Aircraft Engine Construction - real turbojet engine

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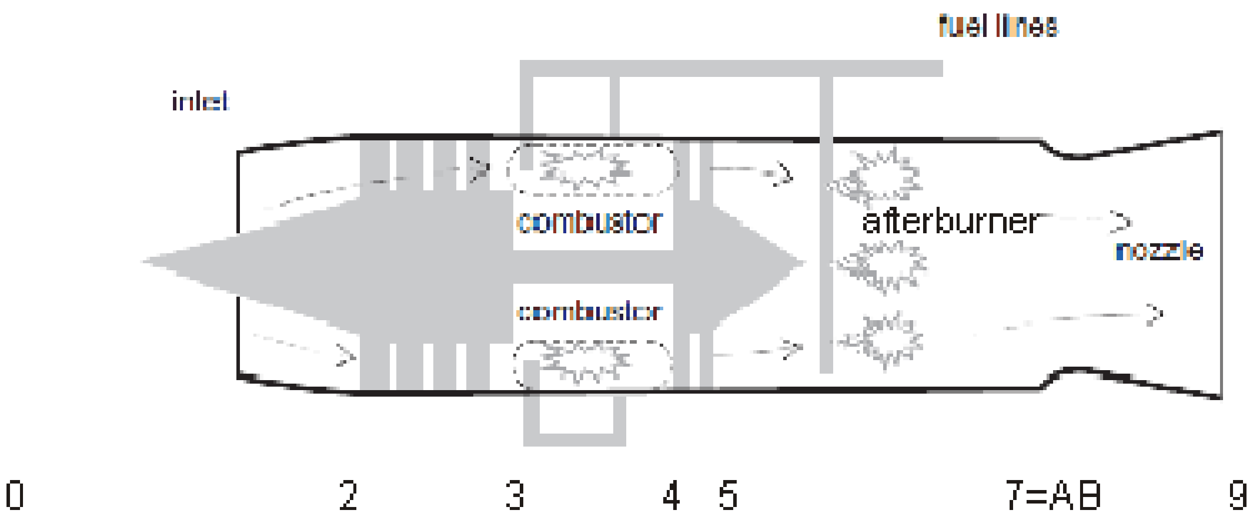
TURBOJET ENGINE with LOSSES

En example of turbojet engin calculation is presented below. Three cases were calculated: turbojet engine, turbojet engine with afterburner and turbojet engine with incomplete expansion in propeling nozzle.



Given

T0=217 K, P0=22 kPa, M0=0.9, compressor pressure ratio 12, Turbine inlet temperature Tt4=1300 K, mass flow m=20 kg/s. For Afterburner ON: TtAB=1750 K

inlet pressure losses coefficient σ_{IN} 0.97, burner pessure losses coefficient σ_B 0.98, nozzle pressure losses coefficient σ_N 0.96, compressor effiiceincy η_C 0.83, turbine efficiency η_T 0.9, burner efficiency η_B 0.98, mechanical efficiency η_M = 0.99. For AB ON state afterburner efficiency η_{AB} 0.95, additional afterburner pressure losses coeficient σ_{AB} 0.98

Gas parameters:

Air: k=1.4; cp=1005 J/kg/K, R=287 J/kg/K,

Fumes in turbine and nozzle kt=1.33, cpt=1170 J/kg/K, Rt=290 J/kg/K, Fumes for Afterburner and nozzle in AB ON mode kAB=1.3, cpAB=1200 J/kg/K, RAB=297 J/kg/K,

For combustion in combustor cpB=1200 J/kg/K,

Fuel heat value: FHV=43 MJ/kg

Flight Mach No

```
M0 = 0.9000
```

Air Mass flow [kg/s]

```
m0 = 20
```

Turbine inlet temperature [K]

```
Tt4 = 1300
```

Compressor pressure ratio

```
CPR = 12
```

Afterburner temperature [K]

```
TtAB = 1750
```

Ambient conditions

Static temperature [K]

```
T0 = 217
```

Static pressure [Pa]

```
P0 = 22000
```

```
e_M = 0.9900
```

TURBOJET ENGINE WITHOUT AFTERBURNER (AB-OFF) - section 7 is disregarded

Section 0

Total temperature [K]

$T_{t0} = T_0\left(1 + \frac{k-1}{2}M_0^2\right)$ - like for ideal engine

```
Tt0 = 252.1540
```

Total pressure [Pa]

$P_{t0} = P_0\left(1 + \frac{k-1}{2}M_0^2\right)^{\frac{k}{k-1}}$ - like for ideal engine

```
Pt0 = 3.7209e+04
```

Speed of sound [m/s]

$a_0 = \sqrt{k * R * T_0}$ - like for ideal engine

```
a0 = 295.2805
```

Flight speed [m/s]

$V_0 = M_0 * a_0$ - like for ideal engine

```
V0 = 265.7525
```

Section 2 Compressor inlet

Total temperature [K]

$T_{t2} = T_{t0}$ - like for ideal engine

```
Tt2 = 252.1540
```

Total pressure [Pa]

$P_{t2} = \sigma_{IN} * P_{t0}$

```
Pt2 = 3.6092e+04
```

Section 3 - Compressor outlet / Burner inlet

Total temperature [K]

$$T_{t3} = T_{t2} * \left(1 + \frac{\mathrm{CPR}^{\frac{k-1}{k}} - 1}{\eta_C}\right)$$

```
Tt3 = 566.2641
```

Total pressure [Pa]

