TURBOFAN WITH MIXED EXHAUST

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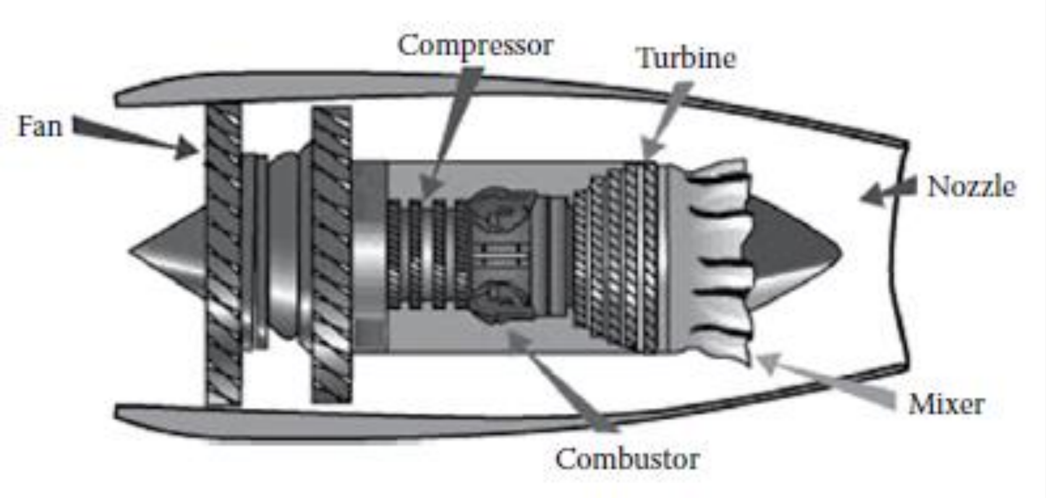
LITERATURE:

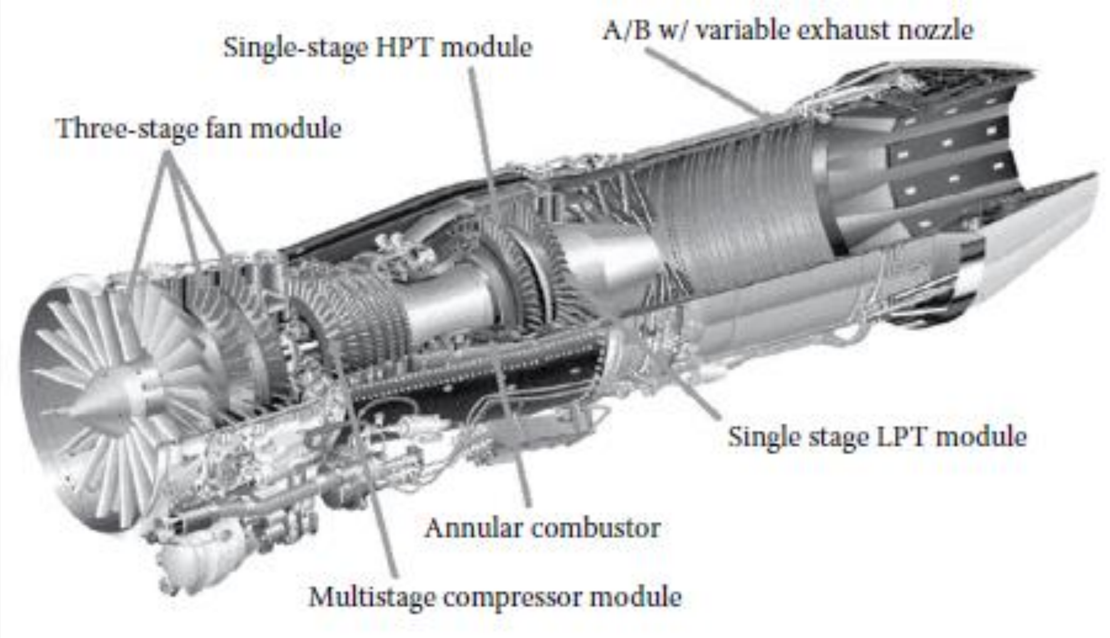
- Ahmed F. El-Sayed, **Aircraft Propulsion and Gas Turbine Engines, Second Edition,** Taylor & Francis Group, 2017, chapter 5.5
- Jack D. Mattingly, William H. Heiser, David T. Pratt, **Aircraft Engine Design, Second Edition,** American Institute of Aeronautics and Astronautics, Inc. 2002

MIXED FLOW TURBOFAN ENGINE

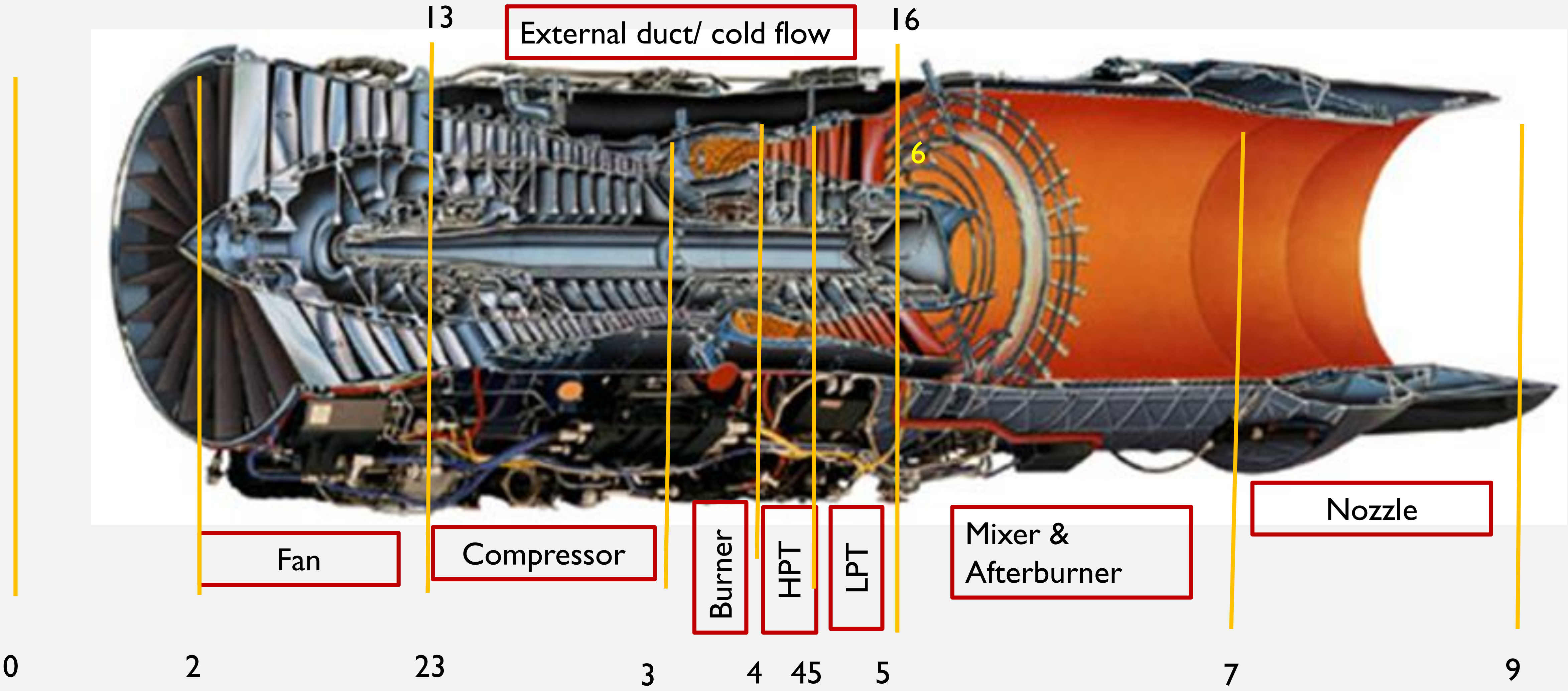
Mixed flow turbofan (middle BPR turbofan)



