# ES-211
# THERMODYNAMICS PROJECT


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## INTRODUCTION

This project is about analysing the performance of a power plant operating on a basic ideal Rankine cycle. The conditions at which the Rankine cycle operates are given to us. But, this restricts the efficiency of the cycle to 41%. This is undesirable and the objective of this project is to increase the efficiency of the power plant while maintaining some values and not letting these values exceed a particular value.

## OBJECTIVE

a) To increase the efficiency over 46% and raise the steam quality (x) to above 85% from the current values of efficiency and steam quality of 41% and 76% respectively while maintaining the boiler and condenser pressure at 15MPa and 10kPa and ensuring that the temperature of turbine does not exceed 500℃.
b) Varying the boiler pressure ($P_b$) and condenser pressure ($P_c$) within ranges 12MPa $< P_b <$ 15MPa and 5kPa $< P_c <$ 10kPa and illustrate the impact of these pressure changes in the thermal efficiency and net work output of the modified cycle.-

## THEORY

Rankine cycle is an ideal thermodynamic cycle which is widely used in vapour power plants such as coal power plants and nuclear reactors. This cycle mainly consists of four intermediate steps which take place in a pump, boiler, turbine and a condenser respectively. The working fluid employed in this process is water which changes its phase several times in the cycle. The following are the steps involved in this cycle:

1. **Isentropic compression in a pump:** Water in saturated liquid form is compressed isentropically to a higher pressure in the pump, i.e, till the operating pressure of the boiler. The compression also causes the temperature of the water to increase due to the decrease in the specific volume of water.
2. **Constant-pressure heat addition in a boiler:** In the boiler, the compressed water enters and is heated at constant pressure till it becomes a superheated vapour. This heat that the water receives comes from combustion of coal in case of coal power plants and nuclear reactions in case of nuclear reactors.
3. **Isentropic expansion in a turbine:** Superheated water vapour enters the turbine where it undergoes isentropic expansion and produces work output. Both the

pressure and temperature of the vapour decrease and it changes its phase to a liquid-vapour mixture with high steam quality.

4. **Constant-pressure heat rejection in a condenser:** In the condenser, the liquid-vapour mixture is condensed at constant pressure by rejecting heat to a reservoir such as a lake, river or the atmosphere. The phase of the liquid-vapour mixture changes to saturated liquid after condensation which is then sent into the pump again, thus continuing the cycle.

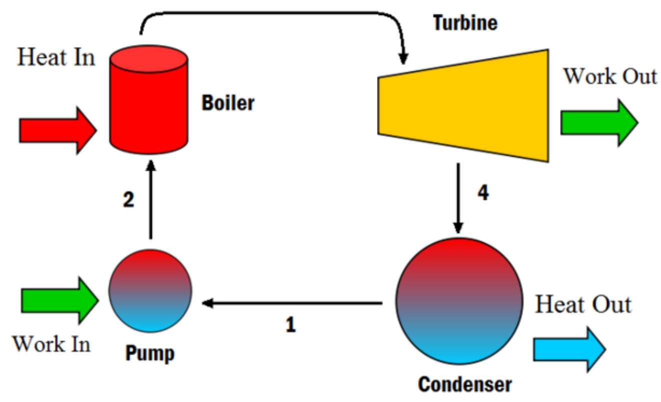



Fig. 1 - Representation of the ideal Rankine cycle

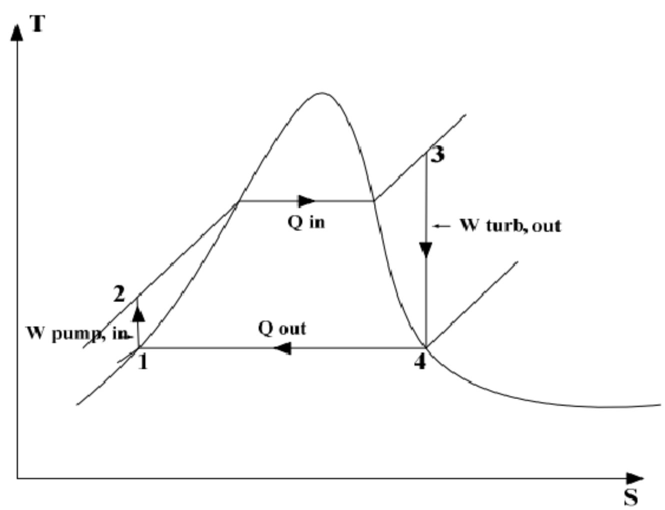



Fig. 2 - Graphical representation of the Rankine cycle on a T-s diagram

## REHEATING IN A RANKINE CYCLE

Reheating in a Rankine cycle is a technique used to improve the overall efficiency of a steam power plant. In a traditional Rankine cycle, steam generated in the boiler expands through the turbine, producing work, and is then condensed in the condenser before being pumped back to the boiler. Reheating involves taking the steam at an intermediate pressure, after it has partially expanded through the turbine, and then raising its temperature back to a high level before allowing it to expand further through a second turbine stage. The steps of a Rankine cycle with reheating are the same as that of a traditional Rankine cycle, except that of the intermediate step of reheating the

