LELME2150 - Thermal Cycles
Homework 2 - GT & ST cycles
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Group 42

Dimitri	Boterberg	10271700
Laurent	Ziegler de Ziegleck aùf Rheingrüb	03821500

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Université catholique de Louvain

1 Gas turbine

For the gas turbine cycle, the basic Brayton (see Fig.1) cycle and the combustion process were studied and implemented together.

A few assumptions were made through the development of the Brayton cycle:

- Potential ($g\Delta z$) and kinetic (ΔK) energy terms are neglected.
- Air enters the cycle in stage 1 at atmospheric pressure (1 bar) and temperature ($15°C$).
- The gases are considered as ideal gases. Thus the ideal gas law holds : pV=nRT.
- The combustible is methane (CH_4), with a LHV of 50150 kJ/kg_{CH_4} and the combustive is air, composed of 21% of O_2 and 79% of N_2.
- In order not to have CO production, the combustion is supposed to be complete.

The states of the gas turbine cycle are explained below.

Compression (1→2): The transformation is supposed to be an adiabatic and polytropic compression, with the compression ratio $r = \frac{p_2}{p_1}$.

In generality, the heat capacities of the air constituents change with temperature. Therefore, in order to consider these variations, a mean specific heat capacity is defined as in eq.(1).

$$\bar{C}_{p,air} = \frac{1}{M_{m,air}} \frac{1}{T_f - T_i} (x_{O_2} \int_{T_i}^{T_f} C_{p,O_2} dT + x_{N_2} \int_{T_i}^{T_f} C_{p,N_2} dT) \qquad [\frac{kJ}{kg_{air}K}] \tag{1}$$

The polytropic compression relation is then

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n_a - 1}{n_a}} \qquad \text{with} \qquad \frac{n_a - 1}{n_a} = \frac{1}{\eta_{piC}} \frac{R_a(T_2 - T_1)}{C_{p,a}|_0^{t_2} t_2 - C_{p,a}|_0^{t_1} t_1} \tag{2}$$

Combustion (2→3): Regarding the combustion process, in order to find the excess-air coefficient, the temperature at the inlet of the turbine (at state 3) is considered as the maximal temperature allowable. Otherwise, damages to the turbine blades could occur.

The balance of the complete and stoechiometric combustion of a fuel of type $C_zH_yO_x$, as shown in p.37 in the book [1], is

$$C_zH_yO_x + \lambda\left(z + \frac{y-2x}{4}\right)(O_2 + 3.76N_2) \rightarrow (\lambda - 1)\left(z + \frac{y-2x}{4}\right)O_2 + zCO_2 + \frac{y}{2}H_2O + 3.76\left(z + \frac{y-2x}{4}\right)N_2 \tag{3}$$

The stoechiometric air-to-fuel ratio, which is the amount of air required for the complete and stoechiometric combustion of one mole of fuel is defined as

$$m_{a1} = \left(1 + \frac{y-2x}{4}\right)\frac{(M_{m,O_2} + 3.76M_{m,N_2})}{(12z + y + 16x)} \qquad \left[\frac{kg_{air}}{kg_{fuel}}\right] \tag{4}$$

With $M_{m,O_2} = 32\ g/mol$ the molar mass of O_2, $M_{m,N_2} = 28\ g/mol$ the molar mass of N_2. The molar mass and the molar fractions of flue gas can be computed using eq.(3). Here, we consider methane as combustible, so $z = 1, y = 4, x = 0$. We then get $m_{a1} = 17.1204\ \frac{kg_{air}}{kg_{fuel}}$

As with the air, the flue gas constituents varies with temperature. Therefore, one can define a mean specific heat capacity to consider these variations, see eq.(5).

$$\bar{C}_{p,flue} = \frac{1}{M_{m,flue}} \frac{1}{T_f - T_i} \Bigg(x_{O_2} \int_{T_i}^{T_f} C_{p,O_2} dT + x_{N_2} \int_{T_i}^{T_f} C_{p,N_2} dT + x_{CO_2} \int_{T_i}^{T_f} C_{p,CO_2} dT + x_{H_2O} \int_{T_i}^{T_f} C_{p,H_2O} dT \Bigg) \qquad \left[\frac{kJ}{kg_{flue}K}\right] \tag{5}$$

The excess-air coefficient λ is found by iteration using the expression of the combustion calorific action

$$Q_{comb} = \frac{1}{\lambda m_{a1}} LHV = \left(1 + \frac{1}{\lambda m_{a1}}\right) h_3 - h_2 \tag{6}$$

which gives

$$\lambda = \frac{LHV - h_3}{m_{a1}(h_3 - h_2)} \tag{7}$$

With heat capacities defined as in eq.(5), and taking the standard conditions $T_s = 273.15\ K, p_s = 1\ bar$, one can get $\lambda = 2.3178$.

