Combustor Heat Transfer and Cooling

Gas Turbine Combustion Short Course

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

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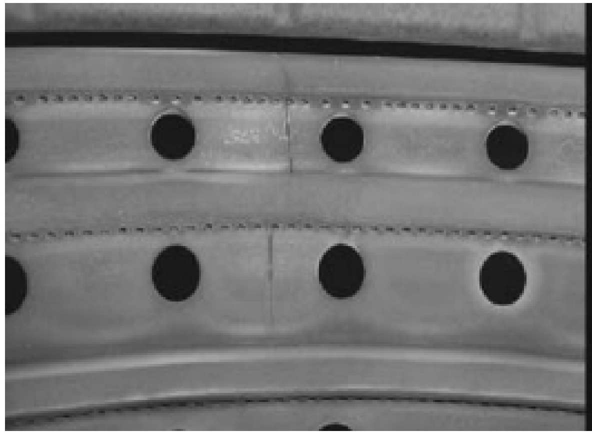
Introduction:

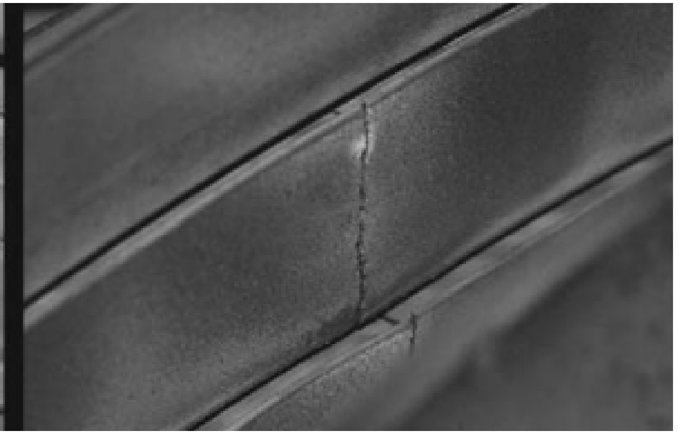
GT Combustor Liner Buckling and Cracking

- GT combustor liners are susceptible to:
  - Buckling (high T and high ΔT)
  - Cracking (LCF – transients (TO/ACC))

- Hot spots may arise due to:
  - Distortion of fuel spray
    - Defective atomisers / Misalignment of atomisers in the chamber
    - Build up of carbon on face of atomiser
  - Obstruction to the cooling flow (igniter plugs, liner support struts etc.) $\Rightarrow$ breakdown in convective cooling
  - Blockage between liner tiles and liner for DSCs (particularly during operation in hot and sandy environments)

- Cracks originate at geometrical discontinuities (cooling strips, air admission holes etc.) or at any points where large residual stress are induced during manufacture





Inner & Outer Liner Cracks

Ref: Tinga, T., van Kampen, J.F., de Jager, B. and Kok, J.B., 2006, "Gas Turbine Combustor Line Life Assessment Using a Combined Fluid/Structural Approach", ASME Journal of Engineering for Gas Turbines and Power, 129(1). doi:10.1115/1.2360603.

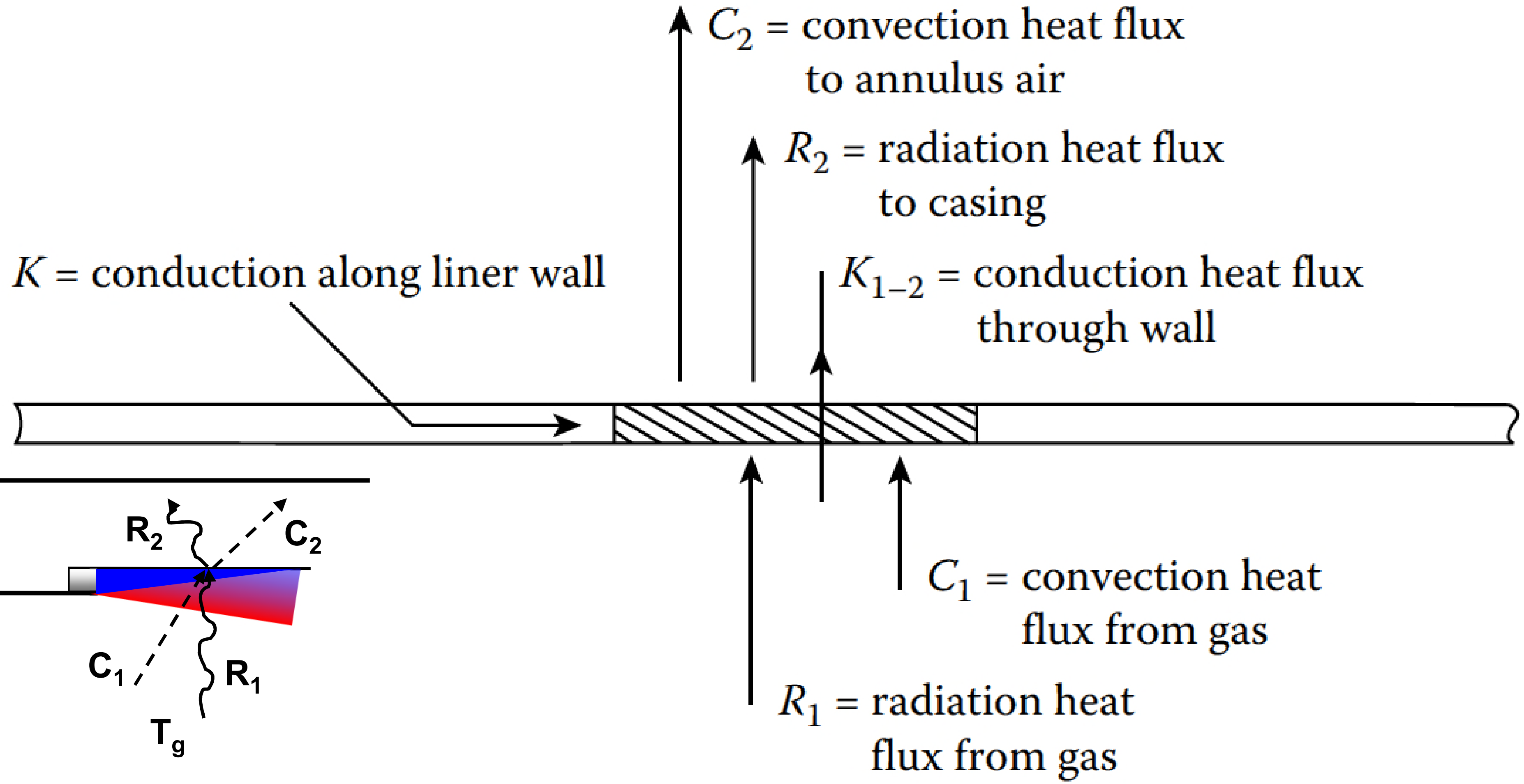
Introduction:
Need for Efficient Methods for Liner Cooling

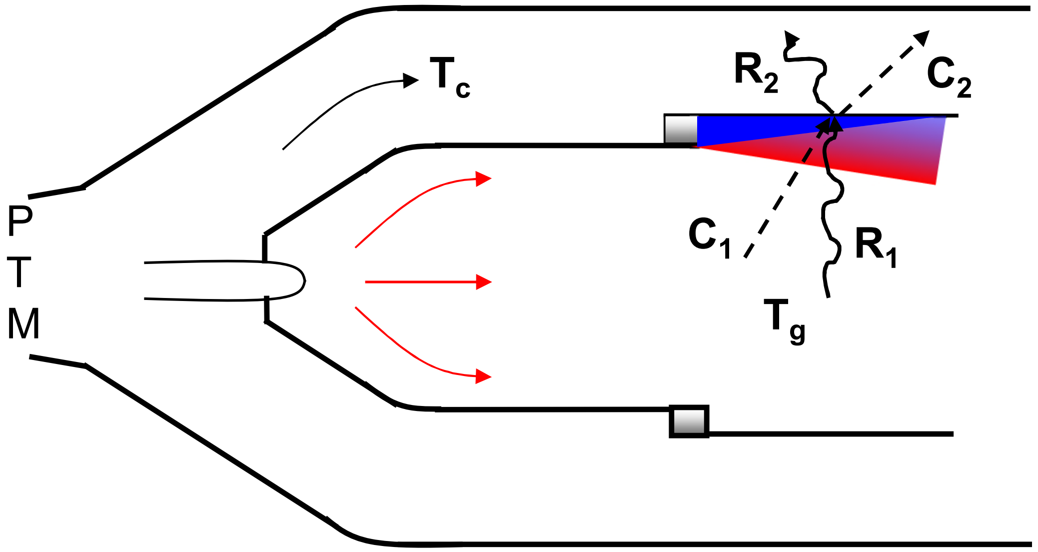
- Requirement for improvement in turbofan SFC $\Rightarrow \eta_{th}\uparrow$ & $\eta_{prop}\uparrow$
  - $\eta_{th}\uparrow \Rightarrow$ OPR$\uparrow$ & TET$\uparrow$
  - OPR$\uparrow \Rightarrow T_3\uparrow$ & $P_3\uparrow \Rightarrow$
    - Heat transfer by radiation from combustion gases to liner wall $\uparrow$
    - Difficult for annulus air to cool liner wall by convection
  - > 1/3 of total combustor airflow is used for film cooling the liner
  - TET$\uparrow \Rightarrow$ improvements in TTQ and RTD required ($W_{cooling}\uparrow$, $W_{mixing}\downarrow$)

- Lean burning for low emission combustors $\Rightarrow$ more air allocated for combustion
  - Less air available for film cooling
  - Less film cooling air also beneficial for lowering CO and UHC

