

***Design of a Steam Power Plant***  
MEMS1051, Applied Thermodynamics  
Dr. John Whitefoot

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Tommy Hinds  
Ryan Rosenbaum  
Noah Sargent  
Seth Strayer

## Abstract

This report details our calculations, data, and analysis used to determine the optimal design for a steam power plant at Pitt's main campus. The requirements for the plant are as follows:

- 2.8 MW of electrical power (at all times)
- 5.0 MW of building heating at a minimum temperature of 80°C (six months of the year)

Our goal was to design a steam power plant that meets these needs while minimizing overall cost. Total cost includes initial investment plus operating and maintenance costs over the expected 15 year operating period. Given the two cycles in *Figure 1* below,

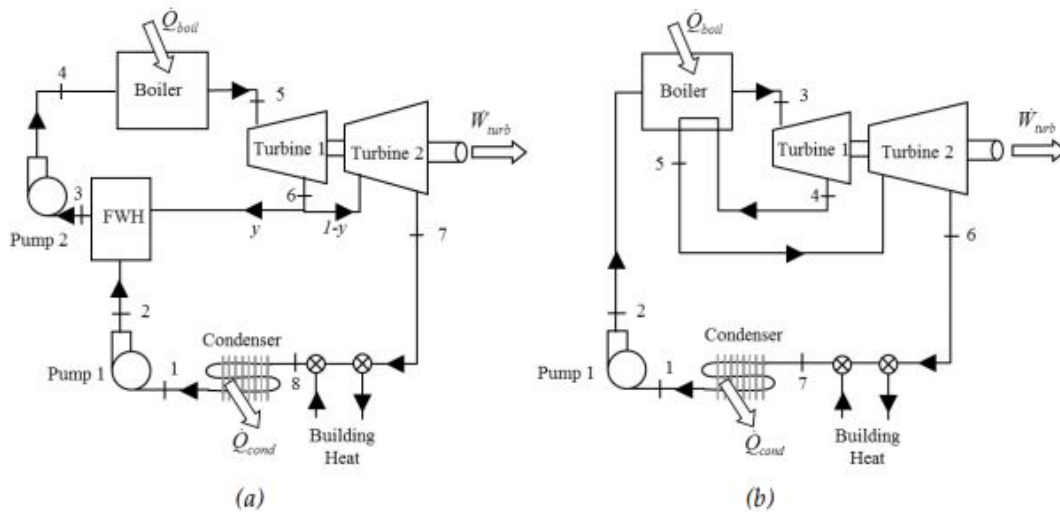


Figure 1 – Rankine cycles with (a) open feedwater heater, or (b) reheat

our goal was to determine which cycle ((a) *open feedwater heater*, or (b) *reheat*) optimizes all of the operating states of the plant while minimizing overall cost. Using the electrical and heating needs of the campus as a starting point, we began analyzing both proposed systems.

The solution method we used was to analyze both cycles state by state through hand-calculations, then use Engineering Equation Solver (EES) to observe and optimize the properties at each state. Variable parametric tables were used to optimize each state and reduce the overall cost. As detailed in the analysis and results sections, there are infinitely many ways to design the system and many different “optimized” systems. After close observation of both cycles, we were able to choose a cycle which struck a very good balance between minimizing overall cost and maximizing thermal efficiency while still meeting the electrical and heating needs of the campus.

From our analysis, we concluded that the feedwater heater cycle outperforms the reheat cycle. The feedwater cycle has a thermal efficiency of 32.42%, 0.89% more efficient than the reheat cycle. Furthermore, the feedwater heater cycle costs an estimated \$18.27 million, \$840,000 less than the installation and operation costs than the reheat cycle. From a emissions standpoint, the FWH system also outperforms the reheat system. Outlined in the remainder of this report are the methods to reach these conclusions, and further analysis.

### **Problem Description**

We are to design the steam power plant to meet the following requirements:

- 2.8 MW of electrical power (at all times)
- 5.0 MW of building heating at a minimum temperature of 80°C (six months of the year)

while also minimizing overall cost of the plant. These costs include initial investment cost and operating costs over the 15 year operating cycle.

Depending on the operating conditions, which are dependent on the operating parameters, the plant may produce net electrical power that equals, exceeds, or falls short of the specified needed power. If there is an excess production of power, the excess is sold to the local utility company for profit. If there is insufficient power produced, the remainder required is bought from the utility at a rate higher than that which the utility pays for excess power.

Furthermore, the plant may also produce building heat that equals, exceeds, or falls short of the required building heat. If an excess of heat is produced, it rejected in the condenser. If a shortfall of heating is produced, the remaining heat is generated in the buildings through the combustion of additional natural gas fuel for a given cost.

The steam necessary for the plant is produced in a boiler that has a maximum allowable temperature and pressure of 550°C and 8000 kPa, respectively. There is a pressure drop of 150 kPa across the boiler and a pressure drop of 5 kPa in the condenser. All other pressure drops in the pipe are negligible.

There are inefficiencies in the turbomachinery. Each turbine has an isentropic efficiency of 84%, and the pumps each have an efficiency of 78%. The power produced by the turbines is used to supply the electrical power needs of the campus (assume a 95% conversion from shaft work into electrical work).

