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THERMODYNAMIC ANALYSIS OF 1200 MW COAL BASED SUPERCRITICAL THERMAL POWER PLANT WITH SINGLE AND DOUBLE REHEATING

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ABSTRACT

This paper presents Thermodynamic analysis of Supercritical Rankine cycle withsingle reheat and double reheat for a modern steam power plant with power generating capacity of 1200 MW. A Software code has been developed to estimate the steam properties using Matlab. The Temperature and pressure at exit and entry of turbine are considered for this study. Cycle energy efficiency and exergy efficiency have been studied. Effect of single reheat Pressure and double reheats in the cycle also been studied. It is observed that both efficiencies increases more with temperature rise than pressure rise. The exergy loss in these individual components have been studied and analyzed by varying the above selected parameters.

KEYWORDS: Supercritical cycle, cycle efficiency, exergy efficiency, fractional exergy loss

INTRODUCTION

Steam Reheatingis a vital process in order to maintain the steam quality to more than 0.85, and employed in conventional steam-power plants. The steam after partial expansion 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. Major source of power generation across the globe as well as in India is from the coal combusted power plants. Societal and economic development is only possible by conserving the energy. By adopting the supercritical technology, we could conserve a greater amount energy which also helps to attain the reduced emissions to the atmosphere. Employing the steam above critical point enables to attain higher power plant efficiencies also lowers fuel consumption significantly simultaneously reduction in emissions for the same amount of power generation.

Exergy analysis is the method of analyzing the energy transformation or conversion which could be calculated based on available/potential quantity of fuel energy. An exergy analysis is carried out for the selected coal combusted supercritical thermal power plant which is focused on the energy convertibility / potential to convert during all the individual processes.

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 geneator. And also the variationsinchemical 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 havebeen 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.

Analysis of thermal power plants by means of the cycle efficiency is a prominent topic in the mechanical engineering. The exergy analysis provides convertibility of the energy and the corresponding efficiency of the supercritical cycle, where asthe conventional energy method gives overall efficiency value which is based on first law of thermodynamics. The steam which is the vapour form of water is the working fluid which is used in vapor power cycles. Thewater is having the desirable characteristics of the working medium that could be used in Rankine cycle. Few required characteristics are abundant availability, reusability, enthalpy of vaporization and low cost. Steam power plants are commonly coal combusted power plants, nuclear power plants, geothermal or natural gas plants. In all these power plants the source is heat given to the water would be different and the working medium would be the vapour form of water which could be used in all these basic cycles. Therefore, all these power plants could be analyzedby using the exergy and energy techniques.

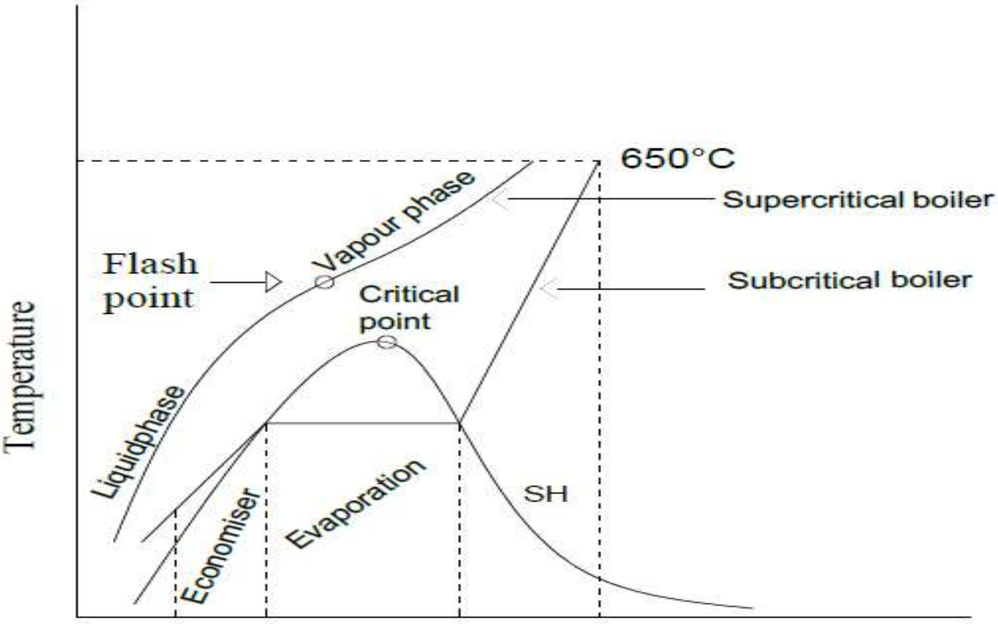

Figure 01: Demonstration of supercritical heating and subcritical heating

This paper analyses a supercritical steam cycle emphasizing the exergy by it application without reheat, reheat and double reheat. The effect of decreasing the discharge pressure from the condenser, Effect of reheat pressure in the boiler has been studied. It is observed that both the efficiencies increases more in temperature rise than the pressure rise. The variations of these reheat temperature and pressure ratios and related exergy losses of individual componentsalso being studied.

