

Rankine reheat cycle selection of best reheat pressure using Python.

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The sole purpose of this document is to illustrate how selection of the most efficient reheat pressure in a Rankine Reheat Steam Cycle could be calculated.

Use the information and code contained at your own risk.

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1 Selecting a Reheat Steam Pressure

When designing a Rankine reheat steam cycle, selecting the most efficient/economical steam pressure is very important for controlling life time costs.

In the case of main steam pressure most sub-critical reheat cycle units have settled on a pressure around 180 bar as it provides a good compromise;

- density difference still large enough to provide some measure of natural circulation.
- material selection does not need to be too extreme and hence construction costs are under control.
- Steam pressure is still high enough to ensure increased power density per/kg of steam and therefore reduced size of plant required.

However when it comes to reheat pressure selection, what is the idea pressure?¹

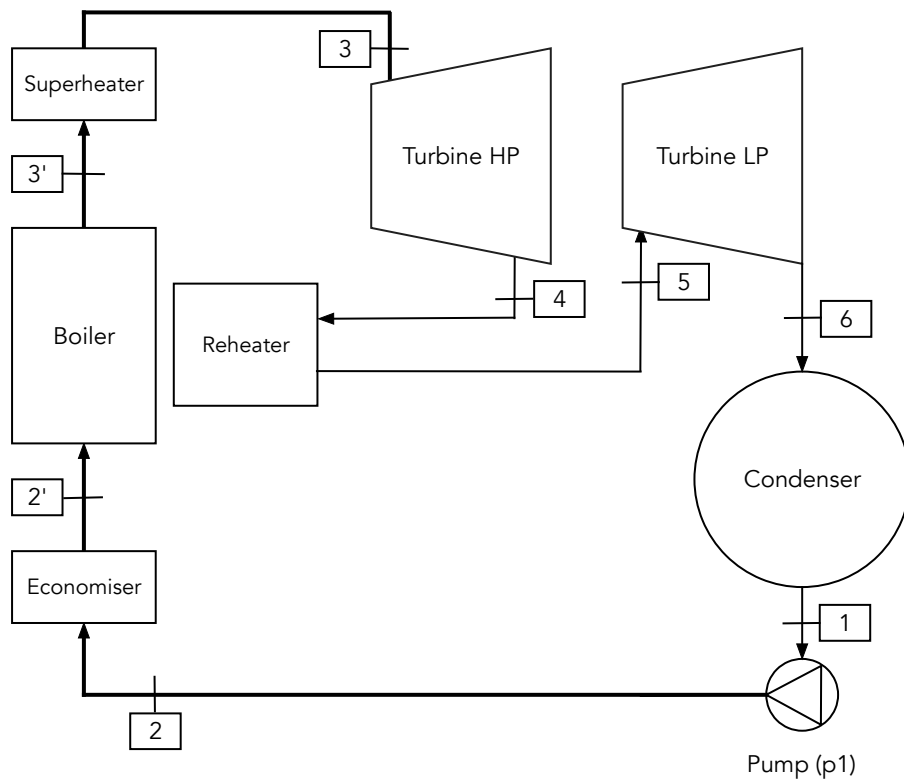


Figure 1: Components of a Rankine reheat cycle

Note: steam conditions at points 1, 2, 2', 3', 3 and 6 will have the same values on all T-s diagrams below (i.e. condenser pressure, feedwater pressure, drum pressure and superheat temperature will remain constant).

¹The idea reheat steam pressure still needs to satisfy the requirement that LP turbine last row blades steam wetness is still within a range that is acceptable.


```
25 Work required by pump: 0.2 kJ/kg
26 Work generated by HP turbine: 592.2 kJ/kg
27 Work generated by LP turbine: 1153.5 kJ/kg
28 Total work output by turbine: 1745.6 kJ/kg
29 Heat input by boiler: 3958.4 kJ/kg
30 Heat rejected by the condenser: 2213.0 kJ/kg
31 Thermal efficiency is: 44.095%
32 HR rankine cycle: 8164.2 kJ/kWh
```

This extracts the maximum energy from the steam in the HP turbine (592.2 kJ/kg in this case) before the steam is returned to the boiler at 18.3 bar. Overall theoretical thermal efficiency is 44.095% which is good, but how do we know it is the best possible.

Let us look at some other options at were to stop the expansion on the HP turbine to get the most efficient cycle possible.

1.1.2 Expansion of main steam only slightly before reheating

The next option to investigate is to expand the steam in the turbine only a little so that the steam returned to the reheat section of the boiler is at nearly the same pressure as the main steam.

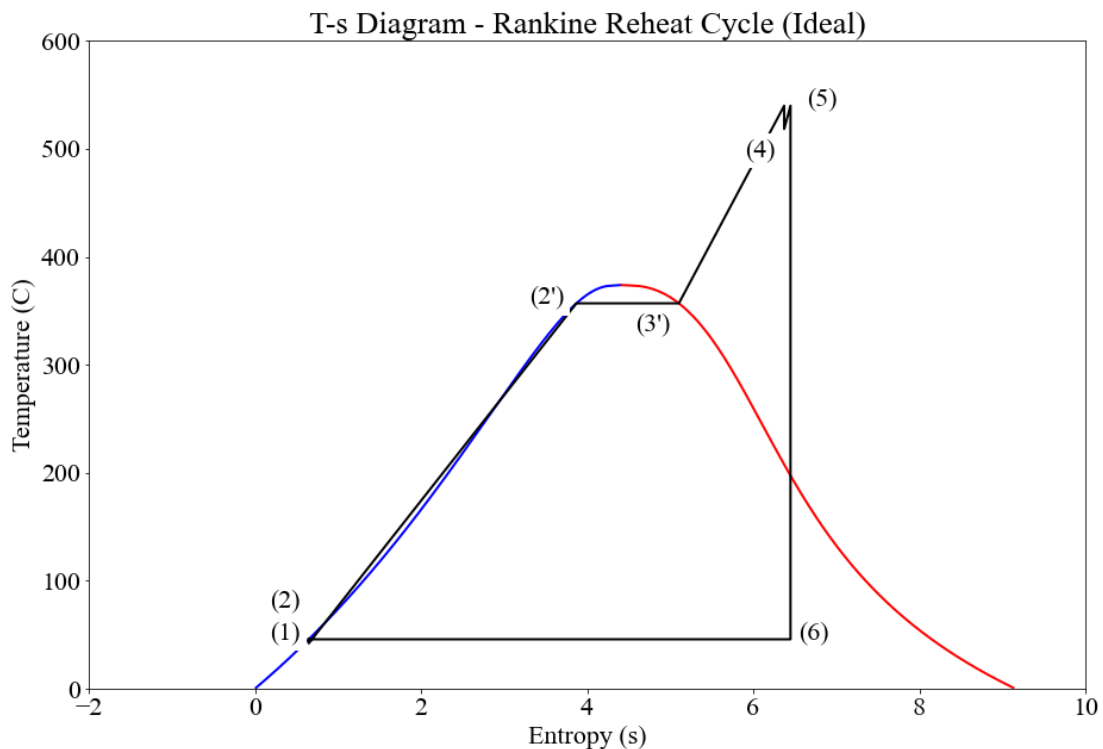


Figure 3: Ts plot of Rankine reheat cycle with HP turbine expansion down to 160 bar

The Python code to generate the plot above and efficiency calculations result below can be found in appendix B.2

```

1 Rankine reheat cycle analysis – reheat pressure at 160 bar
2
3 Reheat Pressure: 160.0 bar
4
5 Point 4
6 T4: 518.5 degC
7 P4: 160.0 bar
8 H4: 3351.2 kJ/kg
9 S4: 6.373 kJ/kg K
10
11 Point 5
12 T5: 540.0 degC
13 p5: 160.0 bar
14 H5: 3412.1 kJ/kg
15 S5: 6.449 kJ/kg K
16
17 Point 6
18 T6: 45.8 degC
19 p6: 0.1 bar
20 H6: 2041.8 kJ/kg
21 S6: 6.449 kJ/kg K
22 x6: 77.3 % dry
23
24 Summary
25 Work required by pump: 0.2 kJ/kg
26 Work generated by HP turbine: 38.4 kJ/kg
27 Work generated by LP turbine: 1370.3 kJ/kg
28 Total work output by turbine: 1408.7 kJ/kg
29 Heat input by boiler: 3258.5 kJ/kg
30 Heat rejected by the condenser: 1850.0 kJ/kg
31 Thermal efficiency is: 43.225%

```

32 HR rankine cycle: 8328.5 kJ/kWh

In this case we have expanded the steam in the HP turbine from 180 bar down to 160 bar.

Only a small amount of energy is extracted from the steam in the HP turbine (38.4 kJ/kg in this case) and overall theoretical thermal efficiency is 43.225% which is worse than the first option.

If fact it is only marginally better than a plain Rankine superheated cycle (theoretical cycle efficiency 42.901% as shown below) but with greatly increased capital costs for the more complex boiler and turbine layout.

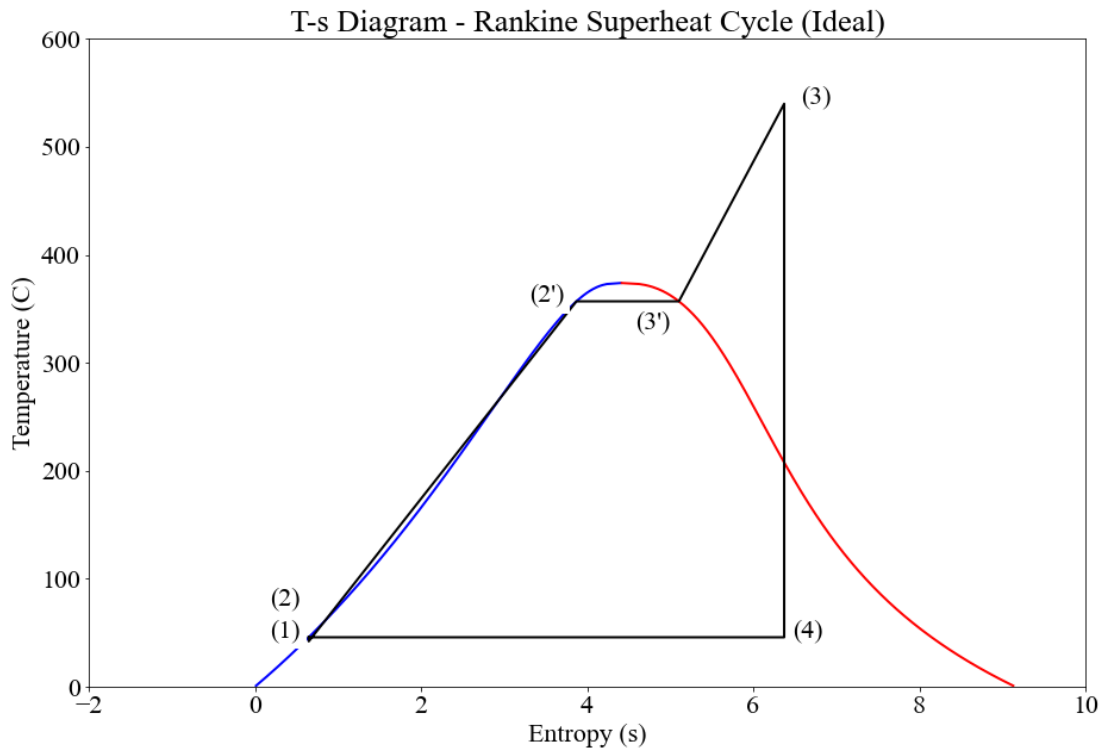


Figure 4: Ts plot of Rankine superheat cycle

1 Rankine superheat cycle analysis — for comparison

2
3 Point 1
4 p1: 0.1 bar
5 T1: 45.8 degC
6 H1: 191.8 kJ/kg
7 S1: 0.649 kJ/kg K

8
9 Point 2
10 H2: 192.0 kJ/kg
11 T2: 42.1 degC
12
13 Point 2 dash
14 T2dash: 357.0 degC
15 p2dash: 180.0 bar
16 H2dash: 1732.0 kJ/kg
17 S2dash: 3.872 kJ/kg K

