Steam Turbine Power Plant Design: An Analysis of Various Modification to the Rankine Cycle

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Nomenclature:

Term	Symbol	Units
Pressure	p	psi
Quality	x	
Thermal Efficiency	η	
Specific volume	v	ft^3/lbm
Mass flow rate	$\dot{m}$	lbm/s
Work by pump	w_{in}	Btu/lbm
Work by turbine	w_{out}	Btu/lbm
Specific entropy	s	Btu/lbm*R
Mass friction	m	
Enthalpy	h	Btu/lbm
Temperature	T	$\circ\ F$
Specific heat	q_{in}/q_{out}	Btu/lbm

Abstract

In this paper, various modification techniques to the steam turbine power plant will be explored through the impact efficiency, cost and other thermodynamic properties. The paper will start off by analyzing the properties of the ideal Rankine cycle followed by additions of a single reheat, combined reheat and regeneration and the addition of feedwater heaters. The design of these modified cycles will be based on these given design parameters: inlet pressure of 2000 psia, power of 150,000 W and a steam quality of 87%. A cost analysis will be done on the additional feedwater heaters into the design of the cycles. Note that in the analysis of various enthalpy and specific entropy values within this paper, values calculated may not always be found in the appendix. Such values are calculated using the simple interpolation MATLAB code provided in the appendix.

Introduction

Steam powered turbines are a widely used medium in generating power due to many of its desirable characteristics including the low costs, high enthalpy value and its availability. Due to this reason, many attempts have been made to improve the efficiency of the cycle as will be discussed in this paper.

The steam turbine power plant runs on what's called a Rankine cycle. The cycle is used in replacement of what is thought of as the ‘ideal’ cycle: The Carnot Cycle. Such a cycle encounters a variety of problems when placed to a vapor powered cycle. Sticking with the Carnot cycle could lead to a two-phase problem as well as a high moisture problem. During the isentropic process of the cycle, the quality of steam decreases, which means a higher moisture medium in the turbine, leading to issues of performance. The Rankine cycle is a modification of the Carnot cycle that looks to superheat the steam in the boiler as well as completely cooling the steam exiting the turbine in the condenser.

At its fundamental level, the Rankine cycle operates on the principle of using highly pressurized and heated fluid (most commonly water) to generate steam to create work in a turbine. Core elements of this cycle include a boiler, pump, turbine and compressor. The boiler serves as the main heat addition stage, the pump is used to increase pressure, the turbine is what generates the work, and the compressor takes the excess unused vapor and cools it down to be used again in the cycle (for a closed cycle). However, additional elements can be added or replaced to increase efficiency and reduce cost. Various methods of modifications will be explored in this paper.

One such method that will be explored is the concept of reheating. In this modification, the main principle driving this addition is increasing efficiency by increasing the temperature limits. Reheating set to minimize work lost from increasing the highest temperature. Other methods that are set to accomplish the same goal are superheating the steam to higher temperature. This method, however, is limited to the metallurgy of the boilers. Increasing boiler pressure would also accomplish this goal but create a high moisture content of the steam, making for a large hindrance on the function of the elements in the powerplant. Reheating is a method in which the excess steam that comes out of the turbine is placed back into the boiler to be used to power another low power turbine. The caveat to this method is noticing that although an additional reheating would increase efficiency of the cycle, additional reheating can be observed to have a lower thermal efficiency addition. This paper will look at a single reheat addition and reheating in tangent with other modifications.

The next implemented modification is the concept of regeneration. This method increases the initial temperature of the fluid before being placed into the boiler. This is done through excess heat that exits the turbine as a source of heat for the fluid. This can be accomplished using two different heater systems: Open feedwater heater or closed feedwater heater. While an open FWH directly mixes the excess steam with the fluid being fed to the boiler, a closed FWH keeps the two apart and the fluid being fed to the boiler is indirectly heated by the steam through a network of tubing. An open FWH would require an additional pump for each FWH, increasing the needed work placed into the cycle, but is usually cheaper and more efficient than a closed FWH. A closed FWH would be more complex due to its internal tubing, hence the higher cost and lower efficiency.

Steam quality is a quantity that is often described as a percentage. It represents the ratio of vapor to liquid of a given fluid. Steam quality will fall between the values of 0 to 1, with a value of 1 being fully vapor and a quality of 0 being a full liquid. Values between the two represent a liquid-vapor mixture. The specific design parameters used in this paper states that the vapor quality will be 0.87 at its max.

Cycle One: Ideal Rankine cycle

Before looking into ways to modify the Rankine Cycle, an ideal case shall be established to evaluate the maximum efficiency with the given data. The Rankine Cycle is seen as the most ideal cycle to be used in a vapor power plant as it is a direct modification of the Carnot Cycle (The theoretical ideal cycle for cycles that operate between two temperature limits). This will help calculate the maximum efficiency of the following modifications. In the figures below, the block diagram shows all parts of an ideal Rankine cycle and the T-s property diagram of the cycle.

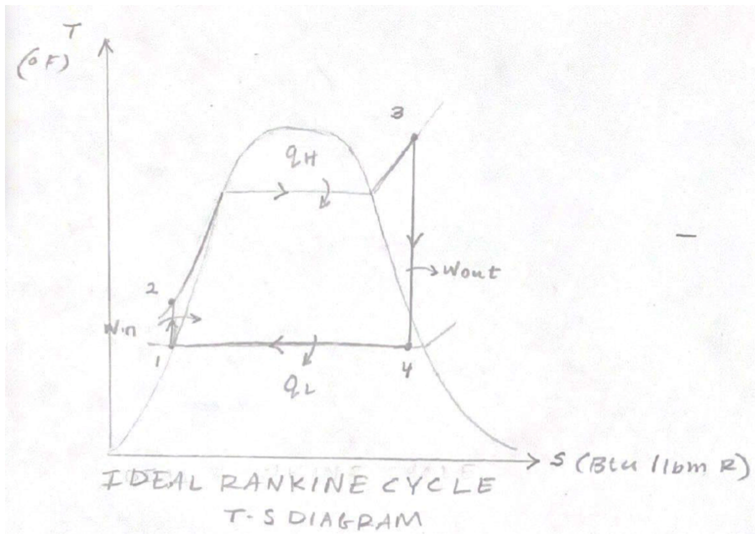

Figure A1: T-s Diagram of an Ideal Rankine Cycle

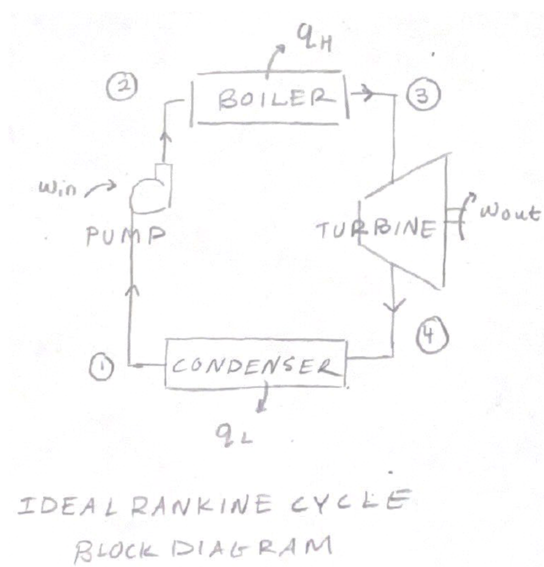

Figure A2: Block diagram of Ideal Rankine Cycle

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

The following calculations show the steps to take to evaluate the quality and efficiencies of the cycle. Various pressures of the exhaust are evaluated in the table. The calculations for a pressure of 1 psi is shown in the calculations following:

Step 1: $p_1 = 1\,psi$	$h_1 = 69.72$ $s_1 = s_f = 0.13262$ $v_1 = v_f = 0.01614$
Step 2: $p_2 = 2000\,psi$	$h_2 = h_1 + v_1(p_2 - p_1)$ $h_2 = 72.692$
Step 3: $p_3 = 2000\,psi$	$h_3 = 1474.9$ $s_3 = 1.5606$
Step 4: $p_4 = p_1 = 1\,psi$ $s_4 = s_3 = 1.5606$ $s_g = 1.9776\ s_{fg} = 1.84495$ $h_g = 1105.4 \quad h_{fg} = 1035.7$	$h_4 = h_g - (1 - x)h_{fg}$ $1 - x = (s_g - s_4)/s_{fg}$ $1 - x = 0.226$ $h_4 = 871.33$
Step 5:	$q_{in} = h_3 - h_2$

$h_1 = 69.72$ $h_2 = 72.692$ $h_3 = 1474.9$ $h_4 = 871.33$	$q_{in} = 1402.208$ $q_{out} = h_4 - h_1$ $q_{out} = 801.61$ $\eta = 1 - (q_{out}/q_{in})$ $\eta = 0.427$

Pressure (psi)	s4	sg4	sfg4	(1-x)
1	1.5606	1.9776	1.84495	0.20428738
5	1.5606	1.8438	1.60894	0.15109327
10	1.5606	1.7875	1.50391	0.12420956
15	1.5606	1.7549	1.4441	0.10677931
20	1.5606	1.7319	1.39606	0.09397877
25	1.5606	1.7141	1.3606	0.08334558
30	1.5606	1.6995	1.33132	0.07421206

Figure A3: Chart of Pressure at exhaust with the different entropy values and (1-x), where x is the quality of Ideal Rankine Cycle.

