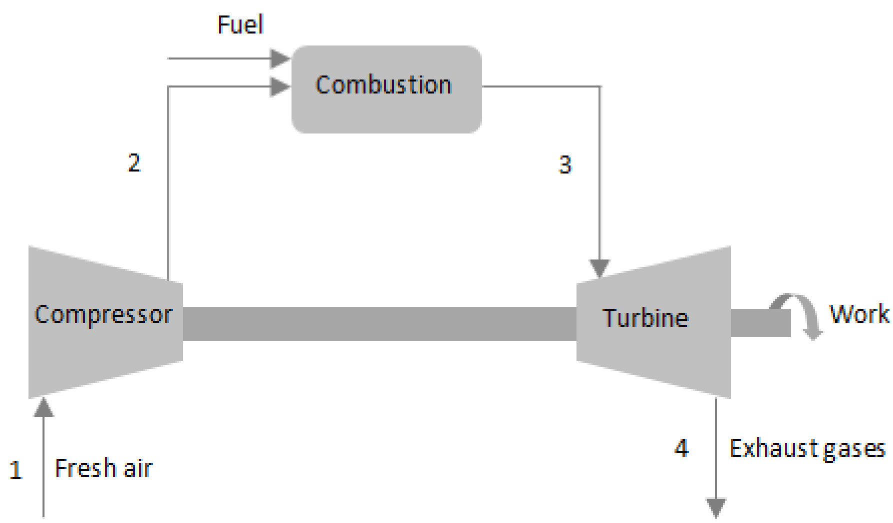
Turbojet Aircraft Engine

An aircraft operates on this thermodynamic cycle.



Get properties from ThermophysicalData package

Property := ThermophysicalData:-Property

Atmosphere := ThermophysicalData:-Atmosphere

TemperatureEntropyChart := ThermophysicalData:-TemperatureEntropyChart

Parameters

Velocity of aircraft and altitude

$v_{aircraft} := 200\ m \cdot s^{-1}$ $\qquad$ $h_{aircraft} := 12\ km$

Heating value of fuel

$H_{fuel} := 4.38 \times 10^{7}\ J \cdot kg^{-1}$

Temperature at point 3

$$T_3 := 1147.63\ \mathrm{K}$$

Compression ratio

$$CPR := 6.5$$

Efficiencies

$$\eta_{combustion} := 0.99 \qquad \eta_{turbine} := 0.9 \qquad \eta_{jetpipe} := 0.95$$

$$\eta_{compressor} := 0.855 \qquad \eta_{drive} := 0.98 \qquad \eta_{intake} := 0.9$$

Area of nozzle

$$A_{nozzle} := 0.168\ \mathrm{m}^2$$

Pressure loss in combustion chamber

$$\Delta P_{chamber} := 0.05793\ \mathrm{bar}$$

Gravity

$$g := 9.81\ \mathrm{m \cdot s^{-2}}$$

Gas constant

$$R_0 := \mathrm{Property}(\mathrm{gasconstant, air, useunits}) = 8.315\ \frac{\mathrm{J}}{\mathrm{mol \cdot K}}$$

Molar mass of dry air

$$M_{DryAir} := \mathrm{Property}(\mathrm{MOLARMASS, air, useunits}) = 2.90 \times 10^{-2}\ \frac{\mathrm{kg}}{\mathrm{mol}}$$

Air Intake to Compressor Inlet

Air temperature and pressure

$$T_0 := \mathrm{Atmosphere}(h_{aircraft}, \mathrm{temperature}) = 216.650\ \mathrm{K}$$

$$p_a := \mathrm{Atmosphere}(h_{aircraft}, \mathrm{pressure}) = 1.933 \times 10^4\ \mathrm{Pa}$$

Kinetic energy of air

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$$KE := 0.5 \cdot v_{aircraft}^2 = 20.00 \ \frac{kJ}{kg}$$

Entropy and enthalpy of air

$$s_0 := \text{Property}(\text{entropy, air, temperature} = T_0, \text{pressure} = p_a) = 4.036 \ \frac{kJ}{kg \cdot K}$$

$$h_0 := \text{Property}(\text{enthalpy, air, temperature} = T_0, \text{pressure} = p_a) = 342.813 \ \frac{kJ}{kg}$$

Assuming air intake is isentropic, entropy at compressor inlet

$$s_1 := s_0$$

Assuming all the kinetic energy turns into sensible heat, the enthalpy at compressor inlet

$$h_1 := h_0 + KE = 3.628 \times 10^5 \ \frac{m^2}{s^2}$$

Temperature at compressor inlet

$$T_{1'} := \text{Property}(\text{temperature, air, enthalpy} = h_1, \text{entropy} = s_1)$$

$$T_1 := \eta_{intake} \cdot (T_{1'} - T_0) + T_0 = 234.614 \ K$$

Pressure at compressor inlet

$$p_1 := \text{Property}(\text{pressure, air, temperature} = T_1, \text{entropy} = s_1) = 25.529 \ kPa$$

Compressor Inlet to Compressor Outlet

Entropy at compressor outlet

$$s_2 := s_1$$

Pressure and temperature at compressor outlet

$$p_2 := CPR \cdot p_1 = 1.659 \times 10^5 \ Pa$$

$$T_2 := \text{Property}(\text{temperature, air, pressure} = p_2, \text{entropy} = s_2) = 400.313 \ K$$

$$T_2 - T_1$$

$$T_{2'} := \frac{\cdots}{\eta_{compressor}} + T_1 = 428.414\ \mathrm{K}$$

Enthalpy at compressor outlet

$$h_2 := \mathrm{Property}\left(\mathrm{enthalpy, air, temperature} = T_{2'}, \mathrm{pressure} = p_2\right) = 556.061\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

