Aircraft Engine Construction - Ideal turbojet engine

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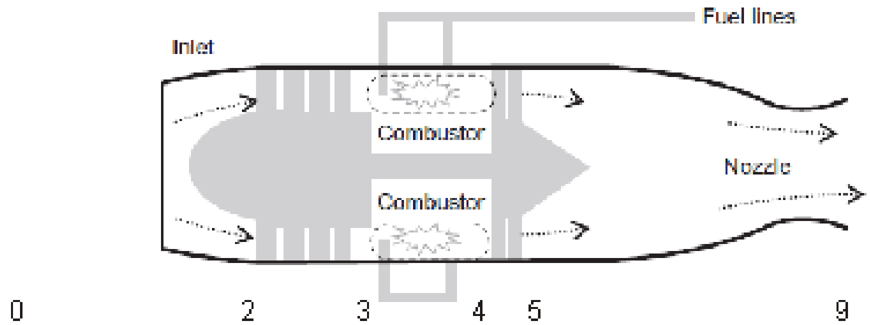
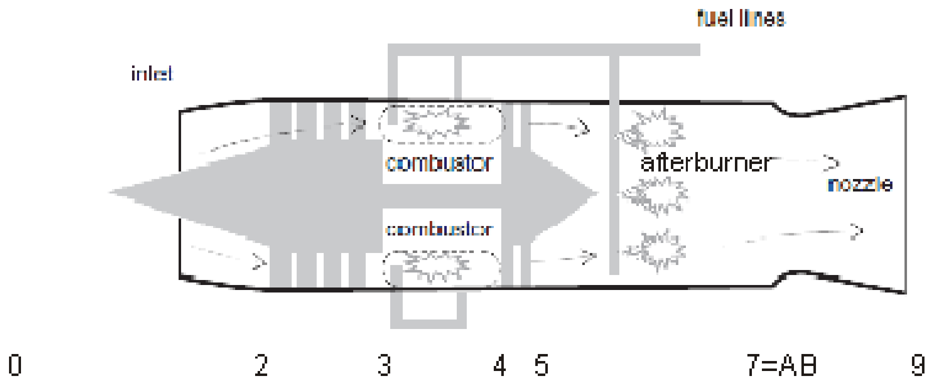
IDEAL TURBOJET ENGINE





Three examples of turbojet engine calculation are presented: for turbojet engine, for turbojet engine with afterburner and for turbojet engine with incomplete expansion in the 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

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
```

TURBOJET ENGINE WITHOUT AFTERBURNER (AB-OFF)

Section 0

Total temperature [K]

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

```
Tt0 = 252.1540
```

Total pressure [Pa]

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

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

Speed of sound [m/s]

$$a_0 = \sqrt{k * R * T_0}$$

```
a0 = 295.2805
```

Flight speed [m/s]

$$V_0 = M_0 * a_0$$

```
V0 = 265.7525
```

Section 2 Compressor inlet

Total temperature [K]

$$T_{t2} = T_{t0}$$

```
Tt2 = 252.1540
```

Total pressure [Pa]

$$P_{t2} = P_{t0}$$

```
Pt2 = 3.7209e+04
```

Section 3 - Compressor outlet / Burner inlet

Total temperature [K]

$$T_{t3} = T_{t2} * \mathrm{CPR}^{\frac{k-1}{k}}$$

```
Tt3 = 512.8654
```

Total pressure [Pa]

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

```
Pt3 = 4.4650e+05
```

COMPRESSOR

Compressor work [J/kg]

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

```
WC = 2.6201e+05
```

Compressor power [W]

$$P_C = m_p * W_C$$

```
PC = 5.2403e+06
```

Section 4 Burner outlet / Turbine inlet

Total temperature [K]

$$T_{t4}$$

```
Tt4 = 1300
```

Total pressure [Pa]

$$P_{t4} = P_{t3}$$

```
Pt4 = 4.4650e+05
```

BURNER

Fuel-air ratio

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

```
fB = 0.0220
```

Fuel mass flow   [kg/s]

$$m_{fB} = m_0 * f_B$$

```
mfB = 0.4393
```

Section 5   Turbine outlet / Nozzle inlet

Total temperature   [K]

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

