Homework 4

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

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

Problem 2. Electrochemical Cells as Sensors and Expanders [50% for Undergrads and Grads]

Electrochemical cells are used extensively as concentration sensors. For instance, as the oxygen sensor of an IC engine. In this case, the products of combustion from the engine are introduced along one electrode of the cell, and air is introduced along the other electrode. The sensor is used to measure the concentration of oxygen in the products given that the oxygen concentration in air is known (0.21). The electrolyte of this cell conducts oxygen ions (O^{2-}). The open circuit potential difference between the two electrodes, which depends on the ratio of oxygen concentration in the two streams, is used to determine the concentration of oxygen in the products.

Please answer the following questions:

a. Drive a relation between the open circuit potential of the cell and the oxygen concentration in the products stream. Plot this relation when the cell temperature is 25 C, 100 C and 400 C.

b. A similar concept can be used as an isothermal expander (electric work producing machine). In this case, pure hydrogen at high pressure is introduced along one electrode of the cell while the hydrogen concentration is maintained at much lower values along the opposite electrode. The electrolyte conducts hydrogen protons (H^+).

   Drive an expression for the open circuit potential and the ideal work of expansion in this case in terms of the hydrogen partial pressure ratio across the electrolyte. Compare this expression with the isothermal mechanical work of expansion across the same pressure ratio. Comment on this result. Calculate the open circuit potential at T = 30 C, and hydrogen pressure ratio across the electrolyte of 100 and 10,000.

c. As shown in **Figure 1**, it has been proposed to construct a power cycle using (i) isothermal compression between pressures p_1 and p_2 at the initial temperature T_1, (ii) constant pressure heating at p_2 to T_3, and (iii) expansion back to p_1. Drive an expression for the efficiency of this cycle and compare it to that of a conventional Bryton cycle between the same two pressures. Calculate both efficiencies for pressure ratio of 30, T_1 = 300 K and T_3 = 1600 K.

For graduate students only

d. How can you improve the efficiency of the cycle proposed in (c) and what is the new efficiency?

e. Explain how the reverse of the set up described in part (b) can be used as an isothermal electrochemical compressor, in which a voltage is applied to pump the gas (hydrogen in the case of part (b)) from the low-pressure side to the high-pressure side. What is the open circuit voltage required to produce an oxygen stream at 10 bars from air?

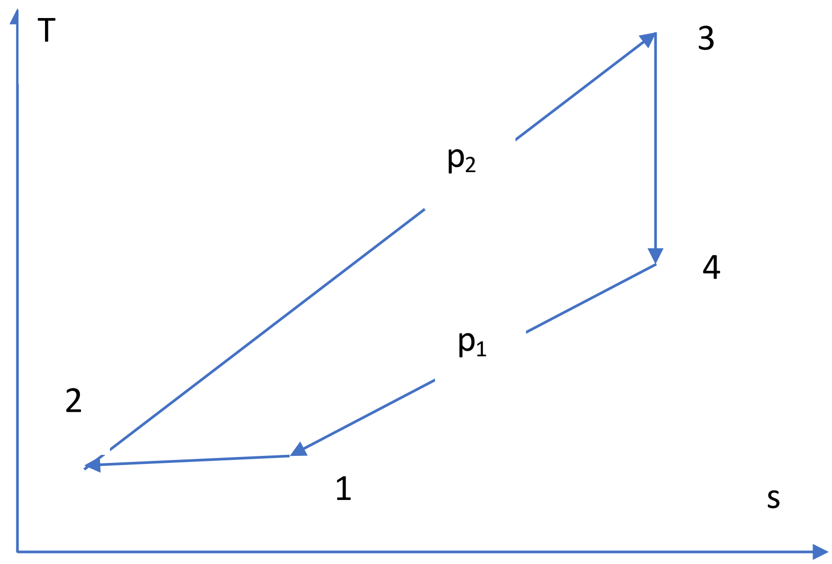

Figure 1 - Proposed Power Cycle

Problem 2. Steam-Injected Gas Turbine Cycle [25% for Undergrads and Grads]

Consider the steam-injected gas turbine cycle shown in the **Figure 2**. Air at 298 K and 100 kPa enters the compressor. The pressure ratio is 9. The turbine inlet temperature is 1423 K. The flue gases leaving the turbine flow through a heat recovery steam generator (HRSG) which produces superheated steam at 700 K. The exhaust gases leave the HRSG at 400 K.

Water at 298K and 100 kPa is pumped to the HRSG. No water recycling from the flue gas is considered. The compressor, turbine and pump operate with isentropic efficiency of 90%, 85% and 70%, respectively. The fuel burnt in the combustor is methane with LHV of 50.05 MJ/kg. The properties of the flow at states 3, 4 and 5 may be modeled as an idea gas of air + steam mixture.

Determine:

a. The amount of steam injection and fuel consumption per unit mass of the air.

b. The net work produced by the cycle.

c. The thermal efficiency of the cycle.

d. The simple gas turbine cycle efficiency (without the steam injection).

