Homework 1

2.60/2.62/10.390 Fundamentals of Advanced Energy Conversion
Spring 2020

Total points: 100 (Undergraduate) | 150 (Graduate)

Problem 1. Compressed Air Storage [40 points for Undergrads and Grads]

Compressed air storage (CAS) has been used to store energy (electricity generated by renewable or other sources) in the form of compressed air in underground caverns.

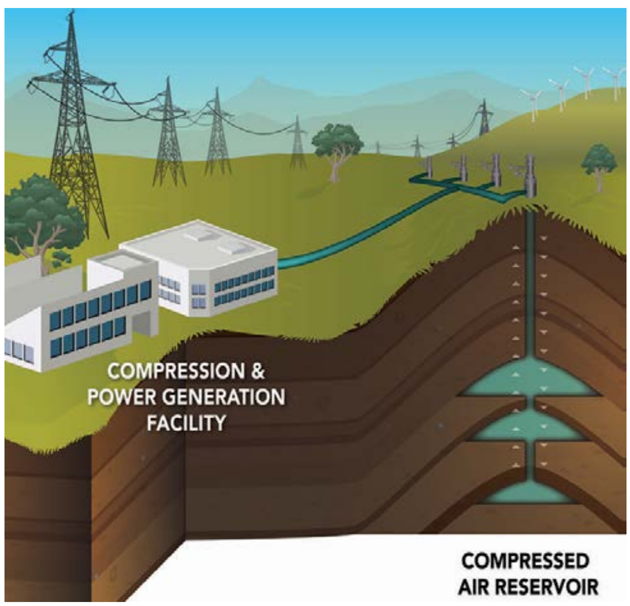

Figure 1: Illustration of a compressed air energy storage system (Courtesy of Pacific Northwest National Laboratory.)

In order to increase the mass of high-pressure air stored in the available volume of the cavern, air may be cooled after compression using a liquid. The heated liquid is then stored in a separate tank. This is the charging process. During discharging, the high-pressure air from the air cavern, and the hot liquid from the tank are used to generate work (electricity) by expanding the air, and extracting heat from the salt tank, respectively, using heat engines interacting with the environment. The overall system (air tank, molten salt tank and heat engines) acts as a giant "thermo-mechanical" battery. In this problem we use an insulated tank to stored high-pressure air, and another insulated tank of molten salt to store the thermal energy, and generic heat engines to generate work from the stored energy.

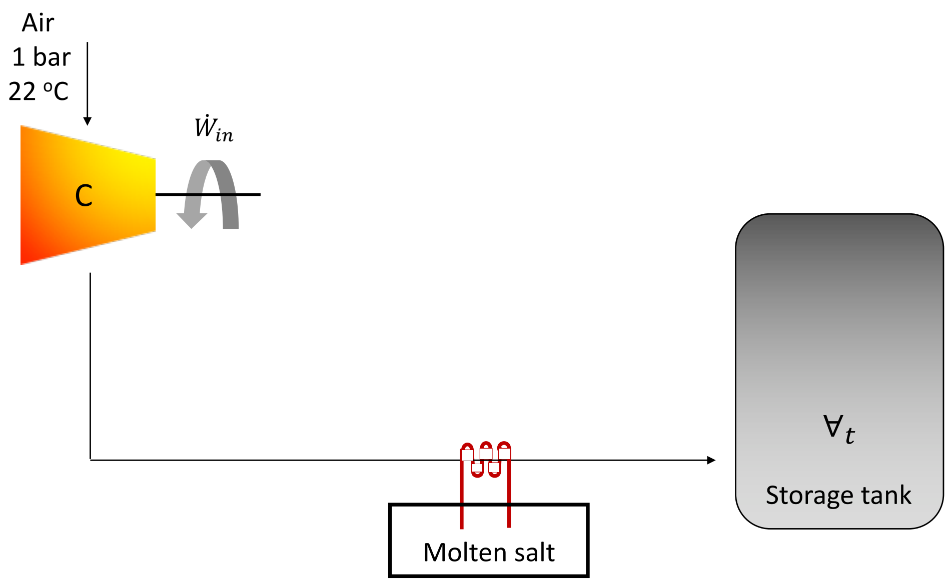

Figure 2: Schematic of the proposed compressed air storage system

The air tank volume is 1000 m^3. The molten salt mass in the tank is 100 ton (10^5 kg). The specific heat of the salt is 1,500 J/kg ^{o}K. The conditions of the gas in the tank when fully discharged is p = 1 bar and T = 22 ^{o}C. The temperature of the salt in the tank when fully discharged is 300 ^{o}C (to maintain the salt in the liquid phase). When fully charged, the conditions in the air tank are: p = 100 bar and T = 600 ^{o}C. When fully charged, the conditions in the salt tank are: T = 600 ^{o}C. Atmospheric conditions are p = 1 bar and T = 22 ^{o}C.