The outlet steam from Turbine 2 is used to provide the building heat (for the six months of the year when heating is required). If the steam heat is insufficient to provide the total required heating amount, then extra natural gas must be burnt at the buildings to provide the remainder.

The condenser in the plant will be designed to reject the necessary heat in the summer when the building heating is not needed.

Our main goal is to design the plant operating parameters in order to minimize the total cost while meeting the operating requirements of the plant. With this in mind, we note that:

- Initial cost *increases* with system size (e.g., mass flow rate)
- Operating cost *decreases* with system size

## Analysis

### i.) Assumptions

- 2.8 MW of electrical power (at all times)
  - 95% conversion of shaft work to electrical output
- 5.0 MW of building heating at a minimum temperature of 80°C (six months of the year)
- Water enters the pumps as a saturated liquid,  $x=0$
- Max Boiler pressure = 8,000 kPa
- Max Boiler temperature = 550 °C
- 150 kPa pressure drop across the Boiler
- 5 kPa pressure drop across the Condenser
- Isentropic Efficiency of the Turbines = 84%
- Isentropic Efficiency of the Pumps = 78%
- Constant pressure Feedwater Heater
- 100% fuel conversion efficiency

Applying conservation of energy for control volumes at every state for both the Feedwater Heater and the Reheat Cycle, we can obtain our state equations as listed in *Table 1*. All analyses was performed by hand and will be omitted from this report. *Figure 1* is listed again below as a reference.

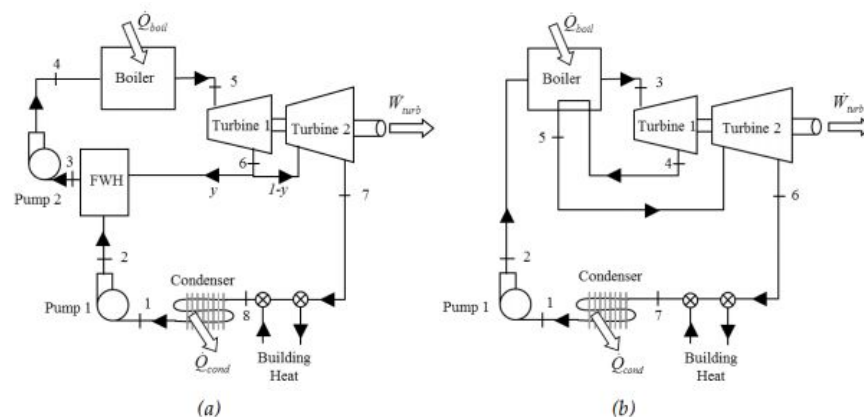


Figure 1 – Rankine cycles with (a) open feedwater heater, or (b) reheat

## ii.) State Equations

Table 1: State Equations	
Feedwater Heater Cycle	Reheat Cycle
<ul style="list-style-type: none"> <li>- <math>\eta_{th\ T1} = \frac{h_5 - h_{6,a}}{h_5 - h_{6,s}}</math></li> <li>- <math>\eta_{th\ T2} = \frac{h_6 - h_{7,a}}{h_6 - h_{7,s}}</math></li> <li>- <math>\eta_{th\ P1} = \frac{h_1 - h_{2,s}}{h_1 - h_{2,a}}</math></li> <li>- <math>\eta_{th\ P2} = \frac{h_3 - h_{4,s}}{h_3 - h_{4,a}}</math></li> <li>- <math>P_5 = P_4 - 150 \text{ [kPa]}</math></li> <li>- <math>P_1 = P_8 - 5 \text{ [kPa]}</math></li> <li>- <math>\dot{Q}_H = \dot{m}(h_5 - h_4) \text{ [kW]}</math></li> <li>- <math>\dot{Q}_L = \dot{m}(1 - y)(h_1 - h_7) \text{ [kW]}</math></li> <li>- <math>\dot{W}_{T1} = \dot{m}(h_5 - h_6) \text{ [kW]}</math></li> <li>- <math>\dot{W}_{T2} = \dot{m}(1 - y)(h_6 - h_7) \text{ [kW]}</math></li> <li>- <math>\dot{W}_{P1} = \dot{m}(1 - y)(h_2 - h_1) \text{ [kW]}</math></li> <li>- <math>\dot{W}_{P2} = \dot{m}(h_4 - h_3) \text{ [kW]}</math></li> <li>- <math>\eta_{th} = \frac{W_{net}}{Q_H}</math></li> <li>- <math>y = \frac{h_3 - h_2}{h_6 - h_2}</math></li> </ul>	<ul style="list-style-type: none"> <li>- <math>P_1 = P_7 - 5 \text{ [kPa]}</math></li> <li>- <math>P_3 = P_2 - 150 \text{ [kPa]}</math></li> <li>- <math>P_7 = P_6 \text{ [kPa]}</math></li> <li>- <math>\eta_{th\ P} = \frac{h_{2,a} - h_1}{h_{2,s} - h_1}</math></li> <li>- <math>h_2 = h_1 - \frac{1}{\eta_{th\ P}} * (h_1 - h_{2,s}) \text{ [kJ/kg]}</math></li> <li>- <math>\eta_{th\ T1} = \eta_{th\ T2} = \frac{h_i - h_{e,a}}{h_i - h_{e,s}}</math></li> <li>- <math>h_4 = h_3 - \frac{1}{\eta_{th\ T1}} * (h_3 - h_{4,s}) \text{ [kJ/kg]}</math></li> <li>- <math>h_6 = h_5 - \frac{1}{\eta_{th\ T2}} * (h_5 - h_{6,s}) \text{ [kJ/kg]}</math></li> <li>- <math>\dot{Q}_H = \dot{m}[(h_3 - h_2) + (h_5 - h_4)] \text{ [kW]}</math></li> <li>- <math>\dot{Q}_L = \dot{m}(h_1 - h_6) \text{ [kW]}</math></li> <li>- <math>\dot{W}_{T1} = \dot{m}(h_3 - h_4) \text{ [kW]}</math></li> <li>- <math>\dot{W}_{T2} = \dot{m}(h_5 - h_6) \text{ [kW]}</math></li> <li>- <math>\dot{W}_P = \dot{m}(h_2 - h_1) \text{ [kW]}</math></li> <li>- <math>\eta_{th} = \frac{W_{net}}{Q_H}</math></li> </ul>