```
Tt5 = 1.0809e+03
```

Total pressure [Pa]

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

```
Pt5 = 2.1219e+05
```

Section 9 Engine Nozzle outlet

Total temperature   [K]

$$T_{t9} = T_{t5}$$

```
Tt9 = 1.0809e+03
```

Total pressure [Pa]

$$P_{t9} = P_{t5}$$

```
Pt9 = 2.1219e+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 = 615.9567
```

Jet stream Mach No

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

```
M9 = 2.1388
```

Speed of sound   [m/s]

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

```
a9 = 487.4162
```

Jet speed   [m/s]

$$V_9 = M_9 * a_9$$

```
V9 = 1.0425e+03
```

TURBOJET ENGINE PERFORMANCE CALCULATION

Thrust   [N]

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

```
T = 1.5993e+04
```

Specific thrust   [Ns/kg]

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

```
ST = 799.6289
```

Specific fuel consumption   [kg/N/s]

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

```
SFC = 2.7471e-05
```

Specific fuel consumption   [kg/N/h]

$$SFC = SFC * 3600$$

```
SFC = 0.0989
```

Thermal efficiency

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

```
etha_th = 0.5505
```

Propulsive efficiency

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

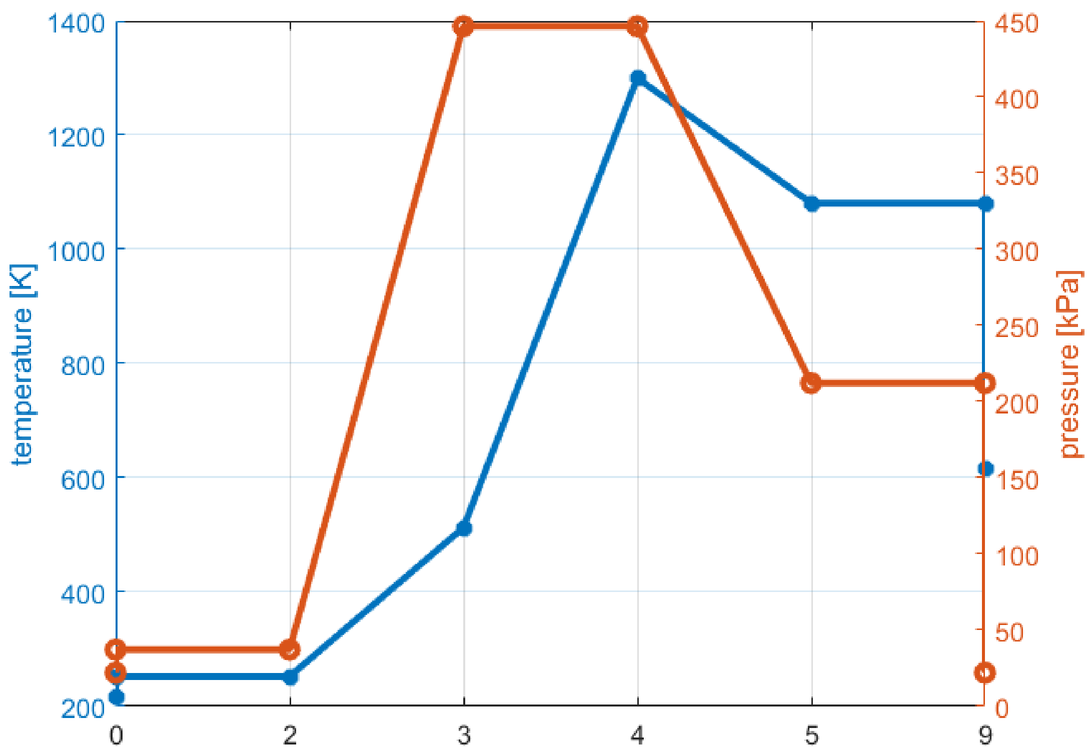
```
etha_p = 0.4087
```

Overall efficiency

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