Calculate:

a. The energy stored in both tanks between the fully charged state and discharged state. [5 points]

b. The work required by the compressor train to charge the system of the air tank and the salt tank. The compressor train operates adiabatically. [10 points]

c. The maximum work that can be extracted from the molten salt tank starting with the fully charged state. [5 points]

d. The maximum work that can be extracted from the gas tank starting with the fully charged state. [10 points]

e. Assume that the second law efficiency of the machinery used to extract work from the gas tank is 70% and that of the machinery used to extract work from the salt tank is 60%, what is the round-trip efficiency of this storage system. [5 points]

f. How long does it take to charge the system using a wind turbine operating at 1 MW. [5 points]

Problem 2. Claude Cycle [Undergrads: 40 Points | Grads: 50 Points]

A schematic of Claude cycle is shown in **Figure 3**. It is identical to the Linde-Hampson cycle except that the high-pressure hydrogen stream is split after heat exchanger 1. A fraction of the high-pressure hydrogen is expanded to the low pressure in a turbine producing some of the work needed by the compressor. This also makes it possible to eliminate the liquid N_2 bath. Following expansion, this stream is mixed with the gas exiting heat exchanger 3 to provide the cooling in heat exchanger 2. The portion of the high-pressure hydrogen stream bypassing the turbine is cooled in heat exchangers 2 and 3, and expanded through the valve. The liquid is passed to the liquid receiver, and the vapor is recycled to provide cooling for the incoming high-pressure stream of the gas. Assume that:

1. All the heat exchangers are perfectly insulated.
2. The two streams from the make-up gas and the exit of the heat exchanger 1 have the same temperature and pressure.
3. The streams exiting the turbine and heat exchanger 3 have the same temperature and pressure.
4. 50% of the high-pressure hydrogen stream leaving heat exchanger 1 is sent through the turbine, and the turbine isentropic efficiency is 80%.

The states are shown in **Table 1**.

a. Draw schematically the T-s diagram of the Clause cycle. [10 points]

b. Calculate the mass of liquid H_2 produced in the hydrogen liquid separator per 1 kg of H_2 at state 2. [5 points]

c. Determine the pressure and temperature of H_2 at states 1-9. [15 points]

d. Calculate the work produced by the turbine per 1kg of the produced liquid H_2. [5 points]

e. Determine the total work required to produce 1 kg of liquid hydrogen. [5 points]

f. **(for Grads only)** Determine the second law efficiency of the Claude cycle. [10 points]

State	Temperature [K]	Pressure [atm]
1	298	1
2	298	100
3	160	100
10	125	1

Table 1: Summary of states

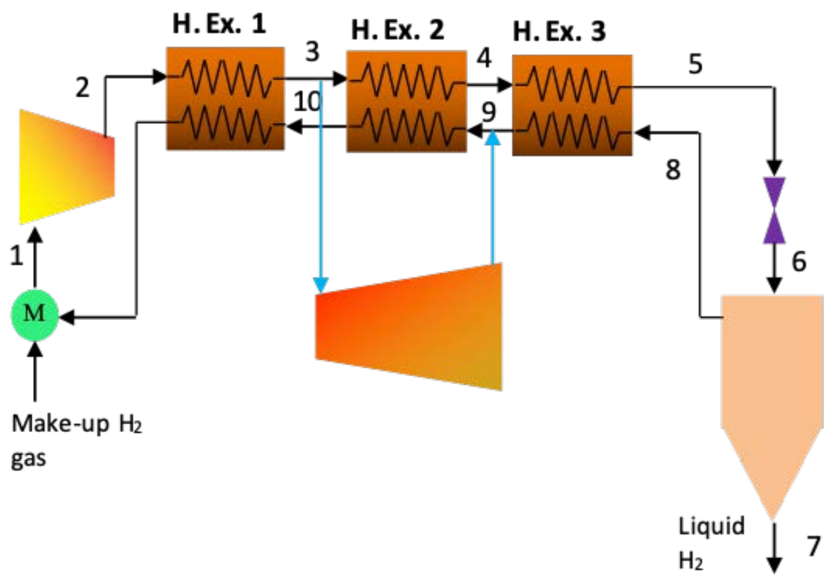

Figure 3: Claude cycle schematic

Problem 3. Desalination [Undergrads: 20 Points | Grads: 60]

Water scarcity is a rising global challenge. The United Nations estimates that 1 in 2 people will experience water scarcity by 2050[1]. The magnitude of the challenge prompted the World Economic Forum to classify water crises for the first time as the top global risk facing humanity in terms of impact in 2015[2].

