The City College Of New York
Grove School of Engineering

Mechanical Engineering Department

Thermo Fluid Systems Analysis and Design (ME 430)

Ideal Rankine Cycle

Mentor:

Huseyin Cekirge

Project Designer:

Josue I. Criollo Sanchez

Table of Contents

List of Figures

List of Tables

1 Abstract

The project consists of designing and optimizing a steam turbine power plant thermodynamic cycle based on the principle of ideal Rankine cycle. The cycle's given properties from the steam table will be examined, then followed by an analysis of the properties at each stage of the process. This design primarily consists of generating a turbine which is efficient such that the ratio of supplied energy and cost incurred, to the amount of energy or work produced is implementable. This project will involve using optimization of a Rankine Cycle throughout methods of reheating and regeneration, which will help increase the efficiency of a steam turbine.

The present paper sets its first study on the Ideal Rankine Basic cycle, followed by the Ideal Rankine cycle with Reheating, and last the Regenerative Ideal Rankine cycle. All cycles will be compared prior to investigations that will lead to an optimal Rankine cycle, considering efficiency and cost effectiveness.

2 Content

Electricity is an extremely important thing in daily human life. At least for the modern-day human who uses it day in and day out for many things. It is important for people to learn about this form of energy and its uses. Steam powerplants have become one of the main sources of electricity, by using water and converting it to steam by an external heat source. The steam's kinetic energy is what operates the shafts to create this source known as electricity. The Rankine cycle is known to be the foundation to all types of powerplants. The Rankine cycle consist of four major components: boiler, pump, condenser, and turbine. Water is first pressurized, heated, and then converted to vapor. The vapor is what turns the turbine creating power. After, the vapor is returned to its liquid state to be taken out. The addition of reheaters and turbines can improve the system depending on specific needs by the handler. In this project we will compare three different systems to see their efficiencies. These are the ideal Rankine cycle, ideal Rankine cycle with reheating, and regenerative ideal Rankine cycle. The project consists of designing and optimizing a thermodynamic cycle for the following specifications:

Inlet Pressure	1900 PSI
Power Plant Power Output	180000 KW
Inlet Temperature	1000 °F
Maximum Moisture Level	13%
Steam Quality	87%

Table 1: Project Specifications

3 Nomenclature

Power	P	KW
Temperature	T	°F
Work	W	BTU

Heat per Mass	Q	BTU/lbm
Mass	M	Lbm
Efficiency	η	%
Specific Volume	V	Ft^3/lbm
Enthalpy	H	BTU/lbm
Entropy	S	BTU/lbm*R
Mass Flow Rate	$\dot{m}$	Lbm/S
Vapor Quality	X	-
Saturated Liquid State	f	-
Saturated Vapor State	g	-

Table 2: Nomenclature

4 Introduction

4.1 The Ideal Ranking Cycle

The Rankine cycle refers to the fundamental operating cycle of all power plants, which involves an operating fluid continuously evaporated and condensed. The available temperature range is the main criteria on which depends the selection of the operating fluid. In this case, the impracticalities associated with the Carnot cycle can be voided. Rankine cycle is the ideal cycle for vapor power plants and does not involve any internal irreversibility.

The efficient of the Rankine Cycle can be increased by adding heat at higher temperature. It refers to an increase of the average temperature at which heat is transferred and a decrease of the average temperature at which heat is rejected. This also entails the lowering of condenser pressure. The solution to this is known as the process of Reheating. During this process, superheated steam leaving the High-Pressure Turbine is recycled through a pipe and then reheated by the boiler through a heat-exchanger of choice, and once again subjected to Isobaric Expansion in a Intermediate Pressure Turbine, before finally leaving to the Condenser for heat rejection. This reduces the waste of the heat input in the cycle. This step involves analysis and optimization of the Rankine Cycle by means of reheating and determining optimal properties by use of Steam Tables.

4.2 Processes of the Ideal Rankine Cycle

There are four components in cycle, which are pump, boiler, turbine, and condenser. Thus, the ideal Rankine cycle consists of the following 4 processes:

Process	Description
1-2	Isentropic compression in a pump
2-3	Constant pressure heat addition in a boiler
3-4	Isentropic expansion in a turbine

4-1	Constant pressure heat rejection in a condenser

Table 3:Cycle Process

Process 1 - 2: Component: Pump (we assume the pump has 100% efficiency.)

Start with one unit of mass of saturated water as working fluid. The rule of the pump is to increase the pressure of water is entropically to the operating pressure of the boiler. Due to a slight change of the specific volume of water, the temperature increases during the isentropic compression process.

Process 2 - 3: Component: Boiler (We also assume the boiler has 100% efficiency.)

Water enters the boiler as compressed liquid at state and leaves as superheated vapor. Heat is added at a constant pressure

Process 3 - 4: Component: Turbine

Superheated vapor at stage 3 enters the turbine and expands is entropically. Pressure and temperature of the vapor drop as it gets to stage 4. Work is produced.

Process 4 - 1: Component: Condenser

Heat is rejected or lost at constant pressure and temperature in a condenser. The working fluid enters the condenser is a saturated liquid-vapor mixture. Steam leaves the condenser as saturated liquid then enters the pump at 1 to complete the cycle.

The figures below show the schematic sketch and *T-s* diagram of a simple ideal Rankine cycle, respectively.

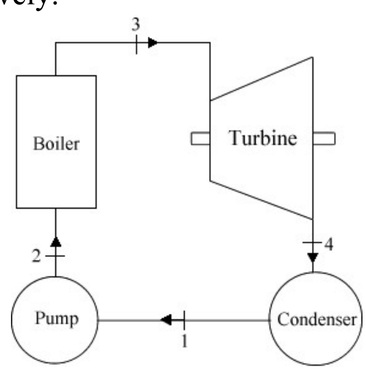

Figure 1: Ideal Rankine Cycle Scheme.

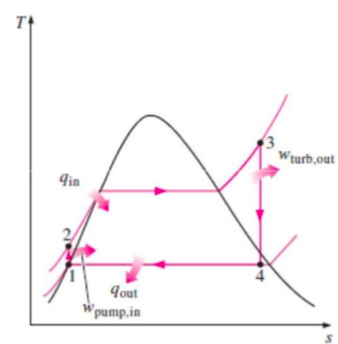

Figure 2: Ideal Rankine Cycle T vs S Diagram

The images above show an ideal Rankine cycle with its typical four major components. These components are the pump, boiler, turbine, and condenser. On the image to the right, we can see a graph known as the T-s diagram, which shows the temperature and entropy relationships throughout the cycle. Process 1-2: Pump to boiler is Isentropic compression ($s_1 = s_2$). Process 2-3: Through the boiler there is constant pressure heat addition inside ($P_2 = P_3$). Process 3-4: Isentropic expansion due to the turbine ($s_3 = s_4$). Process 4-1: Constant pressure heat rejection within condenser ($P_4 = P_1$). For this cycle, we must calculate the turbine exit pressure at a steam quality of 87%. We must calculate the efficiency and steam quality of different inlet pressures, P_1, to choose correct output pressures, P_4, so we can properly obtain the desired quality. The specifications ask for a range of 1-30 psi, therefore we will use P_1 = 5 psi to keep it simple.

4.3 Increase the Thermal Efficiency of the Ideal Rankine Cycle

Any improvement or modification refers to an increase of the thermal efficiency of the power plant. Therefore, several technics are used to improve thermal efficiency: 1- decreasing average temperature at which heat is rejected from the working fluid (steam) in the condenser. (Lowering condenser Pressure). 2- increasing steam temperature entering the turbine. Now, that we have the expression of thermal efficiency of an ideal Rankine cycle and want to increase it, let's consider a cycle that has a *T-s* diagram as shown below in Figure 3 shows a Carnot cycle, with the same TL and entropy interval as the compare cycle, and a T_{avg} less than TH because the thermal efficiency of a Carnot cycle only relates to the temperature we add heat and the one we remove heat.

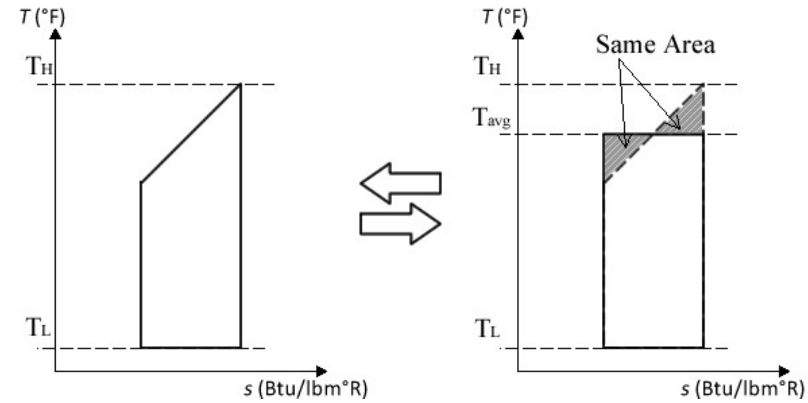

Figure 3: Compare Cycle and Carnot Cycle

By fundamental integration concept, the integral above equals to the area under the T-s curve for a given interval. Since the trapezoid in the ideal Rankine Cycle has the same area as the rectangle at Carnot Cycle diagram below, we can state that their thermal efficiency is the same for both the compare cycle and the Carnot cycle. For the same reason, we can say the ideal Rankine cycle is equivalent to a Carnot cycle in the following figure:

