HACETTEPE UNIVERSITY

Department of Nuclear Engineering

NEM 294 ENGINEERING PROJECT III

Assignment 3. and Consider the REGENERATIVE RANKINE cycle

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1 INTRODUCTION

The Rankine Cycle is a fundamental thermodynamic cycle used in thermal power plants for electricity generation and is especially widely used in steam turbine systems. In addition, studies are ongoing to increase the efficiency of this Rankine cycle, to bring it as close as possible to the Carnot cycle. Methods/tools such as Reheat and OFWH are used.

In this project, it will be analyzed how the efficiency and turbıne exit quality changes by changing the conditions under certain conditions in a regenerative rankine cycle containing OFWH with given characteristics.

In part (a) of the project, the turbine inlet temperature is increased from 300 degrees Celsius to 600 degrees Celsius in 25 degree increments, and the change in efficiency and turbine exit quality is examined.

In part (b) of the project, the turbine inlet temperature is fixed at 500 degrees Celsius. After all the steam enters the high pressure turbine, a portion of the steam is directed to the open feedwater heater (OFWH), while the remaining steam is reheated and then sent to the low pressure turbine. The reheat outlet temperature is varied from 300 to 400 degrees Celsius in 25 degree increments, and its effects on the thermal efficiency and steam quality at the turbine exit are analyzed.

2 METHODS AND CALCULATIONS

This project examines how a Rankine cycle containing OFWH changes in various conditions. The current/fixed characteristics of the turbine are given below. Differently, in part a of the project, the turbine inlet temperature was increased to calculate efficiency and turbine exit quality, while in part b of the project, reheat was activated. This time, while the turbine inlet temperature was constant, the temperature of the steam exiting the reheat was increased, and again efficiency and turbine exit quality were calculated. The calculations were made, and the Python Xsteam library was used to find/use the necessary enthalpies.

The given current/fixed conditions are;

- Boiler pressure: 7 MPa
- OFWH pressure: 800 kPa
- Condenser pressure: 10 kPa
- Turbine efficiency: 90%
- Pump efficiency: 90%
- Saturated liquid is assumed at both the condenser and OFWH exits

Part (a): Effect of Turbine Inlet Temperature

The turbine inlet temperature is varied between 300°C and 600°C in 25°C increments, while other parameters remain constant. The steam expands in a single stage turbine, and some of it is extracted to the open feedwater heater (OFWH).. The equations used are;

1) **Pump Work (Pump 1 and Pump 2):**

$$Wpump = (v \times \Delta P) / \eta\_pump$$

2) **Pump 1 Output Enthalpy:**

$$h2 = h1 + w\_pump1$$

3) **Pump 2 Output Enthalpy:**

$$h4 = h3 + w\_pump2$$

4) **Enthalpy After Pump:**

$$h\_out = h\_in + wpump$$

5) **Turbine Expansion with Isentropic Efficiency:**

$$h\_out = h\_in - \eta\_turbine \times (h\_in - h\_isentropic)$$

- **Turbine Expansion with Isentropic Efficiency (to OFWH):**

$$h6 = h5 - \eta\_turbine \times (h5 - h6s)$$

- **Turbine Expansion with Isentropic Efficiency (to condenser):**

$$h7 = h5 - \eta\_turbine \times (h5 - h7s)$$

6) **Extraction Mass Fraction (y):**

$$y = (h3 - h2)/(h6 - h2)$$

7) **Heat Input:**

$$q\_in = h5 - h4$$

8) **Net Work Output:**

$$w\_net = (h5 - h6) + (1 - y)(h6 - h7) - wpump1 - (1 - y) \times wpump2$$

9) **Thermal Efficiency:**

$$\eta\_th = w\_net / q\_in$$

10) **Turbine Exit Steam Quality:**

$$x = (h7 - h\_f) / h\_fg \qquad h\_fg = h\_v - h\_f$$

Part (b): Effect of Reheat Temperature

While the turbine inlet temperature is fixed at 500C, this time, after the steam leaves the HP turbine, a part of it goes to OFWH , while the remaining part is reheated by reheat and sent to the LP turbine. The outlet temperature of the reheated steam coming out of this reheat is increased from 300C to 400 with 20 degree increments.

In addition, The equaitons follow the same principles as in Part (a), with the following differences;

1) **Total Heat Input:**

$$q\_in = (h5 - h4) + (1 - y) \times (h7 - h6)$$

2) **Net Work Output:**

$$w\_net = (h5 - h6) + (1 - y) \times (h7 - h8) - (1 - y) \times w\_pump1 - w\_pump2$$

3) **Thermal Efficiency:**

$$\eta\_th = w\_net \,/\, q\_in$$

4) **LP Turbine Exit Steam Quality:**

$$x = (h8 - h\_f) \,/\, h\_fg \qquad\qquad h\_fg = h\_v - h\_f$$

3 RESULTS

Effect of Turbine Inlet Temperature on Thermal Efficiency:

When the turbine inlet temperature is increased from 300 degrees to 600 degrees, keeping all other values constant, the most obvious thing we see is the increase in thermal efficiency. The efficiency, which was approximately 32.10% at 300°C, reached 40.30% at

600°C. In the table, we can see the new thermal efficiency and increase for every 25 degrees of temperature. In addition to the table, we will also see how this increase progresses in the graph. Although the graph is not linear, it will shows a constant increase. The heat input in the boiler also increases, but since the net work increase is more dominant, the efficiency increases accordingly.