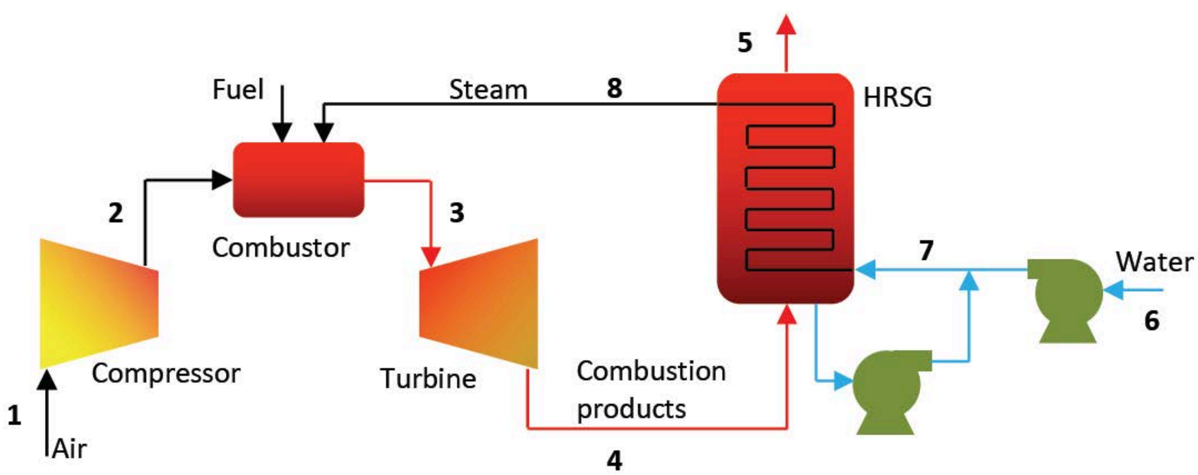

Figure 2 - Steam injected gas turbine cycle

Problem 3. Combined Cycle Power Plant [25% for Undergrads and Grads]

Consider the combined cycle power plant shown in **Figure 3**. Air at 300 K and 100 kPa enters the compressor whose isentropic efficiency is 80%. It is then compressed to 800 kPa, and heated to 1500 K. The hot stream leaving the gas turbine, which operates with an isentropic efficiency of 88%, flows through the HRSG, where it is cooled to 423 K.

Superheated steam at 723 K and 8 MPa enters the steam turbine and it is expanded to 6 kPa. The mass of fuel burnt in the combustor is negligible compared to that of the air. The isentropic efficiencies of the steam turbine and pump are 90% and 70%, respectively.

Determine:

a. The amount of steam produced in the HRSG per unit mass of air.

b. The work output of the gas and steam cycles.

c. The thermal efficiency of gas and steam cycles if they would operate separately.

d. The thermal efficiency of the combined cycle.

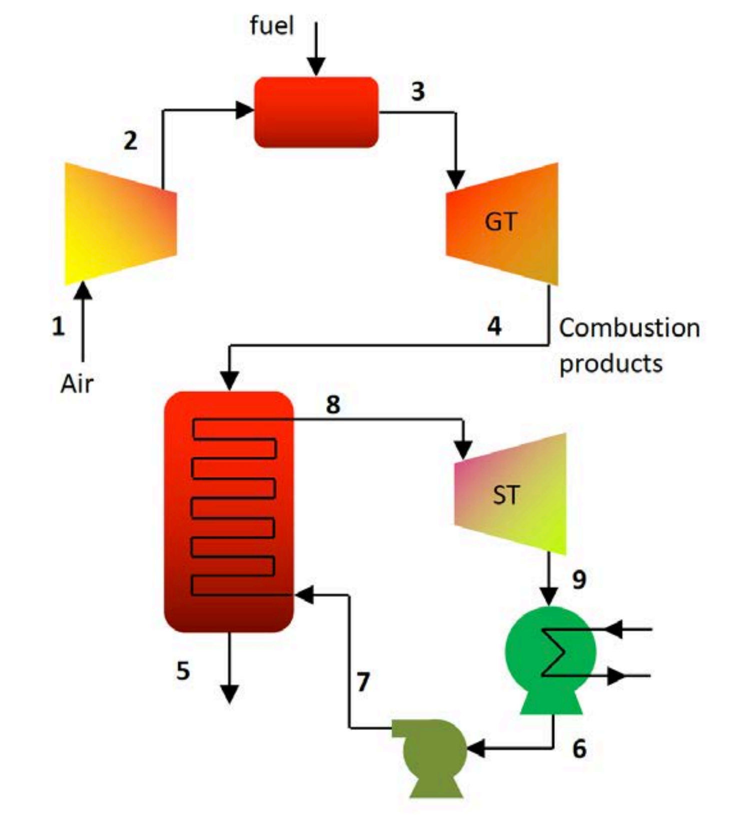

Figure 3 - Combined cycle powerplant