MCEN 3032: Thermodynamics II

A Design of a Rankine Cycle Power Plant with a Recirculating Tower: Design Option 2 - Power Plant with an Evaporative Cooling System

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1 Summary

Based on the assumptions given in the problem statement for design phase 2, as well as the attached paper, we constructed the calculations and code for the requirements. Delta-T-lm calculations are based on the equation in the paper; getting the U (from the initial assumptions as well as the table in the paper) and Q (from the code in design phase 1) we were able to find the A. For the HEXs cost estimates we assumed Fm Fb to be 1 to facilitate the calculations. The costs are 28.2$kforclosedfeedwaterheater$,713.7k for condenser, 343.5$kforboiler, and$55.7k for reheating boiler. For the expected revenue according to our design, we multiplied the expected power outlet depending on the operation of the plant, multiplied the price for the Watts sold. For the fourth requirement, we found that the revenue increases as the cold-water inlet temperature decreases, which means that as we get north in the US, the higher the expected revenue, since the cold water inlet temperature decreases. As for the fifth requirement, the efficiency of the system does not change as the relative humidity changes. Detailed values are found throughout the report.

2 Result Discussion

2.1 Δ TLM, A and U for 4 heat exchangers in the system

The results for the four heat exchangers in the system are shown in Table 1. The mean temperature difference between the hot and the cold fluid Tlm is calculated for all heat exchangers. The overall heat transfer coefficient for the closed feedwater heater and the steam condenser is assumed to be 700 BTU/°F·ft^2·hr based on table 13.5 in [1]. Putting steam on the shell side and feed water on the tube side the table gives a typical value for U between 400 and 1,000. The U-values for the primary boiler and the reheat boiler are given in the problem statement. The area A is calculated based on Q, U, Ft, and Tlm. We assumed $F_t = 1$ for all four heat exchangers since they are all ideal counter current heat exchangers. Q is either calculated or given from results of Design Phase 1. The heat exchange area of the Condenser is the biggest with a value of 92,127 ft^2 due to a high Q and a low Tlm.

2.2 Cost estimate for all 4 HEXs

The results for the calculation of the f.o.b (free-on-board) purchase price. The pressure Factor F_P is calculated based on the shell side pressure for all four HEX. We assumed Fm=1 because we are utilizing carbon steel and set $F_L = 1$ which applies to standard tube length (20 ft). So, the f.o.b purchase price Cp only depends on FP and the base cost CB which is dependent on the heat exchanger area that got calculated in 1. [1] The price for the reheat boiler HEX is the biggest since it has the biggest area. The second highest price has the Condenser HEX followed by the Primary Boiler HEX and the CFWH HEX.

2.3 Estimate of the total plant sales revenue from electricity of the power plant

For the total plant's revenue a value of 595,000,000 is calculated. The estimated capital costs for a power plant are 1000/kW. [2] By applying the capacity factor of 85 to the plant size of 700 MW and multiplying with the capital cost we get the revenue.

2.4 The relationship between cooling water inlet temperature and steam side temperature (Tsteam)

It is observed that as the inlet temperature increases, the steam side temperature increases as well. While, the respective revenue decreases.

2.5 Outlet water temperature as a function of air flow rate through the cooling tower - The relative efficiency of power plants and evaporative cooling towers in humid regions vs non-humid regions and those in the northern U.S. vs the south

As the relative humidity increases, the air flow rate increases and respectively the relative efficiency should increase. Humid regions should posses higher plant relative effeciency.

3 Figure and Tables

3.1 ∆ TLM, A and U for 4 heat exchangers in the system

Equipment	∆ TLM(F)	A(ft^2)	U(BTU/hr)
CFWH	134.7	1972	700
Condenser	68	92127	700
Primary Boiler	623.1	48221	100
Reheat Boiler	737.1	4029	100

3.2 Cost estimate for all 4 HEXs

Equipment	Cost(USD)
CFWH	28191
Condenser	713746
Primary Boiler	343541
Reheat Boiler	55734

3.3 Gross electricity revenue experienced by two plants that are identical in all ways except the inlet temperature of the cooling water

CW Inlet(C)	CW Outlet(C)	Steam Temp(C)	Respective Revenue(USD)
20	35	45	596,041,803
22	35	45.72	595,130,225
24	35	46.48	594,088,421
26	35	47.28	593,046,618
28	35	48.12	591,874,589
30	35	49	590,702,560

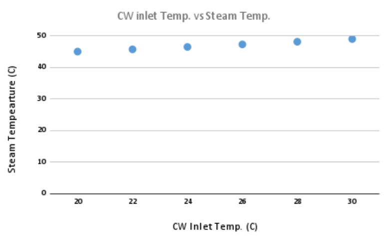

Figure 1: CW Inlet Temp. Vs. Steam Temp.

