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.

Contents

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]

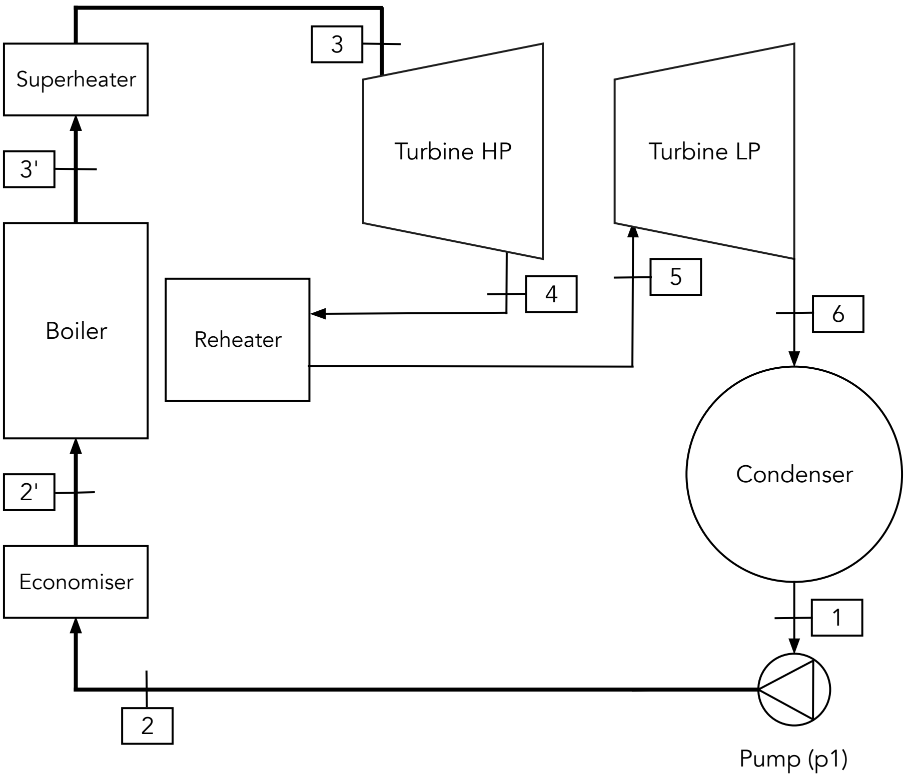

Figure 1: Components of a Rankine reheat cycle

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).

[1]The 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.

1.1 Finding the most efficient reheat pressure

So using a process of elimination, let us look at various possible reheat steam pressures and compare the results so as to zero in on the ideal pressure.

1.1.1 Expansion of main steam down to saturation line

In our quest to select the ideal reheat pressure when designing a Rankine reheat steam cycle our first option to investigate is expanding the steam in the HP turbine from 180 bar down to the saturation pressure before reheating the steam in the boiler.

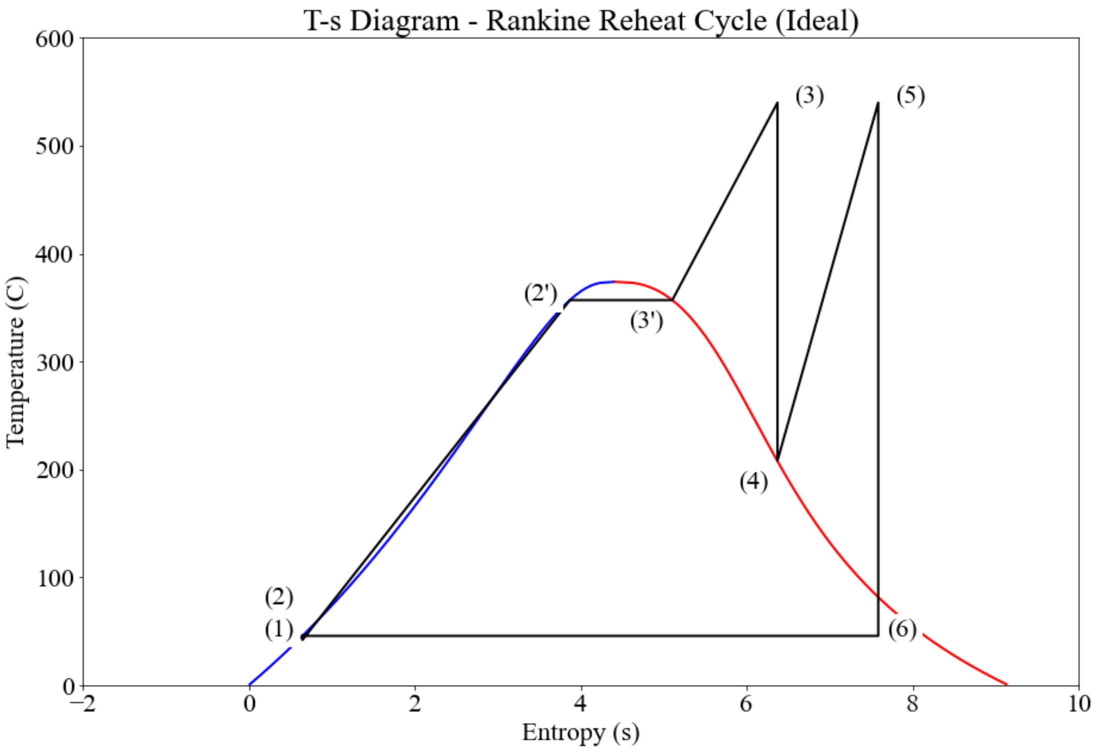

Figure 2: Ts plot of Rankine reheat cycle with HP turbine expansion down to saturation line

The Python code to generate the plot above and efficiency calculations result below can be found in appendix B.1

```
Rankine reheat cycle analysis – main steam expansion down to saturation line

Reheat Pressure: 18.3 bar

Point 4
T4: 208.3 degC
P4: 18.3 bar
H4: 2797.4 kJ/kg
S4: 6.373 kJ/kg K

Point 5
T5: 540.0 degC
p5: 18.3 bar
H5: 3558.3 kJ/kg
S5: 7.587 kJ/kg K

Point 6
T6: 45.8 degC
p6: 0.1 bar
H6: 2404.8 kJ/kg
S6: 7.587 kJ/kg K
x6: 92.5 % dry

Summary
```

```
Work required by pump: 0.2 kJ/kg
Work generated by HP turbine: 592.2 kJ/kg
Work generated by LP turbine: 1153.5 kJ/kg
Total work output by turbine: 1745.6 kJ/kg
Heat input by boiler: 3958.4 kJ/kg
Heat rejected by the condenser: 2213.0 kJ/kg
Thermal efficiency is: 44.095%
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.

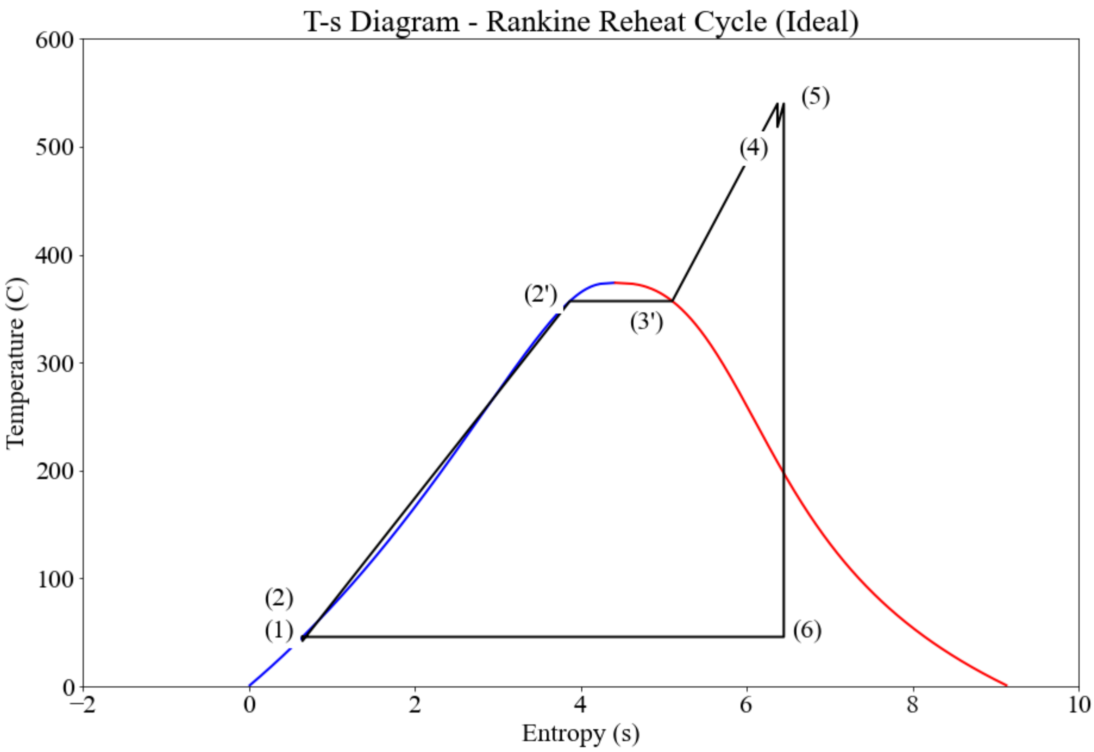

Figure 3: Ts plot of Rankine reheat cycle with HP turbine expansion down to 160 bar

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

```
Rankine reheat cycle analysis - reheat pressure at 160 bar

Reheat Pressure: 160.0 bar

Point 4
T4: 518.5 degC
P4: 160.0 bar
H4: 3351.2 kJ/kg
S4: 6.373 kJ/kg K

Point 5
T5: 540.0 degC
p5: 160.0 bar
H5: 3412.1 kJ/kg
S5: 6.449 kJ/kg K

Point 6
T6: 45.8 degC
p6: 0.1 bar
H6: 2041.8 kJ/kg
S6: 6.449 kJ/kg K
x6: 77.3 % dry

Summary
Work required by pump: 0.2 kJ/kg
Work generated by HP turbine: 38.4 kJ/kg
Work generated by LP turbine: 1370.3 kJ/kg
Total work output by turbine: 1408.7 kJ/kg
Heat input by boiler: 3258.5 kJ/kg
Heat rejected by the condenser: 1850.0 kJ/kg
Thermal efficiency is: 43.225%
```

```
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.

