Jet and Rocket Propulsion

AE4451

LECTURE 34

Sedina Tsikata – April 05, 2023

Overview

- what we saw in Lecture 33
  - analysis of turbine engine components
    - nozzles and thrust reversers:
      - nozzle types and basic structure (fixed, variable geometry)
      - nozzle coefficients
      - nozzle mixing, thrust vectoring, thrust reversal

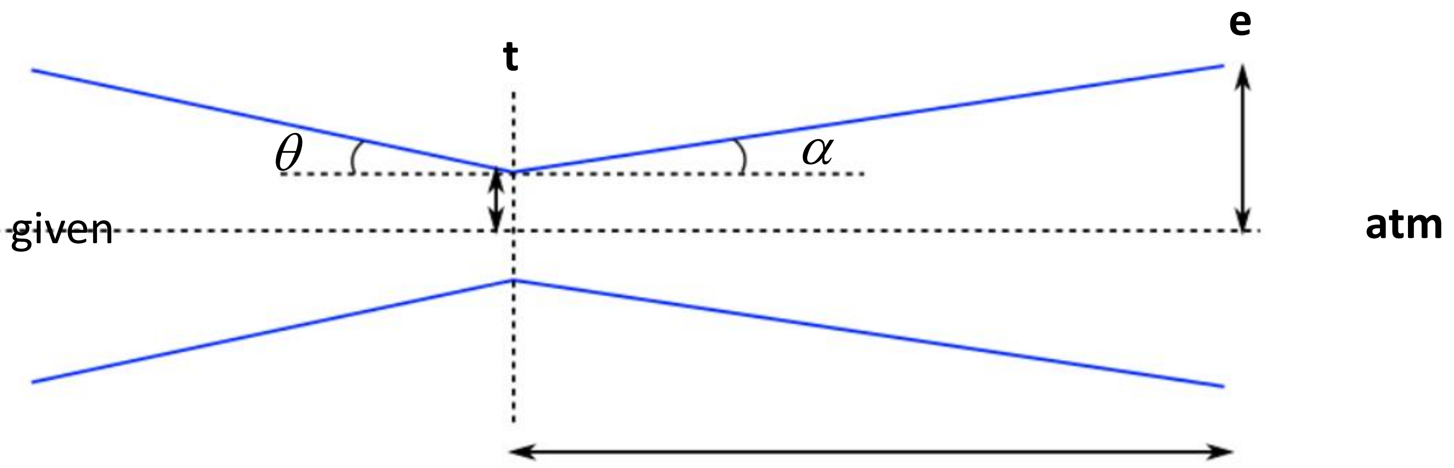
- today
  - quick example of nozzle analysis
  - combustors

Nozzles

Example

- how can we dimension a nozzle?

- assuming simple geometry with some parameters given



area ratio $\frac{A_e}{A_t} = 2$ $\gamma = 1.33$

pressure ratio $\frac{P_{oe}}{P_{ot}} = 0.98$

$P_{ot} = 30\ psia = 2.1\times10^5\ Pa$

$T_{ot} = 2000°R = 1111\,\mathrm{K}$

$P_{atm} = 5\ psia = 3.4\times10^4\ Pa$

discharge coefficient $C_D = 0.98$ (actual mass flow rate/ideal mass flow rate)

mass flow rate $\dot{m} = 90.7\ \mathrm{kg/s}$

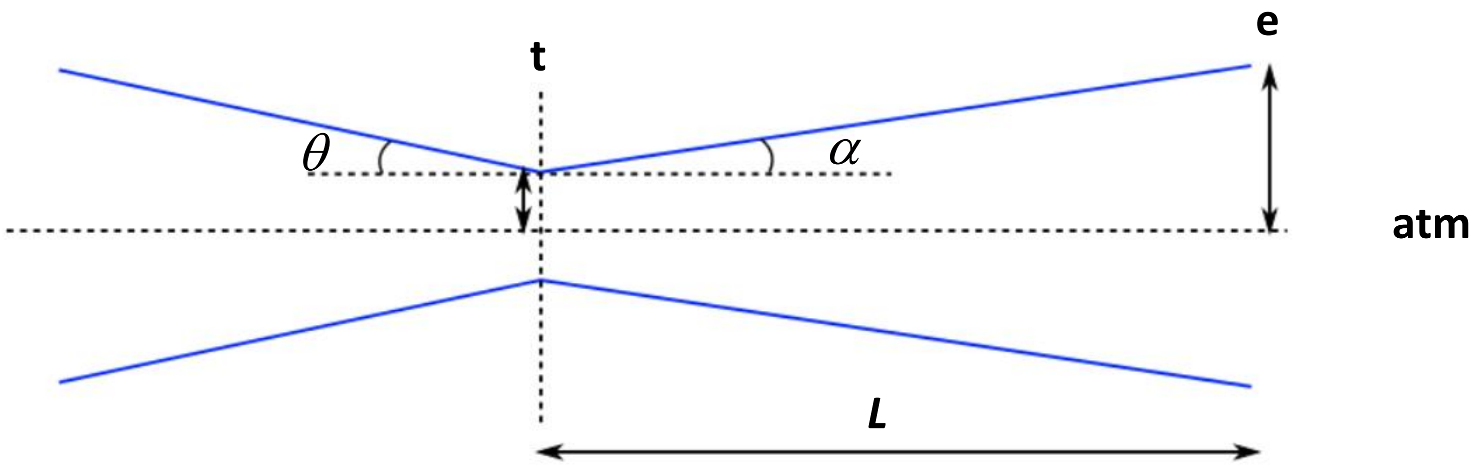
we are also given the mass flow parameter $MFP = \frac{\dot{m}}{A}\frac{\sqrt{T_o}}{p_o} = M\sqrt{\frac{\gamma}{R}}\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}$

see Lec. 29

$MFP = 0.5224$ for $M_t = 1$

Georgia Tech

Example



- starting from the MFP relation, can find the "ideal" throat area

$$MFP = \frac{\dot{m}}{A}\frac{\sqrt{T_o}}{p_o} = M\sqrt{\frac{\gamma}{R}}\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

