Homework 5

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

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

Problem 1. Gas Turbine Powerplant with Pre-combustion Carbon Dioxide Capture [40% for Undergrads and Grads]

A gas turbine power plant operates on pre-combustion CO_2 capture as shown in **Figure 1**. Air at 298K and 1 bar is used for reforming methane (298 K and 1 bar), and as a working fluid. The reformer operates at 1073 K. The reformate mixture passes through a heat exchanger where it preheats the air compressed to 10 bars, so its temperature reduces to 573 K before entering a shift reactor.

Superheated steam at 573 K reacts with CO of the reformate mixture allowing production of additional hydrogen. The byproducts of the shift reactor leave at 308 K, and then they are directed to a membrane separation unit where CO_2 is separated from the rest of the gaseous mixture. The pressure of the gaseous mixture is increased to 10 bars at the feed of the membrane unit. The permeate is a stream of CO_2 at 1 bar, whereas the retentate is a mixture of hydrogen and nitrogen which flows into the combustor.

The temperature of the combustion products is 1473 K. The isentropic efficiency of the compressors and the gas turbine are 75% and 88%, respectively. The exhaust of the gas turbine is at 1 bar, and it provides the heat requirement of the reformer, shift and steam production. Determine the thermal efficiency of the cycle, and the outlet temperature of the turbine exhaust gas.

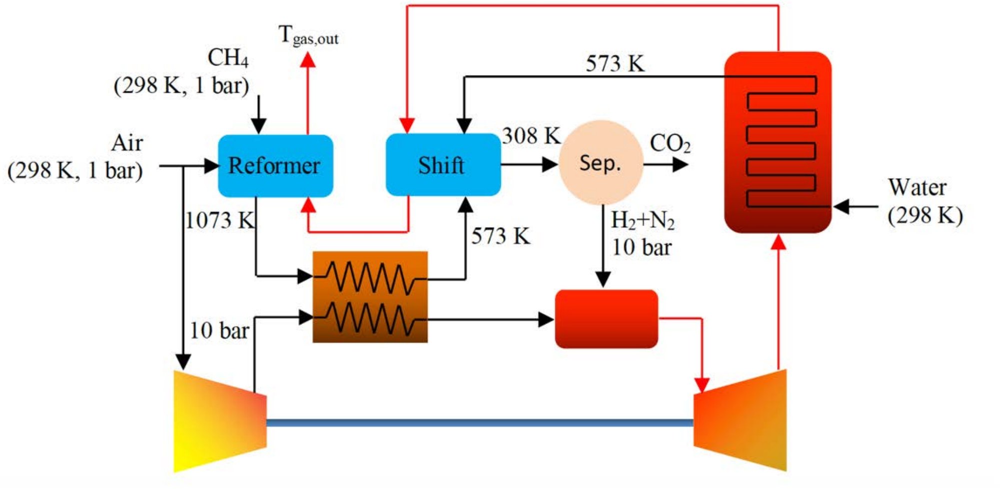

Figure 1 – Gas Turbine Powerplant with Pre-combustion CO_2 Capture

Problem 2. Chemical Looping-based Power Cycle [60% for Undergrads and Grads]

A chemical looping-based power cycle using Ni (metal) and NiO (metal oxide) and methane is schematically presented in **Figure 2**. The dotted line represents the chemical loop of the oxygen carriers (NiO/Ni). In the oxygen reactor, the highly exothermic metal oxidation reaction heats up the air stream, which is utilized to run turbine 1.