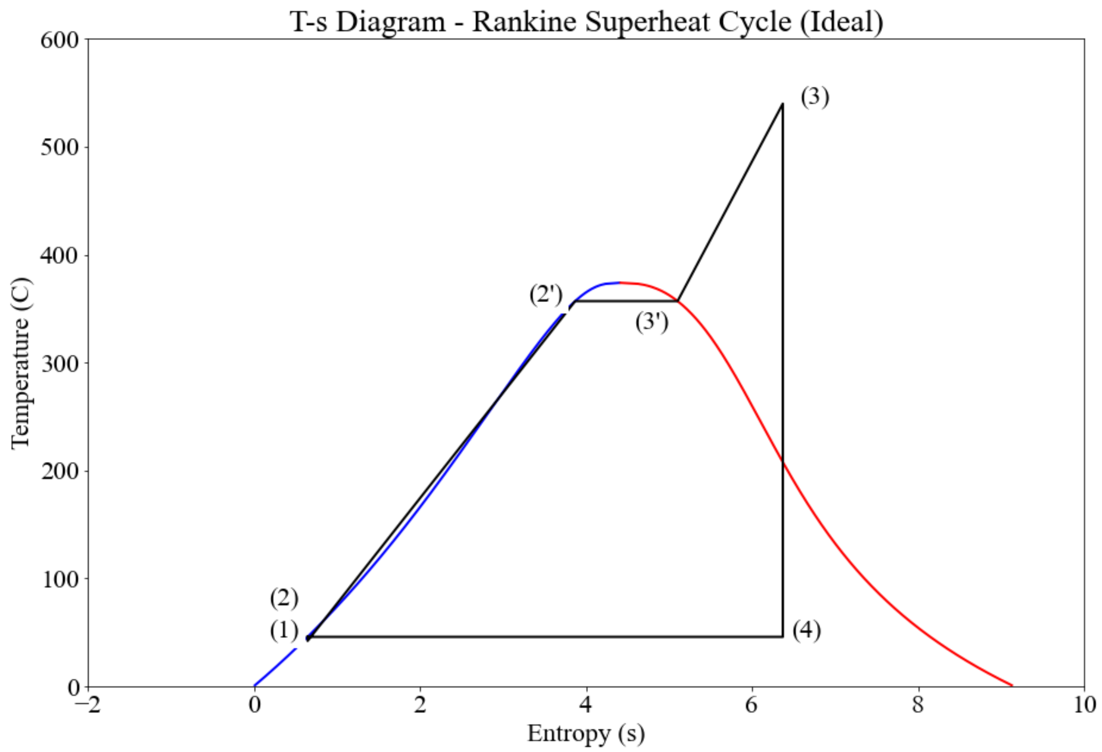

Figure 4: Ts plot of Rankine superheat cycle

```
Rankine superheat cycle analysis − for comparison

Point 1
p1: 0.1 bar
T1: 45.8 degC
H1: 191.8 kJ/kg
S1: 0.649 kJ/kg K

Point 2
H2: 192.0 kJ/kg
T2: 42.1 degC

Point 2 dash
T2dash: 357.0 degC
p2dash: 180.0 bar
H2dash: 1732.0 kJ/kg
S2dash: 3.872 kJ/kg K

Point 3dash
T3dash: 357.0 degC
H3dash: 2509.5 kJ/kg
S3dash: 5.106 kJ/kg K

Point 3
T3: 540.0 degC
p3: 180.0 bar
H3: 3389.5 kJ/kg
```

```
S3: 6.373 kJ/kg K

Point 4
T4: 45.8 degC
p4: 0.1 bar
H4: 2017.6 kJ/kg
S4: 6.373 kJ/kg K
x4: 76.3 % dry

Summary
Work required by pump: 0.2 kJ/kg
Work generated by turbine: 1372.0 kJ/kg
Heat input by boiler: 3197.5 kJ/kg
Heat rejected by the condenser: 1825.8 kJ/kg
Thermal efficiency is: 42.901%
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.

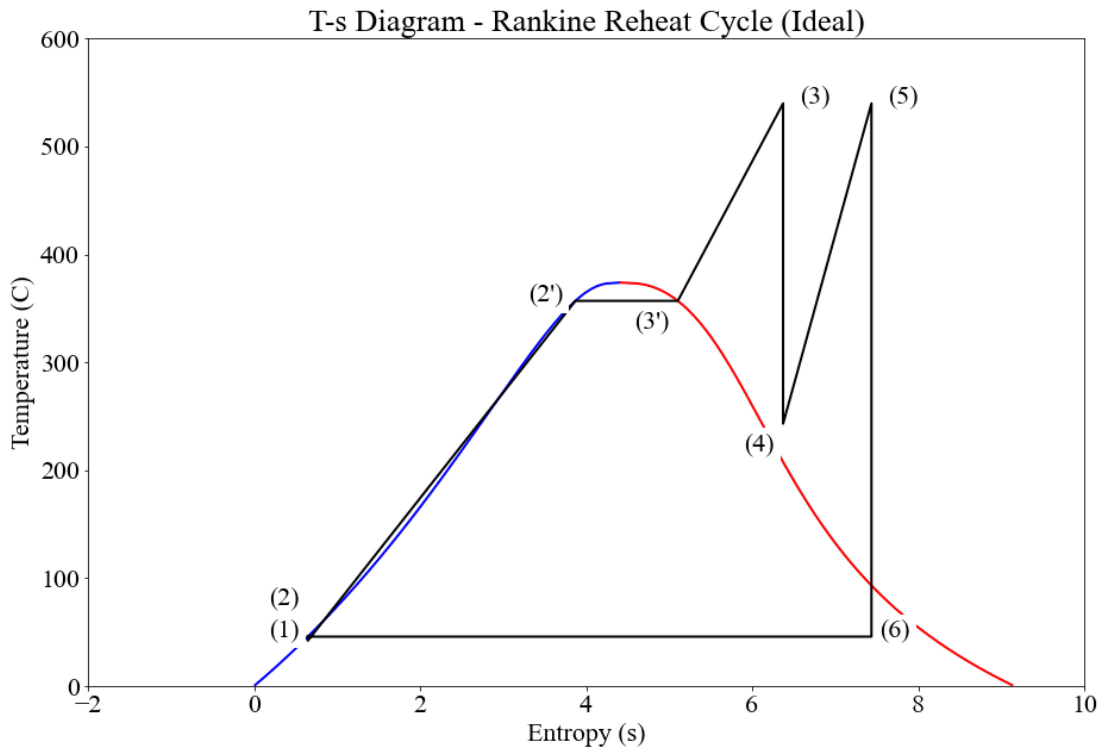

Figure 5: Ts plot of Rankine reheat cycle with HP turbine expansion down to 25 bar

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

```
Rankine reheat cycle analysis - reheat pressure at 25 bar

Reheat Pressure: 25.0 bar

Point 4
T4: 243.2 degC
P4: 25.0 bar
H4: 2861.5 kJ/kg
S4: 6.373 kJ/kg K

Point 5
T5: 540.0 degC
p5: 25.0 bar
H5: 3551.9 kJ/kg
S5: 7.438 kJ/kg K

Point 6
T6: 45.8 degC
p6: 0.1 bar
H6: 2357.0 kJ/kg
S6: 7.438 kJ/kg K
x6: 90.5 % dry

Summary
Work required by pump: 0.2 kJ/kg
Work generated by HP turbine: 528.0 kJ/kg
Work generated by LP turbine: 1194.8 kJ/kg
Total work output by turbine: 1722.8 kJ/kg
Heat input by boiler: 3887.9 kJ/kg
Heat rejected by the condenser: 2165.2 kJ/kg
Thermal efficiency is: 44.308%
```

```
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.

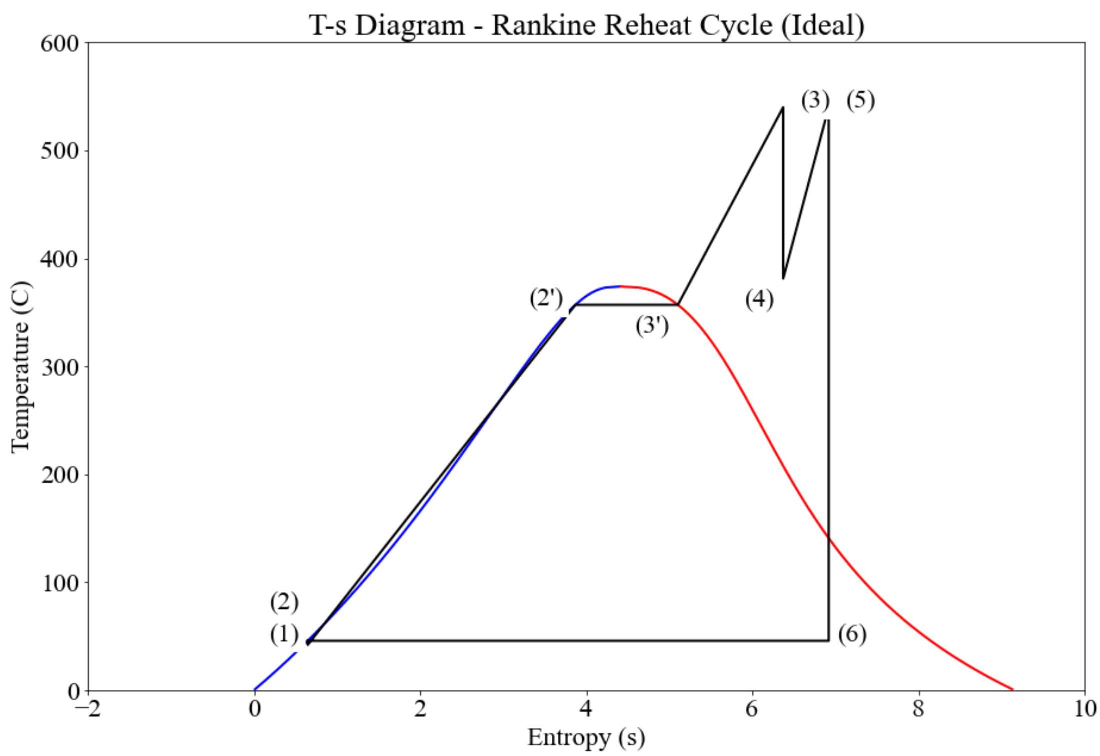

Figure 6: Ts plot of Rankine reheat cycle with HP turbine expansion down to 70 bar

