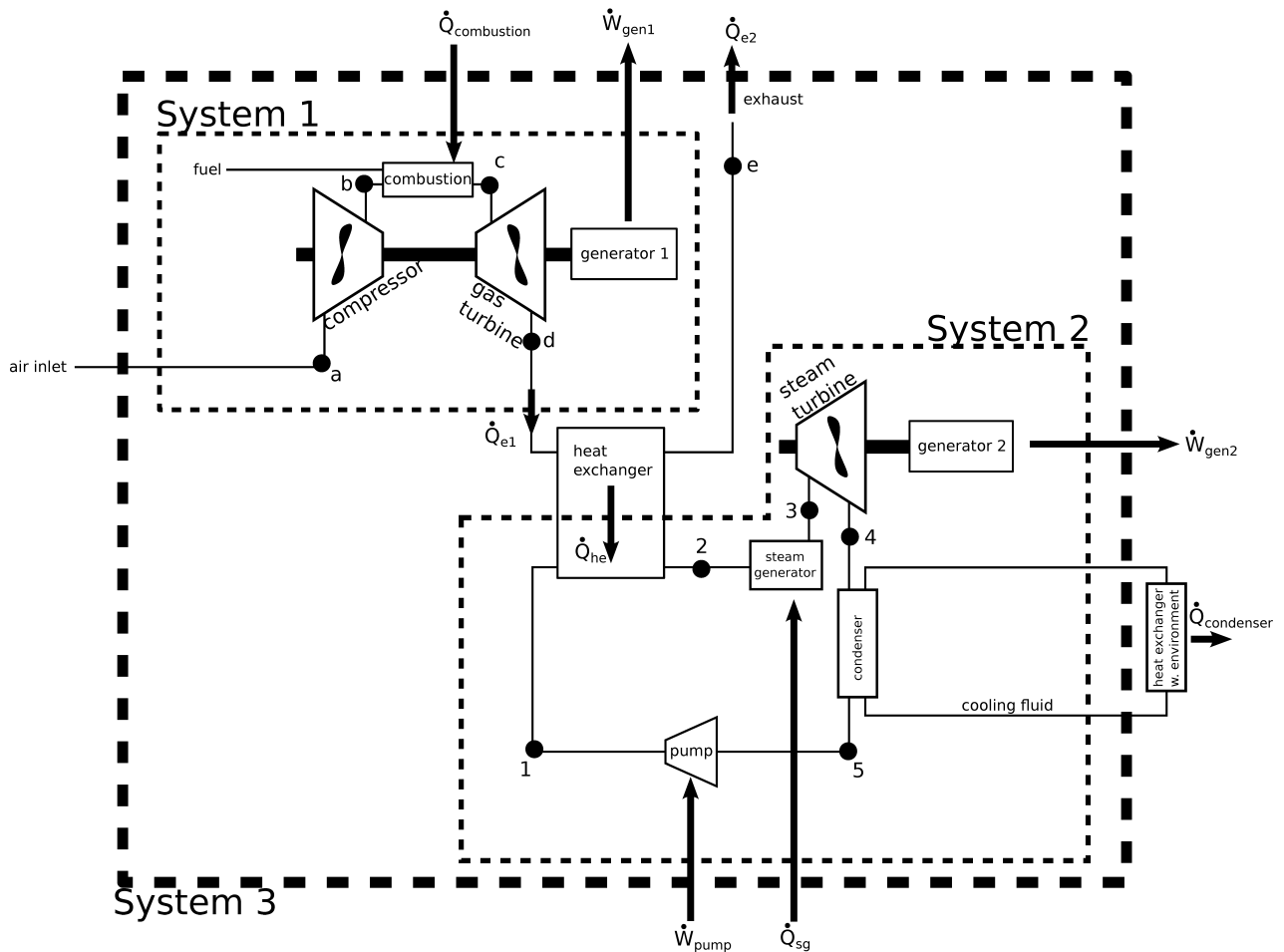


## Renewable Energy: Thermodynamics Exercise

In this exercise, you will evaluate thermodynamic power cycles and apply the thermodynamic basics. One cycle is relevant for combustion processes (combined Rankine and Brayton) and one is relevant for geothermal processes (combined flash and ORC cycle).