## iii.) Cost Analysis

The total cost of the system includes initial investment costs plus the operating costs over the 15 year operating period of the plant. The initial costs of the power devices (turbines and pumps) are dependent on their power levels, and the initial costs of the heat transfer equipment are dependent on their physical size (which is related to the mass flow rate of the working fluids that pass through them). The initial costs are given as:

Turbines: \$260/kW of turbine output

Pumps: \$2400/kW of pump input power

Boiler: \$135,000 per kg/s of steam flow rate

Condenser: \$46,000 per kg/s of flow through the condenser

Feedwater Heater: \$52,000 per kg/s of flow of water being heated (i.e., the water delivered to the heater *by the condenser*)

The operating costs are given as:

Fuel Cost: \$3.8 per million BTU

Purchased Power: \$0.12/kW-hr

Sold Power: Sold at \$0.035/kW-hr

Maintenance Costs: 5% of initial costs *per year* of operation

Thus, given our EES variables, we can write the cost equations as:

Table 2: Initial Cost Equations	
Feedwater Heater Cycle	Reheat Cycle
$Turbine_{IC} = \$260 * (\dot{W}_{T1} + \dot{W}_{T2})$	$Turbine_{IC} = \$260 * (\dot{W}_{T1} + \dot{W}_{T2})$
$Pump_{IC} = \$2,400 * (\dot{W}_{P1} + \dot{W}_{P2})$	$Pump_{IC} = \$2,400 * \dot{W}_P$
$Boiler_{IC} = \$135,000 * \dot{m}$	$Boiler_{IC} = \$135,000 * \dot{m} * 2$
$Condenser_{IC} = \$46,000 * ((1-y) * \dot{m})$	$Condenser_{IC} = \$46,000 * \dot{m}$
$Feedwater_{IC} = \$52,000 * ((1-y) * \dot{m})$	
$Total_{IC} = T_{IC} + P_{IC} + B_{IC} + C_{IC} + FWH_{IC}$	$Total_{IC} = T_{IC} + P_{IC} + B_{IC} + C_{IC}$

Table 3: Operating Cost Equations	
Feedwater Heater Cycle	Reheat Cycle
$Maintenance_{OC} = (Total_{IC} * 0.05) * 15$	$Maintenance_{OC} = (Total_{IC} * 0.05) * 15$
$Fuel_{OC} = \frac{3.8}{293.07107} * \dot{Q}_H * (365.25) * (24) * (15)$	$Fuel_{OC} = \frac{3.8}{293.07107} * \dot{Q}_H * (365.25) * (24) * (15)$

**Table 3: Operating Cost Equations (Cont.)**

$Power_{bought} = (2800 - EP) * (0.12) * (365.25) * (24) * (15)$	$Power_{bought} = (2800 - EP) * (0.12) * (365.25) * (24) * (15)$
$Power_{Sold} = (EP - 2800) * (0.035) * (365.25) * (24) * (15)$	$Power_{Sold} = (EP - 2800) * (0.035) * (365.25) * (24) * (15)$
$Total_{OC} = M_{OC} + F_{OC} + P_{bought} - P_{Sold}$	$Total_{OC} = M_{OC} + F_{OC} + P_{bought} - P_{Sold}$
$Total\ Cost = Total_{IC} + Total_{OC}$	$Total\ Cost = Total_{IC} + Total_{OC}$

#### **iv.) Feedwater Heater Analysis**

With our given state equations, we were able to calculate the final state values with the use of EES. Since there are many variables that affect plant efficiency and overall cost of the system, we used a parametric table to study the effect of multiple variables simultaneously. Given the operation of the Feedwater Heater, we determined the main variables to be:

- $P_6$  - the pressure at the exit of Turbine 1
- $y$  - the extraction fraction sent to the feedwater heater.
- $\dot{m}$  - the mass flowrate of the steam
- $T_5$  - Boiler outlet temperature
- $P_5$  - Boiler outlet pressure