$P_{t3} = P_{t2} * \mathrm{CPR}$

```
Pt3 = 4.3311e+05
```

COMPRESSOR

Compressor work [J/kg]

$W_C = c_p * (T_{t3} - T_{t2})$

```
WC = 3.1568e+05
```

Compressor power [W]

$P_C = m_0 * W_C$

```
PC = 6.3136e+06
```

Section 4 Burner outlet / Turbine inlet

Total temperature [K]

T_{t4}

```
Tt4 = 1300
```

Total pressure [Pa]

$P_{t4} = \sigma_B * P_{t3}$

```
Pt4 = 4.2445e+05
```

BURNER

Fuel-air ratio

$$f_B = c_{pB} * \frac{T_{t4} - T_{t3}}{\mathrm{FHV} * \eta_B}$$

```
fB = 0.0209
```

Fuel mass flow   [kg/s]

$m_{fB} = m_0 * f_B$

```
mfB = 0.4179
```

Section 5   Turbine outlet / Nozzle inlet

Total temperature   [K]

$$T_{t5} = T_{t4} - \frac{W_C}{\eta_M * (1 + f_B) * c_{pt}}$$

```
Tt5 = 1.0330e+03
```

Total pressure [Pa]

$$P_{t5} = P_{t4}\left(\frac{\eta_T + \frac{T_{t5}}{T_{t4}} - 1}{\eta_T}\right)^{\frac{kt}{kt-1}}$$

```
Pt5 = 1.4945e+05
```

Section 9 Engine Nozzle outlet

Total temperature   [K]

$T_{t9} = T_{t5}$

```
Tt9 = 1.0330e+03
```

Total pressure [Pa]

$P_{t9} = P_{t5} * \sigma_N$

```
Pt9 = 1.4347e+05
```

Static pressure [Pa]

$P_9 = P_0$

```
P9 = 22000
```

Static temperature   [K]

$$T_9 = T_{t9} * \left(\frac{P_9}{P_{t9}}\right)^{\frac{kt-1}{kt}}$$

```
T9 = 648.7254
```

Jet stream Mach No

$$M_9 = \sqrt{\left(\frac{T_{t9}}{T_9} - 1\right) * \frac{2}{kt - 1}}$$

```
M9 = 1.8948
```

Speed of sound [m/s]

$$a_9 = \sqrt{kt * Rt * T_9}$$

```
a9 = 500.2133
```

Jet speed [m/s]

$$V_9 = M_9 * a_9$$

```
V9 = 947.8210
```

TURBOJET ENGINE PERFORMANCE CALCULATION

Thrust [N]

$$T = m_0 * (1 + f_B) * V_9 - m_0 * V_0$$

```
T = 1.4037e+04
```

Specific thrust [Ns/kg]

$$ST = \frac{T}{m_0} = (1 + f_B) * V_9 - V_0$$

```
ST = 701.8725
```

Specific fuel consumption [kg/N/s]

$$SFC = \frac{m_{fB}}{T}$$

```
SFC = 2.9769e-05
```

Specific fuel consumption [kg/N/h]

$$SFC = SFC * 3600$$

```
SFC = 0.1072
```

Thermal efficiency

$$\eta_{th} = \frac{(1 + f_B) * {V_9}^2 - {V_0}^2}{2 * f_B * FHV}$$

```
etha_th = 0.4711
```

Propulsive efficiency

$$\eta_p = \frac{2 * V_0 * \mathrm{ST}}{(1+f_B) * {V_9}^2 - {V_0}^2}$$

```
etha_p = 0.4407
```

Overall efficiency

$$\eta_o = \frac{V_0 * \mathrm{ST}}{f_B * \mathrm{FHV}} = \eta_{\mathrm{th}} * \eta_p$$

```
etha_o = 0.2076
```

