CHAPTER 6

THERMODYNAMIC ANALYSIS OF SUPERCRITICAL RANKINE CYCLE WITH DOUBLE REHEAT

A detailed thermodynamic analysis of supercritical Rankine cycle with single reheat and optimization of reheat pressure ratio of steam based 1000MW power plant was carried out in Chapter 5. In this chapter, thermodynamic analysis of Rankine cycle with double reheat and optimization of second reheat pressure ratio of this cycle are presented.

6.1 SUPERCRITICAL CYCLE WITH DOUBLE REHEAT

Figure 6.1 Schematic diagram of the supercritical Rankine cycle with double reheat

Fig. 6.1 shows the flow diagram of the supercritical Rankine cycle with double reheat. The high pressure and high temperature steam from the boiler in the supercritical condition enters the turbine at turbine at state
1 and undergoes the adiabatic reversible expansion process 1-2s as shown in p-v diagram(Fig.6.2), T-s diagram(Fig.6.3) and h-s diagram(Fig.6.4) of the cycle. In this process steam gets partially expanded. However, the actual process of expansion in the turbine has been represented by the process 1-2 and steam comes back to the boiler at state 2 where it gets reheated, at constant pressure by flue gases during process 2-3 and then fed to the turbine for further expansion. The steam reenters the turbine at state 3 and expands in the turbine to state 4. Further the process 3-4s represents the theoretical expansion in the turbine and again further steam is reheated at a constant pressure to state 5. The steam further expands in reversible adiabatic expansion process in the turbine to state 6s during process 5-6s and actually the steam comes out of the turbine at condition 6 in both the phases of liquid and vapour by actual process of expansion,5-6. Thus, steam re-enters in the turbine twice and expands up to condenser pressure. The steam gets condensed during the process 6-7 in the condenser and the condensate gets pumped to the boiler as shown in the process 7-8 where as the process 7-8s represents the ideal pumping process. This condensate (water) gets heated at constant pressure from state 8 to state 1 in the boiler to form steam at state 1. “A” and “B” represents the flue gas inlet and outlet points of the boiler, in which heat transfer from the flue gas to water/steam takes place. Thus the steam generated in the boiler at state 1 will be taken to turbine and thereby the cycle gets repeated.
Figure 6.2 P-v diagram of supercritical Rankine cycle with double reheat
Figure 6.3 T-s diagram of supercritical Rankine cycle with double reheat

Figure 6.4 h-s diagram of supercritical Rankine cycle with double reheat
6.2 FLOWCHART OF SUPERCRITICAL RANKINE CYCLE WITH DOUBLE REHEAT

- Enter $P_1$ (bar), $T_1$ ($^\circ$C), $P_0$ (bar)
- Enter First Reheat Pressure ratio, $R_1$ (0.25)
- Calculate the steam property data ($h_1, h_2, h_3, s_1, s_2, s_3$)
- Enter Second Reheat Pressure ratio, $R_2$
- Calculate the steam property data ($h_4, h_5, h_6, h_7, h_8, s_4, s_5, s_6, s_7, s_8$)
- Identify the components and its related equations (Boiler, Turbine, Condenser, Pump)
- Energy Efficiency
- Enter Flue gas outlet and inlet temperatures ($^\circ$C)
- Calculate irreversibilities of the Supercritical Rankine cycle with single reheat
- Exergy Efficiency

Fig. 6.5 Flow diagrams for finding exergy analysis of Supercritical Rankine cycle with double reheat
6.3 ENERGY EFFICIENCY OF SUPERCRITICAL RANKINE CYCLE WITH DOUBLE REHEAT

Energy efficiency of supercritical Rankine cycle with double reheat, 

Energy efficiency = \( \frac{W_{\text{net}}}{H.S} \) \hspace{1cm} (6.1)

Where, 

\[ W_{\text{net}} = W_{\text{turbine}} - W_{\text{pump}} \] \hspace{1cm} (6.2)

The work done by the turbine per kg of steam supplied, 

\[ W_{\text{turbine}} = ((h_1 - h_2) + (h_3 - h_4) + (h_5 - h_6)) \text{ kJ/kg} \] \hspace{1cm} (6.3)

The work done per kg of water pumped on boiler feed pump, 

\[ W_{\text{pump}} = h_8 - h_7 \text{ kJ/kg} \] \hspace{1cm} (6.4)

Heat supplied to water/steam in the boiler per kg of steam produced, 

\[ H.S = (h_1 - h_8) + (h_3 - h_2) + (h_5 - h_4) \text{ kJ/kg} \] \hspace{1cm} (6.5)

6.4 EXERGY EFFICIENCY OF SUPERCRITICAL RANKINE CYCLE WITH DOUBLE REHEAT

The enthalpies and exergies at inlet to the boiler and at outlet from the boiler for the given 1000 MW capacity have been found by using the equations from 4.6 to 4.11 were used in the chapter 4 for exergy analysis of supercritical Rankine cycle with double reheat.