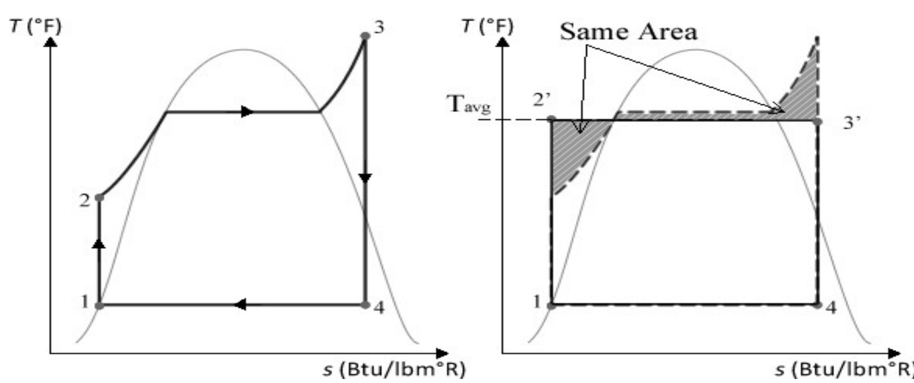

Figure 4: Ideal Rankine Cycle (left), and Carnot Cycle (Right)

The T-s diagrams for the above modifications is shown as:

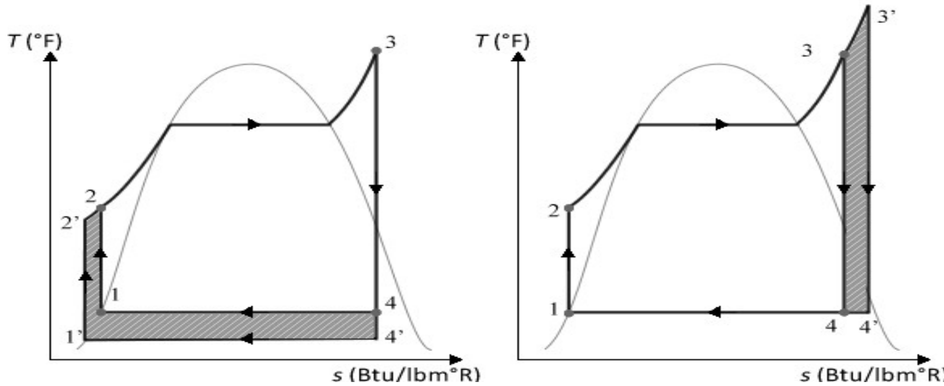

Figure 5: T-s diagrams for Rankine (reduce), and Carnot (Increase)

In the previous figure, we are considering lowering the temperature at stage 1 and 4, there are two approaches to achieve this task. One is to lower the pressure at 4, another one is to cool the condensed water. However, there comes a problem when we lower, that is, when as the temperature decreases, the moisture level gets higher. As our design specification states that the moisture level must be less than 13%, we need to take the moisture level into our design consideration, because moisture of the steam coming out of the turbine will cause cavitation and damage the turbine.

4.4 Reheating

Reheating is illustrated by the following figure and is as follows: superheat the steam before it enters the turbine (point 3), expand the steam in the turbine (step 3 to 4), reheat it (step 4 to 5), and expand again to the condenser pressure (step5 to 6)

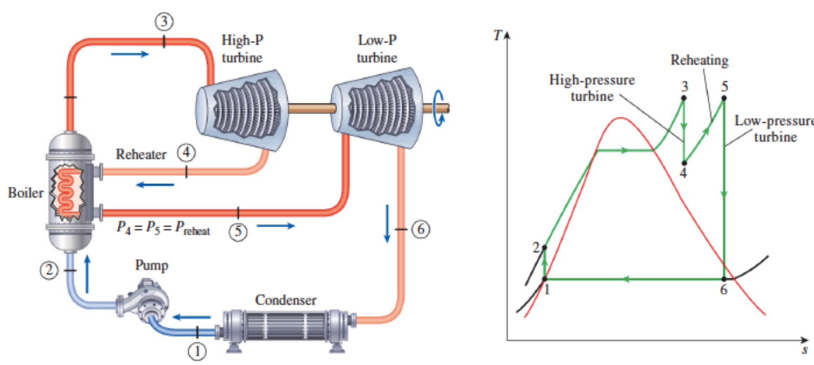

Figure 6: The Reheat Rankine Cycle

The heat added to the system is now equal to both the original heat added from steps 2 to 3 and the heat added from steps 4 to 5.

$$q_{in} = q_{2-3} + q_{4-5} = (h_3 - h_2) + (h_5 - h_4)$$

The work done by the turbine is now equal to both the work done by the high-pressure turbine (steps 3 to 4) and the low-pressure turbine (steps 5 to 6)

$$w_{turb} = w_{HP} + w_{LP} = (h_3 - h_4) + (h_5 - h_6)$$

The overall efficiency of the reheat cycle becomes

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{h_4 - h_1}{(h_3 - h_2) + (h_5 - h_4)}$$

This reheat process can be done several times. However, it is not practical to have more than two reheat stages because the efficiency increases from the second reheat is half of that of the first reheat.

4.5 Regeneration

The idea of regeneration is to extract steam from the turbine to raise the temperature of the liquid leaving the pump before it enters the boiler to decrease the amount of heat added to the boiler. This increases the efficiency and removes air that may have leaked into the condenser by reaerating the water leaving the pump, also called the feedwater. The device that uses the extracted steam to heat the feedwater is conveniently called the feedwater heater.

There are two types of feedwater heaters: open and closed. Open feedwater heaters mix the steam with the feedwater directly. Closed feedwater heaters employ the steam to heat a coil that in turn heats the feedwater. In this paper only open feedwater heaters will be used to improve the Rankine cycle.

Steam at the boiler pressure enters the turbine at step 5 where it expands to the feedwater heater pressure. A portion of that expanded steam (a mass of y kilograms) is extracted into the open feedwater heater at step 6. The rest of the steam (a mass of 1-y kilograms) continues to expand is entropically to the condenser pressure at step 7. The condensed water, or feedwater, enters a pump at step 1 where it is compressed to the open feedwater pressure. The feedwater enters the heater at step 2 where it mixes with the steam from step 6, increasing in temperature due to the steam. The water leaves the heater at step 3 where it enters a second pump to be compressed to the boiler pressure. The water enters the boiler at step 4 where it is heated, now requiring less heat because of its higher temperature. An illustration of this process is shown below.

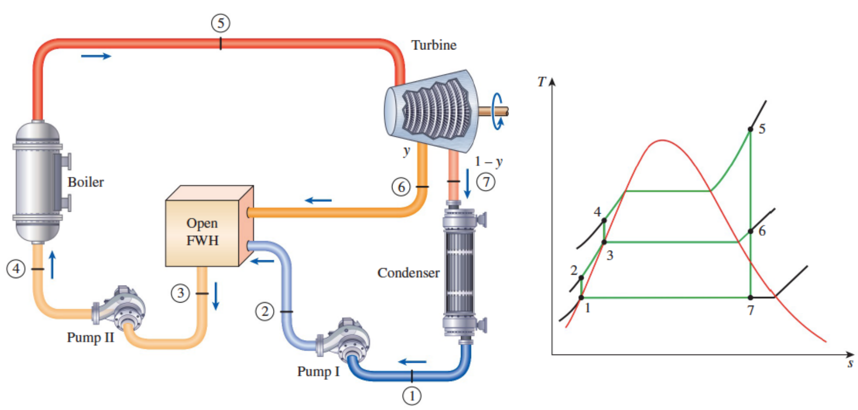

Figure 7: The Open Feedwater Heater Regenerative Rankine Cycle

This cycle can be described by the following equations. The fraction of the steam extracted from the turbine is equal to the mass fraction.

$$y = \dot{m}_6 / \dot{m}_5$$

The heat added to the boiler is

$$q_{in} = h_5 - h_4$$

Since the mass of the steam entering the condenser is (1-y), the heat removed from the condenser becomes

$$q_{out} = (1 - y)(h_7 - h_1)$$

The work of the turbine is a combination of both the change in enthalpy from step 5 to 6 (steam extracted to the feedwater heater) and the change in enthalpy of the remaining steam that enters the condenser.

$$w_{turb} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

The total pump work is equal to the work done by both pumps.

$$w_{pump} = (1 - y)w_{pump\ I} + w_{pump\ II}$$

Where:

$$w_{pump\ I} = v_1(P_2 - P_1)$$
$$w_{pump\ II} = v_2(P_4 - P_3)$$

5 Approach

The overall goal is to find the enthalpy at each point to find the efficiency at the end. Knowing the entropy at some points will help in finding the enthalpy at other points due to isentropic processes. The entropy is also used to determine the moisture content. The enthalpy at point 1 is always going to be found using the Saturated Water Table A-5E. The enthalpy at point 2, which is in the compressed water region, is always going to be found using the equation for the work of the pump. The enthalpy at point 3, which is in the superheated region is found using interpolation of the Superheated Water Table A-6E because the values for the inlet pressure are not available in the steam tables. The enthalpy at point 4 can either be in the superheated region, which is not desirable, or in the saturated liquid-vapor region, desirable. To find the enthalpy at the former, interpolation must be done within the Superheated Water Table A-6E. To find enthalpy at the latter, the moisture content must be found using the known entropy as well as the entropy values in the Saturated Water Table A-5E. The enthalpy is found using the moisture content and the enthalpy values in the Saturated Water Table A-5E.

6 Case Analysis

6.1 Cycle 1: Ideal Rankine Basic Cycle

Given the Inlet pressure and temperature of the turbine, we cannot increase the temperature where we add heat as we mentioned to be one way to increase the efficiency. However, an alternative will be to lower the outlet pressure of the turbine. We will need to find the value of the exhaust pressure which satisfies the conditions of the highest efficiency of the cycle at the moisture level less than 13%. We are going to try different pressures ranged from 1-30 psi to find the proper pressure. Then we will plot the efficiency with respect to exhaust pressure and steam quality with respect to exhaust pressure.

Cycle 1 involves the basic analysis of the Rankine Cycle given the parameters. During this Cycle, Compressor and Turbine Exit Pressure are varied to provide the best efficiency within Steam Quality, x4 = 0.87, while keeping the Inlet Pressure at 1900 psi and Inlet Temperature at

1000 F. It is important to note that if the Exit Pressure falls too low (under 0.4 psi), a vacuum develops in the turbine and causes air from outside to interfere. The limit of 0.4 psi will be set for the duration of the project.