Table 1: Relationship between turbine inlet and thermal efficiency

Turbine Inlet Temp (°C)	Thermal Efficiency (%)
300	32.1
325	33
350	33.9
375	34.7
400	35.5
425	36.3
450	37
475	37.7
500	38.3
525	38.9
550	39.4
575	39.9
600	40.3

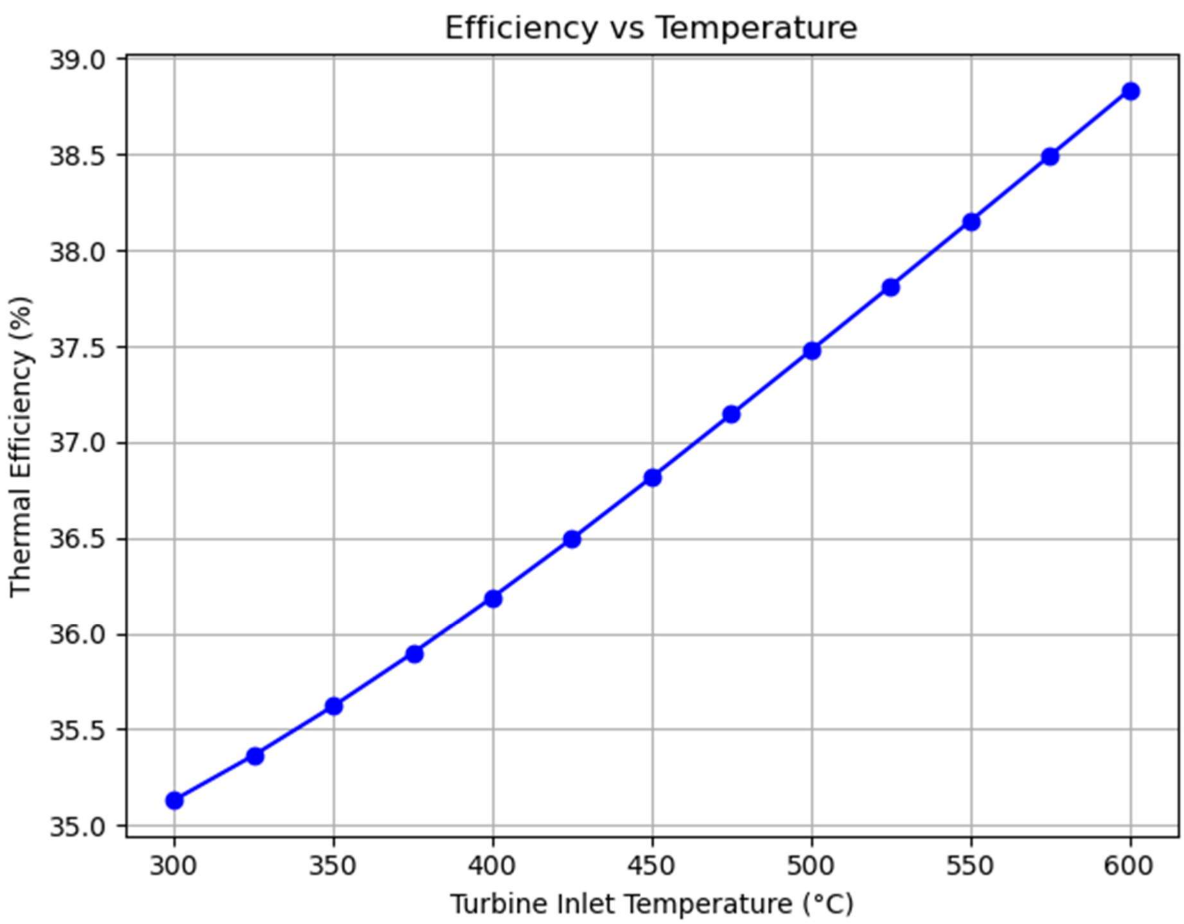

Figure 1: Graph of the change in thermal efficiency while the turbine inlet temperature is increased from 300 to 600 degrees.

Another important variable that changed as the temperature increased was the **Steam Quality at Turbine Exit (x_e),** which also improved with temperature.

In the analysis, it is seen that as the turbine inlet temperature increases, the steam quality at turbine exit increases.
Vapor quality (x_e) is the ratio of the vapor mass in a vapor-liquid mixture to the total mixture. It is usually defined in the saturated vapor region and takes a value between 0 and 1. As seen in the table, while the x_e value at 300°C was approximately 0.870, this value reached 0.940 at 600°C. Although the numerical increase seems low when we look at every 25-degree increase, it should be noted that the maximum number that can occur is 1. As the amount of liquid in the water vapor increases, water droplets damage the turbine, so increasing this value is very important for us as it will increase the efficiency of the turbine and extend its life. Although the ideal x_e value is 0.88, it is critical for this value to fall below 0.85 in terms of safety, it is below the lowest acceptable limit.

Table 2: Relationship between turbine inlet and Steam Quality (x_e)

Turbine Inlet Temp (°C)	Steam Quality (x_e)
300	0.870
325	0.880
350	0.890
375	0.900
400	0.905
425	0.910
450	0.915
475	0.920
500	0.925
525	0.930
550	0.934
575	0.937
600	0.940