- As combustor operating temperatures have increased so have component durability expectations (many thousands of operating hours before maintenance)

Heat Transfer Process





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

Heat Transfer Process

- Under equilibrium conditions, internal and external heat fluxes at any point are equal

- For an element with inside surface area ΔAw_1:

$$(R_1 + C_1 + K)\Delta Aw_1 = (R_2 + C_2)\Delta Aw_2 = K_{1-2}\Delta Aw_1$$

- Assuming:
  - K is negligible compared to R_1, R_2, C_1 and C_2
  - Liner wall is usually so thin $\Rightarrow \Delta Aw_1 = \Delta Aw_2$

$$\Rightarrow \quad R_1 + C_1 = R_2 + C_2 = K_{1-2}$$

Heat Transfer Process:

Conduction through the Liner Wall (K_{1-2})

$$K_{1-2} = \frac{kw}{tw}\left(Tw_1 - Tw_2\right)$$

kw:	Liner wall thermal conductivity (W/mK)
tw:	Liner wall thickness (m)
Tw_1:	Temperature of inner wall of liner (K)
Tw_2:	Temperature of outer wall of liner (K)

Heat Transfer Process:

Internal Radiation (R_1)

- Largest amount of heat transferred to the liner wall is by R_1
  - C_1 comparatively small (negligible if cooling air forms a barrier between liner wall and hot gases)

Internal Radiation (R_1)

<u>Luminous Radiation</u>

- Radiation from solid particles (black bodies - mainly soot)
- IR, visible and UV spectrum

<u>Nonluminous Radiation</u>

- Radiation from hetero-polar gases (mainly CO_2 and H_2O) and intermediate products of combustion (CO and OH)
- IR and UV spectrum only

Heat Transfer Process:
Internal Radiation (R_1)

- For a black body surface:

$$R_1 = \sigma\left(\varepsilon g Tg^4 - \alpha g Tw_1^{\,4}\right)$$

σ: Stefan-Boltzmann constant = 5.67 x 10^{-8} W/(m^2K^4)

εg: Gas emissivity at temperature Tg ($T_3 + \Delta T_{comb}$)
  - Relates to radiation emitted from the gas to the wall

αg: Gas absorptivity at temperature Tw_1
  - Based on radiation of the wall

Functions of gas props.

- But liner surface is not a black body – can be considered as a grey body ⇒

$$R_1 = 0.5\sigma(1+\varepsilon w)\left(\varepsilon g Tg^4 - \alpha g Tw_1^{\,4}\right)$$

- Accounts for liner surface α ≠ 1
- εw dependent on material, temperature & degree of oxidation
- Typical values of εw : Nimonic – 0.7, Stainless steel – 0.8

Heat Transfer Process:
Internal Radiation (R_1)

$$R_1 = 0.5\sigma(1+\varepsilon w)\left(\varepsilon g Tg^4 - \alpha g Tw_1^{\,4}\right)$$

- Studies have shown, to a close approximation: $\dfrac{\alpha g}{\varepsilon g} = \left(\dfrac{Tg}{Tw_1}\right)^{1.5} \Rightarrow$

$$\boxed{R_1 = 0.5\sigma(1+\varepsilon w)\varepsilon g Tg^{1.5}\left(Tg^{2.5} - Tw_1^{\,2.5}\right)}$$

Heat Transfer Process:
Internal Radiation (R_1) - Emissivity

- Emissivity for nonluminous flames:

$$\varepsilon g = 1 - \exp\left[-290P(ql_b)^{0.5}Tg^{-1.5}\right]$$

P:	Gas pressure (KPa)
Tg:	Gas temperature (K)
q:	FAR by mass
l_b:	Beam length (m) ($l_b \approx$ 3.4 (volume) / (surface area))

- For tubular: $l_b \approx 0.6D_L - 0.9D_L$
- For annular: $l_{b(inner)} \approx 1.0D_L$ & $l_{b(outer)} \approx 1.2D_L$

D_L: liner diameter (can) or height (annular)

Beam length: Radius of gas hemisphere which at the same temperature as the combustion gases, radiates to a unit area at the centre of its base the same average radiation as the combustion gases radiate to a unit area of the flame tube

Heat Transfer Process:
Internal Radiation (R_1) - Emissivity

- Emissivity for luminous flames:

$$\varepsilon g = 1 - \exp\left[-290 P \boxed{L} (q l_b)^{0.5} Tg^{-1.5}\right]$$

Luminosity factor

- Correlations for determining L (examples):

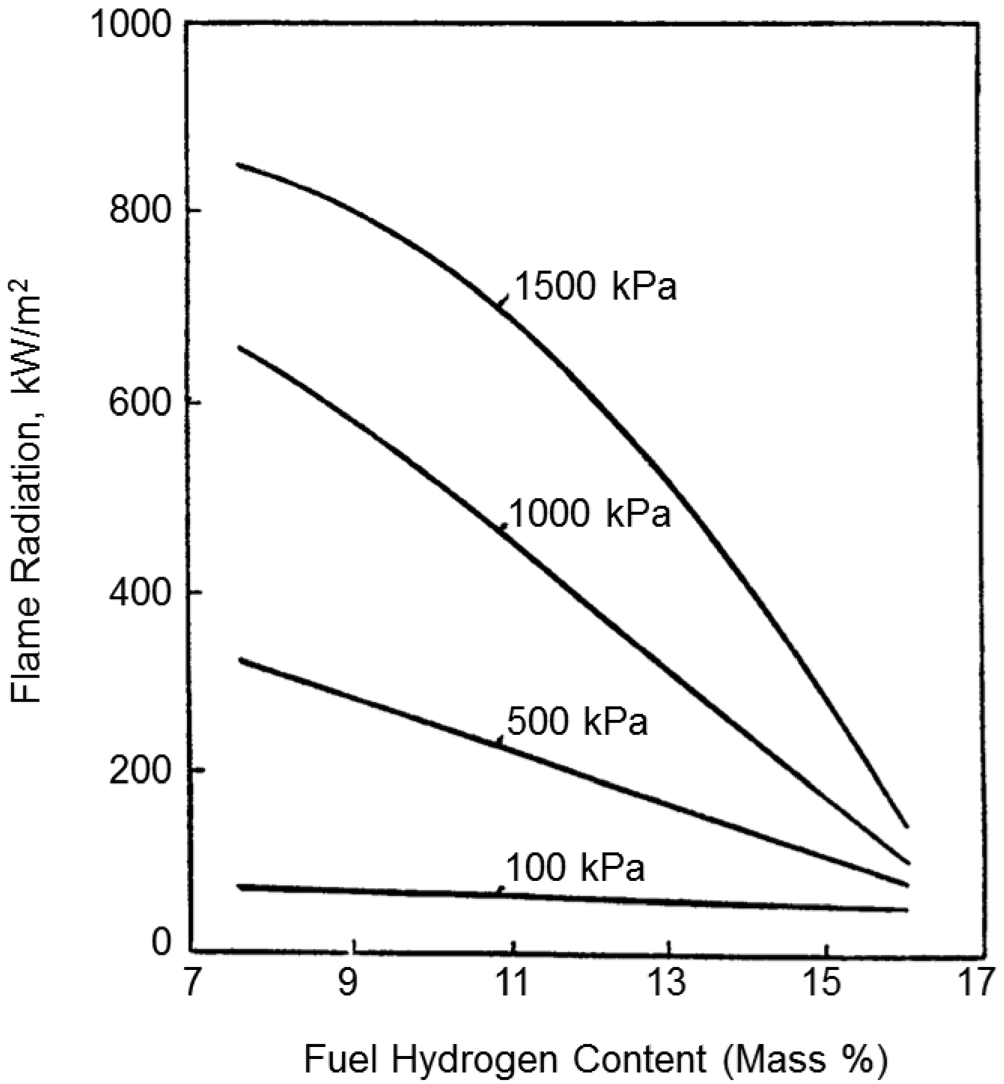
$$L = 3(C/H - 5.2)^{0.75}$$ Lefebvre (1960)

$$L = 336/H^2$$ Lefebvre (1985)

C/H: Carbon to hydrogen ratio of the fuel by mass
H: Fuel hydrogen content by mass (%)