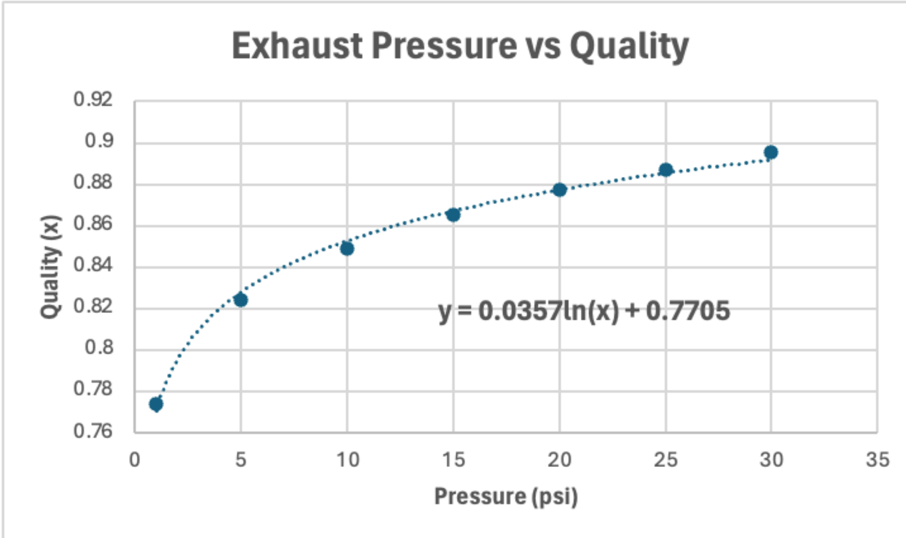

Figure A5: Graph comparing Exhaust pressure to x, where x is the quality of Ideal Rankine Cycle.

$$y = .0357ln(x) + 0.7705$$

$$p_1 = x = exp((0.87 - .7705)/.0357)$$

$$p_1 = 16.2341\, psi$$

Pressure (psi)	vf	h1	h2	h3	h4	(1-x)	n
1	0.01614	69.72	75.691717	1474.9	871.308615	0.226022	0.42711273
5	0.01641	130.18	136.239466	1474.9	954.595484	0.176017	0.38414896
10	0.01659	161.25	167.360579	1474.9	994.969488	0.150873	0.36237526
15	0.01672	181.21	187.352988	1474.9	1020.26027	0.134547	0.34833427
20	0.01683	196.27	202.437827	1474.9	1038.41423	0.122702	0.3381774
25	0.01692	208.52	214.705152	1474.9	1053.194	0.112818	0.32972746
30	0.017	218.93	225.128663	1474.9	1065.48384	0.104333	0.32263302

Figure A6: Chart of exhaust pressure, the enthalpy at each stage, and thermal efficiency of Ideal Rankine Cycle.

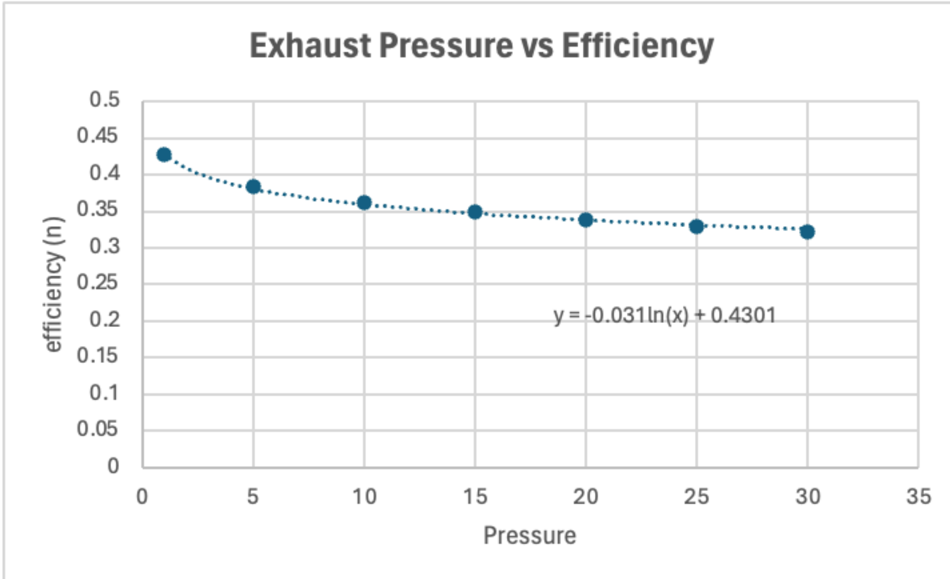

Figure A7: Graph comparing Exhaust pressure and efficiency of ideal Rankine Cycle.

$$\eta = -.031ln(x) + 0.4301$$
$$\eta = -.031ln(16.2341) + 0.4301$$
$$\eta = 34.369\,\%$$

Cycle 2: Ideal Rankine with Single Reheat

Reheating is a type of modification that can be made to the Rankine Cycle to increase efficiency. Single reheating is the most common reheating as increasing the amount of reheating can lead to the inverse effect of decreasing efficiency of the cycle. Reheating reduces the work loss from increasing the temperature limits. In this analysis, exhaust pressure is varied in the first case and the reheat pressure is held constant in the second case.

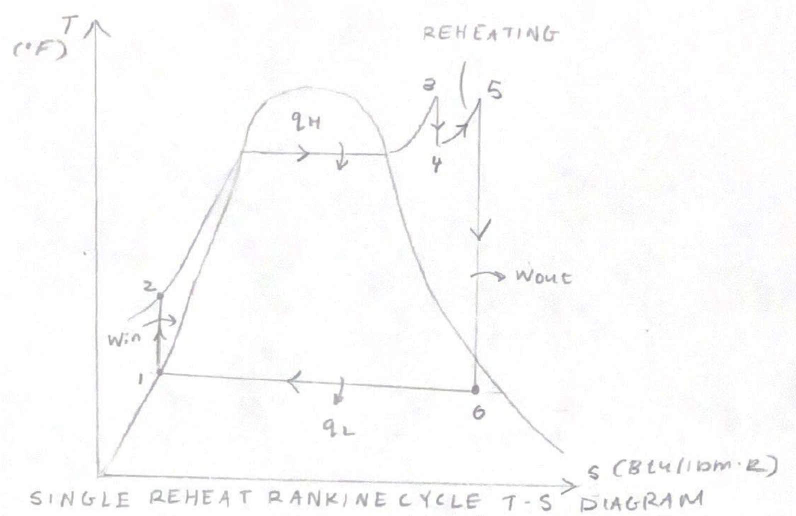

Figure B1: T-s property diagram of a single reheat Rankine Cycle.

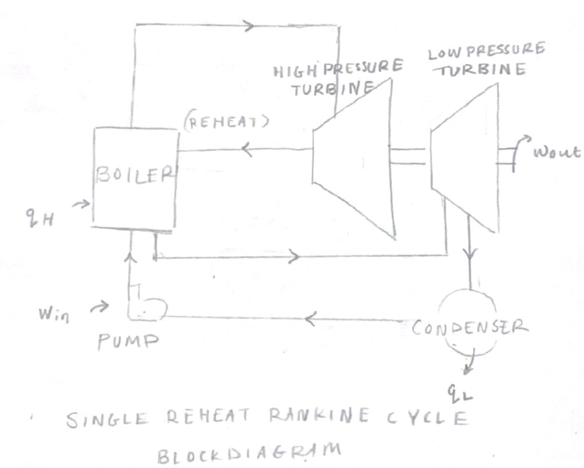

Figure B2: Block diagram of single reheat Rankine Cycle

1-2 Isentropic compression in the pump

2-3 Constant-pressure heat addition in the boiler

3-4 Isentropic expansion in the high-pressure turbine

4-5 Constant pressure heat addition in the boiler

5-6 Constant-pressure heat addition in the low-pressure turbine

6-1 Constant-pressure heat rejection in a condenser

Case One: Determining Optimal Reheat Pressure

Calculations done below will be for the Reheat Pressure of 200 psi.

Step 1: $p_1 = 16.2341\, psi$	$h_1 = 184.9271$ $v_1 = v_f = 0.01672$
Step 2: $p_2 = 2000\, psi$ $p_1 = 16.2341\, psi$	$h_2 = h_1 + v_1(p_2 - p_1)$ $h_2 = 191.06627$
Step 3: $p_3 = p_2 = 2000\, psi$	$h_3 = 1474.9$ $s_3 = 1.5606$
Step 4: $p_4 = 200\, psi$ $s_4 = s_3 = 1.5606$ $s_f = 0.54379$ $s_{fg} = 1.00219$	$x = (s_4 - s_f)/s_{fg}$ $x = 1.014581$ $h_4 = h_f + xh_{fg}$ $h_4 = 1211.0925$

$h_f = 355.46 \quad h_{fg} = 843.33$	
Step 5: $p_5 = p_4 = 200\ psi$	$h_5 = 1529.6$ $s_5 = 1.8430$
Step 6: $p_6 = p_1 = 16.2431\, psi$ $s_6 = s_5 = 1.5606$ $s_f = 0.313915\, s_{fg} = 1.4325$ $h_f = 185.4963772 \quad h_{fg} = 967.115$	$h_6 = h_f + xh_{fg}$ $x = (s_6 - s_f)/s_{fg}$ $x = 1.0217$ $h_6 = 1159.6606$
Efficiency $h_1 = 184.9271$ $h_2 = 191.06627$ $h_3 = 1474.9$ $h_4 = 1211.0925$ $h_5 = 1529.6$ $h_6 = 1159.6606$	$q_{in} = (h_3 - h_2) + (h_5 - h_4)$ $q_{in} = 1635.9305$ $q_{out} = (h_6 - h_1)$ $q_{out} = 974.733$ $\eta = 1 - (q_{out}/q_{in})$ $\eta = 0.382$

pressure (psi)	Pressure inlet	s4	h4	s5	h5	(1-x)	p6	h6	n
200	16.2341	1.5606	1211.092	1.843	1529.6	-0.0217	16.42	1159.66	0.3820
260	16.2341	1.5606	1233.722	1.8133	1527.8	-0.0025	16.423	1140.66	0.3845

450	16.2341	1.5606	1284.274	1.7449	1515.4	0.04175	16.423	1096.8	0.3877
500	16.2341	1.5606	1294.317	1.7376	1517.8	0.04648	16.423	1092.2	0.3877
600	16.2341	1.5606	1311.960	1.716	1518.1	0.06045	16.423	1083.4	0.3865
800	16.2341	1.5606	1340.536	1.6812	1512.2	0.0829	16.423	1072.4	0.3797