18
19 Point 3dash
20 T3dash: 357.0 degC
21 H3dash: 2509.5 kJ/kg
22 S3dash: 5.106 kJ/kg K

23
24 Point 3
25 T3: 540.0 degC
26 p3: 180.0 bar
27 H3: 3389.5 kJ/kg

```
28 S3: 6.373 kJ/kg K
29
30 Point 4
31 T4: 45.8 degC
32 p4: 0.1 bar
33 H4: 2017.6 kJ/kg
34 S4: 6.373 kJ/kg K
35 x4: 76.3 % dry
36
37 Summary
38 Work required by pump: 0.2 kJ/kg
39 Work generated by turbine: 1372.0 kJ/kg
40 Heat input by boiler: 3197.5 kJ/kg
41 Heat rejected by the condenser: 1825.8 kJ/kg
42 Thermal efficiency is: 42.901%
43 HR rankine cycle: 8391.4 kJ/kWh
```


1.1.3 Expansion of main steam to 25 bar

So next let us try a few other points at which to stop the expansion of steam in the HP turbine. Firstly at a pressure of 25 bar.

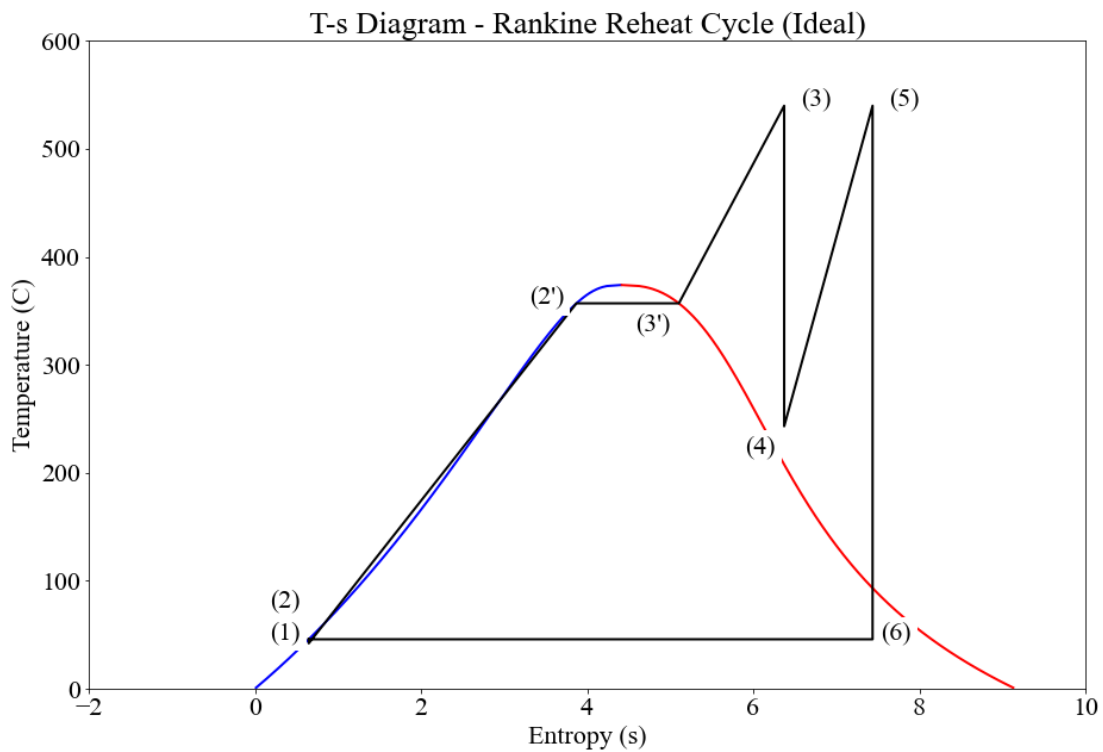


Figure 5: Ts plot of Rankine reheat cycle with HP turbine expansion down to 25 bar

The Python code to generate the plot above and efficiency calculations result below can be found in appendix B.3

```
1 Rankine reheat cycle analysis – reheat pressure at 25 bar
2
3 Reheat Pressure: 25.0 bar
4
5 Point 4
6 T4: 243.2 degC
7 P4: 25.0 bar
8 H4: 2861.5 kJ/kg
9 S4: 6.373 kJ/kg K
10
11 Point 5
12 T5: 540.0 degC
13 p5: 25.0 bar
14 H5: 3551.9 kJ/kg
15 S5: 7.438 kJ/kg K
16
17 Point 6
18 T6: 45.8 degC
19 p6: 0.1 bar
20 H6: 2357.0 kJ/kg
21 S6: 7.438 kJ/kg K
22 x6: 90.5 % dry
23
24 Summary
25 Work required by pump: 0.2 kJ/kg
26 Work generated by HP turbine: 528.0 kJ/kg
27 Work generated by LP turbine: 1194.8 kJ/kg
28 Total work output by turbine: 1722.8 kJ/kg
29 Heat input by boiler: 3887.9 kJ/kg
30 Heat rejected by the condenser: 2165.2 kJ/kg
31 Thermal efficiency is: 44.308%
```

³² HR rankine cycle: 8124.9 kJ/kWh

In this case we have expanded the steam in the HP turbine from 180 bar down to 25 bar.

The amount of energy extracted from the steam in the HP turbine (528.0 kJ/kg in this case) is reasonable and overall theoretical thermal efficiency is 44.308% which is the best achieved so far.

1.1.4 Expansion of main steam to 70 bar

Then at a pressure of 70 bar.

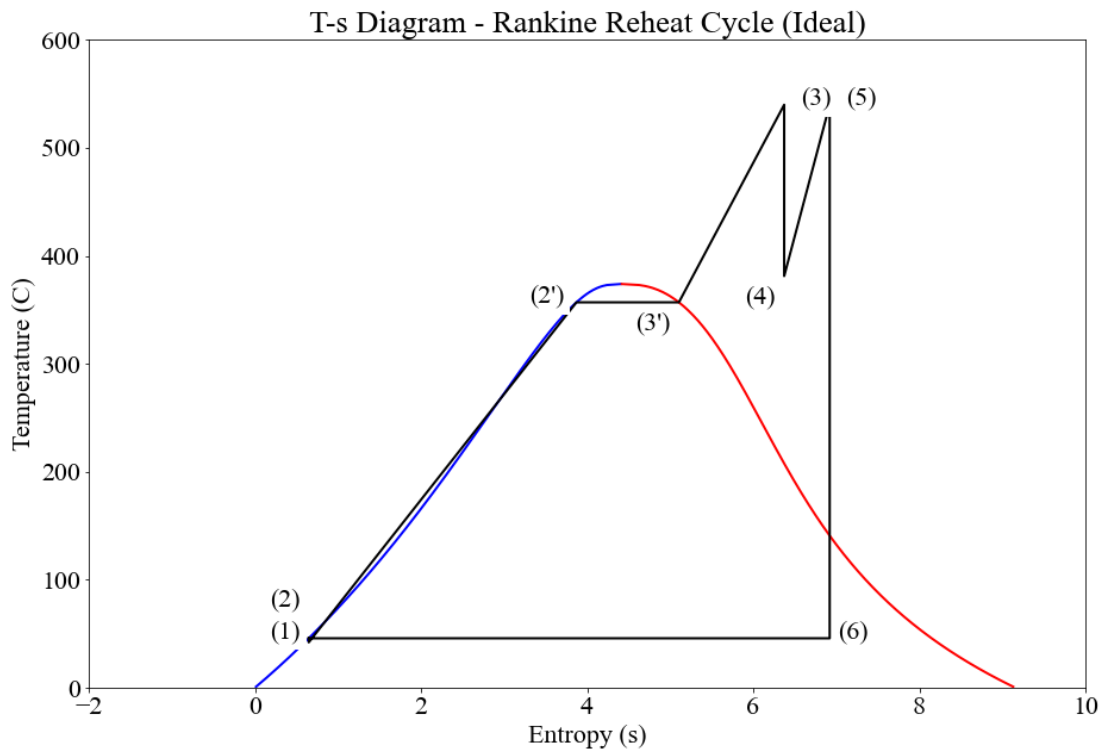


Figure 6: Ts plot of Rankine reheat cycle with HP turbine expansion down to 70 bar

The Python code to generate the plot above and efficiency calculations result below can be found in appendix B.4

```
1 Rankine reheat cycle analysis – reheat pressure at 70 bar
2
3 Reheat Pressure: 70.0 bar
4
5 Point 4
6 T4: 381.3 degC
7 P4: 70.0 bar
8 H4: 3108.2 kJ/kg
9 S4: 6.373 kJ/kg K
10
11 Point 5
12 T5: 540.0 degC
13 p5: 70.0 bar
14 H5: 3507.6 kJ/kg
15 S5: 6.921 kJ/kg K
16
17 Point 6
18 T6: 45.8 degC
19 p6: 0.1 bar
20 H6: 2192.3 kJ/kg
21 S6: 6.921 kJ/kg K
22 x6: 83.6 % dry
23
24 Summary
25 Work required by pump: 0.2 kJ/kg
26 Work generated by HP turbine: 281.3 kJ/kg
27 Work generated by LP turbine: 1315.3 kJ/kg
28 Total work output by turbine: 1596.6 kJ/kg
29 Heat input by boiler: 3597.0 kJ/kg
30 Heat rejected by the condenser: 2000.5 kJ/kg
31 Thermal efficiency is: 44.383%
32 HR rankine cycle: 8111.2 kJ/kWh
```

In this case we have expanded the steam in the HP turbine from 180 bar down to 70 bar.

The amount of energy extracted from the steam in the HP turbine (281.3 kJ/kg in this case) is a little lower but overall theoretical thermal efficiency is 44.383% which is again the best achieved so far.

1.1.5 Finding the most efficient reheat pressure

To find the ideal reheat pressure when designing a Rankine reheat steam cycle we need to analyse each possible/reasonable reheat pressure and plot the outcome. Given the main steam pressure of 180 bar and calculating for a reheat pressure between 25 bar and 90 bar in steps of 0.25 bar.

The code for this is in section B.5.