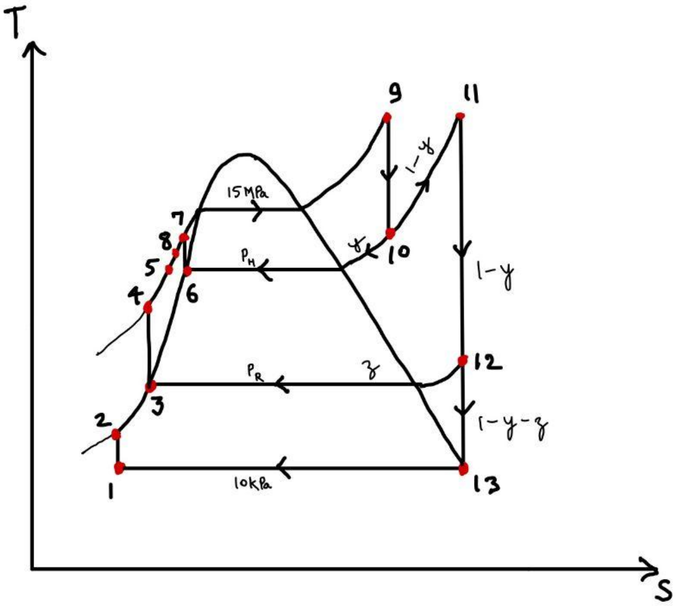
The purpose of reheating is to avoid the high moisture content that can occur at the exit of a high-pressure turbine. Moisture in the steam can lead to erosion and damage to the turbine blades. Reheating allows the steam to be returned to a high-temperature, high-pressure state before it expands further, reducing the moisture content and improving the overall efficiency of the cycle.