After further analyzing the system, we determined that we will achieve the most efficient system when  $P_5$ ,  $T_5$ , are at their maximum values. We also found that the most efficient cycle occurs when the building heat transfer occurred at its minimum temperature of 80°C. Furthermore, we found that the extraction fraction,  $y$ , was dependent on  $P_6$ . Thus, the only variables we had to alter in the parametric table were  $\dot{m}$  and  $P_6$ . As mentioned in the Problem Description, initial cost *increases* with system size and operating cost *decreases* with system size. After manipulation of our two remaining variables, we were able to strike an ideal balance between initial costs and operating costs, i.e.,  $\dot{m}$  and  $P_6$ . We found our most efficient cycle to occur when

$$\begin{aligned}\dot{m} &= 3.282 \text{ [kg/s]} \\ P_6 &= 886.7 \text{ [kPa]}\end{aligned}$$

At this state, our total cost was found to be:

$$Total\ Cost = \$18.27\ million$$

The detailed calculation of this cost can be found in the Cost Analysis section. Given our EES calculations (a screenshot of which is shown below),

Figure 2

Unit Settings: SI C kPa kJ mass deg		
COE = 8.882E-16	EP = 2800	FC = 1.551E+07
IC = 1.579E+06	MC = 1.184E+06	mdot = 3.282 [kg/s]
min <sub>Heat</sub> = 5000 [kJ/s]	min <sub>Power</sub> = 2800 [kJ/s]	Nth = 0.3242
n <sub>p</sub> = 0.78 [-]	n <sub>t</sub> = 0.84 [-]	PH = 0
PP = 0	QH = 9098	QL = 671.5
Q <sub>building</sub> = 5477 [kJ/s]	shaft <sub>eff</sub> = 0.95	SP = 806.1
TC = 1.827E+07	TC <sub>final</sub> = 1.827E+07	Wnet = 2949
WP1 = 3.081	WP2 = 33.47	WT1 = 1726
WT2 = 1260	y = 0.1555	

our efficiency values at this state were determined to be:

$$\eta_{th} = \frac{W_{net}}{Q_H} = \frac{2949 [kW]}{9098 [kW]} = .3242 = 32.42\%$$



Below is a table listing all of the final states for our selected Feedwater Heater design.

<b>Table 4: Feedwater Heater Final States</b>					
State	$P_i$ [kPa]	$T_i$ [°C]	$h_i$ [ $\frac{kJ}{kg}$ ]	$s_i$	$x_i$
1	42.39	77.28	323.5	1.043	0
2	886.7	77.28	324.6	1.044	Compressed liquid
3	886.7	174.8	740.2	2.089	0
4	8000	176.2	750.3	2.094	Compressed liquid
5	7850	550	3522	6.888	Superheated vapor
6	886.7	273.3	2297	7.079	Superheated vapor
7	47.39	80.01	2542	7.325	.9562
8	47.39	80.01	565.8	1.729	0.1

#### **v.) Reheat Analysis**

The state equations for the reheat cycle relate working fluid conditions across processes. While some values are dependent on the functional limits of the equipment, most states can be defined arbitrarily. This allows for flexibility in our state conditions, but it introduces a challenge to optimize both the thermal efficiency of the cycle and the cost. Using an iterative processes in EES we are able to test multitudes of state conditions and arrive at the most cost effective cycle configuration.

The keys to our analysis are the variables we chose to manipulate. Similar to the feedwater heater power plant, parameters which are critical in determining the power output and energy requirements of the system are established. These variables are as follows:

- Mass flow rate,  $\dot{m}$
- Working fluid pressure after Turbine 1,  $P_4$

Our method predicts an optimal mass flow rate of 2.705 kg/s, and intermediate turbine pressure of 1.930 MPa. Additionally, our cycle operates at the limits of our equipment: the boiler has a maximum pressure of 8 MPa and the maximum cycle temperature is 550 °C. In order to minimize the heat lost in the cycle, the building heating temperature  $T_7$  is at a minimum 80°C.

The table below defines each state, using our prescribed initial conditions and optimized variables. The product is a cycle that is both cost-effective and energy efficient.

<b>Table 5: Reheat Cycle Final States</b>					
State	$T_i [^{\circ}\text{C}]$	$P_i [\text{kPa}]$	$h_i [\frac{\text{kJ}}{\text{kg}}]$	$s_i [\frac{\text{kJ}}{\text{kg-K}}]$	$x_i$
1	77.28	42.39	323.5	1.043	0
2	78.26	8000	334	1.049	Compressed liquid
3	550	7850	3522	6.888	Superheated vapor
4	357.8	1930	3155	7.002	Superheated vapor
5	550	1780	3580	7.626	Superheated vapor
6	159.1	47.39	2798	8.006	Superheated vapor
7	80.01	47.39	335	1.075	0

At our optimal flow rate and pressure listed above, we found the total cost of this cycle to be as follows:

$$\text{Total Cost} = \$19.11 \text{ million}$$

The calculation we used to reach this result can be found in the Cost Analysis section. For this cycle, we determined that the thermal efficiency is as follows:

$$\eta_{th} = \frac{W_{net}}{Q_H} = \frac{2927 [\text{kW}]}{9775 [\text{kW}]} = 0.3153 = 31.53\%$$

The work used is this calculation factors in the conversion rate between shaft work and electrical work for the turbines, the difference can be seen in the EES screenshot below ( $W_{net}$  to  $W_{out}$ ):