```
etha_o = 0.2250
```

Temperature, pressure vs engine sections plot



CONCLUSIONS

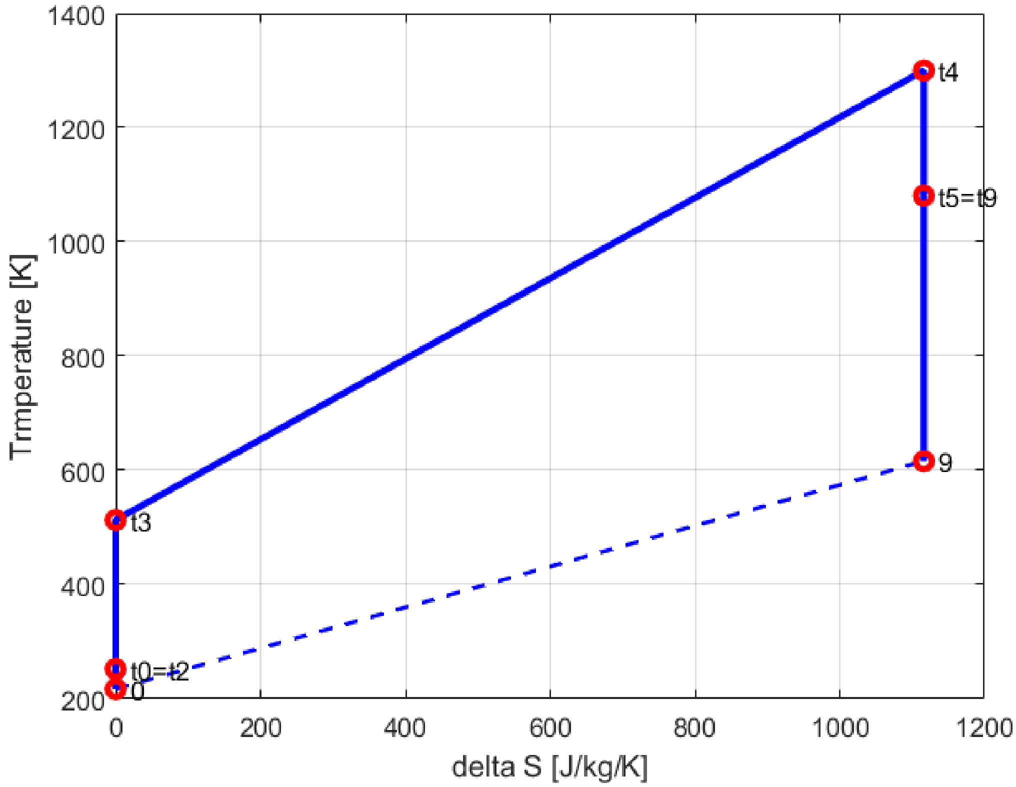
- Pressure increases in inlet (from sataic to total due to flight speed) and compressor
- Pressure decrease in turbine and propelling nozzle (from total to static - jet speed is produecd)
- Tepearture increase in inlet, compressor and combustor
- Temparture decrease in turbine and propeling nozzle

Temperature - entropy plot

Combuctor entropy growth

$$\Delta s = c_{pB} * \ln\frac{T_{t4}}{T_{t3}} - R_t * \ln\frac{P_{t4}}{P_{t3}}$$

```
deltaS = 1.1161e+03
```



CONCLUSIONS

- Ram compression (in the inlet) and compression in the compressor is isentropic as decompression in the turbine and propelling nozzle. The entropy grow is observed in combustion process only

TURBOJET ENGINE WITH AFTERBURNER (AB-ON)

Caclculation done for turbojet engine for Afterburner OFF mode from sections 0 to 5 are valid for Afterburner ON mode

Section AB - AFTERBURNER

Total temperature [K]

$$T_{tAB}$$

```
TtAB = 1750
```

Total pressure [Pa]

$$P_{tAB} = P_{t5}$$

```
PtAB = 2.1219e+05
```

Fuel-air ratio

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

```
fAB = 0.0199
```

Afterburner fuel mass flow [kg/s]

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

```
mfAB = 0.3976
```

Section 9 AB ON

Total temperature [K]

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

```
Tt9AB = 1750
```

Total pressure [Pa]

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

```
Pt9AB = 2.1219e+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 = 1.0373e+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 = 2.1403
```

Speed of sound [m/s]

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

```
a9AB = 632.8441
```

Jet speed [m/s]

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

