SCHOOL OF ENGINEERING
MECHANICAL ENGINEERING
LRESE - Laboratory of Renewable Energy Sciences and Engineering

Renewable Energy: exercise 4, solution

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1. Power Block:

   (a) Calculate the needed rated power of the steam turbine:
   $\dot{W}_{el,net} = \frac{25000\text{households}\cdot 5100\frac{\text{kWh}}{\text{household}}}{0.75(\text{rated capacity})\cdot 24\text{h}\cdot 365\text{d}} = 19'406\,\text{kW}$
   $\dot{W}_{turbine} = \dot{W}_{el,net} + 0.5\,\text{MW} = 19.9\,\text{MW}$

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

State	T	p [bar]	h [kJ/kg]	v [m^3/kg]	w	Solved by:
1	320K =46.85°C	0.10576	196.16	0.0010108	0	Saturated steam table, Interpolation
2	325 K	100	206.26	-	-	Liquid: $h_2 = h_1 + v_1(p_2 - p_1)$
3	542°C =815.5K	100	3481.61	-	-	Superheated steam table, Interpolation
4	320K =46.85°C	0.10576	$h_4 = 2407$ $h_{l,4} = 196$ $h_{v,4} = 2586$	-	0.925	Superheated steam table, Interpolation $h_4 = h_{l,4} + w(h_{v,4} - h_{l,4})$

   (c) Calculate the mass flow rate of water:
   $\dot{W}_{turbine} = |h_{3-4}| \cdot \dot{m}_W \rightarrow \dot{m}_W = \frac{19.9\text{MW}}{(3481.61-2406.52)\text{kJ/kg}} = 18.51\,\text{kg/s}$

2. Storage:

   (a) The net thermal heat flux required from the molten salt tank to run the turbine at the rated power:
   $\dot{Q}_{net,thermal} = \frac{|h_{3-2}|\cdot\dot{m}_W}{0.8} = 75.8\,\text{MW}$

   (b) Calculate the mass flow of the molten salt from the hot to the cold storage:
   $\dot{Q}_{net,thermal} = c_{p,molten\,salt}(T_{hot\,storage} - T_{cold\,storage}) \cdot \dot{m}_{molten\,salt} \rightarrow \dot{m}_{molten\,salt} = 177.83$ kg/s

   (c) Calculate the thermal storage capacity (equivalent hours of turbine operation):
   $t = \frac{V_{tank}\rho_{salt}}{\dot{m}_{molten\ salt}} = \frac{(23\text{m}/2)^2\pi\cdot 14\text{m}\cdot 1750\text{kg/m}^3}{177.83\text{kg/s}} = 15.9\,\text{h}$

3. Solar tower and field:

   (a) Calculate the total heat absorbed by the receiver during an average day in Spain in June:
   $Q_{absorbed} = \sum \text{Irradiance} \cdot \text{Time} \cdot r \cdot C \cdot \eta_{ab} \cdot A_{receiver} = 7857\frac{\text{Wh}}{\text{m}^2} \cdot 0.88 \cdot 1212\text{suns} \cdot 0.95 \cdot 251.3\text{m}^2 = 2.0\,\text{GWh}$

   (b) The total reflectivity area of the heliostat field:
   $A_{heliostat\ field} = C \cdot A_{receiver} = 1212\text{suns} \cdot 8\text{m} \cdot \pi \cdot 10\text{m} = 304609\,\text{m}^2$

   (c) The total number of heliostats needed:
   $N_{heliostats} = \frac{A_{heliostat\ field}}{A_{mirror}} = 2649$

4. Efficiency:

   (a) Calculate the thermal to electric efficiency for a day in June with continuous 24h base load supply:
   $\eta = \frac{\dot{W}_{turbine}}{Q_{absorber}} = \frac{19.9\text{MW}\cdot 24\text{h}}{2.0\text{GWh}} = 0.24$

   (b) Calculate the overall efficiency for a day in June with continuous 24h base load supply (solar energy to electricity supplied to the grid): $\eta = \frac{\dot{W}_{el,net}}{\frac{Q_{absorbed}}{\eta_{ab}\cdot r}} = \frac{19.4\text{MW}\cdot 24\text{h}}{\frac{2.0\text{GWh}}{0.95\cdot 0.88}} = 0.19$

5. Emmision mitigation:

   (a) Calculate the annual electricity generation:
   $W_{annual} = \dot{W}_{el,net} \cdot 0.75 \cdot 24\text{h} \cdot 365\text{d} = 127.5\,\text{GWh}$

