Renewable Energy: Solar Thermal Exercise

In this exercise you will design a concentrating solar power plant and apply basic knowledge in thermodynamics and solar energy conversion technologies.

The Rankine cycle-based power plant Gemasolar was built in Fuentes de Andalucía (Sevilla) in 2011 and is the first of its kind commercially operated. The plant applies the technologies of a central tower receiver and molten salt heat storage. The heat storage permits continuous turbine operation at the rated capacity even after sunset or when there is a reduction in solar radiation due to clouds. Thus, the plan supplies clean and safe base-load power to 25'000 homes. We will use the attached fact sheet to estimate the key figures of the Gemasolar plant.
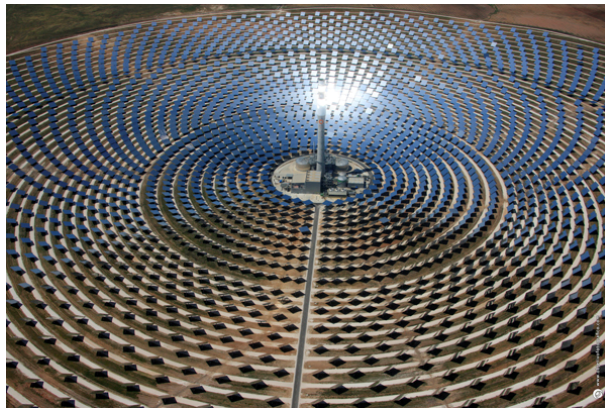

Figure 1: Photo of the Gemasolar power plant (torresolenergy.com).

1. Power block:

   (a) Calculate the rated power of the steam turbine to supply the equivalent of the energy demand of 25'000 homes.

   (b) Calculate pressure, temperature, and enthalpy at each state of the Rankine cycle.

   (c) Calculate the mass flow rate of the water.

   Assumptions:

   - Annual domestic electrical demand in Spain: 5'100 kWh/household.
   - 0.5 MW of the generated electricity is internally used (pumps, control of heliostat field etc.).
   - No pressure drop or heat loss through the connecting lines.

2. Storage:

   (a) Calculate the net thermal heat flux required from the molten salt tank to run the turbine at the rated power.

   (b) Calculate the mass flow of the molten salt from the hot to the cold storage.

   (c) Calculate the thermal storage capacity (equivalent hours of turbine operation).

   Assumption:

   - Adiabatic storage tanks.

3. Solar tower and field:

   (a) Calculate the total heat absorbed by the receiver during an average day in Spain in June.

   (b) Calculate the total reflective area of the heliostat field.

   (c) Calculate the total number of heliostats needed.

   Assumption:

   - Solar receiver: blackbody, perfectly insulated (no convection/conduction losses).

4. Efficiency:

   (a) Calculate the thermal-to-electric efficiency for a day in June with continuous 24h baseload supply.

   (b) Calculate the overall efficiency for a day in June with continuous 24h baseload supply (solar energy to electricity supplied to the grid).

5. Emission mitigation:

   (a) Calculate the annual electricity generation.

   (b) Calculate the annual CO_2 mitigation potential of the solar powered Rankine-cycle compared to a conventional combined cycle power plant with 50% efficiency.

   (c) Calculate the annual CO_2 mitigation potential of the solar powered Rankine-cycle compared to the standard electrical network mix in Spain.

   Assumptions:

   - Heating value of natural gas: 47 MJ/kg.
   - Consider a complete combustion via $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$.
   - The CO_2 emissions of the electrical network mix in Spain is estimated by $300\,\mathrm{g_{CO_2}}/\mathrm{kWh}$.

6. Parameter variation:

   Use Matabl's XSteam function http://www.mathworks.com/matlabcentral/fileexchange/9817-x-steam–thermodynamic-properties-of-water-and-steam and implement the above cycle with storage in Matlab. As an engineer in charge of implementing a new Rankine cycle-based solar power plant, your task is to know if there are possibilities to increase the storage capacity by modifying different operating conditions such as:

   (a) The turbine inlet pressure: varying between 70-250 bar.

   (b) The turbine inlet temperature: varying between 400-750 °C.

   (c) The power block outlet steam quality: varying between 85% and 95%.

   (d) The condenser outlet temperature: varying between 290 K and 322 K.

   Plot these four different cases and comment.

   Hint: Copy the m-file "XSteam.m" in your current MATLAB directory. The following syntax allows for evaluating steam properties: h = XSteam('h_pT',p,T). Three arguments are required, first, a string ('h_pT') indicating which quantity you want to compute based on which two other quantities, and the other two quantities (p,T). The input units are: °C , bar, kJ/kg, kJ/(kg_m) and m^3/kg. A full list of possible strings as first arguments are given in the file "XSteam.m", relevant for the exercise are: h_pT , T_ph , hL_p , Tsat_p , vL_p, where h is specific enthalpy, L after parameter means saturated liquid and V saturated vapor, T is temperature, and p is pressure. The supplement sat can be used after T or p to evaluate saturation temperature or pressure. Note that when evaluating properties at saturation only one value will be required (e.g. Tsat_p or vL_p).