Expansion (3→4): The expansion in the turbine is an adiabatic and polytropic transformation. The expansion ratio is $\frac{p_3}{p_4} = \frac{p_3}{p_1} = k_{cc} r$, with the pressure ratio $k_{cc} = \frac{p_3}{p_2} (< 1)$, which characterizes the aerodynamic perfection of the combustion chamber. The polytropic expansion relation is then

$$\frac{T_4}{T_3} = \left(\frac{p_4}{p_3}\right)^{\frac{n_g - 1}{n_g}} \qquad \text{with} \qquad \frac{n_g - 1}{n_g} = \eta_{piT} \frac{R_g}{C_{p,g}|_{t_4}^{t_3}} \tag{8}$$

States results: With the initial conditions of the numerical application p.125 of the book [2], we get theses results for the states

States	p $[kPa]$	T $[°C]$	h $[kJ/kg]$	s $[kJ/kgK]$	e $[kJ/kg]$
1	100	15	0	0	0
2	1800	429	431.5	0.093	405
3	1710	1400	1652.4	1.200	1307
4	100	658	701.9	1.283	332

The various mass flow rates are

$$\dot{m}_a = 440.7785\ kg/s,\ \dot{m}_c = 11.1076\ kg/s,\ \dot{m}_g = 451.8861\ kg/s$$

Energetic and exergetic analysis: The exergy at state i is computed as $e_i = (h_i - h_1) - T_1(s_i - s_1)$, with the reference state $e_1 = 0\ kJ/kg$.

One can analyse the losses, see Fig.3a and Fig.3b.

- $\dot{L}_{mec} = P_e - \dot{m}_f(h_4 - h_3) + \dot{m}_a(h_2 - h_1)$
- $\dot{L}_{ech} = \dot{m}_g h_4 - \dot{m}_a h_1$
- $\dot{L}_{rotex} = \dot{m}_a \Big[(h_2 - h_1) - (e_2 - e_1)\Big] + \dot{m}_g \Big[(e_3 - e_4) - (h_3 - h_4)\Big]$
- $\dot{L}_{combex} = \dot{m}_c e_c + \dot{m}_a e_2 - \dot{m}_g e_3$
- $\dot{L}_{echex} = \dot{m}_g e_4 - \dot{m}_a e_1$

and the computed efficiencies are

	η_{cyclen}	η_{toten}	η_{cyclex}	η_{totex}	η_{rotex}	η_{combex}
Efficiencies [-]	0.430	0.413	0.581	0.397	0.914	0.711

Table 1: Efficiencies of the gas turbine cycle.

We notice that the main loss of energy and exergy in this Brayton cycle – if we forget about irreversibilities – are located at the exhaust. One way to make use of this loss of exergy would be to combine the gas turbine cycle with a steam turbine.

2 Steam turbine

The steam turbine cycle is computed based on the basic Rankine cycle, see Fig.4. As initial data we have T_1, the temperature at the exit of the condenser, T_3 and p_3 the temperature and pressure at the inlet of the turbine.

State 1: At the exit of the condenser, the fluid is a saturated liquid (x=0). The tables (or the CoolProp python library) are used to compute the thermodynamic properties of state 1.

State 2: The water passes through a pump of internal efficiency η_{pump}. Therefore, one can get

$$T_2 = T_1 + \frac{v\Delta p}{C_p}\left(\frac{1}{\eta_{pump}} - 1\right) \tag{9}$$

The transformation from 2 to 3 is supposed to be isobaric, therefore $p_2 = p_3$.

State 3: The water enters the steam generator, where the combustion of coal will evaporate the water then overheat the steam until it reaches the temperature T_3.

State 4: The expansion is adiabatic with an isentropic efficiency $\eta_{si,T}$. This efficiency can be defined as

$$\eta_{si,T} = \frac{w_m}{w_{m,si}} = \frac{h_4 - h_3}{h_{4_{si}} - h_3} \tag{10}$$

We can therefore find $h_4 = h_3 + \eta_{si,T}(h_{4,si} - h_3)$ and then the vapor quality at state 4

$$x_4 = \frac{h_4 - h_4^{'}}{h_4^{''} - h_4^{'}} \tag{11}$$

Energetic and exergetic analysis: The exergy at state i is computed as $e_i = (h_i - h_1) - T_1(s_i - s_1)$, with the reference state $e_1 = 0\ kJ/kg$.

Based on the numerical application of p.62 of the reference book [2], we can compute the losses and the efficiencies of the basic steam turbine cycle. The different energetic losses in the steam turbine cycle are the mechanical losses, the losses at the condenser and the steam generator losses, see Fig.5.

- $\dot{L}_{mec} = \dot{m}_v(w_{m,T} - w_{m,P}) - P_e = \dot{m}_v\Big[(h_3 - h_4) - (h_2 - h_1)\Big] - P_e$
- $\dot{L}_{cond} = \dot{m}_v(h_4 - h_1)$
- $\dot{L}_{gen} = \dot{m}_c LHV - \dot{m}_v(h_3 - h_2)$

As can be seen in Fig.5, nearly 60% of the primary energy flux is lost at the condenser.