$$\Rightarrow A_{ti} = \frac{\dot{m}\sqrt{T_{ot}}}{p_{ot}MFP(M=1)}$$

- the flow coefficient allows us to determine a "real" throat area A_t

why? actual throat must be sized up slightly to pass the given mass flow rate

$$A_{t,real} = \frac{A_{ti}}{C_D} \Rightarrow$$

assuming circular section, can determine throat radius

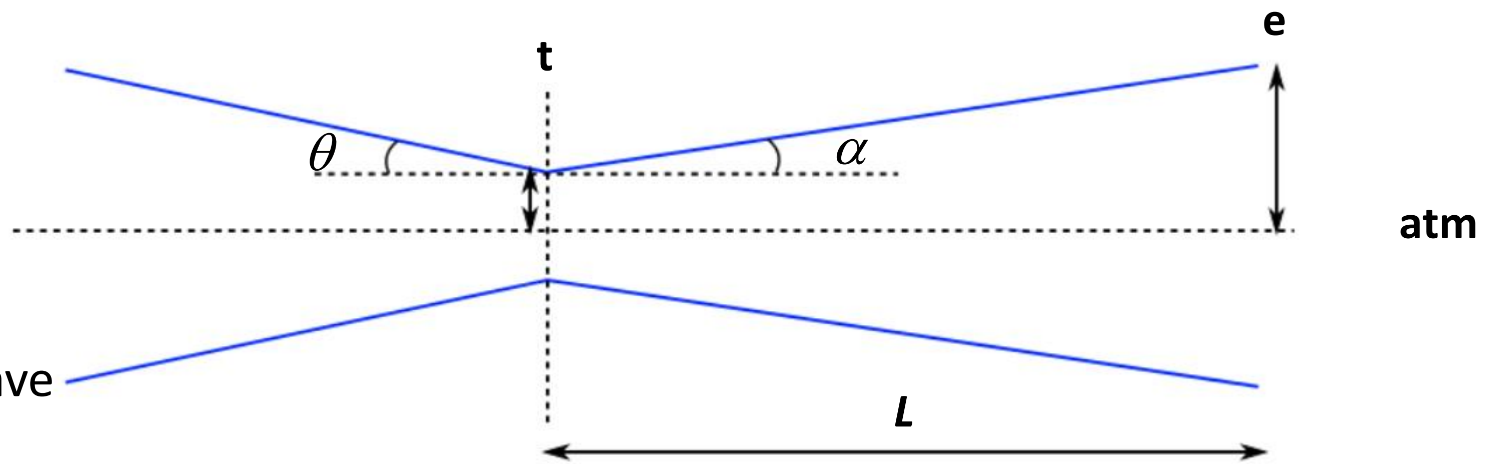
- use given area ratio to determine real area of exhaust $\frac{A_e}{A_t} = 2$

Nozzles

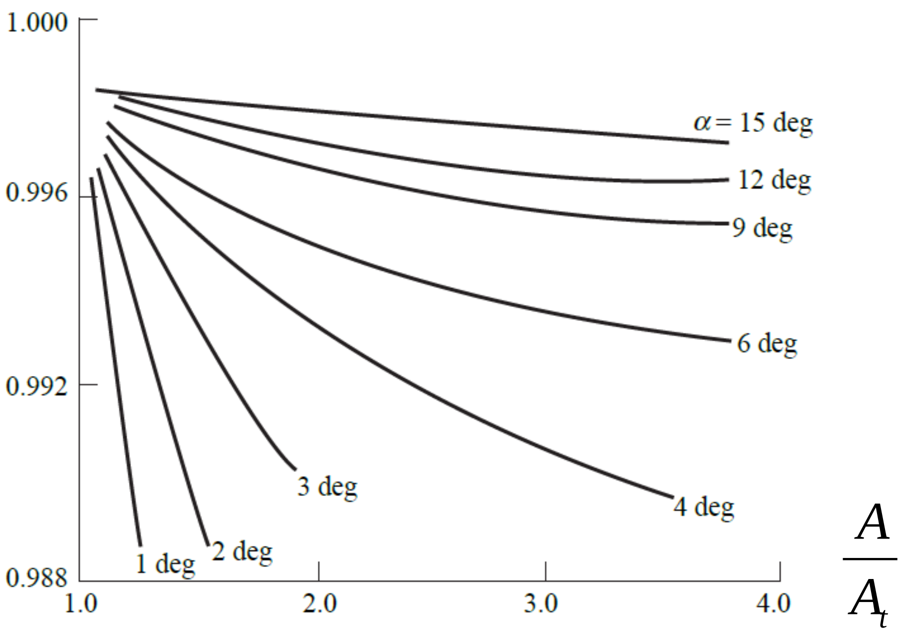
Example

- we have unknown angles
  - primary nozzle half angle θ
  - secondary nozzle half angle α

- to determine them, you would generally have reference figures



e.g.



would need to determine C_v and read off corresponding angular value for the area ratio

- from α and the exhaust area, can determine nozzle length L

Combustors

Overview

combustion system

- main combustor/burner
- afterburner/reheater/augmenter

- aircraft combustion systems differ from conventional devices
  - aircraft: speed up combustion to limit length
  - also higher heat intensities (rate of energy released per unit volume)

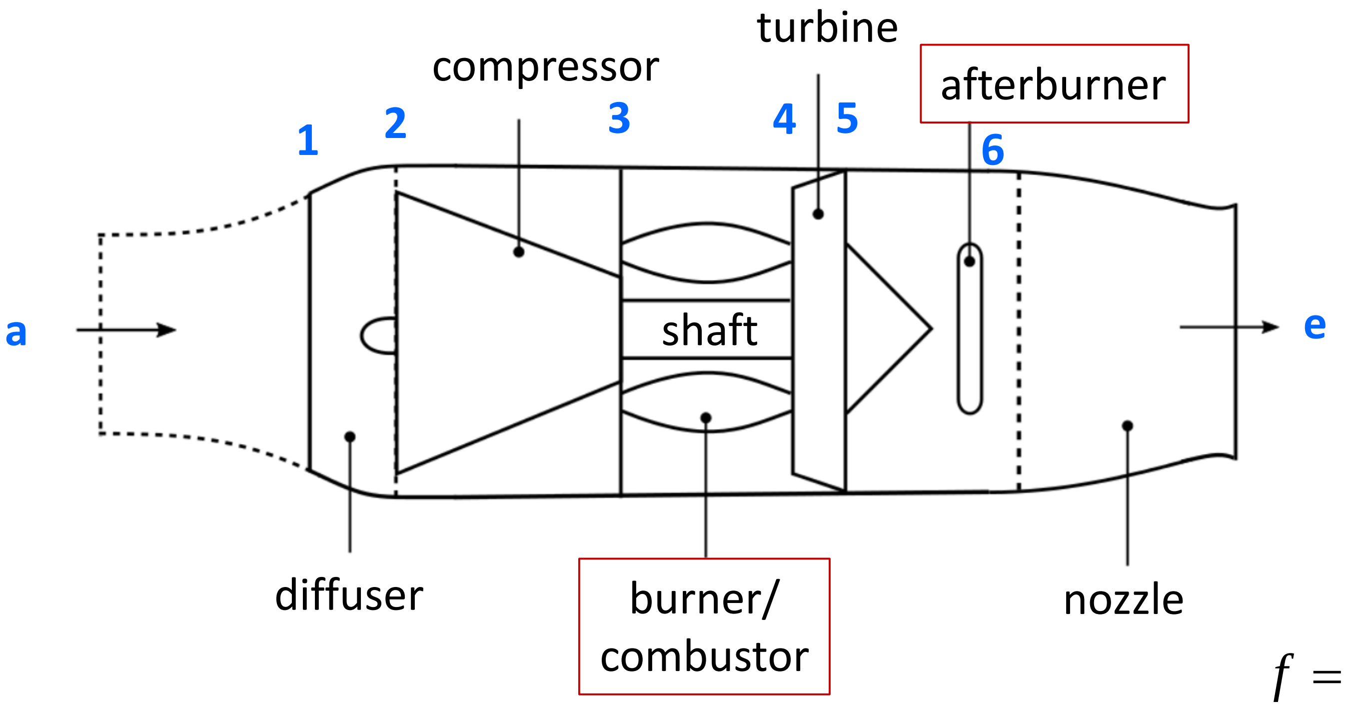
turbojet main burner: > 1 x 10^4 MW/m^3
steam power plant: ~ 3 MW/m^3

