ENGINE COOLING AND SECONDARY AIR SYSTEM

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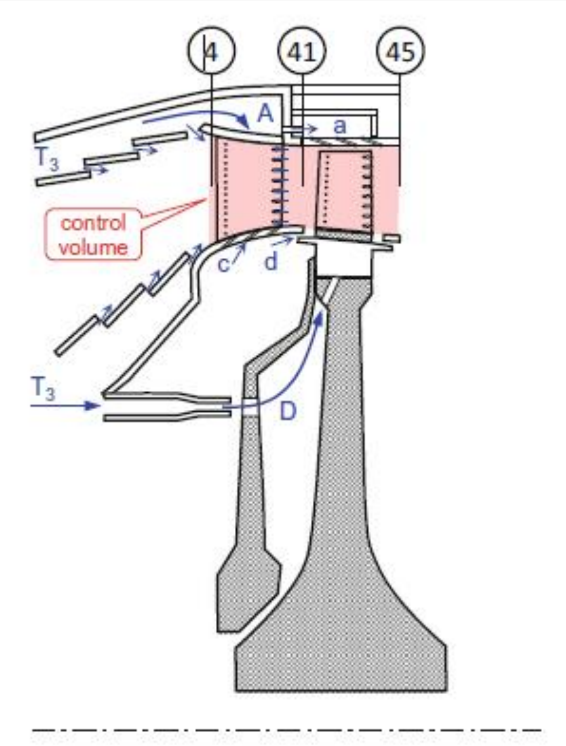
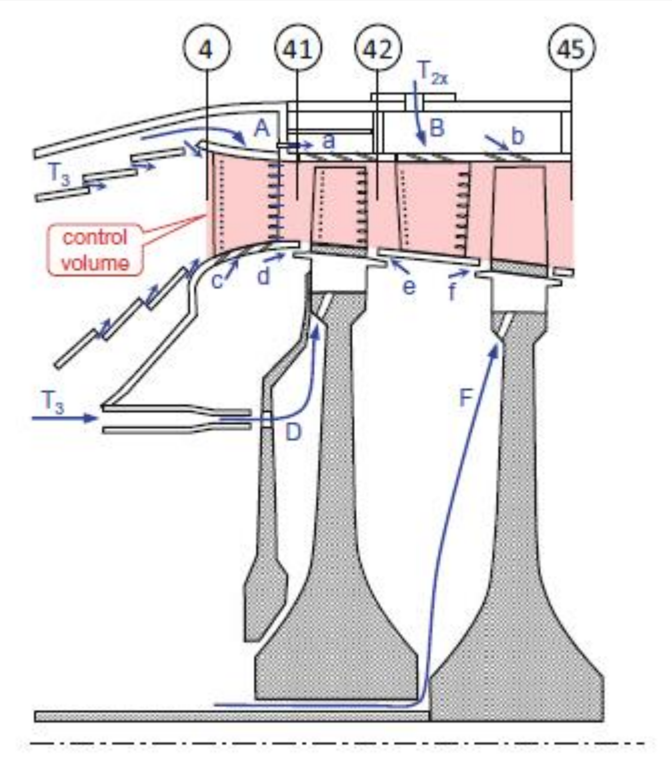
LITERATURE:

- **Jack D. Mattingly, Elements of Propulsion: Gas Turbines and Rockets, AIAA Education Series 2006 (Chapter 7)**
- **Jack D. Mattingly, Elements of Gas Turbine Propulsion, Tata McGraw Hill Education Private Limited, 2013 (Chapter 7)**
- Jack D. Mattingly, William H. Heiser, David T. Pratt, **Aircraft Engine Design, Second Edition,** American Institute of Aeronautics and Astronautics, Inc. 2002 (**Chapter 4**)
- Joachim Kurzke • Ian Halliwell, Propulsion and Power, An Exploration of Gas Turbine Performance Modeling Springer International Publishing AG, part of Springer Nature 2018