### Exercise 1: Combined cycle

Consider the following combined cycle power plant (gas turbine and steam turbine, figure 1).



**Figure 1:** Combined cycle power plant, with system boundaries and energy fluxes

The following assumptions can be used throughout the exercise:

- Steam generation, heat exchange and condensing occur isobarically
- Turbines, pump and compressor operate without heat losses
- Heat exchangers operate adiabatically and isobarically
- Electricity generators have an efficiency of 100%

**Hint:** The information given in a) remains valid in b). b) can be solved without knowledge of the solution of a).

(a) Consider the gas turbine (system 1) only. Assume that air and exhaust gases behaves as a perfect gas with  $\kappa = c_p/c_v = 1.3$  and specific heat of  $c_p = 1100 \text{ J/kg/K}$  ( $\kappa$  and  $c_p$  are constant). Neglect the addition of mass by added fuel. The energy added by the combustion of fuel is taken into account by  $\dot{Q}_{\text{combustion}}$ . A mass flow of air of  $\dot{m}_{\text{air}} = 20 \text{ kg/s}$  enters the compressor at environment conditions ( $p_a = 1\text{bar}$ ,  $T_a = 300\text{K}$ ). The compressor operates isentropically, the combustion occurs isobarically, and the expansion in the turbine is isentropic. At compressor outlet the air pressure reaches  $p_b = 10\text{bar}$ . The maximum temperature reached is  $1500\text{K}$ . After expansion the exhaust temperature is  $T_d = 700\text{K}$ .

- Draw the  $pV$  and  $Ts$ -diagrams of the processes  $a - b - c - d$ .
- Calculate the molar mass of air. What is the volumetric flow rate in  $\text{m}^3/\text{s}$  ( $\dot{V}_{\text{air}}$ ) at the compressor inlet?
- What is the temperature  $T_b$ ?
- How much energy  $\dot{Q}_{\text{combustion}}$  is added during combustion?
- What is the thermal efficiency of system 1 ( $\eta_{th,1}$ )?

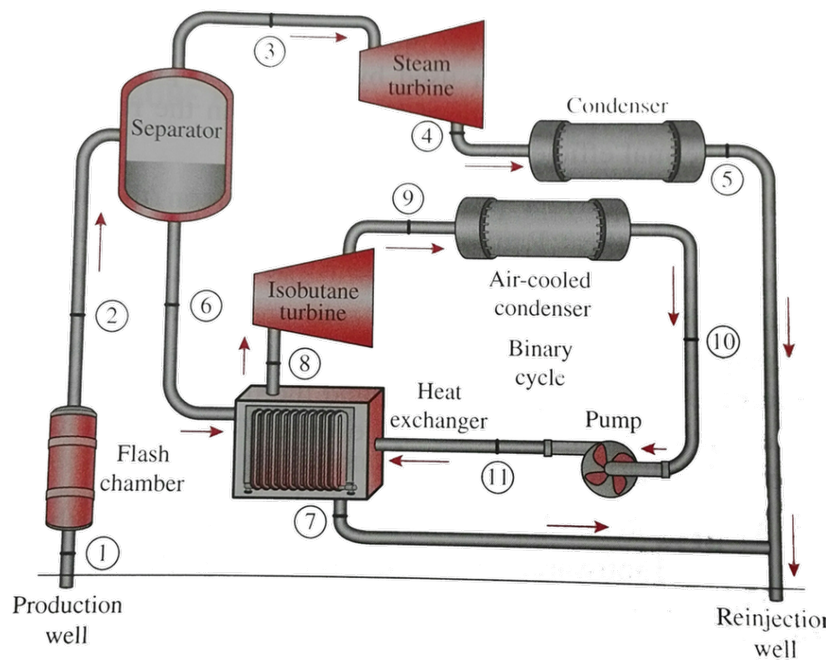
**Hint:** From the point of view of system 1,  $\dot{Q}_{e1}$  is completely lost.