Temperature, pressure vs engine sections plot

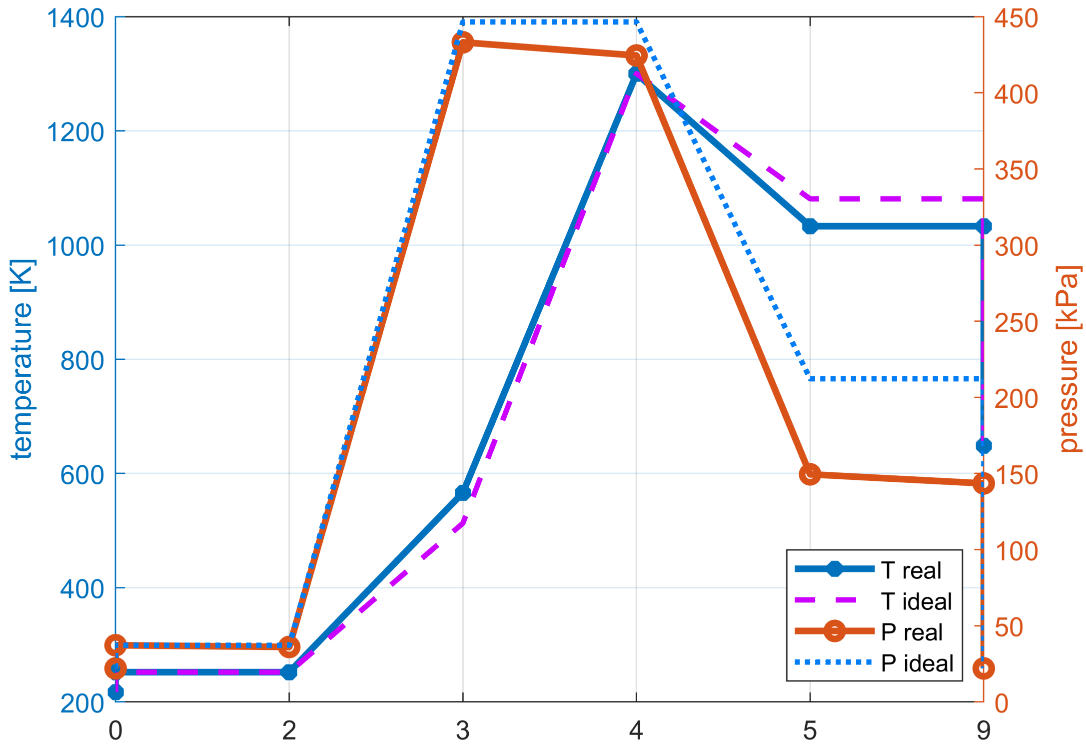


Tabela = 8×5 table

	Section	T real [K]	T ideal [K]	P real [kPa]	P ideal [kPa]
1	'0'	217	217	22	22
2	't0'	252.1540	252.1540	37.2087	37.2087
3	't2'	252.1540	252.1540	36.0924	37.2087
4	't3'	566.2641	512.8654	433.1089	446.5040
5	't4'	1300	1300	424.4467	446.5040
6	't5'	1.0330e+03	1.0809e+03	149.4512	212.1852
7	't9'	1.0330e+03	1.0809e+03	143.4731	212.1852

	Section	T real [K]	T ideal [K]	P real [kPa]	P ideal [kPa]
8	'9'	648.7254	615.9567	22	22

Performance comparison of real and ideal turbojet engine

```
Tabela = 8×4 table
```

	Parameter	Unit	Real turbojet	Ideal turbojet
1	'Thrust'	'kN'	14.0374	15.9926
2	'Specific Thrust'	'N*s/kg'	701.8725	799.6289
3	'Fuel consumption'	'kg/s'	0.4179	0.4393
4	'Specific fuel consump'	'kg/N/h'	0.1072	0.0989
5	'therm. efficiency'	'-'	0.4711	0.5505
6	'prop. efficiency'	'-'	0.4407	0.4087
7	'overall efficiency'	'-'	0.2076	0.2250
8	'V9'	'm/s'	947.8210	1.0425e+03

CONCLUSIONS

Real to ideal jet engine comparison shows

- Total pressure in engine sections is lower in real engine
- Total temperature after compressor is higher, but after turbine is lower in real engine
- Higher temperature after compressor causes lower fuel consumption of the real engine - TIT (turbine inlet temperature) is the same in both cases
- Lower total temperature in the nozzle inlet and higher static temperature in the nozzle outlet causes lower outlet flow velocity and by this way lower thrust and specific thrust of real jet engine
- Specific fuel consumption is higher due to lwer thrust and thermal and overall efficiences are lower in real engine

Temperature - entropy plot

Entropy growth is calculated from equations:

Inlet entropy grow [J/kg/K] :

$$\Delta s_{\mathrm{IN}} = -R * \ln(\sigma_{\mathrm{IN}})$$

```
dS_IN = 8.7418
```

Compressor entropy grow [J/kg/K] :

$$\Delta s_C = c_p * \ln \frac{T_{t3}}{T_{t2}} - R * \ln(\mathrm{CPR})$$

```
dS_C = 99.8974
```

Combustor entropy grow [J/kg/K] :

$$\Delta s_B = c_{pB} * \ln\frac{T_{t4}}{T_{t3}} - R_t * \ln(\sigma_B)$$

```
dS_B = 1.0031e+03
```

Turbine entropy grow   [J/kg/K] :

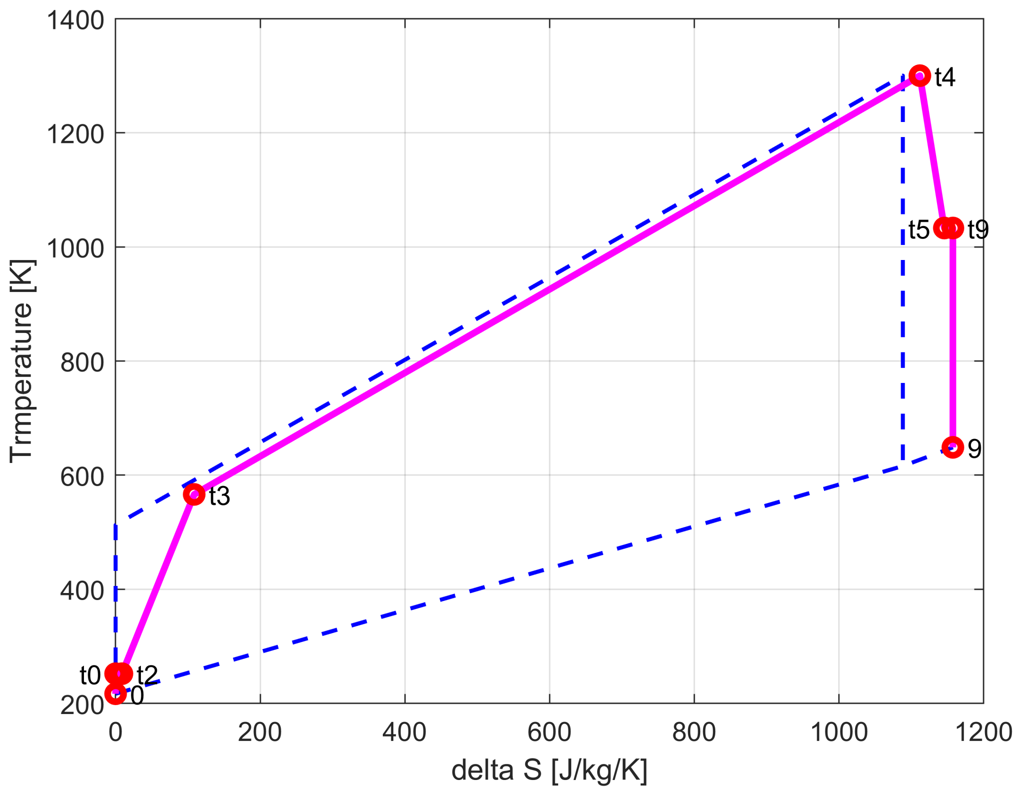
$$\Delta s_T = c_{pt} * \ln\frac{T_{t5}}{T_{t4}} - R_t * \ln\left(\frac{P_{t5}}{P_{t4}}\right)$$

```
dS_T = 33.7726
```