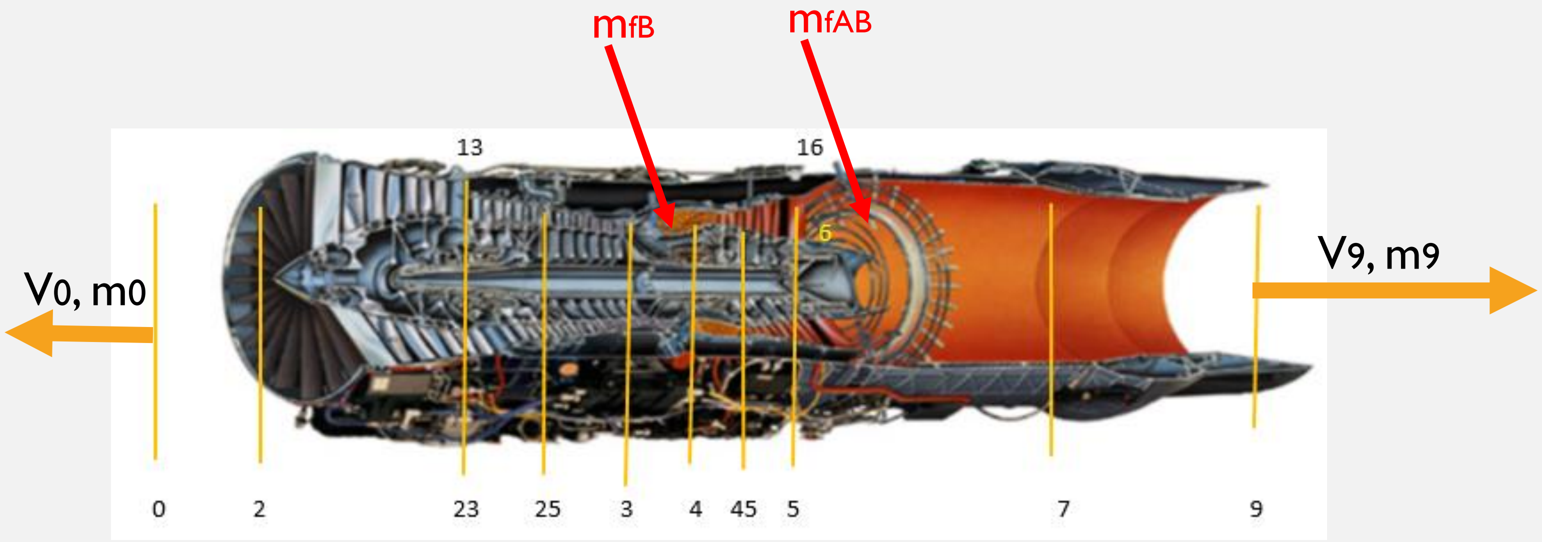
Mixed flow turbofan with afterburner (low BPR turbofan)



MIXED FLOW TURBOFAN CUT SECTIONS



TURBOFAN ENGINE THRUST



THTUST

$$T = \dot{m}_9 V_9 + A_9(P_9 - P_0) - \dot{m}_0 V_0$$

effective exhaust velocity

$$V_{e9} = V_9 + A_9(P_9 - P_0)/\dot{m}_9$$

$$T = \dot{m}_9 V_{e9} - \dot{m}_0 V_0$$

Bypass Ratio $BPR = \dfrac{\dot{m}_{13}}{\dot{m}_{23}}$, **Fuel/air ratio** $f_B = \dfrac{\dot{m}_{fB}}{\dot{m}_{23}}$, $f_{AB} = \dfrac{\dot{m}_{fAB}}{\dot{m}_{23}}$

THRUST AB OFF

$$T = \dot{m}_{23}\big((1 + BPR + f_B)V_{e9} - (1 + BPR)V_0\big)$$

THRUST AB ON

$$T = \dot{m}_{23}\big((1 + BPR + f_B + f_{AB})V_{e9} - (1 + BPR)V_0\big)$$

Engine exit mass flow AB OFF

$$\dot{m}_9 = \dot{m}_0 + \dot{m}_{fB}$$

Engine exit mass flow AB ON

$$\dot{m}_9 = \dot{m}_0 + \dot{m}_{fB} + \dot{m}_{fAB}$$

SPECIFIC THRUST AND SPECIFIC FUEL CONSUMPTION

SPECIFIC THRUST

$$ST = T/\dot{m}_0 = \frac{\dot{m}_9 V_{e9} - \dot{m}_0 V_0}{\dot{m}_{23} + \dot{m}_{13}} = \frac{(1 + BPR + f)V_{e9} - (1 + BPR)V_0}{1 + BPR}$$

AB OFF: $f = f_B$ AB ON: $f = f_B + f_{AB}$

SPECIFIC FUEL CONSUMPTION

$$\mathrm{SFC} = \dot{m}_f/T = \frac{\dot{m}_f}{\dot{m}_9 V_{e9} - \dot{m}_0 V_0} = \frac{f}{(1 + BPR + f)V_{e9} - (1 + BPR)V_0} =$$

$$= \frac{\frac{f}{1 + BPR}}{\frac{(1 + BPR + f_B)V_{e9} - (1 + BPR)V_0}{1 + BPR}} = \frac{f}{(1 + BPR) * ST}$$

TURBOFAN ENGINE EFFICIENCIES

Thermal efficency

$$\eta_{TH} = \frac{\text{Power imparted to engine airflow}}{\text{Rate of energy supplied in the fuel}}$$

$$\eta_{TH} = \frac{0{,}5 * (\dot{m}_9 {V_{9e}}^2 - \dot{m}_0 {V_0}^2)}{\dot{m}_f FHV} = \frac{0{,}5 * ((1 + BPR + f){V_{9e}}^2 - (1 + BPR){V_0}^2)}{f * FHV}$$

Propulsive efficency

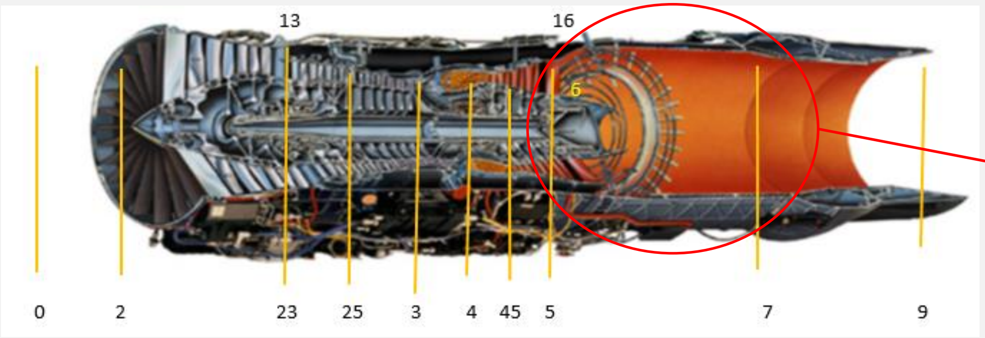
$$\eta_P = \frac{\text{Thrust power}}{\text{Power imparted to engine airflow}}$$

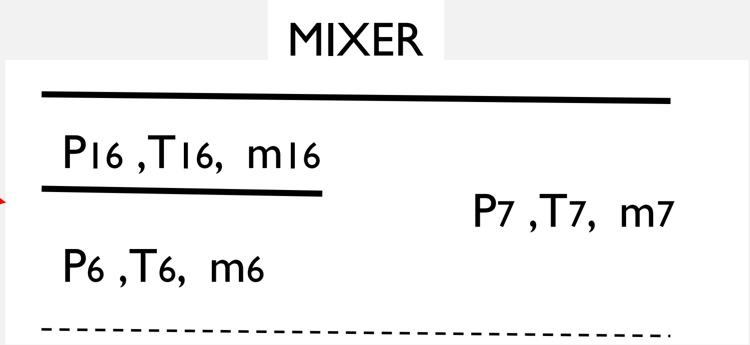
$$\eta_P = \frac{V_0 * T}{0{,}5 * (\dot{m}_9 {V_{9e}}^2 - \dot{m}_0 {V_0}^2)} = \frac{\dot{m}_0 V_0 * \frac{T}{\dot{m}_0}}{0{,}5 * (\dot{m}_9 {V_{9e}}^2 - \dot{m}_0 {V_0}^2)} = \frac{(1 + BPR) * V_0 * ST}{0{,}5 * ((1 + BPR + f){V_{9e}}^2 - (1 + BPR){V_0}^2}$$

Overall efficency

$$\eta_O = \eta_{TH} * \eta_P = \frac{V_0 * T}{\dot{m}_f FHV} = \frac{(1 + BPR) * V_0 * ST}{f * FHV}$$