- (b) Consider the steam turbine (system 2) only. After the pump the working medium is liquid water at  $p_1 = 80\text{bar}$  and with a specific enthalpy of  $h_1 = 1300\text{ kJ/kg}$  and a mass flux of  $\dot{m}_{\text{water}} = 5\text{ kg/s}$ . Due to the added heat ( $\dot{Q}_{\text{he}} + \dot{Q}_{\text{sg}}$ ) the state of superheated steam is reached before entering the turbine ( $p_3 = 80\text{bar}$ ,  $T_3 = 510^\circ\text{C}$ ). The isentropic efficiency of the steam turbine is given as  $\eta_{\text{is,steam turbine}} = 1$  and the turbine exit pressure is  $p_4 = 0.06\text{bar}$ . After the condenser the state of saturated liquid water is reached. The properties of water may be obtained from <http://webbook.nist.gov/chemistry/fluid/>.
- (i) How much heat is added to the steam in total ( $\dot{Q}_{\text{he}} + \dot{Q}_{\text{sg}}$ )?
  - (ii) Assuming that the exhaust gases of system 1 are cooled down from  $T_d = 700\text{K}$  to  $T_e = 400\text{K}$ , what is the percentage of heat recovered from the gas turbine exhaust ( $\frac{\dot{Q}_{\text{he}}}{\dot{Q}_{\text{he}} + \dot{Q}_{\text{sg}}}$ )?  
**Hint:** For properties of air refer to the information given in a).
  - (iii) What is the state of the working fluid at point 2? Calculate  $x_2$ .
  - (iv) What is the pump work? Do not use any approximation regarding the incompressibility of water.
  - (v) What is the thermal efficiency of the steam cycle ( $\eta_{\text{th},2}$ )?  
**Hint:** From the point of view of system 2  $\dot{Q}_{\text{he}}$  is considered as input.
- (c) What is the thermal efficiency  $\eta_{\text{th},3}$  of the combined cycle (system 3)?

### Exercise 2: Geothermal power cycle

The schematic of a geothermal power plant using a single-flash combined with a isobutane-run Rankine cycle with state numbers is given figure 2. A geothermal resource exists as saturated liquid at  $230^\circ\text{C}$ . The geothermal liquid (assumed to be water) is withdrawn from the production well at a rate of  $230\text{ kg/s}$ , and is flashed to a pressure of  $500\text{ kPa}$  by an isenthalpic flashing process where the resulting vapor is separated from the liquid in a separator and directed to the turbine. The steam leaves the turbine at  $10\text{ kPa}$  with a moisture content of 10 percent and enters the condenser where it is condensed and routed to a reinjection well along with liquid coming off the separator and heat exchanger.

For the bottoming cycle, geothermal liquid water leaves the heat exchanger at  $90^\circ\text{C}$  while isobutane enters the isobutane turbine at  $3.25\text{ MPa}$  and  $145^\circ\text{C}$  and leaves it at  $80^\circ\text{C}$  and  $400\text{ kPa}$ . Isobutane is condensed in an air-cooled condenser and then pumped to the heat exchanger pressure. Assume an isentropic efficiency of 90 % for the pump. The properties of water and isobutane may be obtained from <http://webbook.nist.gov/chemistry/fluid/>.



**Figure 2:** Geothermal power plant using a single-flash combined with a isobutane-run Rankine cycle

Draw the topping and bottoming cycle in a  $Ts$ -diagram. Determine

- the mass flow rate of steam through the steam turbine.
- the isentropic efficiency of the steam turbine.
- the power output of the steam turbine.
- the thermal efficiency of the topping cycle (ratio of the steam turbine work output to the energy of the geothermal fluid relative to the standard ambient conditions, i.e. 25 °C and 1 atm).
- the mass flow rate of isobutane in the bottoming cycle.
- the net power outputs of both the topping (flashing) and bottoming (binary) cycles of the plant.
- the thermal efficiencies of the bottoming (binary) cycle and of the combined plant.