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

```
Rankine reheat cycle analysis — reheat pressure at 70 bar

Reheat Pressure: 70.0 bar

Point 4
T4: 381.3 degC
P4: 70.0 bar
H4: 3108.2 kJ/kg
S4: 6.373 kJ/kg K

Point 5
T5: 540.0 degC
p5: 70.0 bar
H5: 3507.6 kJ/kg
S5: 6.921 kJ/kg K

Point 6
T6: 45.8 degC
p6: 0.1 bar
H6: 2192.3 kJ/kg
S6: 6.921 kJ/kg K
x6: 83.6 % dry

Summary
Work required by pump: 0.2 kJ/kg
Work generated by HP turbine: 281.3 kJ/kg
Work generated by LP turbine: 1315.3 kJ/kg
Total work output by turbine: 1596.6 kJ/kg
Heat input by boiler: 3597.0 kJ/kg
Heat rejected by the condenser: 2000.5 kJ/kg
Thermal efficiency is: 44.383%
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.

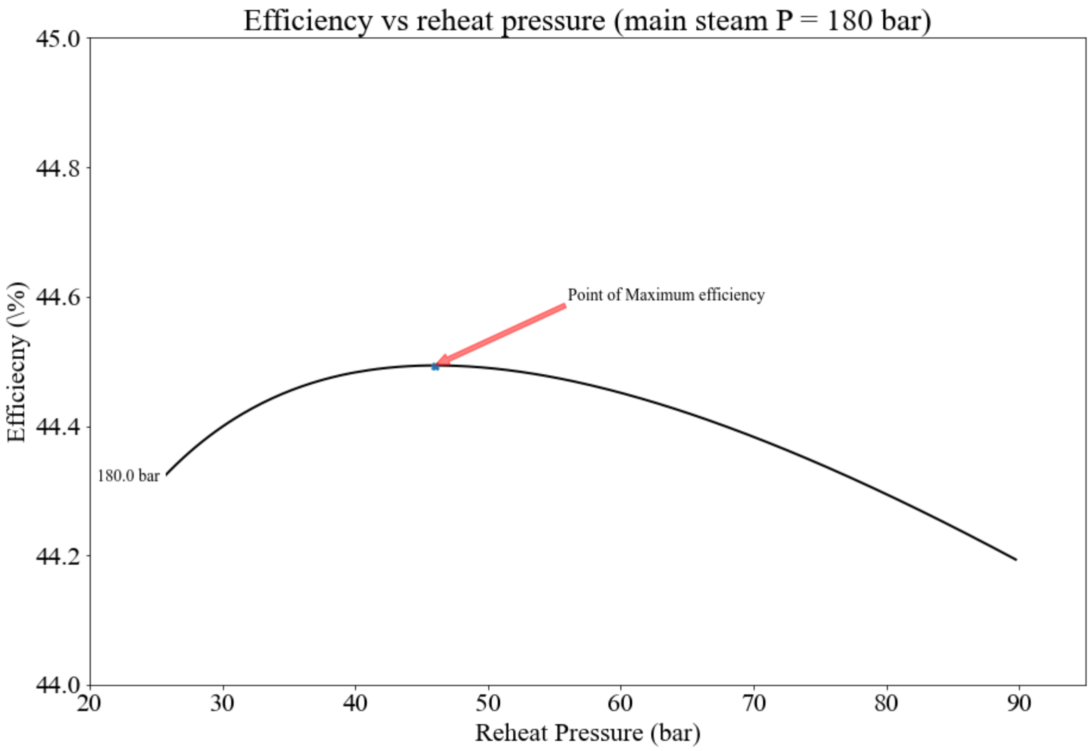

Figure 7: Plot of efficiency vs reheat pressure for a reheat cycle with 180 bar main steam pressure.

```
When MS pressure =  180.0 bar
Maximum potential cycle efficiency =  44.494 %
Maximum cycle efficiency occurs with a reheat pressure =  46.0 bar
 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.

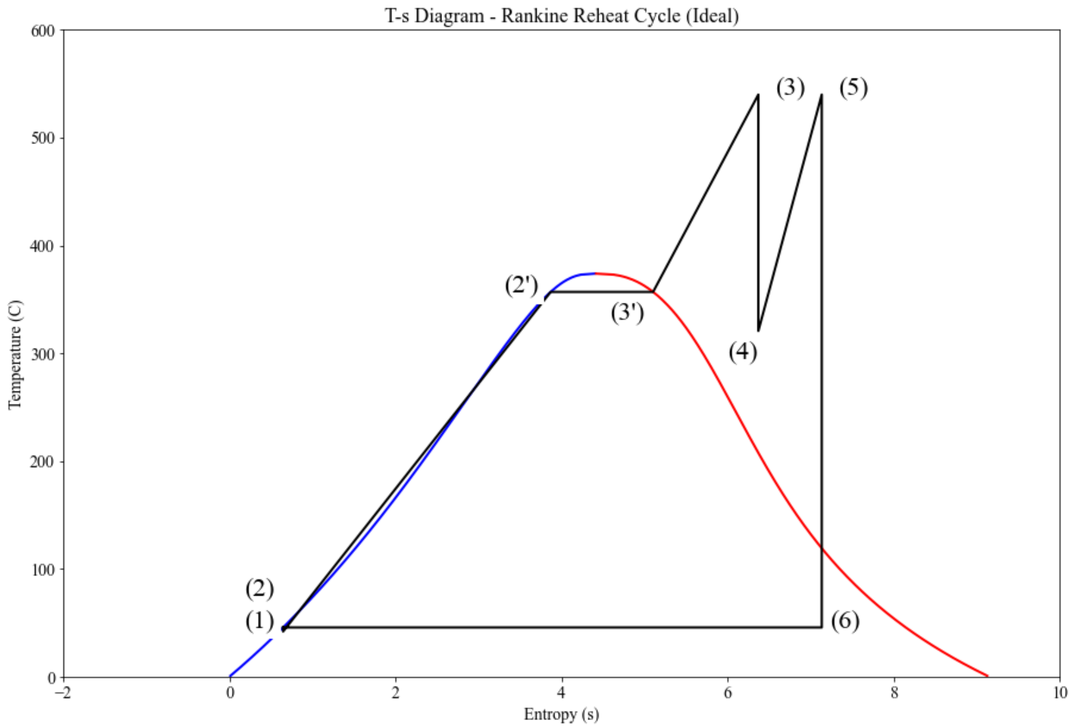

Figure 8: Ts plot of Rankine reheat cycle with HP turbine expansion down to 46 bar

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

```
Rankine reheat cycle analysis - reheat pressure at 46 bar

Reheat Pressure: 46.0 bar

Point 4
T4: 320.8 degC
P4: 46.0 bar
H4: 3000.7 kJ/kg
S4: 6.373 kJ/kg K

Point 5
T5: 540.0 degC
p5: 46.0 bar
H5: 3531.5 kJ/kg
S5: 7.137 kJ/kg K

Point 6
T6: 45.8 degC
p6: 0.1 bar
H6: 2261.2 kJ/kg
S6: 7.137 kJ/kg K
x6: 86.5 % dry

Summary
Work required by pump: 0.2 kJ/kg
Work generated by HP turbine: 388.8 kJ/kg
Work generated by LP turbine: 1270.2 kJ/kg
Total work output by turbine: 1659.0 kJ/kg
Heat input by boiler: 3728.3 kJ/kg
Heat rejected by the condenser: 2069.4 kJ/kg
Thermal efficiency is: 44.494%
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 mositure 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.

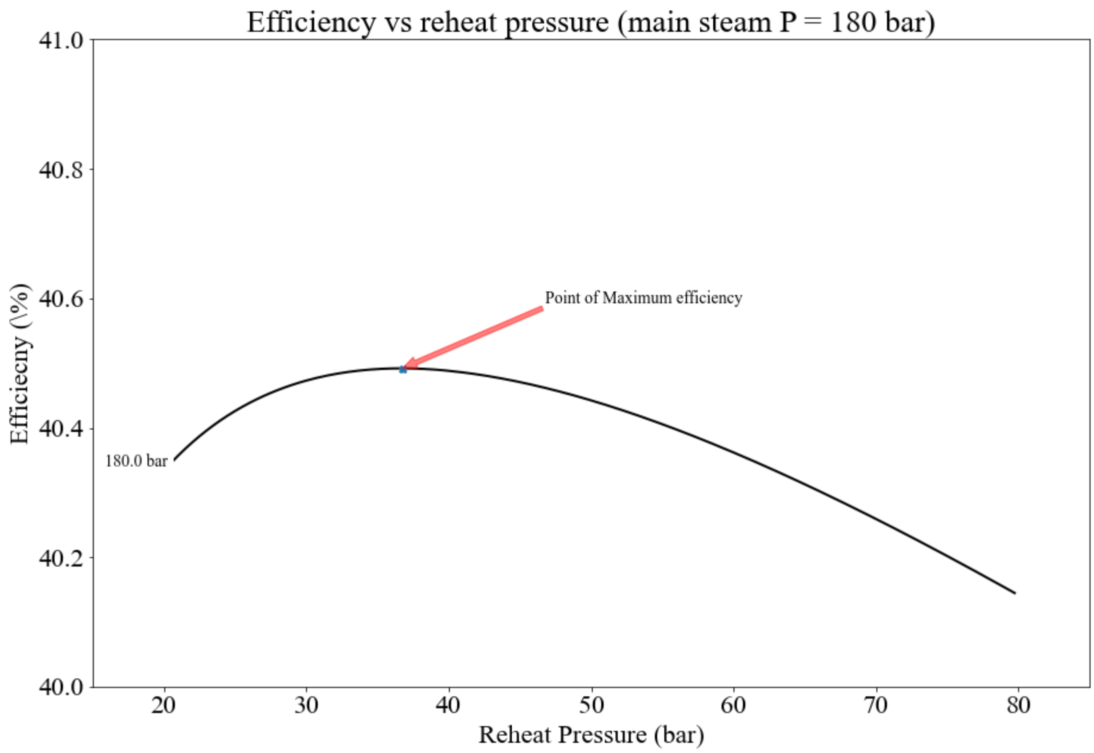

Figure 9: Plot of efficiency vs reheat pressure for a reheat cycle with 180 bar main steam pressure.