MIXER ANALYSIS

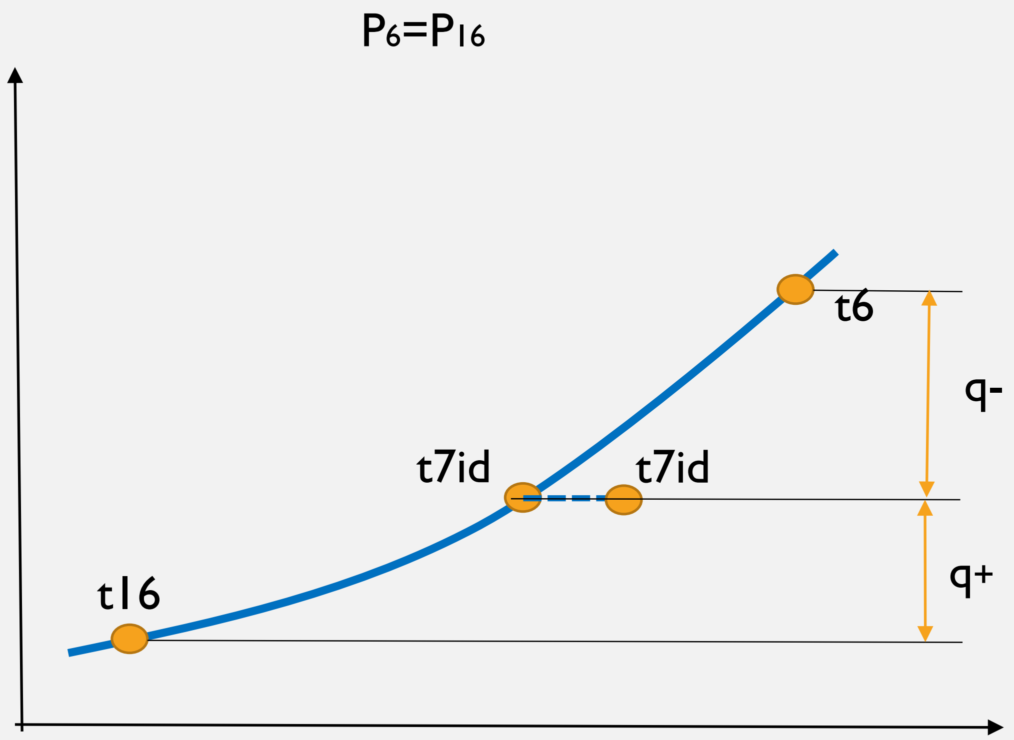




- Mass balance $\dot{m}_7 = \dot{m}_6 + \dot{m}_{16}$
- Energy balance $\dot{m}_7 i_7 = \dot{m}_6 i_6 + \dot{m}_{16} i_{16}$
- Momentum equation $P_6 A_6 + P_{16} A_{16} - P_7 A_7 - X_{AB} = \dot{m}_7 c_7 - (\dot{m}_6 c_6 + \dot{m}_{16} c_{16})$

X_{AB} - pressure force drop in the mixer flow

MIXER ANALYSYS BEST PRACTICE



$$\dot{m}_6 q_- = \dot{m}_6 cp_t (T_{t6} - T_{t7}) = \dot{m}_{16} q_+ = \dot{m}_{16} cp (T_{t7} - T_{t16})$$

$$T_{t7} = \frac{\dot{m}_6 cp_t T_{t6} + \dot{m}_{16} cp T_{t16}}{\dot{m}_6 cp_t + \dot{m}_{16} cp}$$

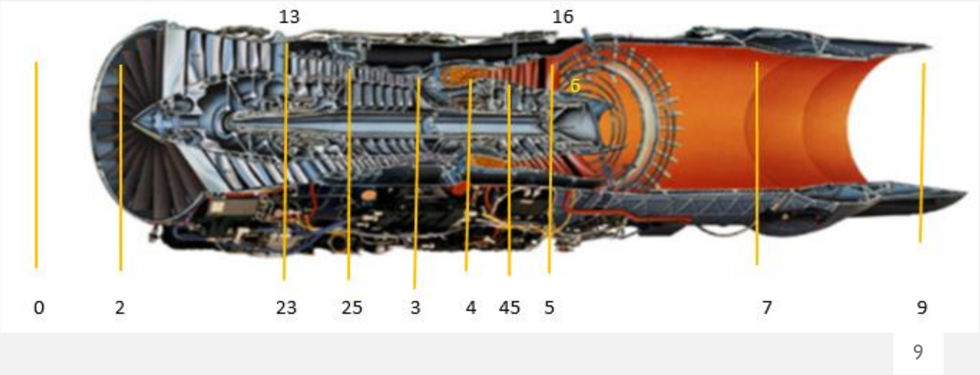
$$P_{t7} = \pi_M P_{av}$$

$$P_{av} = \frac{P_{t6} A_6 + P_{t16} A_{16}}{A_6 + A_{16}}$$ - averaging over the area

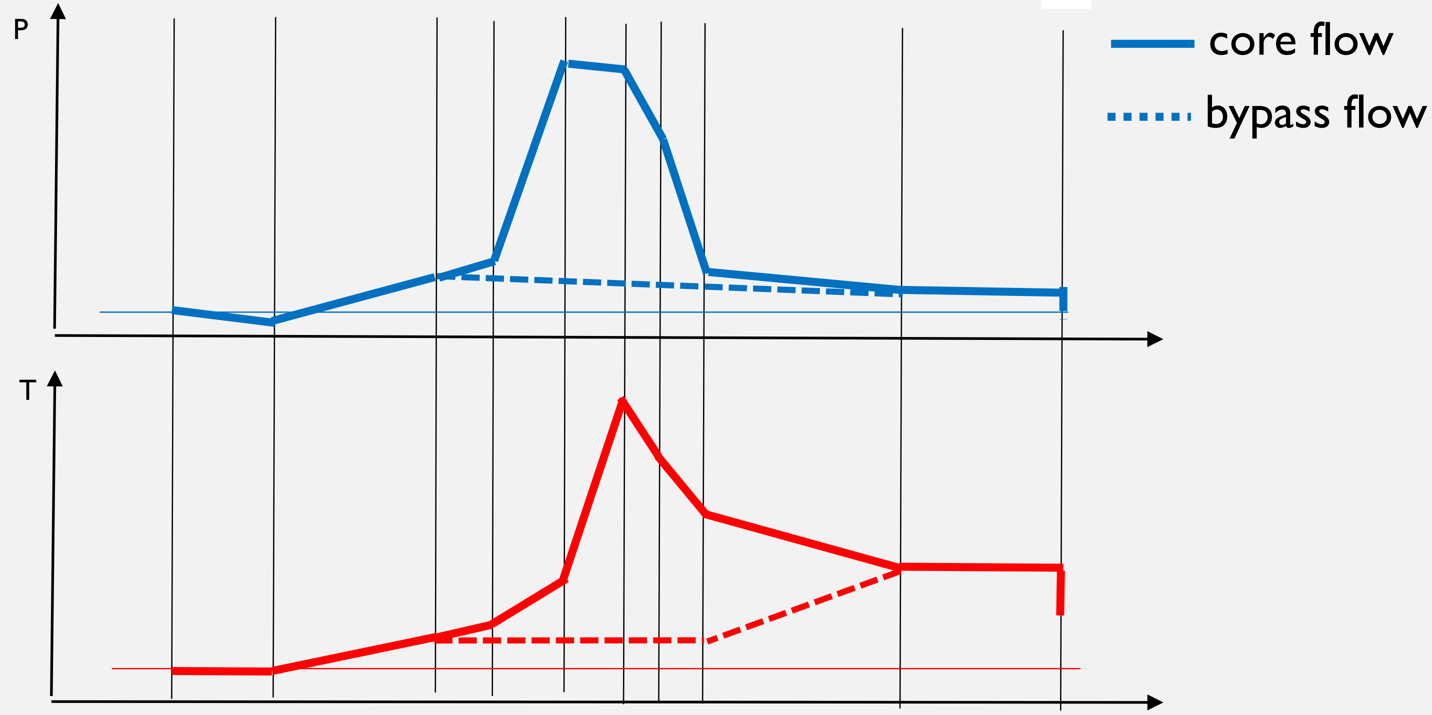
$$P_{av} = \frac{P_{t6} \dot{m}_6 + P_{t16} \dot{m}_{16}}{\dot{m}_6 + \dot{m}_{16}}$$ - averaging over the mase flow