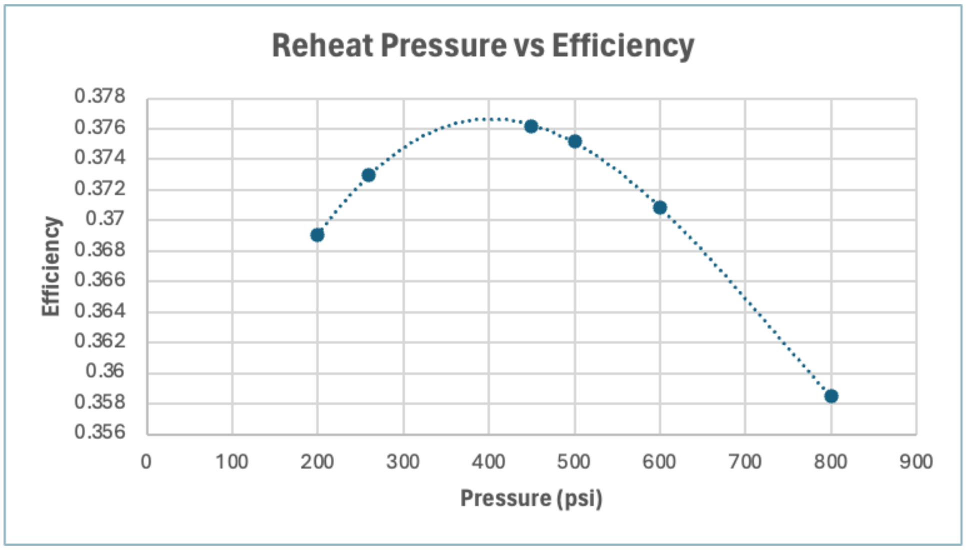

Figure B4: Graph comparing Reheat pressure and efficiency of single reheat Rankine Cycle. Highest reheat pressure occurs at 400 psi

Case Two: Constant Reheat Pressure

In this step, the reheat pressure will be kept constant. Calculations will be done for 1 psi at the entrance.

Step 1: $p_1 = 1\,psi$	$h_1 = 69.72$ $v_1 = v_f = 0.01672$
Step 2: $p_2 = 2000\,psi$	$h_2 = h_1 + v_1(p_2 - p_1)$

	$h_2 = 101.98386$
Step 3: $p_3 = p_2 = 2000\, psi$	$h_3 = 1490.8$ $s_3 = 1.5606$
Step 4: $p_4 = 400\, psi$ $s_4 = s_3 = 1.5606$ $s_f = 0.62168 \;\; s_{fg} = 0.8635$ $h_f = 424.13 \;\; h_{fg} = 780.87$	$x = (s_4 - s_f)/s_{fg}$ $h_4 = h_f + xh_{fg}$ $h_4 = 1309.4657$
Step 5: $p_5 = p_4 = 400\;\; psi$	$h_5 = 1523.28$ $s_5 = 1.7636$
Step 6: $p_6 = p_1 = 1\, psi$ $s_6 = s_5 = 1.7636$ $s_g = 1.9776\, s_{fg} = 1.84495$ $h_g = 1105.4 \;\; h_{fg} = 1035.7$	$h_6 = h_f + xh_{fg}$ $x = (s_6 - s_f)/s_{fg}$ $h_6 = 988.74727$
Efficiency $h_1 = 69.72$ $h_2 = 101.98386$	$q_{in} = (h_3 - h_2) + (h_5 - h_4)$ $q_{in} = 1635.9305$ $q_{out} = (h_6 - h_1)$

$h_3 = 1490.8$ $h_4 = 1309.4657$ $h_5 = 1523.28$ $h_6 = 988.74727$	$q_{out} = 974.733$ $\eta = 1 - (q_{out}/q_{in})$ $\eta = 0.426$

Pressure (psi)	sg	sfg	(1-x)
1	1.9776	1.84495	0.11263178
2	1.9194	1.74444	0.08575818
3	1.8858	1.68489	0.06884722
4	1.8621	1.64225	0.05620338
5	1.8438	1.60894	0.04599301
6	1.8289	1.58155	0.0373684
8	1.8056	1.538	0.02327698
10	1.7875	1.50391	0.01176932
15	1.7549	1.44441	-0.0103156
20	1.7319	1.39606	-0.0271478

Figure B5: Chart of constant reheat pressure, specific entropy of compressed liquid, mixture and (1-x) of a single reheat Rankine Cycle.

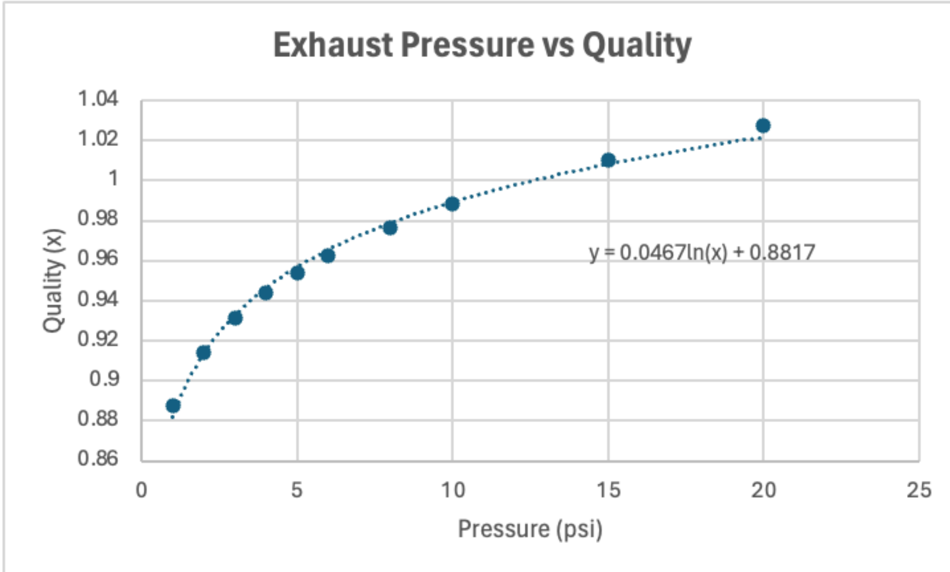

Figure B6: Graph comparing Exhaust pressure vs (1-x) of single reheat Rankine Cycle.

$$y = 0.0467ln(x) + 0.8817$$
$$ln(x) = .87 - .88170.0467$$
$$p_1 = x = 0.7784\, psi$$

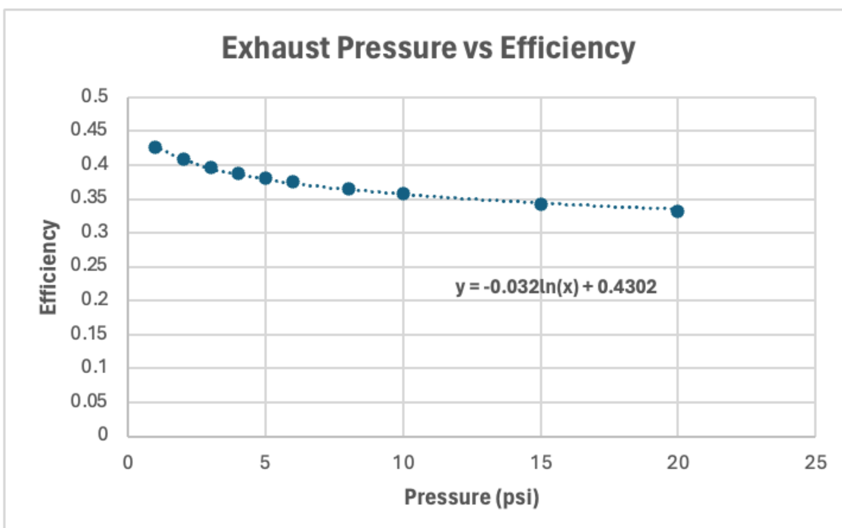

Figure B6: Graph comparing Exhaust pressure vs efficiency of single reheat Rankine Cycle.

$$\eta = -.032ln(x) + 0.4302$$

$$\eta = -.031ln(0.7784) + 0.4301$$
$$\eta = 42.233\,\%$$

Cycle 3: Rankine Cycle with Reheating and Regeneration

Regeneration is a modification that can be made in addition to reheating in the Rankine Cycle. This process takes waste heat/ hot vapor that exits the turbine and uses it to preheat the liquid before entering the boiler. Such methods can increase efficiency by requiring less heat addition in the boiler stage.

There are two types of devices that are used to accomplish this regeneration: Open Feedwater Heater and Closed Feedwater heater, as discussed earlier. For this analysis, different amounts of FWH are added to determine the cost and efficiency benefits of additional FWH.