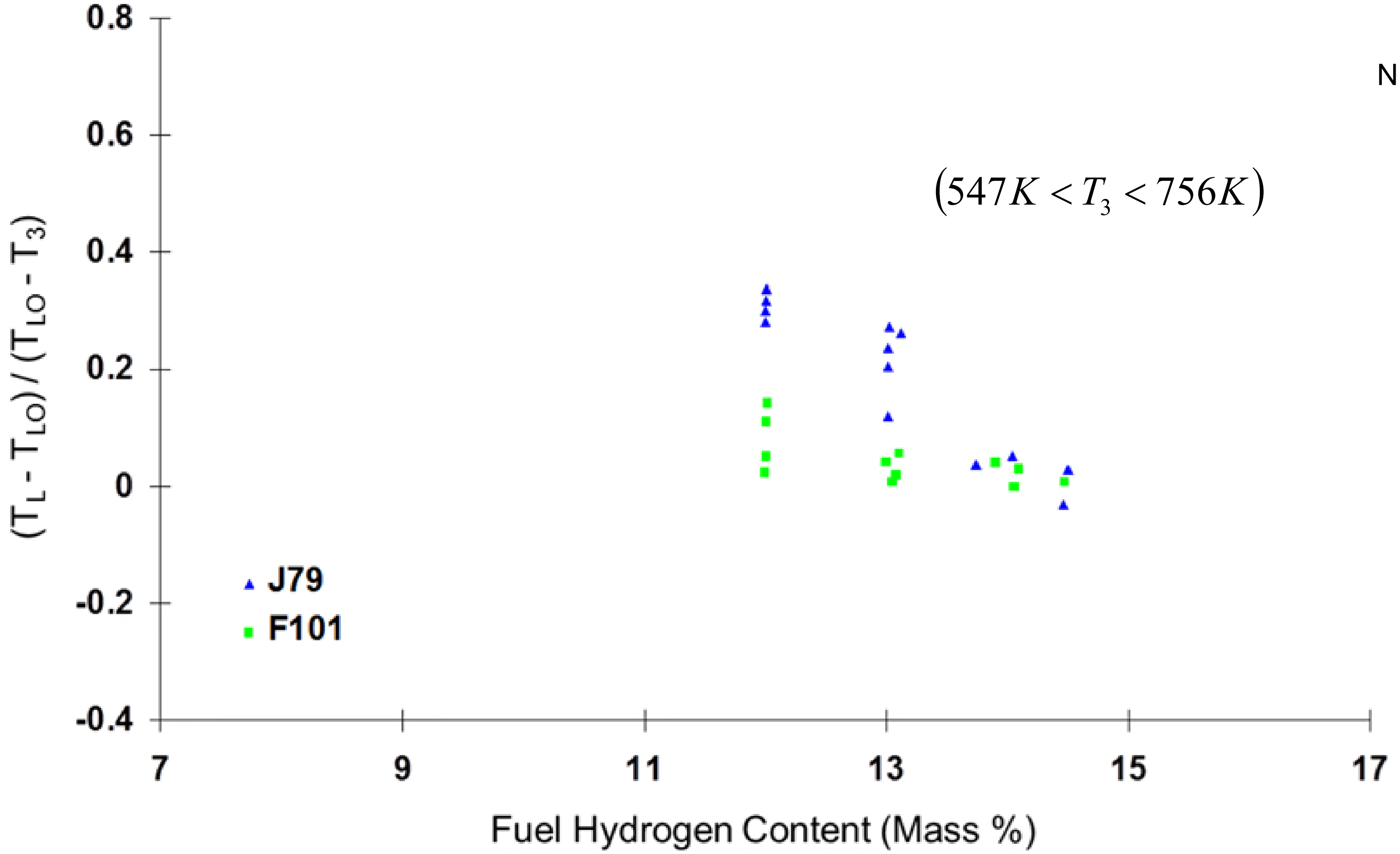
Luminous Radiation:

Influence of Fuel Composition and P_3



Ref: Lefebvre. A. H., 1983, "Gas Turbine Combustion", 1st Edition, McGraw Hill

Effect of Fuel Hydrogen Content on Liner Temperature at Cruise



NB: Results are for combustors with pressure atomisers and rich combustion zones. For air blast atomisers and lean combustion zones sensitivity to hydrogen content is lower

Ref: Lefebvre. A. H., 1983, "Gas Turbine Combustion", 1st Edition, McGraw Hill

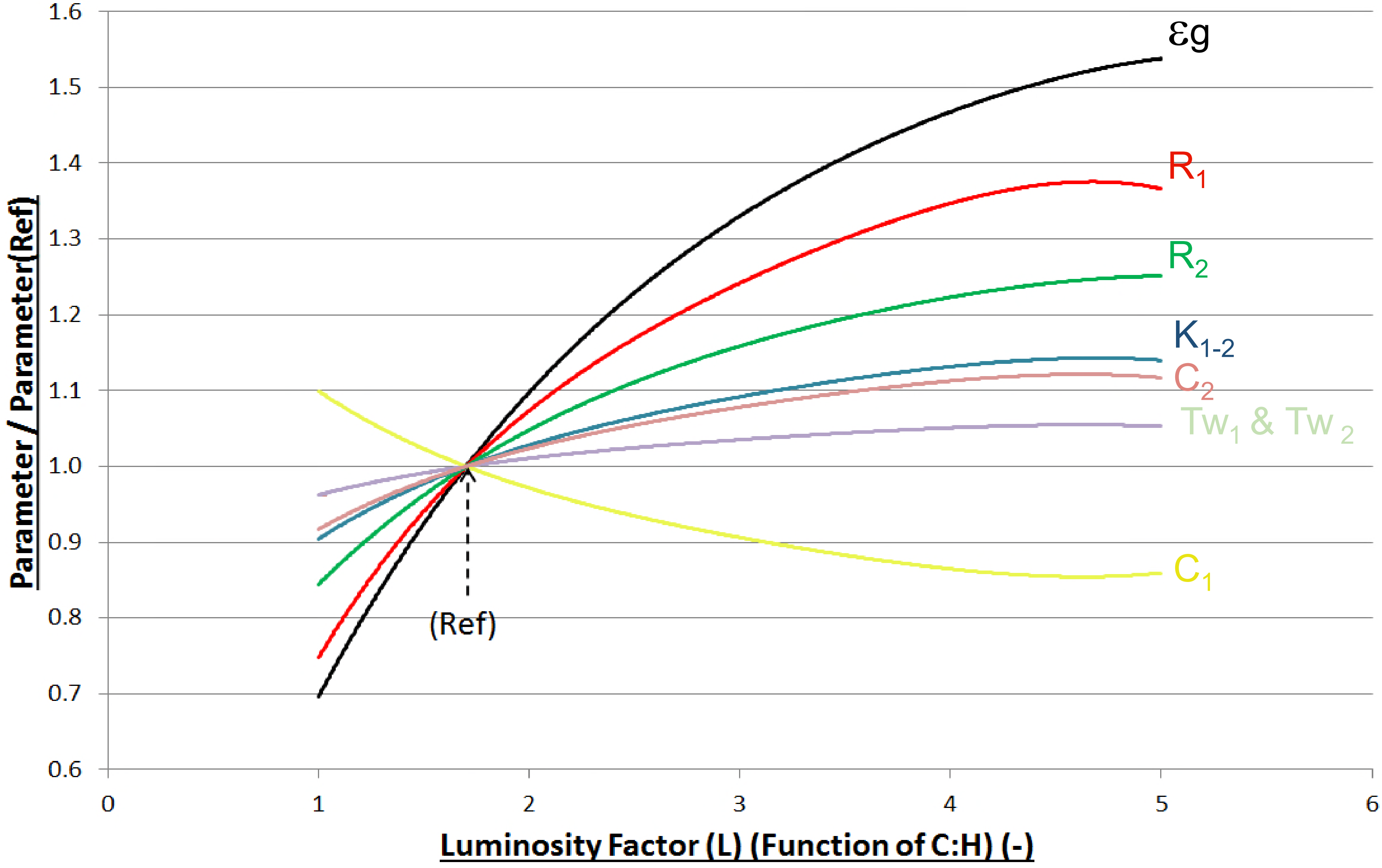
Effect of Fuel Hydrogen Content on Combustor Life

% Hydrogen in Fuel	Relative Combustor Life	
	J79	F101
14.5	1.00	1.00
14.0	0.78	0.72
13.0	0.52	0.52
12.0	0.35	0.47

Ref: Gleason, CC. et al. “Evaluation of Fuel Character Effects on J79 Combustion System” Report No. AFAPL-TR 79-2015 (CEEDO-TR-79-06), General Electric Company. Aircraft Engine Group, Cincinnati, Ohio, June 1979.

Ref: Gleason, CC. et al. “Evaluation of Fuel Character Effects on the FIO Engine Combustion System” Report No. AFAPL-TR-79-2018 (CEEDO-TR-79-07) General Electric Company. Aircraft Engine Group, Cincinnati, Ohio, June 1979.

Effect of Luminosity on Heat Transfer Terms



Heat Transfer Process:
External Radiation (R_2)

- $R_2 << C_2$
- Significance of R_2 increases with Tw_1 (can be neglected at low values)
- Simplified expressions (due to lack of knowledge of wall emissivities):

$$R_2 = \sigma \frac{(\varepsilon w \varepsilon c)}{\varepsilon c + \varepsilon w (1 - \varepsilon c)(Aw / Ac)} (Tw_2{}^4 - T_3{}^4)$$

εc:	Casing emissivity
Tw_2:	Temperature of coolant side of liner wall (K)
Aw:	Surface area of the liner wall (m^2)
Ac:	Surface area of the casing (m^2)

For Aluminium Air Casing: $$R_2 \approx 0.4\sigma(Tw_2{}^4 - T_3{}^4)$$

For Steel Air Casing: $$R_2 \approx 0.6\sigma(Tw_2{}^4 - T_3{}^4)$$

Heat Transfer Process:

Internal Convection (C_1)

- Most difficult heat transfer term to determine accurately:
  - Gases at high temperature and undergo rapid physical and chemical changes
  - Steep gradients of temperature, velocity and composition in primary zone
  - Uncertainties regarding air flow patterns, BL development

- In absence of more exact data, assuming classical heat transfer for straight pipes apply for the liner:

$$\overset{C_{1pz}}{\cancel{C_1}} = \overset{0.017}{\cancel{0.020}} \frac{kg}{{D_L}^{0.2}} \left(\frac{mg}{A_L \mu g} \right)^{0.8} (Tg - Tw_1)$$

kg: Thermal conductivity of the gas (W/mK)
mg: Mass flow rate of the gas (kg/s)
A_L: Cross sectional area of the liner (m^2)
μg: Dynamic viscosity of the gas (kg/ms)

$$D_L = 4 \left(\frac{Cross - sectional\ flow area}{Wetted\ Perimeter} \right)$$

Heat Transfer Process:

External Convection (C_2)

$$C_2 = 0.020 \frac{ka}{D_{an}^{\;0.2}} \left(\frac{m_{an}}{A_{an} \mu a} \right)^{0.8} (Tw_2 - T_3)$$

ka:	Thermal conductivity of the annulus air (W/mK)
m_{an}:	Mass flow rate of the annulus air (kg/s)
A_{an}:	Cross sectional area of the annulus (m^2)
μa:	Dynamic viscosity of the annulus air (kg/ms)

$$D_{an} = 4 \left(\frac{Cross - sectional\ flowarea}{Wetted\ Perimeter} \right)$$

- For tubular: $D_{an} = D_{ref} - D_L$
- For annular: D_{an} = 2 x local annulus height

Heat Transfer Process:

Calculation of “Uncooled” Liner Temperature

1. Estimate mean FAR for zone being considered
   - For maximum possible Tw $\Rightarrow$ use FAR_{Stoich}

2. Obtain R_1

3. Obtain R_2

4. Calculate C_1
   - Values of k and μ for combustion products at T_g

5. Calculate C_2
   - Values of k and μ for air at T_3

6. Using: $$R_1 + C_1 = R_2 + C_2 = \frac{kw}{tw}\left(Tw_1 - Tw_2\right) = K_{1-2}$$ solve for Tw_1 & Tw_2

- Calculation useful for:
  - Determining supplementary cooling requirement
  - Qualitative prediction of the effect of any change in inlet conditions

Heat Transfer Process:
Effect of Chamber Variables

- Increase in pressure
  - Increase in R_1
    - Increase in εg (dominant until $\varepsilon g = 1$)
    - Slight increase in flame temperature (supresses dissociation)
  - Increase in C_2
    - Increase in (m_{an} / A_{an})

- Increase in inlet air temperature
  - Increase in R_1 & C_1 (higher Tg)
  - Decrease in R_2 & C_2 (higher T_3)

Tw$\uparrow$

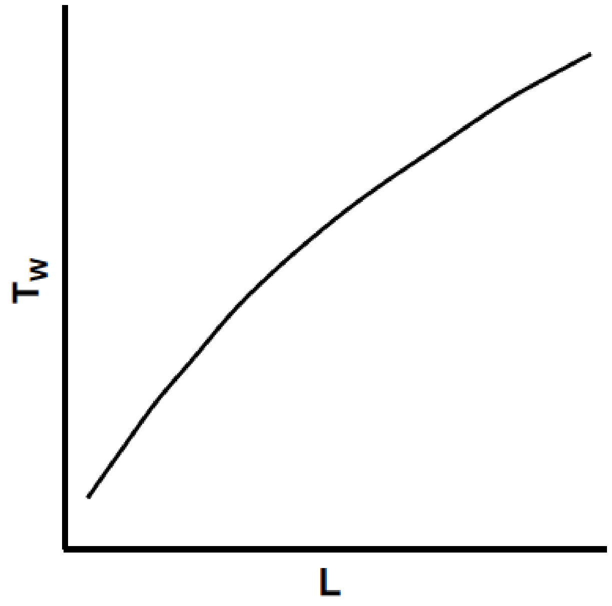
- AFR
  - Tg ($\therefore R_1$, C_1 and Tw) greatest at $\sim$ ($1.1 \times \phi$)

- Increase in air mass flow rate
  - R_1 & R_2 independent of m_3
  - C_1 & $C_2 \propto m_3^{0.8}$
    - C_2 accounts for most of heat transfer from liner
    - C_1 accounts for only about half of heat transfer to liner

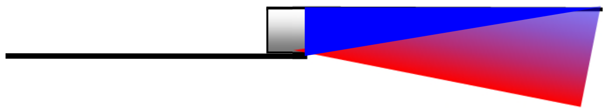
Tw$\downarrow$

Combustor Cooling:
Film Cooling

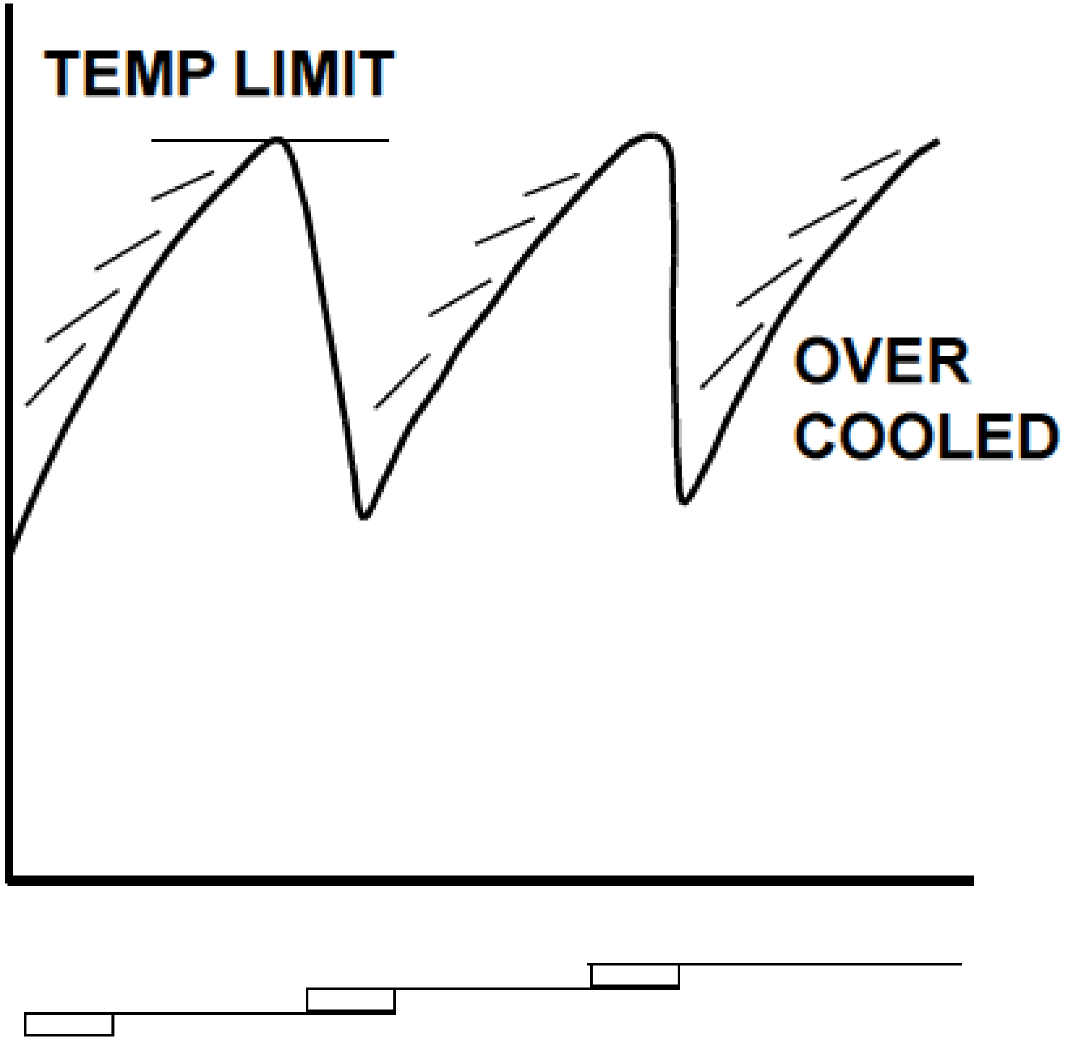
- Air injected axially (via annular slots at ~ 40 - 80mm intervals) along the length of liner to provide protective film of cooling air between the wall & hot gases
- Cooling film gradually destroyed by turbulent mixing with hot gas stream
- At the downstream end of the liner flow acceleration supresses turbulence and film persists for a greater distance



- ✓ Cooling slots can be designed to withstand severe pressure and thermal stresses at high temperatures, up to several thousand hours
- ✓ Stiffness provided by cooling slots results in liner construction which is light and robust