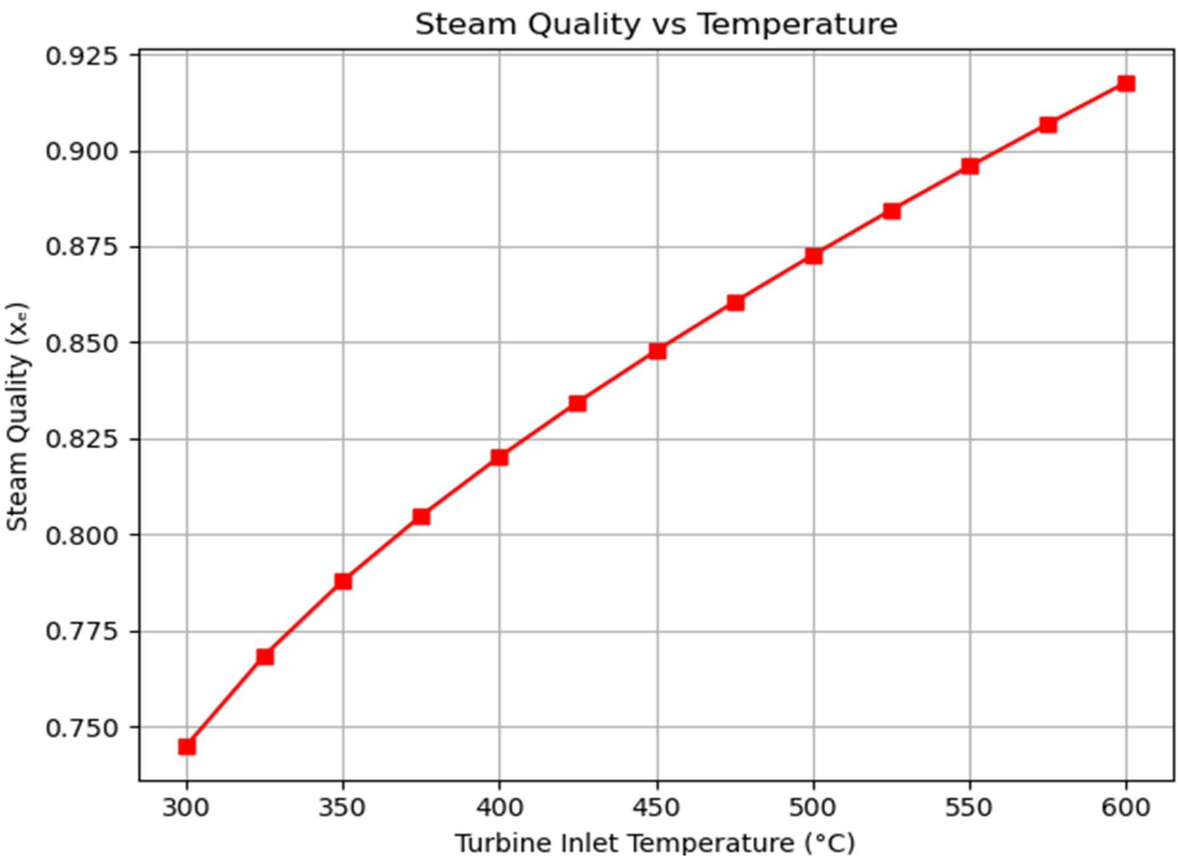

Figure 2: Plot of the relationship between steam quality and turbine exit temperature.

Although there is not a completely parallel and linear increase in this graph, we can say that it becomes increasingly difficult to increase the steam quality, especially as it approaches 1.