In the metal reduction reactor, the endothermic reduction reaction of NiO is used to oxidize methane to CO_2 and H_2O. While these two reactions proceed, the oxygen carriers (Ni/NiO) circulate the chemical loop drawn in dotted line. When the NiO particles are prepared, YSZ (Yttria-stabilized ZrO_2) is added to NiO to improve the reactivity (adding YSZ improves the porosity of the solid particles and raises the oxygen content). The mass ratio of NiO/YSZ is 3:2 when the mixture consists of only NiO and YSZ. To prevent carbon deposition on Ni surface, 3 moles of H_2O is added for each mole of CH_4 in metal oxidation reaction. The degree of reaction, X, is defined at the exit stream of each of the two reactors as follows:

$$X = \frac{m - m_{red}}{m_{ox} - m_{red}}$$

where m_{red} is the mass of the metal when it is fully reduced and m_{ox} is its mass when it is fully oxidized. m stands for the mass of the mixture of NiO and Ni. From experiments, it is shown that X_{ox}=1 at the exit of the oxidation reactor and X_{red}=0.3 at the exit of the reduction reactor.

The oxidation reactor and the reduction reactor are at 1500K and 900K, respectively. Both reactors are at 20 bars. Only solid particles (a mixture of Ni, NiO, YSZ) circulate through the chemical loop.

Assume that YSZ is ZrO_2 with molar weight is 123.2 kg/kmol. The enthalpy of reaction of metal oxidation reaction is Δh_{Ox} = -233.11 kJ at 1500 K. The enthalpy of reaction of metal reduction reaction is Δh_{Red} = 141.38 kJ at 900 K. The isentropic efficiencies of the compressor and turbines are 80% and 90%, respectively.

Methane is supplied at 20 bars, 300 K, and completely oxidized with NiO. The temperature of CH_4 at inlet of the reduction reactor is 730 K. For each mole of CH_4, 6 moles of air are supplied.

Determine:

a. The composition of the chemical loop and the fuel exhaust stream at the exit of the reduction reactor.

b. The composition of the chemical loop and the air stream at the exit of the oxidation reactor.

c. The temperature of air at the inlet of the oxidation reactor.

d. The temperature of the chemical loop at the inlet of the reduction reactor.

e. The temperature at the exit of heat exchanger 2.

f. The thermal efficiency of the plant with 100% CO_2 recovery rate, assuming a liquefaction work of 20 kJ per mole of methane.

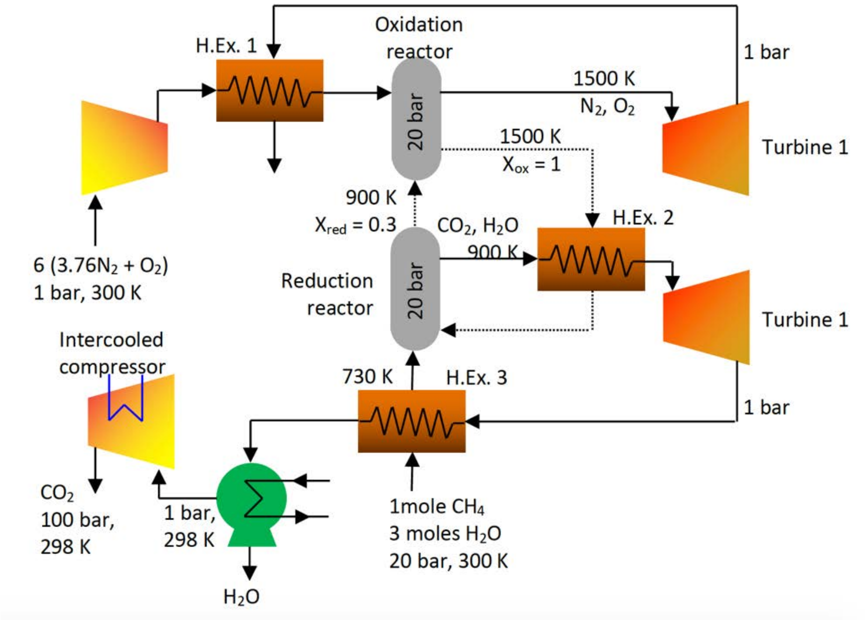

Figure 2 - Chemical Looping-based Power Cycle

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