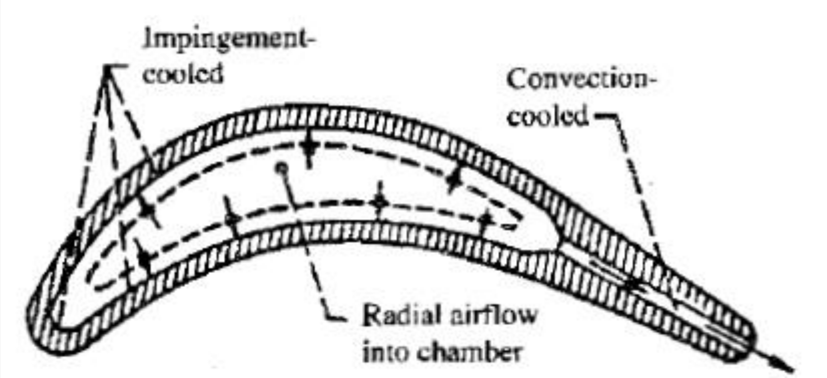
SINGLE AND TWO STAGE TURBINE COOLING



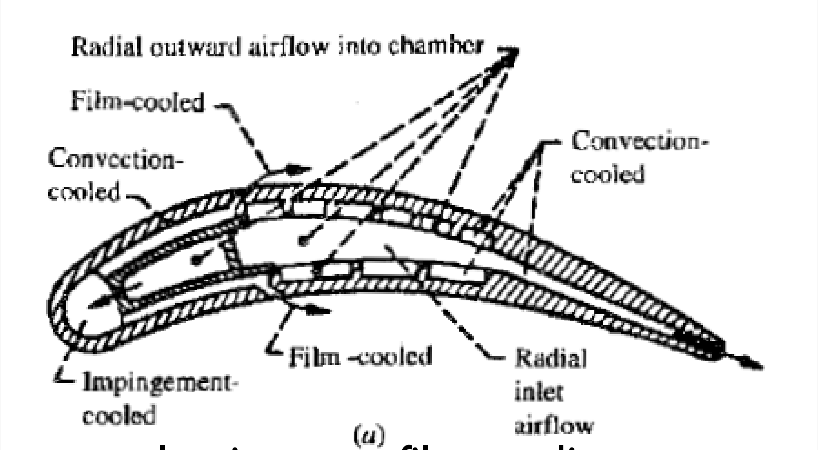


TURBINE COOLING TECHNIQUES

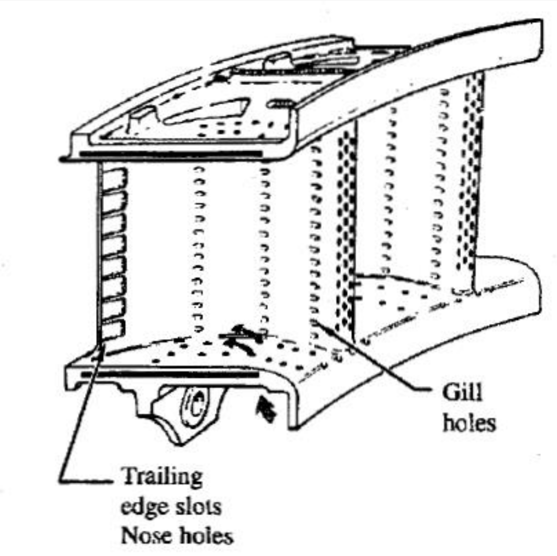
- 1. Convection
- 2. Impingement
- 3. Film cooling
- 4. Full coverage film cooling
- 5. Transpiration

