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# Parametric testing and comparative study of single, double and triple reheats for a 800 MW supercritical power plant

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## Abstract

This research paper presents the thermodynamic analysis of a modern supercritical (SC) steam power plant with a power generating capacity of 800 MW, employing with single, double and triple re-heat configurations. A MATLAB software code and model has been developed to accurately estimate the steam properties and performance calculations. The study focuses reheat pressure ratios, temperature and pressure at the turbine's inlet and outlet. The model based cycle's energy efficiency and exergy efficiency have been examined, for single, double and triple reheats, on the cycle's performance. The exergy destructions were calculated and observed that both efficiencies exhibit a more pronounced increase with rising temperatures compared to increasing pressures. The exergy losses incurred in the powerplant components have been meticulously studied, compared and analyzed by systematically by varying the pressure ratios of SC Power plant for single, double and triple reheats .

Keywords: Supercritical cycle, Single Reheat, Double reheat, triple reheat, exergy destruction, exergy efficiency, energy efficiency

## INTRODUCTION

Steam Reheating is an important process in order to maintain the steam quality to more than 0.85 dryness fraction, and used in conventional steam-power plants. The steam after partly expanded would be sent back to the steam generator to increase the turbine inlet temperature at the next stage of turbine expansion. Doing so the net work output and the thermal efficiency of the steam power plant could be attained. The reheat pressure ratio and reheat temperature ratios plays considerable impact on the network output and life of the turbine blades. The possible reheat pressure ratios and reheat temperature ratios could be studied and optimized for the better performance.

In Present research single reheat, double reheat and triple reheat were employed to a supercritical power plant. The comparative performance analysis was carried out by using a simulated model developed on MATLAB software.

Exergy analysis was the method being employed and exergy destructions were calculated at all the components of the supercritical power plant. Also energy and exergy efficiencies were calculated and compared using graphical analysis

The supercritical cycle is inherited from the basic Rankine cycle and analyzed by E.G. Feher[1], for the preliminary comparison. Kotas [2] described the exergy and enthalpy for the inlet and exit flue gas parameters into the steam generator. And also the variations in chemical compositions in anthracite coal also has been considered by Kotas. Kotas [8] described and explained the nomenclature of the exergy terms and employed for the exergy analysis. In order to calculate the properties of water/steam at supercritical conditions the mathematical models have been developed by W. C. J. D. A. K. J. K. H. K. A. Wagner [4]. The introductory principles of thermodynamics which could be used to analyse the thermodynamic cycles have been explained by P.K. Nag, Moran Shapiro, Bejan, Moran and Cengel. Habib [6] in his publication demonstrated the importance of the reheat in the steam power generation. Rayudu [13] in his publication investigated on supercritical power cycles with single and double reheating.

## SUPERCRITICAL (SC) CYCLE DESCRIPTION USING SINGLE, DOUBLE AND TRIPLE REHEATS.

The layout of the power plant which is proposed to study is illustrated below. It is comprising of a once through boiler, turbines, condenser, feedwater heaters, reheating system and pumps and are arranged as shown in fig. The working principle is described below.

The condensate which leaves the condenser is heated in low pressure feedwater heaters by utilizing the steam extractions at various points. It is then circulated through the deaerator in order to remove the dissolved gasses and also a little temperature rise. Then this feedwater passes through the high pressure feedwater heater, then given to the economizer. Once the feedwater obtains the desired temperature and pressure it would be supplied to the supercritical boiler or once through boiler. The supercritical steam would be fed into the high pressure turbine and gets expanded till the reheat pressure. Then the exhaust steam from the high pressure turbine would be taken into the boiler to rise its temperature to desired level. The reheated steam is given to the intermediate pressure turbine gets expanded to certain pressure and then given to the low pressure turbine for further expansion. Finally, the expanded steam is supplied to the condenser in which its phase will be changed to liquid phase.