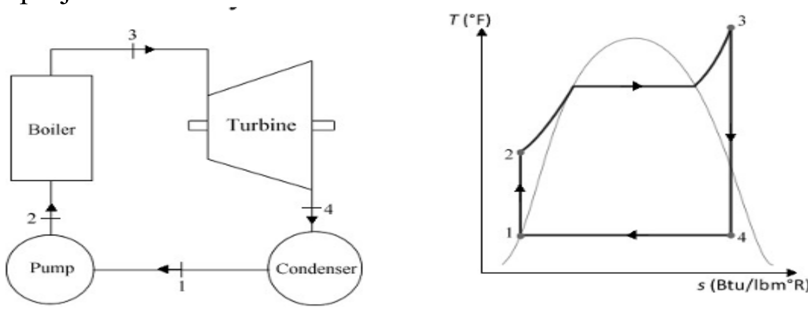

Figure 8: Ideal Rankine Basic Cycle

6.1.1 Stage Calculation for Cycle 1

Stage	*Calculation*
1	$P_1 = 5$ psi (Table A-5E) $h_1 = h_f = 130.18$ Btu/lbm $v_1 = 0.01641$ ft^3/lbm
2	$P_2 = 1900$ psi $h_2 = h_1 + [v_1 (P_2 - P_1) * 144/778]$ $h_2 = 135.935$ Btu/lbm
3	$P_3 = 1900$ psi $T_3 = 1000$ F $h_3 = 1487.7$ Btu/lbm $s_3 = 1.5920$ Btu/lbm.R
4	$P_4 = 5$ psi $s_3 = s_4 = 1.5920$ Btu/lbm.R $x = 0.8435$ $h_4 = 974.122$ $q_{out} = h_4 - h_1$ $\quad q_{in} = h_3 - h_2$ $\eta_{TH} = (1 - q_{out}/q_{in}) = 37.61$ %

Table 4: Stage Calculations for Cycle 1

For this step:

h_{1f} and v_{1f} can be obtained from Saturated Steam Tables

$$h_2 = h_{1f} + v_{1f}(P_2 - P_1)$$

$$\text{Derived from: } \delta w_p = h_2 - h_1 = v_{1f}(P_2 - P_1)$$

h_3 and s_3 can be obtained from Superheated Steam Tables

Values for s_{4g}, s_{4fg}, h_{4g}, h_{4fg} can be found in the Saturated Steam Tables

$$\text{Moisture Content: } (1 - x_4) = \frac{s_{4g} - s_3}{s_{4fg}}$$

$$\text{Enthalpy at Point 4: } h_4 = h_{4g} - (1 - x_4) * h_{4fg}$$

$$\text{Work Turbine: } w_t = h_3 - h_4$$

$$\text{Heat Input: } q_H = h_3 - h_2$$

$$\text{Heat Rejected: } q_L = h_4 - h_1$$

Efficiency: $\eta = \left(1 - \frac{q_L}{q_H}\right) * 100\%$

P_4	x	h_1	h_4	qin	q_{out}	Efficiency (n)
5	0.84512	130.18	974.11	1352.675	834.942	37.61
10	0.87006	161.25	1015.469	1321.568	854.219	35.36
15	0.88722	181.21	1041.364	1301.5845	860.154	33.91
20	0.899882	196.27	1060.00	1286.5019	863.735	32.86
25	0.91014	208.52	1076.162	1275.2466	865.637	31.98
30	0.91771	219.77	1085.736	1266.871	865.721	31.24

Table 5: Efficiency calculations for Cycle 1 at P4

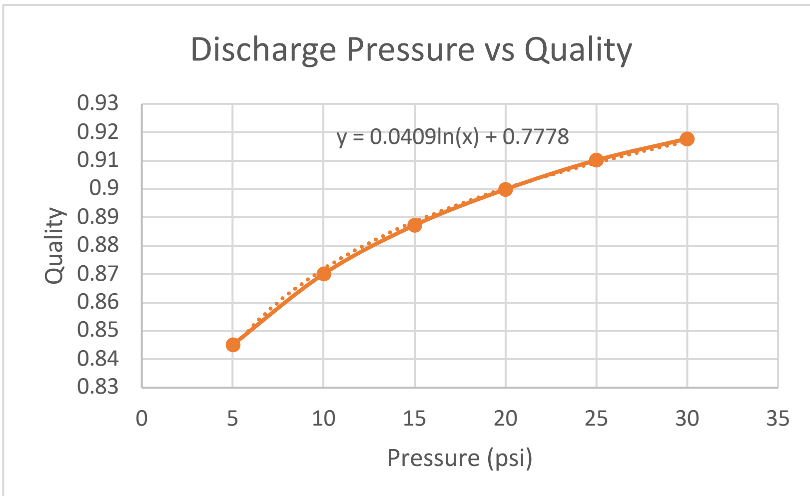

Figure 9: Steam Quality vs Exhaust Pressure (Cycle One at P_4)

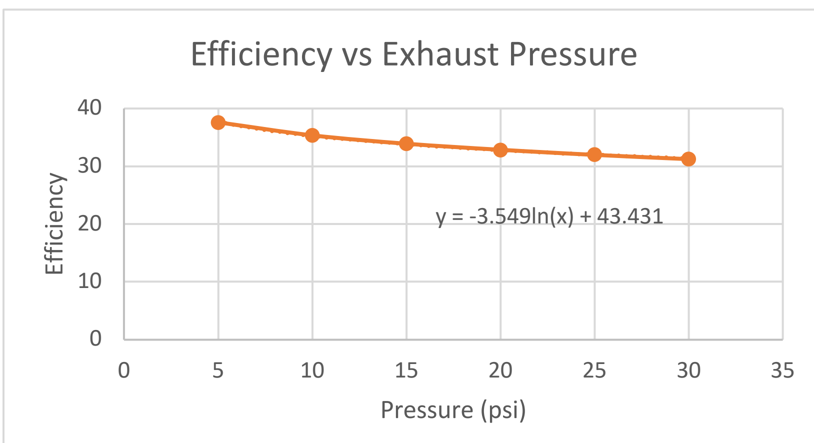

Figure 10: Efficiency vs Exhaust Pressure (Cycle One at P_4)

We can use the logarithmic trendline to be able to calculate the P1 with an exact steam quality of 87%.

Y=0.0409ln(x)+0.778 → ln(x)= (0.87-0.778)/0.0409 → ln(x)=2.249 → x= e^(2.21)= 9.481

Similarly for the efficiency:

Y= -3.540ln(x)+43.431 → -3.540ln(9.481)+43.431= **35.46%**

6.2 Cycle 2: Ideal Rankine Cycle with Reheating

The efficiency can be also increased by reheating. That means we redirect the steam that comes out from the first turbine back to the boiler, and heat up the steam again, then the steam enters the second turbine, at last leaves the second turbine as condensed liquid.
We will find the optimum value of the reheat pressure to achieve the highest efficiency in the domain of the admissible values of the steam quality, for which use the given data and pick up at least 4 different values of the reheat pressure from interval 0.1- 0.4 times of the inlet pressure of first turbine and find the proper reheat pressure. Then we will plot the efficiency with respect to reheat pressure, and the quality of steam with respect to reheat pressure.

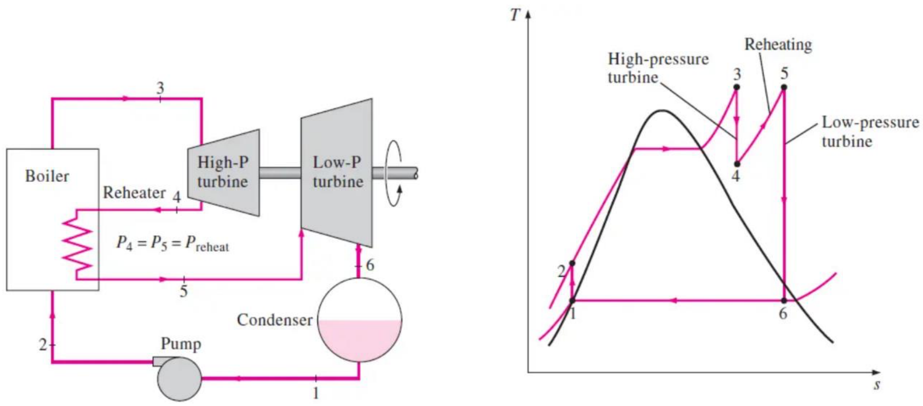

Figure 11: Schematic and T-s diagram of a Rankine basic cycle with reheater

For cycle 2, we will perform an analysis to calculate the adequate reheat pressure that would produce the best efficiency. We will accomplish this by comparing a variety of values of reheat pressures that could be used to find the best efficiency. In this type of cycle, the exhaust steam from high pressure turbine is recycled back through the boiler. This would allow it to gain a bit more heat, increasing the steam enthalpy thus generating more work via the low-pressure turbine.