6.4.1 ESTIMATION OF IRREVERSIBILITY OR EXERGY LOSS IN DIFFERENT COMPONENT OF SUPERCRITICAL RANKINE CYCLE WITH DOUBLE REHEAT

6.4.1.1 Boiler:
The mass flow rate of the steam to be generated in the boiler to produce an output of 1000 MW power can be found from the energy balance as given below:

\[ m_s(W_{net}) = 1000 \text{ MW} \]

\[ m_s = 1000 \times 1000 \text{ kW/}W_{net} \text{ kg/sec} \quad (6.6) \]

In this the mass flow rate of the flue gas \((m_g)\) required to obtain the required mass flow rate of steam can be found by the energy balance equation.

Heat gained by the steam = Heat lost by the flue gas

\[ m_s((h_1- h_8)+(h_3- h_2) +(h_5 -h_4)) = m_g(h_A - h_B) \]

\[ m_g = m_s((h_1- h_8)+(h_3- h_2) +(h_5 -h_4))/(h_A - h_B) \text{ kg/sec} \quad (6.7) \]

Exergy or Availability at different state points are given below:

\[ G_1 = E_1 = m_s (h_1-T_{o1}) \text{ kW} \quad (6.8) \]
\[ G_2 = E_2 = m_s (h_2-T_{o2}) \text{ kW} \quad (6.9) \]
\[ G_3 = E_3 = m_s (h_3-T_{o3}) \text{ kW} \quad (6.10) \]
\[ G_4 = E_4 = m_s (h_4-T_{o4}) \text{ kW} \quad (6.11) \]
\[ G_5 = E_5 = m_s (h_5-T_{o5}) \text{ kW} \quad (6.12) \]
\[ G_8 = E_8 = m_s (h_8-T_{o8}) \text{ kW} \quad (6.13) \]

Irreversibility in the boiler is

\[ I_{boiler} = (E_A-E_B) - (E_1 - E_8) -(E_3 - E_2)- (E_5 - E_4) \]

\[ I_{boiler} = m_g(E_A-E_B) - m_s((h_1- h_8 )-(h_3- h_2) - (h_5-h_4)) - \]
6.4.1.2 Steam Turbine:
The irreversibility in the steam turbine given by Gouy-Stodola equation is
\[ I_{turbine} = T_0 m_s ((s_2 - s_1) + (s_4 - s_3) + (s_6 - s_5)) \text{ kW} \] (6.15)

6.4.1.3 Condenser:
Mass flow rate of cooling water required to be circulated to condense \( m_s \), kg/s, of steam is obtained from the energy balance as shown below.
\[ m_{cw} C_{pw} (T_{wi} - T_{wo}) = m_s (h_6 - h_7) \] (6.16)
\[ m_{cw} = m_s (h_6 - h_7) / C_{pw} (T_{wi} - T_{wo}) \]

Irreversibility in the condenser,
\[ I_{condenser} = T_0 [m_s (s_6 - s_7) - m_{cw} C_{pw} \ln(T_{wo}/T_{wi})] \text{ kW} \] (6.17)

6.4.1.4 Pump:
Irreversibility in the boiler feed pump,
\[ I_{pump} = m_s T_0 (s_8 - s_7) \text{ kW} \] (6.18)

6.4.1.5 Exhaust:
Irreversibility of the exhaust, \( I_{exhaust} = E_B \) (6.19)

6.4.1.6 Total Irreversibility:
Total Irreversibility is
\[ \Sigma I = (I_{boiler} + I_{turbine} + I_{pump} + I_{condenser} + I_{exhaust}) \text{ kW} \] (6.20)

6.4.1.7 Exergy Efficiency:
Exergy efficiency, \( \eta_{II} = \frac{E_A - \sum I}{E_A} \times 100 \) (6.21)
6.5 PARAMETRIC EFFECT ON THE PERFORMANCE OF SUPERCRITICAL RANKINE CYCLE WITH DOUBLE REHEAT

6.5.1 Optimization of Second reheat pressure ratio

In the section 5.5.1 the optimum value of first reheat pressure ratio was found and the second reheat pressure ratio (R₂) is to be optimized for different values of turbine inlet temperature and pressure.