Case One: Single Reheat and One Open FWH

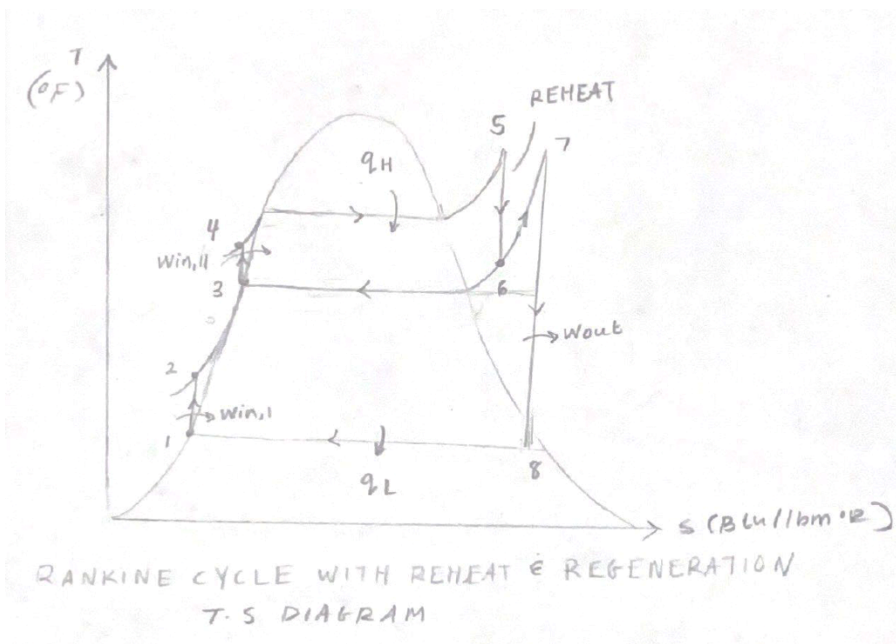

Figure C1: T-s diagram of a single reheat + one open FWH Rankine cycle

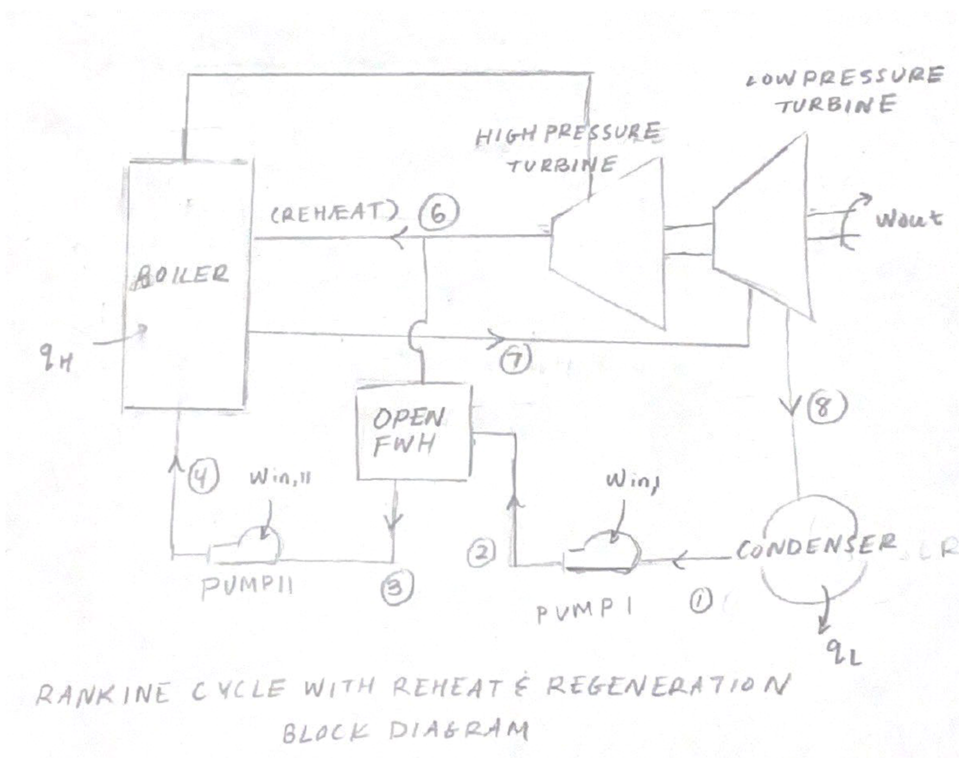

Figure C2: Block Diagram of single reheat + one FWH Rankine Cycle.

1-2 Isentropic compression in the pump 1

2-3 Constant-pressure heat addition in the open FWH

3-4 Isentropic compression in the pump 2

4-5 Constant pressure heat addition in the boiler

5-6 Isentropic expansion in high pressure turbine

6-3 Constant-pressure heat addition in heater

7-8 Isentropic expansion in low pressure turbine

8-1 Constant-pressure heat rejection in a condenser

-Evaluate η;

Step 1:	

$p_1 = 0.7784\, psi$	$h_1 = 60.6923$ $v_1 = 0.01611$
Step 2: $p_2 = 400\, psi$	$h_2 = h_1 + v_1(p_2 - p_1)$ $h_2 = 67.0737$
Step 3: $p_3 = p_2 = 400\, psi$	$v_3 = 0.01934$ $h_3 = 424.13$
Step 4: $p_4 = 2000\, psi$	$h_4 = h_3 + v_3(p_4 - p_3)$ $h_4 = 429.857$
Step 5: $p_5 = p_4 = 2000\, psi$	$s_5 = 1.5606$ $h_5 = 1474.9$
Step 6: $p_6 = 400\, psi$	$s_6 = s_5 = 1.5606$ $h_6 = h_f + xh_{fg}$ $x = (s_f - s_6)/s_{fg}$ $x = 1.08734$ $h_6 = 1273.203$

Step 7: $p_7 = 400\,psi$	$h_7 = 1523.9$
Step 8: $p_8 = p_1 = 0.7784\,psi$	$h_8 = h_f + xh_{fg}$ $x_8 = 0.87$ $h_f = h_1$ $h_8 = 979.36$
Efficiency $\eta = 1 - (q_{out}/q_{in})$	$m_6 = (h_3 - h_2)/(h_6 - h_2)$ $m_6 = 0.296035$ $q_{out} = (1 - m_6)(h_8 - h_1)$ $q_{out} = 646.71$ $q_{in} = (h_5 - h_4) + (1 - m_6)(h_7 - h_6)$ $q_{in} = 1221.525$ $\eta = 0.4706$

Case Two: Single Reheat and Two Open FWH

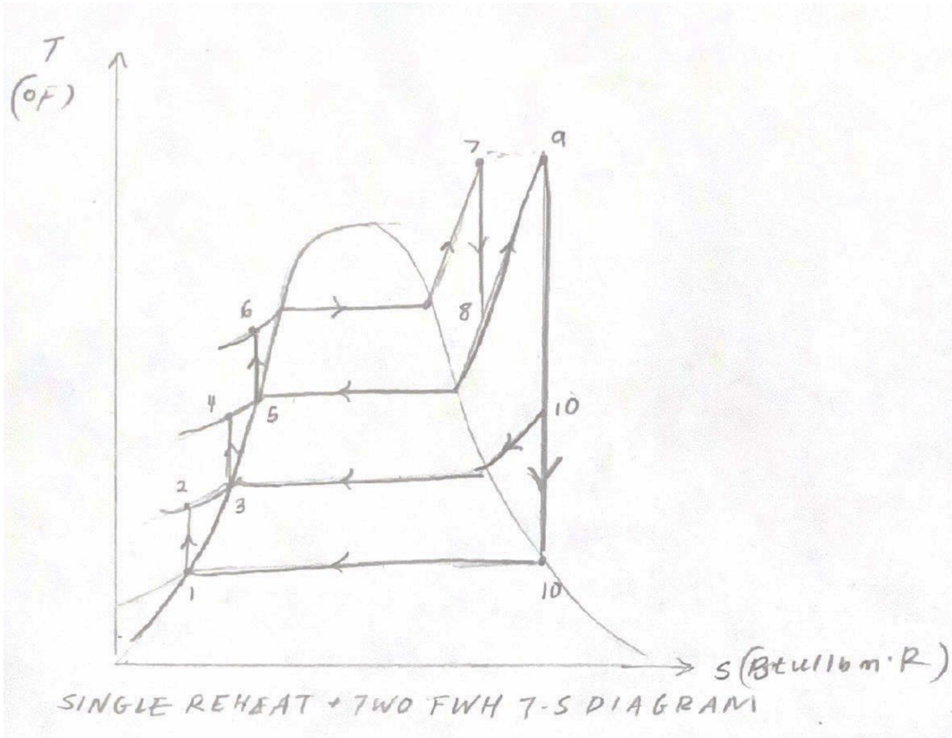

Figure D1: T-s property graph of a single reheat + two FWH Rankine cycle.

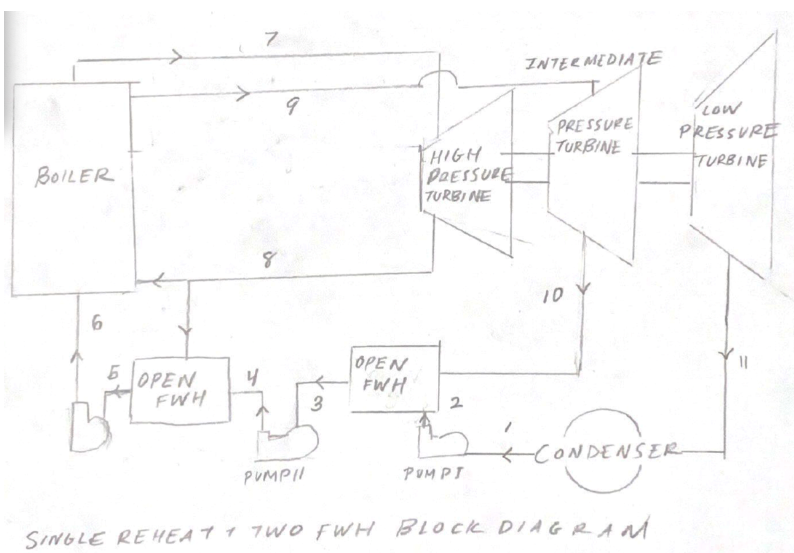

Figure D2: Block diagram of single reheat + two FWH Rankine Cycle.