```
When MS pressure =  180.0 bar
Maximum potential cycle efficiency =  40.492 %
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.

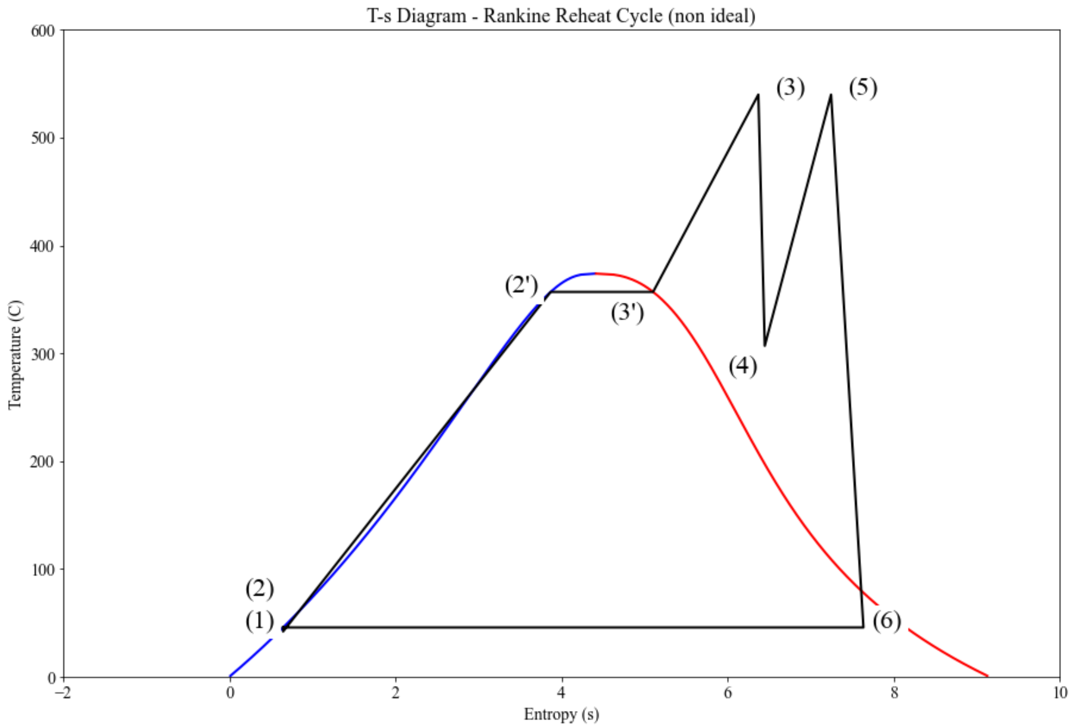

Figure 10: Ts plot of Rankine reheat cycle with HP turbine expansion down to 36.75 bar

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

```
Reheat Pressure: 36.8 bar

Point 4
T4real: 307.0 degC
P4: 36.8 bar
H4real: 2991.5 kJ/kg
S4real: 6.451 kJ/kg K

Point 5
T5: 540.0 degC
P5: 36.8 bar
H5: 3540.5 kJ/kg
S5: 7.249 kJ/kg K

Point 6
T6: 45.8 degC
P6: 0.1 bar
H6real: 2421.3 kJ/kg
S6real: 7.639 kJ/kg K
x6: 93.2 % dry

Summary
Work required by pump: 0.2 kJ/kg
Work generated by HP turbine: 398.1 kJ/kg
Work generated by LP turbine: 1119.2 kJ/kg
Total work output by turbine: 1517.2 kJ/kg
Heat input by boiler: 3746.6 kJ/kg
Heat rejected by the condenser: 2229.5 kJ/kg
Thermal efficiency is: 40.5%
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.

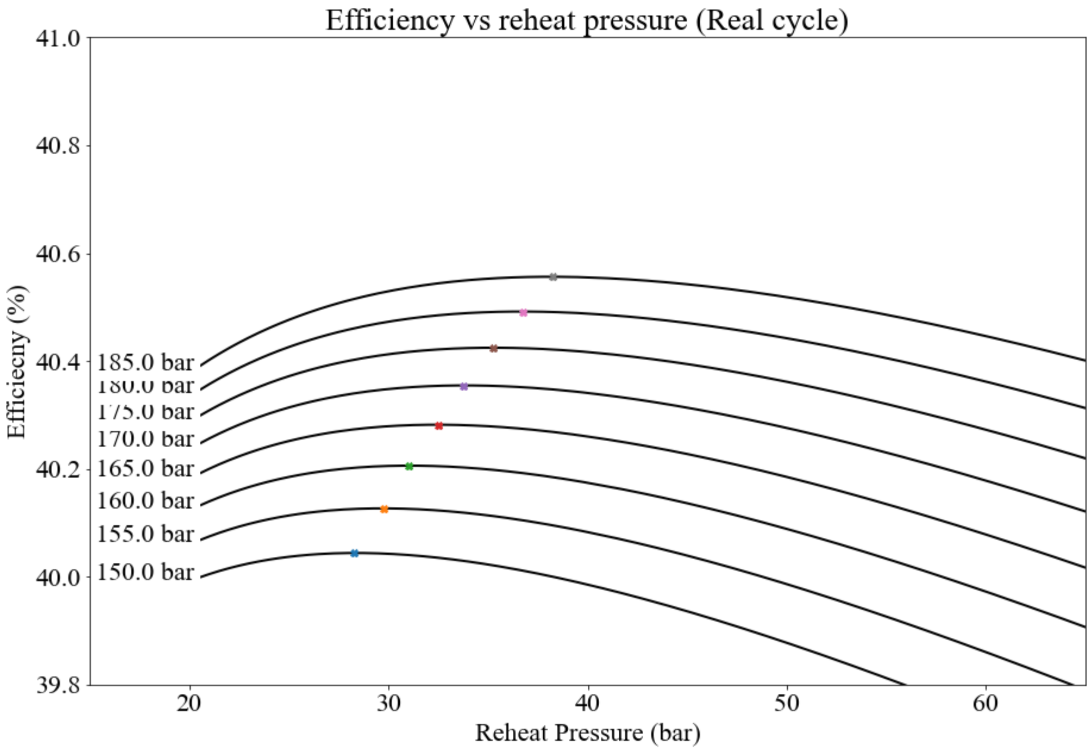

Figure 11: Plot of efficiency vs reheat pressure for a reheat cycle at various main steam pressures.

Table 1: Ideal Reheat Pressure vs Main Steam Pressure

Main Steam Pressure (bar)	**Highest Efficiency Achieved** (%)	**Reheat Pressure** (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 $\longrightarrow$ https://matplotlib.org
- Numpy v1.18.5 $\longrightarrow$ https://numpy.org
- pyXSteam v0.4.4 $\longrightarrow$ https://pypi.org/project/pyXSteam

B Code printouts

B.1 Rankine reheat cycle expansion to saturation line

```python
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)

print('Rankine reheat cycle analysis - main steam expansion doen to saturation line')

p1 = 0.1
s1 = steamTable.sL_p(p1)
T1 = steamTable.t_ps(p1, s1)
h1 = steamTable.hL_p(p1)
print('\nPoint 1')
print(f"P1: {round(float(p1),1)} bar")
print(f"T1: {round(float(T1),1)} degC")
print(f"H1: {round(float(h1),1)} kJ/kg")
print(f"S1: {round(float(s1),3)} kJ/kg K")

p2 = 180
s2 = s1

v = 1/steamTable.rhoL_p(p1)
w_p = v*(p2-p1)

print('\nPoint 2')
h2 = h1+w_p
print(f"H2: {round(float(h2),1)} kJ/kg")

T2 = steamTable.t_ph(p2, h2)
print(f"T2: {round(float(T2),1)} degC")

h2dash = steamTable.hL_p(p2)
s2dash = steamTable.sL_p(p2)
T2dash = steamTable.t_ph(p2, h2dash)
print('\nPoint 2dash')
print(f"T2dash: {round(float(T2dash),1)} degC")
print(f"P2dash: {round(float(p2),1)} bar")
print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")

h3dash = steamTable.hV_p(p2)
s3dash = steamTable.sV_p(p2)
T3dash = T2dash
print('\nPoint 3dash')
print(f"T3dash: {round(float(T3dash),1)} degC")
print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")

p3 = p2
T3 = 540
h3 = steamTable.h_pt(p3, T3)
s3 = steamTable.s_pt(p3, T3)
print('\nPoint 3')
print(f"T3: {round(float(T3),1)} degC")
print(f"P3: {round(float(p3),1)} bar")
print(f"H3: {round(float(h3),1)} kJ/kg")
print(f"S3: {round(float(s3),3)} kJ/kg K")

t4=steamTable.tsat_s(s3)
print(f"t4sat: {round(float(t4),1)} degC")
p4=steamTable.psat_s(s3)+0.1
print(f"P4sat: {round(float(p4),1)} bar")

print(f"Reheat Pressure: {round(float(p4),1)} bar")
s4 = s3
T4 = steamTable.t_ps(p4, s4)
h4 = steamTable.h_pt(p4, T4)
print('\nPoint 4')
print(f"T4: {round(float(T4),1)} degC")
print(f"P4: {round(float(p4),1)} bar")
print(f"H4: {round(float(h4),1)} kJ/kg")
print(f"S4: {round(float(s4),3)} kJ/kg K")
```