To optimize the second reheat pressure ratio, the variations in energy efficiency of cycle has been plotted as a function of it in Fig. 6.6., for a given turbine inlet pressure of 350bar, condenser pressure of 0.05bar and for different turbine inlet temperatures.

![Graph showing variation of energy efficiency with second reheat pressure ratio](image)

Fig 6.6 Variation of energy efficiency of SCRC with DRH with second reheat pressure ratio of turbine inlet temperature

It can be seen from the figure that, energy efficiency increases with an increase of reheat pressure ratio from 0.2 to 0.25 and decreases from 0.25 to 0.4. Further, on careful observation it may also be noted that optimum reheat pressure ratio is 0.25 at all turbine inlet temperatures in
the range of 500°C-800°C. Further, it may be noted that, the fall in the energy efficiency in the reheat pressure ratio range of 0.25 to 0.3 is steep compared to the fall in the energy efficiency in reheat pressure ratio range of 0.3 to 0.4. In fact, the further fall in energy efficiency for reheat pressure ratio beyond 0.4 is negligible. It may also be noted that the maximum variation in the energy efficiency at turbine inlet temperature of 800°C is 2.82%. It may be interesting to note that, the maximum energy efficiency of the cycle is 50.90%, which occurs at turbine inlet temperature of 800°C and at second reheat pressure ratio of 0.25.

Further, it is surprising to note that (i) the trend in variation of energy efficiency with second reheat pressure ratio is similar to that of the trend in the variation on energy efficiency with first reheat pressure ratio. (ii) optimum value of second reheat pressure ratio is also coinciding with the optimum value of first reheat pressure ratio.

The variation in energy efficiency with reheat pressure ratio has been presented in Fig.6.6 at only one turbine inlet pressure of 350 bar. However, the similar variation in energy efficiency at different values of turbine inlet pressure has been presented in the Fig.6.7.
Fig 6.7 Variation of energy efficiency of SCRC with DRH of second reheat pressure ratio of turbine inlet pressure

From this figure, it may be noted that, the trend in the variation of energy efficiency with second reheat pressure ratio at all the values of turbine inlet pressure is similar and the optimum reheat pressure ratio is 0.25 for all the values of turbine inlet pressure. It is significant to note that, the maximum variation in energy efficiency with reheat pressure ratio is 2.60% which occurs at turbine inlet pressure of 425 bar. The maximum energy efficiency of the cycle is 49.35%, which occurs at turbine inlet pressure of 425 bar and second reheat pressure ratio of 0.25.

To offer the explanation for this trend in variation of energy efficiency with second reheat pressure ratio the values of turbine work, heat supplied and energy efficiency at different second reheat pressure ratios have been tabulated in Table 6.1.
Table 6.1 Energy efficiency at reheat pressure ratio

<table>
<thead>
<tr>
<th>R2</th>
<th>Wt (kJ/kg)</th>
<th>Wp (kJ/kg)</th>
<th>Wnet (kJ/kg)</th>
<th>H.S. (kJ/kg)</th>
<th>Energy Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>2384.553</td>
<td>41.37643</td>
<td>2343.176</td>
<td>4857.33</td>
<td>48.24</td>
</tr>
<tr>
<td>0.25</td>
<td>2375.191</td>
<td>41.37643</td>
<td>2333.814</td>
<td>4779.468</td>
<td>48.83</td>
</tr>
<tr>
<td>0.30</td>
<td>2303.723</td>
<td>41.37643</td>
<td>2262.346</td>
<td>4847.538</td>
<td>46.67</td>
</tr>
<tr>
<td>0.35</td>
<td>2261.226</td>
<td>41.37643</td>
<td>2219.849</td>
<td>4783.126</td>
<td>46.41</td>
</tr>
<tr>
<td>0.40</td>
<td>2216.723</td>
<td>41.37643</td>
<td>2175.346</td>
<td>4713.642</td>
<td>46.15</td>
</tr>
</tbody>
</table>

The reason presented in section 5.5.1 for the variation of energy efficiency with first reheat pressure ratio holds good for the variation of energy efficiency with second reheat pressure ratio also. The values given in the tabular form support the reason given above.