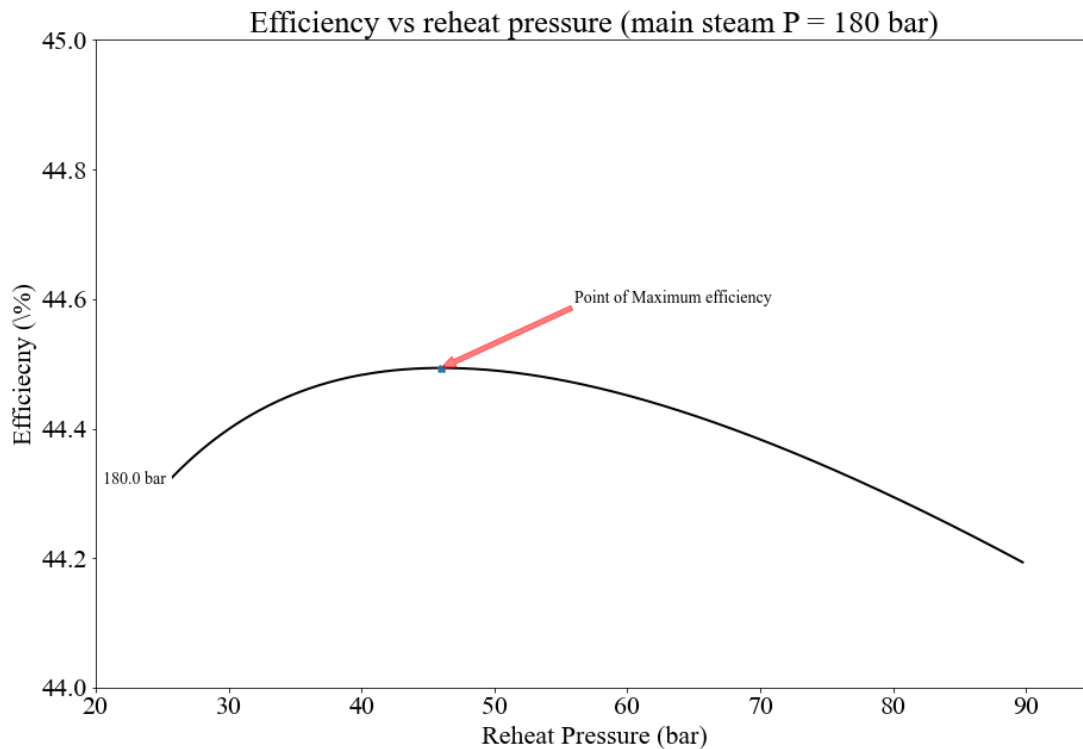


Figure 7: Plot of efficiency vs reheat pressure for a reheat cycle with 180 bar main steam pressure.

```
1 When MS pressure = 180.0 bar
2 Maximum potential cycle efficiency = 44.494 %
3 Maximum cycle efficiency occurs with a reheat pressure = 46.0 bar
4 ratio of MS vs RH pressure = 4.05
```

We can see from figure 7 and code printout that for a main steam pressure of 180 bar an overall cycle theoretical efficiency of 44.494% can be achieved with a reheat pressure of 46.0 bar.

The Ts diagram below and code printout show the cycle calculations with these conditions.

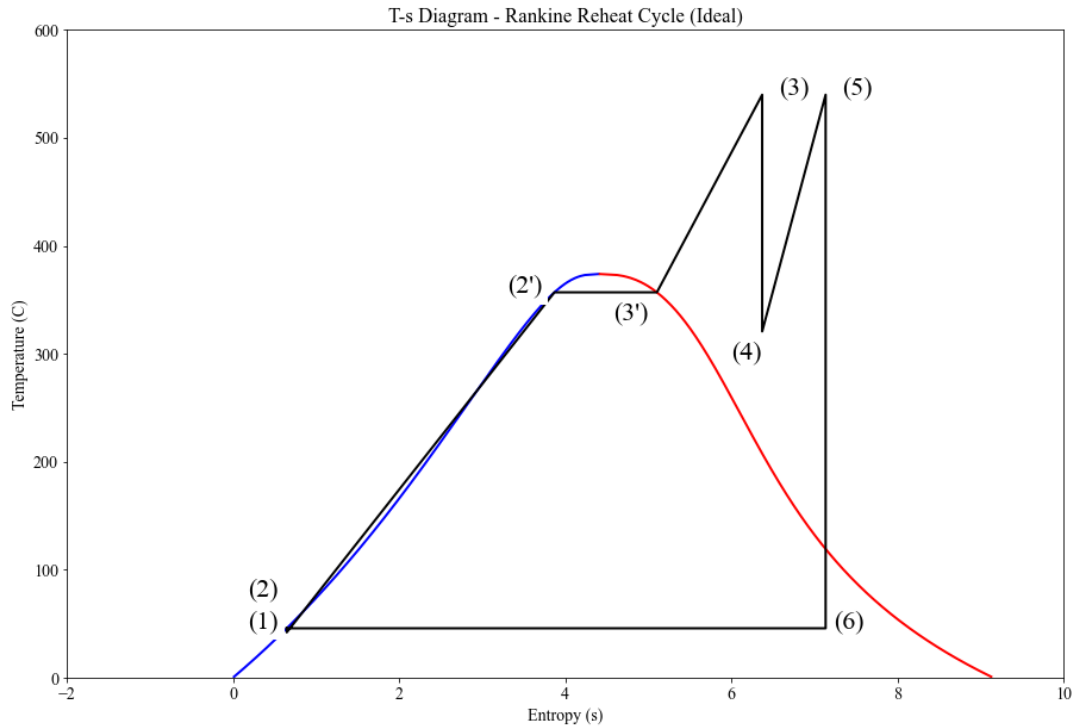


Figure 8: Ts plot of Rankine reheat cycle with HP turbine expansion down to 46 bar

The Python code to generate the plot above and efficiency calculations result below can be found in appendix B.6

```

1 Rankine reheat cycle analysis – reheat pressure at 46 bar
2
3 Reheat Pressure: 46.0 bar
4
5 Point 4
6 T4: 320.8 degC
7 P4: 46.0 bar
8 H4: 3000.7 kJ/kg
9 S4: 6.373 kJ/kg K
10
11 Point 5
12 T5: 540.0 degC
13 p5: 46.0 bar
14 H5: 3531.5 kJ/kg
15 S5: 7.137 kJ/kg K
16
17 Point 6
18 T6: 45.8 degC
19 p6: 0.1 bar
20 H6: 2261.2 kJ/kg
21 S6: 7.137 kJ/kg K
22 x6: 86.5 % dry
23
24 Summary
25 Work required by pump: 0.2 kJ/kg
26 Work generated by HP turbine: 388.8 kJ/kg
27 Work generated by LP turbine: 1270.2 kJ/kg
28 Total work output by turbine: 1659.0 kJ/kg
29 Heat input by boiler: 3728.3 kJ/kg
30 Heat rejected by the condenser: 2069.4 kJ/kg
31 Thermal efficiency is: 44.494%
32 HR rankine cycle: 8091.0 kJ/kWh

```

Result (Theoretical)

In summary for a main steam pressure of 180 bar, the most efficient reheat pressure is 46.0 bar.

1.1.6 Real expansion

It can be seen in the previous example that whilst the reheat steam pressure of 46 bar gives the most efficient cycle (with a main steam pressure of 180 bar) the LP turbine exhaust dryness is only 86.5% (i.e. still 13.5% moisture). This moisture value is a bit high and will lead to increased erosion of last stage LP turbine blading.

Luckily for us the above example is only a theoretical cycle (i.e. steam expansion in the turbine is isentropic). In the real world each turbine stage has losses and therefore the entropy tends to increase during the steam expansion.

We now need to go back and redo the analysis of each possible/reasonable reheat pressure and plot the outcome using non-ideal expansion. Given the main steam pressure of 180 bar, turbine isentropic efficiency of 90% and calculating for a reheat pressure between 25 bar and 90 bar in steps of 0.25 bar.

The code for this is in section B.7.

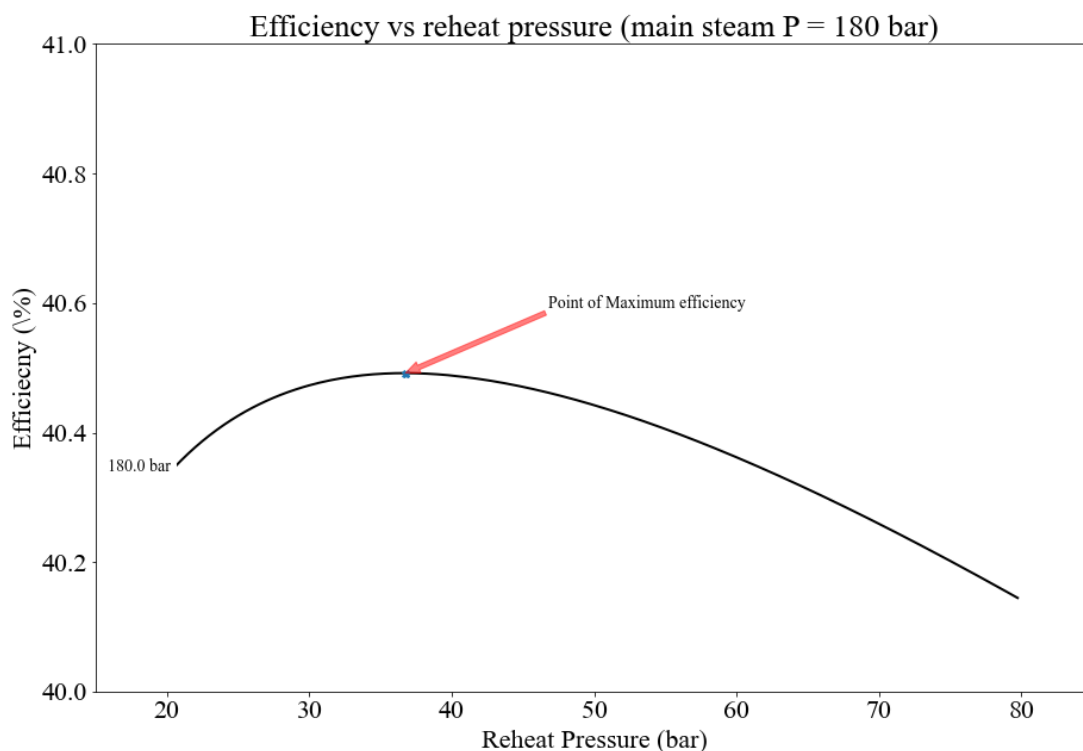


Figure 9: Plot of efficiency vs reheat pressure for a reheat cycle with 180 bar main steam pressure.

- ```
1 When MS pressure = 180.0 bar
2 Maximum potential cycle efficiency = 40.492 %
3 Maximum cycle efficiency occurs with a reheat pressure = 36.75 bar
```

We can see from figure 9 and code printout that for a main steam pressure of 180 bar and turbine isentropic efficiency of 90% an overall cycle theoretical efficiency of 40.492% can be achieved with a reheat pressure of 36.75 bar.

The Ts diagram below and code printout show the cycle calculations with these conditions.