**Unit Settings: SI C kPa kJ mass deg**

B <sub>icost</sub> = 730350	B <sub>ocost</sub> = 1.666E+07	COE = 8.882E-16
C <sub>icost</sub> = 124430	I <sub>cost</sub> = 1.731E+06	mdot = 2.705 [kg/s]
min <sub>Heat</sub> = 5000 [kJ/s]	min <sub>Power</sub> = 2800 [kJ/s]	M <sub>ocost</sub> = 1.299E+06
N <sub>th</sub> = 0.3153	O <sub>cost</sub> = 1.738E+07	PH = 0
PP = 0	P <sub>icost</sub> = 67923	Q <sub>b</sub> = 5000 [kJ/s]
QB <sub>H</sub> = 6661	Q <sub>H</sub> = 9775	Q <sub>L</sub> = -30.97
SP = 582811	T <sub>cost</sub> = 1.911E+07	T <sub>icost</sub> = 808720
W <sub>net</sub> = 3082	W <sub>out</sub> = 2927	WP = 28.3
WT1 = 992.8	WT2 = 2118	

*Figure 3*

**Results:**

**Feedwater Plant Efficiencies**

i.) Thermal Efficiency

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_H} = \frac{2949 [kW]}{9098 [kW]} = .3242 = 32.42\%$$

ii.) Building Heating Efficiency

$$\eta_{bh} = \frac{\dot{Q}_{BH}}{\dot{Q}_H} = \frac{5477}{9098} = 60.2\%$$

iii.) Overall Efficiency

$$\eta_{cycle} = \frac{\dot{Q}_{BH} + (\dot{W}_{Electrical})}{\dot{Q}_H} = \frac{5477 + 2800}{9098} = 91.0\%$$

### Coal vs. Natural gas $CO_2$ emissions

The table below lists the average  $CO_2$  emission values for various types of coal and natural gas in terms of  $\frac{lb \text{ of } CO_2}{\text{Million Btu}}$ , provided by the U.S Energy Information Administration. For our emission analysis we chose to compare Natural gas to Bituminous coal as it is the most common type of coal in the United States. Using dimensional analysis and our heat input  $(Q_H) [KW] = 9098 [KW]$  from the feedwater cycle we were able to calculate and compare  $CO_2$  emissions in  $\frac{kg \text{ of } CO_2}{\text{year}}$ . A brief description of the analysis is listed below..

Table 5: Emissions	
Coal (anthracite)	228.6
Coal (bituminous)	205.7
Coal (lignite)	215.4
Coal (subbituminous)	214.3
Natural gas	117.0

$$\text{Coal} : 25.4 * 10^6 \left[ \frac{kg \text{ of } CO_2}{\text{year}} \right] = (205.7) \left[ \frac{lb \text{ of } CO_2}{\text{Million Btu}} \right] * (9098) [KW] * \frac{(365.25)(24)(0.4536)}{(293.07)}$$

$$\text{Natural Gas} : 14.44 * 10^6 \left[ \frac{kg \text{ of } CO_2}{\text{year}} \right] = (117.0) \left[ \frac{lb \text{ of } CO_2}{\text{Million Btu}} \right] * (9098) [KW] * \frac{(365.25)(24)(0.4536)}{(293.07)}$$

$$\% CO_2 \text{ Emission Reduction} = 43.1 \% \text{ Less } CO_2 \text{ Produced} = \frac{117.0}{205.7} - 1$$

## **Conclusion**

Through analysis of the feedwater heater and reheat power cycles we determined that the feedwater heater system was more efficient with respect to cost. Using EES combined with an iterative optimization process allowed us define the state values for each system and calculate the total cost over its anticipated 15 year operation. While the FWH cycle requires more upfront cost than the reheat cycle, the greater thermal efficiency of FWH cycle makes it the more cost effective option over the expected 15 years of operation. As requested, an environmental impact analysis was conducted in order to highlight the benefits of using natural gas over coal. The results of the analysis predicted a 43% reduction in  $CO_2$  emissions compared to burning standard Bituminous coal. The savings from the optimized FWH cycle combined with the low  $CO_2$  emissions represent the optimal system for the universities needs.

### **Works Cited**

“U.S. Energy Information Administration - EIA - Independent Statistics and Analysis.” *How Much Carbon Dioxide Is Produced When Different Fuels Are Burned? - FAQ - U.S. Energy Information Administration (EIA)*, 8 June 2017, [www.eia.gov/tools/faqs/faq.php?id=73&t=11](http://www.eia.gov/tools/faqs/faq.php?id=73&t=11).

## **Appendices**

### **i.) Feedwater Heater Code REV. 10**

*Procedure* find\_power(EP, min\_Power : PP, SP)

*If* (EP < min\_Power) *Then*

PP := .12\*((min\_Power-EP))\*15\*365.25\*24

SP := 0

*Else*

PP := 0

SP := .035\*((EP - min\_Power))\*15\*365.25\*24

*Endif*

*End*

*Procedure* find\_heat(Q\_building, min\_Heat : PH)

*If* (Q\_building < min\_Heat) *Then*

PH := (3.8/293.07107)\*((min\_Heat-Q\_building))\*15\*365.25\*24

*Else*

PH := 0

*Endif*

*End*

"Parameters: "

n\_t = 0.840 [-]

n\_p = 0.780 [-]

min\_Heat = 5000 [kJ/s]

min\_Power = 2800 [kJ/s]

shaft\_eff = 0.950

"Define initial Variables"

mdot = 3.282 [kg/s]

y = (h[3]-h[2])/(h[6]-h[2])