   (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:
   $\frac{W_{annual}}{0.5\cdot 47\text{MJ/kg}} = 19532\,t_{\text{CH}_4}/\text{year}$
   $19532\frac{t_{\text{CH}_4}}{\text{year}} \cdot \frac{44\frac{\text{g}}{\text{mol}}\text{CO}_2}{16\frac{\text{g}}{\text{mol}}\text{CH}_4} = 53713\,t_{\text{CO}_2}/\text{year}$

   (c) Calculate the annual CO_2 mitigation potential of the solar powered Rankine cycle compared to the standard electrical network mix in Spain:
   $W_{annual} \cdot 0.3\text{kg}_{\text{CO}_2}/\text{kWh} = 38250\,t_{\text{CO}_2}/\text{year}$

6. Parameter variation:

   (a) Increasing the turbine inlet pressure from 70 bar to 240 bar leads to a decrease of the storage capacity (figure 1). This decrease results from the need for additional thermal power coming from the molten salt at increased inlet pressure (and constant temperature). Since the turbine power production is fixed to 19.9 MW, the water mass flow rate is reduced (see 1.c). This reduction of water mass flow rate cannot compensate the enthalpy increase between point 2 and 3 resulting from the pressure increase (see 2.a). Hence, the thermal energy keeps increasing with the pressure. That means a higher molten salt flow rate and consequently a lower storage capacity time.

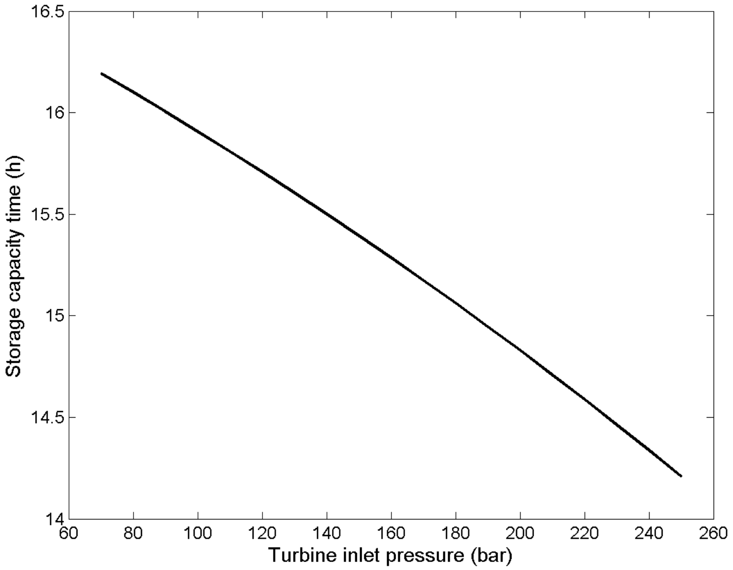

Figure 1: Storage capacity time in hours by varying the turbine inlet pressure

(b) Increasing the turbine inlet temperature from 400 to 750 °C leads to an increase of the storage capacity as depicted in figure 2. It must be mentioned that the hot tank must be at a temperature higher than the turbine inlet temperature (we took the same temperature difference than for Gemasolar, i.e. ΔT=23 °C). Increasing the temperature will increase the thermal power (see 2.a) but will also decrease the temperature difference between the hot and cold tank leading to an overall reduction of mass flow of the molten salt (see 2.b) and therefore an increase of storage capacity. Nowadays, steam turbines are technically limited to temperatures up to 580 °C since the temperature significantly increases the creep experienced by the blades. Temperature increases the efficiency (Carnot efficiency) therefore to limit creep, thermal coatings and superalloys are used in the blade design. It must be mentioned that the entropy at the outlet of the turbine is fixed since steam quality and temperature are fixed and therefore the entropy difference between the inlet and the oulet of the turbine decreases with higher temperature at the inlet. This entropy difference might become too small to be realistic for a state-of-art steam turbine. Two additional technical limitations are: i) the molten salt temperature which might be too high for a realist salt mixture, and ii) the heat losses (radiative and conductive) increasing with temperature and must be limited by a better tank insulation which will have an impact on the cost.

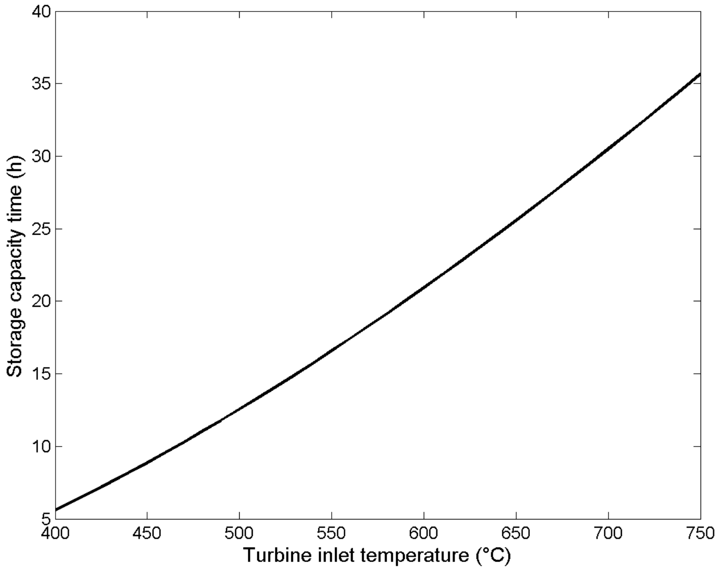

Figure 2: Storage capacity time in hours by varying the turbine inlet temperature