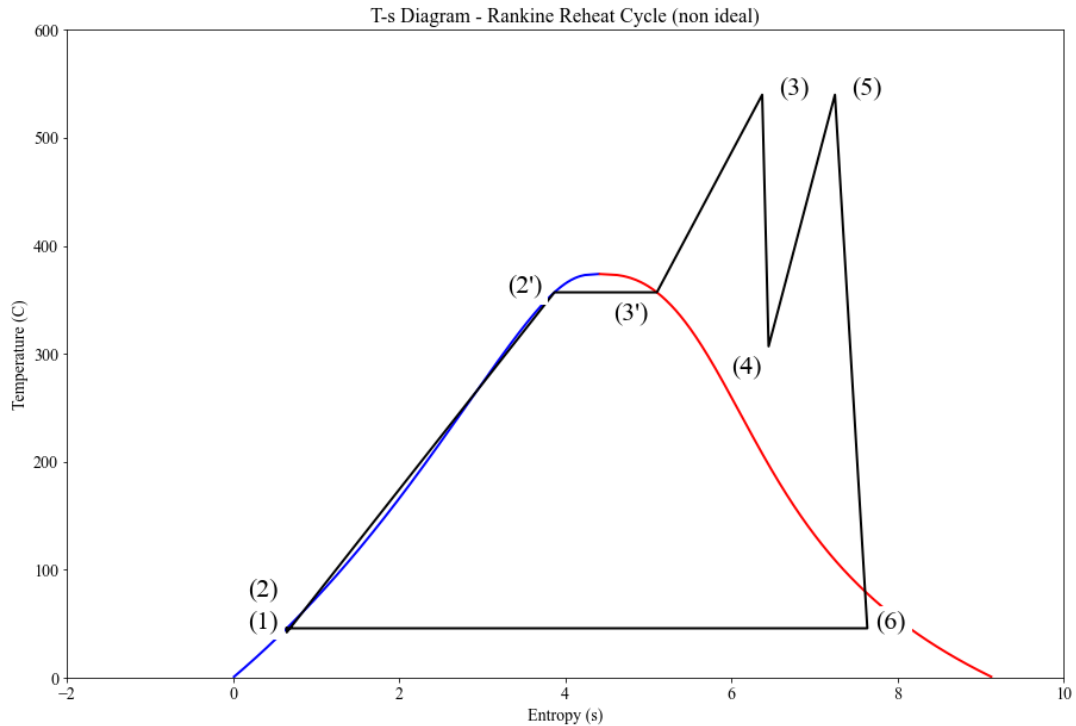


Figure 10: Ts plot of Rankine reheat cycle with HP turbine expansion down to 36.75 bar

The Python code to generate the plot above and efficiency calculations result below can be found in appendix B.8

```

1 Reheat Pressure: 36.8 bar
2
3 Point 4
4 T4real: 307.0 degC
5 P4: 36.8 bar
6 H4real: 2991.5 kJ/kg
7 S4real: 6.451 kJ/kg K
8
9 Point 5
10 T5: 540.0 degC
11 P5: 36.8 bar
12 H5: 3540.5 kJ/kg
13 S5: 7.249 kJ/kg K
14
15 Point 6
16 T6: 45.8 degC
17 P6: 0.1 bar
18 H6real: 2421.3 kJ/kg
19 S6real: 7.639 kJ/kg K
20 x6: 93.2 % dry
21
22 Summary
23 Work required by pump: 0.2 kJ/kg
24 Work generated by HP turbine: 398.1 kJ/kg
25 Work generated by LP turbine: 1119.2 kJ/kg
26 Total work output by turbine: 1517.2 kJ/kg
27 Heat input by boiler: 3746.6 kJ/kg
28 Heat rejected by the condenser: 2229.5 kJ/kg
29 Thermal efficiency is: 40.5%
30 HR rankine cycle: 8890.7 kJ/kWh

```

The LP turbine exhaust dryness is now 93.2% so therefore there is only 6.8% moisture in this steam, which is a much better result for extending turbine last stage blade life.

### **Result**

With a main steam pressure of 180 bar, and turbine isentropic efficiency of 90% the most efficient reheat pressure is 36.75 bar. This also gives a much improved LP turbine exhaust dryness of 93.2%.

We now have a reheat outlet pressure of 36.75 bar which with a main steam pressure of 180 bar will give the highest Ranking cycle efficiency. However, some other items have not been taken into account, as follows;

- We assume that boiler steam drum pressure and turbine inlet pressure are the same, however there will be a pressure drop along this pipe (can be up to 15 bar depending on pipe sizing and length).
- Also for reheat pipework (cold reheat from HP turbine exhaust through reheat tubes inside the furnace and hot reheat pipework to IP turbine, we again assume no pressure drop. This will not be the case.

These will need to be taken into account to determine the most efficient reheat pressure accurately, however much depends on the pipe sizing and distance between boiler and turbine. Therefore I have not gone into that in this document.

## 1.2 multiple results

It can be however that the main steam pressure at your plant is not 180 bar, so therefore we need to calculate the ideal reheat pressure at a number of differing main steam pressures.

The code for this is in section B.9.

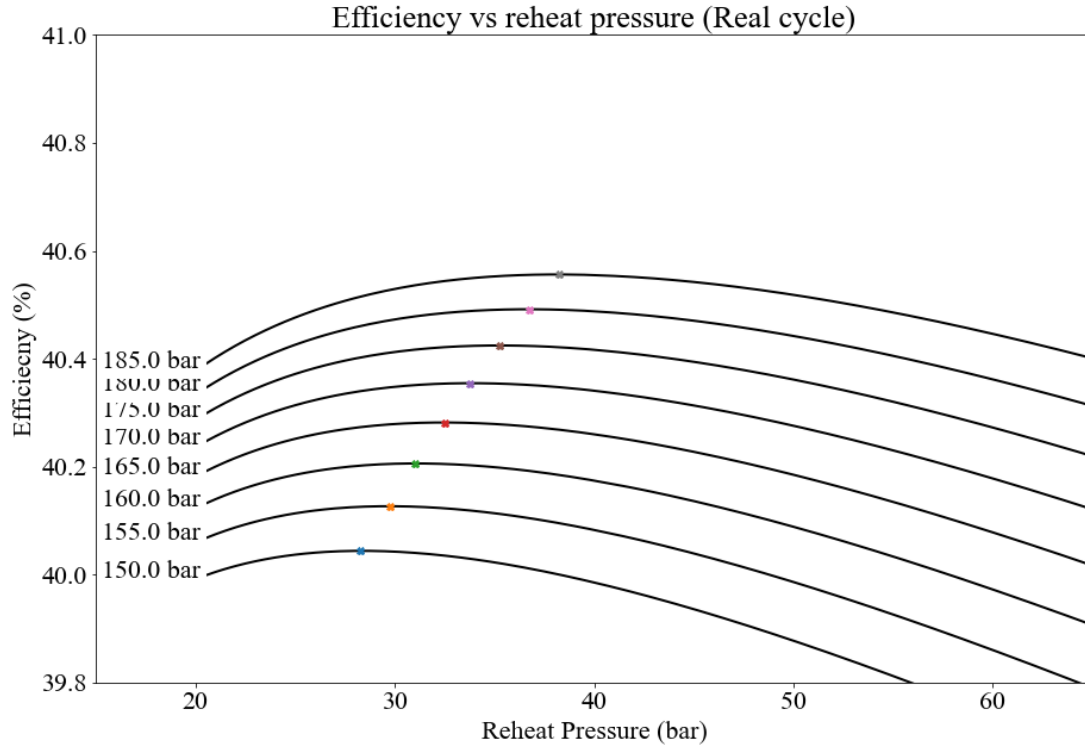


Figure 11: Plot of efficiency vs reheat pressure for a reheat cycle at various main steam pressures.

Table 1: Ideal Reheat Pressure vs Main Steam Pressure

| Main Steam Pressure<br>(bar) | Highest Efficiency Achieved<br>(%) | Reheat Pressure<br>(bar) |
|------------------------------|------------------------------------|--------------------------|
| 150.0                        | 40.044 %                           | 28.25                    |
| 155.0                        | 40.127 %                           | 29.75                    |
| 160.0                        | 40.206 %                           | 31.0                     |
| 165.0                        | 40.282 %                           | 32.5                     |
| 170.0                        | 40.355 %                           | 33.75                    |
| 175.0                        | 40.425 %                           | 35.25                    |
| 180.0                        | 40.492 %                           | 36.75                    |
| 185.0                        | 40.556 %                           | 38.25                    |

**Note:** - it can also be at your plant that turbine isentropic efficiency is not 90% and also can be different for HP, IP and LP turbines. This can be changed in the code provided.

## A Software used

All code example in this document have been tested using Python v3.7.6 under macOS and Windows 8. In addition the following packages within python have been used;

- Matplotlib v3.2.2 → <https://matplotlib.org>
- Numpy v1.18.5 → <https://numpy.org>
- pyXSteam v0.4.4 → <https://pypi.org/project/pyXSteam>

## B Code printouts

### B.1 Rankine reheat cycle expansion to saturation line

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7 print('Rankine reheat cycle analysis – main steam expansion doen to saturation line')
8
9 p1 = 0.1
10 s1 = steamTable.sL_p(p1)
11 T1 = steamTable.t_ps(p1, s1)
12 h1 = steamTable.hL_p(p1)
13 print('\nPoint 1')
14 print(f"P1: {round(float(p1),1)} bar")
15 print(f"T1: {round(float(T1),1)} degC")
16 print(f"H1: {round(float(h1),1)} kJ/kg")
17 print(f"S1: {round(float(s1),3)} kJ/kg K")
18
19 p2 = 180
20 s2 = s1
21
22 v = 1/steamTable.rhoL_p(p1)
23 w_p = v*(p2-p1)
24
25 print('\nPoint 2')
26 h2 = h1+w_p
27 print(f"H2: {round(float(h2),1)} kJ/kg")
28
29 T2 = steamTable.t_ph(p2, h2)
30 print(f"T2: {round(float(T2),1)} degC")
31
32 h2dash = steamTable.hL_p(p2)
33 s2dash = steamTable.sL_p(p2)
34 T2dash = steamTable.t_ph(p2, h2dash)
35 print('\nPoint 2dash')
36 print(f"T2dash: {round(float(T2dash),1)} degC")
37 print(f"P2dash: {round(float(p2),1)} bar")
38 print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
39 print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")
40
41 h3dash = steamTable.hV_p(p2)
42 s3dash = steamTable.sV_p(p2)
43 T3dash = T2dash
44 print('\nPoint 3dash')
45 print(f"T3dash: {round(float(T3dash),1)} degC")
46 print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
47 print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")
48
49 p3 = p2
50 T3 = 540
51 h3 = steamTable.h_pt(p3, T3)
52 s3 = steamTable.s_pt(p3, T3)
53 print('\nPoint 3')
54 print(f"T3: {round(float(T3),1)} degC")
55 print(f"P3: {round(float(p3),1)} bar")
56 print(f"H3: {round(float(h3),1)} kJ/kg")
57 print(f"S3: {round(float(s3),3)} kJ/kg K")
58
59 t4=steamTable.tsat_s(s3)
60 print(f"t4sat: {round(float(t4),1)} degC")
61 p4=steamTable.psat_s(s3)+0.1
62 print(f"P4sat: {round(float(p4),1)} bar")
63
64 print(f'Reheat Pressure: {round(float(p4),1)} bar')
65 s4 = s3
66 T4 = steamTable.t_ps(p4, s4)
67 h4 = steamTable.h_pt(p4, T4)
68 print('\nPoint 4')
69 print(f"T4: {round(float(T4),1)} degC")
70 print(f"P4: {round(float(p4),1)} bar")
71 print(f"H4: {round(float(h4),1)} kJ/kg")
72 print(f"S4: {round(float(s4),3)} kJ/kg K")
```