"State 1 - After Condenser"

P[1] = P[8]-5

T[1] = temperature(Steam, P=P[1], x=x[1])

h[1] = enthalpy(Steam, P=P[1], x=x[1])

s[1] = entropy(Steam, P=P[1], x=x[1])

x[1] = 0

"State 2 - After Pump 1, Before FWH (ISENTROPIC): "

$P_{s[2]} = P[6]$   
 $T_{s[2]} = \text{temperature}(\text{Steam}, s=s_{s[2]}, P=P_{s[2]})$   
 $h_{s[2]} = \text{enthalpy}(\text{Steam}, s=s_{s[2]}, P=P_{s[2]})$   
 $s_{s[2]} = s[1]$   
 $x_{s[2]} = \text{quality}(\text{Steam}, s=s_{s[2]}, P=P_{s[2]})$

"State 2 - After Pump 1, Before FWH (ACTUAL): "

$P[2] = P[6]$   
 $T[2] = \text{temperature}(\text{Steam}, h=h[2], P=P[2])$   
 $h[2] = h[1] - ((h[1] - h_{s[2]})/n_p)$   
 $s[2] = \text{entropy}(\text{Steam}, h=h[2], P=P[2])$   
 $x[2] = \text{quality}(\text{Steam}, h=h[2], P=P[2])$

"State 3 - After FWH, Before Pump 2: "

$P[3] = P[6]$   
 $T[3] = \text{temperature}(\text{Steam}, P=P[3], x=x[3])$   
 $h[3] = \text{enthalpy}(\text{Steam}, P=P[3], x=x[3])$   
 $s[3] = \text{entropy}(\text{Steam}, P=P[3], x=x[3])$   
 $x[3] = 0.0$

"State 4 - After Pump 2, Before Boiler (ISENTROPIC): "

$P_{s[4]} = 8000 \text{ [kPa]}$   
 $T_{s[4]} = \text{temperature}(\text{Steam}, P=P_{s[4]}, s=s_{s[4]})$   
 $h_{s[4]} = \text{enthalpy}(\text{Steam}, P=P_{s[4]}, T=T_{s[4]})$   
 $s_{s[4]} = s[3]$   
 $x_{s[4]} = \text{quality}(\text{Steam}, P=P_{s[4]}, T=T_{s[4]})$

"State 4 - After Pump 2, Before Boiler (ACTUAL): "

$P[4] = P_{s[4]}$   
 $T[4] = \text{temperature}(\text{Steam}, P=P[4], h=h[4])$   
 $h[4] = h[3] - ((h[3] - h_{s[4]})/n_p)$   
 $s[4] = \text{entropy}(\text{Steam}, P=P[4], h=h[4])$   
 $x[4] = \text{quality}(\text{Steam}, P=P[4], h=h[4])$

"State 5 - After Boiler, Before Turbine 1: "

$P[5] = P[4] - 150 \text{ [kPa]}$   
 $T[5] = 550 \text{ [C]}$   
 $h[5] = \text{enthalpy}(\text{Steam}, P=P[5], T=T[5])$   
 $s[5] = \text{entropy}(\text{Steam}, P=P[5], T=T[5])$



$$x[5] = \text{quality}(\text{Steam}, P=P[5], T=T[5])$$

"State 6 - After Turbine 1, Before FWH (ISENTROPIC): "

$$P\_s[6] = P[6]$$

$$T\_s[6] = \text{temperature}(\text{Steam}, P=P\_s[6], s=s\_s[6])$$

$$h\_s[6] = \text{enthalpy}(\text{Steam}, P=P\_s[6], s=s\_s[6])$$

$$s\_s[6] = s[5]$$

$$x\_s[6] = \text{quality}(\text{Steam}, P=P\_s[6], s=s\_s[6])$$

"State 6 - After Turbine 1, Before FWH (ACTUAL): "

$$P[6] = 886.7 \text{ [kPa]}$$

$$T[6] = \text{temperature}(\text{Steam}, P=P[6], h=h[6])$$

$$h[6] = h[5] - n\_t \cdot (h[5] - h\_s[6])$$

$$s[6] = \text{entropy}(\text{Steam}, P=P[6], h=h[6])$$

$$x[6] = \text{quality}(\text{Steam}, P=P[6], h=h[6])$$

"State 7 - After Turbine 2, Before Building Heat (ISENTROPIC): "

$$P\_s[7] = P[7]$$

$$T\_s[7] = \text{temperature}(\text{Steam}, P=P\_s[7], s=s\_s[7])$$

$$h\_s[7] = \text{enthalpy}(\text{Steam}, P=P\_s[7], s=s\_s[7])$$

$$s\_s[7] = s[6]$$

$$x\_s[7] = \text{quality}(\text{Steam}, P=P\_s[7], s=s\_s[7])$$

"State 7 - After Turbine 2, Before Building Heat (ACTUAL): "

$$P[7] = 47.39 \text{ [kPa]}$$

$$T[7] = \text{temperature}(\text{Steam}, P=P[7], h=h[7])$$

"Note: Tmin=80C"