SUPERCRITICAL CYCLE DESCRIPTION

The figure 2 demonstrates the supercritical rankine cycle with single reheat and figure 2 shows with double reheat. The flue gas inlet temperatures considered for this study is in the range of 900^{O}C – 1400^{O}C and the exit temperature is in between 90^{O}C – 160^{O}C. The steam at supercritical temperature enters the turbine and gets expanded till state point 2(Process 1-2), further the expanded steam is taken back to the boiler heated up to desired inlet turbine temperature (Process 2-3). The steam gets expanded in low pressure turbine till state point 4 (Process 3-4). The other processes such as cooling process in condenser and heat addition to the feedwater, pumping the water back to the boiler for steam generation, makes the closed rankine power cycle. The Challenge is that, identifying the reheat pressure point and the pressure at which the steam need to be expanded in the last stage of the turbine. i.e condenser pressure at which the vapour form of water gets cooled to liquid form.

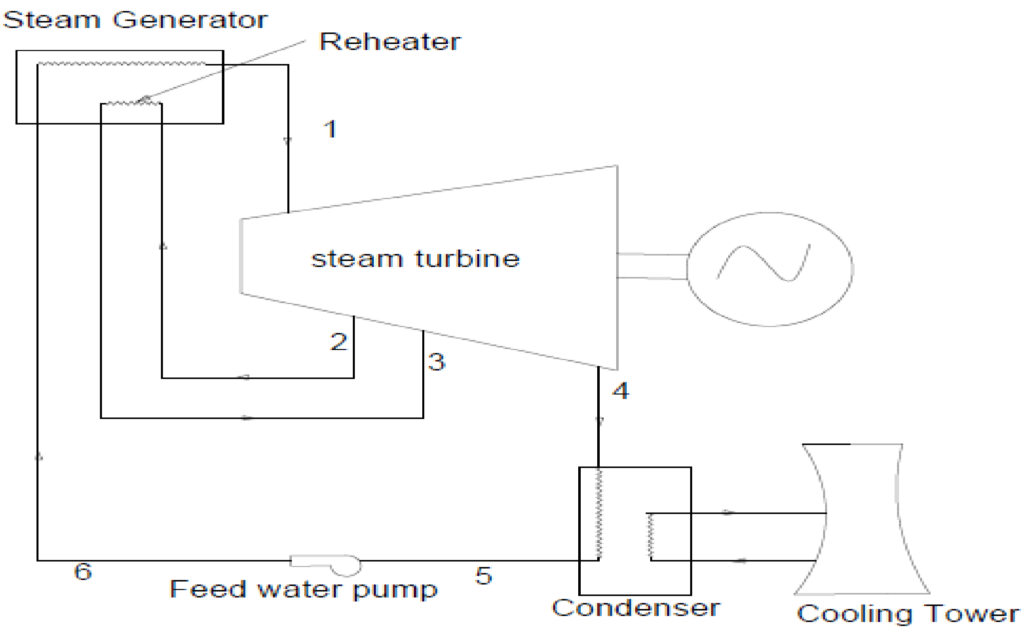

Figure02. Schematic diagram of the supercritical cycle with single reheat

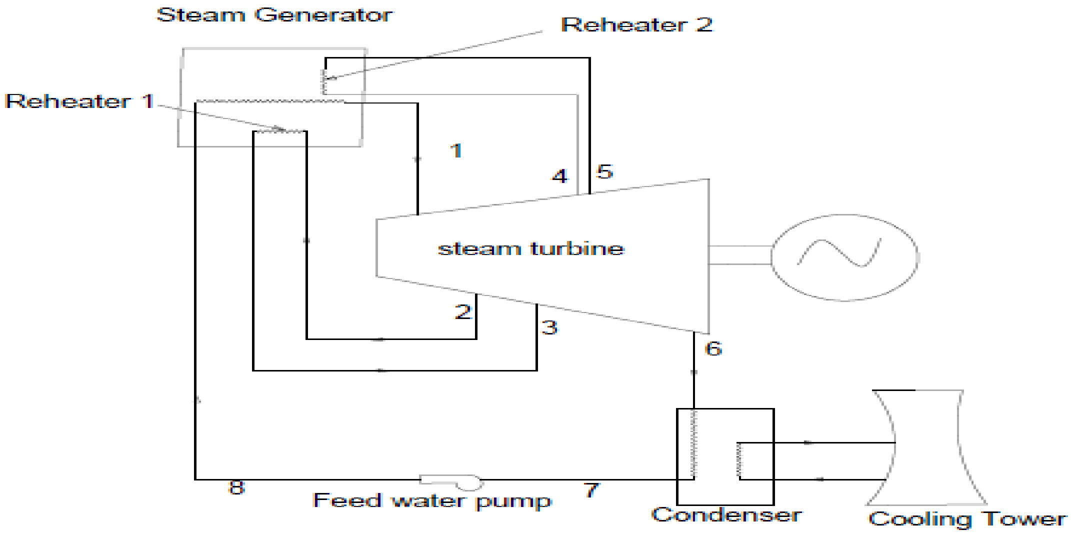

Figure03. Schematic diagram of the supercritical cycle with double reheat

The figure 3 demonstrates the supercritical rankine cycle with double reheat. The flue gas inlet temperatures considered for this study are in the range of 900^{O}C – 1400^{O}C and the exit temperature is in between 90^{O}C – 160^{O}C. The steam at supercritical temperature enters the turbine and gets expanded till state point 2(Process 1-2), further the expanded steam is taken back to the boiler heated up to desired inlet turbine temperature (Process 2-3). The steam gets expanded in pressure turbine till state point 4 (Process 3-4). Further the expanded steam is taken back to the steam generator to rise its temperature till it gets the desired inlet turbine temperature (process 4-5). Then the steam is expanded to the state point 6 (Process 5-6). The other processes such as cooling process in condenser and heat addition to the feedwater, pumping the water back to the boiler for steam generation, makes the closed rankine power cycle. The Challenge is that, identifying the reheat pressure point and the pressure at which the steam need to be expanded in the last stage of the turbine. i.e condenser pressure at which the vapour form of water gets cooled to liquid form.