```
V9AB = 1.3545e+03
```

TURBOJET ENGINE with AFTERBURNER PERFORMANCE CALCULATION

Total fuel-air ratio

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

```
f_AB = 0.0418
```

Total fuel consumption [kg/s]

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

```
mf_AB = 0.8369
```

Thrust [N]

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

```
T_AB = 2.2908e+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 = 1.1454e+03
```

Specific fuel consumption [kg/N/s]

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

```
SFC_AB = 3.6534e-05
```

Specific fuel consumption [kg/N/h]

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

```
SFC_AB = 0.1315
```

Thermal efficiency

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

```
etha_th_AB = 0.5115
```

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 = 0.2309
```

Overall efficiency

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

```
etha_o_AB = 0.1181
```

TURBOJET ENGINE AFTERBURNER OFF/ ON COMPARISON

```
Tabela = 8×4 table
```

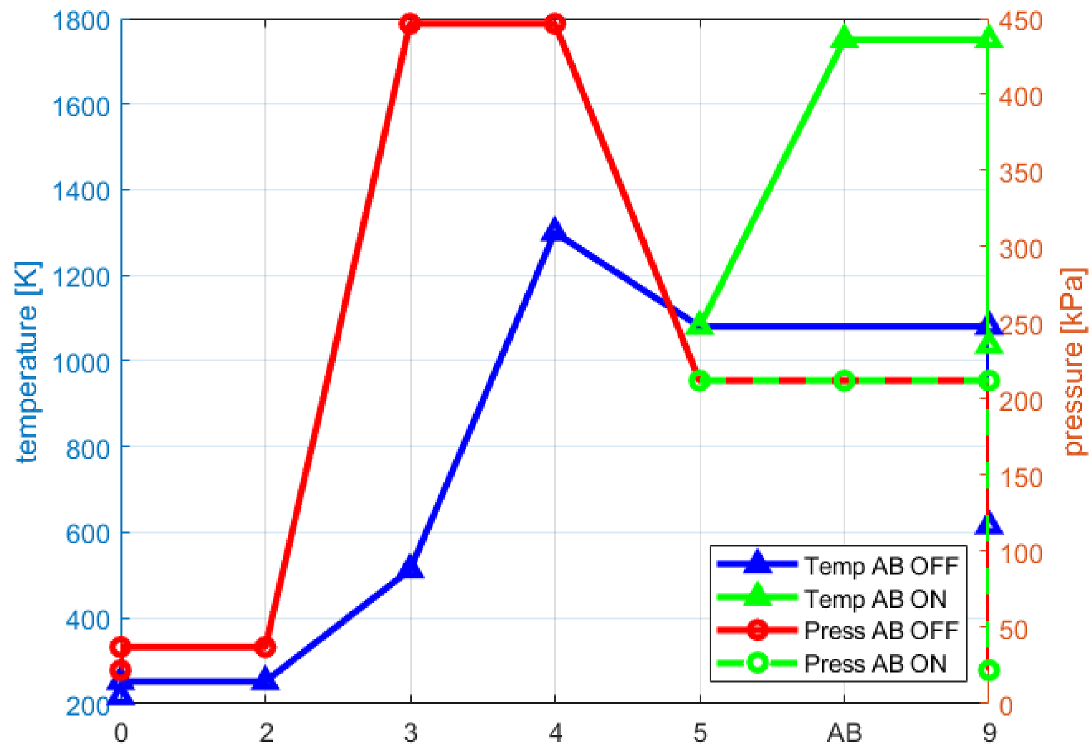
	Parameter	Unit	AB OFF	AB ON
1	'Thrust'	'kN'	15.9926	22.9077
2	'Specific Thrust'	'N*s/kg'	799.6289	1.1454e+03
3	'V9'	'm/s'	1.0425e+03	1.3545e+03
4	'Fuel consumption'	'kg/s'	0.4393	0.8369
5	'Specific fuel...	'kg/N/h'	0.0989	0.1315
6	'therm. effici...	'-'	0.5505	0.5115
7	'prop. efficiency'	'-'	0.4087	0.2309
8	'overall effic...	'-'	0.2250	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 all efficiences (-)