```python

p5 = p4
T5 = T3
h5 = steamTable.h_pt(p5, T5)
s5 = steamTable.s_pt(p5, T5)
print('\nPoint 5')
print(f"T5: {round(float(T5),1)} degC")
print(f"p5: {round(float(p5),1)} bar")
print(f"H5: {round(float(h5),1)} kJ/kg")
print(f"S5: {round(float(s5),3)} kJ/kg K")

p6 = p1
s6 = s5
T6 = steamTable.t_ps(p6, s6)
x6 = steamTable.x_ps(p6, s6)
h6 = steamTable.h_px(p6, x6)
print('\nPoint 6')
print(f"T6: {round(float(T6),1)} degC")
print(f"p6: {round(float(p6),1)} bar")
print(f"H6: {round(float(h6),1)} kJ/kg")
print(f"S6: {round(float(s6),3)} kJ/kg K")
print(f"x6: {round(float(x6*100),1)} % dry")

print('\nSummary')
print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")

w_HPt = h3-h4
print(f"Work generated by HP turbine: {round(float(w_HPt),1)} kJ/kg")

w_LPt = h5-h6
print(f"Work generated by LP turbine: {round(float(w_LPt),1)} kJ/kg")
print(f"Total work output by turbine: {round(float(w_HPt+w_LPt),1)} kJ/kg")

q_H = (h3-h2)+(h5-h4)
print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")

q_L = h6-h1
print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")

eta_th = (w_HPt+w_LPt-w_p)/q_H*100
print(f"Thermal efficiency is: {round(float(eta_th),3)}%")

HRcycle = 3600*100/eta_th
print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
plt.rc('font', **font)

plt.ylabel('Temperature (C)')
plt.xlabel('Entropy (s)')
plt.xlim(-2,10)
plt.ylim(0,600)

T = np.linspace(0, 373.945, 400) # range of temperatures
svap = [s for s in [steamTable.sL_t(t) for t in T]]
sliq = [s for s in [steamTable.sV_t(t) for t in T]]

plt.plot(svap, T, 'b-', linewidth=2.0)
plt.plot(sliq, T, 'r-', linewidth=2.0)

plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6, T1], 'black', linewidth=2.0)

plt.text(s1-.1,T1,f'(1)',
    ha='right',backgroundcolor='white')
plt.text(s1-.1,T1+30,f'(2)',
    ha='right',backgroundcolor='white')
plt.text(s2dash-.15,T2dash,f"(2')",
    ha='right',backgroundcolor='white')
plt.text(s3dash-.1,T3dash-25,f"(3')",
    ha='right',backgroundcolor='white')
plt.text(s3+.2,T3,f'(3)',
```

```
     ha='left',backgroundcolor='white')
plt.text(s4-.1,T4-25,f'(4)',
     ha='right',backgroundcolor='white')
plt.text(s5+.2,T5,f'(5)',
     ha='left',backgroundcolor='white')
plt.text(s6+.1,T6,f'(6)',
     ha='left',backgroundcolor='white')

plt.savefig('Plot-01.png')
```

B.2 Rankine reheat cycle expansion to 160 bar

```python
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)

print('Rankine reheat cycle analysis - reheat pressure at 160 bar')

p1 = 0.1
s1 = steamTable.sL_p(p1)
T1 = steamTable.t_ps(p1, s1)
h1 = steamTable.hL_p(p1)
print('\nPoint 1')
print(f"P1: {round(float(p1),1)} bar")
print(f"T1: {round(float(T1),1)} degC")
print(f"H1: {round(float(h1),1)} kJ/kg")
print(f"S1: {round(float(s1),3)} kJ/kg K")

p2 = 180
s2 = s1

v = 1/steamTable.rhoL_p(p1)
w_p = v*(p2-p1)

print('\nPoint 2')
h2 = h1+w_p
print(f"H2: {round(float(h2),1)} kJ/kg")

T2 = steamTable.t_ph(p2, h2)
print(f"T2: {round(float(T2),1)} degC")

h2dash = steamTable.hL_p(p2)
s2dash = steamTable.sL_p(p2)
T2dash = steamTable.t_ph(p2, h2dash)
print('\nPoint 2dash')
print(f"T2dash: {round(float(T2dash),1)} degC")
print(f"P2dash: {round(float(p2),1)} bar")
print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")

h3dash = steamTable.hV_p(p2)
s3dash = steamTable.sV_p(p2)
T3dash = T2dash
print('\nPoint 3dash')
print(f"T3dash: {round(float(T3dash),1)} degC")
print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")

p3 = p2
T3 = 540
h3 = steamTable.h_pt(p3, T3)
s3 = steamTable.s_pt(p3, T3)
print('\nPoint 3')
print(f"T3: {round(float(T3),1)} degC")
print(f"P3: {round(float(p3),1)} bar")
print(f"H3: {round(float(h3),1)} kJ/kg")
print(f"S3: {round(float(s3),3)} kJ/kg K")

p4 = 160
print(f"Reheat Pressure: {round(float(p4),1)} bar")
s4 = s3
T4 = steamTable.t_ps(p4, s4)
h4 = steamTable.h_pt(p4, T4)
print('\nPoint 4')
print(f"T4: {round(float(T4),1)} degC")
print(f"P4: {round(float(p4),1)} bar")
print(f"H4: {round(float(h4),1)} kJ/kg")
print(f"S4: {round(float(s4),3)} kJ/kg K")

p5 = p4
T5 = T3
h5 = steamTable.h_pt(p5, T5)
s5 = steamTable.s_pt(p5, T5)
print('\nPoint 5')
```

```
print(f"T5: {round(float(T5),1)} degC")
print(f"p5: {round(float(p5),1)} bar")
print(f"H5: {round(float(h5),1)} kJ/kg")
print(f"S5: {round(float(s5),3)} kJ/kg K")

p6 = p1
s6 = s5
T6 = steamTable.t_ps(p6, s6)
x6 = steamTable.x_ps(p6, s6)
h6 = steamTable.h_px(p6, x6)
print('\nPoint 6')
print(f"T6: {round(float(T6),1)} degC")
print(f"p6: {round(float(p6),1)} bar")
print(f"H6: {round(float(h6),1)} kJ/kg")
print(f"S6: {round(float(s6),3)} kJ/kg K")
print(f"x6: {round(float(x6*100),1)} % dry")

print('\nSummary')
print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")

w_HPt = h3-h4
print(f"Work generated by HP turbine: {round(float(w_HPt),1)} kJ/kg")

w_LPt = h5-h6
print(f"Work generated by LP turbine: {round(float(w_LPt),1)} kJ/kg")
print(f"Total work output by turbine: {round(float(w_HPt+w_LPt),1)} kJ/kg")

q_H = (h3-h2)+(h5-h4)
print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")

q_L = h6-h1
print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")

eta_th = (w_HPt+w_LPt-w_p)/q_H*100
print(f"Thermal efficiency is: {round(float(eta_th),3)}%")

HRcycle = 3600*100/eta_th
print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
plt.rc('font', **font)

plt.ylabel('Temperature (C)')
plt.xlabel('Entropy (s)')
plt.xlim(-2,10)
plt.ylim(0,600)

T = np.linspace(0, 373.945, 400) # range of temperatures
svap = [s for s in [steamTable.sL_t(t) for t in T]]
sliq = [s for s in [steamTable.sV_t(t) for t in T]]

plt.plot(svap, T, 'b-', linewidth=2.0)
plt.plot(sliq, T, 'r-', linewidth=2.0)

plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6, T1], 'black', linewidth=2.0)

plt.text(s1-.1,T1,f'(1)',
    ha='right',backgroundcolor='white')
plt.text(s1-.1,T1+30,f'(2)',
    ha='right',backgroundcolor='white')
plt.text(s2dash-.15,T2dash,f"(2')",
    ha='right',backgroundcolor='white')
plt.text(s3dash-.1,T3dash-25,f"(3')",
    ha='right',backgroundcolor='white')
plt.text(s3+.2,T3,f'(3)',
    ha='left',backgroundcolor='white')
plt.text(s4-.1,T4-25,f'(4)',
    ha='right',backgroundcolor='white')
plt.text(s5+.2,T5,f'(5)',
    ha='left',backgroundcolor='white')
plt.text(s6+.1,T6,f'(6)',
```

```
    ha='left',backgroundcolor='white')

plt.savefig('Plot-02.png')
```

B.3 Rankine reheat cycle expansion to 25 bar

```python
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)

print('Rankine reheat cycle analysis - reheat pressure at 25 bar')

p1 = 0.1
s1 = steamTable.sL_p(p1)
T1 = steamTable.t_ps(p1, s1)
h1 = steamTable.hL_p(p1)
print('\nPoint 1')
print(f"P1: {round(float(p1),1)} bar")
print(f"T1: {round(float(T1),1)} degC")
print(f"H1: {round(float(h1),1)} kJ/kg")
print(f"S1: {round(float(s1),3)} kJ/kg K")

p2 = 180
s2 = s1

v = 1/steamTable.rhoL_p(p1)
w_p = v*(p2-p1)

print('\nPoint 2')
h2 = h1+w_p
print(f"H2: {round(float(h2),1)} kJ/kg")

T2 = steamTable.t_ph(p2, h2)
print(f"T2: {round(float(T2),1)} degC")

h2dash = steamTable.hL_p(p2)
s2dash = steamTable.sL_p(p2)
T2dash = steamTable.t_ph(p2, h2dash)
print('\nPoint 2dash')
print(f"T2dash: {round(float(T2dash),1)} degC")
print(f"P2dash: {round(float(p2),1)} bar")
print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")

h3dash = steamTable.hV_p(p2)
s3dash = steamTable.sV_p(p2)
T3dash = T2dash
print('\nPoint 3dash')
print(f"T3dash: {round(float(T3dash),1)} degC")
print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")

p3 = p2
T3 = 540
h3 = steamTable.h_pt(p3, T3)
s3 = steamTable.s_pt(p3, T3)
print('\nPoint 3')
print(f"T3: {round(float(T3),1)} degC")
print(f"P3: {round(float(p3),1)} bar")
print(f"H3: {round(float(h3),1)} kJ/kg")
print(f"S3: {round(float(s3),3)} kJ/kg K")

p4 = 25
print(f"Reheat Pressure: {round(float(p4),1)} bar")
s4 = s3
T4 = steamTable.t_ps(p4, s4)
h4 = steamTable.h_pt(p4, T4)
print('\nPoint 4')
print(f"T4: {round(float(T4),1)} degC")
print(f"P4: {round(float(p4),1)} bar")
print(f"H4: {round(float(h4),1)} kJ/kg")
print(f"S4: {round(float(s4),3)} kJ/kg K")

p5 = p4
T5 = T3
h5 = steamTable.h_pt(p5, T5)
s5 = steamTable.s_pt(p5, T5)
print('\nPoint 5')
```