Figure 6.8 shows the variation at exergy efficiency with second reheat pressure ratio of different turbine inlet temperatures, at a given turbine inlet pressure of 350 bar, first reheat pressure ratio of 0.25 and a condenser pressure of 0.05 bar.

Fig 6.8 Exergy efficiency of supercritical Rankine cycle with double Reheat of second reheat pressure ratio with turbine inlet temperature
It may be observed from this figure that, maximum exergy efficiency of the cycle is 68.67%, which occurs at turbine inlet temperature of 800°C and at second reheat pressure ratio of 0.25.

Figure 6.9 shows exergy efficiencies as function of second reheat pressure ratio at different turbine inlet pressure ranging from 225 bar to 425 bar. It is observed from the result that the variations in exergy efficiency with an second reheat pressure ratio is similar to that of the variation of it with first reheat pressure ratio as discussed in section 5.5.1.

![Figure 6.9 Variation of exergy efficiency of SCRC with DRH with second reheat pressure ratio of turbine inlet pressure](image)

It may be noted from the figure that, maximum exergy efficiency is 67.74% at a second reheat pressure ratio of 0.25, turbine inlet pressure of 425 bar. The data of irreversibility in the individual components if the cycle and total irreversibility (total exergy loss) at a turbine inlet
temperature of 700°C and at a turbine inlet pressure of 350 bar is
presented in the Table 6.2. However, the values of total exergy loss at
different values of turbine inlet temperatures are plotted in Fig.6.10

Table 6.2 Exergy efficiency at different turbine inlet pressures

<table>
<thead>
<tr>
<th>R₂</th>
<th>Iboiler kW</th>
<th>Iturbine kW</th>
<th>Icondenser kW</th>
<th>Ipump kW</th>
<th>Iexhaust kW</th>
<th>Isum kW</th>
<th>Exergy Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>220201.8</td>
<td>90268.04</td>
<td>18790.09</td>
<td>1977.14</td>
<td>13075.68</td>
<td>344312.8</td>
<td>65.70</td>
</tr>
<tr>
<td>0.25</td>
<td>209631.6</td>
<td>89815.82</td>
<td>18814.1</td>
<td>1933.23</td>
<td>13075.74</td>
<td>333270.7</td>
<td>66.80</td>
</tr>
<tr>
<td>0.30</td>
<td>227615.3</td>
<td>90838.48</td>
<td>18796.03</td>
<td>2017.95</td>
<td>13075.68</td>
<td>352343.4</td>
<td>64.91</td>
</tr>
<tr>
<td>0.35</td>
<td>231917.4</td>
<td>91484.12</td>
<td>18828.03</td>
<td>2057.28</td>
<td>13075.68</td>
<td>357362.5</td>
<td>64.41</td>
</tr>
<tr>
<td>0.40</td>
<td>235770.1</td>
<td>92169.34</td>
<td>18870.42</td>
<td>2094.69</td>
<td>13075.68</td>
<td>361980.2</td>
<td>63.95</td>
</tr>
</tbody>
</table>

The reason presented in section 5.5.1 for the variation of exergy
efficiency with first reheat pressure ratio holds good for the variation of
exergy efficiency with second reheat pressure ratio also. It may be noted
observed that, the values given in the Table 6.2 supports this.

Fig 6.10 Variation of total exergy losses of SCRC with DRH of second reheat
pressure ratio of turbine inlet temperature
Figure 6.11 represents the variation of FEL against the variation of second reheat pressure ratio of all components of supercritical cycle with double reheat.

![Graph showing variation of fractional exergy loss of SCRC with DRH of second reheat pressure ratio.](image)

**Figure 6.11** Variation of fractional exergy loss of SCRC with DRH of second reheat pressure ratio

It may be observed that, the FEL of the boiler increases with marginally an increase of reheat pressure ratio. FEL of the boiler found to be vary from 62.19% to 64.55%. Further, FEL of the turbine decreases from 27.47% to 25.89% with an increase of second reheat pressure ratio. FEL of condenser decreases 5.75% to 5.30% with an increase of second reheat pressure ratio.
6.5.2 Effect of turbine inlet pressure and temperature on energy efficiency

Figure 6.12 shows the variation of energy efficiency of supercritical cycle with double reheat with turbine inlet steam temperature at different turbine inlet pressures and at a condenser pressure of 0.05 bar.