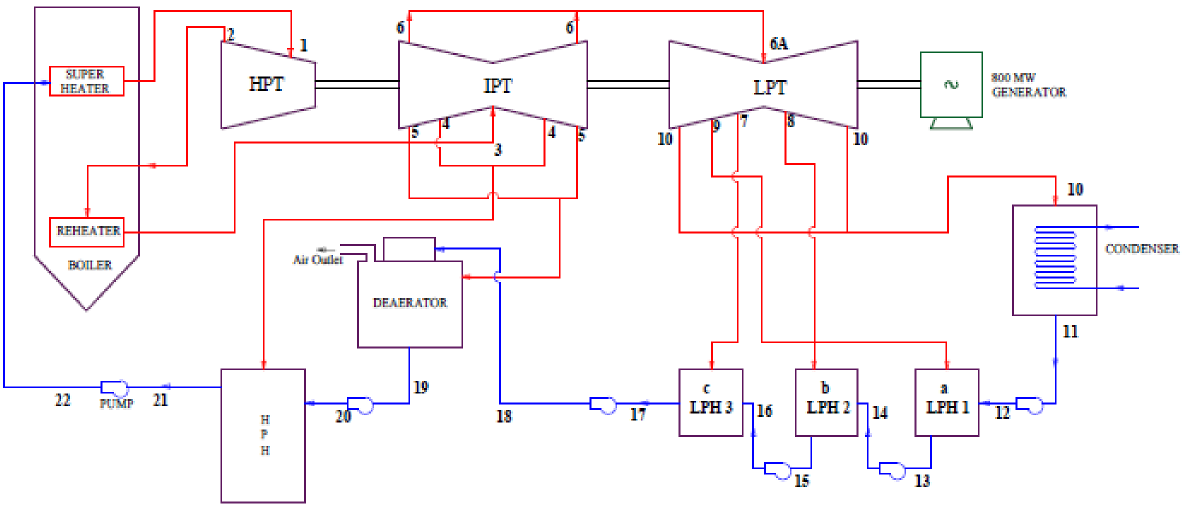


Fig 1: SC Power plant with single reheat

Industrial Engineering Journal
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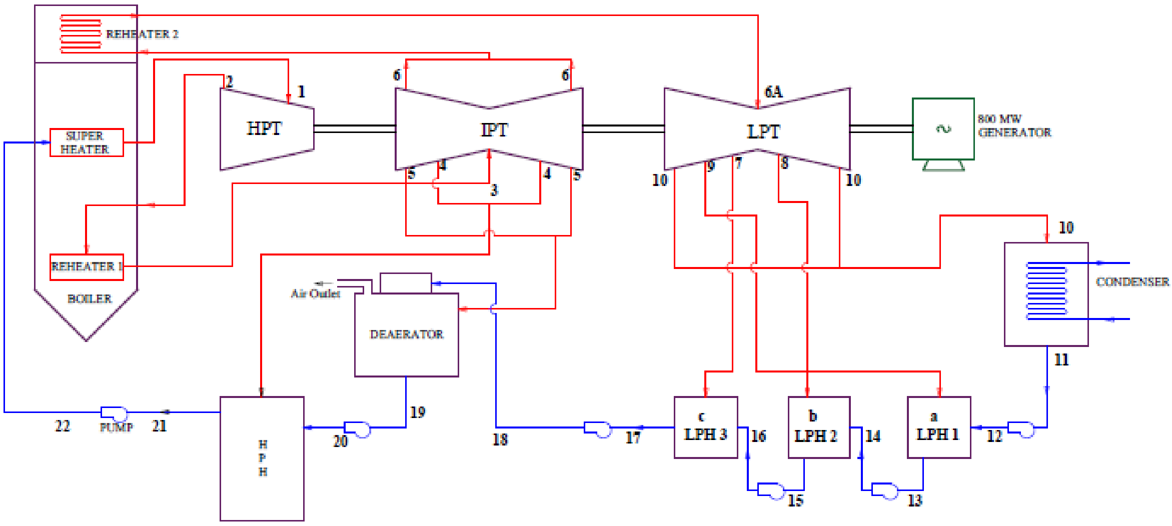