```

73
74 p5 = p4
75 T5 = T3
76 h5 = steamTable.h_pt(p5, T5)
77 s5 = steamTable.s_pt(p5, T5)
78 print('\nPoint 5')
79 print(f"T5: {round(float(T5),1)} degC")
80 print(f"p5: {round(float(p5),1)} bar")
81 print(f"H5: {round(float(h5),1)} kJ/kg")
82 print(f"S5: {round(float(s5),3)} kJ/kg K")
83
84 p6 = p1
85 s6 = s5
86 T6 = steamTable.t_ps(p6, s6)
87 x6 = steamTable.x_ps(p6, s6)
88 h6 = steamTable.h_px(p6, x6)
89 print('\nPoint 6')
90 print(f"T6: {round(float(T6),1)} degC")
91 print(f"p6: {round(float(p6),1)} bar")
92 print(f"H6: {round(float(h6),1)} kJ/kg")
93 print(f"S6: {round(float(s6),3)} kJ/kg K")
94 print(f"x6: {round(float(x6*100),1)} % dry")
95
96 print('\nSummary')
97 print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")
98
99 w_HP_t = h3-h4
100 print(f"Work generated by HP turbine: {round(float(w_HP_t),1)} kJ/kg")
101
102 w_LP_t = h5-h6
103 print(f"Work generated by LP turbine: {round(float(w_LP_t),1)} kJ/kg")
104 print(f"Total work output by turbine: {round(float(w_HP_t+w_LP_t),1)} kJ/kg")
105
106 q_H = (h3-h2)+(h5-h4)
107 print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")
108
109 q_L = h6-h1
110 print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")
111
112 eta_th = (w_HP_t+w_LP_t-w_p)/q_H*100
113 print(f"Thermal efficiency is: {round(float(eta_th),3)}%")
114
115 HRcycle = 3600*100/eta_th
116 print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")
117
118 font = {'family' : 'Times New Roman',
119 'size' : 22}
120
121 plt.figure(figsize=(15,10))
122 plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
123 plt.rc('font', **font)
124
125 plt.ylabel('Temperature (C)')
126 plt.xlabel('Entropy (s)')
127 plt.xlim(-2,10)
128 plt.ylim(0,600)
129
130 T = np.linspace(0, 373.945, 400) # range of temperatures
131 svap = [s for s in [steamTable.sL_t(t) for t in T]]
132 sliq = [s for s in [steamTable.sV_t(t) for t in T]]
133
134 plt.plot(svap, T, 'b-', linewidth=2.0)
135 plt.plot(sliq, T, 'r-', linewidth=2.0)
136
137 plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6,
 T1], 'black', linewidth=2.0)
138
139 plt.text(s1-.1,T1,f'(1)',
140 ha='right',backgroundcolor='white')
141 plt.text(s1-.1,T1+30,f'(2)',
142 ha='right',backgroundcolor='white')
143 plt.text(s2dash-.15,T2dash,f"(2)\"",
144 ha='right',backgroundcolor='white')
145 plt.text(s3dash-.1,T3dash-25,f"(3)\"",
146 ha='right',backgroundcolor='white')
147 plt.text(s3+.2,T3,f'(3)',

```

```
148 ha='left',backgroundcolor='white')
149 plt.text(s4-.1,T4-25,f'(4)',
150 ha='right',backgroundcolor='white')
151 plt.text(s5+.2,T5,f'(5)',
152 ha='left',backgroundcolor='white')
153 plt.text(s6+.1,T6,f'(6)',
154 ha='left',backgroundcolor='white')
155
156 plt.savefig('Plot-01.png')
```

## B.2 Rankine reheat cycle expansion to 160 bar

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7 print('Rankine reheat cycle analysis – reheat pressure at 160 bar')
8
9 p1 = 0.1
10 s1 = steamTable.sL_p(p1)
11 T1 = steamTable.t_ps(p1, s1)
12 h1 = steamTable.hL_p(p1)
13 print('\nPoint 1')
14 print(f"P1: {round(float(p1),1)} bar")
15 print(f"T1: {round(float(T1),1)} degC")
16 print(f"H1: {round(float(h1),1)} kJ/kg")
17 print(f"S1: {round(float(s1),3)} kJ/kg K")
18
19 p2 = 180
20 s2 = s1
21
22 v = 1/steamTable.rhoL_p(p1)
23 w_p = v*(p2-p1)
24
25 print('\nPoint 2')
26 h2 = h1+w_p
27 print(f"H2: {round(float(h2),1)} kJ/kg")
28
29 T2 = steamTable.t_ph(p2, h2)
30 print(f"T2: {round(float(T2),1)} degC")
31
32 h2dash = steamTable.hL_p(p2)
33 s2dash = steamTable.sL_p(p2)
34 T2dash = steamTable.t_ph(p2, h2dash)
35 print('\nPoint 2dash')
36 print(f"T2dash: {round(float(T2dash),1)} degC")
37 print(f"P2dash: {round(float(p2),1)} bar")
38 print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
39 print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")
40
41 h3dash = steamTable.hV_p(p2)
42 s3dash = steamTable.sV_p(p2)
43 T3dash = T2dash
44 print('\nPoint 3dash')
45 print(f"T3dash: {round(float(T3dash),1)} degC")
46 print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
47 print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")
48
49 p3 = p2
50 T3 = 540
51 h3 = steamTable.h_pt(p3, T3)
52 s3 = steamTable.s_pt(p3, T3)
53 print('\nPoint 3')
54 print(f"T3: {round(float(T3),1)} degC")
55 print(f"P3: {round(float(p3),1)} bar")
56 print(f"H3: {round(float(h3),1)} kJ/kg")
57 print(f"S3: {round(float(s3),3)} kJ/kg K")
58
59 p4 = 160
60 print(f"Reheat Pressure: {round(float(p4),1)} bar")
61 s4 = s3
62 T4 = steamTable.t_ps(p4, s4)
63 h4 = steamTable.h_pt(p4, T4)
64 print('\nPoint 4')
65 print(f"T4: {round(float(T4),1)} degC")
66 print(f"P4: {round(float(p4),1)} bar")
67 print(f"H4: {round(float(h4),1)} kJ/kg")
68 print(f"S4: {round(float(s4),3)} kJ/kg K")
69
70 p5 = p4
71 T5 = T3
72 h5 = steamTable.h_pt(p5, T5)
73 s5 = steamTable.s_pt(p5, T5)
74 print('\nPoint 5')
```



```

75 print(f"T5: {round(float(T5),1)} degC")
76 print(f"p5: {round(float(p5),1)} bar")
77 print(f"H5: {round(float(h5),1)} kJ/kg")
78 print(f"S5: {round(float(s5),3)} kJ/kg K")
79
80 p6 = p1
81 s6 = s5
82 T6 = steamTable.t_ps(p6, s6)
83 x6 = steamTable.x_ps(p6, s6)
84 h6 = steamTable.h_px(p6, x6)
85 print('\nPoint 6')
86 print(f"T6: {round(float(T6),1)} degC")
87 print(f"p6: {round(float(p6),1)} bar")
88 print(f"H6: {round(float(h6),1)} kJ/kg")
89 print(f"S6: {round(float(s6),3)} kJ/kg K")
90 print(f"x6: {round(float(x6*100),1)} % dry")
91
92 print('\nSummary')
93 print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")
94
95 w_HP_t = h3-h4
96 print(f"Work generated by HP turbine: {round(float(w_HP_t),1)} kJ/kg")
97
98 w_LP_t = h5-h6
99 print(f"Work generated by LP turbine: {round(float(w_LP_t),1)} kJ/kg")
100 print(f"Total work output by turbine: {round(float(w_HP_t+w_LP_t),1)} kJ/kg")
101
102 q_H = (h3-h2)+(h5-h4)
103 print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")
104
105 q_L = h6-h1
106 print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")
107
108 eta_th = (w_HP_t+w_LP_t-w_p)/q_H*100
109 print(f"Thermal efficiency is: {round(float(eta_th),3)}%")
110
111 HRcycle = 3600*100/eta_th
112 print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")
113
114 font = {'family' : 'Times New Roman',
115 'size' : 22}
116
117 plt.figure(figsize=(15,10))
118 plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
119 plt.rc('font', **font)
120
121 plt.ylabel('Temperature (C)')
122 plt.xlabel('Entropy (s)')
123 plt.xlim(-2,10)
124 plt.ylim(0,600)
125
126 T = np.linspace(0, 373.945, 400) # range of temperatures
127 svap = [s for s in [steamTable.sL_t(t) for t in T]]
128 sliq = [s for s in [steamTable.sV_t(t) for t in T]]
129
130 plt.plot(svap, T, 'b-', linewidth=2.0)
131 plt.plot(sliq, T, 'r-', linewidth=2.0)
132
133 plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6,
134 T1], 'black', linewidth=2.0)
135
136 plt.text(s1-1,T1,f'(1)',
137 ha='right',backgroundcolor='white')
138 plt.text(s1-1,T1+30,f'(2)',
139 ha='right',backgroundcolor='white')
140 plt.text(s2dash-15,T2dash,f'(2)''',
141 ha='right',backgroundcolor='white')
142 plt.text(s3dash-1,T3dash-25,f'(3)''',
143 ha='right',backgroundcolor='white')
144 plt.text(s3+2,T3,f'(3)',
145 ha='left',backgroundcolor='white')
146 plt.text(s4-1,T4-25,f'(4)',
147 ha='right',backgroundcolor='white')
148 plt.text(s5+2,T5,f'(5)',
149 ha='left',backgroundcolor='white')
150 plt.text(s6+1,T6,f'(6)',

```

```
150 ha='left',backgroundcolor='white')
151
152 plt.savefig('Plot-02.png')
```

### B.3 Rankine reheat cycle expansion to 25 bar

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7 print('Rankine reheat cycle analysis – reheat pressure at 25 bar')
8
9 p1 = 0.1
10 s1 = steamTable.sL_p(p1)
11 T1 = steamTable.t_ps(p1, s1)
12 h1 = steamTable.hL_p(p1)
13 print('\nPoint 1')
14 print(f"P1: {round(float(p1),1)} bar")
15 print(f"T1: {round(float(T1),1)} degC")
16 print(f"H1: {round(float(h1),1)} kJ/kg")
17 print(f"S1: {round(float(s1),3)} kJ/kg K")
18
19 p2 = 180
20 s2 = s1
21
22 v = 1/steamTable.rhoL_p(p1)
23 w_p = v*(p2-p1)
24
25 print('\nPoint 2')
26 h2 = h1+w_p
27 print(f"H2: {round(float(h2),1)} kJ/kg")
28
29 T2 = steamTable.t_ph(p2, h2)
30 print(f"T2: {round(float(T2),1)} degC")
31
32 h2dash = steamTable.hL_p(p2)
33 s2dash = steamTable.sL_p(p2)
34 T2dash = steamTable.t_ph(p2, h2dash)
35 print('\nPoint 2dash')
36 print(f"T2dash: {round(float(T2dash),1)} degC")
37 print(f"P2dash: {round(float(p2),1)} bar")
38 print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
39 print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")
40
41 h3dash = steamTable.hV_p(p2)
42 s3dash = steamTable.sV_p(p2)
43 T3dash = T2dash
44 print('\nPoint 3dash')
45 print(f"T3dash: {round(float(T3dash),1)} degC")
46 print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
47 print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")
48
49 p3 = p2
50 T3 = 540
51 h3 = steamTable.h_pt(p3, T3)
52 s3 = steamTable.s_pt(p3, T3)
53 print('\nPoint 3')
54 print(f"T3: {round(float(T3),1)} degC")
55 print(f"P3: {round(float(p3),1)} bar")
56 print(f"H3: {round(float(h3),1)} kJ/kg")
57 print(f"S3: {round(float(s3),3)} kJ/kg K")
58
59 p4 = 25
60 print(f"Reheat Pressure: {round(float(p4),1)} bar")
61 s4 = s3
62 T4 = steamTable.t_ps(p4, s4)
63 h4 = steamTable.h_pt(p4, T4)
64 print('\nPoint 4')
65 print(f"T4: {round(float(T4),1)} degC")
66 print(f"P4: {round(float(p4),1)} bar")
67 print(f"H4: {round(float(h4),1)} kJ/kg")
68 print(f"S4: {round(float(s4),3)} kJ/kg K")
69
70 p5 = p4
71 T5 = T3
72 h5 = steamTable.h_pt(p5, T5)
73 s5 = steamTable.s_pt(p5, T5)
74 print('\nPoint 5')
```