1-2: Isentropic compression in pump 1

2-3: Constant pressure heat addition in first open FWH

3-4: Isentropic compression in pump 2

4-5: Constant pressure heat addition in the second open FWH

5-6: Isentropic compression in pump 3

6-7: Constant pressure heat addition in a boiler

7-8: Isentropic expansion in a high-pressure turbine

8-9: Constant pressure heat addition in a boiler

8-5: Constant pressure heat regeneration in the second FWH

9-11: Isentropic expansion in an intermediate pressure turbine

10-3: Constant pressure heat regeneration in the first FWH

11-1: Constant pressure heat rejection in a condenser

Step 1: $p_1 = 0.7784\, psi$	$h_1 = 60.6923$ $v_1 = 0.01611$
Step 2: $p_2 = 200\, psi$	$h_2 = h_1 + v_1(p_2 - p_1)$ $h_2 = 63.902$
Step 3: $p_3 = p_2 = 200\, psi$	$h_3 = 355.46$ $v_3 = 0.01839$
	$h_4 = h_3 + v_3(p_4 - p_3)$

Step 4: $p_4 = 400\, psi$	$h_4 = 359.138$
Step 5: $p_5 = p_4 = 400\, psi$	$h_5 = 424.13$ $v_3 = 0.019252$
Step 6: $p_6 = 2000\, psi$	$h_6 = h_5 + v_5(p_6 - p_5)$ $h_6 = 429.8314$
Step 7: $p_7 = p_6 = 2000\, psi$	$h_7 = 1472.9$ $v_7 = 1.5606$
Step 8: $p_8 = 400\, psi$	$s_8 = s_8 = 1.5606$ $h_8 = h_f + xh_{fg}$ $x = (s_f - s_8)/s_{fg}$ $x = 1.08734$ $h_8 = 1273.203$
Step 9: $p_9 = 400\, psi$	$s_9 = 1.7636$ $h_9 = 1523.9$
	$h_8 = h_f + xh_{fg}$

Step 10: $p_{10} = 200\, psi$ $s_{10} = s_9$	$x = (s_f - s_{10})/s_{fg}$ $x = 1.217$ $h_{10} = 1456.768$
Step 11: $p_{11} = p_1 = 0.7784\, psi$	$h_{11} = h_f + xh_{fg}$ $x_8 = 0.87$ $h_f = h_1$ $h_{11} = 979.36$
Efficiency $\eta = 1 - (q_{out}/q_{in})$	$m_8 = (h_5 - h_4)/(h_8 - h_4)$ $m_{10} = (1 - m_8) * (h_3 - h_2)/(h_{10} - h_2)$ $q_{in} = (h_7 - h_6) + (1 - m_8)(h_9 - h_8)$ $q_{out} = (1 - m_{10} - m_8)(h_{11} - h_1)$ $\eta = 0.4718$

Case Three : Single Reheat + Four FWH

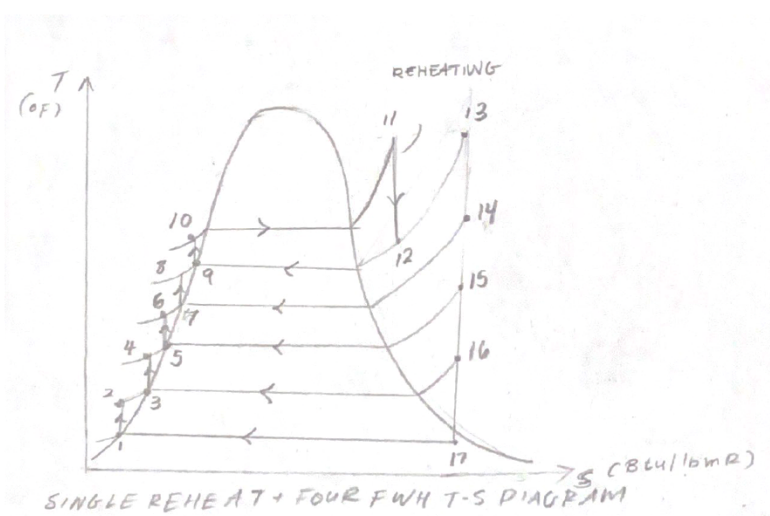

Figure E1: T-s diagram of a single reheat + four FWH Rankine Cycle

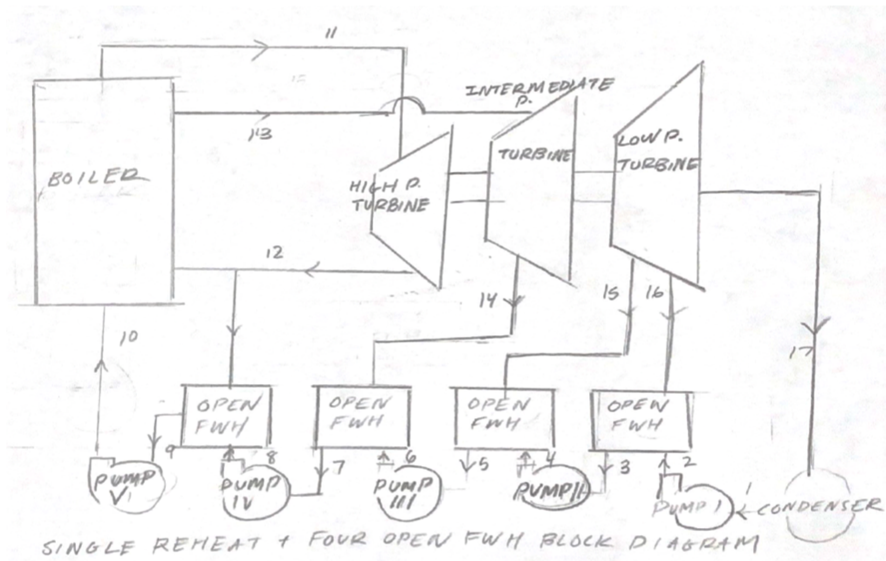

Figure E2: Block diagram of single reheat + four FWH Rankine Cycle.

1-2: Isentropic Compression in pump 1

2-3: Constant pressure heat addition at the first open FWH

3-4: Isentropic compression in pump 2

4-5: Constant pressure heat addition at the second open FWH

5-6: Isentropic compression in pump 3

6-7: Constant pressure heat addition at the third open FWH

7-8: Isentropic compression in pump 4

8-9: Constant pressure heat addition at the fourth open FWH

9-10: Isentropic compression in pump 5

10-11: Constant pressure heat addition in a boiler

11-12: Isentropic expansion in a high-pressure turbine

12-13: Constant pressure heat addition in a boiler

13-17: Isentropic steam expansion at low pressure turbine

12-9: Constant pressure heat regeneration in the fourth FWH

14-7: Constant pressure heat regeneration at the third FWH

15-5: Constant pressure regeneration at the second FWH

16-3: Constant pressure regeneration at the first FWH

17-1: Constant pressure heat rejection in a condenser

Step 1: $p_1 = 0.7784\, psi$	$h_1 = 60.6923$ $v_1 = 0.01611$
Step 2: $p_2 = 100\, psi$	$h_2 = h_1 + v_1(p_2 - p_1)$ $h_2 = 60.9888$
Step 3: $p_3 = p_2 = 100\, psi$	$h_3 = 298.51$ $v_3 = 0.01774$
Step 4: $p_4 = 200\, psi$	$h_4 = v_2(p_4 - p_3)$ $h_4 = 298.838$
Step 5: $p_5 = p_4 = 200\, psi$	$h_5 = 355.46$ $v_5 = 0.01839$
Step 6: $p_6 = 300\, psi$	$h_6 = h_5 + v_5(p_6 - p_5)$ $h_6 = 355.46$
Step 7:	$h_7 = 393.94$

$p_7 = p_6 = 300\,psi$	$v_7 = 0.0189$
Step 8: $p_8 = 400\,psi$	$h_8 = h_7 + v_7(p_8 - p_7)$ $h_8 = 394.30982$
Step 9: $p_9 = p_8 = 400\,psi$	$h_9 = 424.13$ $v_7 = 0.01934$
Step 10: $p_{10} = 2000\,psi$	$h_{10} = h_9 + v_9(p_{10} - p_9)$ $h_{10} = 429.8574$
Step 11: $p_{11} = p_{10} = 2000\,psi$	$h_{11} = 1474.9$ $s_{11} = 1.5606$
Step 12: $p_{12} = 400\,psi$ $s_{12} = s_{11} = 1.5606$	$h_{12} = h_f + xh_{fg}$ $x = (s_f - s_6)/s_{fg}$ $x = 1.08734$ $h_{12} = 1273.203$
Step 13: $p_{13} = 400\,psi$	$h_{13} = 1523.9$ $s_{13} = 1.7636$
Step 14: $p_{14} = 300\,psi$	$h_{14} = 1480.04$ $s_{14} = 1.7636$

Step 15: $p_{15} = 200\, psi$	$h_{15} = 1422.36.04$ $s_{15} = 1.7636$
Step 16: $p_{16} = 100\, psi$	$h_{16} = 1335.02$ $s_{16} = 1.7636$
Step 17: $p_{17} = p_{1} = 0.7784\, psi$	$h_{17} = h_f + xh_{fg}$ $x_8 = 0.87$ $h_f = h_1$ $h_{11} = 966.032$
Mass Friction	$m_{12} = (h_9 - h_8)/(h_{12} - h_8)$ $m_8 = 1 - m_{12}$ $m_{14} = m_8(h_7 - h_6)/(h_{14} - h_6)$ $m_6 = m_8 - m_{14}$ $m_{15} = m_6(h_5 - h_4)/(h_{15} - h_4)$ $m_4 = m_6 - m_{15}$ $m_{16} = m_4 * (h_5 - h_1)/(h_{16} - h_1)$
Efficiency $\eta = 1 - (q_{out}/q_{in})$	$q_{in} = (h_{11} - h_{10}) + (1 - m_{12})(h_{13} - h_{12})$ $q_{in} = 1288.6193$ $q_{out} = (1 - m_{12} - m_{14} - m_{15} - m_{16})$ $(h_{17} - h_1)$ $q_{out} = 656.1544$

	$\eta = 0.4908$

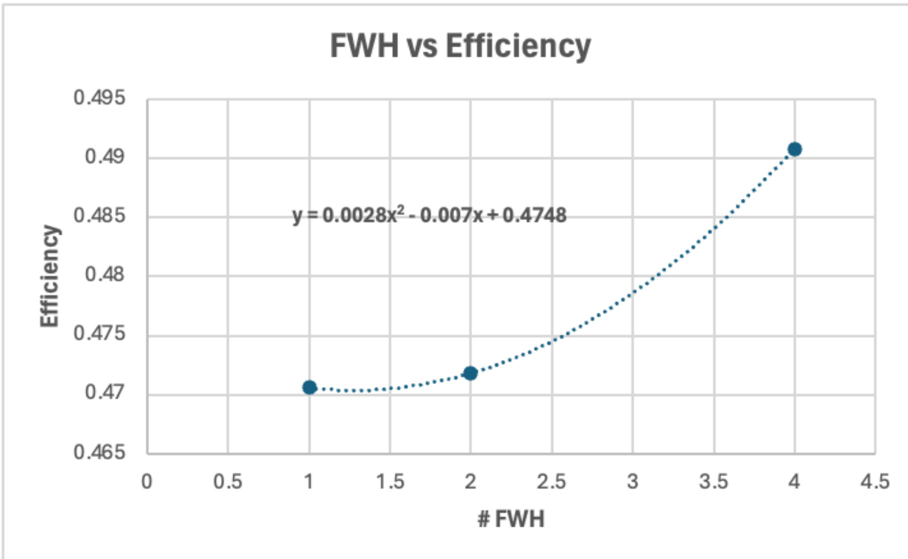

Figure F1: Comparing the number of Feedwater Heater and the Efficiency of the Cycle.