Fig 2: SC Powerplant with double reheat

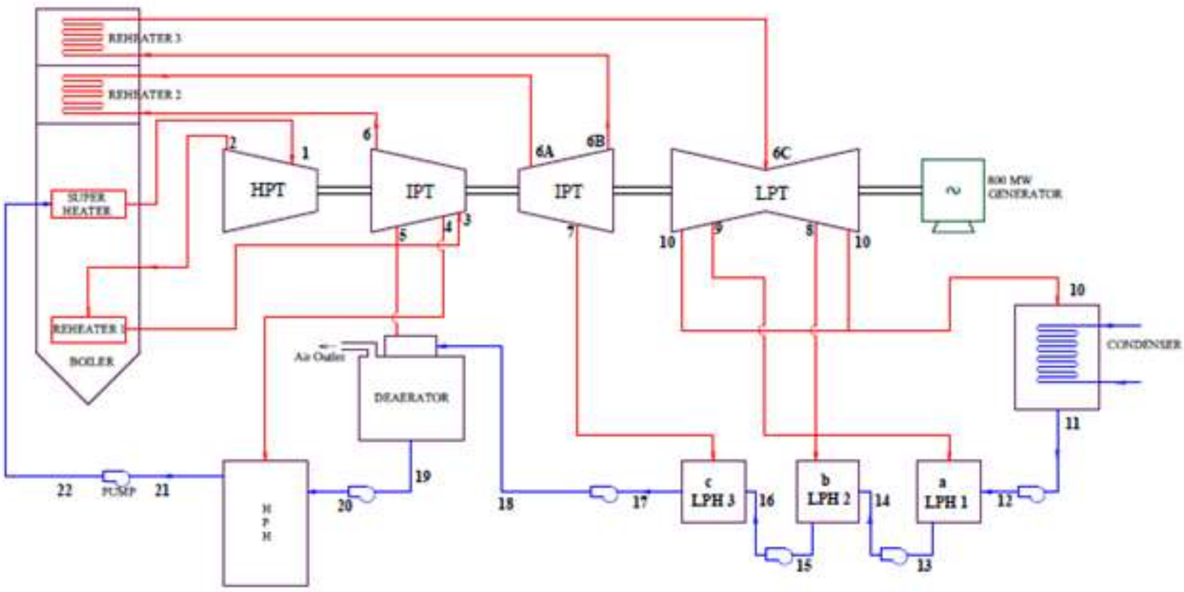


Figure 03. Schematic diagram of the SC with triple reheat

## ASSUMED SCENARIO FOR THE POWER PLANT ANALYSIS

1. Capacity of the supercritical power plant = 800 MW
2. The inlet turbine temperatures in the range of 500$^{O}$C – 800$^{O}$C
3. The inlet turbine pressures are in the range of 221bar – 350 bar
4. Reheat pressure ratio assumed is 0.1 – 0.5 times the initial pressure
5. No heat losses from the individual and no pressure losses
6. Isentropic efficiency of the steam turbine is 85%.
7. Cumulative Pump efficiency is assumed to be 85%.
8. Condenser pressure $P_c$= 0.03 –0.08 bar

9. Cooling water temperature inlet to the condenser $T_{wi}$=28$^0$C
10. The flue gas inlet temperature to the boiler is in the range of 900$^O$C to 1400$^O$C

## EXERGY ANALYSIS

**The Governing Exergy and Energy Equations used in the computational model Supercritical with single, double and triple reheats:**

As can be seen from the Fig 3 the number of feed water heaters is left as a variable parameter ‘n’ and thus the both the number feed water heaters as well as the number of stations at which properties are monitored in the plant are also variables. The numbering of the stations is done in such a way that starting from the first feed water heater, consecutive numbers are assigned to the steam bleed, the feed water heater exit, which is also the inlet for the feed pump which follows that heater, and the exit of the said feed pump. Thus station 1 and 2 are the steam bleed and exit stream of the feed water heater 1, station 4 in the feed water inlet (also the exit from and station 3 is the exit of the first feed pump which is also the inlet to the boiler. For an intermediate feed water heater ‘i’ the steam bleed will be from station ‘3i-2’, water inlet will be from station ‘3i+3’ and exit will be station ‘3i-1’. Similarly, for feed water heater ‘i’, the inlet and exit are ‘3i-1’ and ‘3i’, respectively. In addition, the turbine inlet, re-heater inlet, re-heater exit, turbine exit, and condenser exit are termed as stations ‘A’, ‘B’, ‘C’, ‘D’, ‘E’,’F’, and ‘G’ respectively.

The governing equations for each of the components in the steam power plant could be derived from the general steady flow mass, energy and exergy equations for a control volume given by Moran and Shapiro [7] as:

$$\Sigma_i m_i = \Sigma_e m_e \qquad (1)$$

$$\dot{Q}_{cv} + \sum_i m_i \left(h_i + \frac{V_i^2}{2} + z_i g\right) = \dot{W}_{cv} + \sum_e m_e \left(h_e + \frac{V_e^2}{2} + z_e g\right) \qquad (2)$$

$$\sum_j \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_{CV,j} + \sum_i m_i \mathbf{e}_{f,i} = \dot{W}_{cv} + \sum_e m_e \mathbf{e}_{f,e} + \dot{\mathbf{E}}_d \qquad (3)$$

Here $\mathbf{e}_f$ is the specific flow exergy which is defined as:

$$\mathbf{e}_f = (h - h_0) + T(s - s_0) + \frac{V^2}{2} + gz \qquad (4)$$

In all the components of the cycle, the kinetic and potential energy changes could be neglected. The specific equations for the each of the individual components are given below.