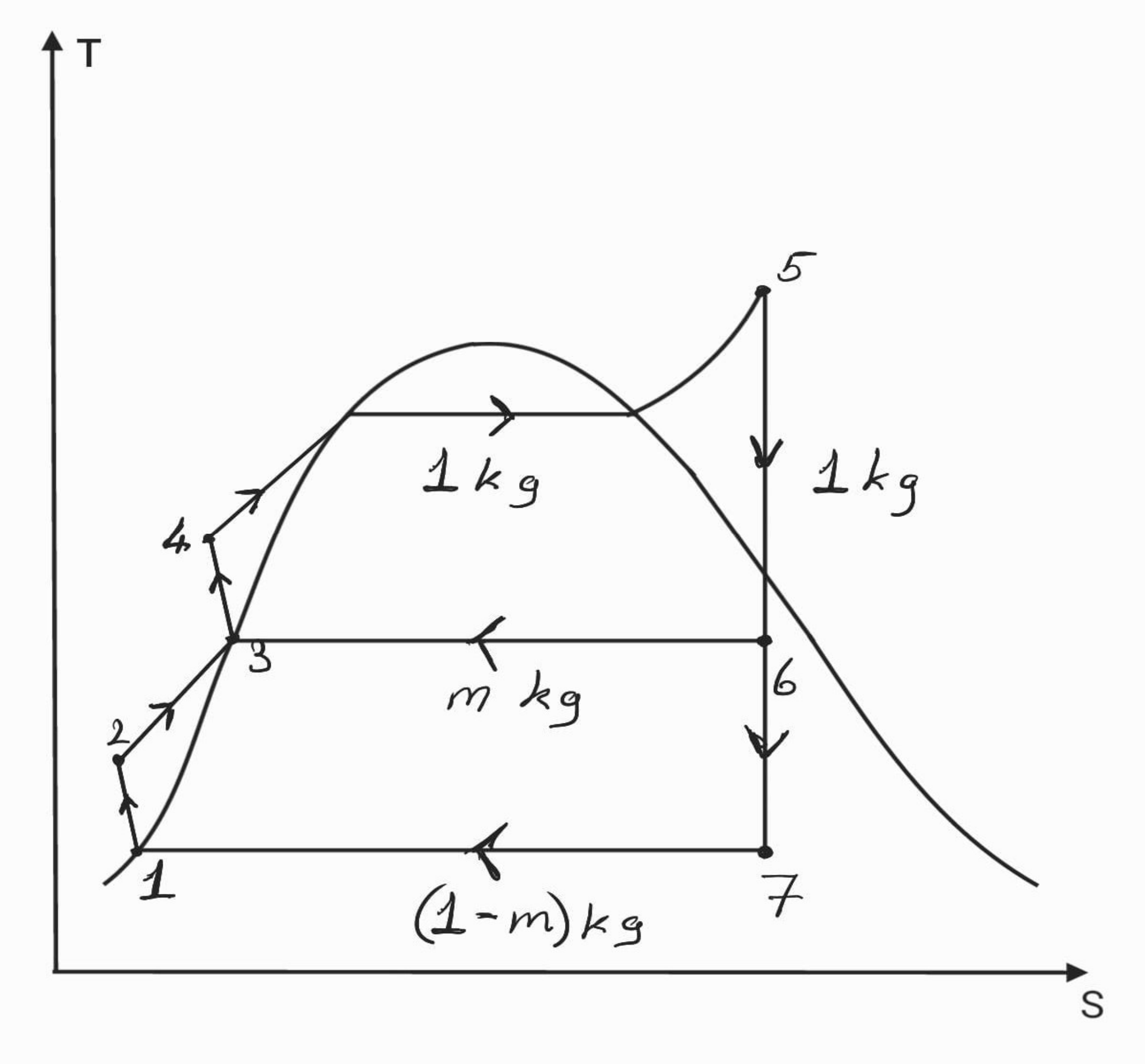

Figure 3: T-s diagram for REGENERATIVE RANKINE cycle

As we see in the table and graph, as the turbine inlet temperature increases, there is a significant increase in efficiency. However, it would be a mistake to focus only on the Turbine Inlet temperature and efficiency. Let's look at the T-s diagram to understand it in more detail.

The temperature and entropy graph of a REGENERATIVE RANKINE cycle is like this. If we explain the graph;

- (1-2) Describes an entropic compression with the help of a pump. As pressure and temperature increase, work is negative. This is very diffucult to achieve in practice because spesific volumes of liqiud and vapor differ to great extent. That's why "pump" are devised to use for liquids, and "compressors" for vapor. If it were isentropic, this line would have to be vertical, not sloping.

- ❖ (2-3-6) is a constant P line, also (4-5). In OFWH, 2 fluids are mixed at the same pressure. 6 and 2 are mixed to yield 3, all the same pressure. (Never mix 2 or more streams at different pressures!) In addition, heat is added by the boiler during these intervals, the temperature first increases and then remains constant.
- ❖ (5-7) is the part where the turbine does work. Work is done while the pressure and temperature decrease. (Of course, since we are not working in an isentropic environment, there will be a deviation in this section, but this situation has been ignored while drawing this diagram.)
- ❖ (6) is called stream-extraction point. Only m kg stream is extracted from turbine, (1-m) kg continues to be expanded in turbine. As number of steam extraction points goes up, boiler inlet Temperature can get higher and efficeny is increased further.
- ❖ (7-1) part is the "heat rejection" part. It is done with a condenser and the temperature and pressure are constant.

In part B of the project, the compared values are the same (efficiency and steam exit quality). What is different this time is the addition of a reheat to the system. In this way, a portion of the steam coming out of the high-pressure turbine is directed to the open feed water heater (OFWH), while the rest is reheated and sent to the low-pressure turbine. The temperature of the reheated steam changes from 300 degrees to 400 degrees. As a result, how the efficiency and steam exit quality change has been analyzed.

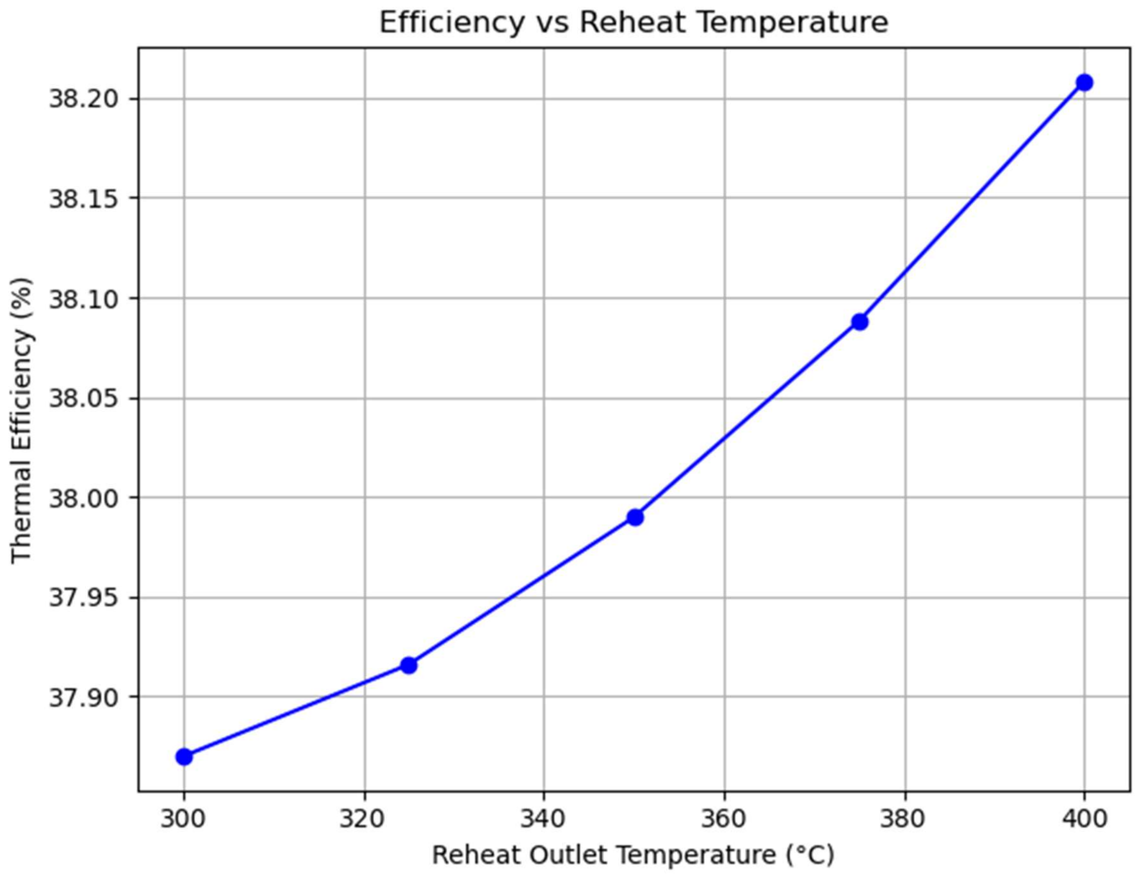

Figure 3: Graph of the increase in thermal efficiency with 25 degree increases in the outlet temperature of the reheated steam