Process	Description
1-2	Isentropic compression in a pump
2-3	Constant pressure heat addition
3-4	Isentropic expansion in first turbine
4-1	Constant pressure heat addition same boiler
5-6	Isentropic expansion in low pressure turbine
6-1	Heat rejection in condenser

Table 6: Process description for Cycle 2

6.2.1 Step One Calculations

Stage	*Calculation*
1	$P_1 = 9.481$ *psi* $h_1 = h_f = 161.2417/lbm$ $v_1 = 0.0166\ ft^3/lbm$
2	$P_2 = 1900$ *psi* $h_2 = h_1 + [v_1\ (P_2 - P_1)\ .\ 144/778]$ $h_2 = 166.12697\ Btu/lbm$
3	$P_3 = 1900$ *psi* $T_3 = 1000\ F$ $h_3 = 1487.7\ Btu/lbm$ $s_3 = 1.5920 Btu/lbm.R$
4	$P_4 = 160$ *psi* $s_3 = s_4 = 1.5920\ Btu/lbm.R$ $h_4 = 1218.5 Btu/lbm$
5	$P_5 = 160$ *psi* $S_5 = 1.8682\ Btu/lbm.R$ $h_5 = 1530.7\ Btu/lbm$
6	$P_6 = 9.481 psi$ $s_5 = s_6 = 1.8682\ Btu/lbm.R$ $x = 1.0537$ $h_6 = 1195.785209\ Btu/lbm$

Table 7: Step One Calculations for Cycle 2

h_{1f} and v_{1f} can be obtained from Saturated Steam Tables

$$h_2 = h_{1f} + v_{1f}(P_2 - P_1)$$

Derived from: $\delta w_p = h_2 - h_1 = v_{1f}(P_2 - P_1)$

P_3 is obtained from the previous cycle.

h_4 and T_4 can be obtained by using interpolation with $x = s_3$, using upper and lower bounds of the entropy s_3 and corresponding enthalpies or temperatures from Superheated Steam Tables.

h_5 and s_5 are found by using the Superheated Steam Tables at Temperature of 1000 F.

Values for s_{6g}, s_{6fg}, h_{6g}, h_{6fg}- can be found in the Saturated Steam Tables

Moisture Content: $(1 - x_6) = \frac{s_{6g} - s_5}{s_{6fg}}$

Enthalpy at Point 4: $h_6 = h_{6g} - (1 - x_6) * h_{6fg}$

Heat Input: $q_H = (h_3 - h_2) + (h_5 - h_4)$

$$\text{Heat Rejected:} \quad q_L = h_6 - h_1$$

$$\text{Efficiency:} \ \eta = \left(1 - \frac{q_L}{q_H}\right) * 100\%$$

P_4	h_4	h_5	x_6	h_6	q_{in}	q_{out}	η
160	1218.5	1530.7	1.05366	1195.785	1633.776	1034.543	36.678
200	1239.0	1529.6	1.03690	1179.333	1612.173	1018.091	36.849
300	1279.0	1526.7	1.00618	1149.176	1569.273	987.929	37.045
400	1309.4	1523.9	0.98410	1127.496	1535.773	966.255	37.081
450	1322.4	1522.4	0.97499	1118.557	1521.271	957.311	37.072
500	1334.6	1521.0	0.96681	1110.522	1507.965	949.280	37.049
600	1356.2	1518.1	0.95245	1096.421	1483.468	935.179	36.961

Table 8: Step One Efficiency Calculations for Cycle 2 at P_4

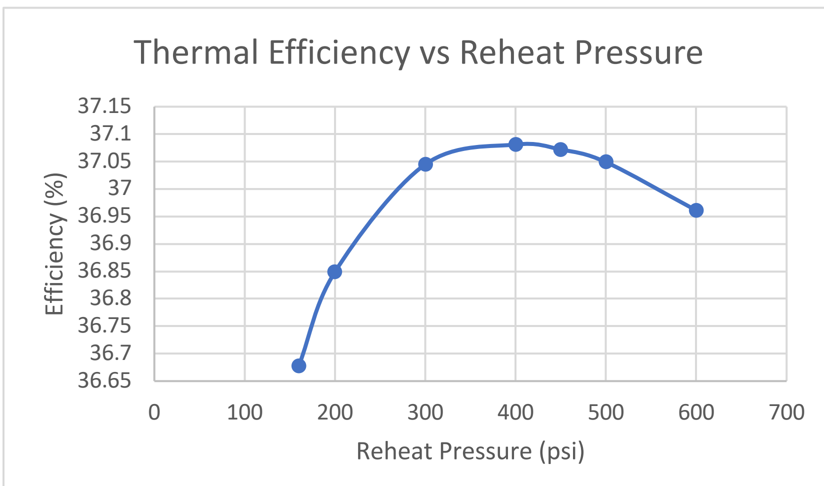

Figure 12: Efficiency vs Reheat Pressure at P_4

As seen on the figure above, we can see that the most efficient point is at 400 psi with 37.8% efficiency.

6.2.2 Step Two Calculations

Stage	*Calculation*
1	$P_1 = 1\ psi$ $h_1 = h_f = 69.72\ Btu/lbm$ $v_1 = 0.01614\ ft^3/lbm$

2	$P_2 = 1900\ psi$ $W_p = h_2 - h_1$ $h_2 = h_1 + w_p$ $h_2 = h_1 + [v_1 (P_2 - P_1) . 144/778]$ $h_2 = 74.49677614\ Btu/lbm$
3	$P_3 = 1900\ psi$ $T_3 = 1000\ F$ $h_3 = 1487.7\ Btu/lbm$ $s_3 = 1.5920\ Btu/lbm.R$
4	$P_4 = 400\ psi$ $s_3 = s_4 = 1.5920\ Btu/lbm.R$ $h_4 = 1301.5801\ Btu/lbm$
5	$P_5 = 400psi$ $S_5 = 1.7636\ Btu/lbm.R$ $h_5 = 1523.9\ Btu/lbm$
6	$P_6 = 1\ psi$ $s_5 = s_6 = 1.7636Btu/lbm.R$ $x = 0.884007$ $h_6 = 985.2667715$ qin=1635.523124 $qout$=915.54677 $\eta_{TH} = (1- q_{out}/q_{in})$ = 44.021%

Table 9: Step Two Calculations for Cycle 2

Repeat the above calculations with different P6 ranged from 0.1 to 1psi, saturated liquid properties are from Steam Table, after the computation is performed, we have the results shown in the table below.

P_6	h_2	X_6	h_6	q_{in}	q_{out}	η
0.1	7.75292	0.784526	845.190	1702.26	842.181	50.52587
0.3	37.2818	0.842839	923.301	1672.738	890.769	46.7478
0.5	52.3764	0.859576	948.6951	1657.643	901.077	45.6410
0.7	62.86583	0.871163	966.16359	1647.154	908.0635	44.870
1	74.4967	0.884008	985.26677	1635.523	915.54677	44.0211

Table 10: Step Two Efficiency Calculation for Cycle 2 at P_6

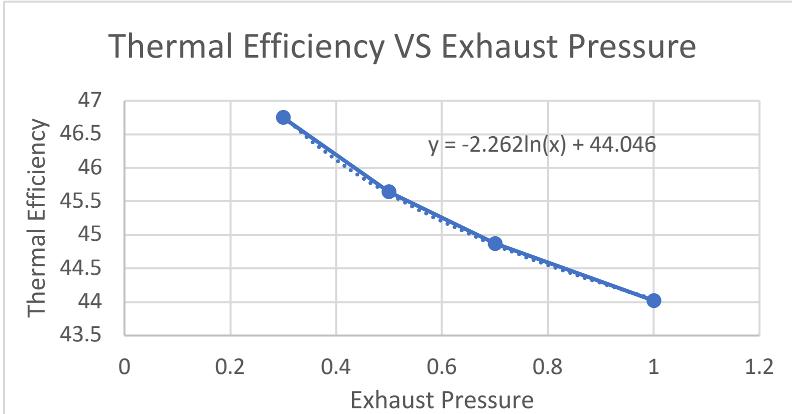

Figure 13: Thermal Efficiency vs Exhaust Pressure (Step Two Cycle 2 at P_6)

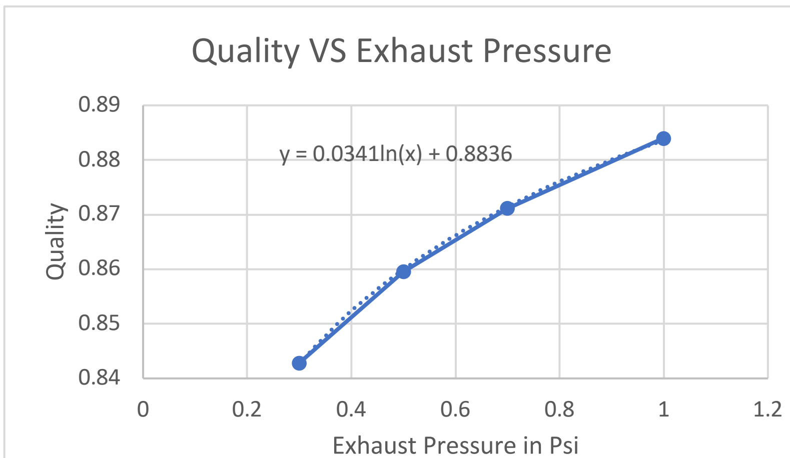

Figure 14: Quality vs Exhaust Pressure (Step two Cycle Two at P_6)

Solving P1: y=0.034ln(x)+0.8836 → Ln(x)= (0.87-0.8836)/0.034 → x= e^(-0.4)= 0.670 =P1=P6
For the efficiency: use the formula from excel graph
y = -2.262ln(x) + 44.046 → -2.262ln(0.670) + 44.046= **50.011% Efficiency**

6.3 Cycle 3: Regenerative Ideal Rankine Cycle with Reheating

A thermodynamics device called open feed water heaters is implemented into the reheat ideal Rankine cycle. The purpose of the open feed water is to increase the temperature of the liquid leaves the pump. This raises the average heat addition temperature in the boiler and thus increasing efficiency of the cycle. This process is constructed by extracting steam from the turbine and directing it into an open feed water heater where it heats up the saturated liquid leaving pumps or condenser.

In this case, there are 3 cycles that need to be studied.

1. Reheat ideal Rankine cycle with one open feed water heater connected to the high-pressure turbine.
2. Preceding cycle with one open feed water heater connected to the intermediate pressure turbine
3. Preceding cycle with two open feed water heaters connected to the low-pressure turbine.