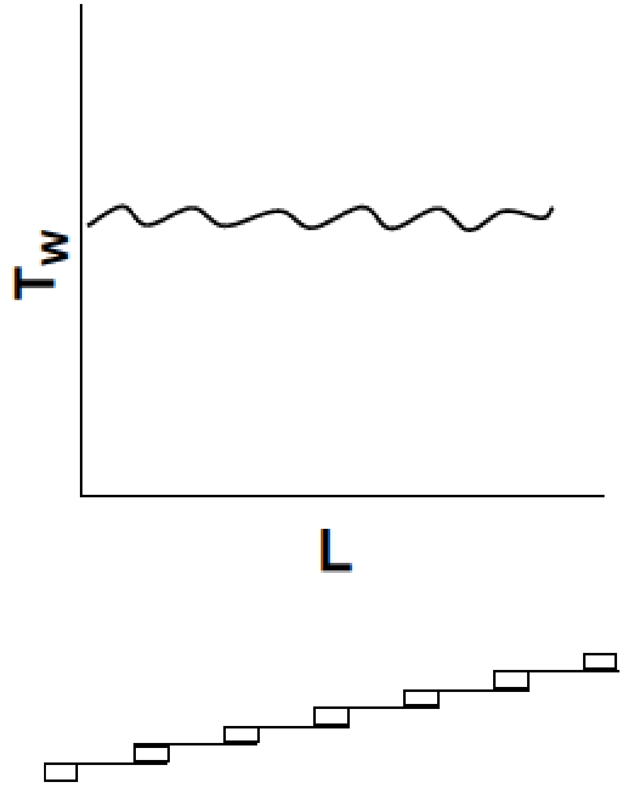


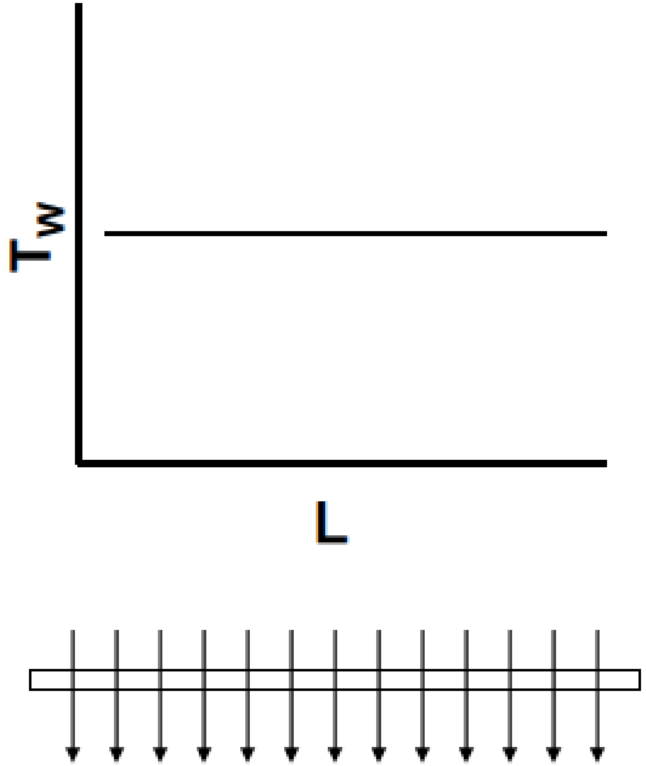
Combustor Cooling:
Film Cooling



- X Does not allow uniform wall temperature ⇒ inherently wasteful of cooling air

Combustor Cooling:
Film Cooling





✓ More uniform wall temperature (less overcooling)

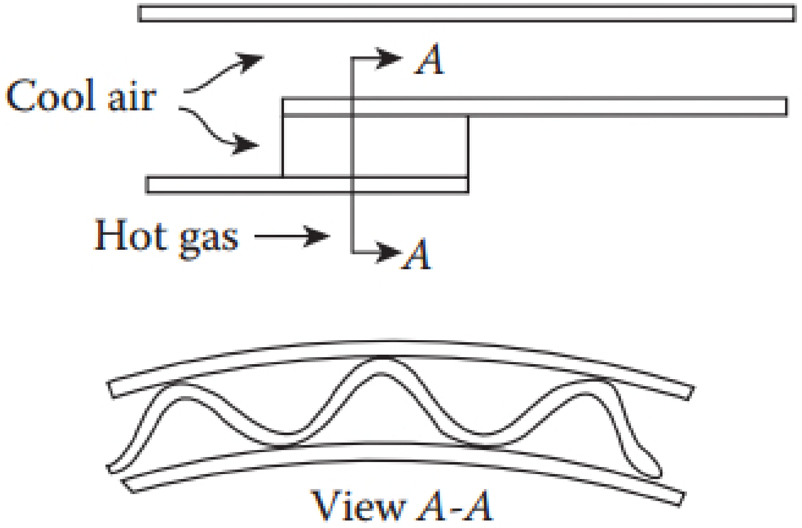
X Heavy and complex combustor

✓ Infinite cooling arrangement ⇒ uniform wall temperature

X Static pressure drop across liner may not be sufficient ⇒ double skin combustor may be required

Film Cooling Techniques:
“Total Pressure” Devices: Wigglestrips

- Corrugated spacer between annular clearance of liner sections



Applications:
- Avon
- Spey
- Cannular Olympus
- Pegasus

✓ Mechanically robust structure
(earlier designs had limited liner life as they were joined together by “fluting”)

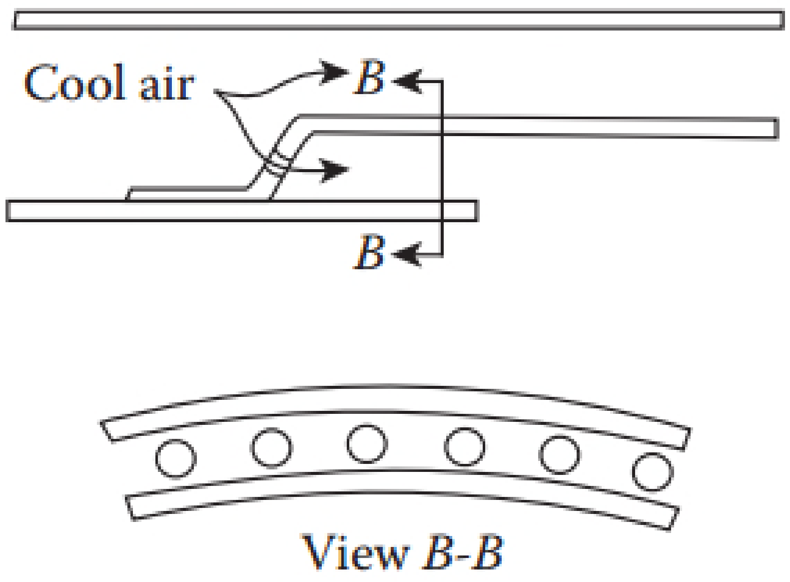
Ref: Lefebvre. A. H., 2010, “Gas Turbine Combustion”, 3rd Edition, McGraw Hill

X Poor aerodynamic quality of cooling film ⇒ long hot streaks downstream of slots

X Wide variations in cooling air quantity between seemingly identical liners
(due to slight differences in wigglestrip material thickness – even within normal manufacturing tolerances)

Film Cooling Techniques:
“Total Pressure” Devices: Stacked Rings

- Punched or drilled air admission holes
- Flow area of holes calculated to meter required amount of cooling air
- Aft end of previous liner provides plenum in which turbulence is dissipated
- At the downstream end gap width is dimensioned to give required air velocity



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

✓ Dimensional accuracy of holes is higher than wigglestrip resulting in smaller variations in cooling air flow rate

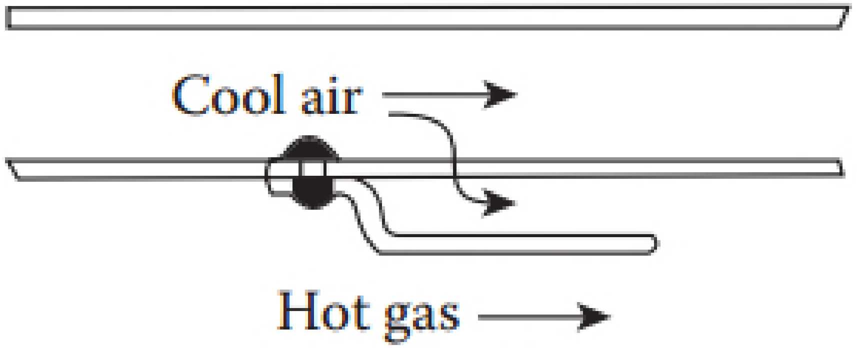
✓ Cooling air velocity can be fixed at optimum value for maximum cooling effectiveness regardless of liner pressure drop

X Less rigid mechanical construction than wigglestrip

Film Cooling Techniques:
Splash-Cooling Rings and Machined Rings

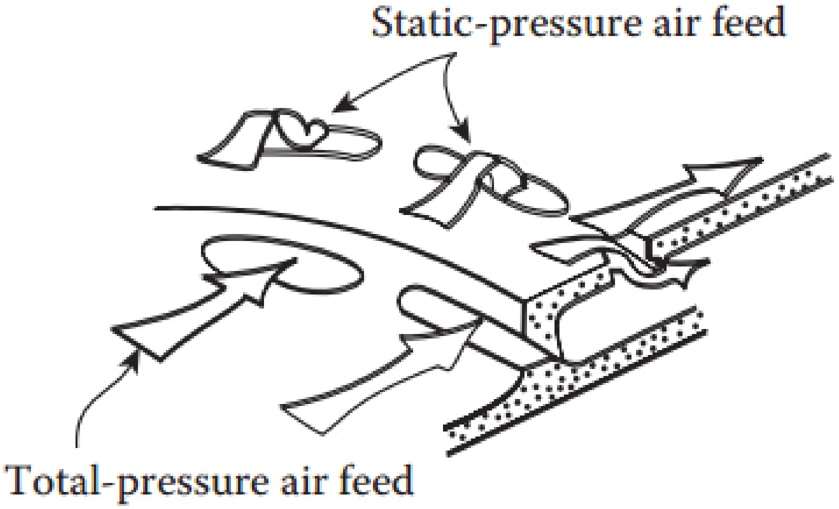
Splash-Cooling Ring

- Cooling air bled from annulus through row of small holes in the wall & along inner surface of liner by internal "lip"
- Lip length ~ 4X slot depth (1.5 -3.0mm)



Machined Ring

- Annulus air enter cooling slot by total/static pressure differential or both
- RB211 combustor & in conjunction with AEC & SAEC in Trent combustor