The computed efficiencies are

	η_{cyclen}	η_{toten}
Efficiencies [-]	0.367	0.339

Table 2: Efficiencies of the basic steam turbine cycle.

A GT cycle figures

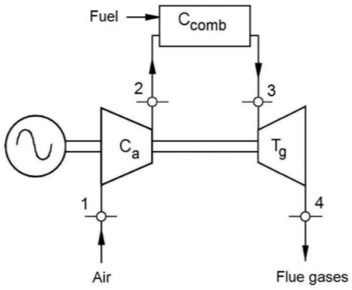
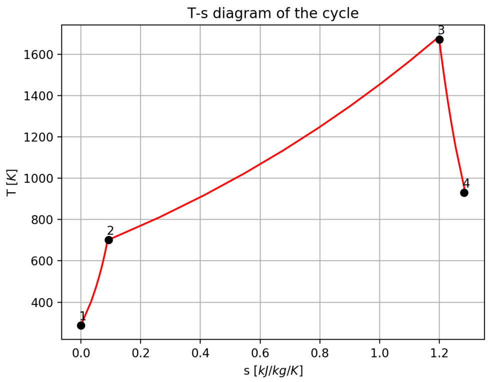
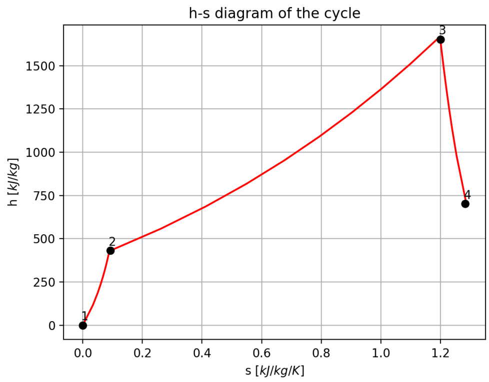


Figure 1: Schematic of the Gas Turbine cycle. (Recovered from the reference book [2] at p.106)

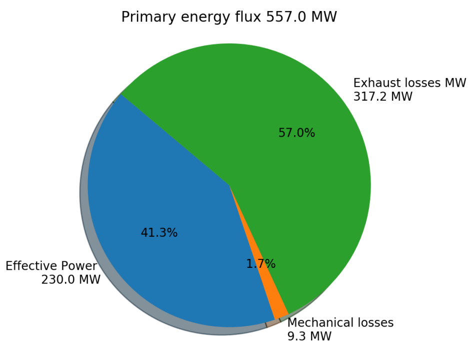


(a) T-s diagram of the gas turbine cycle.

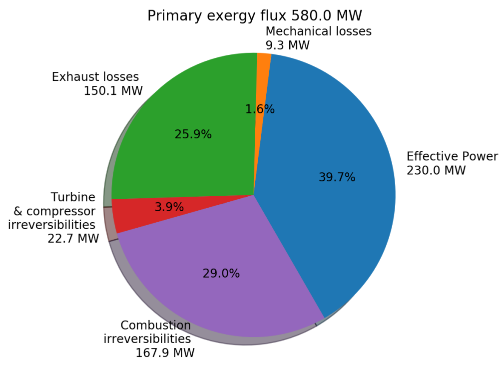


(b) h-s diagram of the gas turbine cycle.

Figure 2: Cycle diagrams for the gas turbine.



(a) Energy fluxes of the gas turbine cycle.



(b) Exergy fluxes of the gas turbine cycle.

Figure 3: Energy fluxes for the gas turbine.

B ST cycle figures

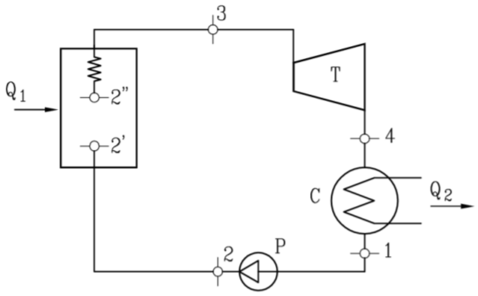


Figure 4: Schematic of the basic Steam Turbine cycle. (Recovered from the reference book [2] at p.42)

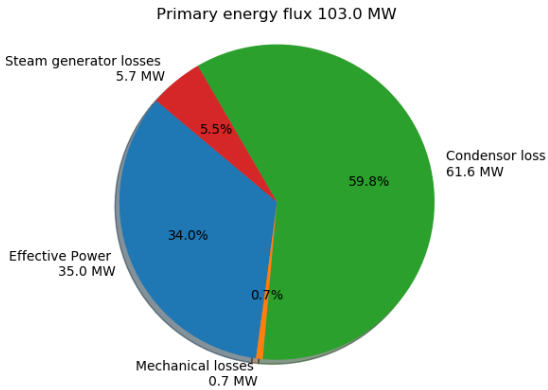


Figure 5: Energy fluxes of the basic steam turbine cycle.

References

[1] Miltiadis V. Papalexandris. Combustion and fuels.

[2] P. Wauters D. Johnson, J. Martin. Thermal power plants, Energetic and exergetic approaches.