```python
print(f"T5: {round(float(T5),1)} degC")
print(f"p5: {round(float(p5),1)} bar")
print(f"H5: {round(float(h5),1)} kJ/kg")
print(f"S5: {round(float(s5),3)} kJ/kg K")

p6 = p1
s6 = s5
T6 = steamTable.t_ps(p6, s6)
x6 = steamTable.x_ps(p6, s6)
h6 = steamTable.h_px(p6, x6)
print('\nPoint 6')
print(f"T6: {round(float(T6),1)} degC")
print(f"p6: {round(float(p6),1)} bar")
print(f"H6: {round(float(h6),1)} kJ/kg")
print(f"S6: {round(float(s6),3)} kJ/kg K")
print(f"x6: {round(float(x6*100),1)} % dry")

print('\nSummary')
print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")

w_HPt = h3-h4
print(f"Work generated by HP turbine: {round(float(w_HPt),1)} kJ/kg")

w_LPt = h5-h6
print(f"Work generated by LP turbine: {round(float(w_LPt),1)} kJ/kg")
print(f"Total work output by turbine: {round(float(w_HPt+w_LPt),1)} kJ/kg")

q_H = (h3-h2)+(h5-h4)
print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")

q_L = h6-h1
print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")

eta_th = (w_HPt+w_LPt-w_p)/q_H*100
print(f"Thermal efficiency is: {round(float(eta_th),3)}%")

HRcycle = 3600*100/eta_th
print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
plt.rc('font', **font)

plt.ylabel('Temperature (C)')
plt.xlabel('Entropy (s)')
plt.xlim(-2,10)
plt.ylim(0,600)

T = np.linspace(0, 373.945, 400) # range of temperatures
svap = [s for s in [steamTable.sL_t(t) for t in T]]
sliq = [s for s in [steamTable.sV_t(t) for t in T]]

plt.plot(svap, T, 'b-', linewidth=2.0)
plt.plot(sliq, T, 'r-', linewidth=2.0)

plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6,
    T1], 'black', linewidth=2.0)

plt.text(s1-.1,T1,f'(1)',
    ha='right',backgroundcolor='white')
plt.text(s1-.1,T1+30,f'(2)',
    ha='right',backgroundcolor='white')
plt.text(s2dash-.15,T2dash,f"(2')",
    ha='right',backgroundcolor='white')
plt.text(s3dash-.1,T3dash-25,f"(3')",
    ha='right',backgroundcolor='white')
plt.text(s3+.2,T3,f'(3)',
    ha='left',backgroundcolor='white')
plt.text(s4-.1,T4-25,f'(4)',
    ha='right',backgroundcolor='white')
plt.text(s5+.2,T5,f'(5)',
    ha='left',backgroundcolor='white')
plt.text(s6+.1,T6,f'(6)',
```

```
    ha='left',backgroundcolor='white')

plt.savefig('Plot-04.png')
```

B.4 Rankine reheat cycle expansion to 70 bar

```
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)

print('Rankine reheat cycle analysis - reheat pressure at 70 bar')

p1 = 0.1
s1 = steamTable.sL_p(p1)
T1 = steamTable.t_ps(p1, s1)
h1 = steamTable.hL_p(p1)
print('\nPoint 1')
print(f"P1: {round(float(p1),1)} bar")
print(f"T1: {round(float(T1),1)} degC")
print(f"H1: {round(float(h1),1)} kJ/kg")
print(f"S1: {round(float(s1),3)} kJ/kg K")

p2 = 180
s2 = s1

v = 1/steamTable.rhoL_p(p1)
w_p = v*(p2-p1)

print('\nPoint 2')
h2 = h1+w_p
print(f"H2: {round(float(h2),1)} kJ/kg")

T2 = steamTable.t_ph(p2, h2)
print(f"T2: {round(float(T2),1)} degC")

h2dash = steamTable.hL_p(p2)
s2dash = steamTable.sL_p(p2)
T2dash = steamTable.t_ph(p2, h2dash)
print('\nPoint 2dash')
print(f"T2dash: {round(float(T2dash),1)} degC")
print(f"P2dash: {round(float(p2),1)} bar")
print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")

h3dash = steamTable.hV_p(p2)
s3dash = steamTable.sV_p(p2)
T3dash = T2dash
print('\nPoint 3dash')
print(f"T3dash: {round(float(T3dash),1)} degC")
print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")

p3 = p2
T3 = 540
h3 = steamTable.h_pt(p3, T3)
s3 = steamTable.s_pt(p3, T3)
print('\nPoint 3')
print(f"T3: {round(float(T3),1)} degC")
print(f"P3: {round(float(p3),1)} bar")
print(f"H3: {round(float(h3),1)} kJ/kg")
print(f"S3: {round(float(s3),3)} kJ/kg K")

p4 = 70
print(f"Reheat Pressure: {round(float(p4),1)} bar")
s4 = s3
T4 = steamTable.t_ps(p4, s4)
h4 = steamTable.h_pt(p4, T4)
print('\nPoint 4')
print(f"T4: {round(float(T4),1)} degC")
print(f"P4: {round(float(p4),1)} bar")
print(f"H4: {round(float(h4),1)} kJ/kg")
print(f"S4: {round(float(s4),3)} kJ/kg K")

p5 = p4
T5 = T3
h5 = steamTable.h_pt(p5, T5)
s5 = steamTable.s_pt(p5, T5)
print('\nPoint 5')
```

```
print(f"T5: {round(float(T5),1)} degC")
print(f"p5: {round(float(p5),1)} bar")
print(f"H5: {round(float(h5),1)} kJ/kg")
print(f"S5: {round(float(s5),3)} kJ/kg K")

p6 = p1
s6 = s5
T6 = steamTable.t_ps(p6, s6)
x6 = steamTable.x_ps(p6, s6)
h6 = steamTable.h_px(p6, x6)
print('\nPoint 6')
print(f"T6: {round(float(T6),1)} degC")
print(f"p6: {round(float(p6),1)} bar")
print(f"H6: {round(float(h6),1)} kJ/kg")
print(f"S6: {round(float(s6),3)} kJ/kg K")
print(f"x6: {round(float(x6*100),1)} % dry")

print('\nSummary')
print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")

w_HPt = h3-h4
print(f"Work generated by HP turbine: {round(float(w_HPt),1)} kJ/kg")

w_LPt = h5-h6
print(f"Work generated by LP turbine: {round(float(w_LPt),1)} kJ/kg")
print(f"Total work output by turbine: {round(float(w_HPt+w_LPt),1)} kJ/kg")

q_H = (h3-h2)+(h5-h4)
print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")

q_L = h6-h1
print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")

eta_th = (w_HPt+w_LPt-w_p)/q_H*100
print(f"Thermal efficiency is: {round(float(eta_th),3)}%")

HRcycle = 3600*100/eta_th
print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
plt.rc('font', **font)

plt.ylabel('Temperature (C)')
plt.xlabel('Entropy (s)')
plt.xlim(-2,10)
plt.ylim(0,600)

T = np.linspace(0, 373.945, 400) # range of temperatures
svap = [s for s in [steamTable.sL_t(t) for t in T]]
sliq = [s for s in [steamTable.sV_t(t) for t in T]]

plt.plot(svap, T, 'b-', linewidth=2.0)
plt.plot(sliq, T, 'r-', linewidth=2.0)

plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6, T1], 'black', linewidth=2.0)

plt.text(s1-.1,T1,f'(1)',
    ha='right',backgroundcolor='white')
plt.text(s1-.1,T1+30,f'(2)',
    ha='right',backgroundcolor='white')
plt.text(s2dash-.15,T2dash,f"(2')",
    ha='right',backgroundcolor='white')
plt.text(s3dash-.1,T3dash-25,f"(3')",
    ha='right',backgroundcolor='white')
plt.text(s3+.2,T3,f'(3)',
    ha='left',backgroundcolor='white')
plt.text(s4-.1,T4-25,f'(4)',
    ha='right',backgroundcolor='white')
plt.text(s5+.2,T5,f'(5)',
    ha='left',backgroundcolor='white')
plt.text(s6+.1,T6,f'(6)',
```

```
    ha='left',backgroundcolor='white')

plt.savefig('Plot-05.png')
```

B.5 Find reheat pressure at 180 bar main steam

```python
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)


def cycle_efficiency(p1, p2, T3, p4):

    h1 = steamTable.hL_p(p1)
    v = 1/steamTable.rhoL_p(p1)
    w_p = v*(p2-p1)

    h2 = h1+w_p

    p3 = p2
    h3 = steamTable.h_pt(p3, T3)
    s3 = steamTable.s_pt(p3, T3)

    s4 = s3
    T4 = steamTable.t_ps(p4, s4)
    h4 = steamTable.h_pt(p4, T4)

    p5 = p4
    T5 = T3
    h5 = steamTable.h_pt(p5, T5)
    s5 = steamTable.s_pt(p5, T5)

    p6 = p1
    s6 = s5
    x6 = steamTable.x_ps(p6, s6)
    h6 = steamTable.h_px(p6, x6)

    w_HPt = h3-h4
    w_LPt = h5-h6
    q_H = (h3-h2)+(h5-h4)
    eta_th = (w_HPt+w_LPt-w_p)/q_H*100
    return [eta_th, x6*100]