Cost Analysis

The cost analysis is done to see the added benefits of various modifications in terms of the costs. Below are the necessary data used to calculate the revenue seen in Figure F2.

Revenue = $\Delta\eta * power * time * Cost/kwh$
Given that power is 150,000 kW
1 year = 8760 hrs
50 year = 438000 hrs

Cycle	$\Delta\eta$	FWH	Revenue (1 yr)	Revenue (30 yr)

1	-	0	-	-
2	0.07864	0	$ 1.55E9	$ 7.75E8
3	0.04827	1	$ 9.514E8	$4.757E8
4	0.0012	2	$ 2.3652E7	$ 1.183E7
5	0.019	4	$ 3.745E8	$ 1.8725E8

Figure F2: Revenue brought from each cycle in 1 and 50 years and the number of feedwater heaters of the cycle.

Real Cycle Analysis

In the real Cycle analysis, it is imperative to take into account the efficiencies of the moving parts of the cycle. Under previous assumptions, the efficiency of the different parts are thought to be ideal. The modified efficiencies are calculated below. Calculations done below is that of cycle 5

Real Cycle Factors

$\eta_{Turb} = 0.92$ $\eta_{pump} = 0.86$ $\eta_{boiler} = 0.84$

$$\eta_{TH} = (w_{out} - w_{in})/q_{out}$$

$$(\eta_{Turb} * (h_{11} - h_{17})) - \eta_{pump} * (h_{10} - h_{1}))/((h_{16} - h_{17})/\eta_{boiler})$$

$$(0.92 * (1474.9 - 966.032)) - 0.86(429.857 - 60.692))/((1335.02 - 966.032)/0.$$

$$\eta_{TH} = 34\%$$

cycle	Real efficiency
1	0.57559452
2	0.24538214

3	0.21351734
4	0.24034291
5	0.34301474

Figure G1: Efficiency of each cycle under a real cycle analysis.

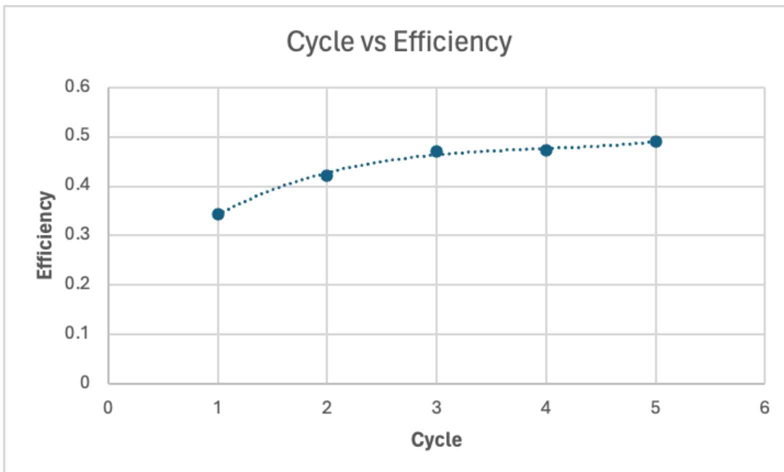

Figure G2: Graph of efficiency of each cycle

Mass Flow Rate

The calculations of the mass flow rate of each cycle is found below. The mass flow rate depends on the power and heat transfer of each cycle.

Cycle 1	$\dot{m} = (\dot{w} * 3412.12)/(q_{in} - q_{out})$ $\dot{m} = (150,000 * 3412.12)/(1565.136 - 959.635)$ $\dot{m} = 841113.2409\ lbm/hr$
Cycle 2	$\dot{m} = (150,000 * 3412.12)/(q_{in} - q_{out})$ $\dot{m} = 869121.7899\ lbm/hr$

Cycle 3	$\dot{m} = (150,000 * 3412.12)/(1221.525 - 646.71)$ $\dot{m} = 890404.7389\ lbm/hr$
Cycle 4	$\dot{m} = (150,000 * 3412.12)/(1277.439 - 674.7235)$ $\dot{m} = 811470.5365\ lbm/hr$
Cycle 5	$\dot{m} = (150,000 * 3412.12)/(1288.619 - 656.15445)$ $\dot{m} = 809243.775\ lbm/hr$

Conclusion

As observed through this paper, the steam powered cycle can be altered through several methods. In observing the efficiencies of each cycle, it can be determined that such modifications can indeed increase the efficiencies. Through the case of regeneration, by applying the cost analysis, the increase in efficiency value is counteracted by the loss in revenue. While increasing the amount of feedwater heat does increase efficiency, such value diminishes the more FWH is added. It must also be noted that the observations made in this paper are specifically for the design parameters of 2000 psi maximum pressure value, 150,000 kW power and a steam quality of 0.87. These values wll alter depending on the specific design parameters required.

This paper shows the two common types of modifications: additions of a single reheat process and regeneration (with different amounts of FWH). Other ways to modify the cycle can include changing the design of the cycles such as relying on one turbine for the regenerative process or the use of closed FWH can also be considered. In developing a more sustainable process, the use of alternative energy sources such as geothermal or solar power can be used in place of the boilers used in the analysis of this paper. Oftentimes, to remove the need of the pumps, to remove the moving parts of the cycle in order to lower the amount of work necessary, the use of heat can also be seen in its place. However, it must be noted the efficiency will be impacted and a separate analysis must be determined whether such methods are suitable to the design parameters given.

References

D. Monika, et. al. (2023). Steam Rankine Cycle. https://www.sciencedirect.com/topics/engineering/steam-rankine-cycle.

Y. Cengal, M. Boles. *Thermodynamics: An Engineering Approach*; Fifth Edition.

Appendix

```matlab
% Interpolation MATLAB Code

clc;
clear all;

% Input
y = input ('What is the between value ');
y1 = input('lower bound y ');
y2 = input('Upper bound y ');

x1 = input ('lower bound x ');
x2 = input('Upper bound x ');


% Function
i = (((x2 - x1)/(y2-y1))*(y-y1))+x1; %Evaluating for x
fprintf('your value is %f',i)
```

Throughout the calculations, values not found in the appendix are found through linear interpolation. Such calculations are done with this Matlab Interpolation code.

Reference Tables

o

Table A-4E - Saturated Water Pressure Table

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–5E

Saturated water—Pressure table (*Concluded*)

		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
700	503.13	0.02051	0.65589	488.96	627.98	1116.9	491.62	710.29	1201.9	0.69279	0.73771	1.4305
800	518.27	0.02087	0.56920	506.74	608.30	1115.0	509.83	689.48	1199.3	0.71117	0.70502	1.4162
900	532.02	0.02124	0.50107	523.19	589.54	1112.7	526.73	669.46	1196.2	0.72793	0.67505	1.4030
1000	544.65	0.02159	0.44604	538.58	571.49	1110.1	542.57	650.03	1192.6	0.74341	0.64722	1.3906
1200	567.26	0.02232	0.36241	566.89	536.87	1103.8	571.85	612.39	1184.2	0.77143	0.59632	1.3677
1400	587.14	0.02307	0.30161	592.79	503.50	1096.3	598.76	575.66	1174.4	0.79658	0.54991	1.3465
1600	604.93	0.02386	0.25516	616.99	470.69	1087.7	624.06	539.18	1163.2	0.81972	0.50645	1.3262
1800	621.07	0.02470	0.21831	640.03	437.86	1077.9	648.26	502.35	1150.6	0.84144	0.46482	1.3063
2000	635.85	0.02563	0.18815	662.33	404.46	1066.8	671.82	464.60	1136.4	0.86224	0.42409	1.2863
2500	668.17	0.02860	0.13076	717.67	313.53	1031.2	730.90	360.79	1091.7	0.91311	0.31988	1.2330
3000	695.41	0.03433	0.08460	783.39	186.41	969.8	802.45	214.32	1016.8	0.97321	0.18554	1.1587
3200.1	705.10	0.04975	0.04975	866.61	0	866.6	896.07	0	896.1	1.05257	0	1.0526

Table A-6E Superheated Water

TABLE A–6E

Superheated water

T °F	v ft^3/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R	v ft^3/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R	v ft^3/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

TABLE A–6E

Superheated water (*Continued*)