Nozzle entropy grow   [J/kg/K] :

$$\Delta s_N = -\mathrm{Rt} * \ln(\sigma_N)$$

```
dS_N = 11.8384
```



CONCLUSIONS

All processes genarte entropy increase.Significant entropy growth is in the burner, compressor and turbine.

TURBOJET ENGINE WITH AFTERBURNER (AB-ON)

Caclculation done for turbojet engine for afterburner OFF mode from section 0 to 5 is valid for the engine with the afterburner ON mode. Differences statr from AB (7) section.

Section AB - AFTERBURNER

Total temperature [K]

T_{tAB}

```
TtAB = 1750
```

Total pressure [Pa]

$P_{\mathrm{tAB}} = \sigma_{\mathrm{AB}} * P_{\mathrm{t5}}$

```
PtAB = 1.4945e+05
```

Fuel-air ratio

$$f_{\mathrm{AB}} = (1 + f_B) * c_{\mathrm{pAB}} * \frac{T_{\mathrm{tAB}} - T_{\mathrm{t5}}}{\mathrm{FHV} * \eta_{\mathrm{AB}}}$$

```
fAB = 0.0224
```

Afterburner fuel mass flow [kg/s]

$m_{\mathrm{fAB}} = m_0 * f_{\mathrm{AB}}$

```
mfAB = 0.4479
```

Section 9 AB ON

Total temperature [K]

$T_{\mathrm{t9AB}} = T_{\mathrm{tAB}}$

```
Tt9AB = 1750
```

Total pressure [Pa]

$P_{\mathrm{t9AB}} = \sigma_N * P_{\mathrm{tAB}}$

```
Pt9AB = 1.4347e+05
```

Staticl pressure [Pa]

$P_{\mathrm{9AB}} = P_0$

```
P9AB = 22000
```

Static temperature [K]

$$T_{\mathrm{9AB}} = T_{\mathrm{t9AB}} * \left(\frac{P_{\mathrm{9AB}}}{P_{\mathrm{t9AB}}}\right)^{\frac{\mathrm{kAB}-1}{\mathrm{kAB}}}$$

```
T9AB = 1.1353e+03
```

Jet stream Mach No

$$M_{\mathrm{9AB}} = \sqrt{\left(\frac{T_{\mathrm{t9AB}}}{T_{\mathrm{9AB}}} - 1\right) * \frac{2}{\mathrm{k}_{\mathrm{AB}} - 1}}$$

```
M9AB = 1.8999
```

Speed of sound [m/s]

$$a_{9\mathrm{AB}} = \sqrt{\mathrm{k}_{\mathrm{AB}} * R_{\mathrm{AB}} * T_{9\mathrm{AB}}}$$

```
a9AB = 662.0727
```

Jet speed [m/s]

$$V_{9\mathrm{AB}} = M_{9\mathrm{AB}} * a_{9\mathrm{AB}}$$

```
V9AB = 1.2579e+03
```

TURBOJET ENGINE with AFTERBURNER - PERFORMANCE CALCULATION

Total fuel-air ratio

$$f = f_B + f_{\mathrm{AB}}$$

```
f_AB = 0.0433
```

Total fuel consumption [kg/s]

$$m_f = m_{\mathrm{fB}} + m_{\mathrm{fAB}}$$

```
mf_AB = 0.8658
```

Thrust [N]

$$T_{\mathrm{AB}} = m_0 * (1 + f) * V_{9\mathrm{AB}} - m_0 * V_0$$

```
T_AB = 2.0931e+04
```

Specific thrust [Ns/kg]

$$\mathrm{ST}_{\mathrm{AB}} = \frac{T_{\mathrm{AB}}}{m_0} = (1 + f) * V_{9\mathrm{AB}} - V_0$$

```
ST_AB = 1.0466e+03
```

Specific fuel consumption [kg/N/s]

$$\mathrm{SFC}_{\mathrm{AB}} = \frac{m_f}{T_{\mathrm{AB}}}$$

```
SFC_AB = 4.1365e-05
```

Specific fuel consumption [kg/N/h]

$$\mathrm{SFC}_{\mathrm{AB}} = \mathrm{SFC}_{\mathrm{AB}} * 3600$$

```
SFC_AB = 0.1489
```

Thermal efficiency

$$\eta_{\mathrm{thAB}} = \frac{(1 + f) * {V_{9\mathrm{AB}}}^2 - {V_0}^2}{2 * f * \mathrm{FHV}}$$

```
etha_th_AB = 0.4244
```