```

75 print(f"T5: {round(float(T5),1)} degC")
76 print(f"p5: {round(float(p5),1)} bar")
77 print(f"H5: {round(float(h5),1)} kJ/kg")
78 print(f"S5: {round(float(s5),3)} kJ/kg K")
79
80 p6 = p1
81 s6 = s5
82 T6 = steamTable.t_ps(p6, s6)
83 x6 = steamTable.x_ps(p6, s6)
84 h6 = steamTable.h_px(p6, x6)
85 print('\nPoint 6')
86 print(f"T6: {round(float(T6),1)} degC")
87 print(f"p6: {round(float(p6),1)} bar")
88 print(f"H6: {round(float(h6),1)} kJ/kg")
89 print(f"S6: {round(float(s6),3)} kJ/kg K")
90 print(f"x6: {round(float(x6*100),1)} % dry")
91
92 print('\nSummary')
93 print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")
94
95 w_HP_t = h3-h4
96 print(f"Work generated by HP turbine: {round(float(w_HP_t),1)} kJ/kg")
97
98 w_LP_t = h5-h6
99 print(f"Work generated by LP turbine: {round(float(w_LP_t),1)} kJ/kg")
100 print(f"Total work output by turbine: {round(float(w_HP_t+w_LP_t),1)} kJ/kg")
101
102 q_H = (h3-h2)+(h5-h4)
103 print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")
104
105 q_L = h6-h1
106 print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")
107
108 eta_th = (w_HP_t+w_LP_t-w_p)/q_H*100
109 print(f"Thermal efficiency is: {round(float(eta_th),3)}%")
110
111 HRcycle = 3600*100/eta_th
112 print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")
113
114 font = {'family' : 'Times New Roman',
115 'size' : 22}
116
117 plt.figure(figsize=(15,10))
118 plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
119 plt.rc('font', **font)
120
121 plt.ylabel('Temperature (C)')
122 plt.xlabel('Entropy (s)')
123 plt.xlim(-2,10)
124 plt.ylim(0,600)
125
126 T = np.linspace(0, 373.945, 400) # range of temperatures
127 svap = [s for s in [steamTable.sL_t(t) for t in T]]
128 sliq = [s for s in [steamTable.sV_t(t) for t in T]]
129
130 plt.plot(svap, T, 'b-', linewidth=2.0)
131 plt.plot(sliq, T, 'r-', linewidth=2.0)
132
133 plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6,
134 T1], 'black', linewidth=2.0)
135
136 plt.text(s1-1,T1,f'(1)',
137 ha='right',backgroundcolor='white')
138 plt.text(s1-1,T1+30,f'(2)',
139 ha='right',backgroundcolor='white')
140 plt.text(s2dash-15,T2dash,f'(2)''',
141 ha='right',backgroundcolor='white')
142 plt.text(s3dash-1,T3dash-25,f'(3)''',
143 ha='right',backgroundcolor='white')
144 plt.text(s3+2,T3,f'(3)',
145 ha='left',backgroundcolor='white')
146 plt.text(s4-1,T4-25,f'(4)',
147 ha='right',backgroundcolor='white')
148 plt.text(s5+2,T5,f'(5)',
149 ha='left',backgroundcolor='white')
150 plt.text(s6+1,T6,f'(6)',

```

```
150 ha='left',backgroundcolor='white')
151
152 plt.savefig('Plot-04.png')
```

## B.4 Rankine reheat cycle expansion to 70 bar

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7 print('Rankine reheat cycle analysis – reheat pressure at 70 bar')
8
9 p1 = 0.1
10 s1 = steamTable.sL_p(p1)
11 T1 = steamTable.t_ps(p1, s1)
12 h1 = steamTable.hL_p(p1)
13 print('\nPoint 1')
14 print(f"P1: {round(float(p1),1)} bar")
15 print(f"T1: {round(float(T1),1)} degC")
16 print(f"H1: {round(float(h1),1)} kJ/kg")
17 print(f"S1: {round(float(s1),3)} kJ/kg K")
18
19 p2 = 180
20 s2 = s1
21
22 v = 1/steamTable.rhoL_p(p1)
23 w_p = v*(p2-p1)
24
25 print('\nPoint 2')
26 h2 = h1+w_p
27 print(f"H2: {round(float(h2),1)} kJ/kg")
28
29 T2 = steamTable.t_ph(p2, h2)
30 print(f"T2: {round(float(T2),1)} degC")
31
32 h2dash = steamTable.hL_p(p2)
33 s2dash = steamTable.sL_p(p2)
34 T2dash = steamTable.t_ph(p2, h2dash)
35 print('\nPoint 2dash')
36 print(f"T2dash: {round(float(T2dash),1)} degC")
37 print(f"P2dash: {round(float(p2),1)} bar")
38 print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
39 print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")
40
41 h3dash = steamTable.hV_p(p2)
42 s3dash = steamTable.sV_p(p2)
43 T3dash = T2dash
44 print('\nPoint 3dash')
45 print(f"T3dash: {round(float(T3dash),1)} degC")
46 print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
47 print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")
48
49 p3 = p2
50 T3 = 540
51 h3 = steamTable.h_pt(p3, T3)
52 s3 = steamTable.s_pt(p3, T3)
53 print('\nPoint 3')
54 print(f"T3: {round(float(T3),1)} degC")
55 print(f"P3: {round(float(p3),1)} bar")
56 print(f"H3: {round(float(h3),1)} kJ/kg")
57 print(f"S3: {round(float(s3),3)} kJ/kg K")
58
59 p4 = 70
60 print(f"Reheat Pressure: {round(float(p4),1)} bar")
61 s4 = s3
62 T4 = steamTable.t_ps(p4, s4)
63 h4 = steamTable.h_pt(p4, T4)
64 print('\nPoint 4')
65 print(f"T4: {round(float(T4),1)} degC")
66 print(f"P4: {round(float(p4),1)} bar")
67 print(f"H4: {round(float(h4),1)} kJ/kg")
68 print(f"S4: {round(float(s4),3)} kJ/kg K")
69
70 p5 = p4
71 T5 = T3
72 h5 = steamTable.h_pt(p5, T5)
73 s5 = steamTable.s_pt(p5, T5)
74 print('\nPoint 5')
```

```

75 print(f"T5: {round(float(T5),1)} degC")
76 print(f"p5: {round(float(p5),1)} bar")
77 print(f"H5: {round(float(h5),1)} kJ/kg")
78 print(f"S5: {round(float(s5),3)} kJ/kg K")
79
80 p6 = p1
81 s6 = s5
82 T6 = steamTable.t_ps(p6, s6)
83 x6 = steamTable.x_ps(p6, s6)
84 h6 = steamTable.h_px(p6, x6)
85 print('\nPoint 6')
86 print(f"T6: {round(float(T6),1)} degC")
87 print(f"p6: {round(float(p6),1)} bar")
88 print(f"H6: {round(float(h6),1)} kJ/kg")
89 print(f"S6: {round(float(s6),3)} kJ/kg K")
90 print(f"x6: {round(float(x6*100),1)} % dry")
91
92 print('\nSummary')
93 print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")
94
95 w_HP_t = h3-h4
96 print(f"Work generated by HP turbine: {round(float(w_HP_t),1)} kJ/kg")
97
98 w_LP_t = h5-h6
99 print(f"Work generated by LP turbine: {round(float(w_LP_t),1)} kJ/kg")
100 print(f"Total work output by turbine: {round(float(w_HP_t+w_LP_t),1)} kJ/kg")
101
102 q_H = (h3-h2)+(h5-h4)
103 print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")
104
105 q_L = h6-h1
106 print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")
107
108 eta_th = (w_HP_t+w_LP_t-w_p)/q_H*100
109 print(f"Thermal efficiency is: {round(float(eta_th),3)}%")
110
111 HRcycle = 3600*100/eta_th
112 print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")
113
114 font = {'family' : 'Times New Roman',
115 'size' : 22}
116
117 plt.figure(figsize=(15,10))
118 plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
119 plt.rc('font', **font)
120
121 plt.ylabel('Temperature (C)')
122 plt.xlabel('Entropy (s)')
123 plt.xlim(-2,10)
124 plt.ylim(0,600)
125
126 T = np.linspace(0, 373.945, 400) # range of temperatures
127 svap = [s for s in [steamTable.sL_t(t) for t in T]]
128 sliq = [s for s in [steamTable.sV_t(t) for t in T]]
129
130 plt.plot(svap, T, 'b-', linewidth=2.0)
131 plt.plot(sliq, T, 'r-', linewidth=2.0)
132
133 plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6,
134 T1], 'black', linewidth=2.0)
135
136 plt.text(s1-1,T1,f'(1)',
137 ha='right',backgroundcolor='white')
138 plt.text(s1-1,T1+30,f'(2)',
139 ha='right',backgroundcolor='white')
140 plt.text(s2dash-15,T2dash,f'(2)''',
141 ha='right',backgroundcolor='white')
142 plt.text(s3dash-1,T3dash-25,f'(3)''',
143 ha='right',backgroundcolor='white')
144 plt.text(s3+2,T3,f'(3)',
145 ha='left',backgroundcolor='white')
146 plt.text(s4-1,T4-25,f'(4)',
147 ha='right',backgroundcolor='white')
148 plt.text(s5+2,T5,f'(5)',
149 ha='left',backgroundcolor='white')
150 plt.text(s6+1,T6,f'(6)',

```

```
150 ha='left',backgroundcolor='white')
151
152 plt.savefig('Plot-05.png')
```



## B.5 Find reheat pressure at 180 bar main steam

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7
8 def cycle_efficiency(p1, p2, T3, p4):
9
10 h1 = steamTable.hL_p(p1)
11 v = 1/steamTable.rhoL_p(p1)
12 w_p = v*(p2-p1)
13
14 h2 = h1+w_p
15
16 p3 = p2
17 h3 = steamTable.h_pt(p3, T3)
18 s3 = steamTable.s_pt(p3, T3)
19
20 s4 = s3
21 T4 = steamTable.t_ps(p4, s4)
22 h4 = steamTable.h_pt(p4, T4)
23
24 p5 = p4
25 T5 = T3
26 h5 = steamTable.h_pt(p5, T5)
27 s5 = steamTable.s_pt(p5, T5)
28
29 p6 = p1
30 s6 = s5
31 x6 = steamTable.x_ps(p6, s6)
32 h6 = steamTable.h_px(p6, x6)
33
34 w_HP_t = h3-h4
35 w_LP_t = h5-h6
36 q_H = (h3-h2)+(h5-h4)
37 eta_th = (w_HP_t+w_LP_t-w_p)/q_H*100
38 return [eta_th, x6*100]
39
40 font = {'family' : 'Times New Roman',
41 'size' : 22}
42
43 plt.figure(figsize=(15,10))
44 plt.title('Efficiency vs reheat pressure (main steam P = 180 bar)')
45 plt.rc('font', **font)
46
47 plt.xlabel('Reheat Pressure (bar)')
48 plt.ylabel('Efficiency (%)')
49 plt.xlim(20,95)
50 plt.ylim(44,45)
51
52 j=180 #bar
53 listx = []
54 listeff = []
55 listdryness = []
56 for i in np.arange(25, 90, 0.25):
57 xsol, ysol = cycle_efficiency(0.1, j, 540, i)
58 listx.append(i)
59 listeff.append(xsol)
60 listdryness.append(ysol)
61
62 plt.plot(listx, listeff, 'black', linewidth=2.0)
63 m = max(listeff)
64 a = listeff.index(m)
65
66 font = {'family' : 'Times New Roman', 'size' : 14}
67 plt.rc('font', **font)
68
69 plt.plot(listx[a], m, 'X')
70 plt.text(listx[1], listeff[1], f'{round(float(j),1)} bar', ha='right', backgroundcolor='white')
71 print(f"When MS pressure = {round(float(j),2)} bar")
72 print(f"Maximum potential cycle efficiency = {round(float(max(listeff)),3)} %")
73 print(f"Maximum cycle efficiency occurs with a reheat pressure = {round(float(listx[a]),2)}
```

