

## ME 18b, HW 2

Due April 14, 2008 (accepted until 4 pm)

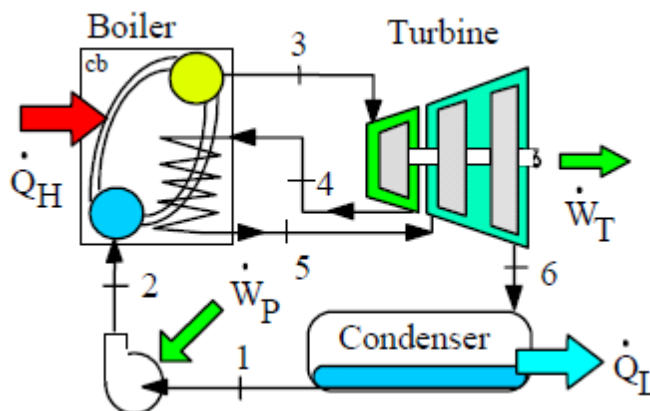
STUDENTS NOTE: We will be taking a tour of Caltech's cogeneration plant on Wilson Avenue on Tuesday April 7 from 1:15-2:15 pm. You will receive homework credit for attending this tour. Please plan accordingly.

TAs for HW #2: Xiaobai Li, TOM 212E, Mon & Fri 3-4 pm; Julianne Gould, SFL 318, Sun 4-6 pm.

1. Please describe 3 things that surprised or impressed you about the Caltech co-generation plant. These 3 things should be about power generation, cooling resources, pollution control, or some other engineering related topic. If you *did not attend* the tour, you will not be able to answer the question.

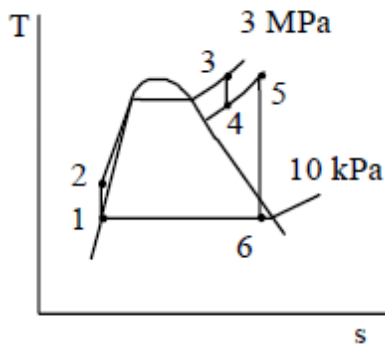
2. This question is a bit open ended so answer it however you wish. I'm expecting about a paragraph or two of information for your response. Do some background research on the Rankine cycle and write a summary of what you found out about it. Describe the person it was named after. When and where did he live, what did he do, when did he develop the cycle etc? Remember to cite your sources of information.

3. **Rankine Cycle with Reheat:** For the ideal steam cycle shown below calculate the net work and heat input to the cycle, the overall thermal efficiency and the moisture content of the steam leaving the low-pressure turbine. The conditions at state 3 are: 3 MPa and 400°C; state 5 is at 0.8 MPa and 400°C; state 1 is at 0.1 MPa. Draw the process on a labeled T-s diagram. What would the moisture content of the steam exiting the low pressure turbine be if there was no reheat process? How much does the thermal efficiency change by having a reheat process in the Rankine cycle? Comment on whether it seems worth the trouble of adding piping and heat exchangers to the basic cycle for this change in thermal efficiency.



Solution:

The T-s diagram for the reheat process is shown below:



Process - Pump reversible, adiabatic and assume incompressible flow

$$w_{\text{Pump}} = v_1(P_2 - P_1) = 0.00101(3000 - 10) = 3.02 \text{ kJ/kg},$$

$$h_2 = h_1 + w_{\text{Pump}} = 191.81 + 3.02 = 194.83 \text{ kJ/kg}$$

Process - HP Turbine section

$$P_3 = 3 \text{ MPa}, T_3 = 400^\circ\text{C} \Rightarrow h_3 = 3230.82 \text{ kJ/kg}, s_3 = 6.9211 \text{ kJ/kg K}$$

$$s_4 = s_3 \Rightarrow h_4 = 2891.6 \text{ kJ/kg}$$

Process - LP Turbine section

$$\text{State 5: } 400^\circ\text{C}, 0.8 \text{ MPa} \Rightarrow h_5 = 3267.1 \text{ kJ/kg}, s_5 = 7.5715 \text{ kJ/kg K}$$

Entropy Eq.:  $s_6 = s_5 = 7.5715 \text{ kJ/kg K} \Rightarrow$  two-phase state

$$x_6 = (s_6 - s_f)/s_{fg} = (7.5715 - 0.6492)/7.501 = \mathbf{0.923} \text{ Moisture content at low press turbine exit}$$

$$h_6 = 191.81 + 0.92285 \times 2392.82 = 2400 \text{ kJ/kg}$$

$$w_{\text{Turb,tot}} = h_3 - h_4 + h_5 - h_6 = 3230.82 - 2891.6 + 3267.1 - 2400 = 1206.3 \text{ kJ/kg}$$

$$q_{H1} = h_3 - h_2 = 3230.82 - 194.83 = 3036 \text{ kJ/kg}$$

$$q_H = q_{H1} + h_5 - h_4 = 3036 + 3267.1 - 2891.6 = 3411.5 \text{ kJ/kg}$$

$$\eta_{\text{CYCLE}} = (w_{\text{Turb,tot}} - w_{\text{Pump}})/q_H = (1206.3 - 3.02)/3411.5 = \mathbf{0.353}$$

Without reheat  $s_{6n} = s_{3n}$ ,  $\Rightarrow h_{6n} = 2193 \text{ kJ/kg}$  and  $x_{6n} = \mathbf{0.836}$  Moisture content at low press turbine exit. Note the moisture content is significantly reduced without reheat and would cause pitting and erosion of turbine blades in the last stages.

$w_{\text{Turb,tot}} = h_3 - h_{6n} = 3230.82 - 2193 = 1038 \text{ kJ/kg}$  which is about 20% less work output from the turbines.