As expected, the thermal efficiency increases significantly as the reheater steam leaves the reheater. This is due to the steam gaining more energy before the second expansion process. If you compare this to part a of the project, there is a much stronger increase in efficiency. In other words, reheating the steam and extracting work from it significantly increases the thermal efficiency.

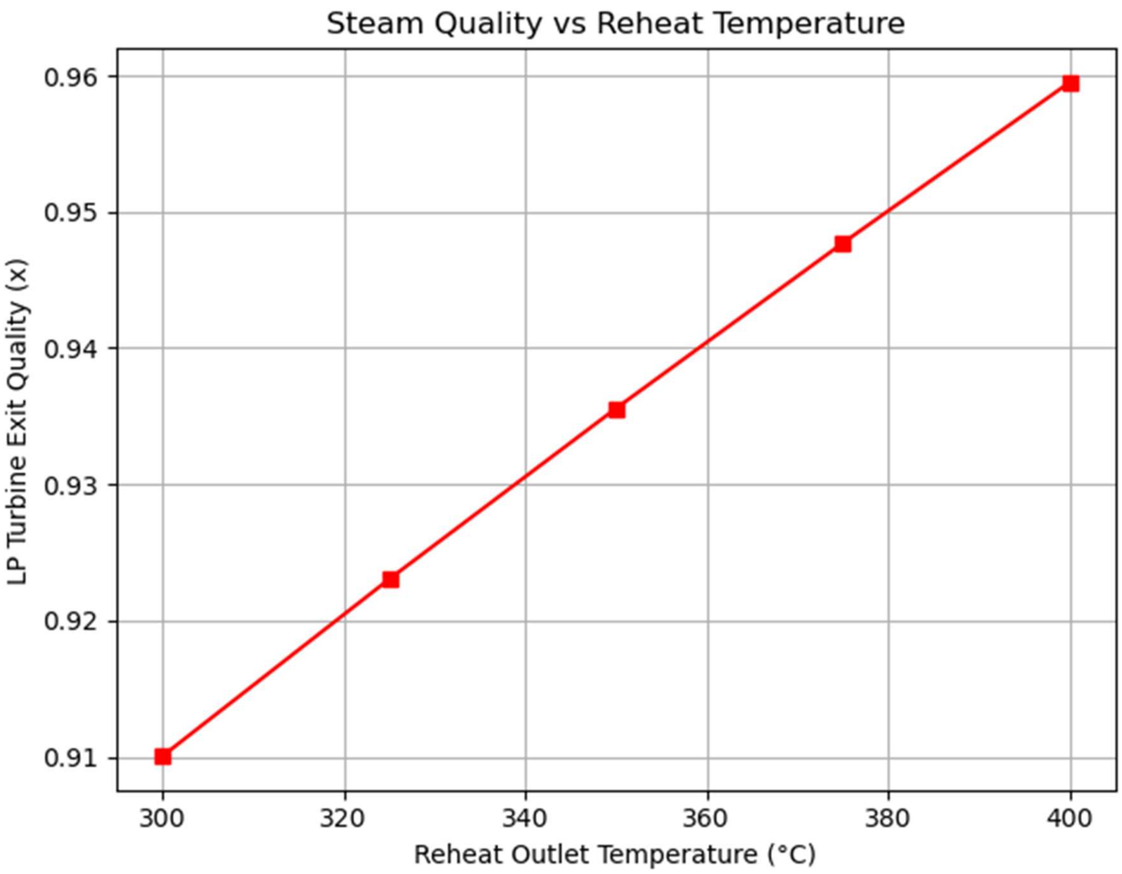

Figure 4: Plot of the relationship between LP Turbine Exit Quality and Reheat Outlet Temperature.

As for steam quality, as the reheat outlet temperature increased, the quality also increased. More accurately, higher reheat temperature provided drier steam at the LP turbine outlet. Of course, this is an extremely positive development in terms of the life of the turbine.