Industrial Engineering Journal
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Volume : 52, Issue 5, May : 2023

**Boiler**

Here only the water tube banks of the boiler are taken as the system. Thus the system becomes a single inlet single outlet control volume. Also, there is no work interaction in the boiler. With these assumptions and the notations given in the figure A the following equations are obtained for the boiler.

$$\dot{Q}_{boiler} = m_A(h_A - h_3) + m_B(h_C - h_B) \quad (5)$$

$$\dot{\mathbf{E}}_{d,boiler} = \left(1 - \frac{T_0}{T_{boiler}}\right)\dot{Q}_{boiler} + m_A\left(\mathbf{e}_{f,A} - \mathbf{e}_{f,3}\right) + m_B\left(\mathbf{e}_{f,C} - \mathbf{e}_{f,B}\right) \quad (6)$$

**Turbine**

The mass, energy and exergy equations for the turbine could be written as:

$$m_1 = m_3 + \sum_{l=1}^{n} m_{3l-2} \quad (7)$$

$$\dot{Q}_{turb} = m_A h_A + m_C h_C - m_B h_B - m_B h_B - \sum_{l=1}^{n} m_{3l-2} h_{3l-2} \quad (8)$$

$$\dot{\mathbf{E}}_{d,turb} = \left(1 - \frac{T_0}{T_{turb}}\right)\dot{Q}_{turb} + m_A\mathbf{e}_{f,A} + m_C\mathbf{e}_{f,\mathrm{C}} - m_B\mathbf{e}_{f,B} - m_D\mathbf{e}_{f,D} - \sum_{l=1}^{n} m_{3l-2}\mathbf{e}_{f,3l-2} - \dot{W}_{turb} \quad (9)$$

**Condenser**

As was done in the case of the boiler, only the hot fluid circuit in the condenser is analyzed as the system of interest. With the usual assumptions, the energy and exergy equations for the condenser could be written as

$$\dot{Q}_{cond} = m_D h_D - m_E h_E \quad (10)$$

$$\dot{\mathbf{E}}_{d,cond} = \left(1 - \frac{T_0}{T_{cond}}\right)\dot{Q}_{cond} + m_D\mathbf{e}_{f,D} - m_E\mathbf{e}_{f,E} \quad (11)$$

**Feed Water Heaters**

The mass conservation equation for any feed water ‘i’ is given by:

$$m_{3i-2} + m_{3i+3} = m_{3i-1} \quad (12)$$

The energy equation for the feed water heater ‘i’ is:

$$m_{3i-2}h_{3i-2} + m_{3i+3}h_{3i+3} = m_{3i-1}h_{3i-1} \quad (13)$$

The exergy equation is:

$$\dot{\mathbf{E}}_{d,Hi} = m_{3i-2}\mathbf{e}_{\mathrm{f},3i-2} + m_{3i+3}\mathbf{e}_{f,3i+3} - m_{3i-1}\mathbf{e}_{f,3i-1} \quad (14)$$

**Pumps**

For any feed pump ‘i’ other than the last feed water heater is, the energy and exergy equations are

$$W_{pump\ i} = m_{3i-1}(h_{3i} - h_{3i-1}) \quad (15)$$

$$\dot{\mathbf{E}}_{d,pump\ i} = m_{3i-1}(\mathbf{e}_{f,3i} - \mathbf{e}_{f,3i-1}) - W_{pump\ i} \quad (16)$$

Industrial Engineering Journal
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Volume : 52, Issue 5, May : 2023

The mass, energy and exergy equations for the last feed pump are given respectively by:

$$W_{pump\,n+1} = m_E(h_{3n-1} - h_E) \quad (17)$$

$$\dot{\mathbf{E}}_{d,pump\,n+1} = m_E(\mathbf{e}_{f,3n-1} - \mathbf{e}_{f,E}) - W_{pump\,n+1} \quad (18)$$

**Overall Performance**

The net amount of work generated in the power plant is given by:

$$W_{plant} = W_{turb} - \sum_{l=1}^{n+1} W_{pump\,i} \quad (19)$$

The efficiency of the plant can be calculated as:

$$\eta_{plant} = \frac{W_{plant}}{\dot{Q}_{boiler}} \quad (20)$$

The exergy efficiency of the plant is given by:

$$\eta_{plant} = \frac{W_{plant}}{\left(1-\frac{T_0}{T_{boiler}}\right)\dot{Q}_{boiler}} \quad (21)$$

The total exergy destruction in the plant is given by:

$$\dot{\boldsymbol{E}}_{d,plant} = \sum_{all\ components} \dot{\boldsymbol{E}}_d \quad (22)$$

**MATLAB Code for the model:** A computer code was developed using the scripting language MATLAB to solve the model equations given above. The code is written such that it takes the turbine inlet temperature and the pressure ratios for various stages of expansion as the input and calculates the mass, energy and exergy balances for each of the components to determine the thermodynamic performance characteristics of various components in the system. The amount of steam taken from each bleed is computed by assuming that in each feed water heater the condensate is heated to the saturation temperature at the corresponding pressure. Isentropic efficiencies of the turbines are assumed to be 85%. The net work output of the cycle is then computed. The mass flow rate of steam in the power plant is computed based on the total power generated by the plant and the specific work output of the cycle. Energy and exergy losses in each of the components are then estimated. The reheat pressure ratio and the reheat temperature are also given as input parameters and their effect on the cycle performance is analyzed.