```

 bar")
74
75 plt.annotate('Point of Maximum efficiency', xy=(float(listx[a]), float(max(listeff))), xytext
 =(float(listx[a])+10, float(max(listeff))+0.1), arrowprops=dict(alpha=0.5, fc='r', ec='r',
 headwidth=10))
76
77 plt.savefig('Plot-06.png')

```

## B.6 Rankine reheat cycle expansion to 46 bar

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7 print('Rankine reheat cycle analysis – reheat pressure at 46 bar')
8
9 p1 = 0.1
10 s1 = steamTable.sL_p(p1)
11 T1 = steamTable.t_ps(p1, s1)
12 h1 = steamTable.hL_p(p1)
13 print('\nPoint 1')
14 print(f"P1: {round(float(p1),1)} bar")
15 print(f"T1: {round(float(T1),1)} degC")
16 print(f"H1: {round(float(h1),1)} kJ/kg")
17 print(f"S1: {round(float(s1),3)} kJ/kg K")
18
19 p2 = 180
20 s2 = s1
21
22 v = 1/steamTable.rhoL_p(p1)
23 w_p = v*(p2-p1)
24
25 print('\nPoint 2')
26 h2 = h1+w_p
27 print(f"H2: {round(float(h2),1)} kJ/kg")
28
29 T2 = steamTable.t_ph(p2, h2)
30 print(f"T2: {round(float(T2),1)} degC")
31
32 h2dash = steamTable.hL_p(p2)
33 s2dash = steamTable.sL_p(p2)
34 T2dash = steamTable.t_ph(p2, h2dash)
35 print('\nPoint 2dash')
36 print(f"T2dash: {round(float(T2dash),1)} degC")
37 print(f"P2dash: {round(float(p2),1)} bar")
38 print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
39 print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")
40
41 h3dash = steamTable.hV_p(p2)
42 s3dash = steamTable.sV_p(p2)
43 T3dash = T2dash
44 print('\nPoint 3dash')
45 print(f"T3dash: {round(float(T3dash),1)} degC")
46 print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
47 print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")
48
49 p3 = p2
50 T3 = 540
51 h3 = steamTable.h_pt(p3, T3)
52 s3 = steamTable.s_pt(p3, T3)
53 print('\nPoint 3')
54 print(f"T3: {round(float(T3),1)} degC")
55 print(f"P3: {round(float(p3),1)} bar")
56 print(f"H3: {round(float(h3),1)} kJ/kg")
57 print(f"S3: {round(float(s3),3)} kJ/kg K")
58
59
60 p4 = 46
61 print(f"Reheat Pressure: {round(float(p4),1)} bar")
62 s4 = s3
63 T4 = steamTable.t_ps(p4, s4)
64 h4 = steamTable.h_pt(p4, T4)
65 print('\nPoint 4')
66 print(f"T4: {round(float(T4),1)} degC")
67 print(f"P4: {round(float(p4),1)} bar")
68 print(f"H4: {round(float(h4),1)} kJ/kg")
69 print(f"S4: {round(float(s4),3)} kJ/kg K")
70
71 p5 = p4
72 T5 = T3
73 h5 = steamTable.h_pt(p5, T5)
74 s5 = steamTable.s_pt(p5, T5)
```

```

75 print('\nPoint 5')
76 print(f"T5: {round(float(T5),1)} degC")
77 print(f"p5: {round(float(p5),1)} bar")
78 print(f"H5: {round(float(h5),1)} kJ/kg")
79 print(f"S5: {round(float(s5),3)} kJ/kg K")
80
81 p6 = p1
82 s6 = s5
83 T6 = steamTable.t_ps(p6, s6)
84 x6 = steamTable.x_ps(p6, s6)
85 h6 = steamTable.h_px(p6, x6)
86 print('\nPoint 6')
87 print(f"T6: {round(float(T6),1)} degC")
88 print(f"p6: {round(float(p6),1)} bar")
89 print(f"H6: {round(float(h6),1)} kJ/kg")
90 print(f"S6: {round(float(s6),3)} kJ/kg K")
91 print(f"x6: {round(float(x6*100),1)} % dry")
92
93 print('\nSummary')
94 print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")
95
96 w_HP_t = h3-h4
97 print(f"Work generated by HP turbine: {round(float(w_HP_t),1)} kJ/kg")
98
99 w_LP_t = h5-h6
100 print(f"Work generated by LP turbine: {round(float(w_LP_t),1)} kJ/kg")
101 print(f"Total work output by turbine: {round(float(w_HP_t+w_LP_t),1)} kJ/kg")
102
103 q_H = (h3-h2)+(h5-h4)
104 print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")
105
106 q_L = h6-h1
107 print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")
108
109 eta_th = (w_HP_t+w_LP_t-w_p)/q_H*100
110 print(f"Thermal efficiency is: {round(float(eta_th),3)}%")
111
112 HRcycle = 3600*100/eta_th
113 print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")
114
115 font = {'family' : 'Times New Roman',
116 'size' : 22}
117
118 plt.figure(figsize=(15,10))
119 plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
120 plt.rc('font', **font)
121
122 plt.ylabel('Temperature (C)')
123 plt.xlabel('Entropy (s)')
124 plt.xlim(-2,10)
125 plt.ylim(0,600)
126
127 T = np.linspace(0, 373.945, 400) # range of temperatures
128 svap = [s for s in [steamTable.sL_t(t) for t in T]]
129 sliq = [s for s in [steamTable.sV_t(t) for t in T]]
130
131 plt.plot(svap, T, 'b-', linewidth=2.0)
132 plt.plot(sliq, T, 'r-', linewidth=2.0)
133
134 plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6,
 T1], 'black', linewidth=2.0)
135
136 plt.text(s1-.1,T1,f'(1)',
137 ha='right',backgroundcolor='white')
138 plt.text(s1-.1,T1+30,f'(2)',
139 ha='right',backgroundcolor='white')
140 plt.text(s2dash-.15,T2dash,f"(2)\"",
141 ha='right',backgroundcolor='white')
142 plt.text(s3dash-.1,T3dash-25,f"(3)\"",
143 ha='right',backgroundcolor='white')
144 plt.text(s3+.2,T3,f'(3)',
145 ha='left',backgroundcolor='white')
146 plt.text(s4,T4-25,f'(4)',
147 ha='right',backgroundcolor='white')
148 plt.text(s5+.2,T5,f'(5)',
149 ha='left',backgroundcolor='white')

```

```
150 plt.text(s6+.1,T6,f'(6)',
151 ha='left',backgroundcolor='white')
152
153 plt.savefig('Plot-07.png')
```

## B.7 Find reheat pressure at 180 bar main steam - real expansion

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7
8 def cycle_efficiency(p1, p2, T3, p4):
9
10 h1 = steamTable.hL_p(p1)
11 v = 1/steamTable.rhoL_p(p1)
12 w_p = v*(p2-p1)
13
14 h2 = h1+w_p
15
16 p3 = p2
17 h3 = steamTable.h_pt(p3, T3)
18 s3 = steamTable.s_pt(p3, T3)
19
20 s4 = s3
21 T4 = steamTable.t_ps(p4, s4)
22 h4 = steamTable.h_pt(p4, T4)
23
24 HPturbeff = 0.90 # HP turbine isentropic efficiency can be entered here (typically 0.85 -
25 0.95)
26 h4r = h3 - (HPturbeff * h3) + (HPturbeff * h4)
27
28 w_HPt = h3-h4r
29
30 p5 = p4
31 T5 = T3
32 h5 = steamTable.h_pt(p5, T5)
33 s5 = steamTable.s_pt(p5, T5)
34
35 p6 = p1
36 s6 = s5
37 x6 = steamTable.x_ps(p6, s6)
38 h6 = steamTable.h_px(p6, x6)
39
40 LPturbeff = 0.90 # IP/LP turbine isentropic efficiency can be entered here (typically 0.85
41 - 0.95)
42 h6r = h5 - (LPturbeff * h5) + (LPturbeff * h6)
43
44 w_LPt = h5-h6r
45 q_H = (h3-h2)+(h5-h4r)
46 eta_th = (w_HPt+w_LPt-w_p)/q_H*100
47
48 return [eta_th, x6*100]
49
50 font = {'family' : 'Times New Roman',
51 'size' : 22}
52
53 plt.figure(figsize=(15,10))
54 plt.title('Efficiency vs reheat pressure (main steam P = 180 bar)')
55 plt.rc('font', **font)
56
57 plt.xlabel('Reheat Pressure (bar)')
58 plt.ylabel('Efficiency (%)')
59 plt.xlim(15,85)
60 plt.ylim(40,41)
61
62 j=180 #bar
63 listx = []
64 listeff = []
65 listdryness = []
66 for i in np.arange(20, 80, 0.25):
67 xsol, ysol = cycle_efficiency(0.1, j, 540, i)
68 listx.append(i)
69 listeff.append(xsol)
70 listdryness.append(ysol)
71
72 plt.plot(listx, listeff, 'black', linewidth=2.0)
73 m = max(listeff)
74 a = listeff.index(m)
```

```

73 font = {'family' : 'Times New Roman', 'size' : 14}
74 plt.rc('font', **font)
75
76
77 plt.plot(listx[a], m, 'X')
78 plt.text(listx[1], listeff[1], f'{round(float(j),1)} bar', ha='right', backgroundColor='white'
79)
80 print(f"When MS pressure = {round(float(j),2)} bar")
81 print(f"Maximum potential cycle efficiency = {round(float(max(listeff)),3)} %")
82 print(f"Maximum cycle efficiency occurs with a reheat pressure = {round(float(listx[a]),2)}
83 bar")
84
85 plt.annotate('Point of Maximum efficiency', xy=(float(listx[a]), float(max(listeff))), xytext
86 =(float(listx[a])+10, float(max(listeff))+0.1), arrowprops=dict(alpha=0.5, fc='r', ec='r',
87 headwidth=10))
88
89 plt.savefig('Plot-08.png')

```

## B.8 Rankine reheat cycle expansion to 36.75 bar