Characteristics sought

- high combustion efficiency (chemical to thermal)
- low total pressure loss
- combustion stability
- proper temperature distribution at exit with no hot spots (otherwise possible turbine damage)
- short length and small cross section
- no flameout
- long lifetime
- reliable ignition (takeoff, relighting)
- operation over a wide range of mass flow rates, pressures, and temperatures
- low emissions

Combustors

Combustor stations in overall system (e.g. turbojet)



- in main combustors: spray fuel into warm air
- simplified combustor energy equation

$$f = \frac{T_{o4} - T_{o3}}{\Delta h_R / c_p - T_{o4}}$$ ideal combustor

see Lec. 13, 14

$$f = \frac{T_{o4}/T_{o3} - 1}{\left(\eta_b \Delta h_R / c_{pb} T_{o3}\right) - T_{o4}/T_{o3}}$$ non-ideal combustor

$$\frac{p_{o4}}{p_{o3}} = P_{rb}$$ burner pressure ratio

Combustors

Key combustion parameters

equivalence ratio ϕ

$$\phi = \frac{f}{f_{stoich}} = \frac{m_{fuel}/m_{ox}}{(m_{fuel}/m_{ox})_{stoich}} = \frac{n_{fuel}/n_{ox}}{(n_{fuel}/n_{ox})_{stoich}}$$

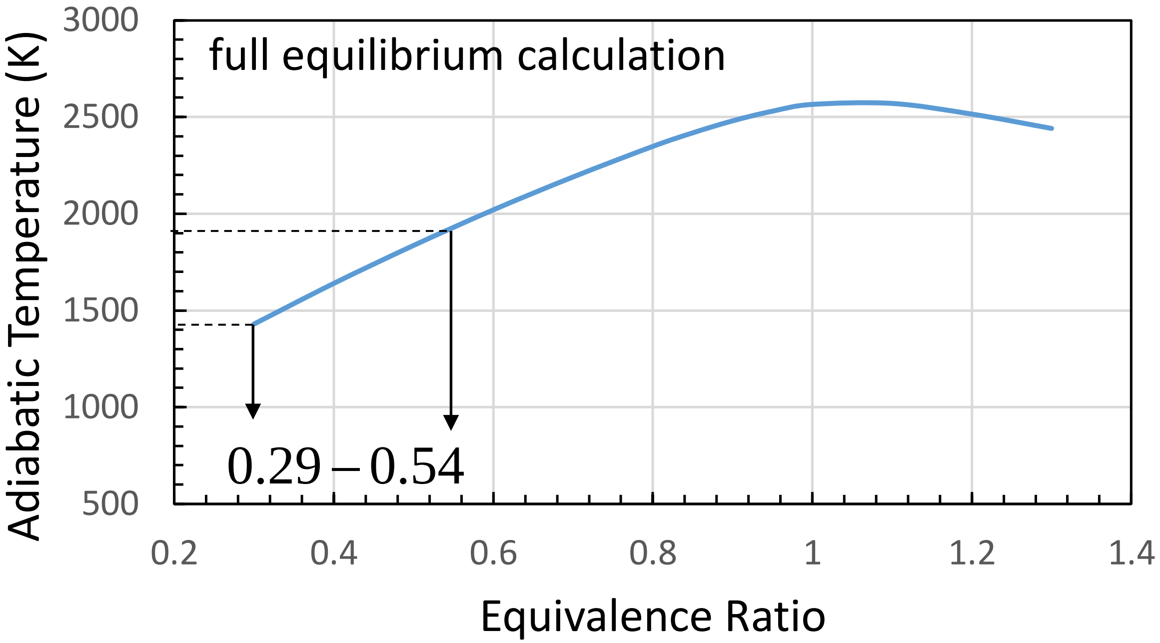
see Lec. 19

$\varphi > 1: \text{rich fuel} - \text{air ratio}$

$\varphi < 1: \text{lean fuel} - \text{air ratio}$

- to prevent excessive temperatures at the exit of main burner or afterburner: use $\phi < 1$

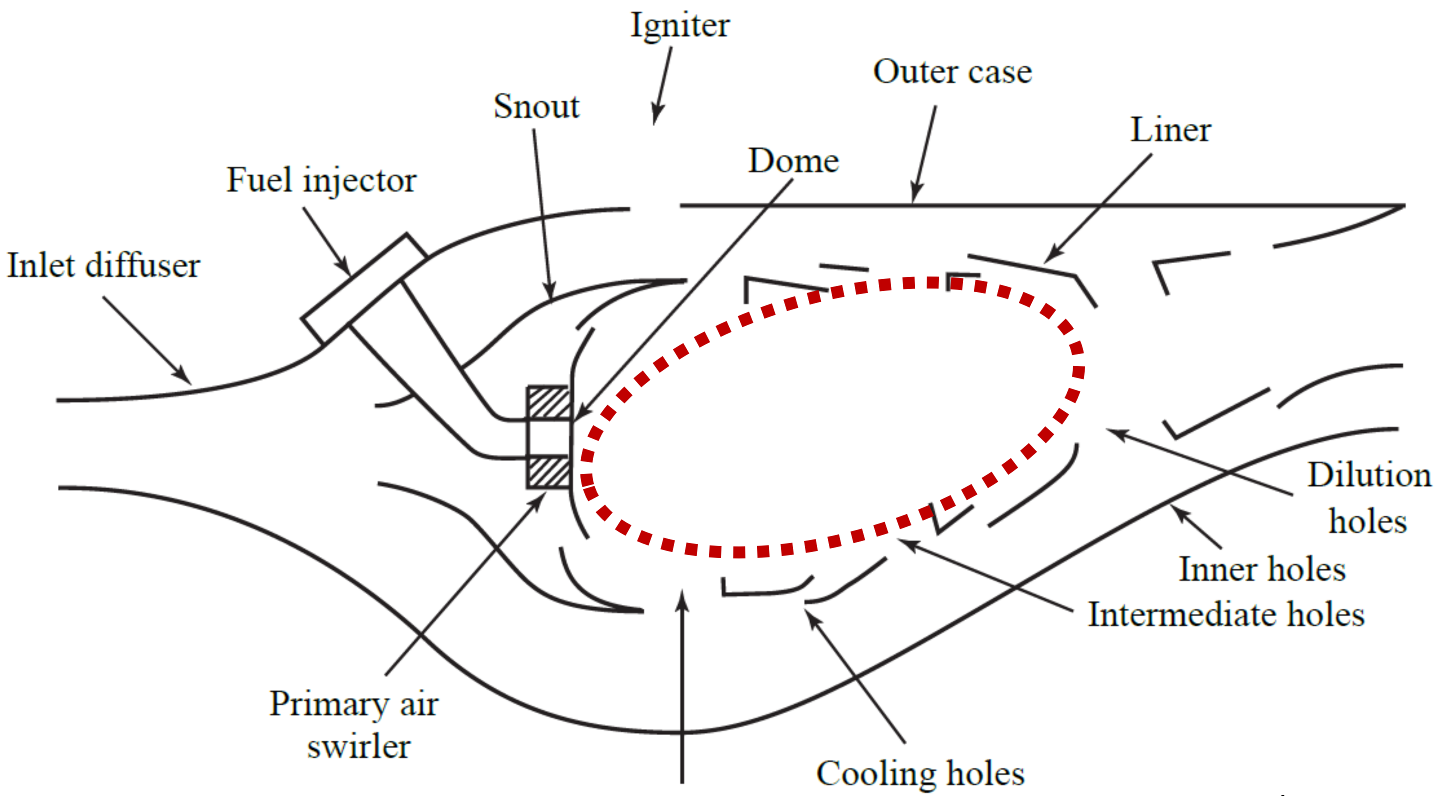
- value of equivalence ratio: same value regardless of moles (n), mass (m) used
- for jet fuel, $f_{stoich} \sim 0.067, \Delta h_R \sim 43.4\ \mathrm{MJ/kg}$
- in analyzing combustion reaction, more realistic to consider:
  - non-calorically perfect gas (c_p varies with T)
  - actual equilibrium composition
- for $T_{o4,max}$ = 1400 - 1900K, equivalence ratio range limited