## RESULTS AND DISCUSSION

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 5, May : 2023

The parametric investigation and comparative study was conducted for this simulated model power plant of Supercritical with single, double and triple reheats. The energy and exergy analysis for all the considered scenario's are carried out and presented below.

The operating conditions for Supercritical, Ultra Supercritical and advanced Ultra Supercritical power plants are taken from the national electricity plan released by central electricity authority of Government of India [1]. The range of operating parameters considered for this study are listed below table.

| Technology | Turbine inlet pressure | Turbine inlet temperature |
|---|---|---|
| Supercritical (SC) power plant | 221 bar to 250 bar | $500^{O}$ C to $600^{O}$ C |
| Ultra Supercritical (USC) power plant | 251 bar to 300 bar | $550^{O}$ C to $700^{O}$ C |
| Advanced Ultra Supercritical (AUSC) power plant | 301 bar to 350 bar | $700^{O}$ C to $800^{O}$ C |

## Supercritical power plant with single reheating:

The power plant simulated model for supercritical power plant scenario was run by varying pressure ratios ranging from 0.1 to 0.5.

**Comparison based on network output:**

Fig 4 shows the effect of reheat pressure ratio on the net work output of the supercritical power plant works with single, double and triple reheats. The operating parameters considered for this 800MW supercritical power plant are turbine inlet pressure 240 bar, turbine inlet temperature $580^{O}$C and condenser pressure 0.04 bar and pressure ratio is varied from 0.1 to 0.5.

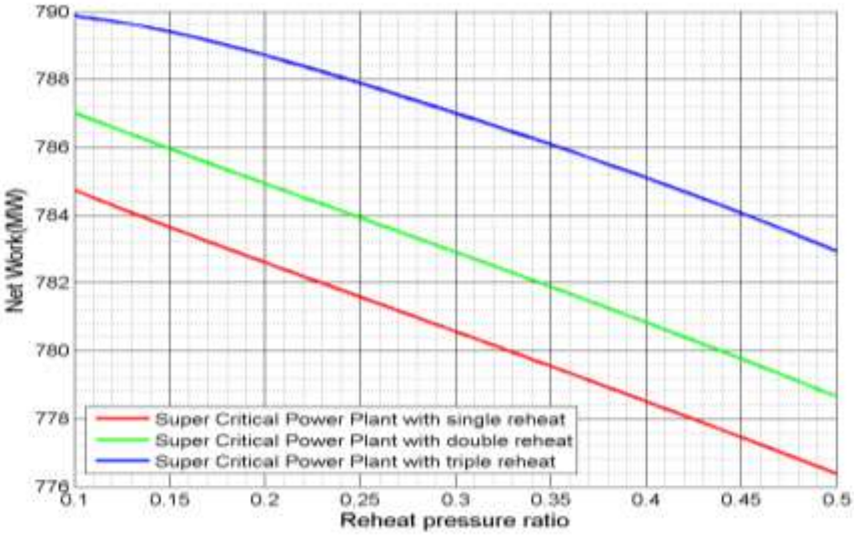


Fig 4: Impact of reheat pressure ratio on network output for supercritical power cycle with single, double and triple reheats.

In Fig 4 the trend indicates that, the net work output is reduced with the varying pressure ratio from 0.1 to 0.5. When the triple reheat is adopted instead of single reheat, a 3 MW increase in net work output is observed at 0.1 reheat ratio, and 4MW increase is observed after the reheat ratio of 0.22. The influence of this variation will be considered when the comparison carried out on energy efficiency and mass flow rate of steam required in later part of the current unit.

**Comparison based on Heat supplied:** Fig 5 illustrates that the impact of reheat pressure ratio on heat supplied for the supercritical power cycle with single, double and triple reheats.

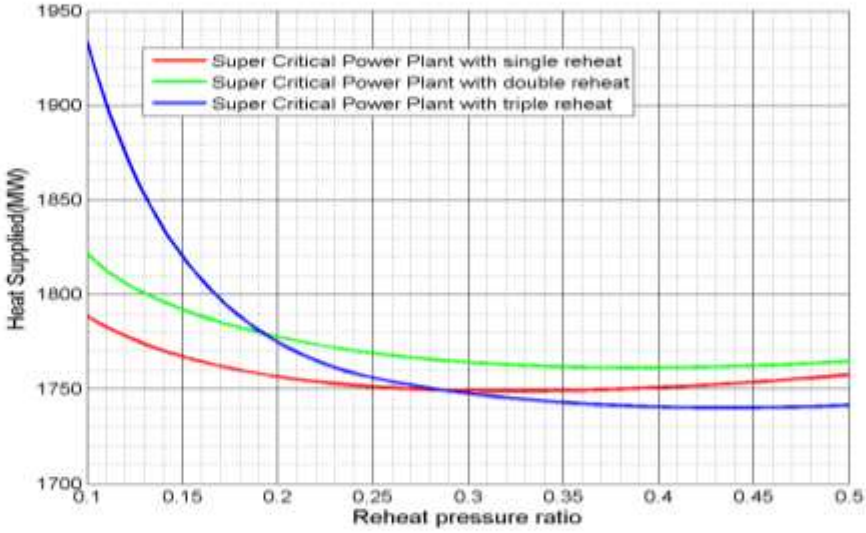


Fig 5: Heat supplied Vs Reheat pressure ratios for SC Powerplant with single, double and triple reheats.