Propulsive efficiency

$$\eta_{\mathrm{pAB}} = \frac{2 * V_0 * \mathrm{ST}_{\mathrm{AB}}}{(1+f) * {V_{9\mathrm{ANB}}}^2 - {V_0}^2}$$

```
etha_p_AB = 0.2361
```

Overall efficiency

$$\eta_{\mathrm{oAB}} = \frac{V_0 * \mathrm{ST}_{\mathrm{AB}}}{f * \mathrm{FHV}} = \eta_{\mathrm{thAB}} * \eta_{\mathrm{pAB}}$$

```
etha_o_AB = 0.1002
```

TURBOJET ENGINE AFTERBURNER OFF/ ON COMPARISON

```
Tabela = 8×5 table
```

	Parameter	Unit	AB OFF	AB ON	AB ON ideal
1	'Thrust'	'kN'	14.0374	20.9314	22.9077
2	'Specific Thrust'	'N*s/kg'	701.8725	1.0466e+03	1.1454e+03
3	'V9'	'm/s'	947.8210	1.2579e+03	1.3545e+03
4	'Fuel consumption'	'kg/s'	0.4179	0.8658	0.8369
5	'Specific fuel consump'	'kg/N/h'	0.1072	0.1489	0.1315
6	'therm. efficiency'	'-'	0.4711	0.4244	0.5115
7	'prop. efficiency'	'-'	0.4407	0.2361	0.2309
8	'overall efficiency'	'-'	0.2076	0.1002	0.1181

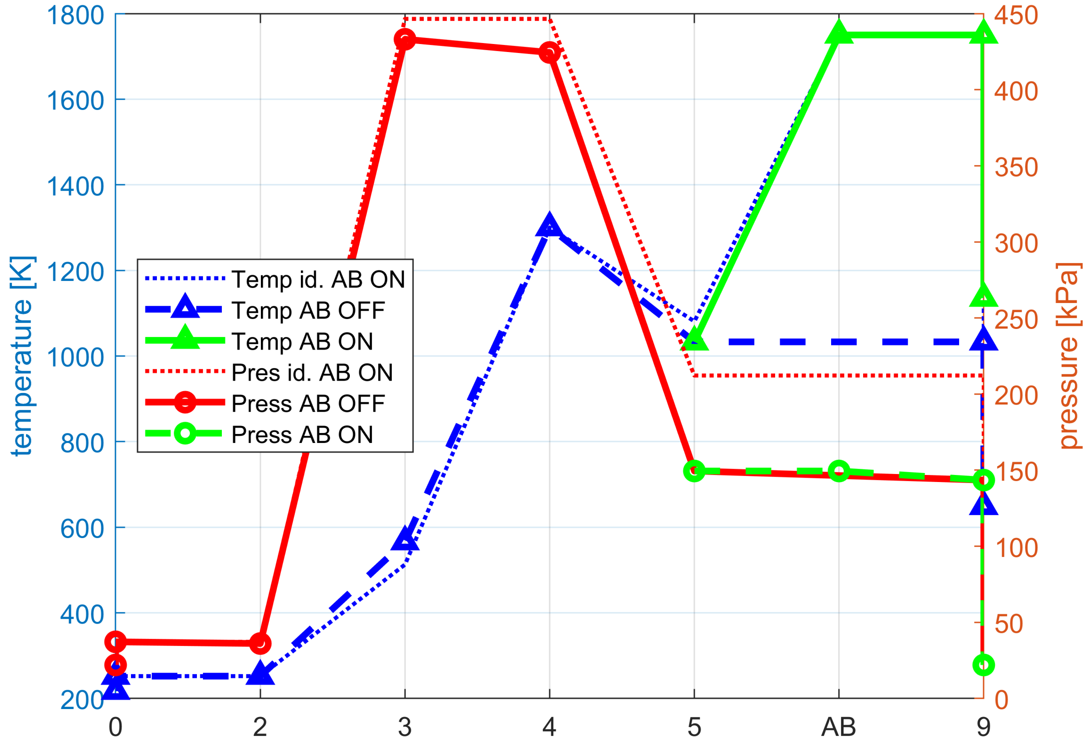
CONCLUSIONS:

Engine with AB ON has:

- higher thrust and specific thust due to higher jet speed (+)
- significantly higher fuel consumption and specific fuel consumption (-)
- lower thermal and overall efficiences (-)

Real engine has worse performance efficiency than ideal engine

Temperature, pressure plot vs engine sections for ideal and real turbojet with AB ON



CONCLUSIONS:

When AB is on than pressure profile in the engine is unchanged and temperature profile is hanged from AB section (temperature is significantly higher in afterburner and propelling nozzle)

Temperature - entropy plot

Afterburner entropy growth [J/kg/K]