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 = 120 psia (341.25°F)				*P* = 140 psia (353.03°F)				*P* = 160 psia (363.54°F)			
Sat.	3.7289	1107.9	1190.8	1.5883	3.2202	1109.9	1193.4	1.5757	2.8347	1111.6	1195.5	1.5647
360	3.8446	1116.7	1202.1	1.6023	3.2584	1113.4	1197.8	1.5811				
400	4.0799	1134.0	1224.6	1.6292	3.4676	1131.5	1221.4	1.6092	3.0076	1129.0	1218.0	1.5914
450	4.3613	1154.5	1251.4	1.6594	3.7147	1152.6	1248.9	1.6403	3.2293	1150.7	1246.3	1.6234
500	4.6340	1174.4	1277.3	1.6872	3.9525	1172.9	1275.3	1.6686	3.4412	1171.4	1273.2	1.6522
550	4.9010	1193.9	1302.8	1.7131	4.1845	1192.7	1301.1	1.6948	3.6469	1191.4	1299.4	1.6788
600	5.1642	1213.4	1328.0	1.7375	4.4124	1212.3	1326.6	1.7195	3.8484	1211.3	1325.2	1.7037
700	5.6829	1252.2	1378.4	1.7829	4.8604	1251.4	1377.3	1.7652	4.2434	1250.6	1376.3	1.7498
800	6.1950	1291.4	1429.0	1.8247	5.3017	1290.8	1428.1	1.8072	4.6316	1290.2	1427.3	1.7920
1000	7.2083	1371.7	1531.8	1.9005	6.1732	1371.3	1531.3	1.8832	5.3968	1370.9	1530.7	1.8682
1200	8.2137	1455.3	1637.7	1.9684	7.0367	1455.0	1637.3	1.9512	6.1540	1454.7	1636.9	1.9363
1400	9.2149	1542.3	1746.9	2.0305	7.8961	1542.1	1746.6	2.0134	6.9070	1541.8	1746.3	1.9986
1600	10.2135	1633.0	1859.8	2.0881	8.7529	1632.8	1859.5	2.0711	7.6574	1632.6	1859.3	2.0563
1800	11.2106	1727.2	1976.1	2.1420	9.6082	1727.0	1975.9	2.1250	8.4063	1726.9	1975.7	2.1102
2000	12.2067	1824.8	2095.8	2.1928	10.4624	1824.6	2095.7	2.1758	9.1542	1824.5	2095.5	2.1610
	P = 180 psia (373.07°F)				*P* = 200 psia (381.80°F)				*P* = 225 psia (391.80°F)			
Sat.	2.5322	1113.0	1197.3	1.5548	2.2882	1114.1	1198.8	1.5460	2.0423	1115.3	1200.3	1.5360
400	2.6490	1126.3	1214.5	1.5752	2.3615	1123.5	1210.9	1.5602	2.0728	1119.7	1206.0	1.5427
450	2.8514	1148.7	1243.7	1.6082	2.5488	1146.7	1241.0	1.5943	2.2457	1144.1	1237.6	1.5783
500	3.0433	1169.8	1271.2	1.6376	2.7247	1168.2	1269.0	1.6243	2.4059	1166.2	1266.3	1.6091
550	3.2286	1190.2	1297.7	1.6646	2.8939	1188.9	1296.0	1.6516	2.5590	1187.2	1293.8	1.6370
600	3.4097	1210.2	1323.8	1.6897	3.0586	1209.1	1322.3	1.6771	2.7075	1207.7	1320.5	1.6628
700	3.7635	1249.8	1375.2	1.7361	3.3796	1249.0	1374.1	1.7238	2.9956	1248.0	1372.7	1.7099
800	4.1104	1289.5	1426.5	1.7785	3.6934	1288.9	1425.6	1.7664	3.2765	1288.1	1424.5	1.7528
900	4.4531	1329.7	1478.0	1.8179	4.0031	1329.2	1477.3	1.8059	3.5530	1328.5	1476.5	1.7925
1000	4.7929	1370.5	1530.1	1.8549	4.3099	1370.1	1529.6	1.8430	3.8268	1369.5	1528.9	1.8296
1200	5.4674	1454.3	1636.5	1.9231	4.9182	1454.0	1636.1	1.9113	4.3689	1453.6	1635.6	1.8981
1400	6.1377	1541.6	1746.0	1.9855	5.5222	1541.4	1745.7	1.9737	4.9068	1541.1	1745.4	1.9606
1600	6.8054	1632.4	1859.1	2.0432	6.1238	1632.2	1858.8	2.0315	5.4422	1632.0	1858.6	2.0184
1800	7.4716	1726.7	1975.6	2.0971	6.7238	1726.5	1975.4	2.0855	5.9760	1726.4	1975.2	2.0724
2000	8.1367	1824.4	2095.4	2.1479	7.3227	1824.3	2095.3	2.1363	6.5087	1824.1	2095.1	2.1232
	P = 250 psia (400.97°F)				*P* = 275 psia (409.45°F)				*P* = 300 psia (417.35°F)			
Sat.	1.8440	1116.3	1201.6	1.5270	1.6806	1117.0	1202.6	1.5187	1.5435	1117.7	1203.3	1.5111
450	2.0027	1141.3	1234.0	1.5636	1.8034	1138.5	1230.3	1.5499	1.6369	1135.6	1226.4	1.5369
500	2.1506	1164.1	1263.6	1.5953	1.9415	1162.0	1260.8	1.5825	1.7670	1159.8	1257.9	1.5706
550	2.2910	1185.6	1291.5	1.6237	2.0715	1183.9	1289.3	1.6115	1.8885	1182.1	1287.0	1.6001
600	2.4264	1206.3	1318.6	1.6499	2.1964	1204.9	1316.7	1.6380	2.0046	1203.5	1314.8	1.6270
650	2.5586	1226.8	1345.1	1.6743	2.3179	1225.6	1343.5	1.6627	2.1172	1224.4	1341.9	1.6520
700	2.6883	1247.0	1371.4	1.6974	2.4369	1246.0	1370.0	1.6860	2.2273	1244.9	1368.6	1.6755
800	2.9429	1287.3	1423.5	1.7406	2.6699	1286.5	1422.4	1.7294	2.4424	1285.7	1421.3	1.7192
900	3.1930	1327.9	1475.6	1.7804	2.8984	1327.3	1474.8	1.7694	2.6529	1326.6	1473.9	1.7593
1000	3.4403	1369.0	1528.2	1.8177	3.1241	1368.5	1527.4	1.8068	2.8605	1367.9	1526.7	1.7968
1200	3.9295	1453.3	1635.0	1.8863	3.5700	1452.9	1634.5	1.8755	3.2704	1452.5	1634.0	1.8657
1400	4.4144	1540.8	1745.0	1.9488	4.0116	1540.5	1744.6	1.9381	3.6759	1540.2	1744.2	1.9284
1600	4.8969	1631.7	1858.3	2.0066	4.4507	1631.5	1858.0	1.9960	4.0789	1631.3	1857.7	1.9863
1800	5.3777	1726.2	1974.9	2.0607	4.8882	1726.0	1974.7	2.0501	4.4803	1725.8	1974.5	2.0404
2000	5.8575	1823.9	2094.9	2.1116	5.3247	1823.8	2094.7	2.1010	4.8807	1823.6	2094.6	2.0913

TABLE A–6E

Superheated water (*Continued*)

T °F	v ft^3/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R	v ft^3/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R	v ft^3/lbm	u Btu/lbm	h Btu/lbm	s Btu/lbm · R
	P = 350 psia (431.74°F)				*P* = 400 psia (444.62°F)				*P* = 450 psia (456.31°F)			
Sat.	1.3263	1118.5	1204.4	1.4973	1.1617	1119.0	1205.0	1.4852	1.0324	1119.2	1205.2	1.4742
450	1.3739	1129.3	1218.3	1.5128	1.1747	1122.5	1209.4	1.4901				
500	1.4921	1155.2	1251.9	1.5487	1.2851	1150.4	1245.6	1.5288	1.1233	1145.4	1238.9	1.5103
550	1.6004	1178.6	1282.2	1.5795	1.3840	1174.9	1277.3	1.5610	1.2152	1171.1	1272.3	1.5441
600	1.7030	1200.6	1310.9	1.6073	1.4765	1197.6	1306.9	1.5897	1.3001	1194.6	1302.8	1.5737
650	1.8018	1221.9	1338.6	1.6328	1.5650	1219.4	1335.3	1.6158	1.3807	1216.9	1331.9	1.6005
700	1.8979	1242.8	1365.8	1.6567	1.6507	1240.7	1362.9	1.6401	1.4584	1238.5	1360.0	1.6253
800	2.0848	1284.1	1419.1	1.7009	1.8166	1282.5	1417.0	1.6849	1.6080	1280.8	1414.7	1.6706
900	2.2671	1325.3	1472.2	1.7414	1.9777	1324.0	1470.4	1.7257	1.7526	1322.7	1468.6	1.7117
1000	2.4464	1366.9	1525.3	1.7791	2.1358	1365.8	1523.9	1.7636	1.8942	1364.7	1522.4	1.7499
1200	2.7996	1451.7	1633.0	1.8483	2.4465	1450.9	1632.0	1.8331	2.1718	1450.1	1631.0	1.8196
1400	3.1484	1539.6	1743.5	1.9111	2.7527	1539.0	1742.7	1.8960	2.4450	1538.4	1742.0	1.8827
1600	3.4947	1630.8	1857.1	1.9691	3.0565	1630.3	1856.5	1.9541	2.7157	1629.8	1856.0	1.9409
1800	3.8394	1725.4	1974.0	2.0233	3.3586	1725.0	1973.6	2.0084	2.9847	1724.6	1973.2	1.9952
2000	4.1830	1823.3	2094.2	2.0742	3.6597	1823.0	2093.9	2.0594	3.2527	1822.6	2093.5	2.0462
	P = 500 psia (467.04°F)				*P* = 600 psia (486.24°F)				*P* = 700 psia (503.13°F)			
Sat.	0.92815	1119.1	1205.0	1.4642	0.77020	1118.3	1203.9	1.4463	0.65589	1116.9	1201.9	1.4305
500	0.99304	1140.1	1231.9	1.4928	0.79526	1128.2	1216.5	1.4596				
550	1.07974	1167.1	1267.0	1.5284	0.87542	1158.7	1255.9	1.4996	0.72799	1149.5	1243.8	1.4730
600	1.15876	1191.4	1298.6	1.5590	0.94605	1184.9	1289.9	1.5325	0.79332	1177.9	1280.7	1.5087
650	1.23312	1214.3	1328.4	1.5865	1.01133	1209.0	1321.3	1.5614	0.85242	1203.4	1313.8	1.5393
700	1.30440	1236.4	1357.0	1.6117	1.07316	1231.9	1351.0	1.5877	0.90769	1227.2	1344.8	1.5666
800	1.44097	1279.2	1412.5	1.6576	1.19038	1275.8	1408.0	1.6348	1.01125	1272.4	1403.4	1.6150
900	1.57252	1321.4	1466.9	1.6992	1.30230	1318.7	1463.3	1.6771	1.10921	1316.0	1459.7	1.6581
1000	1.70094	1363.6	1521.0	1.7376	1.41097	1361.4	1518.1	1.7160	1.20381	1359.2	1515.2	1.6974
1100	1.82726	1406.2	1575.3	1.7735	1.51749	1404.4	1572.9	1.7522	1.29621	1402.5	1570.4	1.7341
1200	1.95211	1449.4	1630.0	1.8075	1.62252	1447.8	1627.9	1.7865	1.38709	1446.2	1625.9	1.7685
1400	2.1988	1537.8	1741.2	1.8708	1.82957	1536.6	1739.7	1.8501	1.56580	1535.4	1738.2	1.8324
1600	2.4430	1629.4	1855.4	1.9291	2.0340	1628.4	1854.2	1.9085	1.74192	1627.5	1853.1	1.8911
1800	2.6856	1724.2	1972.7	1.9834	2.2369	1723.4	1971.8	1.9630	1.91643	1722.7	1970.9	1.9457
2000	2.9271	1822.3	2093.1	2.0345	2.4387	1821.7	2092.4	2.0141	2.08987	1821.0	2091.7	1.9969
	P = 800 psia (518.27°F)				*P* = 1000 psia (544.65°F)				*P* = 1250 psia (572.45°F)			
Sat.	0.56920	1115.0	1199.3	1.4162	0.44604	1110.1	1192.6	1.3906	0.34549	1102.0	1181.9	1.3623
550	0.61586	1139.4	1230.5	1.4476	0.45375	1115.2	1199.2	1.3972				
600	0.67799	1170.5	1270.9	1.4866	0.51431	1154.1	1249.3	1.4457	0.37894	1129.5	1217.2	1.3961
650	0.73279	1197.6	1306.0	1.5191	0.56411	1185.1	1289.5	1.4827	0.42703	1167.5	1266.3	1.4414
700	0.78330	1222.4	1338.4	1.5476	0.60844	1212.4	1325.0	1.5140	0.46735	1198.7	1306.8	1.4771
750	0.83102	1246.0	1369.1	1.5735	0.64944	1237.6	1357.8	1.5418	0.50344	1226.4	1342.9	1.5076
800	0.87678	1268.9	1398.7	1.5975	0.68821	1261.7	1389.0	1.5670	0.53687	1252.2	1376.4	1.5347
900	0.96434	1313.3	1456.0	1.6413	0.76136	1307.7	1448.6	1.6126	0.59876	1300.5	1439.0	1.5826
1000	1.04841	1357.0	1512.2	1.6812	0.83078	1352.5	1506.2	1.6535	0.65656	1346.7	1498.6	1.6249
1100	1.13024	1400.7	1568.0	1.7181	0.89783	1396.9	1563.1	1.6911	0.71184	1392.2	1556.8	1.6635
1200	1.21051	1444.6	1623.8	1.7528	0.96327	1441.4	1619.7	1.7263	0.76545	1437.4	1614.5	1.6993
1400	1.36797	1534.2	1736.7	1.8170	1.09101	1531.8	1733.7	1.7911	0.86944	1528.7	1729.8	1.7649
1600	1.52283	1626.5	1851.9	1.8759	1.21610	1624.6	1849.6	1.8504	0.97072	1622.2	1846.7	1.8246
1800	1.67606	1721.9	1970.0	1.9306	1.33956	1720.3	1968.2	1.9053	1.07036	1718.4	1966.0	1.8799
2000	1.82823	1820.4	2091.0	1.9819	1.46194	1819.1	2089.6	1.9568	1.16892	1817.5	2087.9	1.9315