$$h[7] = h[6] - n\_t \cdot (h[6] - h\_s[7])$$

$$s[7] = \text{entropy}(\text{Steam}, P=P[7], h=h[7])$$

$$x[7] = \text{quality}(\text{Steam}, P=P[7], h=h[7])$$

"State 8 - After Building Heat:"

$$P[8] = P[7]$$

$$T[8] = \text{temperature}(\text{Steam}, P=P[8], x=x[8])$$

$$h[8] = \text{enthalpy}(\text{Steam}, P=P[8], x=x[8])$$

$$s[8] = \text{entropy}(\text{Steam}, P=P[8], x=x[8])$$

$$x[8] = .1$$

"Calculating Outputs"

$$WT1 = \dot{m} \cdot (h[5] - h[6])$$

$$WT2 = \dot{m}(1-y)(h[6]-h[7])$$

$$WP1 = \dot{m}(1-y)(h[2]-h[1])$$

$$WP2 = \dot{m}(h[4]-h[3])$$

$$W_{net} = WT1 + WT2 - WP1 - WP2$$

$$EP = \text{shaft\_eff} \cdot (WT1 + WT2) - WP1 - WP2$$

$$Q_{\text{building}} = \dot{m}(1-y)(h[7] - h[8])$$

$$QH = \dot{m}(h[5]-h[4])$$

$$QL = \dot{m}(1-y)(h[8]-h[1])$$

$$N_{th} = W_{net}/QH$$

$$COE = W_{net} + Q_{\text{building}} + QL - QH$$

### "Calculating Costs"

$$FC = (3.8/293.07107) \cdot QH \cdot 15 \cdot 365.25 \cdot 24$$

$$IC = 260 \cdot (WT1+WT2) + 2400 \cdot (WP1+WP2) + 135000 \cdot \dot{m} + 46000 \cdot ((1-y) \cdot \dot{m}) + 52000 \cdot ((1-y) \cdot \dot{m})$$

$$MC = (.05 \cdot IC) \cdot 15$$

*Call find\_power(EP, min\_Power : PP, SP)*

*Call find\_heat(Q\_building, min\_Heat : PH)*

$$TC = FC + IC + MC$$

$$TC_{\text{final}} = FC + PP + PH - SP + IC + MC$$

## ii.) Reheat Code REV. 5

"Given Parameters"

"n\_t = 0.840"

"n\_p = 0.780"

**Procedure find\_power**(Wnet, min\_Power : PP, SP)

**If** (min\_Power < Wnet) **Then**

SP := ((Wnet-min\_Power))\*(.035)\*(365.25)\*(24)\*(15)

PP := 0

**Else**

SP := 0

PP := (.12)\*((min\_Power-Wnet))\*(365.25)\*(24)\*(15)

**Endif**

**End**

**Procedure find\_heat**(QBH, min\_heat : PH)

**If** (QBH < min\_heat) **Then**

PH := (3.8/293.07107)\*((min\_Heat-QBH))\*15\*365.25\*24

**Else**

PH := 0

**Endif**

**End**

"Initial Variables"

mdot = 2.705 [kg/s]

min\_Heat = 5000 [kJ/s]

min\_Power = 2800 [kJ/s]

"State 1 - After condenser, Before Pump"

P[1] = P[7] - 5

x[1] = 0

T[1] = **temperature**(*Steam*, P=P[1], x=x[1])

s[1] = **entropy**(*Steam*, P=P[1], x=x[1])

h[1] = **enthalpy**(*Steam*, P=P[1], x=x[1])

"State 2 - After Pump, Before Boiler (ISENTROPIC)"

P\_s[2] = 8000 [kPa]

s\_s[2] = s[1]

T\_s[2] = **temperature**(*Steam*, s=s\_s[2], P=P\_s[2])

h\_s[2] = **enthalpy**(*Steam*, s=s\_s[2], P=P\_s[2])

$$x\_s[2] = \text{quality}(\text{Steam}, s=s\_s[2], P=P\_s[2])$$

"State 2 - After Pump, Before Boiler (ACTUAL)"

$$P[2] = P\_s[2]$$

$$h[2] = h[1] - ((h[1] - h\_s[2])/0.780)$$

$$T[2] = \text{temperature}(\text{Steam}, h=h[2], P=P[2])$$

$$s[2] = \text{entropy}(\text{Steam}, h=h[2], P=P[2])$$

$$x[2] = \text{quality}(\text{Steam}, h=h[2], P=P[2])$$

"State 3 - After Boiler, Before Turbine 1"

$$P[3] = P[2] - 150 \text{ [kPa]}$$

$$T[3] = 550 \text{ [C]}$$

$$h[3] = \text{enthalpy}(\text{Steam}, P=P[3], T = T[3])$$

$$s[3] = \text{entropy}(\text{Steam}, P=P[3], T = T[3])$$

$$x[3] = \text{quality}(\text{Steam}, P=P[3], T = T[3])$$

"State 4 - After Turbine 1, Before Reheat(ISENTROPIC)"

$$P\_s[4] = P[4]$$

$$s\_s[4] = s[3]$$

$$T\_s[4] = \text{temperature}(\text{Steam}, P=P[4], s=s\_s[4])$$

$$h\_s[4] = \text{enthalpy}(\text{Steam}, P=P[4], s=s\_s[4])$$

$$x\_s[4] = \text{quality}(\text{Steam}, P=P[4], s=s\_s[4])$$

"State 4 - After Turbine 1, Before Reheat(ACTUAL)"

