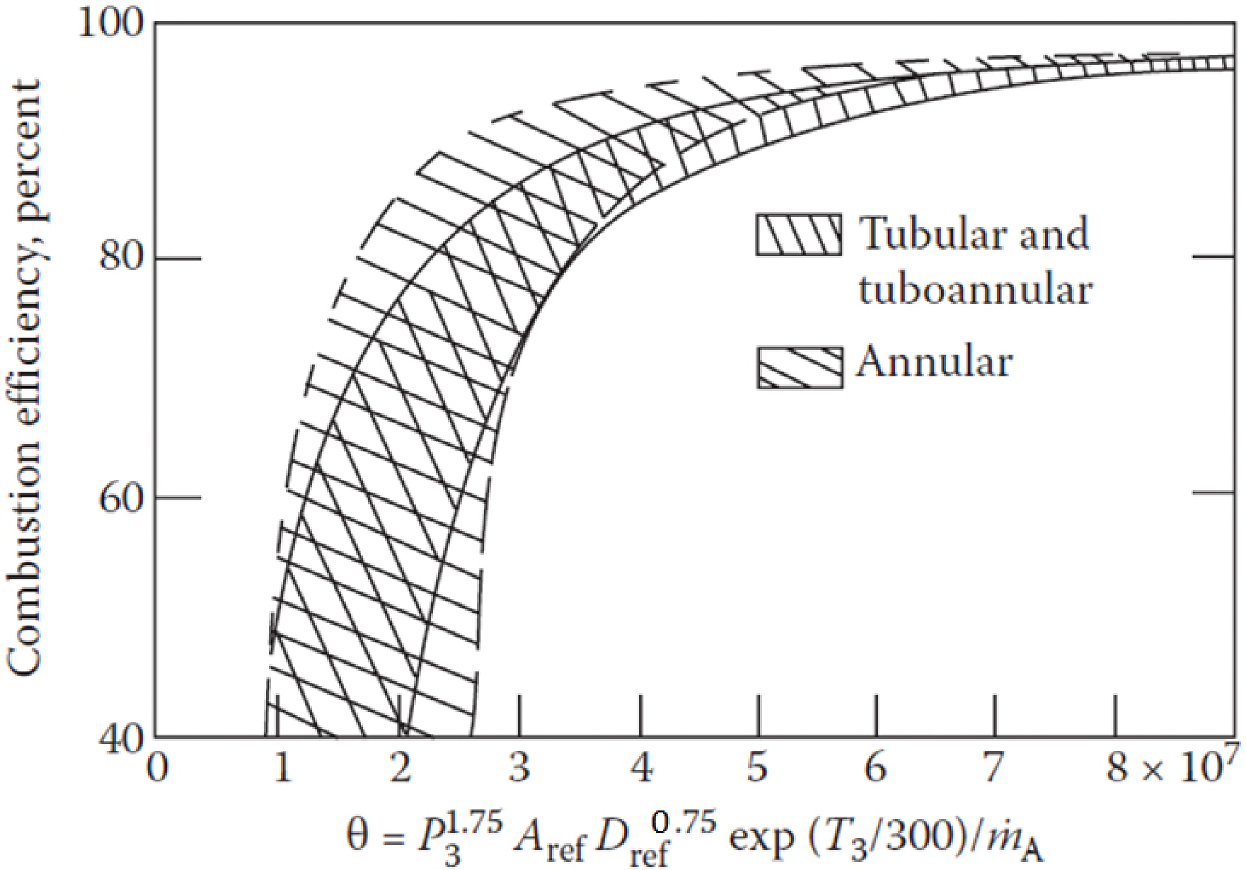


Image courtesy of: Lefebvre. A. H., 2010, "Gas Turbine Combustion", 3rd Edition, McGraw Hill

- Final selection made by choosing the larger diameter based on the Pressure Loss Approach and efficiency requirements for altitude relight