In Cycle 3, the determined Reheat Pressure and will be kept constant along with its correspondingly determined properties, while the Exit Pressure P6 will be varied. This is done to find the limit of how low the Exit Pressure can be reduced to for a range of values, that can give the best efficiency. This will optimize the Cycle's lower bounds. In this cycle feedwater heaters are introduced. An open feedwater heater will be attached to the high-pressure (HP) turbine at point 6. By adding a feedwater heater, a fraction of the total steam in the turbine is extracted to mix with water exiting the first pump at step 3.

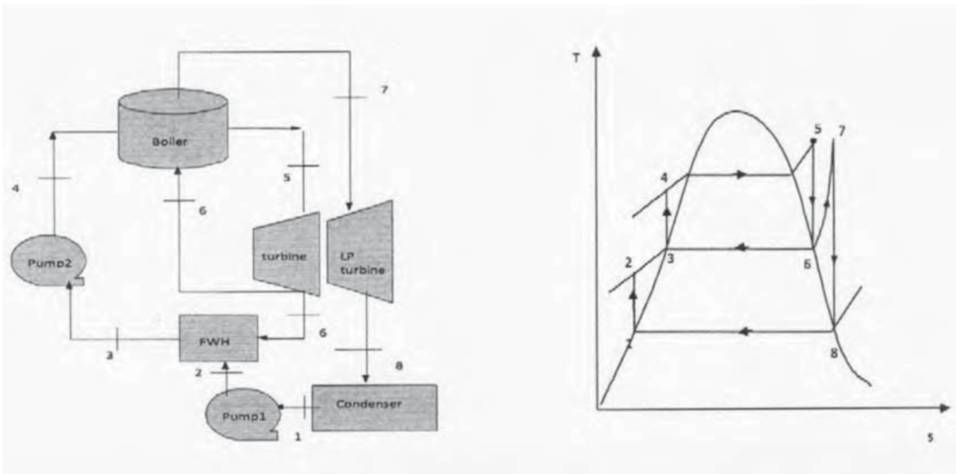

Figure 15: Regenerative Ideal Rankine Cycle with Reheating

Process	Description
1-2	Isentropic compression in a pump (s1=s2)
2-3	Constant pressure heat added to open feed water
3-4	Isentropic compression pump (s3=s4)
4-5	Constant pressure heat addition in boiler (P4=P5)
5-6	Isentropic expansion in high pressure turbine (s5=s6)
6-7	Constant pressure heat addition in boiler (P6=P7)
7-8	Isentropic expansion in low pressure turbine (s7=s8)
8-1	Constant pressure heat rejected in condenser (P6=P1)

Table 11: Process description for Cycle 3

6.3.1 Stage Calculation for Cycle 3

Stage	*Calculation*
1	$P_1 = 0.670\ psi$ $h_1 = h_f = 57.0466 Btu/lbm$

	$v_1 = 0.0161\ ft^3/lbm$
2	$P_2 = 400\ psi$ $h_2 = h_1 + w_p$ $h_2 = h_1 + [v_1 (P_2 - P_1) . 144/778]$ $h_2 = 58.23655\ Btu/lbm$
3	$P_3 = 400\ psi$ $v_3 = 0.01934\ ft^3/lbm$ $h_3 = 424.13\ Btu/lbm$
4	$P_4 = 1900\ psi$ $h_4 = h_3 + [v_3 (P_4 – P_3) . 144/778]$ $h_4 = 428.4255\ Btu/lbm$
5	$P_5 = 1900\ psi$ $s_5 = 1.5920\ Btu/lbm.R$ $h_5 = 1487.7\ Btu/lbm$
6	$P_6 = 400\ psi$ $s_5 = s_6 = 1.5920\ Btu/lbm.R$ $h_6 = 1309.4\ Btu/lbm$
7	$P_7 = 400\ psi$ $s_7 = 1.7636\ Btu/lbm.R$ $h_7 = 1523.9\ Btu/lbm$
8	$P_8 = 0.670psi$ $s_7 = 1.7636\ Btu/lbm.R$ $X = 0.8699631773$ $h_8=964.284$

Table 12: Stage Calculations for Cycle 3

Using Continuity Equation

m6 = h3 – h2 / h6 – h2 = 0.2924
qout = (1 - m6)(h8 – h1)=641.922
qin= (h5 – h4) + (1 - m6)(h7 - h6)=1211.015
ηTH = (1- ql/qh) = **46.992 %**

6.4 Cycle 4: Ideal Rankine Cycle with Regeneration (2 Open Feed Water Heater)

In this cycle an open feedwater heater will be added to the intermediate pressure (IP) turbine. Two new states are added, 2 and 10. State 10 is the location of the new open feedwater heater. The open feedwater heater added in Cycle Three to state 6 is now on state 8.

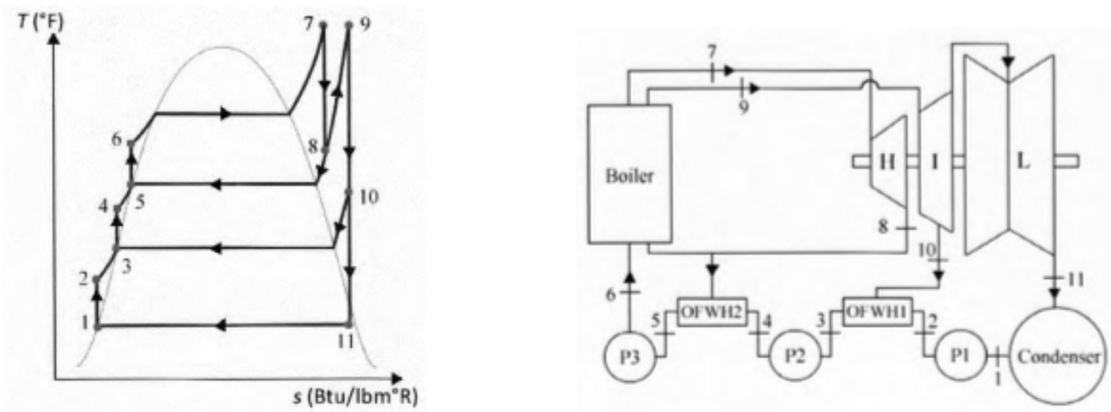

Figure 16: Regenerative Ideal Rankine Cycle with Reheater (2 OFWH)

Process	Description
1-2	Isentropic compression in a pump (s1=s2)
2-3	Constant pressure heat added at the first open FWH (P2=P3)
3-4	Isentropic compression pump (s3=s4)
4-5	Constant pressure heat addition at FWH number 2 (P2=P3)
5-6	Isentropic compression in pump (s5=s6)
6-7	Constant pressure heat addition in boiler (P6=P7)
7-8	Isentropic expansion in high pressure turbine (s7=s8)
8-9	Constant pressure heat added in boiler (P8=P9)
8-5	Constant pressure heat regeneration in second FWH (P8=P5)
9-11	Isentropic expansion in intermediate pressure turbine(s9=s11)
10-3	Constant pressure heat regeneration in first FWH (P10=P3)
11-1	Constant pressure heat rejection in condenser (P11-P1)

Table 13: Process description for Cycle 4

6.4.1 Stage Calculation for Cycle 4

Stage	Calculation
1	$P_1 = 0.670$ psi $h_1 = h_f = 57.0466$ Btu/lbm $v_1 = 0.0161\ ft^3/lbm$
2	$P_2 = 200$ psi $W_p = h_2 - h_1$ $h_2 = h_1 + w_p$ $h_2 = h_1 + [v_1 (P_2 - P_1) . 144/778]$ $h_2 = 57.64056365$ Btu/lbm
3	$P_3 = 200$psi $v_3 = 0.01839\ ft^3/lbm$ $h_3 = 355.46$ Btu/lbm
4	$P_4 = 400$ psi $h_4 = h_3 + [v_3 (P_4 - P_3) . 144/778]$ $h_4 = 356.1407609$ Btu/lbm
5	$P_5 = 400$ psi $h_5 = 424.13$ Btu/lbm $v_5 = 0.01934\ ft^3/lbm$
6	$P_6 = 1900$ psi $H6 = h5 + [v5 (P6 - P4) . 144/778]$ $h_6 = 428.4255681$ Btu/lbm
7	$P_7 = 1900$ psi $S_7 = 1.5920$ Btu/lbm.R $h_7 = 1487.7$ Btu/lbm
8	$P_8 = 400$ psi $S_8 = 1.5920$ Btu/lbm.R $h_8 = 1309.4$ Btu/lbm
9	$P_9 = 400$ psi $S_9 = 1.7636$ Btu/lbm.R $h_9 = 1523.9$ Btu/lbm
10	$P_{10} = 200$ psi $S_{10} = 1.7636$ Btu/lbm.R $h_{10} = 1390.8$
11	$P_{11} = 0.670$ psi $X = 0.87$ $h_{11} = 964.323$ Btu/lbm

Table 14: Stage Calculation for Cycle 4

Using Continuity Equation:

$$m8 = h5 - h4 / h8 - h4 = 0.0713$$
$$m10=(1-m8)\ [(h3-h2)/(h10-h2)]$$

$$m10 = 0.20745$$

$$\text{Heat Input: } q_{in} = (h_7 - h_6) + (1 - m_8 - m_{10})(h_9 - h_8) = 1213.97 \text{ Btu/lbm}$$

$$\text{Heat Rejected: } q_{out} = (1 - m_8 - m_{10})(h_{11} - h_1) = 654.3471 \text{Btu/lbm}$$

$$\text{Net Work: } w_{net} = q_{in} - q_{out}$$

$$\text{Efficiency: } \eta = \left(\frac{w_{net}}{q_{in}}\right) * 100\% = \mathbf{47.098\%}$$

6.5 Cycle 5: Ideal Rankine Cycle with Regeneration (4 Open Feed Water Heater)

In this cycle two open feedwater heaters will be added to the low pressure (LP) turbine. Seven new states are added, 2 to 6 and 15 to 16. State 15 and 16 are the locations of the new open feedwater heater. The open feedwater heater added in Cycle Three to state 6 became state 8 in Cycle Four and state 12 in this cycle. The open feedwater heater added in Cycle Four to state 10 is now state 14.