ASSUMED SCENARIO FOR THE POWER PLANT ANALYSIS

1. Capacity of the supercritical power plant = 1200 MW
2. The inlet turbine temperatures in the range of $600^{O}C$ – $800^{O}C$
3. The inlet turbine pressures are in the range of 280bar – 380 bar
4. Reheat pressure ratio assumed is 0.1 – 0.32 times the initial pressure
5. No heat losses from the individual and no pressure losses
6. Isentropic efficiency of the steam turbine is 90%.
7. Cumulative Pump efficiency is assumed to be 95%.
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

This analysis is performed based on the availability and unavailability concepts. The following empirical equations are being used to calculate the Rankine cycle efficiency for the supercritical without reheat, with single reheat and double reheat. Part of it the work output and heat addition also being calculated for no reheat cycle, single reheat cycle and double reheat cycle cases.

No Reheat Cycle

The work output per kg of steam supplied to the turbine,

$$W_{turb}= h_1 – h_2 \quad kJ/kg \qquad (1)$$

The Pump work required per kg of steam supplied,

$$W_p= h_4 – h_3 \quad kJ/kg \qquad (2)$$

Heat supplied to the steam generator

$$Q_{Supply} = h_1– h_4 \quad kJ/kg \qquad (3)$$

Single Reheat Cycle

The work output per kg of steam supplied to the turbine,

$$W_{turb} = (h_1 – h_2) + (h_3 – h4) \quad kJ/kg \qquad (4)$$

The Pump work required per kg of steam supplied,

$$W_p = h_6 – h_5 \quad kJ/kg \qquad (5)$$

Heat supplied to the steam generator,

$$Q_{Supply} = h_1– h_6 \quad kJ/kg \qquad (6)$$

Double Reheat Cycle

The work output per kg of steam supplied to the turbine / Work output in HP, IP & LP Turbines,

$$W_{turb} = ((h_1 – h_2) + (h_3 – h4) + (h_5 –h_6)) \quad kJ/kg \qquad (7)$$

The pump work required per kg of steam supplied,

$$W_{pump} = (h_8 – h_7) kJ/kg \qquad (8)$$

The heat supplied to steam generator,

$$Q_{Supply} = h_1– h_8 \quad kJ/kg \qquad (9)$$

$$W_{network} =W_{turb} - W_p \quad kJ/kg \qquad (10)$$

The rankine cycle efficiency is the ratio of net workoutput to the total heat supplied to the system.

