LELME2150 - Thermal Cycles
Homework 2 - Gas Turbines

Introduction

The objective of this homework is to simulate basic gas turbines to quantify the energy and exergy losses in different conditions. Through this work, students will be able to:

- Apply energy and exergy analyses to the gas turbine technology;
- Understand which parameters are energy and exergy efficiencies most sensitive to;
- Discuss how gas turbines could be further improved;
- Demonstrate an in-depth understanding of the gas turbine technology.

The **deadline** for this homework is **Sunday 12 October at 23:59**. Before submitting, we advise you to test your code! A code that does not pass the basic test provided will receive a score of 0. Please submit your `Python` script and the 4-page report in the designated area on Moodle.

Tasks

1. Download the signature (gas_turbine_group_xx.py);
2. Rename the script with your group number (0x if number lower than 10);
3. Download the test code (gas_turbine_test.py);
4. Fill the signature with your own gas turbine model;
5. Prepare a **max 4-page report** to summarise your modelling assumptions and present key findings. This report must at least include (see examples later):
   - relevant equations, modelling assumptions and methodology;
   - table of the states obtained with your model in default conditions (the ones that are given in the test code);
   - T-s and p-h diagrams in default conditions (with correct curvature - no straight lines);
   - energy and exergy pie charts in default conditions;
   - relevant and meaningful parametric analyses (sensitivity of e.g. cycle energy efficiency, net specific work, CO2 emissions, ... to e.g. compression ratio, turbine inlet temperature, polytropic efficiencies, pressure losses in combustor, fuel composition, ambient air pressure and temperature, ...);
   - a conclusion where you suggest cycle/system improvements, discuss the main constraints and connect your results to real applications (power plant, jet engines, ...).

Your codes will be tested. The final grade will be highly correlated to the quality of the parametric analyses and discussions.

Statement

Consider the gas turbine cycle as shown in Figure 1.

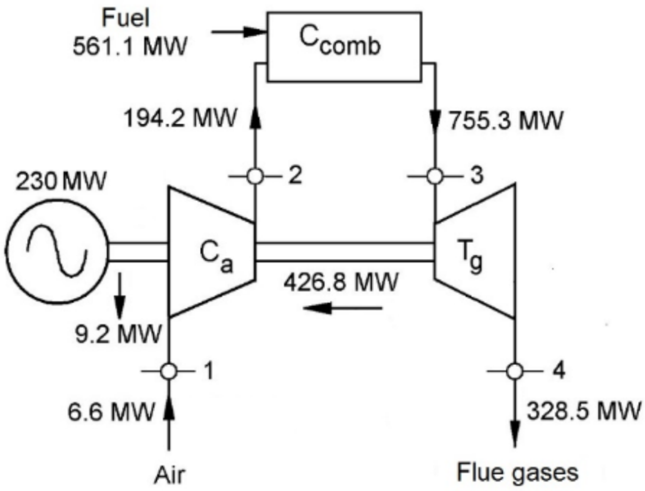

Figure 1: Basic gas turbine in default conditions.

In HW1, you have modelled the combustion process a simple adiabatic heat transfer assuming air as working fluid all along the cycle. However, in a real gas turbine, the flue gas also contain H2O and CO2 and this significantly modifies the heat capacity of the working fluid (see fig 3.12 in the textbook). Therefore, in this homework you will include a combustion model to your gas turbine model.
The analysis of combustion leads to an implicit problem:

1. Chemical reaction:

$$C_xH_y+\lambda\left(x+\frac{y}{4}\right)\left(O_2+\frac{x_{N_2}}{x_{O_2}}N_2\right)\rightarrow\left(x+\frac{y}{4}\right)(\lambda-1)O_2+xCO_2+\frac{y}{2}H_2O+\frac{x_{N_2}}{x_{O_2}}\lambda\left(x+\frac{y}{4}\right)N_2$$

2. Energy conservation:

$$\dot{m}_g h_3 = \dot{m}_a h_2 + \dot{m}_f(LHV + h_f)$$

3. Mass conservation:

$$\dot{m}_g = \dot{m}_a + \dot{m}_f$$

4. Specific combustive index and excess air coefficient:

$$\dot{m}_a = \lambda m_{a1}\dot{m}_f$$

With the 3 last relations, we can obtain:

$$\lambda = \frac{LHV + h_f - h_3}{m_{a1}(h_3 - h_2)}$$

This equation must be solved iteratively, since h_3 depends on the combustion products composition, which itself is a function of λ:

$$h_3 = x_{O_2}(\lambda)h_{O_2}(p_3,T_3) + x_{N_2}(\lambda)h_{N_2}(p_3,T_3) + x_{CO_2}(\lambda)h_{CO_2}(p_3,T_3) + x_{H_2O}(\lambda)h_{H_2O}(p_3,T_3)$$

To obtain the values tabulated in the book p.125, the reference state for enthalpies and entropies should be set at $p_0 = 1$ bar and $T_0 = 0°C$[1]. This can be done using the `set_reference_state()` function from `CoolProp.CoolProp`.

In addition to this, you will perform exergy analyses of the gas turbine. Based on the methodology learned from lecture 1 to 3, you will assess which part of the system is the main exergy destructor and discuss potential improvements.

The inputs of your model will be the following:

- p_1, T_1: the compressor supply pressure and temperature;
- P_e: the gas turbine net power output;
- T_3: the turbine inlet temperature;
- r_c: the compressor pressure ratio;
- η_{pC}: the compressor polytropic efficiency;
- η_{pT}: the turbine polytropic efficiency;
- k_{cc}: the combustor pressure losses coefficient;
- k_{mec}: the mechanical losses coefficient;
- air = ['N2','O2'] and air_prop = [x_{N_2},x_{O_2}]: the air molar composition;
- alkane = [x_C,x_H]: the fuel composition (only methane will be tested but you can implement other fuels for your analyses);
- display: a boolean to choose to plot the diagrams (i.e. T-s, p-h, energy pie chart and exergy pie chart).

For more information on these variables, please refer to the textbook.
The necessary outputs of your model are:

- DAT = p,T,s,h,e: the thermodynamic states (pressure [Pa], temperature [K], entropy [J/kg/K], enthalpy [J/kg] and exergy [J/kg]);
- COMBUSTION = LHV,e_f,excess_air,gas,gas_prop: the combustion parameters (fuel lower heating value [J/kg], fuel exergy [J/kg], excess air coefficient, flue gas species and associated molar fractions);
- MASSFLOW = dotm_a,dotm_f,dotm_g: mass flow rates [kg/s] (air, fuel and flue gas);
- ETA = eta_cyclen,eta_toten,eta_mec,eta_cyclex,eta_totex,eta_rotex,eta_combex: energy and exergy efficiencies (cycle, total, mechanical, rotor assembly, combustion);
- DATEN = loss_mec,loss_echen: energy losses [W] (mechanical and exhaust);

[1]Remark: For water, the reference state must be defined at T_0 and saturated vapor.

- DATEX = loss_mec,loss_rotex,loss_combex,loss_echex: exergy losses [W];
- FIG = fig_pie_en,fig_pie_ex,fig_Ts,fig_ph: figures (energy and exergy pie charts, T-s and p-h diagrams with correct curvature - no straight line connecting the points).

Before submitting, please make sure that you follow these guidelines:

- If `display` is set to `False`, the code must not generate any plots.
- Do not import any additional packages beyond those already provided.
- The code should produce no printed output, as this complicates the evaluation process.
- All output variables must be filled in.
- The submission must consist of a single, self-contained file that can be executed independently.