3.4 Outlet water temperature as a function of air flow rate through the cooling tower - The relative efficiency of power plants and evaporative cooling towers in humid regions vs non-humid regions and those in the northern U.S. vs the south

20%RH		
Toutlet [ºC]	m_air [kg/s]	η [%]
5	11391	45.69
10	11369	45.69
15	11347	45.69
20	11325	45.69
25	11303	45.69
30	11281	45.69

Figure 2: 20 Percent RH Table

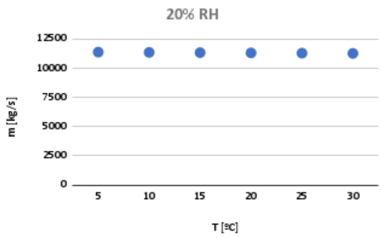

Figure 3: 20 Percent RH

40%RH		
Toutlet [ºC]	m_air [kg/s]	η [%]
5	13494	45.69
10	13468	45.69
15	13442	45.69
20	13416	45.69
25	13391	45.69
30	13365	45.69

Figure 4: 40 Percent RH Table

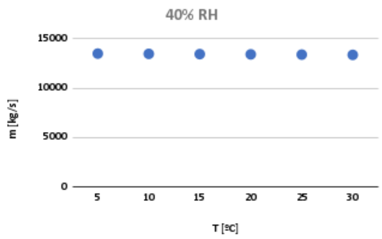

Figure 5: 40 Percent RH

80%RH		
Toutlet [ºC]	m_air [kg/s]	η [%]
5	21634	45.69
10	21595	45.69
15	21556	45.69
20	21518	45.69
25	21480	45.69
30	21442	45.69