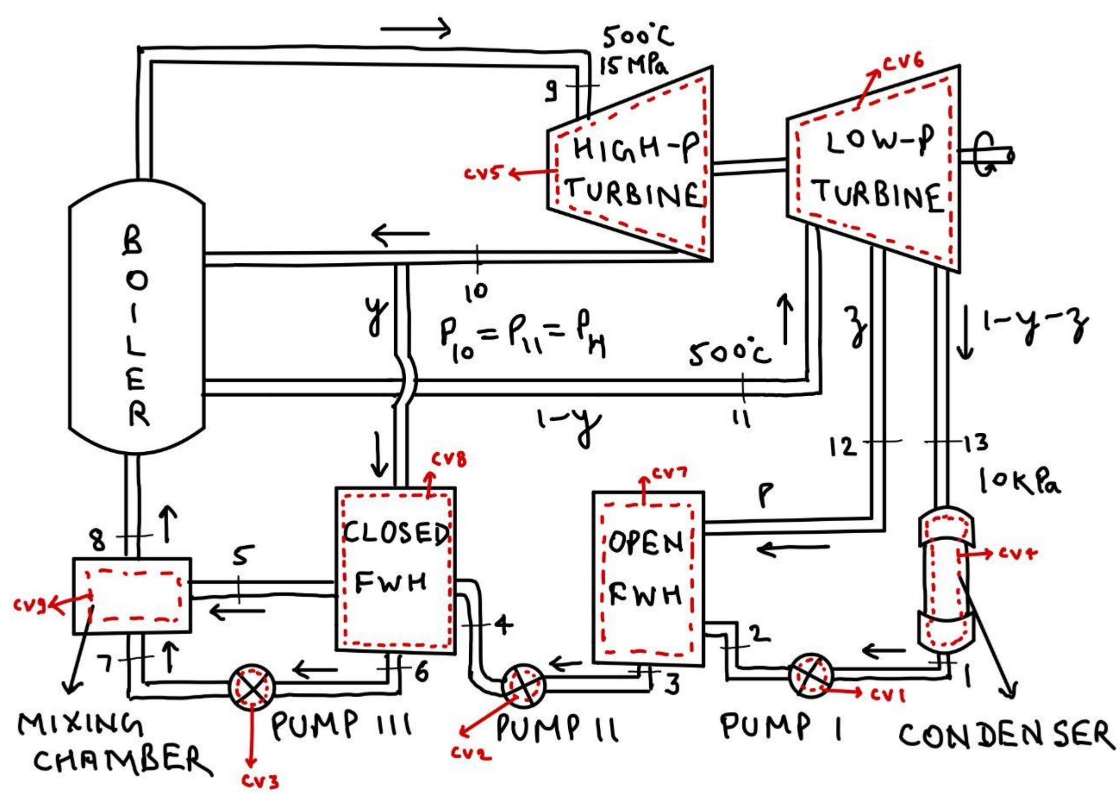
## CLOSED FEEDWATER HEATERS

In a Rankine cycle, a closed feedwater heater is a type of heat exchanger used to preheat the feedwater before it enters the boiler. The feedwater is the water that is supplied to the boiler to be converted into steam. The purpose of preheating the feedwater is to improve the overall efficiency of the power plant by reducing the amount of heat that needs to be added in the boiler.

In a closed feedwater heater, the extracted steam from the turbine is passed through one side of the heat exchanger, while the cold feedwater is passed through the other side. The heat from the steam is transferred to the feedwater, raising its temperature before it enters the boiler, reducing the amount of heat that needs to be added in the boiler to achieve the desired steam conditions, thereby improving the efficiency of the Rankine cycle. The term "closed" refers to the fact that the water and steam sides of the heat exchanger are physically separated, and there is no direct mixing of the two fluids.

**T-s DIAGRAMS OF THE MODIFIED RANKINE CYCLES, AND CONTROL VOLUME ANALYSIS:**



# Energy Balance Equations —:

For CV1,

$$\cancelto{0}{\dot{Q}} - \dot{W} + (1-y-z)(h_1 - h_2)\dot{m} = 0$$

$$\therefore W_{PUMP\,I} = (1-y-z)(h_1-h_2)\dot{m}$$

For CV2,

$$\cancelto{0}{\dot{Q}} - \dot{W} + (1-y)(h_3 - h_4)\dot{m} = 0$$

$$\therefore W_{PUMP\,II} = (1-y)(h_3-h_4)\dot{m}$$

For CV3,

$$\cancelto{0}{\dot{Q}} - \dot{W} + y(h_6 - h_7)\dot{m} = 0$$

$$\therefore W_{PUMP\,III} = y(h_6-h_7)\dot{m}$$

For CV4,

$$\dot{Q} - \cancelto{0}{\dot{W}} + (1-y-z)(h_{13} - h_1)\dot{m} = 0$$

$$\therefore \dot{Q} = (1-y-z)(h_1 - h_{13})\dot{m}$$

For CV5,

$$\cancelto{0}{\dot{Q}} - \dot{W} + \dot{m}(h_9 - h_{10}) = 0$$

$$\therefore \dot{W}_{HIGH-P} = \dot{m}(h_9 - h_{10})$$

For CV6,

$$\cancelto{0}{\dot{Q}} - \dot{W} + \dot{m}(1-y)h_{11} - \dot{m}(1-y)h_{12} = 0$$

$$\therefore \dot{W}_{LOW-P} = \dot{m}(1-y)(h_{11}-h_{12})$$

For CV7,

$$\dot{m}\left[z h_{12} + (1-y-z)h_2 - (1-y)h_3\right] = 0$$

$$\therefore z = \frac{(1-y)(h_3-h_2)}{(h_{12}-h_2)}$$

For CV8,

$$\dot{m}\left[y h_{10} + (1-y) h_4 - (1-y) h_5 - y h_6\right] = 0$$

$$\therefore y = \frac{(h_5 - h_4)}{(h_{10} - h_6) + (h_5 - h_4)}$$

For CV9,

$$\dot{m}\left[(1) h_8 - (1-y) h_5 - y h_7\right] = 0$$

$$\therefore h_8 = (1-y) h_5 + y h_7$$

## PROCEDURE

We had two tasks to accomplish, one was to increase the efficiency, and simultaneously increase the steam quality. The second task was to vary the boiler and condenser pressures, and plot the efficiency and work output graphs.

Firstly, in order to increase the steam quality, we had to perform reheating. Therefore, we fixed the quality of the steam to the minimum threshold of 85% and fixed the first regeneration pressure to be the same as the pressure of reheat.

Now, after combining these two, we still weren't able to achieve an efficiency above 46%. Therefore, we had to add another regeneration cycle.

Now, our task was to choose the optimum pressure for second regeneration in order to achieve the maximum efficiency. To do so, we created a function in MATLAB (Cantera) which calculated the efficiency of the cycle for various second regeneration pressures. We then stored the data in an array and found out the maximum value of efficiency and the value of optimum pressure.