Tapping into Earth's most abundant resource, desalination, that is the removal of a significant fraction of the salt (NaCl), provides a potential solution. However, seawater desalination is an energy intensive process. At its core, desalination is a separation process that aims to remove salt and produce a stream of pure water using thermal or mechanical energy.

Consider the desalination of seawater at standard temperature and pressure. Seawater is modeled as a 1% concentration by mass of NaCl. We can assume that:

1. The solution is an incompressible liquid with ideal entropy of mixing and zero enthalpy of mixing.
2. The molar heat capacity of seawater is constant and equal to the molar heat capacity of pure water.
3. The density of seawater is constant and equal to the pure water density.

The objective is to produce 1 kg/s of pure water from 2 kg/s of seawater. In the desalination process, there are two outlet streams: the product or permeate (pure water) and the brine or concentrate (the remaining solution).

a. Calculate the brine flow rate and composition. [5 points]

b. Calculate the minimal work transfer rate (also known as the least work of separation if expressed in kJ/m^3 of product). [15 points]

Note that in a liquid mixture, the entropy of component i is approximately $s_i = s_i^\circ - R \ln X_i$.

Hint: For an incompressible liquid $h = c(T - T_0) + pv$.

[1] "The United Nations World Water Development Report 2018: Nature-Based Solutions for Water.," WWAP (United Nations World Water Assessment Programme)/UN-Water. 2018., Paris, UNESCO, 2018.

[2] http://reports.weforum.org/global-risks-2015/executive-summary/

For Grads only.

Two technologies, thermal and membrane-based, are to be analyzed in this problem.

Technology I: Once-Through Boiling

Once-through boiling is the most basic thermal desalination method, which heats the seawater feed to the boiling point, bringing about fresh water vaporization. You can ignore the boiling point elevation and any change in the enthalpy of vaporization associated with the addition of salt.

c. Draw a flow diagram for the once-through boiling process. [2.5 points]

d. Calculate the required heat transfer rate. [5 points]

e. What work transfer rate could this heat transfer rate produce in an ideal heat engine, assuming that the heat source is at the boiling temperature of water? What is the ratio of this work transfer rate to the minimal work transfer rate? [5 points]

f. Propose an improvement for this design. [5 points]

Technology II: Reverse Osmosis (RO)

Osmosis refers to the movement of water across the membrane from a region of low salt concentration to that of a higher salt concentration. This transport of water is caused by the buildup of a pressure difference between the two sides of a membrane due to a difference in the chemical potential of water. For more information about osmosis, please refer to Physical Chemistry by P.W. Atkins or https://en.wikipedia.org/wiki/Osmosis.

While desalination has historically been a thermal process, the invention of Reverse Osmosis (RO) membranes in the 1960's revolutionized the process. In contrast to osmosis, RO produces fresh water by pumping the seawater to a pressure, P_H, higher than the osmotic pressure as shown in **Figure 4**. The osmotic pressure is given by the Morse equation as:

$$\Pi = 2\hat{\rho}_{sol}RT$$

where $\hat{\rho}_{sol}$ is the molar density of the solute in the brine, R is the ideal gas constant, and T is the temperature.

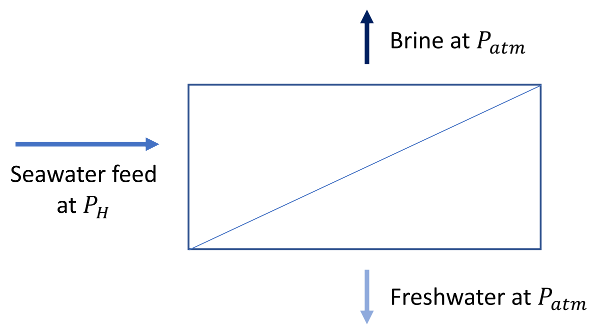

Figure 4: Schematic of the reverse osmosis process

Consider a basic RO process. This consists of a high-pressure pump increasing the pressure of the feed solution from ambient P_0 to the desired operating pressure P_H, and a perfect semipermeable RO membrane through which water can pass, but dissolved ion species cannot.

g. Draw a flow diagram for the RO process. [2.5 points]

h. Calculate the minimum pressure for the outlet of the pump and the corresponding work transfer rate. How does this compare to the minimal work transfer rate and why? [10 points]

i. Calculate the second law efficiency of a RO pump operating at a pressure of 30 bars. [5 points]

j. Propose an improvement for this design. [5 points]