T_{o3} = 700K

Combustors

Main combustor components



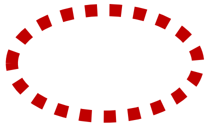
Mattingly

3 principal elements

- inlet diffuser
- dome and snout or cowl
- liner

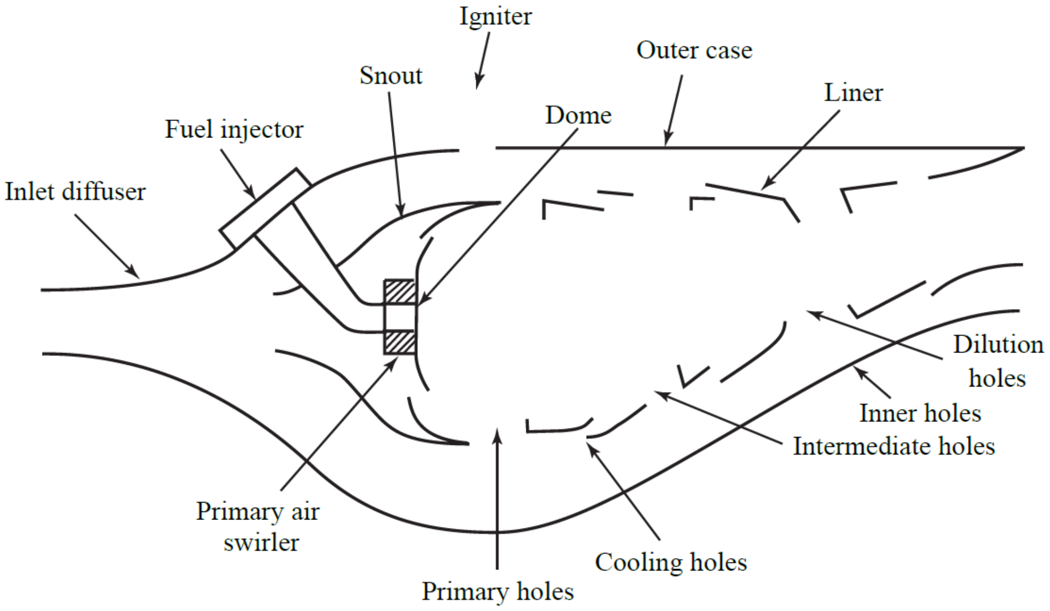
subcomponents

- fuel injector
- igniter
- burner case
- primary swirler

 combustion zone

Combustors

Main combustor components



functions

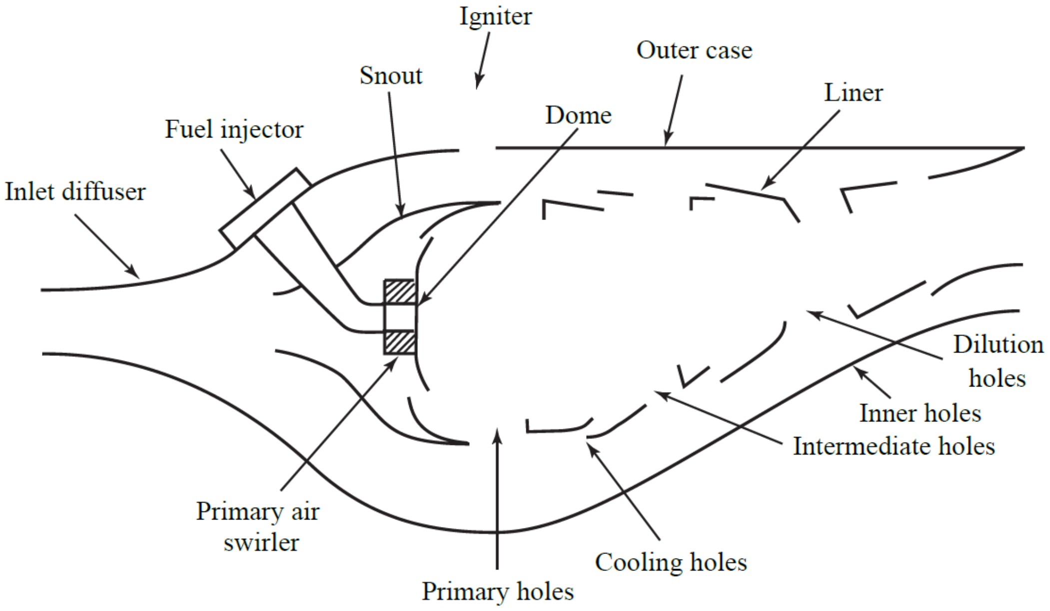
- inlet diffuser
  - reduce velocity of the air from compressor
  - provide air to combustion zone in stable, uniform flowfield
  - maximize pressure recovery

- snout
  - divides incoming air into primary air and other airflows (intermediate, dilution, and cooling air).
  - streamlines combustor dome
  - permits larger diffuser divergence angle and reduced overall diffuser length

- combustor dome
  - produce area of high turbulence and flow shear near fuel nozzle to finely atomize the fuel spray and promote rapid fuel/air mixing

Combustors

Main combustor components



- injector/atomizer
  - facilitate fuel atomization and mixing

functions

- liner
  - contains combustion process
  - allows introduction of intermediate and dilution airflow and liner's cooling airflow
  - must support forces resulting from pressure drop
  - must have high thermal resistance capable of continuous and cyclic high-temperature operation
  - requires use of high-strength, high-temperature, oxidation-resistant materials (e.g., Hastalloy X) and cooling air

- igniter
  - spark igniters, similar to automotive spark plugs
  - ignites the cold, flowing fuel/air mixture in main burner
  - requires 1000s of volts at tip