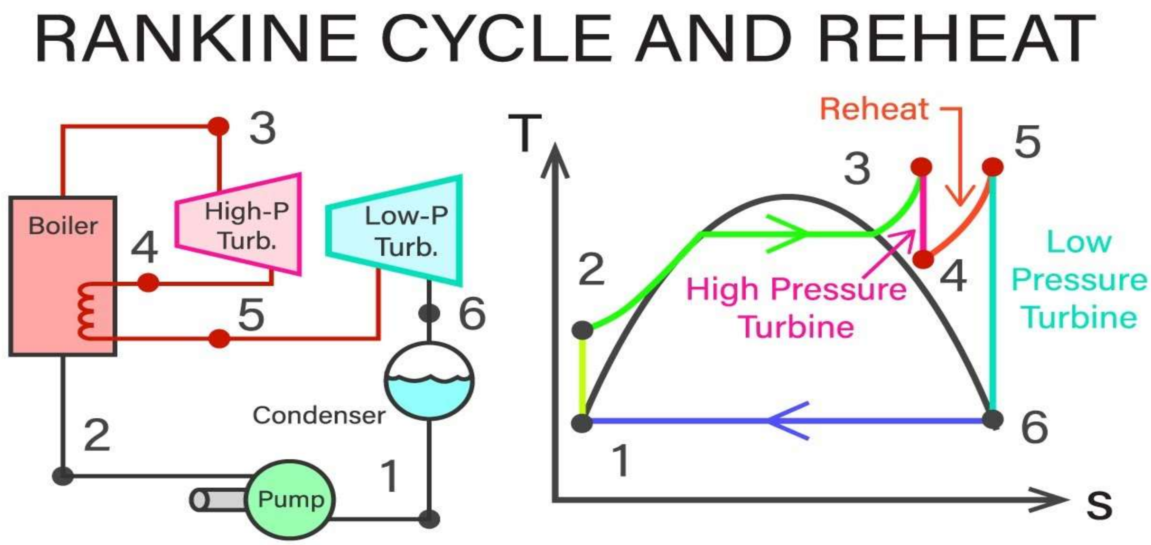

Figure 5: This image shows a Rankine cycle T-s diagram that includes reheat.

The part that needs to be paid attention to in this image is between (4-5). We can say that the steps 1-2-3-4 are exactly the same as the previous example, the important difference here is the part between 4-5. In other words, reheating the steam and producing extra work. All the information mentioned in Figure 3 is also valid here. However, I need to mention that this diagram is not the diagram of our question because it does not contain an OFWH. This image is only important to understand the reheat part.

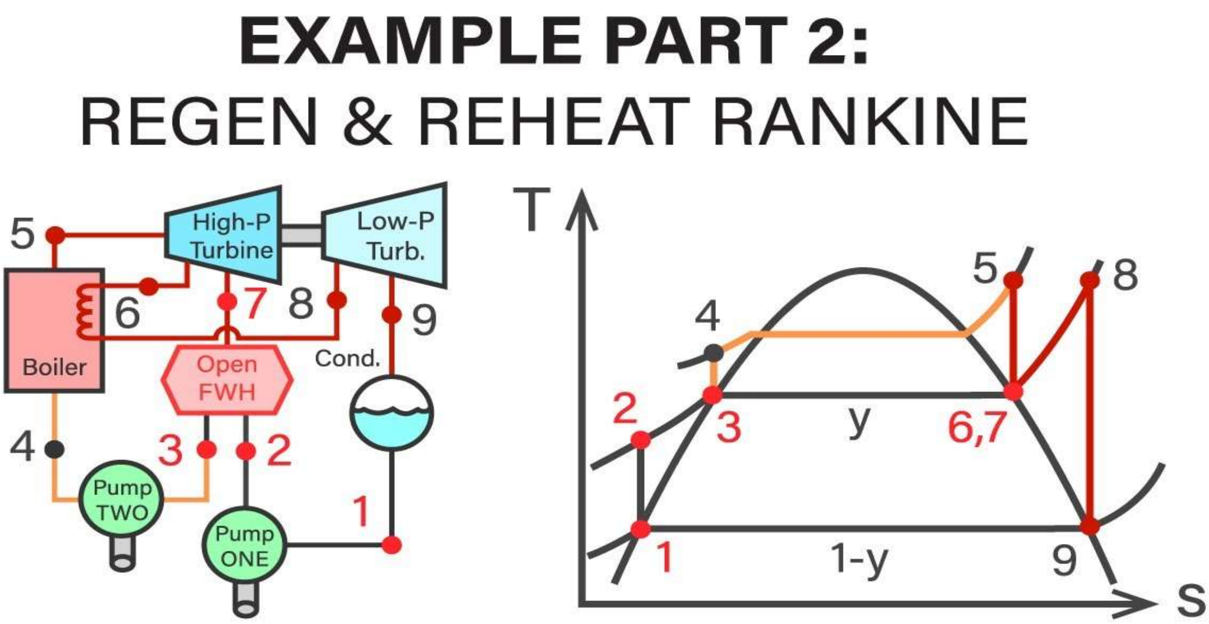

Figure 6: T-s diagram of a regenerative rankine cycle with both OFWH and reheat

This is the desired situation in part b of this project. We have a regeneration cycle with OFWH and we are producing extra work by reheating. In this diagram we see very clearly the steam mixed with OFWH, the masses of the steam and the work produced by the LP turbine(8-9). From the clear results we see in the graph that the efficiency is increased and from this T-s diagram we see that the work produced is clearly increased.

4 CONCLUSION

There were two main topics investigated in this project, "a" and "b". In one of these main topics, the turbine inlet temperature was changed and the thermal efficiency and steam exit quality were analyzed, and in the other, the temperature of the reheated steam leaving the reheater was changed, again its efficiency and quality were analyzed. To see more clearly, let's look at the tables that summarize everything.

Table 3: Change in both thermal efficiency and steam quality when the reheat outlet temperature is increased from 300 degrees to 400 degrees in 25 degree increments

T_reheat = 300 °C → efficiency = 37.87 %, x = 0.9100
T_reheat = 325 °C → efficiency = 37.92 %, x = 0.9230
T_reheat = 350 °C → efficiency = 37.99 %, x = 0.9356
T_reheat = 375 °C → efficiency = 38.09 %, x = 0.9477
T_reheat = 400 °C → efficiency = 38.21 %, x = 0.9595

Table 4: Change in both thermal efficiency and steam quality when the temperature is increased from 300 degrees to 600 degrees in 25 degree increments