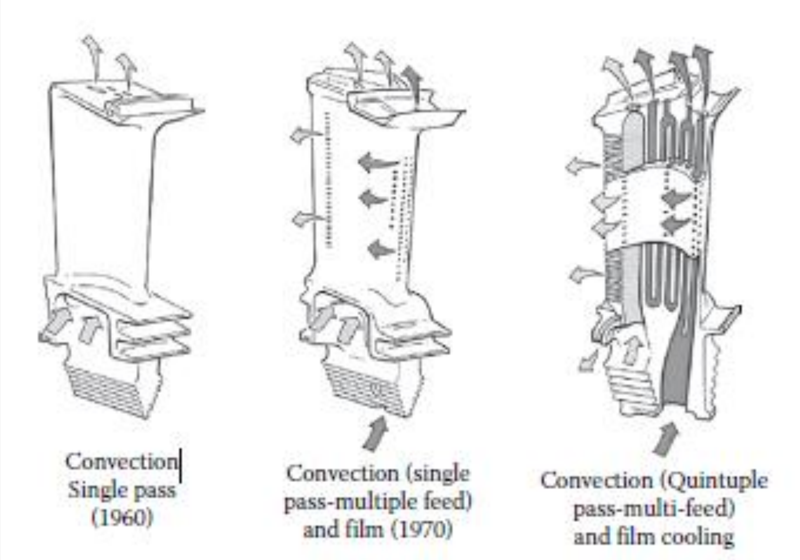


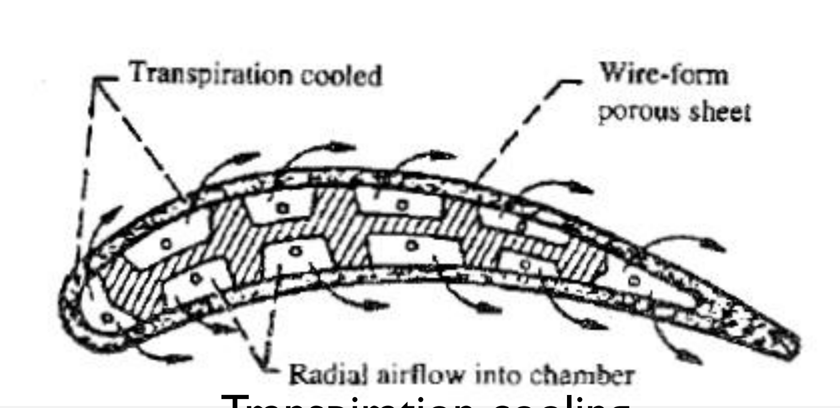
Impingement cooling



Impingment film cooling

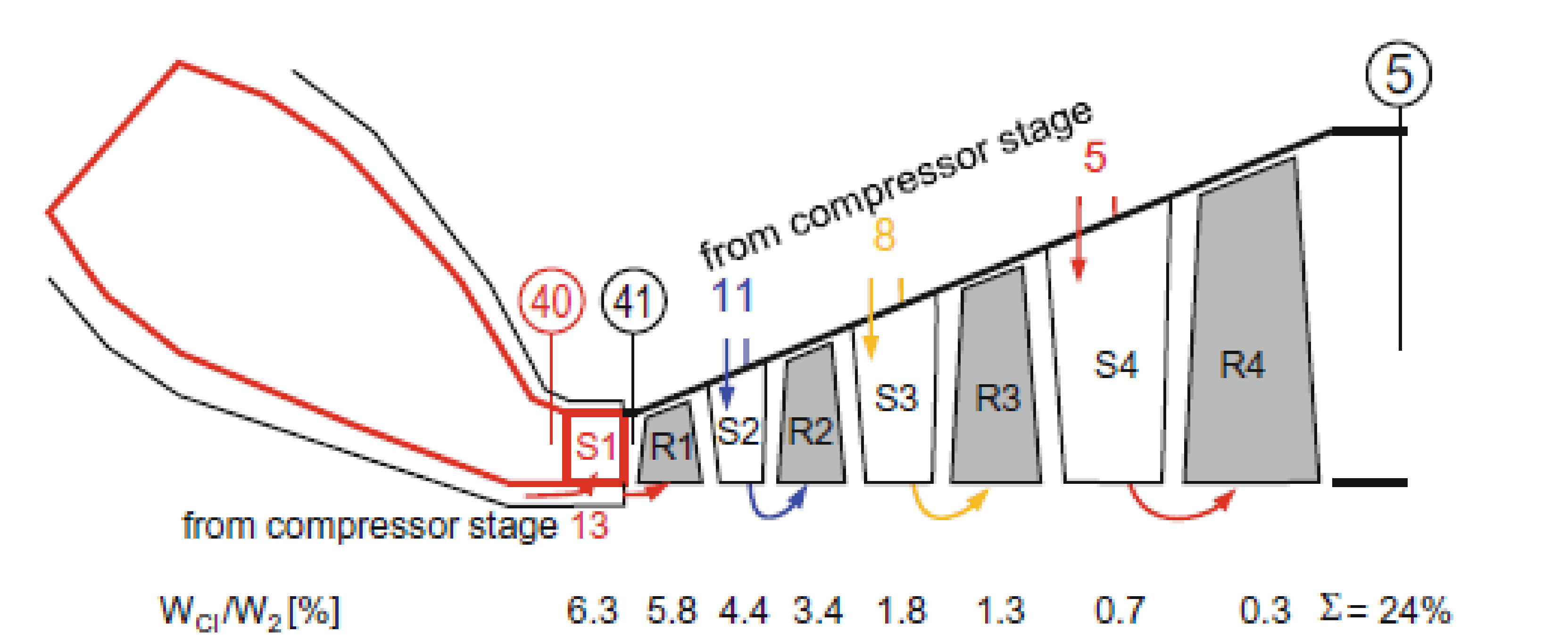




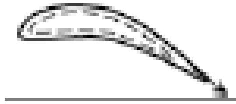
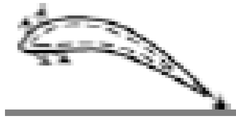
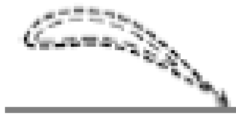