We also plotted a graph of efficiency versus second  regeneration pressure to see visually how it varies with pressure.

Now, we come to the second part of the question, which involves changing the Boiler and Condenser pressures.

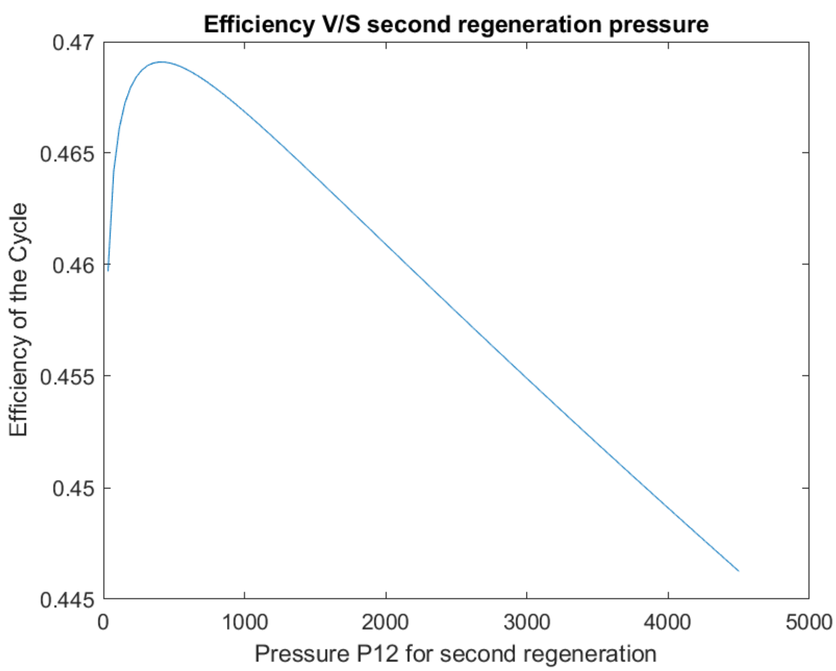
To do so, we first fixed the steam quality once again at 85%. This fixed the pressure for reheating and first regeneration. For the second regeneration pressure, we fixed the value of the optimum pressure obtained from the first part of the question.

We created another function in MATLAB which took the boiler and condenser pressures as inputs and returned efficiency and work output of the cycle as outputs.

This was done using loops and updating the values of boiler and condenser pressures and inputting them to the function we created. We stored the data in arrays and plotted graphs for the same to visualize the variation in the required quantities.

## RESULTS

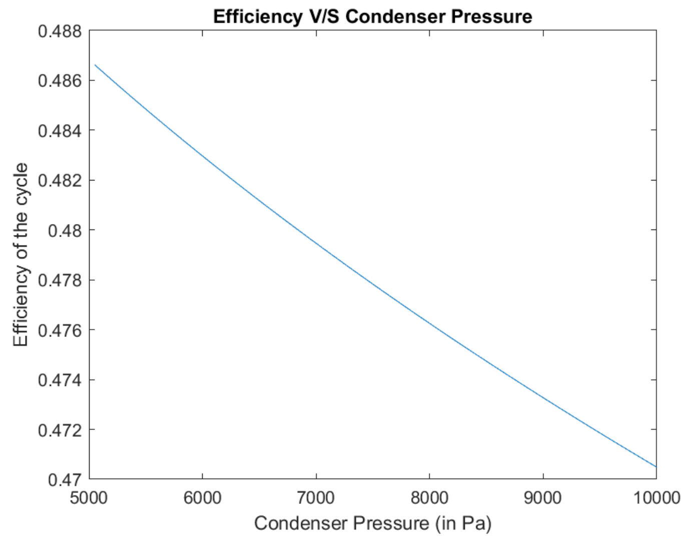
The following graphs were obtained after complete analysis on MATLAB:




From the above graph, we can see that the optimum pressure for second regeneration (Maximizing efficiency) is $3.9129 \times 10^{6}\ Pa$.

Also, the value of maximum efficiency for the first part is 46.91%. The quality of the low pressure turbine outlet was fixed at 85%.