TABLE A–6E

Superheated water (*Concluded*)

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 = 1500 psia (596.26°F)				*P* = 1750 psia (617.17°F)				*P* = 2000 psia (635.85°F)			
Sat.	0.27695	1092.1	1169.0	1.3362	0.22681	1080.5	1153.9	1.3112	0.18815	1066.8	1136.4	1.2863
600	0.28189	1097.2	1175.4	1.3423								
650	0.33310	1147.2	1239.7	1.4016	0.26292	1122.8	1207.9	1.3607	0.20586	1091.4	1167.6	1.3146
700	0.37198	1183.6	1286.9	1.4433	0.30252	1166.8	1264.7	1.4108	0.24894	1147.6	1239.8	1.3783
750	0.40535	1214.4	1326.9	1.4771	0.33455	1201.5	1309.8	1.4489	0.28074	1187.4	1291.3	1.4218
800	0.43550	1242.2	1363.1	1.5064	0.36266	1231.7	1349.1	1.4807	0.30763	1220.5	1334.3	1.4567
850	0.46356	1268.2	1396.9	1.5328	0.38835	1259.3	1385.1	1.5088	0.33169	1250.0	1372.8	1.4867
900	0.49015	1293.1	1429.2	1.5569	0.41238	1285.4	1419.0	1.5341	0.35390	1277.5	1408.5	1.5134
1000	0.54031	1340.9	1490.8	1.6007	0.45719	1334.9	1482.9	1.5796	0.39479	1328.7	1474.9	1.5606
1100	0.58781	1387.3	1550.5	1.6402	0.49917	1382.4	1544.1	1.6201	0.43266	1377.5	1537.6	1.6021
1200	0.63355	1433.3	1609.2	1.6767	0.53932	1429.2	1603.9	1.6572	0.46864	1425.1	1598.5	1.6400
1400	0.72172	1525.7	1726.0	1.7432	0.61621	1522.6	1722.1	1.7245	0.53708	1519.5	1718.3	1.7081
1600	0.80714	1619.8	1843.8	1.8033	0.69031	1617.4	1840.9	1.7852	0.60269	1615.0	1838.0	1.7693
1800	0.89090	1716.4	1963.7	1.8589	0.76273	1714.5	1961.5	1.8410	0.66660	1712.5	1959.2	1.8255
2000	0.97358	1815.9	2086.1	1.9108	0.83406	1814.2	2084.3	1.8931	0.72942	1812.6	2082.6	1.8778
	P = 2500 psia (668.17°F)				*P* = 3000 psia (695.41°F)				*P* = 3500 psia			
Sat.	0.13076	1031.2	1091.7	1.2330	0.08460	969.8	1016.8	1.1587				
650									0.02492	663.7	679.9	0.8632
700	0.16849	1098.4	1176.3	1.3072	0.09838	1005.3	1059.9	1.1960	0.03065	760.0	779.9	0.9511
750	0.20327	1154.9	1249.0	1.3686	0.14840	1114.1	1196.5	1.3118	0.10460	1057.6	1125.4	1.2434
800	0.22949	1195.9	1302.0	1.4116	0.17601	1167.5	1265.3	1.3676	0.13639	1134.3	1222.6	1.3224
850	0.25174	1230.1	1346.6	1.4463	0.19771	1208.2	1317.9	1.4086	0.15847	1183.8	1286.5	1.3721
900	0.27165	1260.7	1386.4	1.4761	0.21640	1242.8	1362.9	1.4423	0.17659	1223.4	1337.8	1.4106
950	0.29001	1289.1	1423.3	1.5028	0.23321	1273.9	1403.3	1.4716	0.19245	1257.8	1382.4	1.4428
1000	0.30726	1316.1	1458.2	1.5271	0.24876	1302.8	1440.9	1.4978	0.20687	1289.0	1423.0	1.4711
1100	0.33949	1367.3	1524.4	1.5710	0.27732	1356.8	1510.8	1.5441	0.23289	1346.1	1496.9	1.5201
1200	0.36966	1416.6	1587.6	1.6103	0.30367	1408.0	1576.6	1.5850	0.25654	1399.3	1565.4	1.5627
1400	0.42631	1513.3	1710.5	1.6802	0.35249	1507.0	1702.7	1.6567	0.29978	1500.7	1694.8	1.6364
1600	0.48004	1610.1	1832.2	1.7424	0.39830	1605.3	1826.4	1.7199	0.33994	1600.4	1820.5	1.7006
1800	0.53205	1708.6	1954.8	1.7991	0.44237	1704.7	1950.3	1.7773	0.37833	1700.8	1945.8	1.7586
2000	0.58295	1809.4	2079.1	1.8518	0.48532	1806.1	2075.6	1.8304	0.41561	1802.9	2072.1	1.8121
	P = 4000 psia				*P* = 5000 psia				*P* = 6000 psia			
650	0.02448	657.9	676.1	0.8577	0.02379	648.3	670.3	0.8485	0.02325	640.3	666.1	0.8408
700	0.02871	742.3	763.6	0.9347	0.02678	721.8	746.6	0.9156	0.02564	708.1	736.5	0.9028
750	0.06370	962.1	1009.2	1.1410	0.03373	821.8	853.0	1.0054	0.02981	788.7	821.8	0.9747
800	0.10520	1094.2	1172.1	1.2734	0.05937	986.9	1041.8	1.1581	0.03949	897.1	941.0	1.0711
850	0.12848	1156.7	1251.8	1.3355	0.08551	1092.4	1171.5	1.2593	0.05815	1018.6	1083.1	1.1819
900	0.14647	1202.5	1310.9	1.3799	0.10390	1155.9	1252.1	1.3198	0.07584	1103.5	1187.7	1.2603
950	0.16176	1240.7	1360.5	1.4157	0.11863	1203.9	1313.6	1.3643	0.09010	1163.7	1263.7	1.3153
1000	0.17538	1274.6	1404.4	1.4463	0.13128	1244.0	1365.5	1.4004	0.10208	1211.4	1324.7	1.3578
1100	0.19957	1335.1	1482.8	1.4983	0.15298	1312.2	1453.8	1.4590	0.12211	1288.4	1424.0	1.4237
1200	0.22121	1390.3	1554.1	1.5426	0.17185	1372.1	1531.1	1.5070	0.13911	1353.4	1507.8	1.4758
1300	0.24128	1443.0	1621.6	1.5821	0.18902	1427.8	1602.7	1.5490	0.15434	1412.5	1583.8	1.5203
1400	0.26028	1494.3	1687.0	1.6182	0.20508	1481.4	1671.1	1.5868	0.16841	1468.4	1655.4	1.5598
1600	0.29620	1595.5	1814.7	1.6835	0.23505	1585.6	1803.1	1.6542	0.19438	1575.7	1791.5	1.6294
1800	0.33033	1696.8	1941.4	1.7422	0.26320	1689.0	1932.5	1.7142	0.21853	1681.1	1923.7	1.6907
2000	0.36335	1799.7	2068.6	1.7961	0.29023	1793.2	2061.7	1.7689	0.24155	1786.7	2054.9	1.7463