.Transpiration cooling

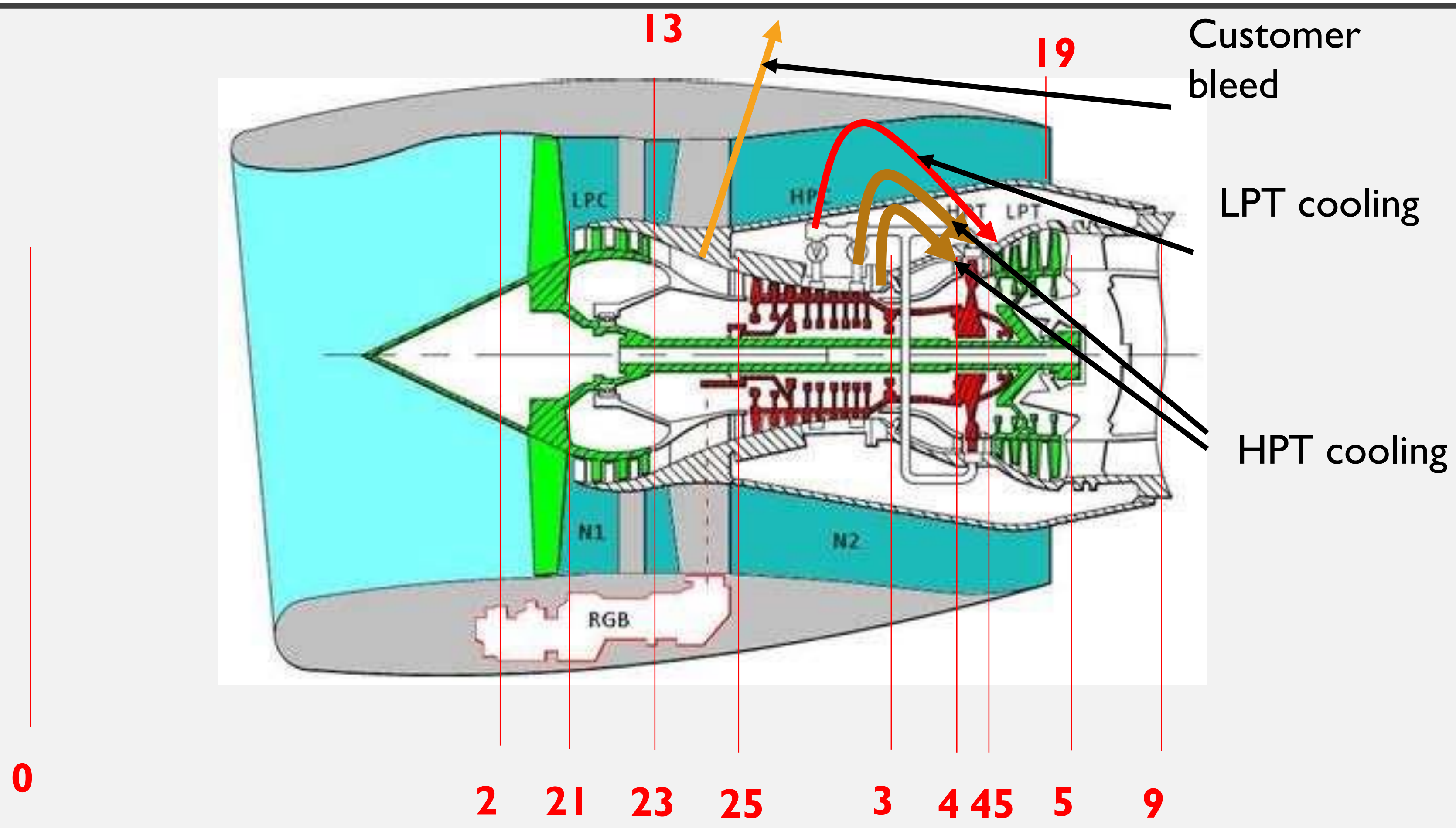
MULTISTAGE TURBINE COOLING EXAMPLE



EFFICIENCY LOSS FOR 1% COOLING AIR

		% Trailing edge ejection	Rel. cooling flow	$\Delta\eta_{stage}$	
				Stator	Rotor
	Advanced convection	100	1.5	0.001	0.002
	Film with convection	75	1.4	0.0012	0.0024
	Film with convection	50	1.3	0.0015	0.003
	Film with convection	25	1.0	0.0018	0.0036
	Transpiration with convection	25	0.8	0.005	0.01

TURBOFAN ENGINE WITH COOLING SYSTEM



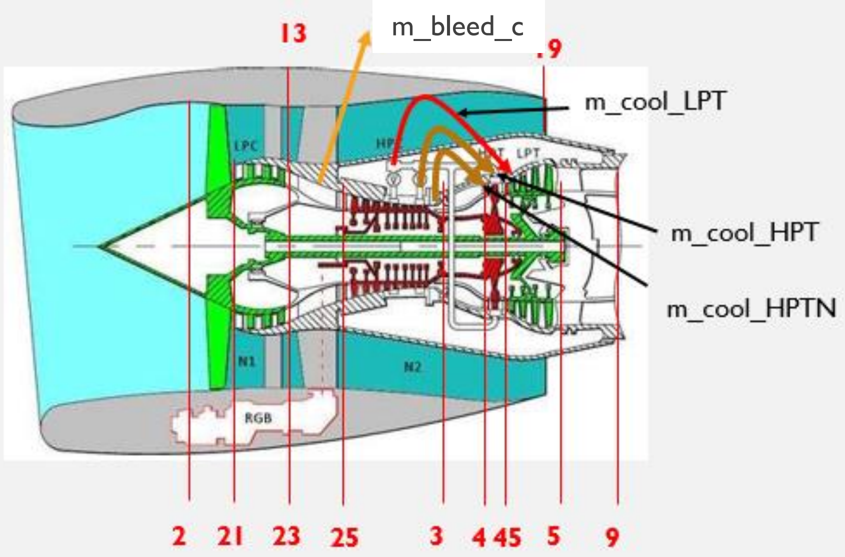
Cooling of HPT: Bcool1 – turbine nozzle cooling (air from section 3)

Bcool2, PRB2 – cooling of next parts of HPT

Cooling of LPT: Bch3, PRBch3

Customer bleed B_bleed, PR_bleed - bleed from LPC

MASS FLOW CALCULATION



Mass flow and relative mass flow in engine sections:

Customer bleed:

$$\dot{m}_{bleed\_c} = \beta_{bleed\_c}\dot{m}_{21}$$

Air mass flow in 25

$$\dot{m}_{25} = \dot{m}_{21} - \dot{m}_{bleed\_c}$$

$$\frac{\dot{m}_{25}}{\dot{m}_{21}} = 1 - \beta_{bleed\_c}$$

LPT cooling bleed:

$$\dot{m}_{cool\_LPT} = \beta_{cool\_LPT}\dot{m}_{21}$$

HPT cooling bleed:

$$\dot{m}_{cool\_HPT} = \beta_{cool\_HPT}\dot{m}_{21}$$

HPT nozzle cooling bleed:

$$\dot{m}_{cool\_HPTN} = \beta_{cool\_HPTT}\dot{m}_{21}$$

Air mass flow in 3

$$\dot{m}_3 = \dot{m}_{21} - \dot{m}_{bleed_c} - \dot{m}_{cool_{LPT}} - \dot{m}_{cool\_HPT}$$

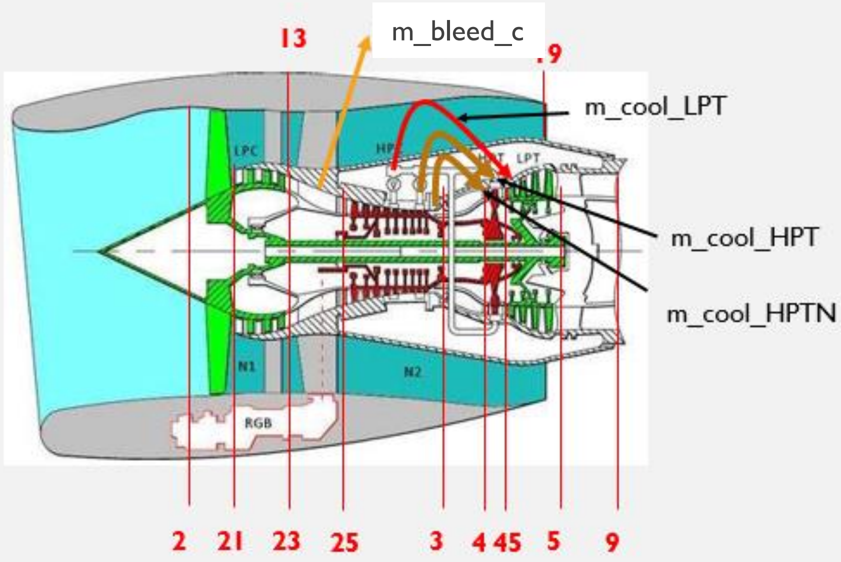
$$\dot{m}_3/\dot{m}_{21} = 1 - \beta_{bleed_c} - \beta_{cool_{LPT}} - \beta_{cool\_HPT}$$

Air mass flow in 31

$$\dot{m}_{31} = \dot{m}_{21} - \dot{m}_{bleed_c} - \dot{m}_{cool_{LPT}} - \dot{m}_{cool_{HPT}} - \dot{m}_{cool\_HPTN}$$

$$\dot{m}_{31}/\dot{m}_{21} = 1 - \beta_{bleed_c} - \beta_{cool_{LPT}} - \beta_{cool\_HPT} - \beta_{cool\_HPTN}$$

MASS FLOW CALCULATION C.D.



Mass flow / relative mass flow in 4

$$\dot{m}_4 = \dot{m}_{21} - \dot{m}_{bleed_c} - \dot{m}_{cool_{LPT}} - \dot{m}_{cool_{HPT}} - \dot{m}_{cool_{HPTN}} + \dot{m}_{fB}$$

$$\dot{m}_4/\dot{m}_{21} = 1 - \beta_{bleed_c} - \beta_{cool_{LPT}} - \beta_{cool_{HPT}} - \beta_{cool_{HPTN}} + f_B$$

Mass flow / relative mass flow in 45

$$\dot{m}_{45} = \dot{m}_{21} - \dot{m}_{bleed_c} - \dot{m}_{cool_{LPT}} + \dot{m}_{fB}$$

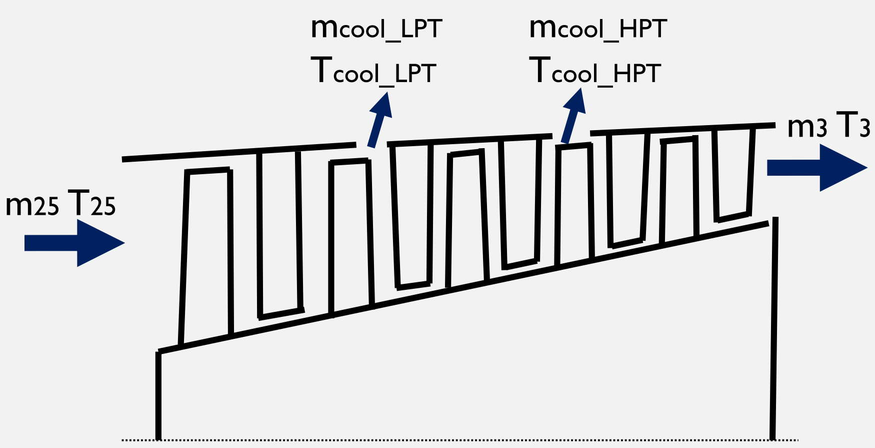
$$\dot{m}_{45}/\dot{m}_{21} = 1 - \beta_{bleed_c} - \beta_{cool_{LPT}} + f_B$$