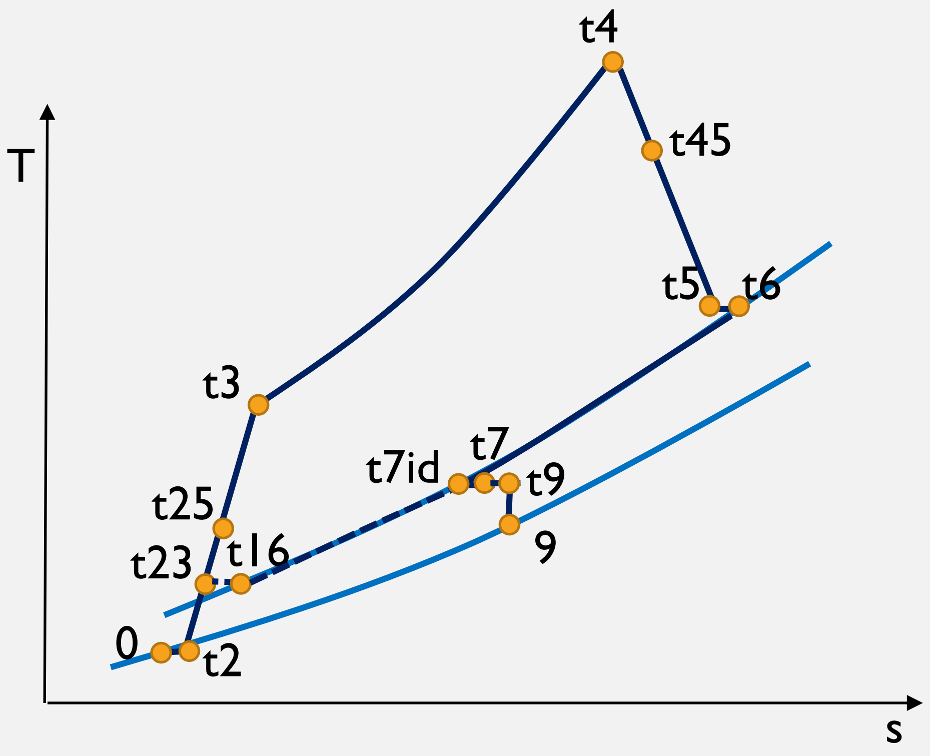
$$P_{av} = P_{t6} = P_{t16}$$ - For $P_6 = P_{16}$

TEMPERATURE & PRESSURE DISTRIBUTION



For proper work of mixed stream engine equal pressure in the mixer inlet of cold and hot stream is required





MIXED FLOW TURBOFAN PARAMETERS SELECTION

- For the mixed stream turbofan engine parameters selection one of them should be matched to fulfil mixer pressure requirments:
- Thypical parameters for the mixed turbofan:
  - TIT - turbine inlet temperature,
  - FPR – fan pressuere ratio,
  - CPR (HPC PR) – compressor pressure ratio,
  - BPR – bypass ratio

Equation to fulfil: $$CPR * \pi_B = HPT\ PR * LPT\ PR$$

While:

$$HPT\ PR = f(TIT, CPR)$$
$$LPT\ PR = f(BPR, FPR, TIT, HPT\ PR)$$

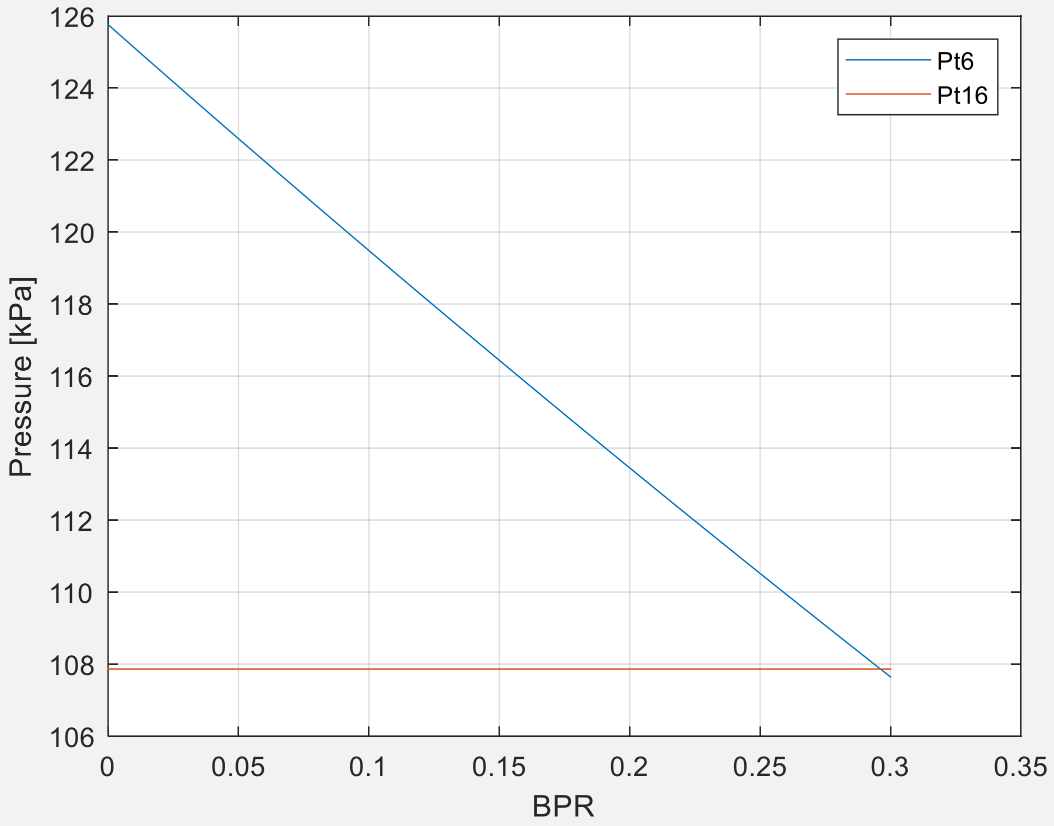
Existing dependencies don't allow to find direct relation to pick up the parameter to match the equal value of the mixer inlet pressure. Typically the iteration lookup is needed.

EXAMPLE OF BPR SELECTION

Given:

FPR, CPR, TIT and engine flight conditions plus all component pressure losses and efficiencies.

Starting from possible minimum BPR=0.01 value we count tempearures and pressures for each section from 0 up to 6 in the core engine and 16 in bypass duct. We compare pressure Pt16 and Pt6. If they are different, we increase BPR of specified gradient (for example BPR+0.01) and count Pt16 and Pt6. Proces is repeated till the parameters Pt16 and Pt6 are nearly equal.



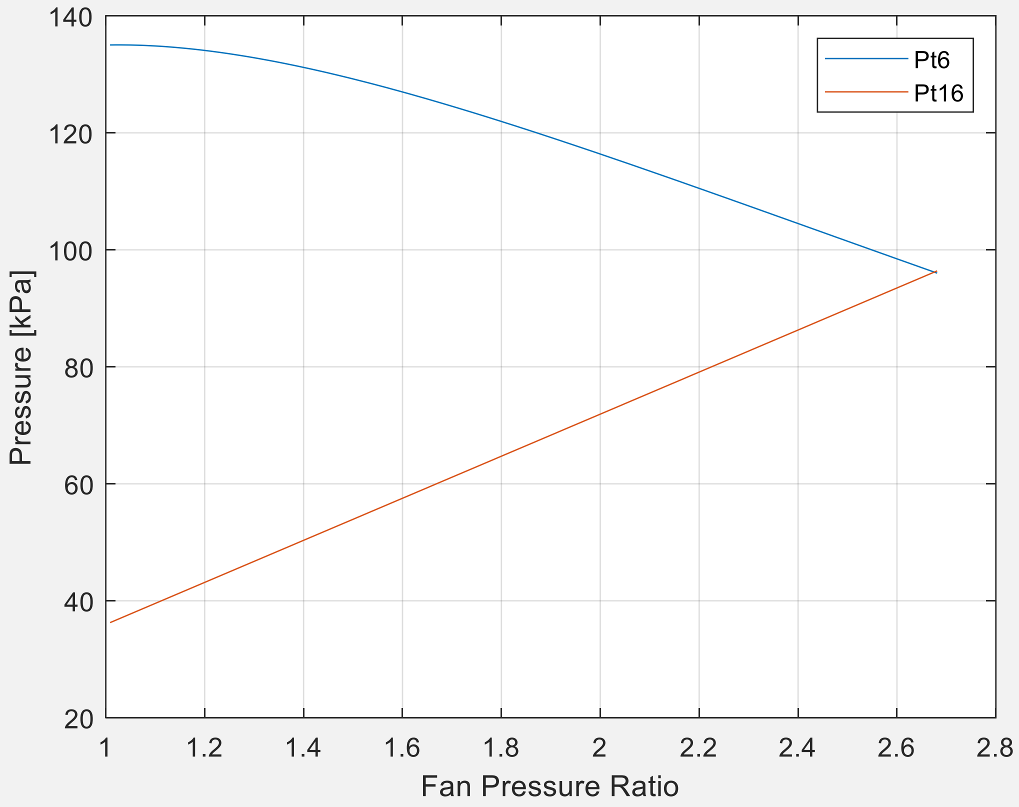
Example shows that for specified engine parameters BPR should be about 0.3 to fulfil condition of Pt16 equal Pt6