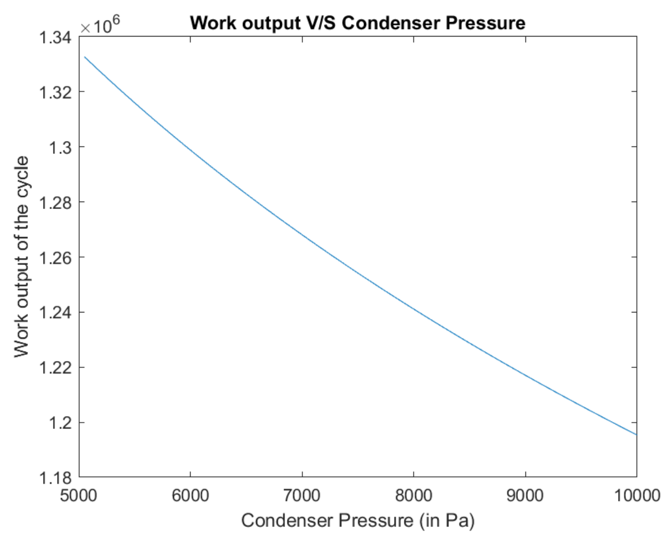
Part II




From the above graph, we can observe that the efficiency of the cycle decreases with an increase in Condenser pressure.

To obtain the graph, we held the boiler pressure constant at 12 $MPa$. Only the condenser pressure was varied, and as we can see, the maximum efficiency of the modified cycle is about 48.7%, with a condenser pressure of 5 kPa.

All the states of the cycle were fixed at




Similar to the efficiency V/S condenser pressure curve, we can see that the work output varies in a similar fashion. Maximum work output is obtained at a condenser pressure of

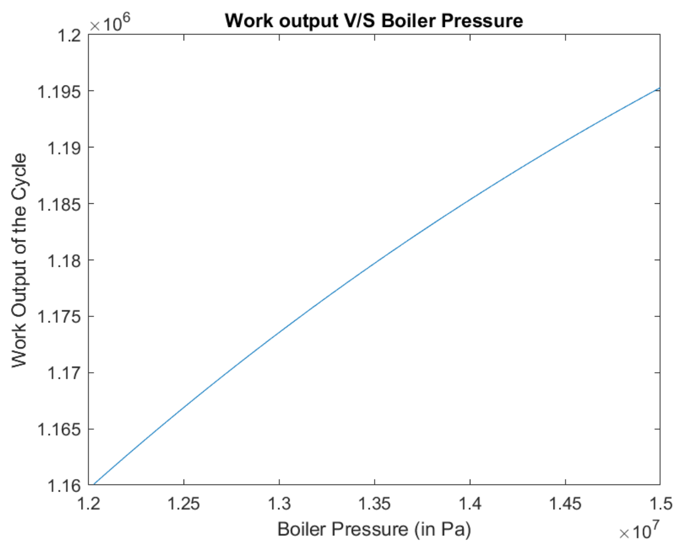
5 kPa and a boiler pressure of 15 MPa.

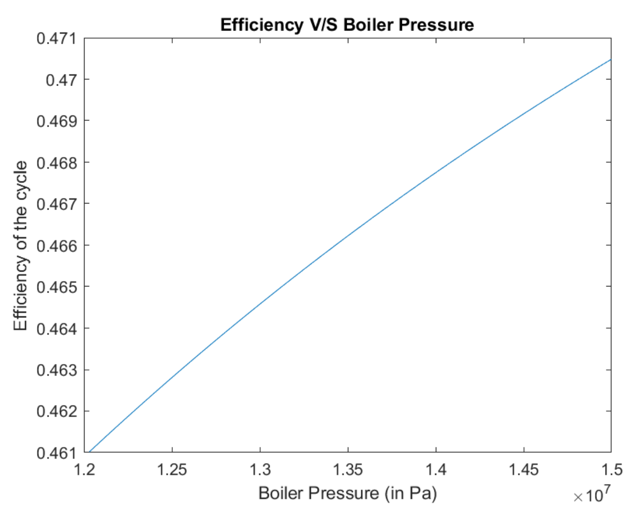
The magnitude of the maximum work output is about 1.33 MW.

Moving on to the graph below, we see the variation of work output with boiler pressure.

Clearly, the work output increases with an increase in boiler pressure. We can also say the same for efficiency of the cycle. At a constant condenser pressure of 10 kPa, the maximum work output of the cycle with varying boiler pressures is about 1.195 MW, at a boiler pressure of 15 MPa.

The maximum efficiency of the cycle touches 47.1 %.



There are a few reasons for this behavior of the cycle. The perfect combination would be achieved with the maximum boiler pressure and minimum condenser pressure. This is because as the boiler pressure increases, the temperature of the working fluid also increases, thus resulting in a higher specific enthalpy. Thus, the amount of work extracted by the turbine automatically increases, resulting in higher efficiencies.