Combustors

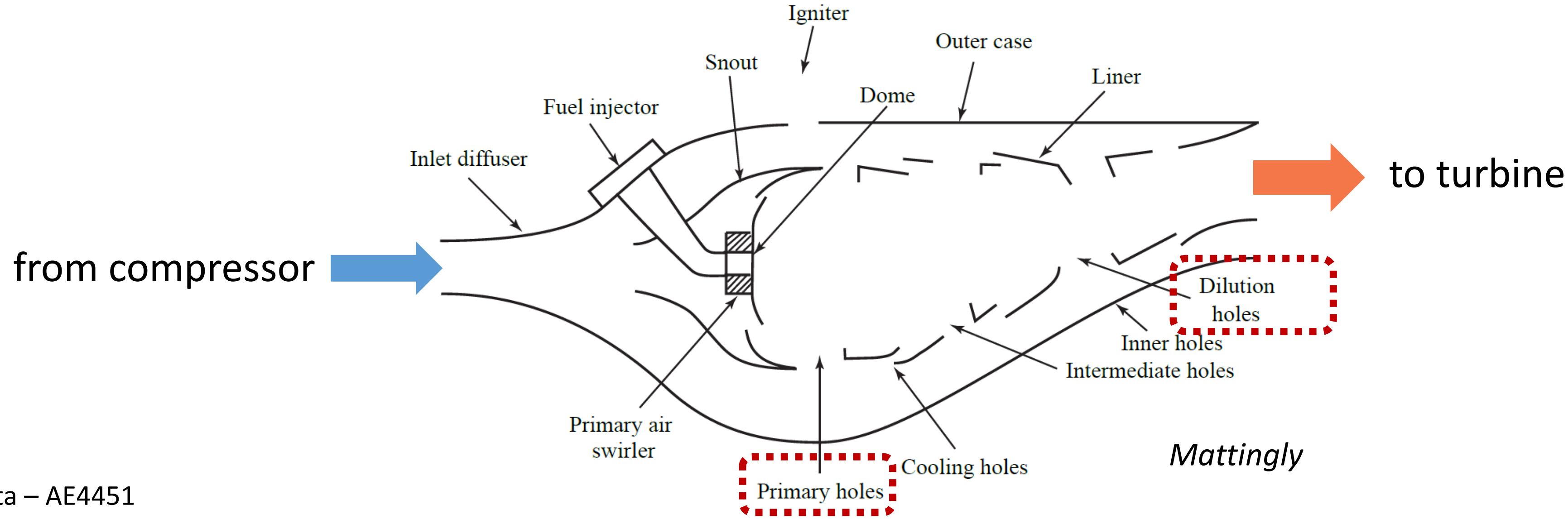
Flammability limits and dilution

- for pre-mixed jet fuel-air at typical T3 values, we cannot sustain a flame (without help) below a threshold equivalence ratio value ϕ of 0.35 – 0.43

  - this is the lean flammability limit

- for lower range of our operation, we cannot premix all air and fuel entering the combustor

  - run richer in primary zone (more stable)
  - add dilution air downstream (intermediate zone) to lower temperature (known as "air staging")
  - also use some of the excess air to cool the combustor walls, keep flame and hot gases away from liner



Mattingly

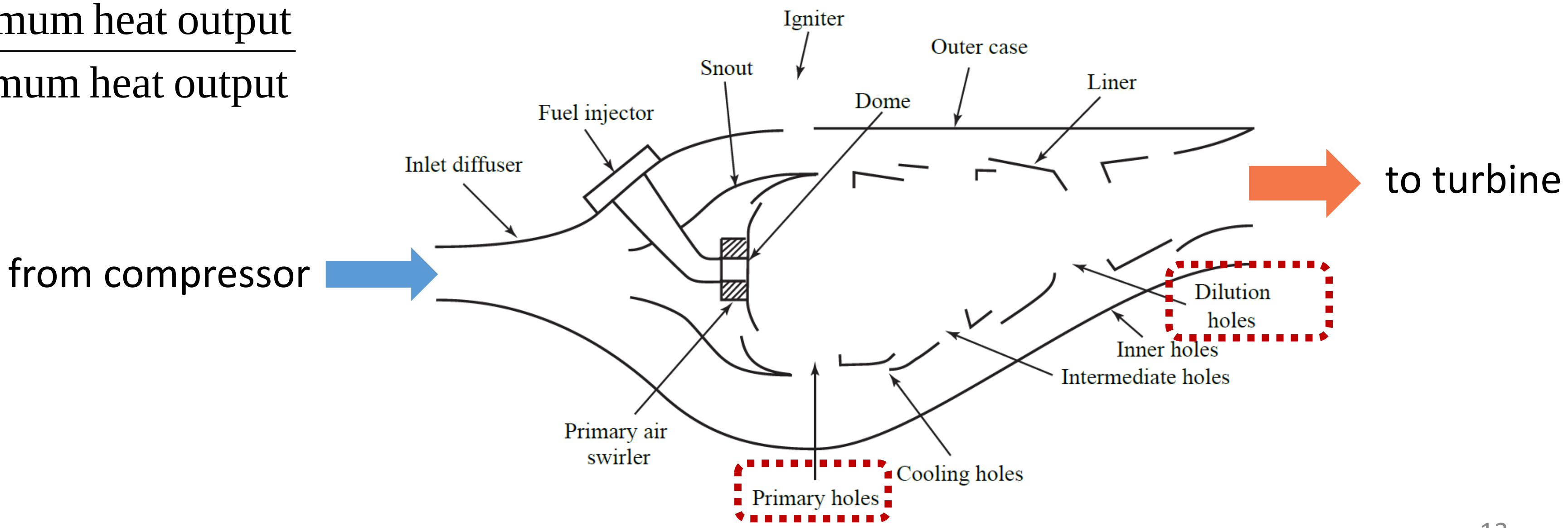
Combustors

Air staging options

- to reduce soot and NOx emissions, some combustor designs have moved to increasing the fraction of air introduced near the head end of combustor (lean burn)

- with reduction in dilution air
  - less air for cooling
  - can be harder to reduce hot streaks
  - leaner primary zone susceptible to stability problems
  - can require complicated fuel management for turndown (reduced f)

turndown ratio of burner: $$\frac{\text{maximum heat output}}{\text{minimum heat output}}$$