The Rankine Cycleefficiency=$W_{network}/Q_{Supply}$ (11)

Steam Rate or Rate of steam per KW-hour = 3600/$W_{network}$ kg/kW-hr (12)
Rate of heat supplied / Heat Rate = 3600/Cycle efficiency kJ/kW-hr (13)
Work Ratio = $W_{network}/W_{turb}$ (14)

EMPIRICAL FORMULAE FOR EXERGY EFFICIENCY

The exergy analysis focusses on the quantitative evaluation of the exergy destructions and losses due to irreversibility, associated with the processes which are under goes by system. In order to estimate the exergy efficiency the irreversibility's of all the individual components of the power plant cycle need to be calculated. The irreversibility or exergy destruction for each of the thermal equipment need to be calculated for the specified dead state. Let P_O, T_O are the pressure and temperature of the system at the dead state.

$$Q_A = \left(\theta_A - \theta^0\right)\sum_k n_k \tilde{c}_{pk}^{\,h} \text{ kJ} \qquad (15)$$

$$Q_B = \left(\theta_B - \theta^0\right)\sum_k n_k \tilde{c}_{ph}^{\,h} \text{ kJ} \qquad (16)$$

$$e_A = \left(\theta_A - \theta^0\right)\sum_k n_k \tilde{c}_{pk}^{\,\varepsilon} \text{ kJ} \qquad (17)$$

$$e_B = \left(\theta_B - \theta^0\right)\sum_k n_k \tilde{c}_{pk}^{\,\varepsilon} \text{ kJ} \qquad (18)$$

The irreversibility or exergy destruction is caused due to reduction in availability function across the thermal equipment in the power plant cycle. Exergy of the inlet temperature of the flue gas at the entry of the steam generator, for the range of temperature · $_A$ = 900°C to 1400°C and · $_B$ = 90°C to 160°C and · ^{0}=30°C, for all these variants of the combusted products composition the enthalpy and exergy values could be calculated.
Themean isobaric heat capacity in order to evaluate enthalpy changes is given by

$$\bar{c}_p{}^h = \left[\frac{\bar{h} - \bar{h}^0}{T - T_0}\right] = \frac{1}{T - T_0}\int_{T_0}^{T} \bar{c}_p dT \text{ and} \qquad (19)$$

Mean molar isobaric exergy capacity in order to evaluate the changes in physical exergy is

$$\bar{c}_p^{\,\varepsilon} = \left[\frac{\bar{\varepsilon}^{\Delta T}}{T - T_0}\right] = \frac{1}{T - T_0}\left[\int_{T_0}^{T} \bar{c}_p dT - T_0\int_{T_0}^{T}\frac{\bar{c}_p dT}{T}\right] \qquad (20)$$

Where Q_A = Enthalpy of flue gases at the entry of the steam generator,
Q_B = Enthalpy of flue gases at the exit of the steam generator
e_A= Exergy of the flue gas at the entry of the steam generator
e_B= Exergy of the flue gas at the exit of the steam generator

The values of Q_A, Q_B, e_A, and $e_B$are the enthalpy and exergy parameters for the selected supercritical cycle, single reheat cycle and double reheat rankine cycle.

Single Reheat Cycle

Steam generator

The mass of stream produced for the given rate of flue gases could be calculated from the energy balance equation. Based on the capacity of the power plant the mass of the steam could be calculated.
m_s= 1000x1200kg/sec (21)
Applying the energy balance equation ,
Heat lost by the flue gases = Heat gained by the steam
$m_s((h_1– h_6)-(h_3-h_2)) = m_g(Q_A – Q_B)$
$m_g = m_s((h_1– h_6)-(h_3-h_2)) /(Q_A – Q_B)$ kg/Sec (22)
$I_{steamgen} = m_g(e_A-e_B) – m_s((h_1– h_6)-(h_3-h_2)) – (T_0(s_1-s_6) – T_0(s_3 –s_2))$ kW (23)

Steam Turbine

The irreversibility rate in the steam turbine would be calculated by Gouy-Stodola equation is

$I_{turb}=T_0.\ [m_s((s_2-s_1)+(s_4-s_3))\ ]$ kW (24)