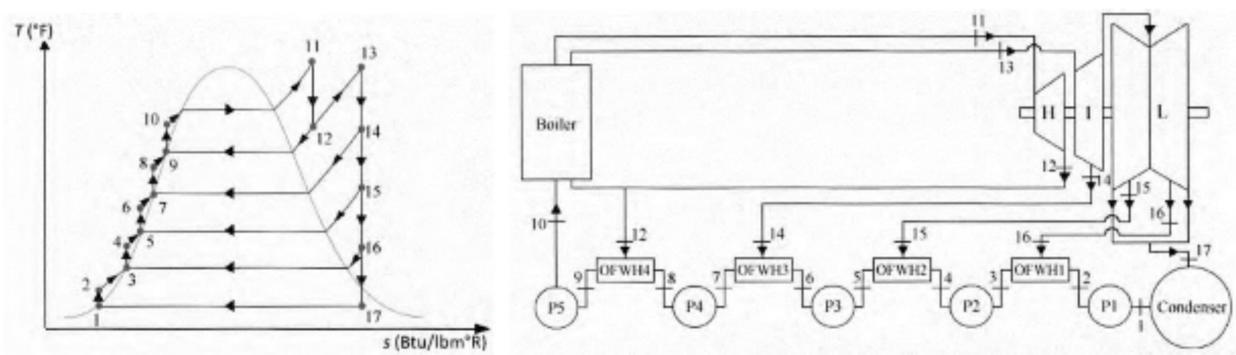

Figure 17: Regenerative Ideal Rankine Cycle with Reheating (Cycle 5)

Process	Description
1-2	Isentropic compression in a pump (s1=s2)
2-3	Constant pressure heat added at the first FWH (P2=P3=P16)
3-4	Isentropic compression pump 2 (s3=s4)
4-5	Constant pressure heat add in second FWH (P4=P5=P15)
5-6	Isentropic compression in pump 3 (s5=s6)
6-7	Constant pressure heat addition in third FWH (P6=P7=P14)
7-8	Isentropic compression in pump 4 (s7=s8)
8-9	Constant pressure heat addition in fourth FWH (P8=P9)
9-10	Isentropic compression in pump 5 (s9=s100)
10-11	Constant pressure heat addition in boiler (P10=P11)

11-12	Isentropic expansion in a high-pressure turbine (s11=s12)
12-13	Constant pressure heat addition in a boiler (P12=P13)
13-17	Isentropic steam expansion at low pressure turbine(s13=s14=s15=s16=s17)
12-9	Constant pressure heat regeneration in fourth FWH (P12=P9)
14-7	Constant pressure heat regeneration in third FWH (P14=P7)
15-5	Constant pressure heat regeneration in second FWH (P15=P5)
16-3	Constant pressure heat regeneration in first FWH (P16=P3)
17-1	Constant pressure heat rejection in condenser. End

Table 15: Process description for Cycle 5

6.5.1 Stage Calculation for Cycle 5

Stage	*Calculation*
1	$P_1 = 0.670$ psi $h_1 = h_f = 57.0466$ Btu/lbm $v_1 = 0.0161$ ft^3/lbm
2	$P_2 = 100$ psi $h_2 = h_1 + w_p$ $h_2 = h_1 + [v_1 (P_2 - P_1) . 144/778]$ $h_2 = 57.34256879$ Btu/lbm
3	$P_3 = 100$ psi $v_3 = 0.01774$ ft^3/lbm $h_3 = 298.51$ Btu/lbm
4	$P_4 = 200$ psi $h_4 = h_3 + [v_3 (P_4 – P_3) . 144/778]$ $h_4 = 298.8383496$ Btu/lbm
5	$P_5 = 200$ psi $h_5 = 355.46$ Btu/lbm $v_5 = 0.01839$ ft^3/lbm
6	$P_6 = 300$ psi $h_6 = h_5 + [v_5 (P_6 – P_5) . 144/778]$ $h_6 = 355.8003805$ Btu/lbm

7	$P_7 = 300$ psi $V_7 = 0.01890\ ft^3/lbm$ $h_7 = 393.94$ Btu/lbm
8	$P_8 = 400$ psi $h_8 = h_7 + [v_7 (P_8 - P_7) . 144/778]$ $h_8 = 394.2898201$ Btu/lbm
9	$P_9 = 400$ psi $v_9 = 0.01934\ ft^3/lbm$ $h_9 = 424.13$ Btu/lbm
10	$P_{10} = 1900$ psi $h_{10} = h_9 + [v_9 (P_{10} - P_8) . 144/778]$ $h_{10} = 428.4255681$ Btu/lbm
11	$P_{11} = 1900$ psi $S_{11} = 1.5920$ Btu/lbm.R $h_{11} = 1487.7$ Btu/lbm
12	$P_{12} = 400$psi $S_{12} = 1.5920$ Btu/lbm.R $h_{12} = 1309.4$ Btu/lbm
13	$P_{13} = 400$ psi $S_{13} = 1.7636$ Btu/lbm.R $h_{13} = 1523.9$ Btu/lbm
14	$P_{14} = 300$ psi $s_{14} = 1.7636$ Btu/lbm.R $h_{14} = 1480.0$Btu/lbm
15	$P_{15} = 200$ psi $s_{15} = 1.7636$ Btu/lbm.R $h_{15} = 1422.2$ Btu/lbm
16	$P_{16} = 100$ psi $s_{16} = 1.7636$ Btu/lbm.R

	H_{16} = 1335.0 Btu/lbm
17	P_{17} = 0.670 psi x = 0.87 h_{17} = 964.323 Btu/lbm

Table 16: Stage Calculations for Cycle 5

Mass Fraction

$$m_{12} = \frac{h_9 - h_8}{h_{12} - h_8} = 0.03260$$
$$m_{14} = (1 - m_{12}) \frac{h_7 - h_6}{h_{14} - h_6} = 0.03281$$
$$m_{15} = (1 - m_{12} - m_{14}) \frac{h_5 - h_4}{h_{15} - h_4} = 0.04710$$
$$m_{16} = (1 - m_{12} - m_{14} - m_{15}) \frac{h_3 - h_2}{h_{16} - h_2} = 0.1764$$
$$q_{out} = (1 - m_{12} - m_{14} - m_{15} - m_{16})(h_{17} - h_1) = 645.1266$$
$$q_{in} = (1 - m_{12})(h_{13} - h_{12}) + (h_{11} - h_{10}) = 1266.77995$$
$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{(1 - m_{12} - m_{14} - m_{15} - m_{16})(h_{17} - h_1)}{(1 - m_{12})(h_{13} - h_{12}) + (h_{11} - h_{10})}$$
$$= \mathbf{49.1\%}$$
$$\boldsymbol{\eta_{TH} = 49.1\ \%}$$

7 Discussion

7.1 Efficiency Per Each Cycle

We can observe that with the addition of reheat and regenerative process, the efficiency of the Rankine cycle increases. The results are shown in the graph below

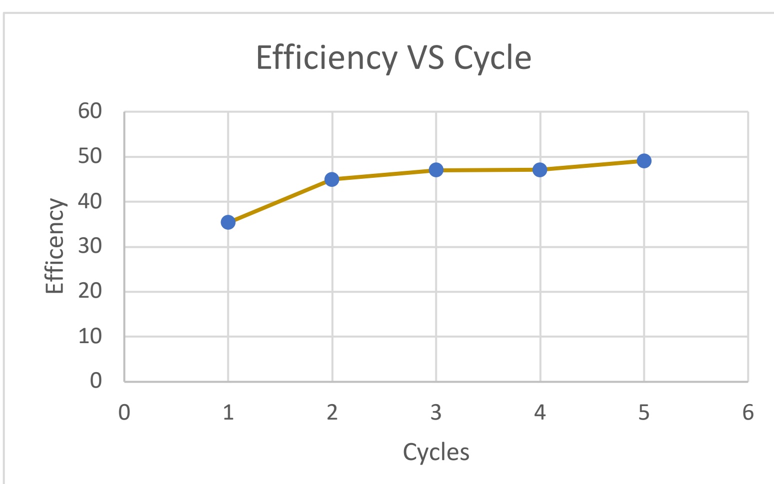

Figure 18:Efficiency per Cycle

7.2 Cost Effectiveness of Feedwater Heaters

It is apparent that the efficiency of the cycle increases with the addition of feedwater heaters. However, it must be noted that feedwater heaters are rather expensive. If the price of a feedwater heater is taken to be \$1.25 million, to justify this cost in 10 years, a feedwater heater would have to produce at least \$125,000 in savings per year.

A cost analysis can be done to determine the optimal amount of feedwater heaters. The industry standard for a maximum number of feedwater heaters is 9. The amount of money in savings is

$$savings/year = price \times power \times time \times change\ in\ efficiency$$

$$\begin{array}{ll} Price\ of\ electricity: & \$0.19/kWh \\ Power\ requirement: & 180{,}000\ kW \\ Time: & 8760\ hours/year \end{array}$$

Number of FWH	Efficiency	Change in Efficiency	Savings per year
0	0.50011	0	0
1	0.46992	0.03019	\$9,044,682.48
2	0.47098	0.001058	\$316,968.336
4	0.491	0.019746	\$5,915,743.632

Table 17: Cost Analysis

This graph is shown to easily observe that as we increased the cycles, also adding the FWH, we see an increase in efficiency. However, we reach a steady value after the fourth cycle. We know that by adding FWH to more cycles we increase the funds as well.