Combustors

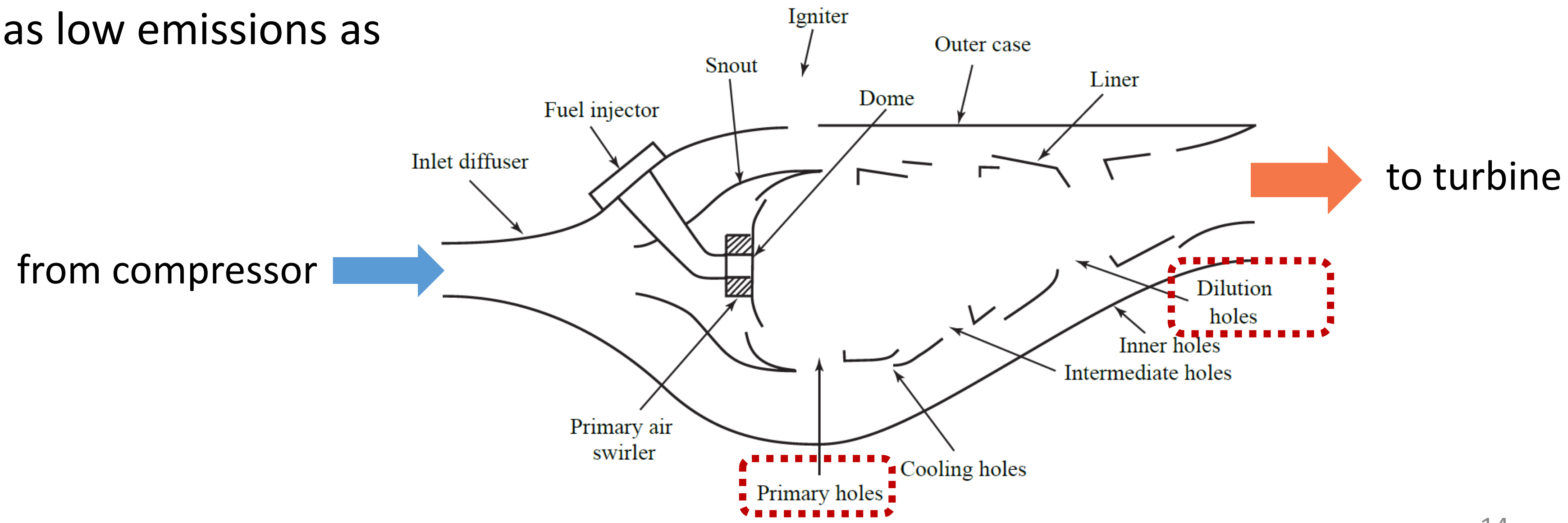
Air staging options

- alternate approach: maintain original rich primary zone and use strong dilution air jets

  referred to as RQL (Rich burn – Quick quench – Lean burn)

- can keep emissions levels low and promote exit uniformity while maintaining stability advantages of rich primary
  zone

- may not be able to achieve as low emissions as
  lean burn designs



Combustors

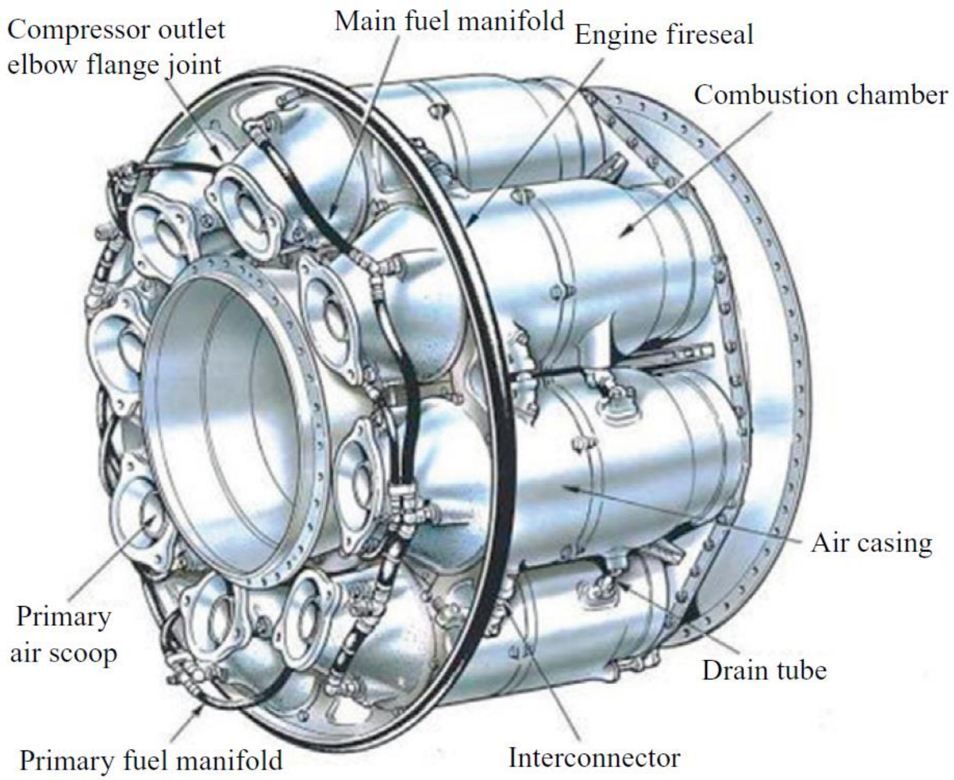
Main combustor types

3 types

1. can
2. can-annular (cannular)
3. annular

Can

- one or more cylindrical burners, each contained in a burner case
- each can has fuel injector, liner, interconnectors, casing
- modular design: used during early development of the turbojet engine, facilitates testing
- further advantage: simple control of *f*
- disadvantage: weight, pressure loss (7%), non-uniformity



Gharehpetian and Agah, Distributed Generation Systems (2017)