Condenser

The mass of cooling water required to be circulated for effective condensation perkg mass of steam could be calculated from the energy balance equation is

$m_{cw}C_{pw}(T_{wi}-T_{wo})= m_s\ (h_4-h_5)$ (25)

Mass flow rate of cooling water is, $m_{cw}= m_s(h_4-h_5)/\ C_{pw}(T_{wi}-T_{wo})$

The Irreversibility or exergy destruction in condenser could be calculated from,

$I_{cond}=T_0[m_{cw}C_{pw}\ln(T_{wi}/T_{wo})–m_s(s_4-s_5)]$ kW (26)

Pump

Irreversibility or exergy destruction in feed pump is ,

$I_p=m_sT_0(s_6-s_5)$ kW (27)

Exhaust

Irreversibility or exergy destruction caused due to the exhaust of the flue gasses is given by , $I_{exha} = e_B$

DoubleReheat

The mass of stream produced for the given rate of flue gases could be calculated from the energy balance equation. Based on the capacity of the power plant the mass of the steam could be calculated.

$m_s= 1000x1200$ kg/sec (28)

Applying the energy balance equation

Heat gained by the steam = Heat lost by the flue gases.

$m_s((h_1– h_8)-(h_3-h_2) –(h_5 –h_4)) = m_g(Q_A – Q_B)$

$m_g = m_s((h_1– h_8)-(h_3-h_2) –(h_5 –h_4))/\ (Q_A – Q_B)$ (29)

Steam Turbine

The irreversibility rate in the steam turbine would be calculated by Gouy-Stodola equation is

$I_{turb}=T_0.m_s((s_6-s_1)+(s_3-s_2) + (s_5 – s_4))$ kW (30)

Condenser

Mass of cooling water circulated to condense ms kg of steam is obtained from the energy balance is

$m_{cw}C_{pw}(T_{wi}-T_{wo})= m_s\ (h_6-h_7)$ (31)

$m_{cw}= m_s(h_6-h_7)/\ C_{pw}(T_{wi}-T_{wo})$

The Irreversibility or exergy destruction in condenser could be calculated from,

$I_{cond}=T_0[m_{cw}C_{pw}\ln(T_{wi}/T_{wo})–m_s(s_6-s_7)]$ kW (32)

Pump

Irreversibility or exergy destruction in feed pump is,

$I\ _p=m_sT_0(s_8-s_7)$ kW (33)

Exhaust

Irreversibility or exergy loss through the exhaust, $I_{exhaust} = E_B$

Total Irreversibility is

$\cdot\ I =I_{steamgen} + I_{turb} + I_p + I_{cond} + I_{exha}$kW (34)

Hence, based on the definitions of many thermal professionals the exergy efficiency could be defined as the ratio of exergy output to the exergy input. Exergy output depends on the degree of Irreversibility of the cycle.

Exergy efficiency, $$\eta exergy = \frac{e_A - \sum I}{e_A} * 100 \qquad (35)$$

RESULTS AND DISCUSSION

A Matlab simulation program is the basis for this analysis. Considered and tested various live steam temperatures and pressures of the supercritical power plants. The analysis has been done by considering the optimum reheat pressure ratio as 0.22. It is observed from figure 4 shows that with the increase in Temperaturecauses the increase in cycle efficiency for a supercritical cycle with single and double reheat .

Figure05: Effect of increase inturbine inlet temperatures on rankine cycle efficiency

figure 5 demonstrates that for a double reheating, the exergy efficiency also increased with the increase in Turbine inlet Temperature. The increase in exergy efficiency is high for a supercritical cycle double reheat cycle than the single reheat cycle. It is also observed that the increase in cycle efficiency is very less for the increase in turbine inlet Temperature limits. At 325 bar / 700^0C, the cycle efficiency single reheat/double reheat is 46.45% / 49.4%. At 350 bar / 650^0C, the cycle efficiency single reheat/double reheat is 45.40% / 47.92%.

Figure06: Effect of increase in Turbine inlet Temperature on exergy efficiency

CONCLUSION

This paper analyzed the supercritical cycle with single and double reheats in a termsof energy efficiency and exergy efficiency. The total exergy loss and fractional exergy losses are calculated for the cycle with single reheat and double reheat. It is observed that the cycle efficiency is high in double reheat than the single reheat supercritical cycle. It is also concluded that exergy efficiency is high in double reheat than in single reheat supercritical cycle. The higher cycle efficiency and exergy gains can be achieved by using the higher steam pressures and temperatures on a single and double reheat supercritical cycle.

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