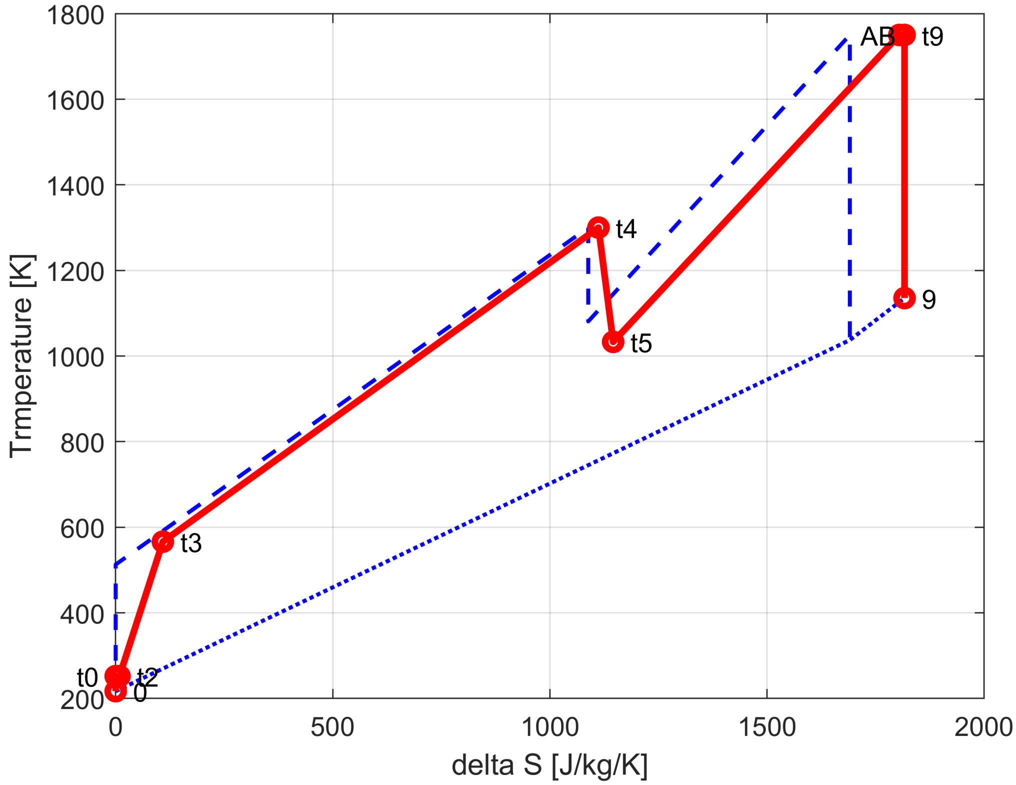
$$\Delta s_{\mathrm{AB}} = c_{\mathrm{pAB}} * \ln \frac{T_{\mathrm{tAB}}}{T_{\mathrm{t5}}} - R_{\mathrm{AB}} * \ln \frac{P_{\mathrm{tAB}}}{P_{\mathrm{t5}}}$$

```
dS_AB = 658.8873
```

Nozzle entropy growth [J/kg/K]

$$\Delta s_N = -R_{\mathrm{AB}} * \ln(\sigma_N)$$

```
dS_N = 12.1241
```



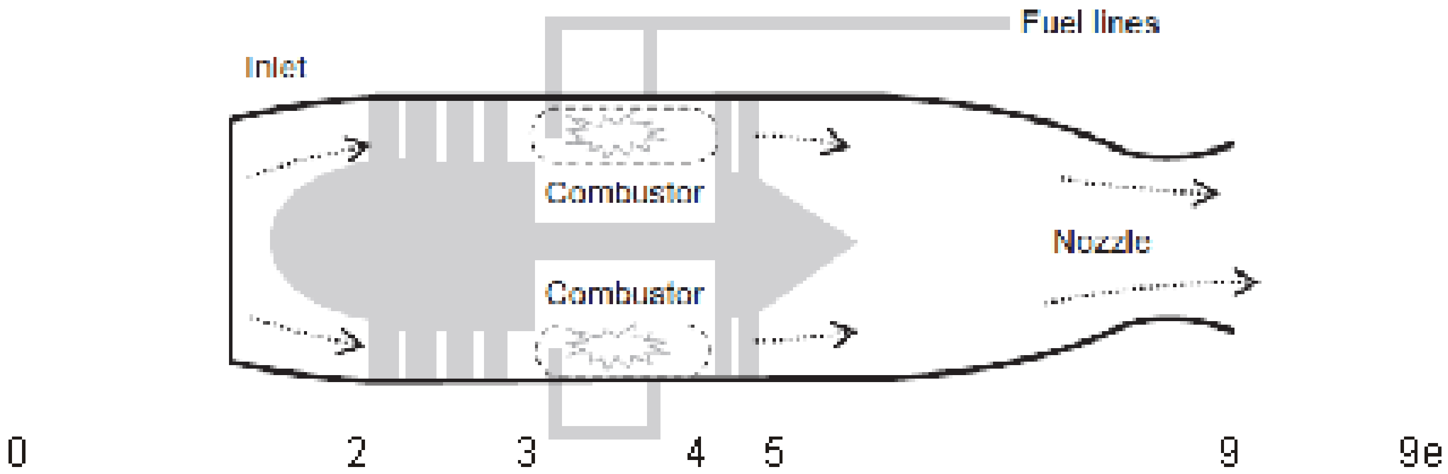
Conclusions:

In AB ON mode additional entropy increase is in the afterburner process

TURBOJET ENGINE - INCOMPLETE EXPANSION IN THE PROPELLING NOZZLE

Calculation example of a turbojet engine with incomplete expansion in the propelling nozzle is presented on the example done above for turbojet engin without afterburner. Calcilation conditions are the same like for turbojet engine without afterburner (first example). The difference is only that the static pressure in section 9 isn't equal ambient pressure, but is higher. In the example p9=Pt9/1.85, than expansion is conducted outside the nozzle in free stream process.

To present the calculation the additional section 9e is added - in this section jet stream acheieve ambient pressure.