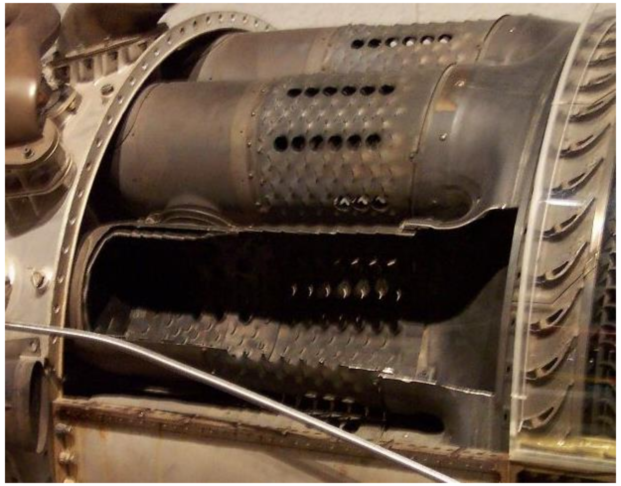
Jumo004b

Combustors

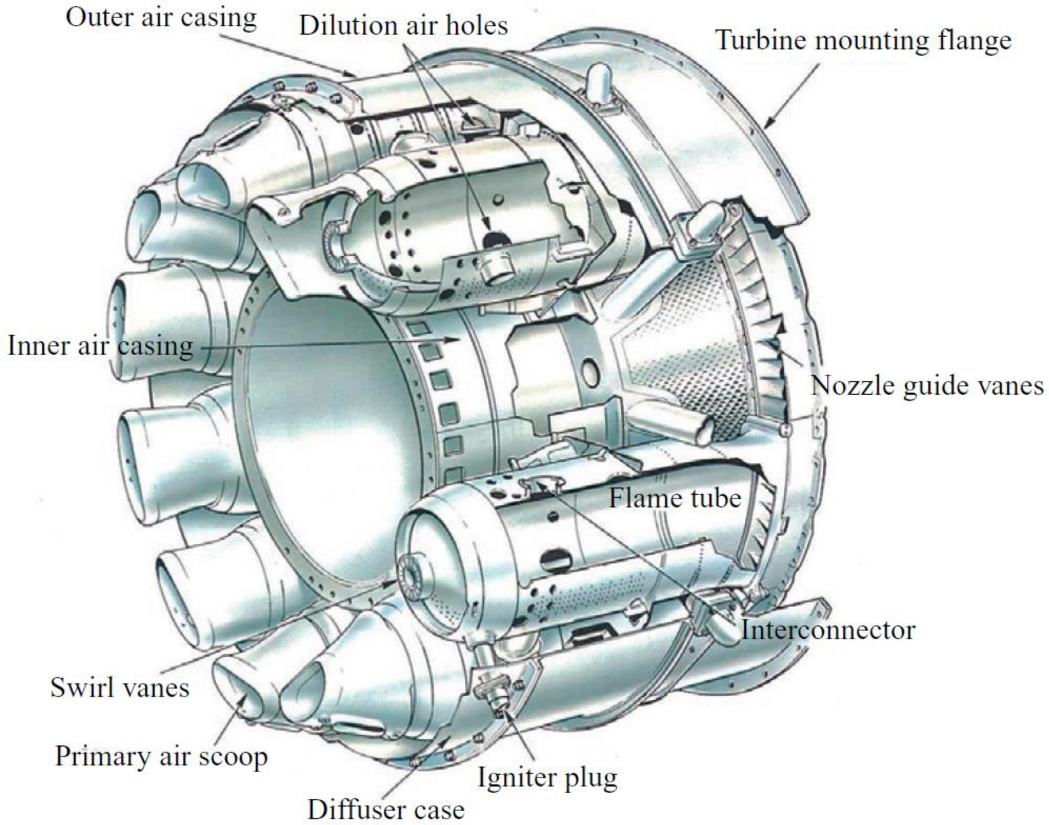
Main combustor types

Cannular

- consists of a series of cylindrical burners arranged within a common annulus
- originally most common in the aircraft turbine engines
- slightly lower pressure loss than can configuration (6%)



GE79 combustor (GE Aviation)



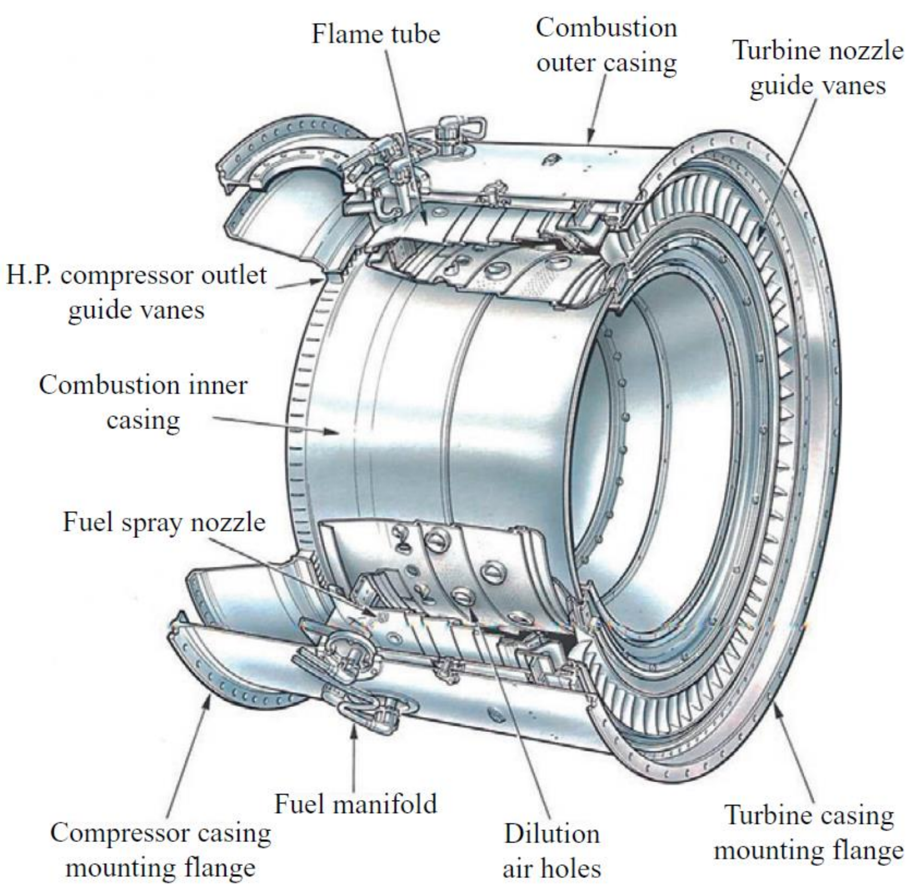
Gharehpetian and Agah, Distributed Generation Systems (2017)

Combustors

Main combustor types

Annular

- consists of a single burner with an annular cross section
- has largely replaced cannular design in modern engines
- multiple favorable features
  - improved combustion zone uniformity
  - design simplicity
  - reduced liner surface area
  - shorter system length
  - minimized pressure loss (5%)
- disadvantage: full rig-testing needed, full liner replacement costly



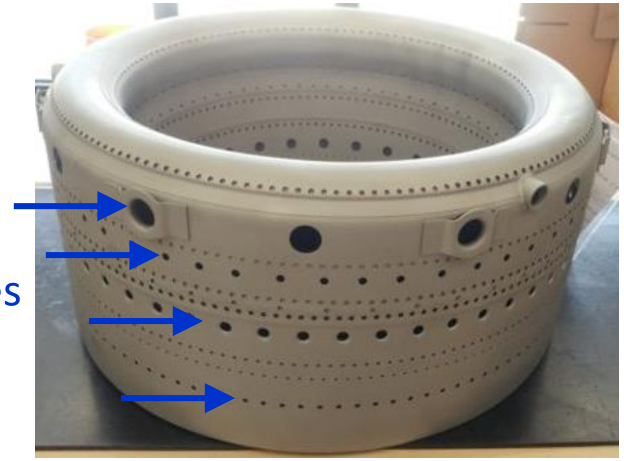
Gharehpetian and Agah, Distributed Generation Systems (2017)

GE90 combustor (GE Aviation)

Combustors

Annular combustor liners

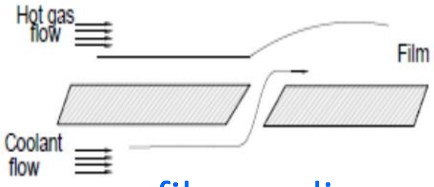
dilution holes



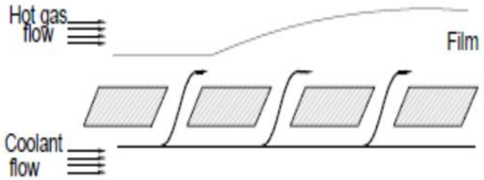
PT6 (PW Canada, Turboprop, King Air, Cessna)

KJ66 Pegasus (RR, Harrier)

JT9D (PW, 747, 767, A300)

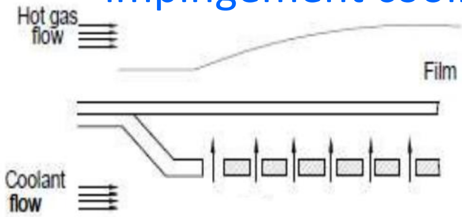


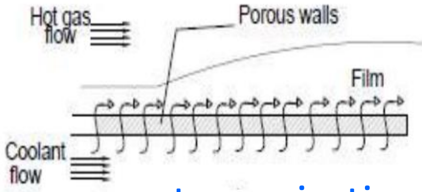
film cooling



effusion cooling

impingement cooling





transpiration cooling

to cool liner:

- cooling air flowed between liner and liner outer case
- can define a cooling effectiveness

$$\Phi = \frac{T_g - T_m}{T_g - T_c}$$

T_g = mainstream gas temp.

T_m = average metal temp.