Combustor Inlet to Outlet

Pressure loss over combustor

$$p_3 := p_2 - \Delta P_{chamber} = 1.601 \times 10^5\ \mathrm{Pa}$$

Entropy and enthalpy at outlet

$$s_3 := \mathrm{Property}\left(\mathrm{entropy, air}, T = T_3, P = p_3\right) = 5.181\ \frac{\mathrm{kJ}}{\mathrm{kg} \cdot \mathrm{K}}$$

$$h_3 := \mathrm{Property}\left(\mathrm{enthalpy, air, temperature} = T_3, \mathrm{pressure} = p_3\right) = 1.343 \times 10^3\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

Turbine Inlet to Outlet

For an isentropic turbine

$$s_4 := s_3$$

Temperature at outlet

$$T_{4'} := \mathrm{Property}\left(\mathrm{temperature, air, enthalpy} = h_3 - \frac{h_2 - h_1}{\eta_{drive}}, \mathrm{entropy} = s_4\right) = 976.508\ \mathrm{K}$$

Using isentropic efficiency for turbine, pressure and temperature at outlet

$$T_4 := T_3 - \frac{T_3 - T_{4'}}{\eta_{turbine}} = 957.494\ \mathrm{K}$$

$$p_4 := \mathrm{Property}\left(\mathrm{pressure, air, temperature} = T_4, \mathrm{entropy} = s_4\right) = 77.527\ \mathrm{kPa}$$

Nozzle

For choked flow in the nozzle (assuming isentropic operation)

$$\gamma_{expand} := \frac{\text{Property}(C, \text{air}, \text{pressure} = p_4, \text{temperature} = T_4, \text{useunits})}{\text{Property}(\text{Cvmass}, \text{air}, \text{pressure} = p_4, \text{temperature} = T_4, \text{useunits})} = 1.340$$

$$p_c := p_4 \cdot \left(\frac{2}{\gamma_{expand} + 1}\right)^{\frac{\gamma_{expand}}{\gamma_{expand} - 1}} = 41.763 \text{ kPa}$$

$$\text{ifelse}(p_a < p_c, \text{"sonic"}, \text{"subsonic"}) = \text{"sonic"}$$

$$T_{5'} := \frac{2}{\gamma_{expand} + 1} \cdot T_{4'} = 834.791 \text{ K}$$

$$T_5 := T_{4'} - \frac{T_{4'} - T_{5'}}{\eta_{jetpipe}} = 827.332 \text{ K}$$

Jet Pipe

$$p_5 := p_4 \cdot \left(\frac{T_5}{T_{4'}}\right)^{\frac{\gamma_{expand}}{\gamma_{expand} - 1}} = 40.310 \text{ kPa}$$

$$R := \frac{R_0}{M_{DryAir}} = 287.049 \ \frac{\text{J}}{\text{kg} \cdot \text{K}}$$

Specific volume

$$v_{5'} := \frac{R \cdot T_{5'}}{p_5} = 5.945 \ \frac{\text{m}^3}{\text{kg}}$$

Jet gas velocity

$$C_{jet} := \sqrt{\gamma_{expand} \cdot R \cdot T_{5'}} = 566.556 \ \frac{\text{m}}{\text{s}}$$

Mass flow

$$\text{Mflow} := \frac{A_{nozzle} \cdot C_{jet}}{v_{5'}} = 16.011 \ \frac{\text{kg}}{\text{s}}$$

Total thrust

$$\text{Thrust}_{momentum} := \text{Mflow} \cdot \left(C_{jet} - v_{aircraft}\right) = 5.869 \ \text{kN}$$

$$\text{Thrust}_{pressure} := \left(p_5 - p_a\right) \cdot A_{nozzle} = 3.525 \times 10^3 \ \text{N}$$

$$\text{Thrust}_{total} := \text{Thrust}_{momentum} + \text{Thrust}_{pressure} = 9.394 \ \text{kN}$$

Heat supplied

$$Q_{input} := \text{Mflow} \cdot \left(h_3 - h_2\right) = 12.599 \ \text{MW}$$

$$\text{Mflow}_{fuel} := \frac{Q_{input}}{H_{fuel} \cdot \eta_{combustion}} = 0.291 \ \frac{\text{kg}}{\text{s}}$$

Specific fuel consumption

$$\text{SFC} := \frac{\text{Mflow}_{fuel}}{\text{Thrust}_{total}} = 3.09 \times 10^{-5} \ \frac{\text{s}}{\text{m}}$$

Gas temperature as it leaves the jet pipe into the atmosphere

$$T_6 := T_{5'} \cdot \left(\frac{p_a}{p_5}\right)^{\frac{\gamma_{expand} - 1}{\gamma_{expand}}} = 692.913 \ \text{K}$$

Plot Cycle on Temperature-Entropy Plot

Define data to plot

$\text{Temps} := \left[T_0, T_1, T_2, T_3, T_4, T_5, T_6\right]$ $\text{Pressures} := \left[p_a, p_1, p_2, p_3, p_4, p_5, p_a\right]$

NDEntropies :=
[seq(Property(entropy, air, P = Pressures[i], temperature = Temps[i]), i = 1 ..nops(Temps))]

```
p1 := plots:-pointplot(NDEntropies, Temps, connect = true, color = red)

p2 := TemperatureEntropyChart(air, T = 200 K..1200 K,
entropy = 4000 J·kg^-1·K^-1..5500 J·kg^-1·K^-1, isobars = 0.025 bar..20.0 bar )

plots:-display(p1, p2) =
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