All parameters from section 0 to 9t are the same as for previosly was calculated for the engine without afterburner. The difference is in section 9 static parameters calculation

Section 9 - incomplete decompression in the nozzle

Total pressure [Pa]

$$P_{t9}$$

```
Pt9 = 1.4347e+05
```

Total temperature [K]

$$T_{t9}$$

```
Tt9 = 1.0330e+03
```

Static pressure [Pa]

$$P_{9\,\mathrm{IE}} = \frac{P_{t9}}{1.85}$$

```
P9_IE = 7.7553e+04
```

Static temperature [K]

$$T_{9\,\mathrm{IE}} = T_{t9} * \left(\frac{P_{9\,\mathrm{IE}}}{P_{t9}}\right)^{\frac{\mathrm{kt}-1}{\mathrm{kt}}}$$

```
T9_IE = 886.8015
```

Mach No. in section 9

$$M_{9\,\mathrm{IE}} = \sqrt{\left(\frac{T_{t9}}{T_{9\mathrm{IE}}} - 1\right) * \frac{2}{\mathrm{k}_t - 1}}$$

```
M9_IE = 0.9997
```

Speed of sound [m/s]

$$a_{9\,\mathrm{IE}} = \sqrt{\mathrm{k}_t * R_t * T_{9\,\mathrm{IE}}}$$

```
a9_IE = 584.8413
```

Jet speed in section 9 [m/s]

$$V_{9\,\mathrm{IE}} = M_{9\,\mathrm{IE}} * a_{9\,\mathrm{IE}}$$

```
V9_IE = 584.6740
```

Gas density in section 9 [kg/m^3]

$$\rho_{9\,\mathrm{IE}} = \frac{P_{9\,\mathrm{IE}}}{R_t * T_{9\,\mathrm{IE}}}$$

```
RO9_IE = 0.3016
```

Section 9e

Jet speed after decompression to ambient pressure [m/s]

$$V_{9\,e} = V_{9\,\mathrm{IE}} + \frac{P_{9\,\mathrm{IE}} - P_0}{\rho_{9\,\mathrm{IE}} * V_{9\,\mathrm{IE}}}$$

```
V9e = 899.7531
```

Static temperature [K]

$$T_{9\mathrm{e}} = T_{\mathrm{t}9} - \frac{{V_{9e}}^2}{2 * c_{\mathrm{pt}}}$$

```
T9e = 687.0761
```

Staticl pressure [Pa]

$$P_{9\,e} = P_0$$

```
P9e = 22000
```

PERFORMANCE OF TURBOJET ENGINE WITH INCOMPLTE EXPANSION IN THE NOZZLE

Thrust [N]

$$T_{\mathrm{IE}} = m_0 * (1 + f_B) * V_{9e} - m_0 * V_0$$

```
T_IE = 1.3056e+04
```

Specific thrust [Ns/kg]

$$\mathrm{ST}_{\mathrm{IE}} = \frac{T_{\mathrm{IE}}}{m_0} = (1 + f_B) * V_{9e} - V_0$$

```
ST_IE = 652.8003
```

Specific fuel consumption [kg/N/s]

$$\mathrm{SFC_{IE}} = \frac{m_{\mathrm{fB}}}{T_{\mathrm{IE}}}$$

```
SFC_IE = 3.2007e-05
```

Specific fuel consumption   [kg/N/h]

$$\mathrm{SFC_{IE}} = \mathrm{SFC_{IE}} * 3600$$

```
SFC_IE = 0.1152
```

Thermal efficiency

$$\eta_{\mathrm{th\ IE}} = \frac{(1 + f_B) * {V_9}_e^2 - {V_0}^2}{2 * f_B * \mathrm{FHV}}$$

```
etha_th_IE = 0.4206
```

Propulsive efficiency

$$\eta_{p\ \mathrm{IE}} = \frac{2 * V_0 * \mathrm{ST_{IE}}}{(1 + f_B) * {V_9}_e^2 - {V_0}^2}$$

```
etha_p_IE = 0.4590
```

Overall efficiency

$$\eta_{o\ \mathrm{IE}} = \frac{V_0 * \mathrm{ST_{IE}}}{f_B * \mathrm{FHV}} = \eta_{\mathrm{th\ IE}} * \eta_{p\ \mathrm{IE}}$$