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('Efficiency vs reheat pressure (main steam P = 180 bar)')
plt.rc('font', **font)

plt.xlabel('Reheat Pressure (bar)')
plt.ylabel('Efficiecny (\%)')
plt.xlim(20,95)
plt.ylim(44,45)

j=180 #bar
listx = []
listeff = []
listdryness = []
for i in np.arange(25, 90, 0.25):
    xsol, ysol = cycle_efficiency(0.1, j, 540, i)
    listx.append(i)
    listeff.append(xsol)
    listdryness.append(ysol)

plt.plot(listx, listeff, 'black', linewidth=2.0)
m = max(listeff)
a = listeff.index(m)

font = {'family' : 'Times New Roman', 'size'   : 14}
plt.rc('font', **font)

plt.plot(listx[a], m, 'X')
plt.text(listx[1] ,listeff[1], f'{round(float(j),1)} bar', ha='right', backgroundcolor='white'
    )
print(f"When MS pressure = {round(float(j),2)} bar")
print(f"Maximum potential cycle efficiency = {round(float(max(listeff)),3)} %")
print(f"Maximum cycle efficiency occurs with a reheat pressure = {round(float(listx[a]),2)}
```

```
    bar")

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))

plt.savefig('Plot-06.png')
```

B.6 Rankine reheat cycle expansion to 46 bar

```python
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)

print('Rankine reheat cycle analysis - reheat pressure at 46 bar')

p1 = 0.1
s1 = steamTable.sL_p(p1)
T1 = steamTable.t_ps(p1, s1)
h1 = steamTable.hL_p(p1)
print('\nPoint 1')
print(f"P1: {round(float(p1),1)} bar")
print(f"T1: {round(float(T1),1)} degC")
print(f"H1: {round(float(h1),1)} kJ/kg")
print(f"S1: {round(float(s1),3)} kJ/kg K")

p2 = 180
s2 = s1

v = 1/steamTable.rhoL_p(p1)
w_p = v*(p2-p1)

print('\nPoint 2')
h2 = h1+w_p
print(f"H2: {round(float(h2),1)} kJ/kg")

T2 = steamTable.t_ph(p2, h2)
print(f"T2: {round(float(T2),1)} degC")

h2dash = steamTable.hL_p(p2)
s2dash = steamTable.sL_p(p2)
T2dash = steamTable.t_ph(p2, h2dash)
print('\nPoint 2dash')
print(f"T2dash: {round(float(T2dash),1)} degC")
print(f"P2dash: {round(float(p2),1)} bar")
print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")

h3dash = steamTable.hV_p(p2)
s3dash = steamTable.sV_p(p2)
T3dash = T2dash
print('\nPoint 3dash')
print(f"T3dash: {round(float(T3dash),1)} degC")
print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")

p3 = p2
T3 = 540
h3 = steamTable.h_pt(p3, T3)
s3 = steamTable.s_pt(p3, T3)
print('\nPoint 3')
print(f"T3: {round(float(T3),1)} degC")
print(f"P3: {round(float(p3),1)} bar")
print(f"H3: {round(float(h3),1)} kJ/kg")
print(f"S3: {round(float(s3),3)} kJ/kg K")


p4 = 46
print(f"Reheat Pressure: {round(float(p4),1)} bar")
s4 = s3
T4 = steamTable.t_ps(p4, s4)
h4 = steamTable.h_pt(p4, T4)
print('\nPoint 4')
print(f"T4: {round(float(T4),1)} degC")
print(f"P4: {round(float(p4),1)} bar")
print(f"H4: {round(float(h4),1)} kJ/kg")
print(f"S4: {round(float(s4),3)} kJ/kg K")

p5 = p4
T5 = T3
h5 = steamTable.h_pt(p5, T5)
s5 = steamTable.s_pt(p5, T5)
```

```
print('\nPoint 5')
print(f"T5: {round(float(T5),1)} degC")
print(f"p5: {round(float(p5),1)} bar")
print(f"H5: {round(float(h5),1)} kJ/kg")
print(f"S5: {round(float(s5),3)} kJ/kg K")

p6 = p1
s6 = s5
T6 = steamTable.t_ps(p6, s6)
x6 = steamTable.x_ps(p6, s6)
h6 = steamTable.h_px(p6, x6)
print('\nPoint 6')
print(f"T6: {round(float(T6),1)} degC")
print(f"p6: {round(float(p6),1)} bar")
print(f"H6: {round(float(h6),1)} kJ/kg")
print(f"S6: {round(float(s6),3)} kJ/kg K")
print(f"x6: {round(float(x6*100),1)} % dry")

print('\nSummary')
print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")

w_HPt = h3-h4
print(f"Work generated by HP turbine: {round(float(w_HPt),1)} kJ/kg")

w_LPt = h5-h6
print(f"Work generated by LP turbine: {round(float(w_LPt),1)} kJ/kg")
print(f"Total work output by turbine: {round(float(w_HPt+w_LPt),1)} kJ/kg")

q_H = (h3-h2)+(h5-h4)
print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")

q_L = h6-h1
print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")

eta_th = (w_HPt+w_LPt-w_p)/q_H*100
print(f"Thermal efficiency is: {round(float(eta_th),3)}%")

HRcycle = 3600*100/eta_th
print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('T-s Diagram - Rankine Reheat Cycle (Ideal)')
plt.rc('font', **font)

plt.ylabel('Temperature (C)')
plt.xlabel('Entropy (s)')
plt.xlim(-2,10)
plt.ylim(0,600)

T = np.linspace(0, 373.945, 400) # range of temperatures
svap = [s for s in [steamTable.sL_t(t) for t in T]]
sliq = [s for s in [steamTable.sV_t(t) for t in T]]

plt.plot(svap, T, 'b-', linewidth=2.0)
plt.plot(sliq, T, 'r-', linewidth=2.0)

plt.plot([s1, s2, s2dash, s3dash, s3, s4, s5, s6, s1],[T1, T2, T2dash, T3dash, T3, T4, T5, T6, T1], 'black', linewidth=2.0)

plt.text(s1-.1,T1,f'(1)',
    ha='right',backgroundcolor='white')
plt.text(s1-.1,T1+30,f'(2)',
    ha='right',backgroundcolor='white')
plt.text(s2dash-.15,T2dash,f"(2')",
    ha='right',backgroundcolor='white')
plt.text(s3dash-.1,T3dash-25,f"(3')",
    ha='right',backgroundcolor='white')
plt.text(s3+.2,T3,f'(3)',
    ha='left',backgroundcolor='white')
plt.text(s4,T4-25,f'(4)',
    ha='right',backgroundcolor='white')
plt.text(s5+.2,T5,f'(5)',
    ha='left',backgroundcolor='white')
```

```
plt.text(s6+.1,T6,f'(6)',
     ha='left',backgroundcolor='white')

plt.savefig('Plot-07.png')
```

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

```python
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)


def cycle_efficiency(p1, p2, T3, p4):

    h1 = steamTable.hL_p(p1)
    v = 1/steamTable.rhoL_p(p1)
    w_p = v*(p2-p1)

    h2 = h1+w_p

    p3 = p2
    h3 = steamTable.h_pt(p3, T3)
    s3 = steamTable.s_pt(p3, T3)

    s4 = s3
    T4 = steamTable.t_ps(p4, s4)
    h4 = steamTable.h_pt(p4, T4)

    HPturbeff = 0.90 # HP turbine isentropic efficiency can be entered here (typically 0.85 - 0.95)
    h4r = h3 - (HPturbeff * h3) + (HPturbeff * h4)

    w_HPt = h3-h4r

    p5 = p4
    T5 = T3
    h5 = steamTable.h_pt(p5, T5)
    s5 = steamTable.s_pt(p5, T5)

    p6 = p1
    s6 = s5
    x6 = steamTable.x_ps(p6, s6)
    h6 = steamTable.h_px(p6, x6)

    LPturbeff = 0.90 # IP/LP turbine isentropic efficiency can be entered here (typically 0.85 - 0.95)
    h6r = h5 - (LPturbeff * h5) + (LPturbeff * h6)

    w_LPt = h5-h6r
    q_H = (h3-h2)+(h5-h4r)
    eta_th = (w_HPt+w_LPt-w_p)/q_H*100

    return [eta_th, x6*100]

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('Efficiency vs reheat pressure (main steam P = 180 bar)')
plt.rc('font', **font)

plt.xlabel('Reheat Pressure (bar)')
plt.ylabel('Efficiecny (\%)')
plt.xlim(15,85)
plt.ylim(40,41)

j=180 #bar
listx = []
listeff = []
listdryness = []
for i in np.arange(20, 80, 0.25):
    xsol, ysol = cycle_efficiency(0.1, j, 540, i)
    listx.append(i)
    listeff.append(xsol)
    listdryness.append(ysol)

plt.plot(listx, listeff, 'black', linewidth=2.0)
m = max(listeff)
a = listeff.index(m)
```

```python

font = {'family' : 'Times New Roman', 'size'   : 14}
plt.rc('font', **font)

plt.plot(listx[a], m, 'X')
plt.text(listx[1] ,listeff[1], f'{round(float(j),1)} bar', ha='right', backgroundcolor='white'
    )
print(f"When MS pressure =  {round(float(j),2)} bar")
print(f"Maximum potential cycle efficiency =  {round(float(max(listeff)),3)} %")
print(f"Maximum cycle efficiency occurs with a reheat pressure =  {round(float(listx[a]),2)}
    bar")

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))

plt.savefig('Plot-08.png')
```

B.8 Rankine reheat cycle expansion to 36.75 bar

```python
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)

print('Rankine reheat cycle analysis (non ideal)')

p1 = 0.1
s1 = steamTable.sL_p(p1)
T1 = steamTable.t_ps(p1, s1)
h1 = steamTable.hL_p(p1)
print('\nPoint 1')
print(f"T1: {round(float(T1),1)} degC")
print(f"P1: {round(float(p1),1)} bar")
print(f"H1: {round(float(h1),1)} kJ/kg")
print(f"S1: {round(float(s1),3)} kJ/kg K")

p2 = 180
s2 = s1

v = 1/steamTable.rhoL_p(p1)
w_p = v*(p2-p1)

print('\nPoint 2')
h2 = h1+w_p
print(f"H2: {round(float(h2),1)} kJ/kg")