EXAMPLE OF FPR SELECTION

Given:

BPR, CPR, TIT and engine flight conditions plus all component pressure losses and efficiencies.

Starting from possible minimum FPR=1.01 we count tempearures and pressures for each section from 0 up to 6 and 16. We compare pressure Pt16 and Pt6. If they are different, we increase FPR of specified gradient (for example FPR+0.01) and count Pt16 and Pt6. Proces is repeated till the parameters Pt16 and Pt6 are nearly equal.



In both cases when Pt6<Pt16 in start point then it is not possible to find condition fulfil this requirement without other parameters change.

Example shows that for specified engine parameters FPR should be about 2,65-2,7 to fulfil condition of Pt16 equal Pt6

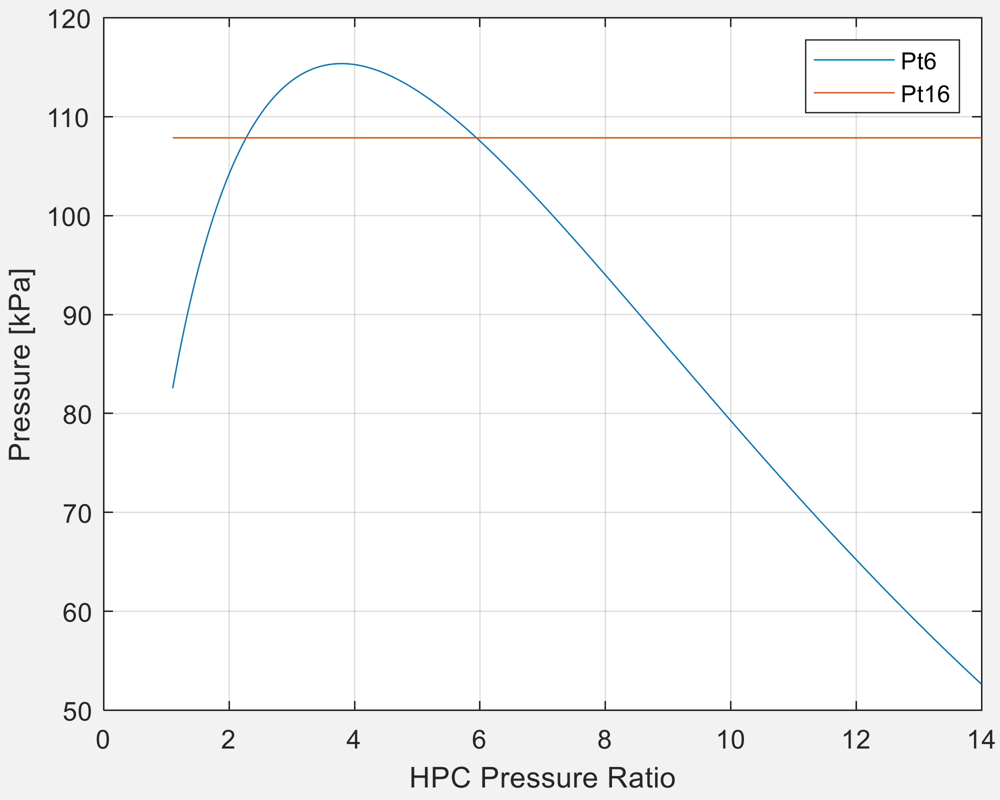
EXAMPLE OF CPR SELECTION

Given:

BPR, FPR, TIT and engine flight conditions plus all component pressure losses and efficiencies.

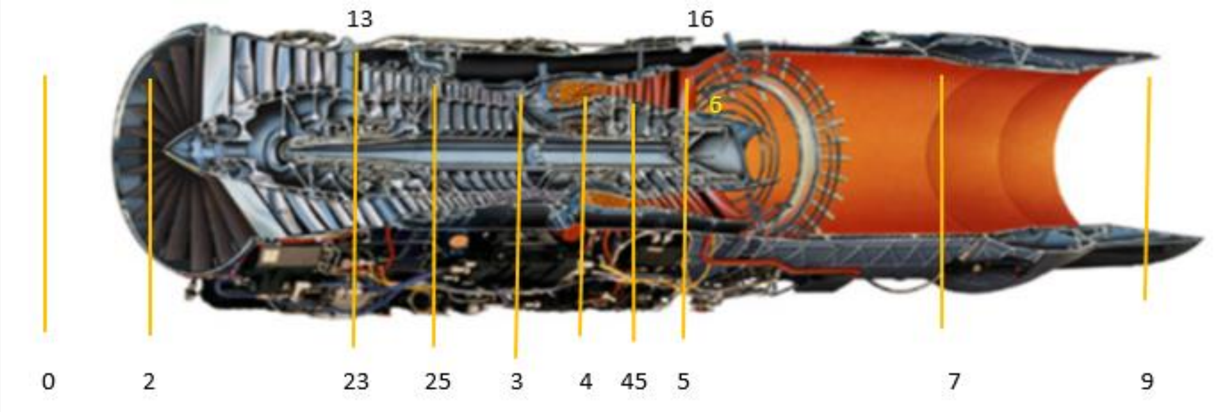
Starting from possible minimum CPR=1.1 we count tempearures and pressures for each section from 0 up to 6 and 16. We compare pressure Pt16 and Pt6. If they are different, we increase CPR of specified gradient (for example CPR+0.1) and count Pt16 and Pt6. Proces is repeated till the parameters Pt16 and Pt6 are nearly equal.