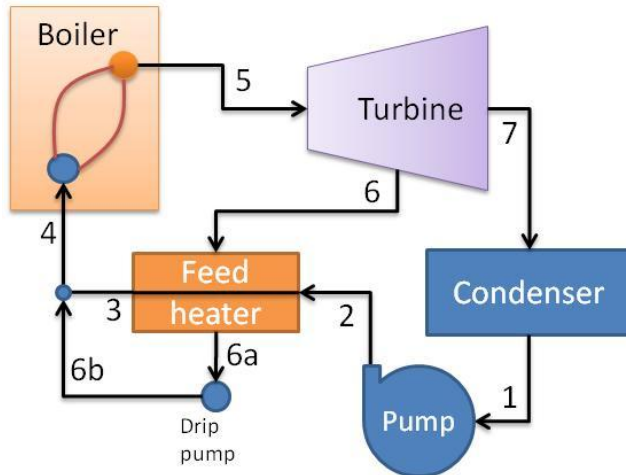
$$q_{Hn} = q_{H1}$$

$$\eta_{\text{CYCLE}} = (w_{\text{Turb,tot}} - w_{\text{Pump}})/q_{Hn} = (1038 - 3)/3036 = \mathbf{0.341}$$

While the difference in efficiency with reheat cycle having 36% and no reheat at 34% doesn't seem like very much improvement, it is significant over the lifetime of the power plant, it allows for better quality steam at the turbine exit and it produces more power at the turbine for the cost of additional piping and heat exchangers.

**4. Rankine Cycle with Closed Feedwater Heater:** A Rankine cycle with ammonia as a working fluid has a mass flow rate of 5 kg/s. The turbine inlet conditions are 2 MPa and 140°C. Ammonia is extracted from the turbine at 800 kPa for the closed ammonia feed heater. The condenser operates at -20°C and the closed ammonia feed heater has an exit state (3) at the temperature of the condensing extraction flow and a drip pump. Find the extraction flow rate and the state 4 Temperature and Enthalpy into the boiler. Find the heat transfer rate to the ammonia in the boiler and the total work output of the turbine. Draw a sketch of the process.

Solution:



Rankine cycle with closed feedwater heater

Determine State Properties:

$$P_1 = 190.2 \text{ kPa,}$$

$$h_1 = 89.05 \text{ kJ/kg}$$

$$v_1 = 0.001504 \text{ m}^3/\text{kg,}$$

$$s_5 = 5.5022 \text{ kJ/kg K,}$$

$$h_5 = 1738.2 \text{ kJ/kg}$$

$$T_{6a} = T_{\text{sat}} @ 800 \text{ kPa} = 17.85^\circ\text{C} \Rightarrow h_{6a} = 264.18 \text{ kJ/kg}$$

Process - Turbine: Reversible, adiabatic so constant  $s$  from inlet to extraction point and to exit

$$s_6 = s_5 = 5.5022 \text{ kJ/kg K} \Rightarrow T_6 = 63.4^\circ\text{C, } h_6 = 1580.89 \text{ kJ/kg}$$

$$h_7 = 1389 \text{ kJ/kg, } x_7 = 0.978 \text{ (high quality vapor)}$$

$$\text{Process - Pump: } w_{\text{Pump}} = v_1(P_2 - P_1) = 0.001504(2000 - 190.2) = 2.722 \text{ kJ/kg}$$

$$\Rightarrow h_2 = h_1 + w_{\text{Pump}} = 91.772 \text{ kJ/kg}$$

$$\text{Process Drip Pump: } w_{\text{Pump2}} = v_{6a}(P_4 - P_6) = 0.0016108(2000 - 800) = 1.933 \text{ kJ/kg}$$

$$\Rightarrow h_{6b} = h_{6a} + w_{\text{Pump2}} = 266.11 \text{ kJ/kg}$$

Process - Total Feed Heater and pump (notice  $h_3 = h_{6a}$  as we do not have table for this state)

The extraction fraction is:  $y = \dot{m}_6/\dot{m}_4$

Energy:  $(1 - y)h_2 + yh_6 = (1 - y)h_3 + yh_{6a}$

$$y = h_3 - h_2h_3 - h_2 + h_6 - h_{6a} = 264.18 - 91.772264.18 - 91.772 + 1580.89 - 264.18 = 0.1158$$

$$\dot{m}_6 = y\dot{m}_4 = 0.1158 \times 5 = \mathbf{0.5789 \text{ kg/s [Extraction Flow Rate]}}$$

State 4, boiler inlet conditions - The junction after Feed heater and drip pump.

$$h_4 = (1-y)h_3 + y h_{6b} = (1 - 0.1158) \times 264.18 + 0.1158 \times 266.11 = \mathbf{264.4 \text{ kJ/kg}}$$

At 800 kPa with  $h_4 = 264.4 \text{ kJ/kg}$ , find  $T_4 = \mathbf{17.9^\circ\text{C}}$

We note the feed heater increased the liquid ammonia temperature by almost  $38^\circ\text{C}$  and it is a liquid vapor mixture but at a very low quality.

The heat input to the boiler is:

$$Q = \dot{m}_5(h_5 - h_4) = 5 \text{ kg/s}(1738.2 - 264.4)\text{kJ/kg} / 1000\text{MW/kW} = \mathbf{7.4 \text{ MW}}$$

The work output of the turbine is:

$$W_{\text{turb}} = \dot{m}_5(h_5 - h_6) + (\dot{m}_5 - \dot{m}_6)(h_6 - h_7)$$

$$W_{\text{turb}} = [5\text{kg/s}(1738 - 1581)\text{kJ/kg} + (5 - 0.6)\text{kg/s}(1581 - 1389)]/1000\text{MW/kW} = \mathbf{1.63\text{MW}}$$