✓ More accurate control of cooling air quantity

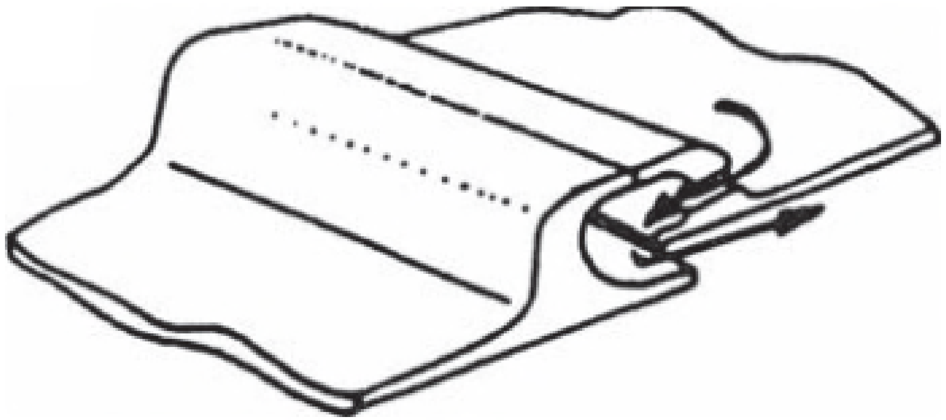
✓ Marked improvement in liner strength

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

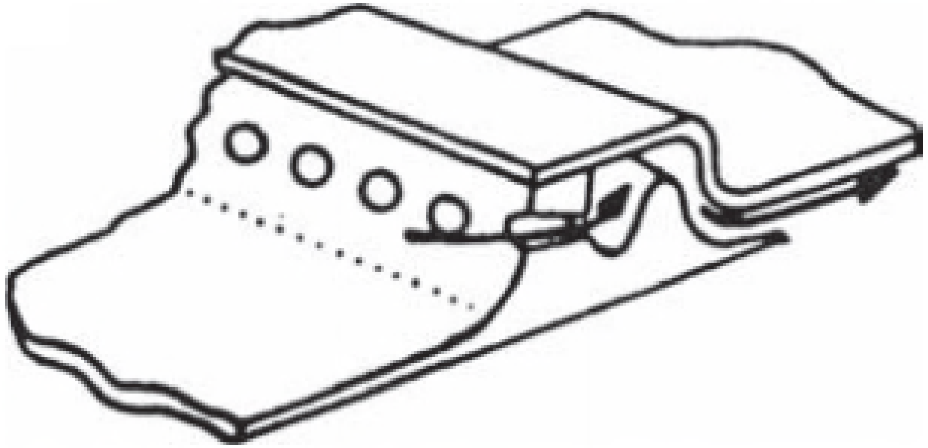
Film Cooling Techniques:
Rolled Rings

- Fabricated from series of rings that are rolled into shape and welded together
- Static pressure feeds provide impingement cooling to the rolled ring before emerging from the slot for film cooling

✓ Stacked and machined rings liners experience steep temperature gradients between slot lip and metal adjacent to cooling air feed holes ⇒ high stress ⇒ liner distortion and cracking



GE Rolled Ring

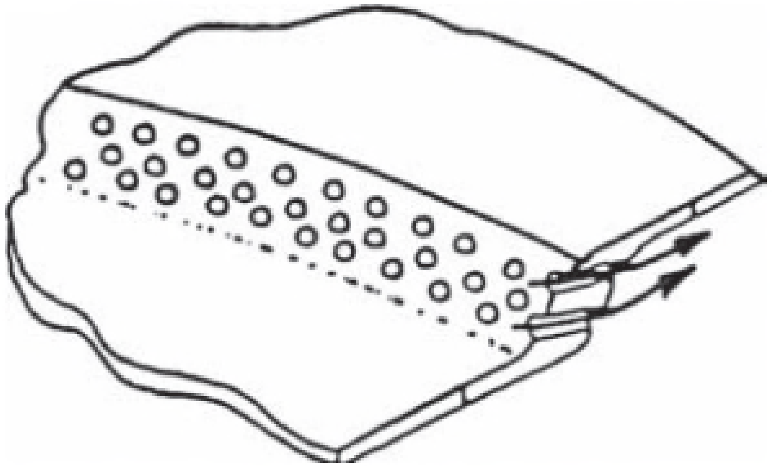


P&W Double-Pass Ring

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

Film Cooling Techniques:
Z Rings

- “Zero lip length” design (reduction in initial diameter of jets)
- Large number of closely pitched, small diameter holes ensures jets mix quickly to form a uniform film without needing protection of a lip
- Design made possible by increased availability of electrical discharge machining & laser drilling techniques



RR Z Ring

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

✓ Superior cooling performance

✓ Eliminates life limitation due to lip cracking

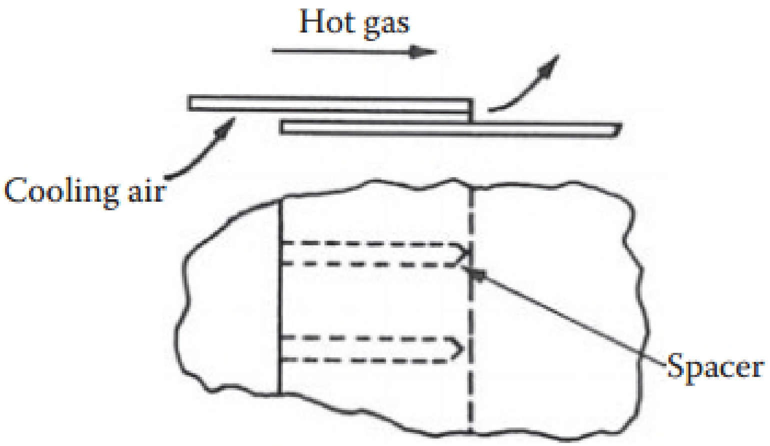
X High cost of drilling large number of small holes
(improved manufacturing methods should alleviate this problem)

X Requires careful control width between holes and other critical dimensions to ensure satisfactory integrity without loss of cooling performance

Advanced Wall Cooling Techniques:
Double Skin Combustors

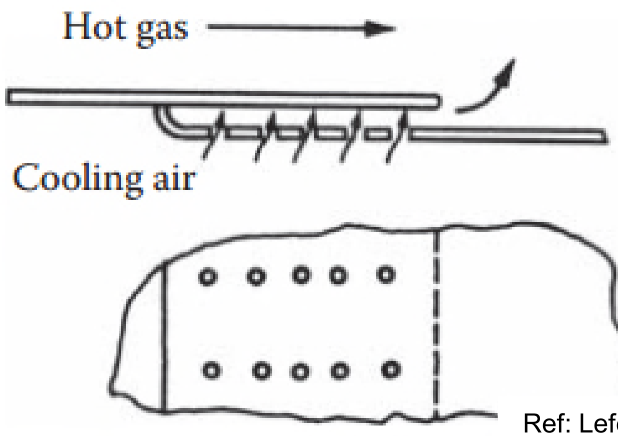
Film Cooling + AEC

Augmented external convection ⇒ $C_2\uparrow$



Multi-jet Impingement + Film Cooling

Similar to AEC but double wall passage is blocked at upstream end



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✓ Substantial reduction in film cooling air flow requirement

✓ Jets can be positioned to provide extra cooling on liner hot spots (MJI only)

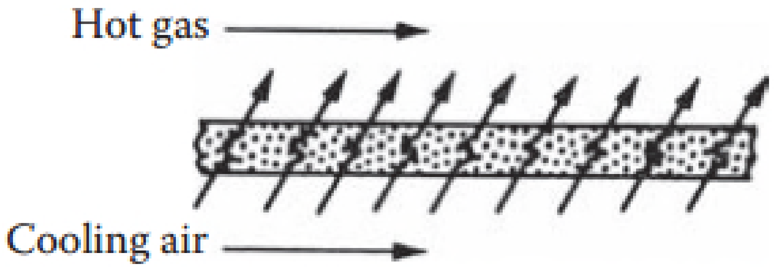
✓ Cooling air serves dual purpose (MJI Only)
- Jets provide impingement cooling to one section of liner wall and then merge to provide further film cooling

X Double wall construction ⇒ weight & cost penalties

X Temperature difference between two walls ⇒ buckling of inner wall

Advanced Wall Cooling Techniques:
Transpiration Cooling

- Liner wall constructed from porous material ⇒ provides large SA for heat transfer
- Air jets from uniformly dispersed pores rapidly mix to provide a layer of cool air
- R_1 removed by transfer to cooling air during its passage through the porous wall



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

✓ Substantial reduction in C_1 possible

✓ Closest to ideal cooling arrangement (ideal wall cooling ⇒ least wasteful)

X Conflict since in order to form a stable boundary layer on the inner surface, coolant flow should emerge with as low a velocity as possible but if $V\downarrow \Rightarrow C_2\downarrow$

X Passages prone to blockages (susceptible to oxidation & airborne debris)

Advanced Wall Cooling Techniques:
Transpiration Cooling – Practical Applications

<u>Transply – RR Spey Mk 512 Combustor &</u>
<u>Lamilloy – RR formerly GM Allison Engine Company</u>

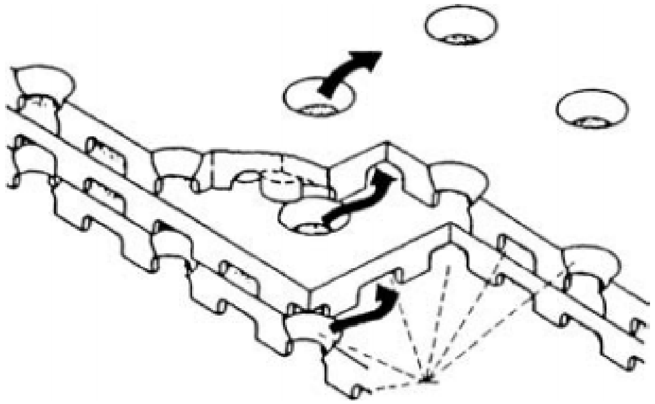
- Produce by brazing two or more laminates of a high temperature alloy
- Passages photo-chemically etched for maximum heat transfer
- Liner cooled by both air passing through the wall and leaving film cooling air