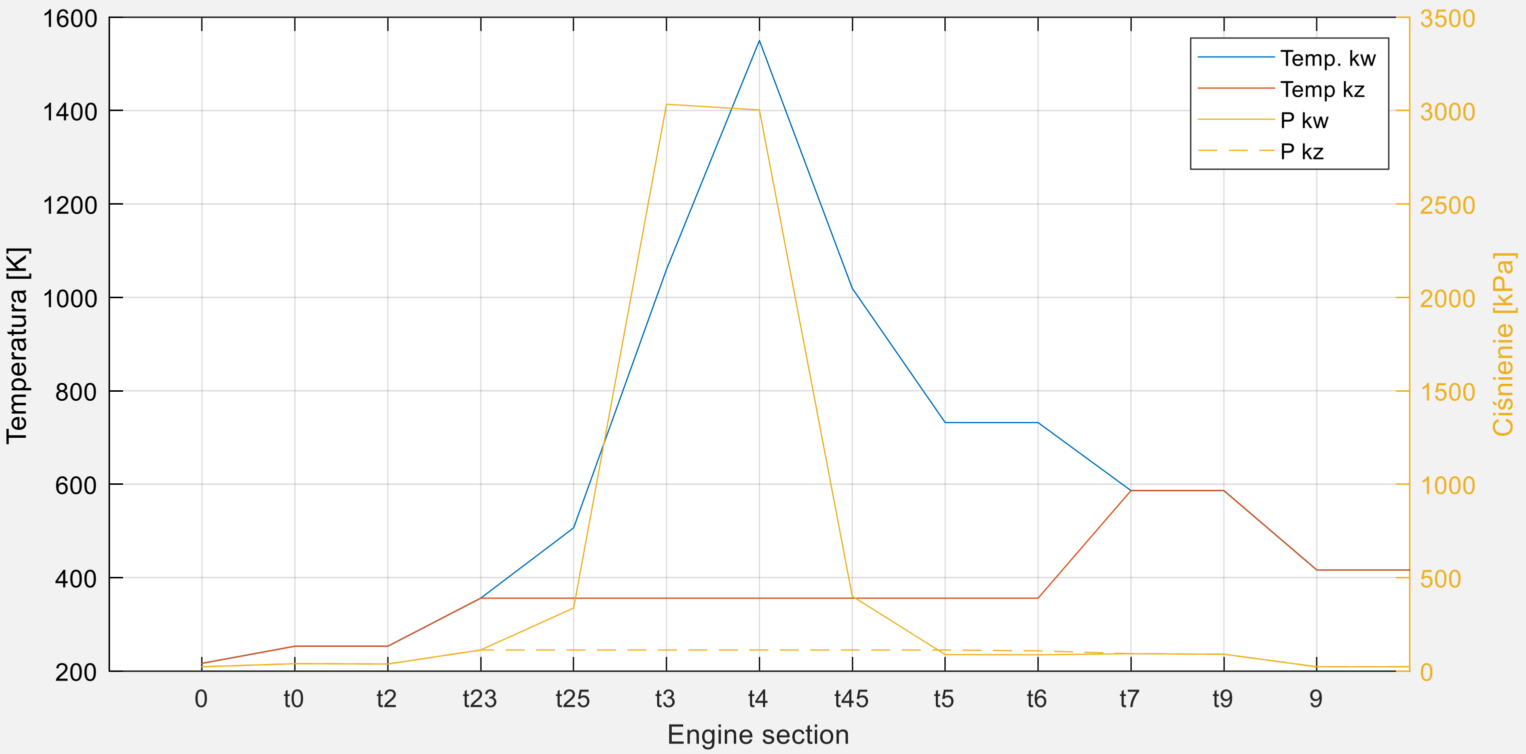
The second point which fulfil that the mixer inlet pressure is equal is preferred. Engine SFC for higher CPR is lower.



Example shows that for specified engine parameters CPR should be about 2,2 or 6 to fulfil criteria of Pt16 equal Pt6

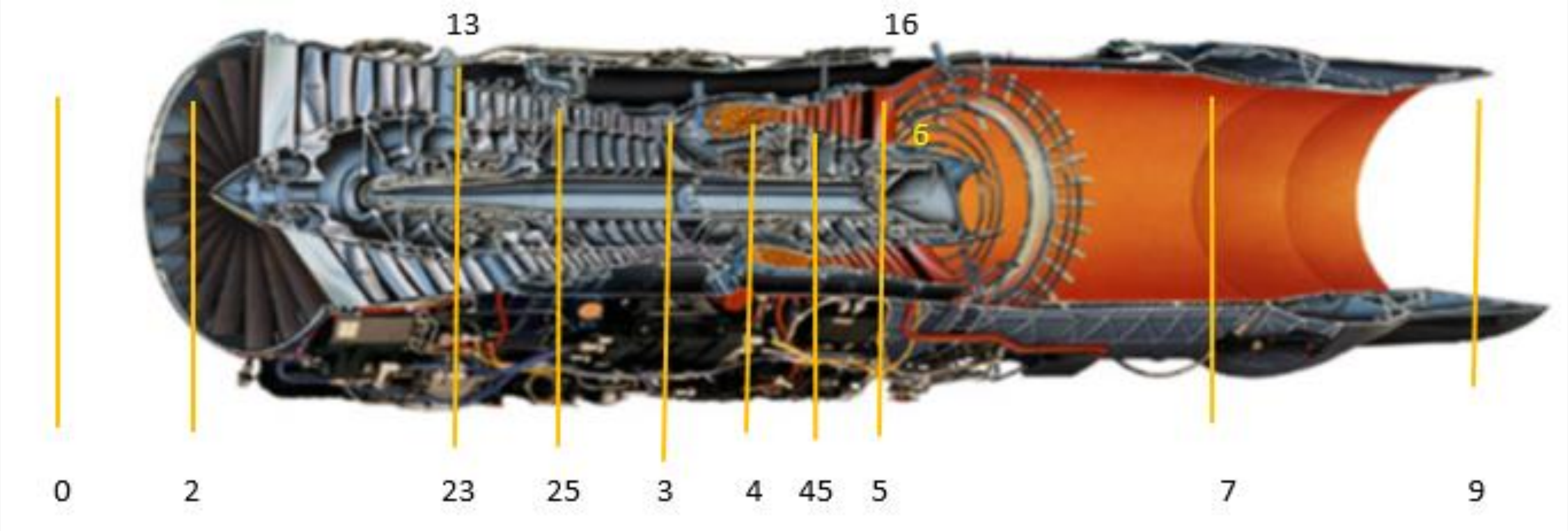
EXAMPLE OF MIXED FLOW TURBOFAN ENGINE CALCULATION





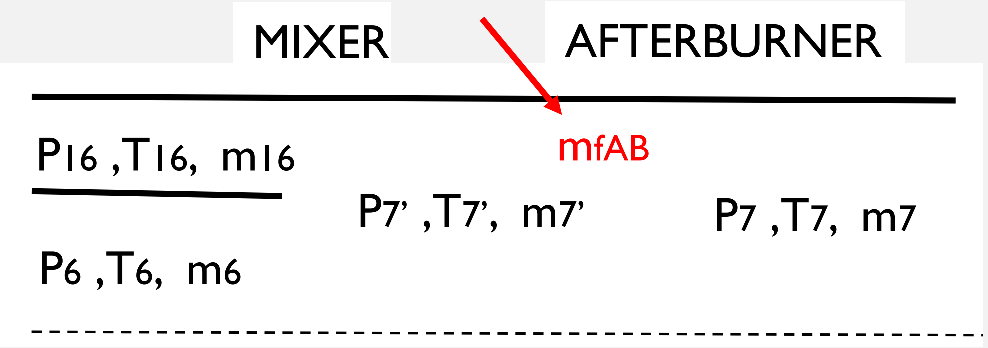
Przykład obliczeniowy dla:
H=11 km
M0=0,92
m0=20 kg/s
BPR=0.7
FPR=3
LPC=3
HPC=9
TIT=1550

TURBOFAN ENGINE WITH MIXER AND AFTERBURNER



Mixing process and burning process in the afterburner are in the same place and time in the mixed flow turbofan engine with afterburner.

For calculation simplfication typical attempt is that mixing process is calculated first and burning process in the afterburner is calculated next. By this way the mixing prosess products are assumet in the begining to the afterburner process.



$$\eta_{AB}\dot{m}_{f\_AB}FHV = \dot{m}_{7'}Cp_{AB}(T_{t7} - T_{t7'})$$

$$\dot{m}_{7'} = \dot{m}_0 + \dot{m}_{fB} \qquad T_{t7} = T_{tAB}$$

Afterburner fuel mass flow

$$\dot{m}_{f\_AB} = \frac{\dot{m}_{7'}Cp_{AB}(T_{tAB} - T_{t7'})}{\eta_{AB}FHV}$$

Afterburner fuel-air ratio

$$f_{AB} = \frac{\dot{m}_{f\_AB}}{\dot{m}_{21}} = \frac{Cp_{AB}(1 + BPR + f_B)(T_{tAB} - T_{t7'})}{\eta_B FHV}$$