Mass flow / relative mass flow in 5 and 9

$$\dot{m}_5 = \dot{m}_{21} - \dot{m}_{bleed_c} + \dot{m}_{fB}$$

$$\dot{m}_5/\dot{m}_{21} = 1 - \beta_{bleed_c} + f_B$$

HPC COMPRESSOR WITH BLEED ANALISIS



LPT coolant temperature:

$$T_{cool\_LPT} = T_{t25}(CPR_{cool\_LPT})^{\frac{k-1}{e_{HPC}\,k}}$$

HPC polytropic efficiency: $e_{HPC} = \frac{k-1}{k} ln(HPC\ PR)/\text{ln}\left(\frac{(HPC\ PR)^{\frac{k-1}{k}} - 1}{\eta_{HPC}} - 1\right)$

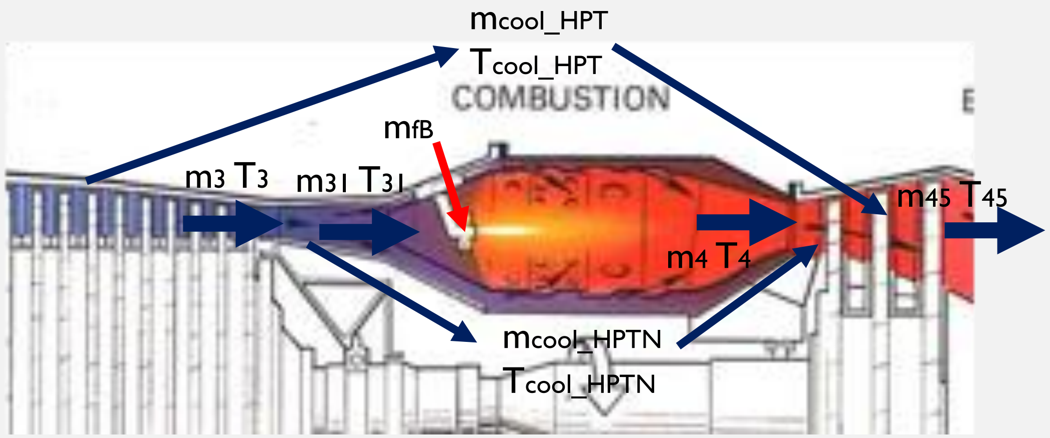
HPT coolant temperature:

$$T_{cool\_HPT} = T_{t25}(CPR_{cool\_HPT})^{\frac{k-1}{e_{HPC}\,k}}$$

HPC power $P_{HPC} = \dot{m}_{25}Cp(T_{cool\_LPT} - T_{t25}) + (\dot{m}_{25} - \dot{m}_{cool\_LPT})Cp(T_{cool\_HPT} - T_{cool\_LPT}) +$
$(\dot{m}_{25} - \dot{m}_{cool\_LPT} - \dot{m}_{cool\_HPT})Cp(T_3 - T_{cool\_HPT})$

$$\frac{P_{HPC}}{\dot{m}_{21}} = (1 - \beta_{bleed\_c})Cp(T_{cool\_LPT} - T_{t25}) + (1 - \beta_{bleed_c} - \beta_{cool_{LPT}})Cp(T_{cool\_HPT} - T_{cool\_LPT})$$
$$(1 - \beta_{bleed_c} - \beta_{cool_{LPT}} - \beta_{cool\_HPT})Cp(T_{t3} - T_{cool\_HPT})$$

ENGINE COMBUSTOR AND HPT WITH BLEEDED AIR



FUEL CONSUMPTION CALCULATION:

$$\dot{m}_{fB} = \frac{\dot{m}_{31} Cp_B (T_{t4} - T_{t31})}{\eta_B FHV}$$

$$f_B = \frac{\dot{m}_{fB}}{\dot{m}_{21}} = \frac{(1 - \beta_{bleed_c} - \beta_{cool_{LPT}} - \beta_{cool_{HPT}} - \beta_{cool_{HPTN}}) Cp_B (T_{t4} - T_{t31})}{\eta_B FHV}$$

HPT power

$$P_{HPC}/\eta_{m\_HP} = \dot{m}_4 Cp_T (T_{t4} - T_{t45}) + (\dot{m}_{cool\_HPTN}) Cp' (T_{cool\_HPTN} - T_{t45}) + (\dot{m}_{cool\_HPT}) Cp' (T_{cool\_HPT} - T_{t45})$$

$$\frac{P_{HPC}}{\dot{m}_{21} \eta_{m\_HP}} = (1 - \beta_{bleed_c} - \beta_{cool_{LPT}} - \beta_{cool_{HPT}} - \beta_{cool_{HPTN}} + f_B) Cp_T (T_{t4} - T_{t45}) + \beta_{cool_{HPTH}} Cp' (T_{cool\_HPTH} - T_{t45}) + \beta_{cool_{HPT}} Cp' (T_{cool\_HPT} - T_{t45})$$