(c) Decreasing the steam quality increases the power output of the turbine and consequently the water mass flow rate is decreased (see 1.c). Since the steam generator is kept at the same mass flow rate, the thermal power is reduced (see 2.a) and so is the molten salt mass flow rate which increases the storage capacity (see figure 3). Even though this result is interesting, there exists a technical limitation which prevents the operation at lower steam quality at the outlet. Namely, the blades in the last stage of the turbine will be damaged more quickly as the higher moisture contents, i.e. droplets in the steam, act like "bullets at a very high velocity". To avoid problems related to steam quality, the vapour could be reheated and a second turbine can be added which will induce a shift to the right in the Ts-diagram and therefore increase the steam quality.

(d) Decreasing the condenser temperature leads to lower water flow rates but higher heat exchange with the steam generator. As seen in figure 4, decreasing condenser temperature leads to an overall increase of the storage capacity. It might be infeasible to reach temperatures down to 17 °C because of the outside temperature of the region where the solar power plant is installed.

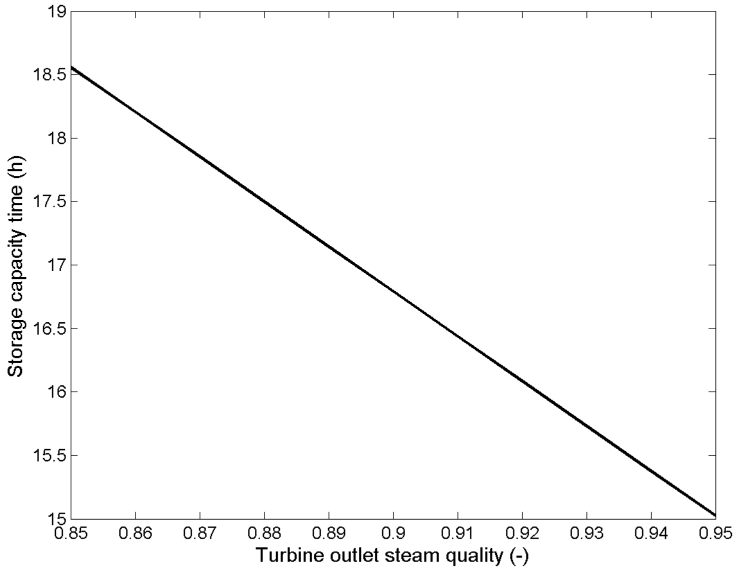

Figure 3: Storage capacity time in hours by varying the turbine outlet steam quality

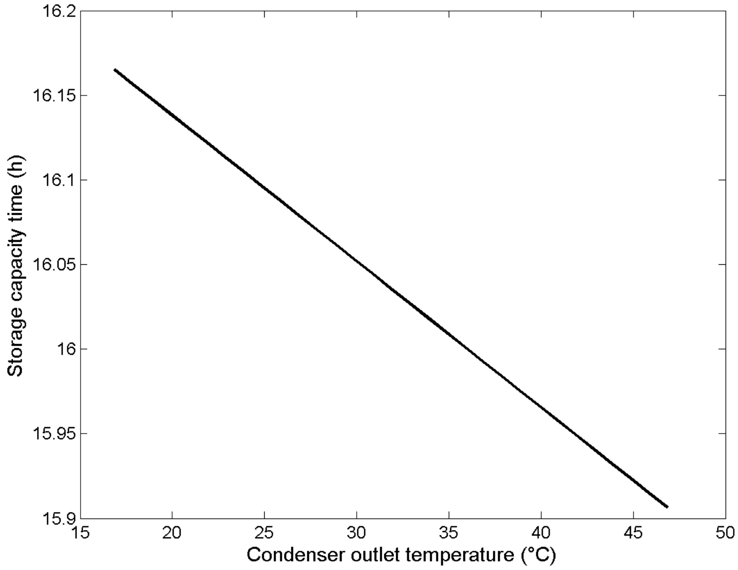

Figure 4: Storage capacity time in hours by varying the condenser outlet temperature