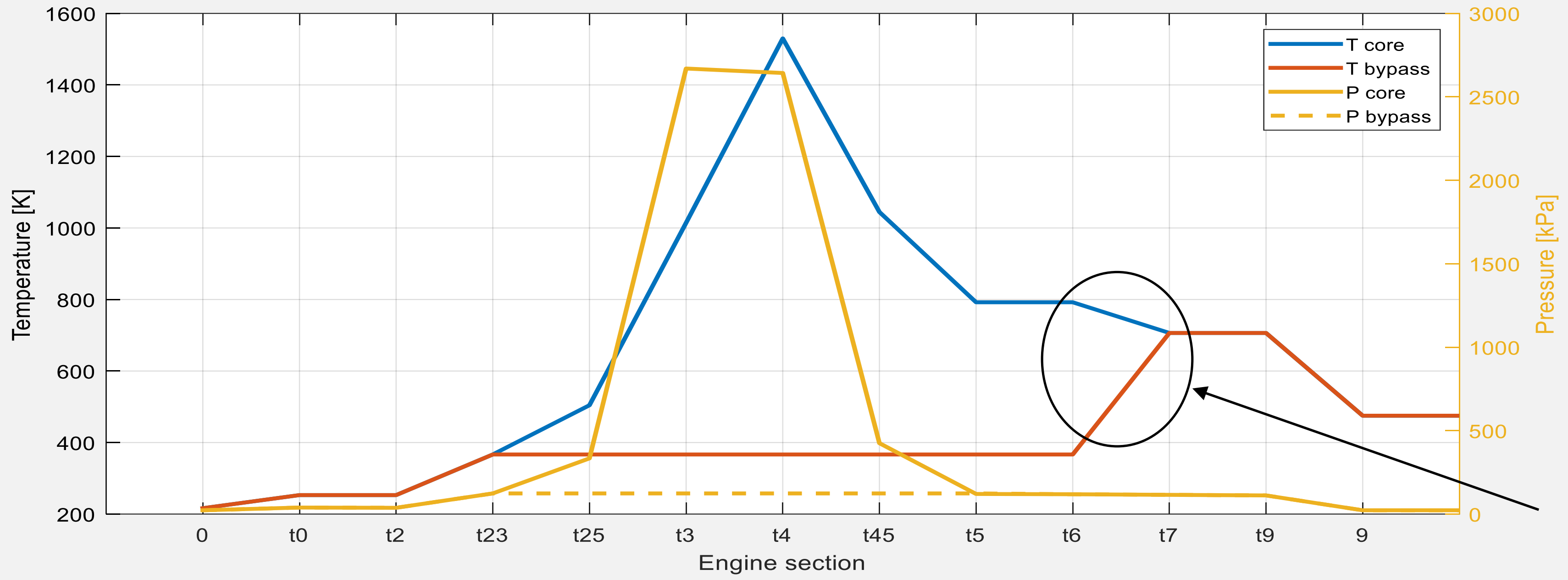
Mass flow in the AB outlet $\dot{m}_7 = \dot{m}_0 + \dot{m}_{fB} + \dot{m}_{fAB}$

Additional pressure losses caused by burning process increases pressure losses in mixer and afterburner.

$$P_{t7} = \pi_{AB}P_{t7}'$$

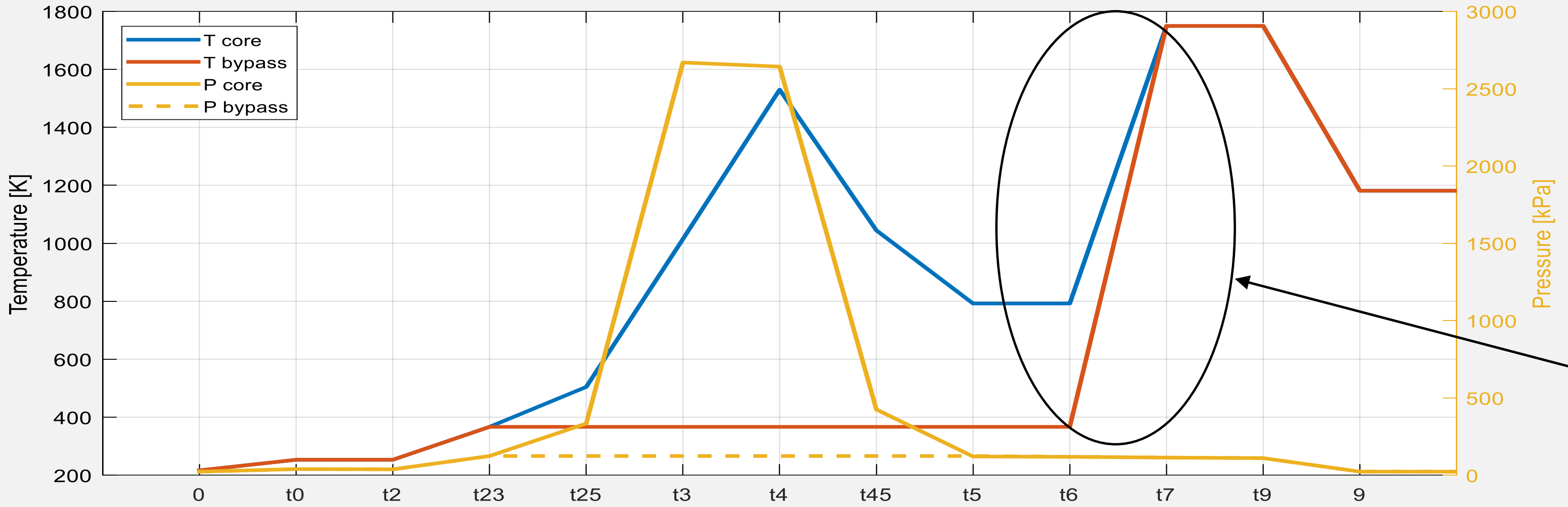
TEMPEARATURE AND PRESSURE DISTRIBUTION FOR AB ON

AB-OFF



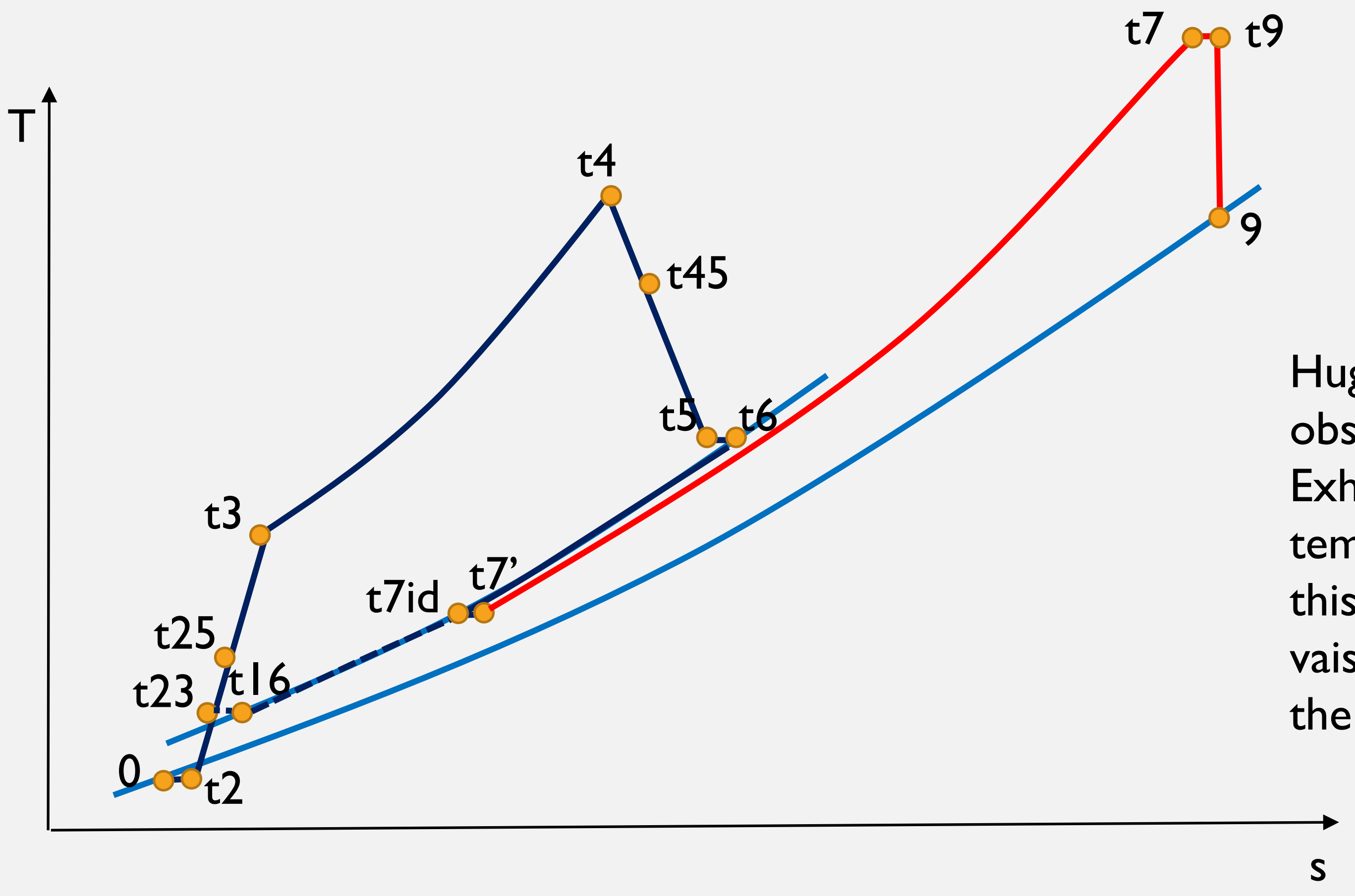
Small BPR=0.27: Small temperature drop for core flow, high temperature grow for bypass flow