```
1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7 print('Rankine reheat cycle analysis (non ideal)')
8
9 p1 = 0.1
10 s1 = steamTable.sL_p(p1)
11 T1 = steamTable.t_ps(p1, s1)
12 h1 = steamTable.hL_p(p1)
13 print('\nPoint 1')
14 print(f"T1: {round(float(T1),1)} degC")
15 print(f"P1: {round(float(p1),1)} bar")
16 print(f"H1: {round(float(h1),1)} kJ/kg")
17 print(f"S1: {round(float(s1),3)} kJ/kg K")
18
19 p2 = 180
20 s2 = s1
21
22 v = 1/steamTable.rhoL_p(p1)
23 w_p = v*(p2-p1)
24
25 print('\nPoint 2')
26 h2 = h1+w_p
27 print(f"H2: {round(float(h2),1)} kJ/kg")
28
29 T2 = steamTable.t_ph(p2, h2)
30 print(f"T2: {round(float(T2),1)} degC")
31
32 h2dash = steamTable.hL_p(p2)
33 s2dash = steamTable.sL_p(p2)
34 T2dash = steamTable.t_ph(p2, h2dash)
35 print('\nPoint 2dash')
36 print(f"T2dash: {round(float(T2dash),1)} degC")
37 print(f"P2dash: {round(float(p2),1)} bar")
38 print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
39 print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")
40
41 h3dash = steamTable.hV_p(p2)
42 s3dash = steamTable.sV_p(p2)
43 T3dash = T2dash
44 print('\nPoint 3dash')
45 print(f"T3dash: {round(float(T3dash),1)} degC")
46 print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
47 print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")
48
49 p3 = p2
50 T3 = 540
51 h3 = steamTable.h_pt(p3, T3)
52 s3 = steamTable.s_pt(p3, T3)
53 print('\nPoint 3')
54 print(f"T3: {round(float(T3),1)} degC")
55 print(f"P3: {round(float(p3),1)} bar")
56 print(f"H3: {round(float(h3),1)} kJ/kg")
57 print(f"S3: {round(float(s3),3)} kJ/kg K")
58
59 p4 = 36.75
60 print(f"Reheat Pressure: {round(float(p4),1)} bar")
61 s4 = s3
62
63 T4 = steamTable.t_ps(p4, s4)
64 h4 = steamTable.h_pt(p4, T4)
65
66 HPTurbEff = 0.90 # HP turbine isentropic efficiency can be entered here (typically 0.85 -
67 0.95)
68 h4r = h3 - (HPTurbEff * h3) + (HPTurbEff * h4)
69
70 s4r = steamTable.s_ph(p4, h4r)
71 T4r = steamTable.t_ps(p4, s4r)
72 print('\nPoint 4')
73 #print(f"T4ideal: {round(float(T4),1)} degC")
74 print(f"T4real: {round(float(T4r),1)} degC")
```



```

74 print(f"P4: {round(float(p4),1)} bar")
75 #print(f"H4ideal: {round(float(h4),1)} kJ/kg")
76 print(f"H4real: {round(float(h4r),1)} kJ/kg")
77 #print(f"S4ideal: {round(float(s4),3)} kJ/kg K")
78 print(f"S4real: {round(float(s4r),3)} kJ/kg K")
79
80 w_HPt = h3-h4r
81
82 p5 = p4
83 T5 = T3
84 h5 = steamTable.h_pt(p5, T5)
85 s5 = steamTable.s_pt(p5, T5)
86 print('\nPoint 5')
87 print(f"T5: {round(float(T5),1)} degC")
88 print(f"P5: {round(float(p5),1)} bar")
89 print(f"H5: {round(float(h5),1)} kJ/kg")
90 print(f"S5: {round(float(s5),3)} kJ/kg K")
91
92 p6 = p1
93 s6 = s5
94 T6 = steamTable.t_ps(p6, s6)
95 x6 = steamTable.x_ps(p6, s6)
96 h6 = steamTable.h_px(p6, x6)
97 print('\nPoint 6')
98 print(f"T6: {round(float(T6),1)} degC")
99 print(f"P6: {round(float(p6),1)} bar")
100
101 LPturbeff = 0.90 # IP/LP turbine isentropic efficiency can be entered here (typically 0.85 -
102 0.95)
103 h6r = h5 - (LPturbeff * h5) + (LPturbeff * h6)
104 #print(f"H6ideal: {round(float(h6),1)} kJ/kg")
105 print(f"H6real: {round(float(h6r),1)} kJ/kg")
106 s6r = steamTable.s_ph(p6, h6r)
107 x6r = steamTable.x_ps(p6, s6r)
108 #print(f"S6ideal: {round(float(s6),3)} kJ/kg K")
109 print(f"S6real: {round(float(s6r),3)} kJ/kg K")
110 #print(f"x6ideal: {round(float(x6),2)} ")
111 #print(f"x6real: {round(float(x6r),2)} ")
112 print(f"x6: {round(float(x6r*100),1)} % dry")
113
114
115
116 print('\nSummary')
117 print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")
118 print(f"Work generated by HP turbine: {round(float(w_HPt),1)} kJ/kg")
119
120 w_LPt = h5-h6r
121 print(f"Work generated by LP turbine: {round(float(w_LPt),1)} kJ/kg")
122 print(f"Total work output by turbine: {round(float(w_HPt+w_LPt),1)} kJ/kg")
123
124 q_H = (h3-h2)+(h5-h4r)
125 print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")
126
127 q_L = h6r-h1
128 print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")
129
130 eta_th = (w_HPt+w_LPt-w_p)/q_H*100
131 print(f"Thermal efficiency is: {round(float(eta_th),1)}%")
132
133 HRcycle = 3600*100/eta_th
134 print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")
135
136 font = {'family' : 'Times New Roman',
137 'size' : 22}
138
139 plt.figure(figsize=(15,10))
140 plt.title('T-s Diagram - Rankine Reheat Cycle (non ideal)')
141 plt.rc('font', **font)
142
143 plt.ylabel('Temperature (C)')
144 plt.xlabel('Entropy (s)')
145 plt.xlim(-2,10)
146 plt.ylim(0,600)
147
148 T = np.linspace(0, 373.945, 400) # range of temperatures

```

```

149 svap = [s for s in [steamTable.sL_t(t) for t in T]]
150 sliq = [s for s in [steamTable.sV_t(t) for t in T]]
151
152 plt.plot(svap, T, 'b-', linewidth=2.0)
153 plt.plot(sliq, T, 'r-', linewidth=2.0)
154
155 plt.plot([s1, s2, s2dash, s3dash, s3, s4r, s5, s6r, s1], [T1, T2, T2dash, T3dash, T3, T4r, T5,
 T6, T1], 'black', linewidth=2.0)
156
157 plt.text(s1-.1, T1, f'(1)',
158 ha='right', backgroundcolor='white')
159 plt.text(s1-.1, T1+30, f'(2)',
160 ha='right', backgroundcolor='white')
161 plt.text(s2dash-.15, T2dash, f"(2)",
162 ha='right', backgroundcolor='white')
163 plt.text(s3dash-.1, T3dash-25, f"(3)",
164 ha='right', backgroundcolor='white')
165 plt.text(s3+.2, T3, f'(3)',
166 ha='left', backgroundcolor='white')
167 plt.text(s4, T4r-25, f'(4)',
168 ha='right', backgroundcolor='white')
169 plt.text(s5+.2, T5, f'(5)',
170 ha='left', backgroundcolor='white')
171 plt.text(s6r+.1, T6, f'(6)',
172 ha='left', backgroundcolor='white')
173
174 plt.savefig('Plot-9.png')

```

## B.9 Find reheat pressure at various main steam pressures

```

1 import matplotlib.pyplot as plt
2 import numpy as np
3 from pyXSteam.XSteam import XSteam
4
5 steamTable = XSteam(XSteam.UNIT.SYSTEM.MKS)
6
7
8 def cycle_efficiency(p1, p2, T3, p4):
9 #print('Rankine reheat cycle analysis')
10
11 #p1 = 0.1
12 s1 = steamTable.sL_p(p1)
13 T1 = steamTable.t_ps(p1, s1)
14 h1 = steamTable.hL_p(p1)
15
16 #p2 = 180
17 s2 = s1
18
19 v = 1/steamTable.rhoL_p(p1)
20 w_p = v*(p2-p1)
21
22 h2 = h1+w_p
23
24 T2 = steamTable.t_ph(p2, h2)
25
26 h2dash = steamTable.hL_p(p2)
27 s2dash = steamTable.sL_p(p2)
28 T2dash = steamTable.t_ph(p2, h2dash)
29
30 h3dash = steamTable.hV_p(p2)
31 s3dash = steamTable.sV_p(p2)
32 T3dash = T2dash
33
34 p3 = p2
35 #T3 = 540
36 h3 = steamTable.h_pt(p3, T3)
37 s3 = steamTable.s_pt(p3, T3)
38
39 #p4 = 25
40 s4 = s3
41
42 T4 = steamTable.t_ps(p4, s4)
43 h4 = steamTable.h_pt(p4, T4)
44
45 HPturbeff = 0.90 # HP turbine isentropic efficiency can be entered here (typically 0.85 -
46 0.95)
47 h4r = h3 - (HPturbeff * h3) + (HPturbeff * h4)
48
49 s4r = steamTable.s_ph(p4, h4r)
50 T4r = steamTable.t_ps(p4, s4r)
51
52 w_HPt = h3-h4r
53
54 p5 = p4
55 T5 = T3
56 h5 = steamTable.h_pt(p5, T5)
57 s5 = steamTable.s_pt(p5, T5)
58
59 p6 = p1
60 s6 = s5
61 T6 = steamTable.t_ps(p6, s6)
62 x6 = steamTable.x_ps(p6, s6)
63 h6 = steamTable.h_px(p6, x6)
64
65 LPturbeff = 0.90 # IP/LP turbine isentropic efficiency can be entered here (typically 0.85
66 - 0.95)
67 h6r = h5 - (LPturbeff * h5) + (LPturbeff * h6)
68 s6r = steamTable.s_ph(p6, h6r)
69 x6r = steamTable.x_ps(p6, s6r)
70
71 w_LPt = h5-h6r
72 q_H = (h3-h2)+(h5-h4r)
73 q_L = h6r-h1
74 eta_th = (w_HPt+w_LPt-w_p)/q_H*100

```

```

73 #HRcycle = 3600*100/eta_th
74
75 return [eta_th, x6*100]
76
77
78 font = {'family' : 'Times New Roman',
79 'size' : 22}
80
81 plt.figure(figsize=(15,10))
82 plt.title('Efficiency vs reheat pressure (Real cycle)')
83 plt.rc('font', **font)
84
85 plt.xlabel('Reheat Pressure (bar)')
86 plt.ylabel('Efficiency (%)')
87 plt.xlim(15,65)
88 plt.ylim(39.8,41)
89
90 for j in np.arange(150, 190, 5):
91 listx = []
92 listeff = []
93 listdryness = []
94 for i in np.arange(20, 80, 0.25):
95 xsol, ysol = cycle_efficiency(0.1, j, 540, i)
96 listx.append(i)
97 listeff.append(xsol)
98 listdryness.append(ysol)
99
100 plt.plot(listx, listeff, 'black', linewidth=2.0)
101 m = max(listeff)
102 a = listeff.index(m)
103
104 plt.plot(listx[a], m, 'X')
105 plt.text(listx[a], listeff[a], f'{round(float(j),1)} bar', ha='right', backgroundcolor='
white')
106 print(f"When MS pressure = {round(float(j),2)} bar")
107 print(f"Maximum potential cycle efficiency = {round(float(max(listeff)),3)} %")
108 print(f"Maximum cycle efficiency occurs with a reheat pressure = {round(float(listx[a]),
2)} bar")
109 print(f"ratio of MS vs RH pressure = {round(float(j/m),2)} ")
110
111 plt.savefig('Plot-10.png')

```

## C Figures and Tables

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