The trend of the curves depicts the reduction in heat supplied with the increase in reheat ratio. Three separate curves are drawn to compare the heat supplied trends with the increase in reheat pressure ratio. It also could be observed a steep reduction in heat supplied till the reheat ratio increased to 0.3/0.34/0.38 for single/double/triple reheat ratio's which are optimum reheat pressure ratio's.

**Comparison based on energy efficiency:**

**Error! Reference source not found.** demonstrates the effect of reheat pressure ratio on energy efficiency of a supercritical power plant works with single, double and triple reheats. It illustrates the variation in energy efficiency with the increase in pressure ratio from 0.1 to 0.5. After the reheat ratio of 0.22 it is noted that, the energy efficiency of the triple reheat power plant is higher than the double and single reheats.

Industrial Engineering Journal
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Volume : 52, Issue 5, May : 2023

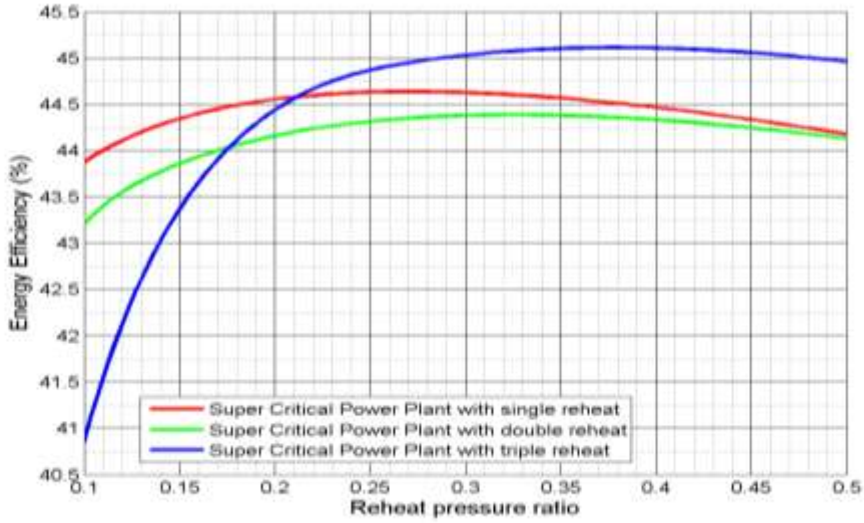


*Fig 6: Impact of reheat pressure ratio on energy efficiency for supercritical power cycle.*

Till this reheat pressure ratio the rate of reduction in heat supplied is more than the rate of reduction in net work output which causes the high rate of increase in energy efficiency.

It is noted that the energy efficiency of single reheat cycle is more than the double reheat, at all the reheat pressure ratios. The optimum reheat pressure ratio can be read as 0.27/0.33/0.38 for single reheat/double /triple reheat power cycles respectively. The corresponding energy efficiencies at these optimum pressure ratios are 44.64% / 44.39% / 45.12% . Also it can be noted that, after the optimum reheat ratio the energy efficiency curves for single reheat and double reheat are almost flat or goes down a little.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 5, May : 2023

**Comparison based on mass flow rate of steam:**

illustrates the effect of reheat pressure ratio on mass flow rate of steam, for the Supercritical power plant works with single, double and triple reheats. The operating parameters considered for the 800MW supercritical power plant are 240 bar / 580$^{O}$C / 0.04 bar and pressure ratio is varied from 0.1 to 0.5.