Temperature, pressure vs engine sections plot



CONCLUSIONS:

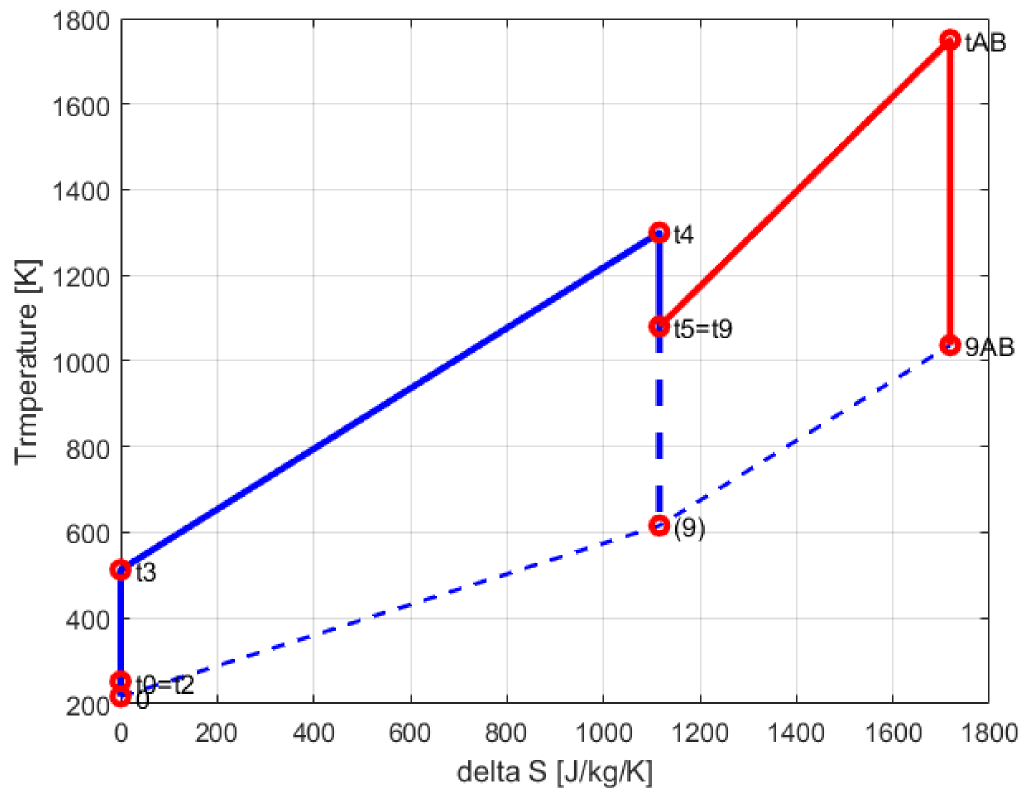
When AB is on than pressure profile in the engine is unchanged and temperature profile is hanged from AB section (temperature is significantly higher in afterburner and propelling nozzle)

Temperature - entropy plot

Afterburner entropy growth

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

```
deltaS_AB = 602.3128
```

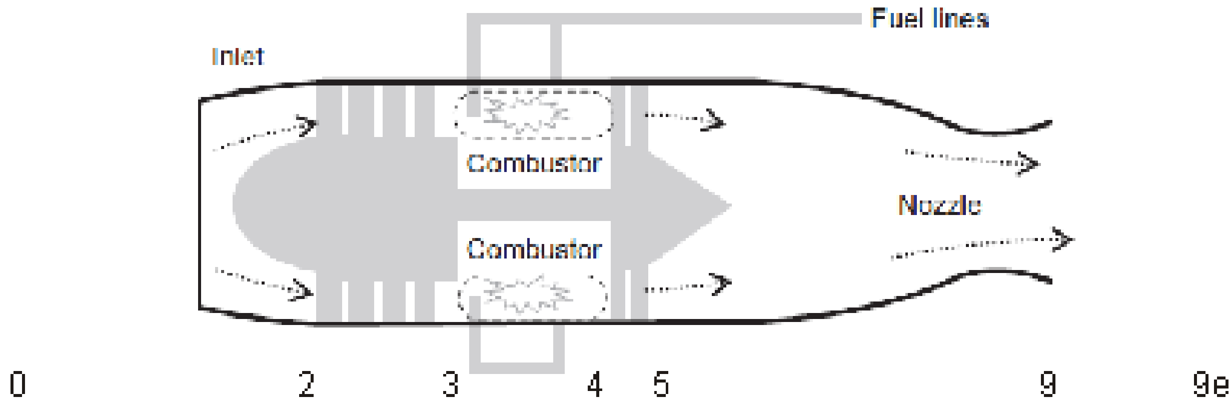


Conclusions:

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. The difference is only that the static pressure in the section 9 isn't equal to ambient pressure, but is higher. In the example p9=Pt9/1.85. 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 done calculation for the engine without afterburner. The difference is only in section 9 static parameters calculation

Section 9 - incomplete expansion in the nozzle

Total pressure [Pa]

$$P_{t9}$$

```
Pt9 = 2.1219e+05
```

Total temperature [K]

$$T_{t9}$$

```
Tt9 = 1.0809e+03
```

Static pressure [Pa]

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

```
P9_IE = 1.1469e+05
```

Static temperature [K]

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

```
T9_IE = 927.8599
```

Mach No. in section 9

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

```
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 = 598.2270
```

Jet speed in section 9 [m/s]

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

```
V9_IE = 598.0558
```

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 = 0.4262
```

Section 9e

Jet speed after expanison 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 = 961.6779
```

Static temperature [K]

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

```
T9e = 685.6451
```

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 = 1.4341e+04
```

Specific thrust [Ns/kg]

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

```
ST_IE = 717.0502
```

Specific fuel consumption [kg/N/s]

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

```
SFC_IE = 3.0635e-05
```

Specific fuel consumption   [kg/N/h]

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

```
SFC_IE = 0.1103
```

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 = 0.4629
```

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 = 0.4358
```

Overall efficiency

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

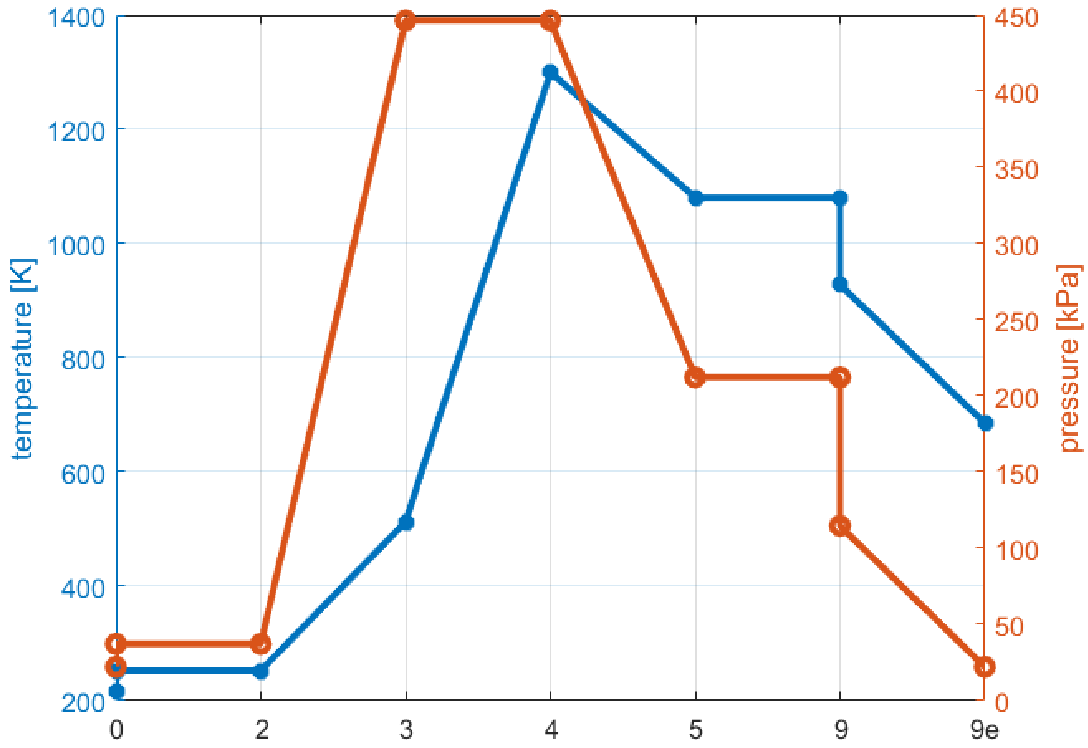
```
etha_o_IE = 0.2017
```

FULL PRESSURE PRESSURE EXPANSION IN THE PROPELLING NOZZLE vs INCOMPLETE PRESSURE EXPANSION - PERFORMANCE COMPARISON

Tabela = 11×4 table

	Parameter	Unit	FULL EXP.	INCOMPLETE EXP.
1	'T9'	'K'	615.9567	927.8599
2	'V9'	'm/s'	1.0425e+03	598.0558
3	'P9'	'kPa'	22	114.6947
4	'T9e'	'K'	615.9567	685.6451
5	'V9e'	'm/s'	1.0425e+03	961.6779
6	'Thrust'	'kN'	15.9926	14.3410
7	'Specific Thrust'	'N*s/kg'	799.6289	717.0502
8	'Specific fuel...	'kg/N/h'	0.0989	0.1103
9	'therm. effici...	'-'	0.5505	0.4629
10	'prop. efficiency'	'-'	0.4087	0.4358
11	'overall effic...	'-'	0.2250	0.2017

Temperature, pressure vs engine sections plot

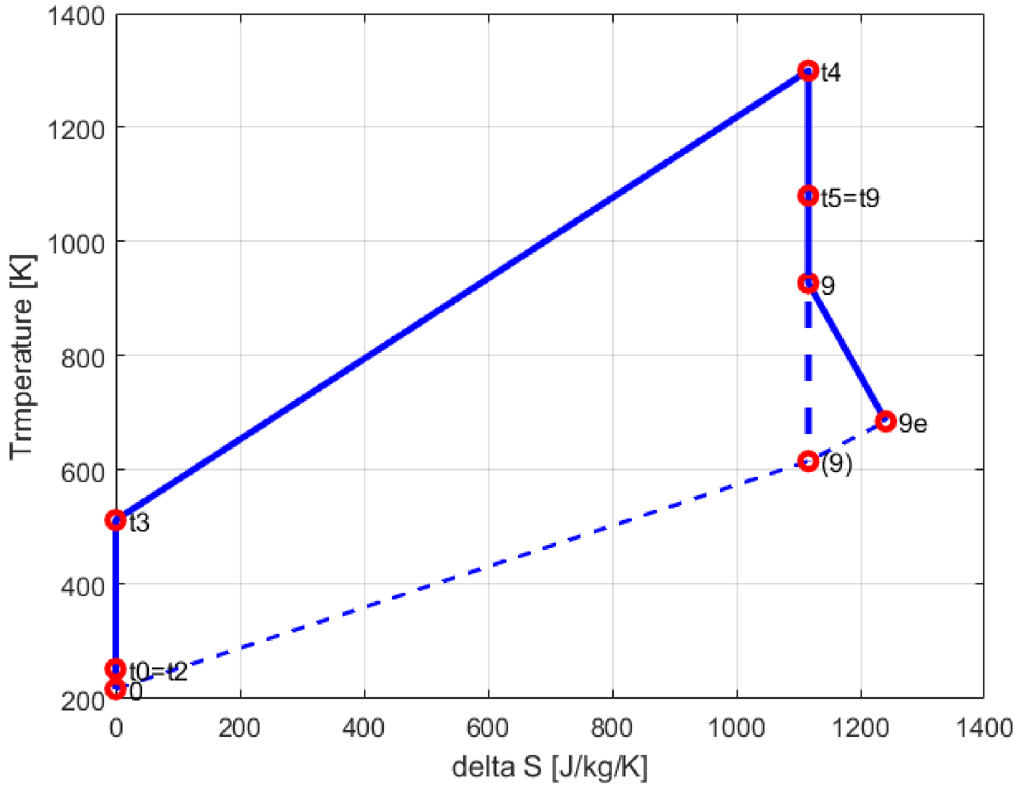


Temperature - entropy plot

Entropy growth 9-9e

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

```
deltaS_9_9e = 124.9080
```



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