T2 = steamTable.t_ph(p2, h2)
print(f"T2: {round(float(T2),1)} degC")

h2dash = steamTable.hL_p(p2)
s2dash = steamTable.sL_p(p2)
T2dash = steamTable.t_ph(p2, h2dash)
print('\nPoint 2dash')
print(f"T2dash: {round(float(T2dash),1)} degC")
print(f"P2dash: {round(float(p2),1)} bar")
print(f"H2dash: {round(float(h2dash),1)} kJ/kg")
print(f"S2dash: {round(float(s2dash),3)} kJ/kg K")

h3dash = steamTable.hV_p(p2)
s3dash = steamTable.sV_p(p2)
T3dash = T2dash
print('\nPoint 3dash')
print(f"T3dash: {round(float(T3dash),1)} degC")
print(f"H3dash: {round(float(h3dash),1)} kJ/kg")
print(f"S3dash: {round(float(s3dash),3)} kJ/kg K")

p3 = p2
T3 = 540
h3 = steamTable.h_pt(p3, T3)
s3 = steamTable.s_pt(p3, T3)
print('\nPoint 3')
print(f"T3: {round(float(T3),1)} degC")
print(f"P3: {round(float(p3),1)} bar")
print(f"H3: {round(float(h3),1)} kJ/kg")
print(f"S3: {round(float(s3),3)} kJ/kg K")

p4 = 36.75
print(f"Reheat Pressure: {round(float(p4),1)} bar")
s4 = s3

T4 = steamTable.t_ps(p4, s4)
h4 = steamTable.h_pt(p4, T4)

HPturbeff = 0.90 # HP turbine isentropic efficiency can be entered here (typically 0.85 - 0.95)
h4r = h3 - (HPturbeff * h3) + (HPturbeff * h4)

s4r = steamTable.s_ph(p4, h4r)
T4r = steamTable.t_ps(p4, s4r)
print('\nPoint 4')
#print(f"T4ideal: {round(float(T4),1)} degC")
print(f"T4real: {round(float(T4r),1)} degC")
```

```
print(f"P4: {round(float(p4),1)} bar")
#print(f"H4ideal: {round(float(h4),1)} kJ/kg")
print(f"H4real: {round(float(h4r),1)} kJ/kg")
#print(f"S4ideal: {round(float(s4),3)} kJ/kg K")
print(f"S4real: {round(float(s4r ),3)} kJ/kg K")

w_HPt = h3-h4r

p5 = p4
T5 = T3
h5 = steamTable.h_pt(p5, T5)
s5 = steamTable.s_pt(p5, T5)
print('\nPoint 5')
print(f"T5: {round(float(T5),1)} degC")
print(f"P5: {round(float(p5),1)} bar")
print(f"H5: {round(float(h5),1)} kJ/kg")
print(f"S5: {round(float(s5),3)} kJ/kg K")

p6 = p1
s6 = s5
T6 = steamTable.t_ps(p6, s6)
x6 = steamTable.x_ps(p6, s6)
h6 = steamTable.h_px(p6, x6)
print('\nPoint 6')
print(f"T6: {round(float(T6),1)} degC")
print(f"P6: {round(float(p6),1)} bar")

LPturbeff = 0.90 # IP/LP turbine isentropic efficiency can be entered here (typically 0.85 - 0.95)
h6r = h5 - (LPturbeff * h5) + (LPturbeff * h6)

#print(f"H6ideal: {round(float(h6),1)} kJ/kg")
print(f"H6real: {round(float(h6r),1)} kJ/kg")
s6r = steamTable.s_ph(p6, h6r)
x6r = steamTable.x_ps(p6, s6r)
#print(f"S6ideal: {round(float(s6),3)} kJ/kg K")
print(f"S6real: {round(float(s6r ),3)} kJ/kg K")
#print(f"x6ideal: {round(float(x6),2)} ")
#print(f"x6real: {round(float(x6r),2)} ")
print(f"x6: {round(float(x6r*100),1)} % dry")



print('\nSummary')
print(f"Work required by pump: {round(float(w_p),1)} kJ/kg")
print(f"Work generated by HP turbine: {round(float(w_HPt),1)} kJ/kg")

w_LPt = h5-h6r
print(f"Work generated by LP turbine: {round(float(w_LPt),1)} kJ/kg")
print(f"Total work output by turbine: {round(float(w_HPt+w_LPt),1)} kJ/kg")

q_H = (h3-h2)+(h5-h4r)
print(f"Heat input by boiler: {round(float(q_H),1)} kJ/kg")

q_L = h6r-h1
print(f"Heat rejected by the condenser: {round(float(q_L),1)} kJ/kg")

eta_th = (w_HPt+w_LPt-w_p)/q_H*100
print(f"Thermal efficiency is: {round(float(eta_th),1)}%")

HRcycle = 3600*100/eta_th
print(f"HR rankine cycle: {round(float(HRcycle),1)} kJ/kWh")

font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('T-s Diagram - Rankine Reheat Cycle (non ideal)')
plt.rc('font', **font)

plt.ylabel('Temperature (C)')
plt.xlabel('Entropy (s)')
plt.xlim(-2,10)
plt.ylim(0,600)

T = np.linspace(0, 373.945, 400) # range of temperatures
```

```python
svap = [s for s in [steamTable.sL_t(t) for t in T]]
sliq = [s for s in [steamTable.sV_t(t) for t in T]]

plt.plot(svap, T, 'b-', linewidth=2.0)
plt.plot(sliq, T, 'r-', linewidth=2.0)

plt.plot([s1, s2, s2dash, s3dash, s3, s4r, s5, s6r, s1],[T1, T2, T2dash, T3dash, T3, T4r, T5,
    T6, T1], 'black', linewidth=2.0)

plt.text(s1-.1,T1,f'(1)',
    ha='right',backgroundcolor='white')
plt.text(s1-.1,T1+30,f'(2)',
    ha='right',backgroundcolor='white')
plt.text(s2dash-.15,T2dash,f"(2')",
    ha='right',backgroundcolor='white')
plt.text(s3dash-.1,T3dash-25,f"(3')",
    ha='right',backgroundcolor='white')
plt.text(s3+.2,T3,f'(3)',
    ha='left',backgroundcolor='white')
plt.text(s4,T4r-25,f'(4)',
    ha='right',backgroundcolor='white')
plt.text(s5+.2,T5,f'(5)',
    ha='left',backgroundcolor='white')
plt.text(s6r+.1,T6,f'(6)',
    ha='left',backgroundcolor='white')

plt.savefig('Plot-9.png')
```

B.9 Find reheat pressure at various main steam pressures

```
import matplotlib.pyplot as plt
import numpy as np
from pyXSteam.XSteam import XSteam

steamTable = XSteam(XSteam.UNIT_SYSTEM_MKS)


def cycle_efficiency(p1, p2, T3, p4):
    #print('Rankine reheat cycle analysis')

    #p1 = 0.1
    s1 = steamTable.sL_p(p1)
    T1 = steamTable.t_ps(p1, s1)
    h1 = steamTable.hL_p(p1)

    #p2 = 180
    s2 = s1

    v = 1/steamTable.rhoL_p(p1)
    w_p = v*(p2-p1)

    h2 = h1+w_p

    T2 = steamTable.t_ph(p2, h2)

    h2dash = steamTable.hL_p(p2)
    s2dash = steamTable.sL_p(p2)
    T2dash = steamTable.t_ph(p2, h2dash)

    h3dash = steamTable.hV_p(p2)
    s3dash = steamTable.sV_p(p2)
    T3dash = T2dash

    p3 = p2
    #T3 = 540
    h3 = steamTable.h_pt(p3, T3)
    s3 = steamTable.s_pt(p3, T3)

    #p4 = 25
    s4 = s3

    T4 = steamTable.t_ps(p4, s4)
    h4 = steamTable.h_pt(p4, T4)

    HPturbeff = 0.90 # HP turbine isentropic efficiency can be entered here (typically 0.85 - 0.95)
    h4r = h3 - (HPturbeff * h3) + (HPturbeff * h4)

    s4r = steamTable.s_ph(p4, h4r)
    T4r = steamTable.t_ps(p4, s4r)

    w_HPt = h3-h4r

    p5 = p4
    T5 = T3
    h5 = steamTable.h_pt(p5, T5)
    s5 = steamTable.s_pt(p5, T5)

    p6 = p1
    s6 = s5
    T6 = steamTable.t_ps(p6, s6)
    x6 = steamTable.x_ps(p6, s6)
    h6 = steamTable.h_px(p6, x6)

    LPturbeff = 0.90 # IP/LP turbine isentropic efficiency can be entered here (typically 0.85 - 0.95)
    h6r = h5 - (LPturbeff * h5) + (LPturbeff * h6)
    s6r = steamTable.s_ph(p6, h6r)
    x6r = steamTable.x_ps(p6, s6r)

    w_LPt = h5-h6r
    q_H = (h3-h2)+(h5-h4r)
    q_L = h6r-h1
    eta_th = (w_HPt+w_LPt-w_p)/q_H*100
```

```
    #HRcycle = 3600*100/eta_th

    return [eta_th, x6*100]


font = {'family' : 'Times New Roman',
        'size'   : 22}

plt.figure(figsize=(15,10))
plt.title('Efficiency vs reheat pressure (Real cycle)')
plt.rc('font', **font)

plt.xlabel('Reheat Pressure (bar)')
plt.ylabel('Efficiecny (%)')
plt.xlim(15,65)
plt.ylim(39.8,41)

for j in np.arange(150, 190, 5):
    listx = []
    listeff = []
    listdryness = []
    for i in np.arange(20, 80, 0.25):
        xsol, ysol = cycle_efficiency(0.1, j, 540, i)
        listx.append(i)
        listeff.append(xsol)
        listdryness.append(ysol)

    plt.plot(listx, listeff, 'black', linewidth=2.0)
    m = max(listeff)
    a = listeff.index(m)

    plt.plot(listx[a], m, 'X')
    plt.text(listx[1] ,listeff[1], f'{round(float(j),1)} bar', ha='right', backgroundcolor='
    white')
    print(f"When MS pressure = {round(float(j),2)} bar")
    print(f"Maximum potential cycle efficiency = {round(float(max(listeff)),3)} %")
    print(f"Maximum cycle efficiency occurs with a reheat pressure = {round(float(listx[a])
    ,2)} bar")
    print(f"ratio of MS vs RH pressure = {round(float(j/m),2)} ")

plt.savefig('Plot-10.png')
```

C Figures and Tables

List of Figures

List of Tables