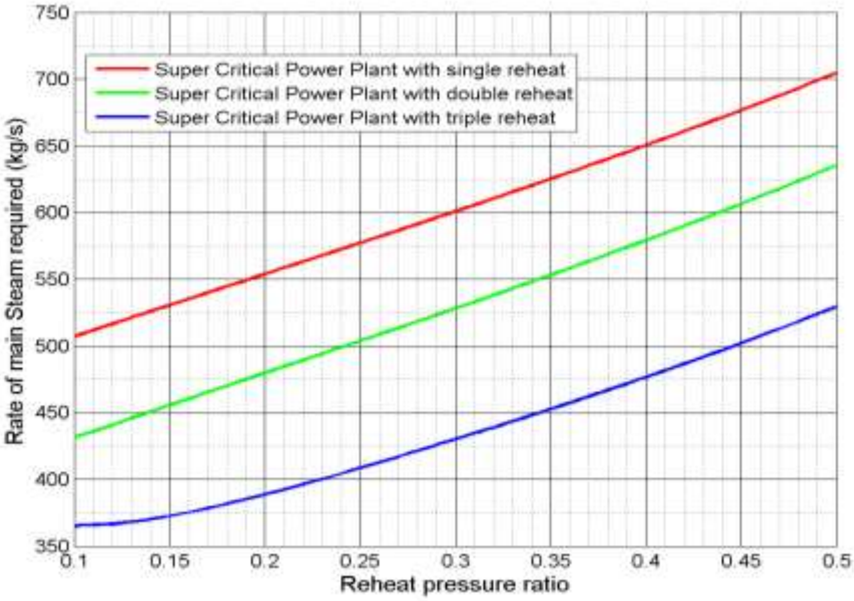


Fig 8: Impact of reheat pressure ratio on mass flow rate of steam required for supercritical power cycle

Three separate comparative curves in a single graph, are drawn between the main steam rate vs reheat pressure ratio which depicts the trends of single / double / triple reheat power cycles. These curves evidently indicate the increase in rate of main steam with the increase in reheat pressure ratio. The rate of main steam required at the optimum reheat pressure ratios 0.27/0.33/0.38 are 587/544/466 kg/s for the single/double/triple reheats respectively. It can be noted that the rate of main steam required is reduced from 600 kg/s to 430 kg/s when triple reheat is introduced instead of single reheat, for a given reheat ratio of 0.3. This reduction in mass of steam required leads to economic savings in power generation.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 5, May : 2023

**Comparison based on exergy destruction:**

Figure 9 demonstrates the effect of reheat pressure ratio on total exergy loss, of the Supercritical power plant for single, double and triple reheats. The operating parameters considered for the 800MW supercritical power plant are 240 bar / 580$^{O}$C / 0.04 bar and reheat pressure ratio is varied from 0.1 to 0.5.

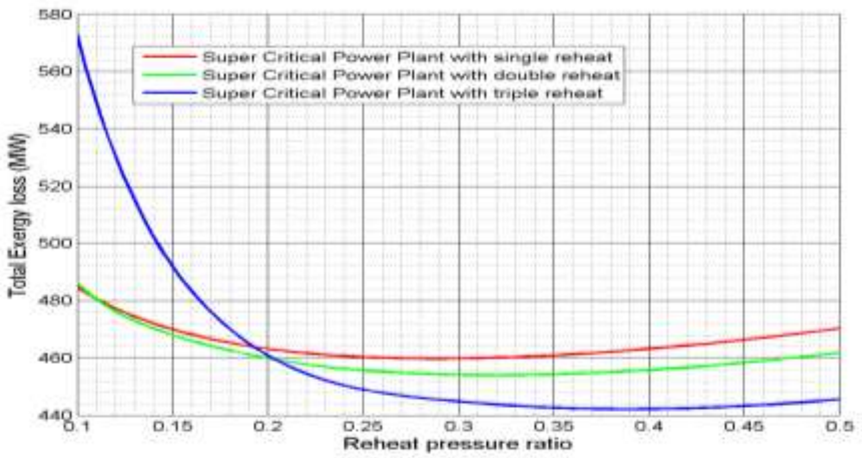


Fig 10: Exergy destruction in SC Power plant with single, double, triple reheats

Reduction in exergy loss can be viewed with the increase in reheat pressure ratio. Three separate curves are drawn to compare the total exergy loss trends with the increase in reheat pressure ratios.

The trend depicts that there is a steep reduction in exergy destruction till the reheat ratio increased to 0.25 in case of triple reheat and nominal reduction can be observed on further increase in reheat ratio. Unlike triple reheat in case of single and double reheat a uniform decrease in exergy loss can be noticed with increase in reheat pressure ratio. The amount of exergy destruction at optimum reheat ratios of 0.27/0.288/0.368 are 459/454/442 MW for single/double/triple reheats respectively.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 5, May : 2023