$$P[4] = 1930$$

$$T[4] = \text{temperature}(\text{Steam}, P=P[4], h=h[4])$$

$$h[4] = h[3] - 0.840 \cdot (h[3] - h\_s[4])$$

$$s[4] = \text{entropy}(\text{Steam}, P=P[4], h=h[4])$$

$$x[4] = \text{quality}(\text{Steam}, P=P[4], h=h[4])$$

"State 5 - After Reheat, Before Turbine 2"

$$P[5] = P[4] - 150 \text{ [kPa]}$$

$$T[5] = 550 \text{ [C]}$$

$$h[5] = \text{enthalpy}(\text{Steam}, P=P[5], T = T[5])$$

$$s[5] = \text{entropy}(\text{Steam}, P=P[5], T = T[5])$$

$$x[5] = \text{quality}(\text{Steam}, P=P[5], T = T[5])$$

"State 6 - After Turbine 2, Before Building Heat(ISENTROPIC)"

$$P\_s[6] = P[6]$$

$s\_s[6] = s[5]$   
 $T\_s[6] = \text{temperature}(\text{Steam}, P=P[6], s=s\_s[6])$   
 $h\_s[6] = \text{enthalpy}(\text{Steam}, P=P[6], s=s\_s[6])$   
 $x\_s[6] = \text{quality}(\text{Steam}, P=P[6], s=s\_s[6])$

"State 6 - After Turbine 2, Before Building Heat(ACTUAL)"

$P[6] = 47.39$   
 $T[6] = \text{temperature}(\text{Steam}, P=P[6], h=h[6])$   
 $h[6] = h[5] - .840*(h[5] - h\_s[6])$   
 $s[6] = \text{entropy}(\text{Steam}, P=P[6], h=h[6])$   
 $x[6] = \text{quality}(\text{Steam}, P=P[6], h=h[6])$

"Note:  $T_{min} = 80^\circ\text{C}$ "

"State 7 - After Building Heat"

$P[7] = P[6]$   
 $h[7] = \text{enthalpy}(\text{Steam}, P=P[7], x=x[7])$   
 $T[7] = \text{temperature}(\text{Steam}, P=P[7], x=x[7])$   
 $s[7] = \text{entropy}(\text{Steam}, P=P[7], x=x[7])$   
 $x[7] = 0$

"Output Calculations"

$WT1 = \dot{m}(h[3] - h[4])$   
 $WT2 = \dot{m}(h[5] - h[6])$   
 $WP = \dot{m}(h[2] - h[1])$   
 $W_{net} = 0.95*(WT1+WT2) - WP$   
 $QH = \dot{m}((h[3] - h[2]) + (h[5] - h[4]))$   
 $QBH = \dot{m}(h[6] - h[7])$   
 $QL = \dot{m}(h[1] - h[7])$   
 $N_{th} = W_{net}/QH$

"Initial Cost Calculations"

$T\_icost = 260*(WT1+WT2)$   
 $P\_icost = 2400*WP$   
 $B\_icost = 135000*\dot{m}*2$   
 $C\_icost = 46000*\dot{m}$   
 $Icost = T\_icost + P\_icost + B\_icost + C\_icost$

"Use initial flow plus reheat flow"

"Operating Cost Calculations"

$M\_ocost = (Icost * .05)*(15)$   
 $B\_ocost = QH*(3.8/293.07107)*(365.25)*(24)*(15)$

**Call find\_power**(Wnet, min\_Power : PP,SP)

**Call find\_heat**(QBH, min\_Heat : PH)

Ocost = M\_ocost + B\_ocost + PP + PH - SP

Tcost = Icost + Ocost

### **iii.) Meeting Minutes**

Meeting 1 (3/30/18)

Members present: Noah Sargent, Seth Strayer, Ryan Rosenbaum, Tommy Hinds

Purpose: Members met to plan out a schedule for the upcoming weeks and discuss the project.

Group 1: Noah Sargent and Seth Strayer: Feedwater Heater

Group 2: Tommy Hinds, Ryan Rosenbaum: Reheat

Meeting 2 (4/10/18)

Members present: Noah Sargent and Seth Strayer

Purpose: Work on the EES code for the feedwater heater.

Meeting 3 (4/13/18)

Members present: Noah Sargent, Seth Strayer, Ryan Rosenbaum, Tommy Hinds

Purpose: Went to the help session during class and stayed after to work on the EES code

Meeting 4 (4/14/18)

Members present: Ryan Rosenbaum and Tommy Hinds

Purpose: Worked on EES code for the reheat cycle

Meeting 5 (4/18/18)

Members present: Noah Sargent and Seth Strayer

Purpose: Complete and Optimize EES code for the Feedwater Heater. Started working on the report as well.

Meeting 6 (4/19/18)

Members present: Noah Sargent, Seth Strayer, Ryan Rosenbaum, Tommy Hinds

Purpose: Reviewed EES code for both systems to choose the best optimized system. Continued to work on the written report.

Meeting 7 (4/20/18)

Members present: Noah Sargent, Seth Strayer, Ryan Rosenbaum, Tommy Hinds

Purpose: All members met to make sure both systems EES codes were correct and complete. All group members contributed to complete the written report.