Figure 6: 80 Percent RH Table

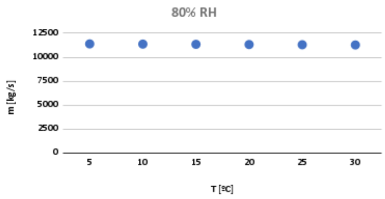

Figure 7: 80 Percent RH

4 Design Calulations

4.1 Part 1 2: Log mean Temperature Difference, A, U, and Cost Calculation

```
{Closed Feed Water heater}
{calculating LMTD}
Thot_in[1] = 485.5 * (9/5) + 32  {F}
Thot_out[1]  = 170.4 * (9/5) + 32  {F}
Tcold_in[1] = 163.5 * (9/5) + 32  {F}
Tcold_out[1] = 200 * (9/5) + 32  {F}
deltaT_lm[1] = ( (Thot_in[1] - Tcold_out[1]) -  (Thot_out[1] - Tcold_in[1]))
/ ln((Thot_in[1] - Tcold_out[1])/(Thot_out[1] - Tcold_in[1]))
{calcualting Q}
m_in[1] = 347.6
h_in[1] = 708.2
m_out[1] = 347.6
h_out[1] = 865
Q[1] = abs(m_in[1] *h_in[1] - m_out[1]*h_out[1]) {kW} * 3412.142 {BTU/hr}
{-------------------}
U[1] = 700 {From notes: range 400 - 1000}
A[1] = Q[1]/(F_t[1]*deltaT_lm[1]*U[1]) {ft^2}
{cost calculation}
C_B[1] = exp(11.667 - 0.8709 * ln(A[1]) + 0.09005 * (ln(A[1]))^2)
F_M[1] = 1 {for carbon steel}
F_t[1] = 1 {from notes - assume}
F_L[1] = 1 {from notes - assume}
{F_P[1] = 1 {needs to be changed to inlet stream
pressure of CFWH - needs to be in psig}}
P[1] = 810 {KPa} * 0.145038 {psig}

F_P[1] = 0.9803 + 0.018*(P[1]/100) + 0.0017* (P[1]/100)^2


C_p[1] = C_B[1] *F_M[1]*F_P[1]*F_L[1]



{Condenser}
{calculating LMTD}
Thot_in[2] = 51.55 * (9/5) + 32  {F}
Thot_out[2]  = 45.85 * (9/5) + 32  {F}
Tcold_in[2] = 20 * (9/5) + 32  {F}
Tcold_out[2] = 35 * (9/5) + 32  {F}
deltaT_lm[2] = ( (Thot_in[2] - Tcold_out[2]) -  (Thot_out[2] - Tcold_in[2]))
/ln((Thot_in[2] - Tcold_out[2])/(Thot_out[2] - Tcold_in[2]))
{calcualting Q}
Q[2] = 709499 {kW} * 3412.142 {BTU/hr}
{-------------------}
U[2] = 700 {From notes: range 400 - 1000}
A[2] = Q[2]/(F_t[2]*deltaT_lm[2]*U[2]) {ft^2}
{cost calculation}
C_B[2] = exp(11.667 - 0.8709 * ln(A[2]) + 0.09005 * (ln(A[2]))^2)
F_t[2] = 1 {from notes - assume}
F_M[2] = 1 {for carbon steel}
F_L[2] = 1 {from notes - assume}
{F_P[2] = 1 {1 for a boiler in a condenser in our case}}
```

```
P[2] = 10 {kPa} * 0.145038 {psig}
{F_P[2] = 0.9803 + 0.018*(P[2]/100) + 0.0017* (P[2]/100)^2}
F_P[2] = 1

C_p[2] = C_B[2] *F_M[2]*F_P[2]*F_L[2]



{Primary Boiler}
{calculating LMTD}
Thot_in[3] = 1020 * (9/5) + 32  {F}
Thot_out[3]  = 720 * (9/5) + 32  {F}
Tcold_in[3] = 328.4 * (9/5) + 32  {F}
Tcold_out[3] = 620 * (9/5) + 32  {F}
deltaT_lm[3] = ( (Thot_in[3] - Tcold_out[3]) -  (Thot_out[3] - Tcold_in[3]))
/ ln((Thot_in[3] - Tcold_out[3])/(Thot_out[3] - Tcold_in[3]))
{calcualting Q}
m_in[3] = 496.2
h_in[3] = 1480
m_out[3] = 496.2
h_out[3] = 3509
Q[3] = abs(m_in[3] *h_in[3] - m_out[3]*h_out[3]) {kW} * 3412.142 {BTU/hr}
{--------------------------}
U[3] = 100 {range is given 50-150} {BTU/hr.ft^2.F}
A[3] = Q[3]/(F_t[3]*deltaT_lm[3]*U[3]) {ft^2}
{cost calculation}
C_B[3] = exp(11.667 - 0.8709 * ln(A[3]) + 0.09005 * (ln(A[3]))^2)
F_M[3] = 1 {for carbon steel}
F_L[3] = 1 {from notes - assume}
F_t[3] = 1 {from notes - assume}
{F_P[3] = 1 {1 for a boiler in our case}}
P[3] = 1000
{F_P[3] = 0.9803 + 0.018*(P[2]/100) + 0.0017* (P[2]/100)^2}
F_P[3] = 1

C_p[3] = C_B[3] *F_M[3]*F_P[3]*F_L[3]



{Reheat Boiler}
{calculating LMTD}
Thot_in[4] = 720 * (9/5) + 32  {F}
Thot_out[4]  = 4491.7 * (9/5) + 32  {F}
Tcold_in[4] = 391.7 * (9/5) + 32  {F}
Tcold_out[4] = 620 * (9/5) + 32  {F}
deltaT_lm[4] = ( (Thot_in[4] - Tcold_out[4]) -  (Thot_out[4] - Tcold_in[4]))
/ ln((Thot_in[4] - Tcold_out[4])/(Thot_out[4] - Tcold_in[4])) {F}
{calcualting Q}
m_in[4] = 403.1
h_in[4] = 3126
m_out[4] = 403.1
h_out[4] = 3694
Q[4] = abs(m_in[4] *h_in[4] - m_out[4]*h_out[4]) {kW} * 3412.142 {BTU/hr}
{--------------------------}
U[4] = 100  {range is given 50-150} {BTU/hr.ft^2.F}
A[4] = Q[4]/(F_t[4]*deltaT_lm[4]*U[4]) {ft^2}
{cost calculation}
C_B[4] = exp(11.667 - 0.8709 * ln(A[4]) + 0.09005 * (ln(A[4]))^2)
```

```
F_M[4]  = 1 {for carbon steel}
F_t[4]  = 1 {from notes - assume}
F_L[4]  = 1 {from notes - assume}
{F_P[4]  = 1  {1 for a boiler in our case}}
P[4]   = 1000
F_P[4]  = 0.9803 + 0.018*(P[4]/100) + 0.0017* (P[4]/100)^2
C_p[4]  = C_B[4] *F_M[4]*F_P[4]*F_L[4]
```