**Comparison based on exergy efficiency:**

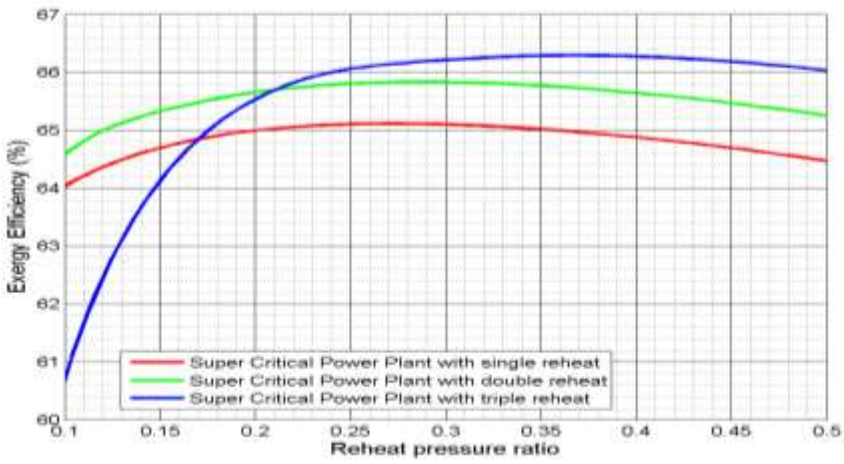


Fig 11: Exergy efficiency - SC Power plant with single, double, triple reheats

Fig 11 shows the effect of reheat pressure ratio on exergy efficiency of Supercritical power plant works on single, double and triple reheats. The operating parameters considered for the 800MW supercritical power plant are 240 bar / 580$^{O}$C / 0.04 bar and pressure ratio is varied from 0.1 to 0.5. The exergy efficiency curves indicates the increase in exergy efficiency with the increase in pressure ratio from 0.1 to 0.5. Also the exergy efficiency of the triple reheat power plant is higher than the double reheat and single reheat after the reheat pressure ratio crosses 0.25.

The optimum reheat pressure ratios observed are 0.27/0.288/0.368 for single reheat/double /triple reheat power cycles. The corresponding exergy efficiencies for these optimum pressure ratios are 65.12% / 65.84% / 66.3% . Also it can be noted that, after the optimum reheat ratio the trends of the exergy efficiency curves for single reheat and double reheat are almost flat or goes down a little.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 52, Issue 5, May : 2023

**Comparison based on flue gas inlet temperature to the boiler:**

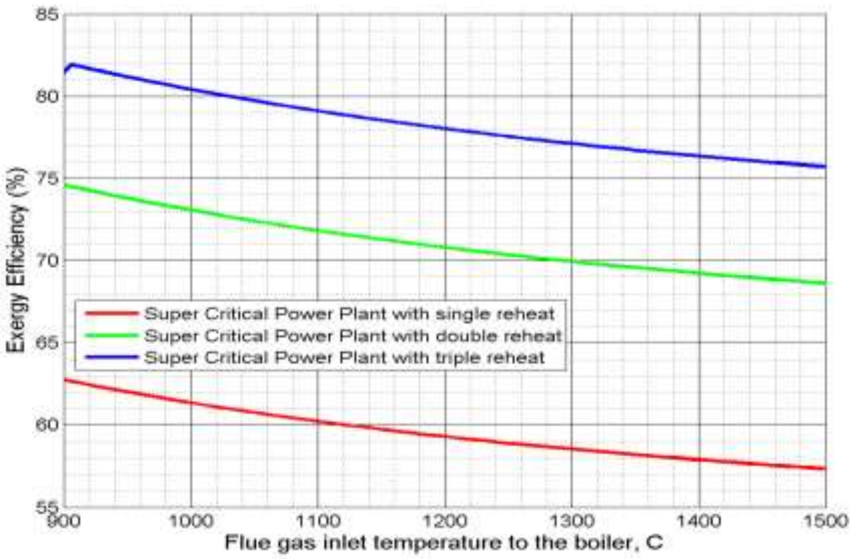


Fig 12: Impact of flue gas inlet temperature on exergy efficiency

Fig 12 demonstrates the effect of flue gas inlet temperature on exergy efficiency of the supercritical power plant works with single, double and triple reheats. The operating parameters considered for the 800MW supercritical power plant are 240 bar / 580$^{O}$C / 0.04 bar and the flue gas inlet temperatures varied from 900$^{O}$C to 1500$^{O}$C.

It can be noted that, the exergy efficiency increases with the use of triple reheat instead of double and double reheat in place of single reheat. And also the exergy efficiency found reduced by varying the flue gas inlet temperatures for each of the cases i.e single, double and triple reheats.

## CONCLUSION

This research paper analyzed the supercritical (SC) power plant cycle with single, double, triple reheats in a terms of energy efficiency and exergy efficiency. The energy losses and exergy losses were calculated for all these power plant scenarios with single, double and triple reheat. It is observed that the power plant efficiency of double reheat is better that of single and triple reheat conditions. It is also concluded that exergy efficiency is maximum for the SC power plant with double reheat processes. The exact critical reheat pressure ratios were found, observed and calculated for SC power plant with single, double and triple reheats. In which it is concluded that SC power plant with double reheat provide best results of energy and exergy efficiencies when compared with single and triple reheats.

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