AB-ON



Temperature after flow mixing isn’t presented. Temepratute AB ON is shown directly after mixing

TEMPERATURE - ENTROPY PLOT FOR AB ON



Huge entropy grow is observed by AB ON Exhaust stream temperature is very high, by this way lot of heat is vaisted – this lead to low thermal efficiency

AB OFF - ON ENGINE PERFORMANCE COMPARISON

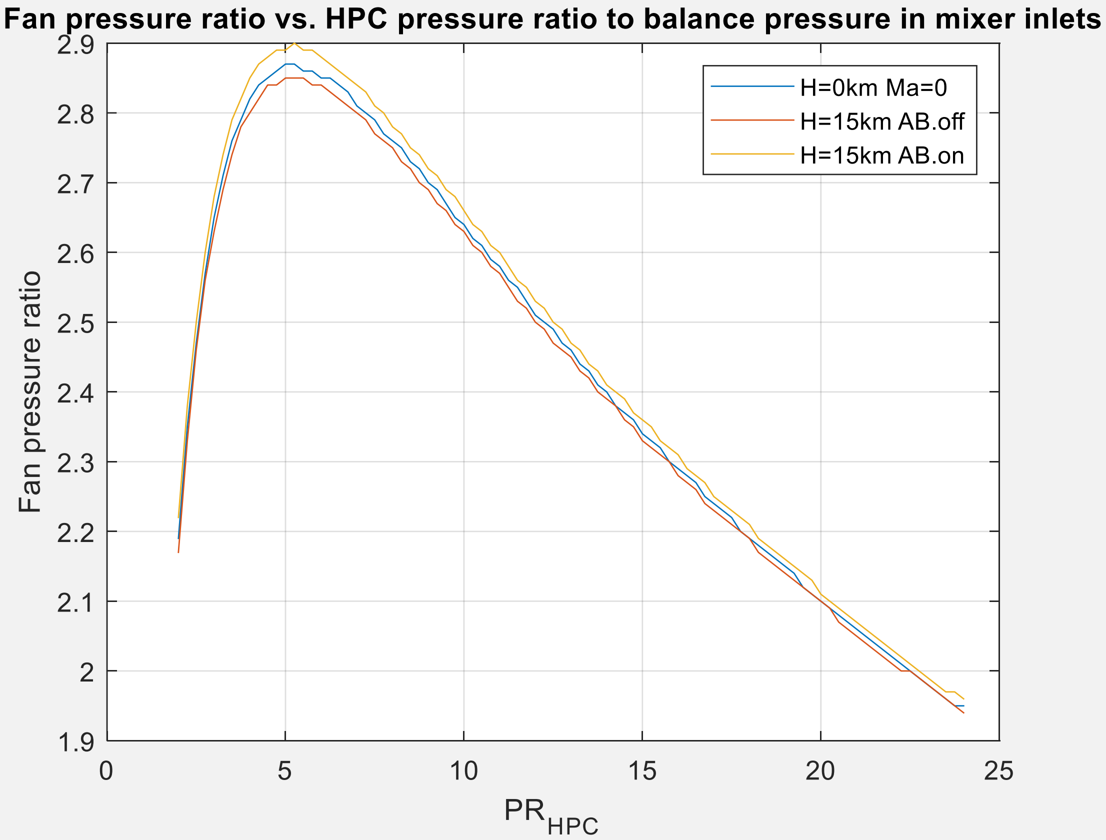
	Parameter	Unit	AB OFF	AB ON
1	'Alt'	'm'	11000	11000
2	'M0'	'-'	0.9200	0.9200
3	'Thrust'	'kN'	9.4992	18.7226
4	'Specific Thrust'	'N*s/kg'	474.9619	936.1287
5	'fuel consumption'	'kg/s'	0.1996	0.8447
6	'Specific fuel consump'	'kg/N/h'	0.0756	0.1624
7	'therm. efficiency'	'-'	0.5567	0.3649
8	'prop. efficiency'	'-'	0.5394	0.3833
9	'overall efficiency'	'-'	0.3003	0.1398
10	'AWDT_HPT'	'm'	0.0054	0.0054
11	'AWDT_LPT'	'm'	0.0319	0.0319
12	'A_9min'	'm'	0.1205	0.1987
13	'A_9'	'm'	0.1669	0.2731

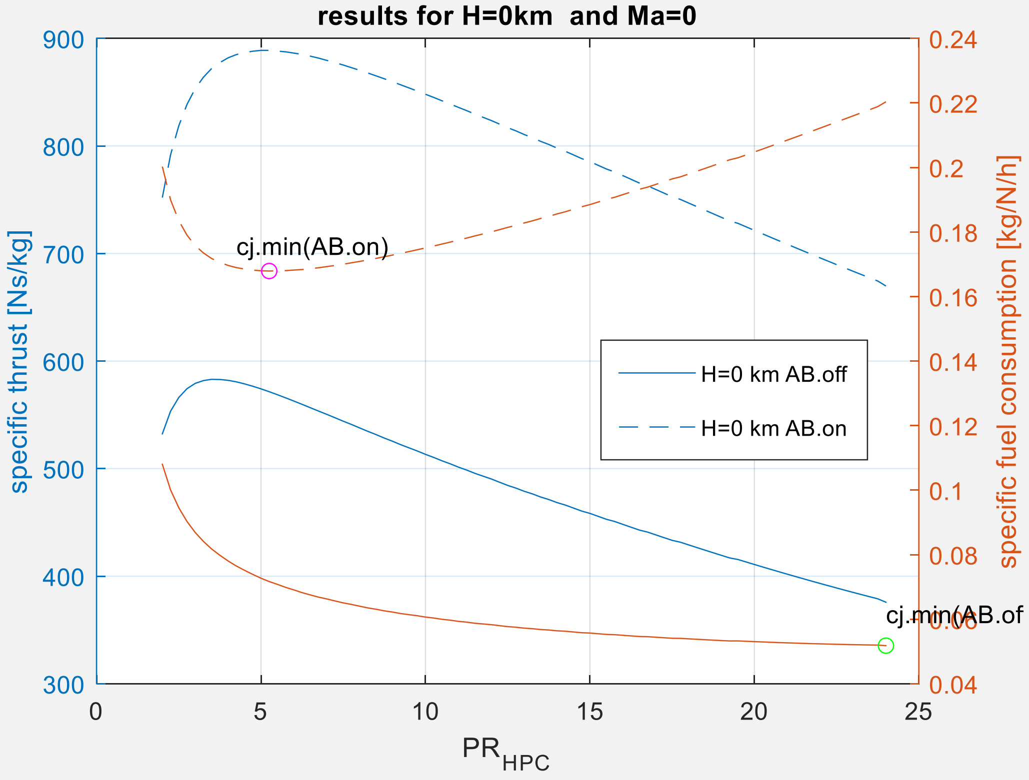
AB ON:

- Thrust / specific thrust is higher (2 times)
- Fuel consumption is higher (4 times)
- SFC is higher (2 times)
- Thermal propulsive annd overall efficiencies are lower
- Exit nozzle area is higher

AB ON ENGINE CYCLE OPTIMISATION

There are different possible way to search optimal conditions of the mixed flow turbofan engine with afterburner. On of them wich is wery usful and similar to the turbojet engine with afterburner is presented





HPC PR of minimum SFC and maximum ST for AB ON is in the same HPC PR about 6 and this point is between HPC PR of max ST for AB OFF (HPCPR=3) and HPC PR of SFC min for AB OFF (HPCPR=24).

THANKS FOR YOUR ATENTION

Questions and Comments ?

1. …….
2. …….
3. …….