T_c = cooling air temp.

Kumar et al, IOP Conf. Ser.: Mater. Sci. Eng. 804, 012003 (2020)

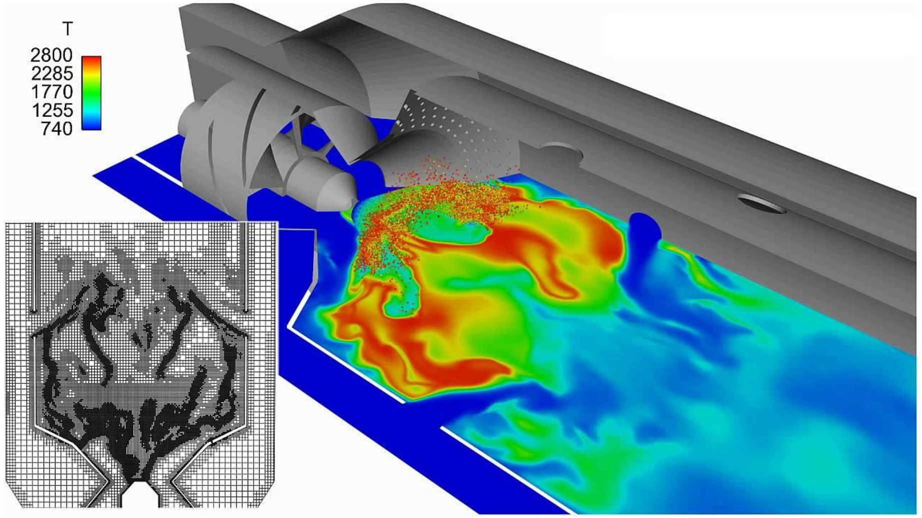
Combustors

Fuel injection/atomization

- liquid hydrocarbon fuels will burn only after becoming a gas/vapor
  - pre-vaporizing fuel in heat exchanger would
  (i) require additional weight
  (ii) lead to fuel coking; heated fuel pyrolyzes and forms carbon residue that clogs fuel lines

- combustors therefore use atomizers to produce fine liquid fuel droplets

3D printed fuel nozzle for LEAP engine (GE)



fuel atomization simulation example from convergeCFD

Combustors

Fuel injectors/atomizers

4 types, according to injection method

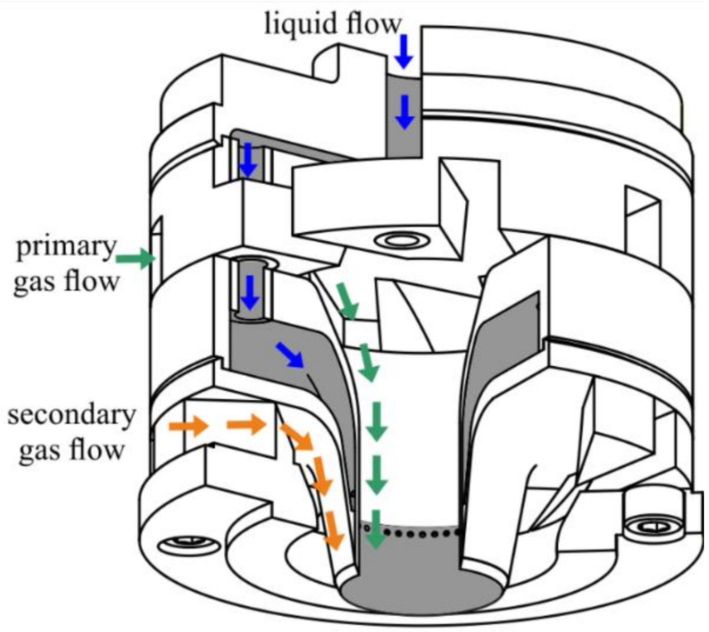
1. pressure-atomizing
2. air blast
3. vaporizing
4. premix/prevaporizing

Pressure atomizers

- provides best atomization at high pressures; 500 psi above main burner pressure
- poor performance at reduced fuel flow rates (low pressure)
- prone to fuel leaks (due to high fuel pressures) and plugging of orifices from fuel contaminants

Air blast atomizers

- fuel atomization and mixing through the use of primary air momentum with strong swirling motion
- rely less on fuel pressure and more on shear induced by air flow
- lower fuel pressures: 50 – 200 psi above main burner pressure



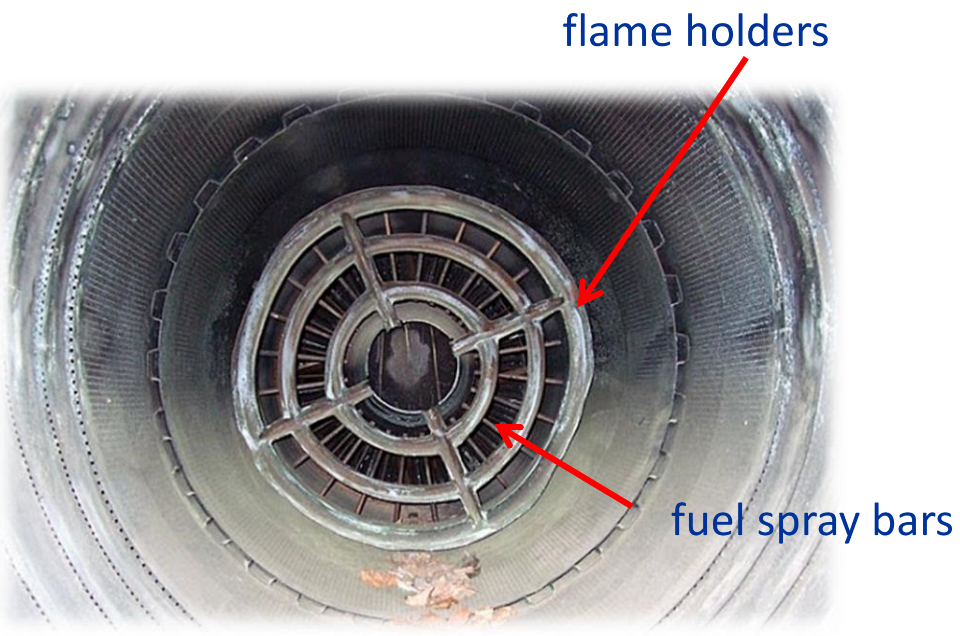
Holz et al., Energies 12, 2835 (2019)

Combustors

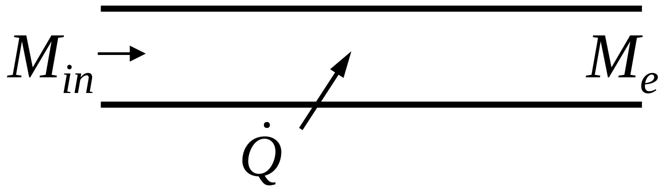
Afterburners/augmentors

- fuel is being injected into high temperature flow
- fuel needs to be distributed radially and azimuthally
- need flame holding for high velocity flow
  - prevents flame from being extinguished
  - creates low speed eddies in the flow

- choking of high speed flow a possibility (heat addition)



Rayleigh Flow



$$M_e \to 1$$

avoid this by using expanded nozzle area:
hence variable area nozzle, not simple fixed
convergent nozzle