T45

$$T_{t45} = \frac{\dot{m}_4 Cp_T T_{t4} + \dot{m}_{cool\_HPTM} Cp' T_{cool\_HPTM} + \dot{m}_{cool\_HPT} Cp' T_{cool\_HPT} - P_{HPC}/\eta_{m\_HP}}{\dot{m}_4 Cp_T + \dot{m}_{cool\_HPTN} Cp' + \dot{m}_{cool\_HPT} Cp'}$$

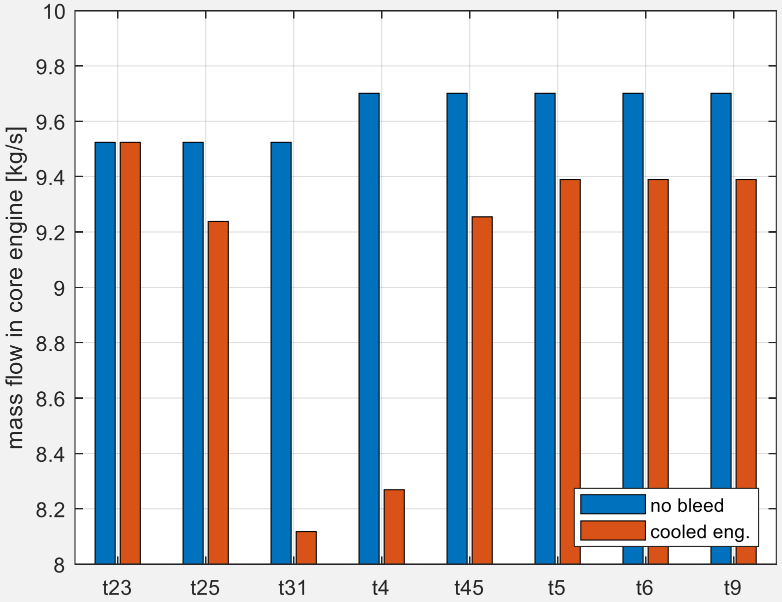
Cp' - specific heat value for hot air (1100-1130 J/kg/K)

RESULTS COMPARISON OF ENGINE WITH AND WITHOUT COOLING CALCULATION

	Parameter	customer bleed	LPT cool.	HPT cool.	HPTN cool.
1	'relative mass'	0.0300	0.0150	0.0300	0.0800
2	'mass flow [kg/s]'	0.2857	0.1344	0.2688	0.7169
3	'Temperature [K]'	389.4948	513.9169	755.9731	990.2732
4	'Pressure [kPa]'	149.6221	353.1082	1.1671e+03	2.6932e+03

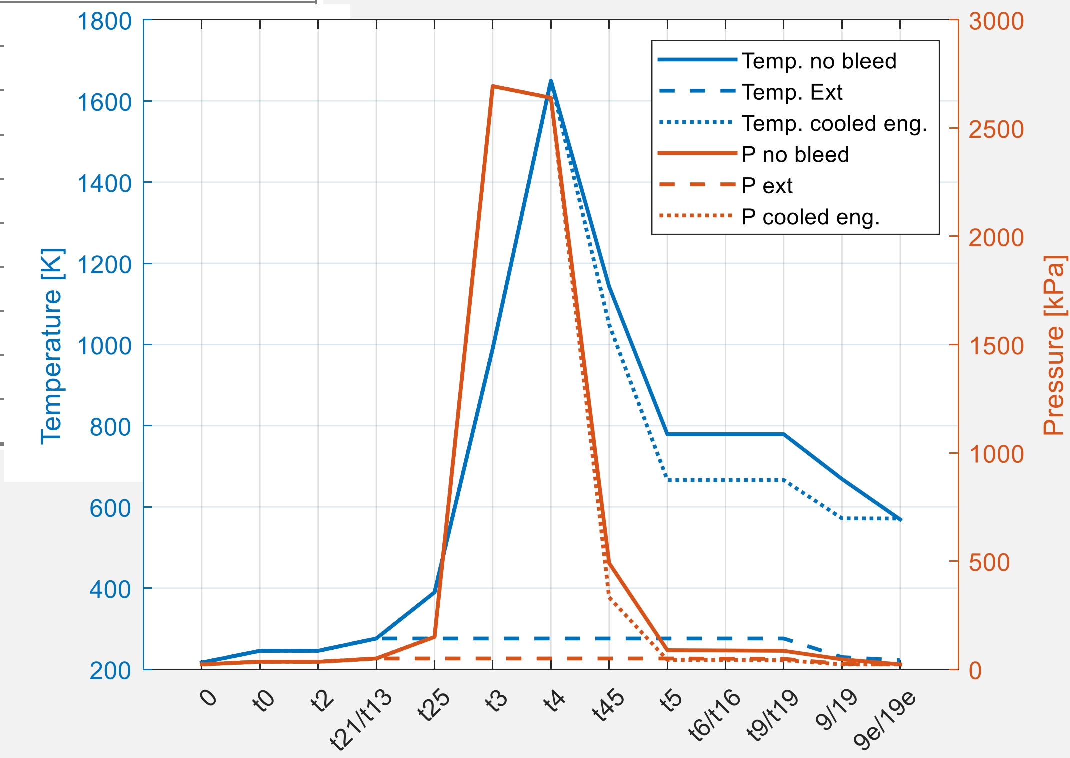
Mass flow discusion in the engine with bleeds and turbine cooling