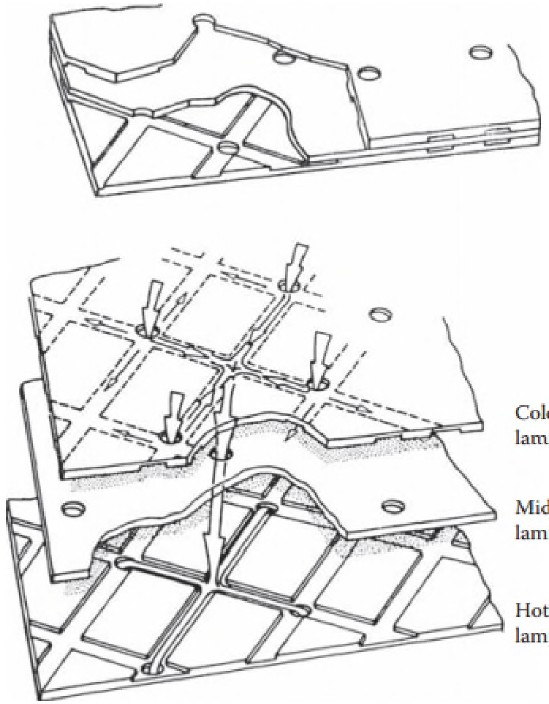
✓ ~70% reduction in cooling flow requirement

✓ Internal airflow distribution can be optimised for low emissions

X Passages prone to blockages (susceptible to oxidation & airborne debris)

X Weight and cost penalties





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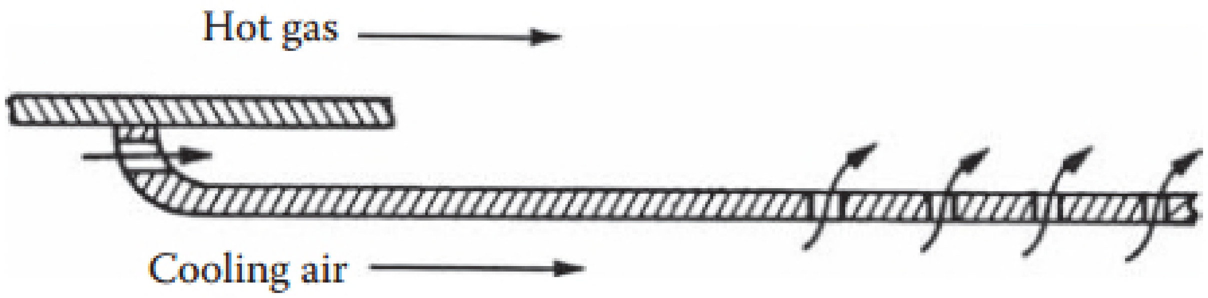
Advanced Wall Cooling Techniques:
Transpiration Cooling – Effusion Cooling

Effusion Cooling + Film Cooling

- Liner holes large enough to remain free form blockages but small enough to prevent excessive penetration of air jets
- Effusion cooling introduced (just before downstream slot when film cooling has lost effectiveness



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Selective Angled Effusion Cooling (GE90 Combustor ~ 30% reduction in cooling air)

- Holes drilled at more shallow angle (as opposed to normal to liner wall)

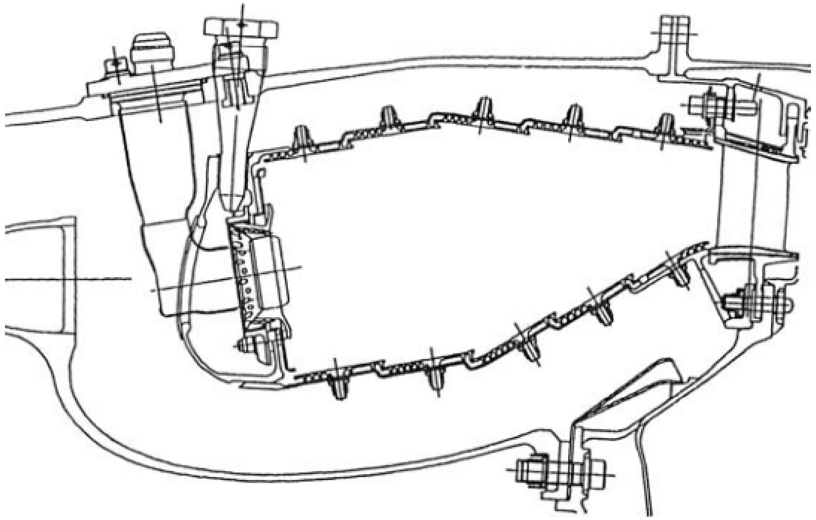
✓ Increase in internal SA for heat removal (hole drilled at 20° ⇒ ~ 3X SA)

✓ Shallow angle of emerging jets ⇒ lower penetration ⇒ better cooling effectiveness

X Thicker walls required for given hole length to prevent buckling ⇒ weight ↑ (~ 20%)

Advanced Wall Cooling Techniques:
Transpiration Cooling – Effusion Cooling

- Well established for large industrial engines using refractory bricks (heavy)
- Metallic tiles (lower weight) offer an attractive solution for aero applications
- Tiles mounted on a support shell (decouples thermal & mechanical loads)



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

✓ Tiles can be cast from higher temperature (by ~ 100K) blade alloys

✓ Combustor shell remains at a uniform, lower temperature ⇒ cheap alloys used & minimises thermal growth relative to casing

✓ Ease of maintenance (replacing tiles)

✓ Significant reduction in cooling air requirement

X Weight

X Difficult to scale down tile attachment features for smaller engines

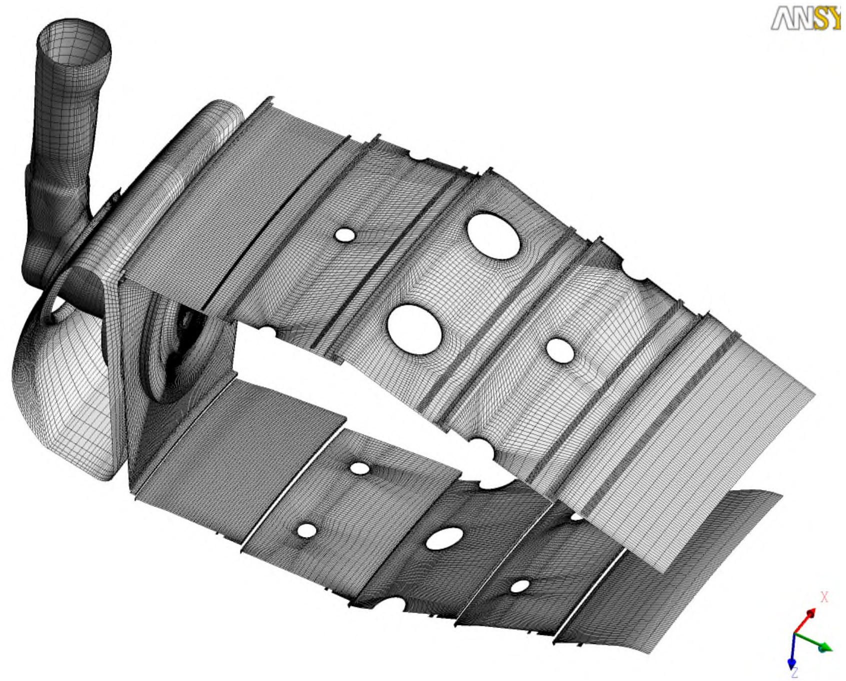
V2500 RQL Combustor:
Durability Issue – Case Study

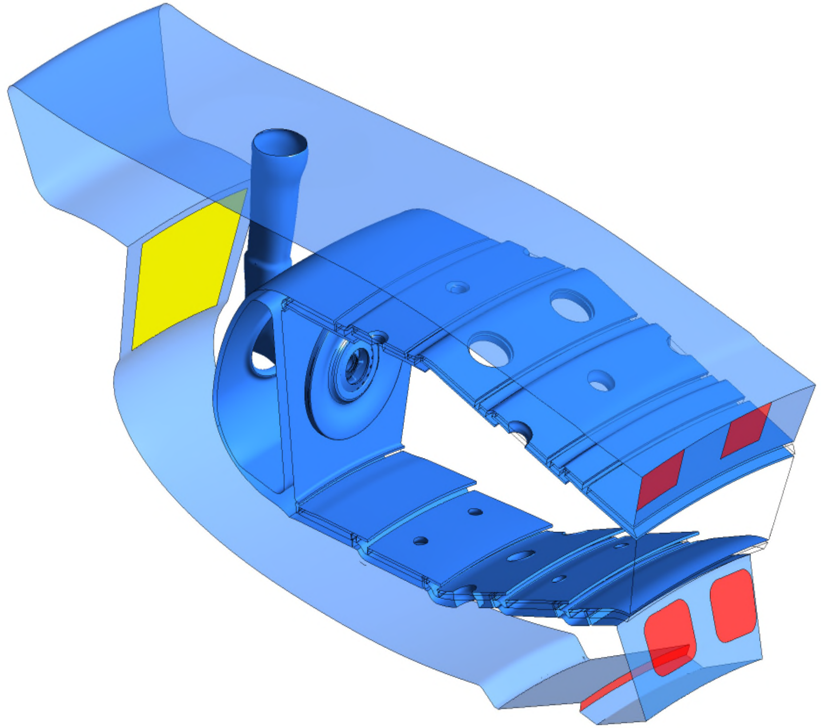
Case study courtesy of J. Kraft and S. Kuntzagk (LHT)

Lufthansa Technik

<u>CFD Analysis</u>

- Investigation of a single segment (one of twenty sections)
- Calculated with periodic walls
- Simulation includes detailed representation of the double skin