4.2 part 3: Estimate of total plant sales revenue from electricity for the power plant

700 MW = 700,000 kW

capacity factor : 85 %

Capital cost : $1000 / kW

$$700{,}000\ \text{kW} \cdot 0.85 \cdot \frac{\$1000}{\text{kW}} = \underline{\underline{\$595{,}000{,}000}}$$

Revenue

Figure 8: Total Plant Revenue.

4.3 part 4: Estimate the difference in gross electricity revenue experienced by two plants that are identical in all ways except the inlet temperature of the cooling water

All Temp. in C

								efficiency @ P=10kPa =	0.4569	
CW inlet	CW outlet	Steam Temp						Revenue @ P=10kPa =	$ 595,000,000.00	
T1	T2	Ts1	Ts2	delta T1	delta T2	delta Tlm	Psat (Ts1&Ts2) kPa	efficiency	efficiency Ratio	Respective Revenue
20	35	45	45	25	10	16.37	9.595	0.4577	1.00175093	$ 596,041,803.46
22	35	45.72	45.72	23.72	10.72	16.37	9.956	0.457	1.000218866	$ 595,130,225.43
24	35	46.48	46.48	22.48	11.48	16.37	10.35	0.4562	0.9984679361	$ 594,088,421.97
26	35	47.28	47.28	21.28	12.28	16.37	10.78	0.4554	0.9967170059	$ 593,046,618.52
28	35	48.12	48.12	20.12	13.12	16.37	11.25	0.4545	0.9947472095	$ 591,874,589.63
30	35	49	49	19	14	16.37	11.75	0.4536	0.992777413	$ 590,702,560.74

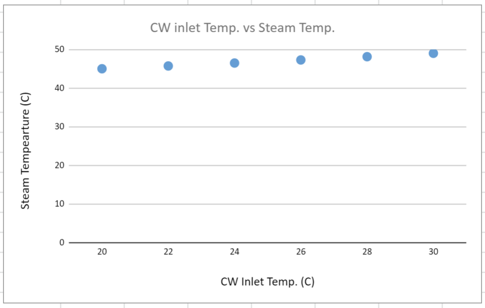

Figure 9: Difference in gross electricity revenue

4.4 part 5: Set of curves that describes outlet water temperature as a function of air flow rate through the cooling tower.

20%RH			40%RH			80%RH		
Toutlet [ºC]	m_air [kg/s]	η [%]	Toutlet [ºC]	m_air [kg/s]	η [%]	Toutlet [ºC]	m_air [kg/s]	η [%]
5	11391	45.69	5	13494	45.69	5	21634	45.69
10	11369	45.69	10	13468	45.69	10	21595	45.69
15	11347	45.69	15	13442	45.69	15	21556	45.69
20	11325	45.69	20	13416	45.69	20	21518	45.69
25	11303	45.69	25	13391	45.69	25	21480	45.69
30	11281	45.69	30	13365	45.69	30	21442	45.69

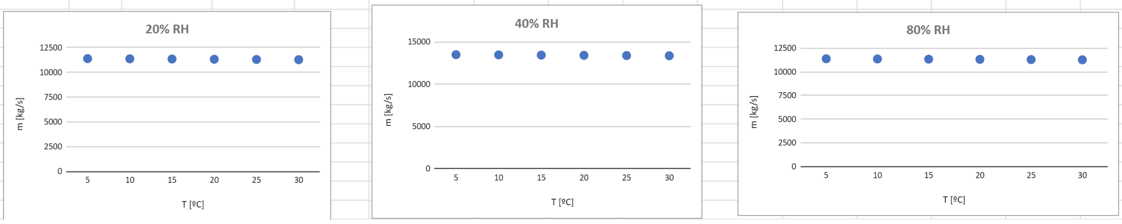

Figure 10: Outlet water temperature as a function of air flow rate through the cooling tower

5 Acknowledgements

Huge thanks to Dr. Micheal Walker, department of Mechanical Engineering, University of Colorado Boulder.

6 Reference

[1] Heat Exchanger Notes - Excerpt from Seider et al. 2004.PDF

[2] "Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2019" (PDF). U.S. Energy Information Administration. 2019.