7.3 Assuming the Processes as Real

All the above has assumed that the Rankine cycle is operating ideally. However, this is not the case. There is pressure loss, heat loss, and practically anything can go wrong. This can be described in an increase in entropy. All the processes above that were considered isentropic are not isentropic. The second law of thermodynamics leads to the belief that entropy always increases. To include the increase in entropy, the enthalpy at each point must be recalculated. Each enthalpy found will lead to a recalculation of the enthalpy at the next point. This procedure is incredibly time consuming. Therefore, to save time, a different approach will be taken.
The work of a real pump is

$$w_{P,R} = \frac{w_{P,I}}{\eta_P}$$

where $w_{P,R}$ is the work of a real pump, $w_{P,I}$ is the work of an ideal pump, and η_P is the pump efficiency given by the manufacturer.
Similarly, the heat added to a real boiler is:

$$q_{B,R} = \frac{q_{B,I}}{\eta_B}$$

where $q_{B,R}$ is the heat added to a real boiler, $q_{B,I}$ is the heat added to an ideal boiler, and η_B is the boiler efficiency given by the manufacturer.
The work of a real turbine is

$$w_{T,R} = w_{T,I}\eta_T$$

where $w_{T,R}$ is the work of a real turbine, $w_{T,I}$ is the work of an ideal turbine, and η_T is the turbine efficiency given by the manufacturer.

The overall efficiency of the real Rankine cycle including reheating and regeneration given by Cycle 5 is

$$\eta_R = \frac{w_{net}}{q_{in}} = \frac{w_{T,R} - w_{P,R}}{q_{B,R}}$$

The mass flow rate into the boiler can be found as well using the net work and the power requirement.

$$P = \dot{m}w_{net}$$

$$\dot{m} = \frac{P}{w_{net}} = \frac{P}{w_{T,R} - w_{P,R}}$$

Calculation

The work of a pump in a simple Rankine cycle is

$$w_{pump} = h_2 - h_1 = v(P_2 - P_1)$$

Since there are now five pumps and four feedwater heaters, the equation of the total work from the ideal pumps can be written as

$$w_{P,I} = (1 - m_{12} - m_{14} - m_{15} - m_{16})(h_2 - h_1) + (1 - m_{12} - m_{14} - m_{15})(h_4 - h_3) + (1 - m_{12} - m_{14})(h_6 - h_5) + (1 - m_{12})(h_8 - h_7) + (h_{10} - h_9)$$

Substituting the values of enthalpy and mass from Cycle 5 gives

$$w_{P,I} = 5.453823\frac{Btu}{lbm}$$

The work of a turbine in a simple Rankine cycle is

$$w_{turb} = h_3 - h_4$$

In this case which includes reheating and regeneration with four feedwater heaters and 3 turbines, the total work of all of the turbines is

$$w_{T,I} = (1 - m_{12} - m_{14} - m_{15} - m_{16})(h_{16} - h_{17}) + (1 - m_{12} - m_{14} - m_{15})(h_{15} - h_{16}) + (1 - m_{12} - m_{14})(h_{14} - h_{15}) + (1 - m_{12})(h_{13} - h_{14}) + (h_{11} - h_{12})$$

Substituting the values from Cycle 5 gives

$$w_{T,I} = 550.789238\frac{Btu}{lbm}$$

The heat added to a simple Rankine cycle is

$$q_{in} = h_3 - h_2$$

This equation is modified to include reheating and regeneration and is written as

$$q_{B,I} = (h_{11} - h_{10}) + (1 - m_{12})(h_{13} - h_{12})$$

Substituting the values from Cycle 5 gives

$$q_{B,I} = 1266.780014\ \frac{Btu}{lbm}$$

The efficiencies were found

$$\eta_P = 0.9 = 90\%$$
$$\eta_B = 0.8 = 80\%$$
$$\eta_T = 0.87 = 87\%$$

The real work done by the pumps is

$$w_{P,R} = \frac{w_{P,I}}{\eta_P} = \frac{5.453823}{0.9} = 6.059803\frac{Btu}{lbm}$$

The heat added to a real boiler is

$$q_{B,R} = \frac{q_{B,I}}{\eta_B} = \frac{1266.780014}{0.8} = 1583.475018\ \frac{Btu}{lbm}$$

The work of a real turbine is

$$w_{T,R} = w_{T,I}\eta_T = (550.789238)(0.87) = 521.65246\ \frac{Btu}{lbm}$$

Therefore, the real efficiency of Cycle 5 is

$$\eta_R = \frac{w_{net}}{q_{in}} = \frac{w_{T,R} - w_{P,R}}{q_{B,R}} = \frac{521.65246 - 6.059803}{1583.475018} = 0.29879 = 29.879\%$$

The mass flow rate into the boiler is

$$\dot{m} = \frac{P}{w_{net}} = \frac{P}{w_{T,R} - w_{P,R}} = \frac{180{,}000\ kW}{(521.65246 - 6.059803)\frac{Btu}{lbm}}\left(\frac{3412.14\frac{Btu}{hr}}{1\ kW}\right)$$
$$= 1298140.701\frac{lbm}{hr}$$

8 Conclusion

It can be concluded that the efficiencies for all the cycles shown in this report are: η_1 = 35.46%, η_2 = 50.011%, η_3 = 46.991%, η_4 = 47.992%, and η_5 = 49.1%. It has been proven that as the feed water heaters are added to the ideal Rankine cycle, the overall efficiency of the system increases. However, the final system containing 4 feed water heaters, a reheater and 3 turbines with an overall efficiency of 50% and convert it from an ideal cycle to a real cycle, the efficiency drops to 35%, which is less than the efficiency for the standard Rankine cycle calculated for an ideal cycle.

This assignment was able to prove various methods of improving the efficiency of a ranking cycle proved that the addition of reheaters and preheaters could increase the efficiency of the plant and in fact increased revenue. The addition feed water heaters, the overall efficiency of the plant may increase, but at costs in the millions of dollars, there will be a point of diminishing returns where the feed water heaters will actually affect revenue.

9 References

- Çengel, Yunus A., and Michael A. Boles. Thermodynamics: an engineering approach.
- McGraw-Hill Education, 2015.
- Raj, Rishi S. Thermo-Fluid Systems - Analysis and Design. N.p.: n.p., 2013. Print.
- U.S. Department of Energy: Combined Heat and Power Technology Fact Sheet Series –-

  https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Steam%20Turbine.pdf

10 Appendix

10.1 Used Tables

TABLE A–5E

Saturated water—Pressure table

		Specific volume, ft³/lbm		Internal energy, Btu/lbm			Enthalpy, Btu/lbm			Entropy, Btu/lbm · R		
Press., P psia	Sat. temp., T_{sat} °F	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
1	101.69	0.01614	333.49	69.72	973.99	1043.7	69.72	1035.7	1105.4	0.13262	1.84495	1.9776
2	126.02	0.01623	173.71	94.02	957.45	1051.5	94.02	1021.7	1115.8	0.17499	1.74444	1.9194
3	141.41	0.01630	118.70	109.39	946.90	1056.3	109.40	1012.8	1122.2	0.20090	1.68489	1.8858
4	152.91	0.01636	90.629	120.89	938.97	1059.9	120.90	1006.0	1126.9	0.21985	1.64225	1.8621
5	162.18	0.01641	73.525	130.17	932.53	1062.7	130.18	1000.5	1130.7	0.23488	1.60894	1.8438
6	170.00	0.01645	61.982	138.00	927.08	1065.1	138.02	995.88	1133.9	0.24739	1.58155	1.8289
8	182.81	0.01652	47.347	150.83	918.08	1068.9	150.86	988.15	1139.0	0.26757	1.53800	1.8056
10	193.16	0.01659	38.425	161.22	910.75	1072.0	161.25	981.82	1143.1	0.28362	1.50391	1.7875
14.696	211.95	0.01671	26.805	180.12	897.27	1077.4	180.16	970.12	1150.3	0.31215	1.44441	1.7566
15	212.99	0.01672	26.297	181.16	896.52	1077.7	181.21	969.47	1150.7	0.31370	1.44441	1.7549
20	227.92	0.01683	20.093	196.21	885.63	1081.8	196.27	959.93	1156.2	0.33582	1.39606	1.7319
25	240.03	0.01692	16.307	208.45	876.67	1085.1	208.52	952.03	1160.6	0.35347	1.36060	1.7141
30	250.30	0.01700	13.749	218.84	868.98	1087.8	218.93	945.21	1164.1	0.36821	1.33132	1.6995
35	259.25	0.01708	11.901	227.92	862.19	1090.1	228.03	939.16	1167.2	0.38093	1.30632	1.6872
40	267.22	0.01715	10.501	236.02	856.09	1092.1	236.14	933.69	1169.8	0.39213	1.28448	1.6766
45	274.41	0.01721	9.4028	243.34	850.52	1093.9	243.49	928.68	1172.2	0.40216	1.26506	1.6672
50	280.99	0.01727	8.5175	250.05	845.39	1095.4	250.21	924.03	1174.2	0.41125	1.24756	1.6588
55	287.05	0.01732	7.7882	256.25	840.61	1096.9	256.42	919.70	1176.1	0.41958	1.23162	1.6512
60	292.69	0.01738	7.1766	262.01	836.13	1098.1	262.20	915.61	1177.8	0.42728	1.21697	1.6442
65	297.95	0.01743	6.6560	267.41	831.90	1099.3	267.62	911.75	1179.4	0.43443	1.20341	1.6378
70	302.91	0.01748	6.2075	272.50	827.90	1100.4	272.72	908.08	1180.8	0.44112	1.19078	1.6319
75	307.59	0.01752	5.8167	277.31	824.09	1101.4	277.55	904.58	1182.1	0.44741	1.17895	1.6264
80	312.02	0.01757	5.4733	281.87	820.45	1102.3	282.13	901.22	1183.4	0.45335	1.16783	1.6212
85	316.24	0.01761	5.1689	286.22	816.97	1103.2	286.50	898.00	1184.5	0.45897	1.15732	1.6163
90	320.26	0.01765	4.8972	290.38	813.62	1104.0	290.67	894.89	1185.6	0.46431	1.14737	1.6117
95	324.11	0.01770	4.6532	294.36	810.40	1104.8	294.67	891.89	1186.6	0.46941	1.13791	1.6073
100	327.81	0.01774	4.4327	298.19	807.29	1105.5	298.51	888.99	1187.5	0.47427	1.12888	1.6032
110	334.77	0.01781	4.0410	305.41	801.37	1106.8	305.78	883.44	1189.2	0.48341	1.11201	1.5954
120	341.25	0.01789	3.7289	312.16	795.79	1107.9	312.55	878.20	1190.8	0.49187	1.09646	1.5883
130	347.32	0.01796	3.4557	318.48	790.51	1109.0	318.92	873.21	1192.1	0.49974	1.08204	1.5818
140	353.03	0.01802	3.2202	324.45	785.49	1109.9	324.92	868.45	1193.4	0.50711	1.06858	1.5757
150	358.42	0.01809	3.0150	330.11	780.69	1110.8	330.61	863.88	1194.5	0.51405	1.05595	1.5700
160	363.54	0.01815	2.8347	335.49	776.10	1111.6	336.02	859.49	1195.5	0.52061	1.04405	1.5647
170	368.41	0.01821	2.6749	340.62	771.68	1112.3	341.19	855.25	1196.4	0.52682	1.03279	1.5596
180	373.07	0.01827	2.5322	345.53	767.42	1113.0	346.14	851.16	1197.3	0.53274	1.02210	1.5548
190	377.52	0.01833	2.4040	350.24	763.31	1113.6	350.89	847.19	1198.1	0.53839	1.01191	1.5503
200	381.80	0.01839	2.2882	354.78	759.32	1114.1	355.46	843.33	1198.8	0.54379	1.00219	1.5460
250	400.97	0.01865	1.8440	375.23	741.02	1116.3	376.09	825.47	1201.6	0.56784	0.95912	1.5270
300	417.35	0.01890	1.5435	392.89	724.77	1117.7	393.94	809.41	1203.3	0.58818	0.92289	1.5111
350	431.74	0.01912	1.3263	408.55	709.98	1118.5	409.79	794.65	1204.4	0.60590	0.89143	1.4973
400	444.62	0.01934	1.1617	422.70	696.31	1119.0	424.13	780.87	1205.0	0.62168	0.86350	1.4852
450	456.31	0.01955	1.0324	435.67	683.52	1119.2	437.30	767.86	1205.2	0.63595	0.83828	1.4742
500	467.04	0.01975	0.92819	447.68	671.42	1119.1	449.51	755.48	1205.0	0.64900	0.81521	1.4642
550	476.97	0.01995	0.84228	458.90	659.91	1118.8	460.93	743.60	1204.5	0.66107	0.79388	1.4550
600	486.24	0.02014	0.77020	469.46	648.88	1118.3	471.70	732.15	1203.9	0.67231	0.77400	1.4463