- Air mass flow decreases in section 25 due to customer bleed
- Significant air mass flow drop is in HPC and after it therefore in section 31 it is the lowest.
- In section 3 mass flow grow is caused by fuel
- Mass flow grow in sections 45 and 5 is coused by turbines coolant which is transfered to main flow



RESULTS COMPARISON OF ENGINE WITH AND WITHOUT COOLING CALCULATION

	section	T. [K] no bleed	T. [K] cooled engine	P [kPa] no bleed	P [kPa] cooled engine
1	'0'	216.4	216.4	22.57	22.57
2	't0'	245.5	245.5	35.1	35.1
3	't2'	245.5	245.5	34.4	34.4
4	't21/t13'	275.9	275.9	49.87	49.87
5	't25'	389.5	389.5	149.6	149.6
6	't3'	990.3	990.3	2693	2693
7	't4'	1650	1650	2639	2639
8	't45'	1143	1049	490.4	331.9
9	't5'	779.1	666.1	88.27	43.39
10	't6/t16'	779.1	666.1	86.94	42.74
11	't9/t19'	779.1	666.1	85.2	41.89
12	'9/19'	668.7	571.8	46.04	22.64
13	'9e/19e'	569	571.4	22.57	22.57



Temperature and pressure in cooled engine starting from section 45 are lower than in engine without bleed

Due to significant pressure drop in the cooled engine the full expansion is observed in convergent nozzle, instead of chocked nozzle in the engien without bleeds and cooling.

RESULTS COMPARISON OF ENGINE WITH AND WITHOUT COOLING CALCULATION

- Thrust and specific thrust of the cooled engine is lower
- Fuel consumption of the cooled engine is lower however SFC is higher
- Thermal and overall efficiencies are lower while propulsive efficiency is higher of of the cooled engine

	Parameter	Unit	no bleed engine	cooled engine
1	'Altitude'	'km'	11	11
2	'Mach No'	'-'	0.82	0.82
3	'm0'	'kg/s'	100	100
4	'Thrust'	'kN'	12.37	9.978
5	'Specific Thrust'	'N*s/kg'	123.7	99.78
6	'fuel consumption'	'kg/s'	0.1771	0.151
7	'Specific fuel consump'	'kg/N/h'	0.05155	0.05447
8	'therm. efficiency'	'-'	0.5727	0.4632
9	'prop. efficiency'	'-'	0.6856	0.8023
10	'overall efficiency'	'-'	0.3927	0.3716

Compressor air blieeds and turbines cooling are typical for modern engine of high TIT. Contemporarry engnes typically got very high TIT, significantly higher than the turbine material durability allow, therefore turbine cooling system is required.

COMPONENT POLYTROPIC EFFICIENCIES AND TOTAL PRESSURE LOSSES

Component	Figure of merit	Type	Level of technology 1	2	3	4
		A[a]	0.90	0.95	0.98	0.995
Diffuser	$\pi_{d\,\max}$	B[b]	0.88	0.93	0.96	0.97
		C[c]	0.85	0.90	0.94	0.96
Compressor	e_c	—	0.80	0.84	0.88	0.90
Fan	e_f	—	0.78	0.82	0.86	0.89
Burner	π_b	—	0.90	0.92	0.94	0.96
	η_b		0.88	0.94	0.99	0.995
Turbine	e_t	Uncooled	0.80	0.85	0.89	0.91
		Cooled		0.83	0.87	0.89
Afterburner	π_{AB}	—	0.90	0.92	0.94	0.95
	η_{AB}		0.85	0.91	0.96	0.97
		D[d]	0.95	0.97	0.98	0.995
Nozzle	π_n	E[e]	0.93	0.96	0.97	0.985
		F[f]	0.90	0.93	0.95	0.98
Maximum T_{t4}		(K)	1110	1390	1780	2000
		(°R)	2000	2500	3200	3600
Maximum T_{t7}		(K)	1390	1670	2000	2220
		(°R)	2500	3000	3600	4000

A = subsonic aircraft with engines in nacelles.
B = subsonic aircraft with engine(s) in airframe.
C = supersonic aircraft with engine(s) in airframe.
D = fixed-area convergent nozzle.
E = variable-area convergent nozzle.
F = variable-area convergent-divergent nozzle.
G Stealth may reduce Jrd max, 7rAB, and zrn.

Note: The levels of technology can be thought of as representing the technical capability for 20-year increments in time beginning in 1945. Thus level 3 technology presents typical component design values for the time period 1985-2005.

Jack D. Mattingly, William H. Heiser, David T. Pratt, **Aircraft Engine Design,**

THANKS FOR YOUR ATENTION

Questions and Comments ?

1. …….
2. …….
3. …….