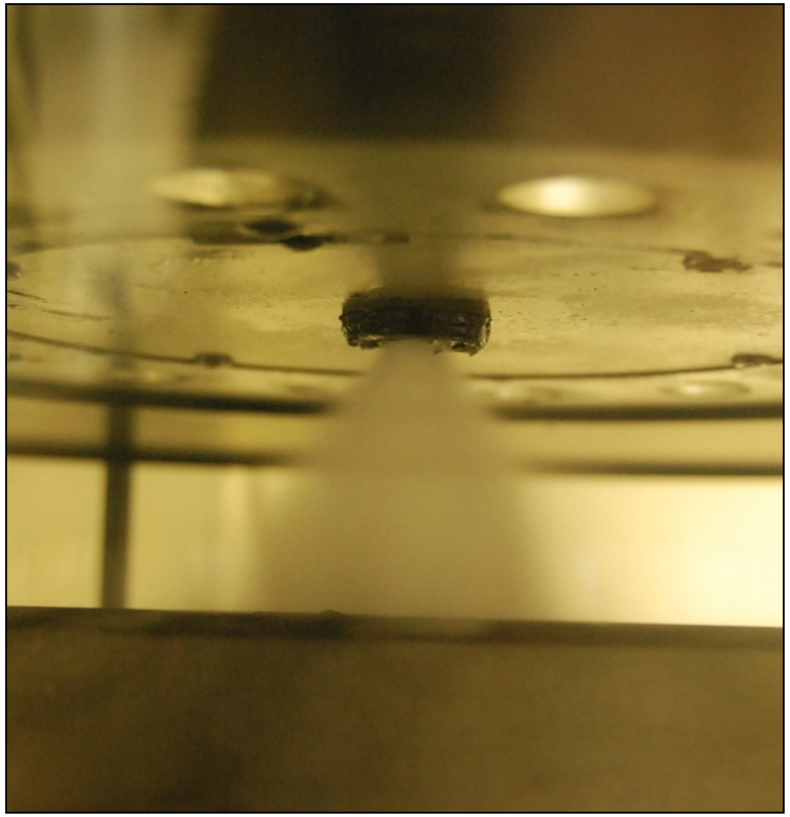


V2500 RQL Combustor:
Durability Issue – Case Study

Case study courtesy of J. Kraft and S. Kuntzagk (LHT)

Lufthansa Technik

<u>CFD Analysis</u>
- Large effort to develop representative model of the fuel atomisation (critical)
- Simulations compared with fuel injector experiments (comparison of spray angles)

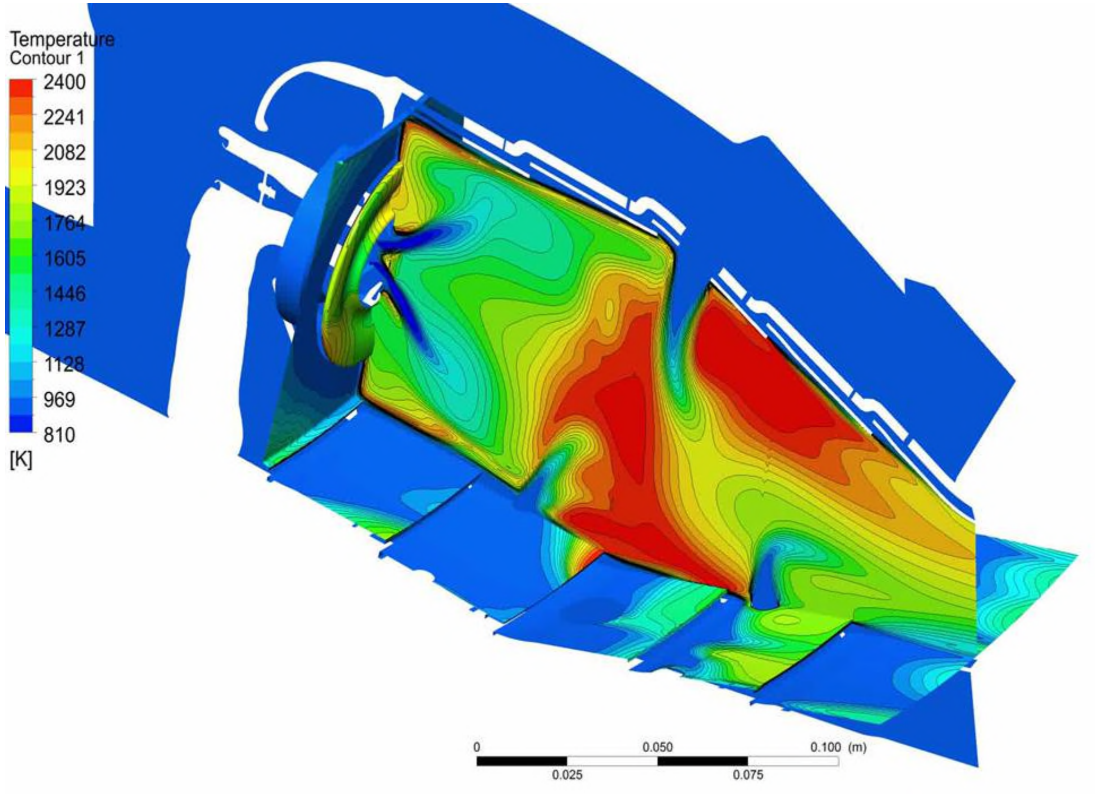


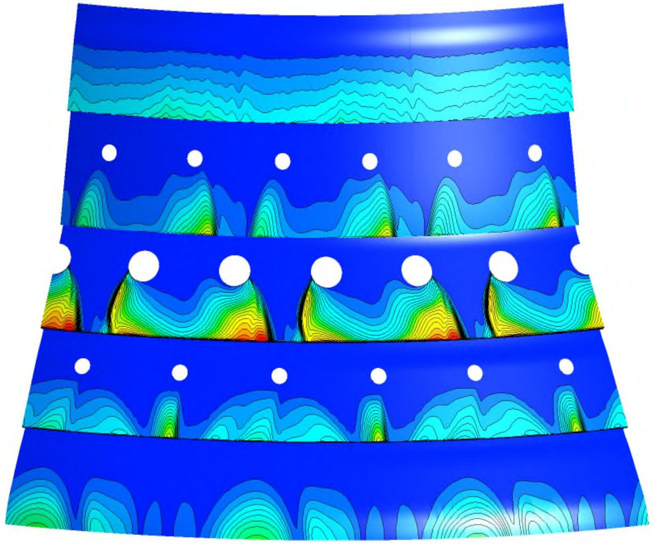
V2500 RQL Combustor:
Durability Issue – Case Study

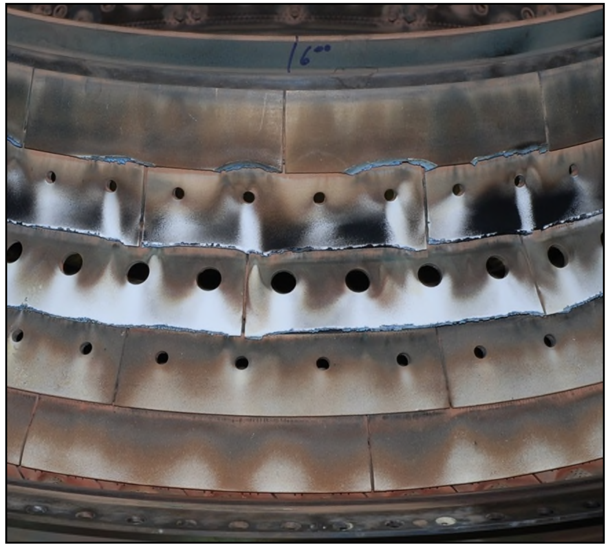
Case study courtesy of J. Kraft and S. Kuntzagk (LHT)

<u>CFD Results and Verification</u>

- Hot spot just after dilution zone (change from rich to lean burn) clearly captured
- Verification of CFD with visual inspection of hardware







Combustor Materials:
Thermal Barrier Coatings (TBCs)

- Suitable material of low emissivity and low conductivity reduces wall temperature:
  - Reflects large part of gas radiation
  - Provides layer of thermal insulation between hot gas and wall
  - Further benefit if oxidant resistant base coat is applied

- Ideal TBC (additionally):
  - Chemically inert
  - Good mechanical strength (resilience to thermal shock, resistance to wear)
  - Thermal expansion coefficient similar to base metal

- Typical TBC comprises
  - A metallic base coat
  - One or two layers of ceramics (partially yttria-stabilised zirconia)

- Typical thickness ~ 0.4 – 0.5mm, Metal temperature reduction ~ 80 – 120K

$$R_1 + C_1 = R_2 + C_2 = K_{1-i} = K_{i-2} \qquad K_{1-i} = \left(\frac{k}{t}\right)_{TBC} (T_1 - T_i) \qquad K_{i-2} = \left(\frac{k}{t}\right)_{w} (T_i - T_2)$$

Combustor Materials

- Basic requirements
  - High temperature strength
  - Resistance to oxidation
  - Resistance to corrosion
  - Low density
  - Low thermal expansion
  - Low Young’s modulus
  - Resistance to thermal fatigue
  - Low cost
  - Easy to fabricate
  - High thermal conductivity
- Combustor casing must last for engine lifetime
  - ~15,000 hrs (marine)
  - ~25,000 hrs (civil aero)
  - ~100,000 hrs (industrial)

Material	Max. Temperature (K)
Nimonic 75	~ 973 - 1023
Hastelloy X	~ 1023 – 1073
Nimonic C263	~ 1023 – 1123
Haynes 188000	~1173
TD Nickel	~ 1173 – 1323
TBCs	~ +80 – 120
Ceramics	~ 1573 – 1773