T = 300 °C → η = 35.13 %, x_e = 0.7448
T = 325 °C → η = 35.36 %, x_e = 0.7685
T = 350 °C → η = 35.62 %, x_e = 0.7879
T = 375 °C → η = 35.90 %, x_e = 0.8048
T = 400 °C → η = 36.19 %, x_e = 0.8202
T = 425 °C → η = 36.50 %, x_e = 0.8344
T = 450 °C → η = 36.82 %, x_e = 0.8478
T = 475 °C → η = 37.14 %, x_e = 0.8605
T = 500 °C → η = 37.48 %, x_e = 0.8727
T = 525 °C → η = 37.81 %, x_e = 0.8844
T = 550 °C → η = 38.15 %, x_e = 0.8958
T = 575 °C → η = 38.49 %, x_e = 0.9069
T = 600 °C → η = 38.84 %, x_e = 0.9176

As seen in Table 4, increasing the turbine inlet temperature always works for us. Thermal efficiency in particular, as well as steam exit quality, clearly increases. Therefore, increasing the inlet temperature always seems to be in our favor. At least when we ignore real life and only talk about diagrams. In real life, it may be difficult to reach these inlet temperatures, both in terms of the fuel required and the boiler must have the material to withstand those inlet temperatures. Even if it has that material, how long it will wear out when operating at high temperatures is also important, these also lead to a completely different efficiency calculation, but when we ignore such things, we can clearly say that increasing the turbine inlet temperature increases both efficiency and the life of the turbine by looking at the table and the results.

As seen in Table 3, for part b of the project, reheating the steam again and more and then producing work again is always positive for us. What we really need to see in Table 3 is that the main purpose/benefit of the reheat process is not efficiency but increasing turbine exit quality. The results of the project show very well that the reheat process is a very effective method for increasing turbine exit quality.

However, it should be noted that the following situations apply to both OFWH and Reheater. Anything extra means extra equipment. Both OFWH and reheat installations mean extra piping, extra valves etc. and hence extra complication and extra investment cost. Too many steam extraction points can have a negative impact on the overall plant. Considering all these, the efficiencies and benefits obtained are as in the tables.

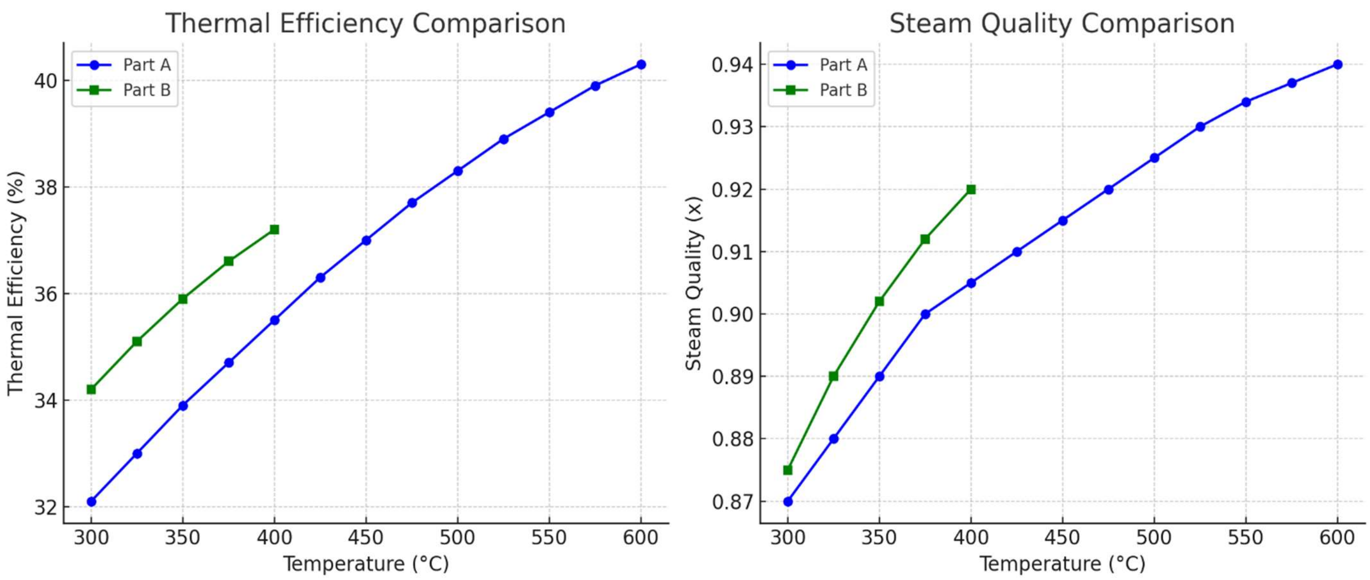

Figure 7:Graph of the comparison of the obtained efficiency graphs with each other

In the first graph in Figure 7, the Blue curve shows the increase in efficiency as the turbine inlet temperature increases, while the Green curve shows that the efficiency increases as the reheat temperature increases, but it does not show as strong an increasing trend as the Blue curve. Therefore, if our goal is thermal efficiency, it may be more logical to try to increase the turbine inlet temperature instead of investing in reheat. Of course, the most effective situation would be when both are done. In addition, it should be added that it is much easier to increase the turbine inlet temperature to 600 degrees than to increase the reheat to 600 degrees. It would not be right to say that if we just look at the slope of the graphs and make the other 600 degrees, it would also be efficient. It is also important how possible this is.

When we look at the second graph, although we see that increasing the turbine inlet temperature increases the stream exit quality, using a reheat mechanism for this is much more efficient, we see this very clearly. This is necessary for the longevity of the turbine.