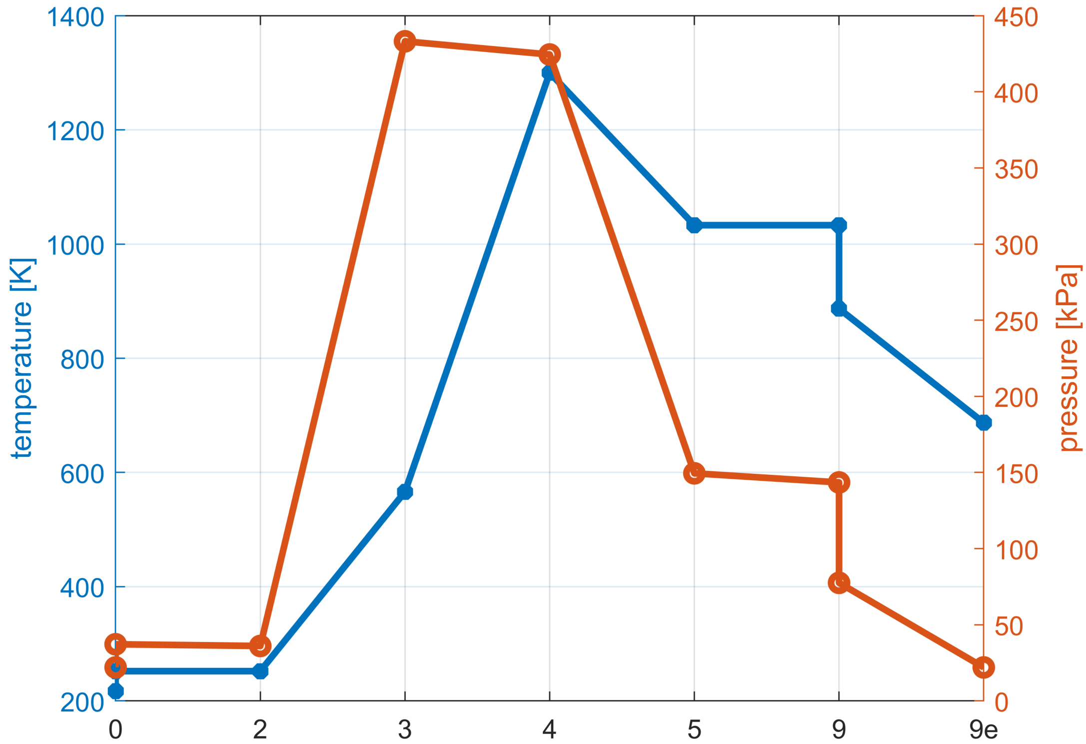
```
etha_o_IE = 0.1931
```

FULL EXPANSION IN PROPELING NOZZLE vs. ICOMPLETE EXPANSION IN PROPELING NOZZLE ENGINE PERFORMANCE COMPARISON

```
Tabela = 11×4 table
```

	Parameter	Unit	FULL EXP.	INCOMPLETE EXP.
1	'T9'	'K'	648.7254	886.8015
2	'V9'	'm/s'	947.8210	584.6740
3	'P9'	'kPa'	22	77.5530
4	'T9e'	'K'	648.7254	687.0761
5	'V9e'	'm/s'	947.8210	899.7531
6	'Thrust'	'kN'	14.0374	13.0560
7	'Specific Thrust'	'N*s/kg'	701.8725	652.8003
8	'Specific fuel consump'	'kg/N/h'	0.1072	0.1152
9	'therm. efficiency'	'-'	0.4711	0.4206
10	'prop. efficiency'	'-'	0.4407	0.4590
11	'overall efficiency'	'-'	0.2076	0.1931

Temperature, pressure vs engine sections plot

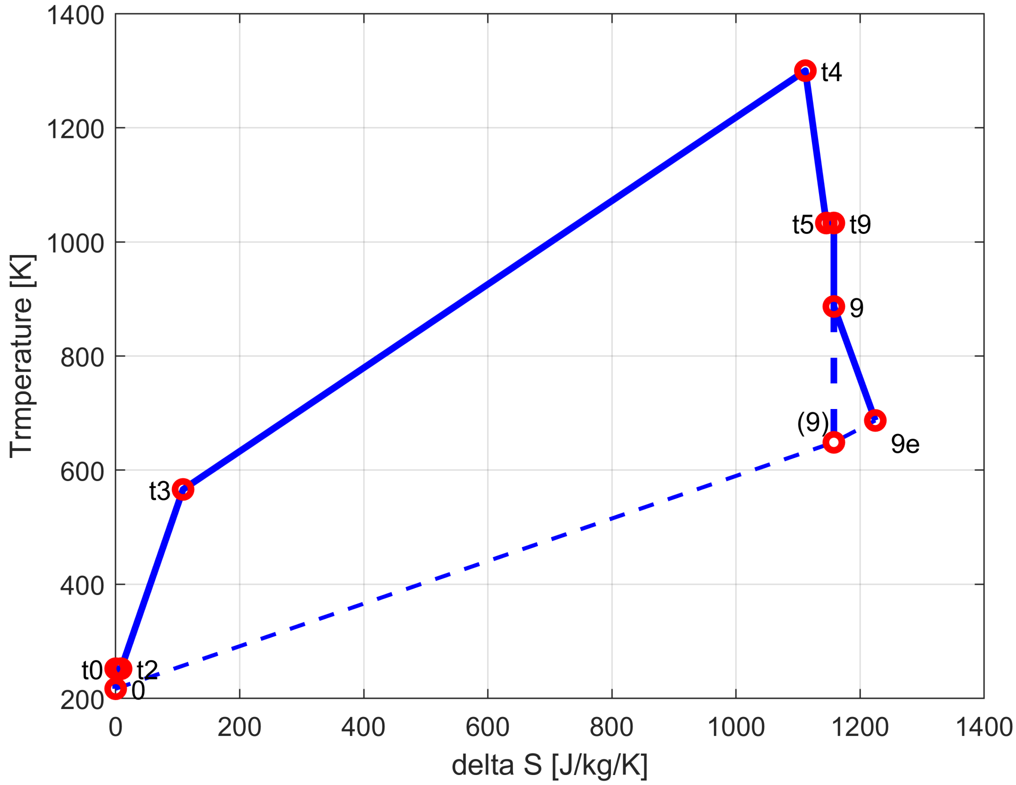


Temperature - entropy plot

Additional entropy growth 9-9e [J/kg/K]

$$\Delta s_{9-9e} = c_{\text{pt}} * \ln \frac{T_{9\text{e}}}{T_{9\,\text{IE}}} - R_t * \ln \frac{P_{9e}}{P_{9\,\text{IE}}}$$

```
deltaS_9_9e = 66.8206
```



CONCLUSIONS:

Incomplete expansion in the engine propelling nozzle causes:

- Lower thrust and specific thrust than it is in full decompression mode
- Higher specific fuel consumption
- Additional entropy increas caused by jet decompression outside the nozzle