TABLE A–6E

Superheated water

T °F	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R	v ft³/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R
	P = 1.0 psia (101.69°F)*				*P* = 5.0 psia (162.18°F)				*P* = 10 psia (193.16°F)			
Sat.†	333.49	1043.7	1105.4	1.9776	73.525	1062.7	1130.7	1.8438	38.425	1072.0	1143.1	1.7875
200	392.53	1077.5	1150.1	2.0509	78.153	1076.2	1148.5	1.8716	38.849	1074.5	1146.4	1.7926
240	416.44	1091.2	1168.3	2.0777	83.009	1090.3	1167.1	1.8989	41.326	1089.1	1165.5	1.8207
280	440.33	1105.0	1186.5	2.1030	87.838	1104.3	1185.6	1.9246	43.774	1103.4	1184.4	1.8469
320	464.20	1118.9	1204.8	2.1271	92.650	1118.4	1204.1	1.9490	46.205	1117.6	1203.1	1.8716
360	488.07	1132.9	1223.3	2.1502	97.452	1132.5	1222.6	1.9722	48.624	1131.9	1221.8	1.8950
400	511.92	1147.1	1241.8	2.1722	102.25	1146.7	1241.3	1.9944	51.035	1146.2	1240.6	1.9174
440	535.77	1161.3	1260.4	2.1934	107.03	1160.9	1260.0	2.0156	53.441	1160.5	1259.4	1.9388
500	571.54	1182.8	1288.6	2.2237	114.21	1182.6	1288.2	2.0461	57.041	1182.2	1287.8	1.9693
600	631.14	1219.4	1336.2	2.2709	126.15	1219.2	1335.9	2.0933	63.029	1219.0	1335.6	2.0167
700	690.73	1256.8	1384.6	2.3146	138.09	1256.7	1384.4	2.1371	69.007	1256.5	1384.2	2.0605
800	750.31	1295.1	1433.9	2.3553	150.02	1294.9	1433.7	2.1778	74.980	1294.8	1433.5	2.1013
1000	869.47	1374.2	1535.1	2.4299	173.86	1374.2	1535.0	2.2524	86.913	1374.1	1534.9	2.1760
1200	988.62	1457.1	1640.0	2.4972	197.70	1457.0	1640.0	2.3198	98.840	1457.0	1639.9	2.2433
1400	1107.8	1543.7	1748.7	2.5590	221.54	1543.7	1748.7	2.3816	110.762	1543.6	1748.6	2.3052
	P = 15 psia (212.99°F)				*P* = 20 psia (227.92°F)				*P* = 40 psia (267.22°F)			
Sat.	26.297	1077.7	1150.7	1.7549	20.093	1081.8	1156.2	1.7319	10.501	1092.1	1169.8	1.6766
240	27.429	1087.8	1163.9	1.7742	20.478	1086.5	1162.3	1.7406				
280	29.085	1102.4	1183.2	1.8010	21.739	1101.4	1181.9	1.7679	10.713	1097.3	1176.6	1.6858
320	30.722	1116.9	1202.2	1.8260	22.980	1116.1	1201.2	1.7933	11.363	1112.9	1197.1	1.7128
360	32.348	1131.3	1221.1	1.8496	24.209	1130.7	1220.2	1.8171	11.999	1128.1	1216.9	1.7376
400	33.965	1145.7	1239.9	1.8721	25.429	1145.1	1239.3	1.8398	12.625	1143.1	1236.5	1.7610
440	35.576	1160.1	1258.8	1.8936	26.644	1159.7	1258.3	1.8614	13.244	1157.9	1256.0	1.7831
500	37.986	1181.9	1287.3	1.9243	28.458	1181.6	1286.9	1.8922	14.165	1180.2	1285.0	1.8143
600	41.988	1218.7	1335.3	1.9718	31.467	1218.5	1334.9	1.9398	15.686	1217.5	1333.6	1.8625
700	45.981	1256.3	1383.9	2.0156	34.467	1256.1	1383.7	1.9837	17.197	1255.3	1382.6	1.9067
800	49.967	1294.6	1433.3	2.0565	37.461	1294.5	1433.1	2.0247	18.702	1293.9	1432.3	1.9478
1000	57.930	1374.0	1534.8	2.1312	43.438	1373.8	1534.6	2.0994	21.700	1373.4	1534.1	2.0227
1200	65.885	1456.9	1639.8	2.1986	49.407	1456.8	1639.7	2.1668	24.691	1456.5	1639.3	2.0902
1400	73.836	1543.6	1748.5	2.2604	55.373	1543.5	1748.4	2.2287	27.678	1543.3	1748.1	2.1522
1600	81.784	1634.0	1861.0	2.3178	61.335	1633.9	1860.9	2.2861	30.662	1633.7	1860.7	2.2096
	P = 60 psia (292.69°F)				*P* = 80 psia (312.02°F)				*P* = 100 psia (327.81°F)			
Sat.	7.1766	1098.1	1177.8	1.6442	5.4733	1102.3	1183.4	1.6212	4.4327	1105.5	1187.5	1.6032
320	7.4863	1109.6	1192.7	1.6636	5.5440	1105.9	1187.9	1.6271				
360	7.9259	1125.5	1213.5	1.6897	5.8876	1122.7	1209.9	1.6545	4.6628	1119.8	1206.1	1.6263
400	8.3548	1140.9	1233.7	1.7138	6.2187	1138.7	1230.8	1.6794	4.9359	1136.4	1227.8	1.6521
440	8.7766	1156.1	1253.6	1.7364	6.5420	1154.3	1251.2	1.7026	5.2006	1152.4	1248.7	1.6759
500	9.4005	1178.8	1283.1	1.7682	7.0177	1177.3	1281.2	1.7350	5.5876	1175.9	1279.3	1.7088
600	10.4256	1216.5	1332.2	1.8168	7.7951	1215.4	1330.8	1.7841	6.2167	1214.4	1329.4	1.7586
700	11.4401	1254.5	1381.6	1.8613	8.5616	1253.8	1380.5	1.8289	6.8344	1253.0	1379.5	1.8037
800	12.4484	1293.3	1431.5	1.9026	9.3218	1292.6	1430.6	1.8704	7.4457	1292.0	1429.8	1.8453
1000	14.4543	1373.0	1533.5	1.9777	10.8313	1372.6	1532.9	1.9457	8.6575	1372.2	1532.4	1.9208
1200	16.4525	1456.2	1638.9	2.0454	12.3331	1455.9	1638.5	2.0135	9.8615	1455.6	1638.1	1.9887
1400	18.4464	1543.0	1747.8	2.1073	13.8306	1542.8	1747.5	2.0755	11.0612	1542.6	1747.2	2.0508
1600	20.438	1633.5	1860.5	2.1648	15.3257	1633.3	1860.2	2.1330	12.2584	1633.2	1860.0	2.1083
1800	22.428	1727.6	1976.6	2.2187	16.8192	1727.5	1976.5	2.1869	13.4541	1727.3	1976.3	2.1622
2000	24.417	1825.2	2096.3	2.2694	18.3117	1825.0	2096.1	2.2376	14.6487	1824.9	2096.0	2.2130