5 REFERENCES

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6 APPENDIX

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

# Initialize IAPWS-97 Steam Tables (MKS Units: bar, °C, kJ/kg)
steam = XSteam(XSteam.UNIT_SYSTEM_MKS)

# ==========================================
# SYSTEM PARAMETERS
# ==========================================
P_boiler = 70.0   # 7 MPa -> 70 bar
P_ofwh   = 8.0    # 800 kPa -> 8 bar
P_cond   = 0.1    # 10 kPa -> 0.1 bar

eta_turb = 0.90   # Turbine Isentropic Efficiency
eta_pump = 0.90   # Pump Isentropic Efficiency

print(">>> RANKINE CYCLE ANALYSIS RESULTS <<<\n")

# ==========================================
# PART A: EFFECT OF TURBINE INLET TEMPERATURE
```

```
    # ==========================================
    # Temperature range: 300°C to 600°C with 25°C increments
    temps_a = list(range(300, 625, 25))

    eff_a = []
    quality_a = []

    for T_inlet in temps_a:
        # 1. Condenser Exit
        h1 = steam.hL_p(P_cond)
        v1 = steam.vL_p(P_cond)

        # 2. Condensate Pump (Pump 1)
        # Work = v * dP (converted to kJ/kg)
        w_pump1 = (v1 * (P_ofwh - P_cond) * 100) / eta_pump
        h2 = h1 + w_pump1

        # 3. OFWH Exit
        h3 = steam.hL_p(P_ofwh)
        v3 = steam.vL_p(P_ofwh)

        # 4. Feedwater Pump (Pump 2)
        w_pump2 = (v3 * (P_boiler - P_ofwh) * 100) / eta_pump
        h4 = h3 + w_pump2

        # 5. Turbine Inlet
        h5 = steam.h_pt(P_boiler, T_inlet)
        s5 = steam.s_pt(P_boiler, T_inlet)

        # 6. Extraction to OFWH
        h6s = steam.h_ps(P_ofwh, s5)
        h6 = h5 - eta_turb * (h5 - h6s)

        # 7. Turbine Exit to Condenser
        # Expansion assumes single stage efficiency characteristic from
inlet
        h7s = steam.h_ps(P_cond, s5)
        h7 = h5 - eta_turb * (h5 - h7s)

        # Mass Fraction (y)
```

```
    y = (h3 - h2) / (h6 - h2)

    # Steam Quality at Exit
    h_f = steam.hL_p(P_cond)
    h_fg = steam.hV_p(P_cond) - h_f
    x_exit = (h7 - h_f) / h_fg

    # Energy Balance
    w_t1 = h5 - h6
    w_t2 = (h6 - h7) * (1 - y)

    # Pump Work Allocation
    w_p1 = w_pump1
    w_p2 = w_pump2 * (1 - y)

    q_in = h5 - h4
    w_net = w_t1 + w_t2 - w_p1 - w_p2

    eta = (w_net / q_in) * 100

    eff_a.append(eta)
    quality_a.append(x_exit)

# Output Table Part A
df_a = pd.DataFrame({
    "T_inlet (°C)": temps_a,
    "Efficiency (%)": np.round(eff_a, 2),
    "Exit Quality": np.round(quality_a, 4)
})
print("--- PART A RESULTS ---")
print(df_a.to_string(index=False))
print("\n")


# ==========================================
# PART B: EFFECT OF REHEAT TEMPERATURE
# ==========================================
# Fixed Inlet Temperature
T_inlet_fixed = 500.0
# Reheat Temperature range: 300°C to 400°C
```

```
temps_b = list(range(300, 425, 25))

eff_b = []
quality_b = []

for T_reheat in temps_b:
    # Pumps and OFWH states (1-4) remain identical to Part A logic
    h1 = steam.hL_p(P_cond)
    v1 = steam.vL_p(P_cond)
    w_pump1 = (v1 * (P_ofwh - P_cond) * 100) / eta_pump
    h2 = h1 + w_pump1

    h3 = steam.hL_p(P_ofwh)
    v3 = steam.vL_p(P_ofwh)
    w_pump2 = (v3 * (P_boiler - P_ofwh) * 100) / eta_pump
    h4 = h3 + w_pump2

    # 5. HP Turbine Inlet
    h5 = steam.h_pt(P_boiler, T_inlet_fixed)
    s5 = steam.s_pt(P_boiler, T_inlet_fixed)

    # 6. HP Turbine Exit (Extraction)
    h6s = steam.h_ps(P_ofwh, s5)
    h6 = h5 - eta_turb * (h5 - h6s)

    # Mass Fraction (y)
    y = (h3 - h2) / (h6 - h2)

    # 7. Reheat Exit / LP Turbine Inlet
    h7 = steam.h_pt(P_ofwh, T_reheat)
    s7 = steam.s_pt(P_ofwh, T_reheat)

    # 8. LP Turbine Exit
    h8s = steam.h_ps(P_cond, s7)
    h8 = h7 - eta_turb * (h7 - h8s)

    # Steam Quality at LP Exit
    h_f = steam.hL_p(P_cond)
    h_fg = steam.hV_p(P_cond) - h_f
    x_exit = (h8 - h_f) / h_fg
```

```
    # Energy Balance
    w_hp = h5 - h6
    w_lp = (1 - y) * (h7 - h8)

    # Pump Work Allocation (Corrected for Reheat Cycle)
    w_p1 = (1 - y) * w_pump1
    w_p2 = w_pump2

    q_main = h5 - h4
    q_reheat = (1 - y) * (h7 - h6)
    q_total = q_main + q_reheat

    w_net = w_hp + w_lp - w_p1 - w_p2
    eta = (w_net / q_total) * 100

    eff_b.append(eta)
    quality_b.append(x_exit)

# Output Table Part B
df_b = pd.DataFrame({
    "T_reheat (°C)": temps_b,
    "Efficiency (%)": np.round(eff_b, 2),
    "Exit Quality": np.round(quality_b, 4)
})
print("--- PART B RESULTS ---")
print(df_b.to_string(index=False))
```