It may be observed from this figure that, the energy efficiency of the cycle increases with an increase of turbine inlet temperature at different turbine inlet pressures. The energy efficiency at turbine inlet pressure of 425 bar is found to be maximum at all values of turbine inlet temperature which is 43.50%, 46.51%, 49.10% and 51.52% at 500°C, 600°C, 700°C and 800°C respectively.
To bring out the possible reason for this variation, the values of net work, heat supplied and energy efficiency have been presented in Table 6.3.

Table 6.3 Energy efficiency at different turbine inlet pressures

<table>
<thead>
<tr>
<th>P bar</th>
<th>T (°C)</th>
<th>$W_t$ (kJ/kg)</th>
<th>$W_p$ (kJ/kg)</th>
<th>$W_{net}$ (kJ/kg)</th>
<th>H.S. (kJ/kg)</th>
<th>Energy Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>700</td>
<td>2086.96</td>
<td>27.37</td>
<td>2059.59</td>
<td>4306.88</td>
<td>47.82</td>
</tr>
<tr>
<td>250</td>
<td>700</td>
<td>2087.33</td>
<td>30.44</td>
<td>2056.89</td>
<td>4260.49</td>
<td>48.27</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>2089.22</td>
<td>40.87</td>
<td>2048.35</td>
<td>4215.66</td>
<td>48.58</td>
</tr>
<tr>
<td>350</td>
<td>700</td>
<td>2091.92</td>
<td>46.45</td>
<td>2045.47</td>
<td>4188.36</td>
<td>48.83</td>
</tr>
<tr>
<td>400</td>
<td>700</td>
<td>2092.23</td>
<td>49.62</td>
<td>2042.61</td>
<td>4165.81</td>
<td>49.03</td>
</tr>
<tr>
<td>425</td>
<td>700</td>
<td>2092.65</td>
<td>53.59</td>
<td>2039.06</td>
<td>4152.06</td>
<td>49.11</td>
</tr>
</tbody>
</table>

It may be noted from Table 6.3 that, turbine work increases with increases marginally in turbine inlet pressure but the pump work increases significantly at a given turbine inlet temperature, due to increase in the pump work significantly. As a result, the net work reduces with increase in turbine inlet pressure. Interestingly, the energy input (Heat Supplied) to the boiler also decreases as the turbine inlet pressure increases at a given steam turbine inlet temperature.

So, as the turbine inlet pressure increases in both the $W_{net}$ and heat supplied decreases. But the rate of decrease of heat supplied is more than the rate of decrease of $W_{net}$. Hence, the energy efficiency increases as the pressure increases at a given inlet turbine temperature.

For the sake of convenience this data is presented in a different form in Fig. 6.13.
Fig. 6.13 Variation of energy efficiency of SCRC with DRH with different turbine inlet pressure of steam

It may also be noted from this figure that the energy efficiency increases with increase of turbine inlet pressure at different turbine inlet temperatures. The energy efficiency is maximum at a turbine inlet temperature of 800°C at all the values of turbine inlet pressure which is at a 225 bar 250 bar,300 bar,350 bar ,400bar and 425 bar is 49.77 %, 49.96%, 50.13% , 50.43% , 50.57% and 50.76% respectively.

6.5.3 Effect of turbine inlet pressure and temperature on exergy efficiency

In the section 4.7.2 the effect of steam turbine inlet temperature and steam turbine inlet pressure on the exergy efficiency of SCRC without reheat was discussed. Similarly, the effect of these parameters on the
exergy efficiency, total exergy loss of SCRC with DRH is presented on the Figures 6.14, 6.15, 6.16 and 6.17.

Figure 6.14 represents the variation of exergy efficiency with turbine inlet temperature at a different turbine inlet pressure. Exergy efficiency increases with increase of turbine inlet temperature at a given turbine inlet pressure. Further, a similar trend in the variation was found at all turbine inlet pressures in the range of 170 bar to 425 bar. At a turbine inlet pressure of 425bar (maximum pressure), the exergy efficiency at different turbine inlet temperatures of 500°C, 600°C, 700°C and 800°C are 62.82%, 65.32%, 67.85% and 70.14%, respectively.

Fig. 6.14 Variation of Exergy efficiency of SCRC with DRH with different turbine inlet temperature values of steam
The possible reason for the increasing trend of exergy efficiency of this cycle with turbine inlet temperature at different turbine inlet pressure, Table 6.4 has been presented below.

Table 6.4 Exergy efficiency at different turbine inlet pressures

<table>
<thead>
<tr>
<th>$P_1$ (bar)</th>
<th>$T_1$ ($^\circ$C)</th>
<th>$I_{\text{boiler}}$ (kW)</th>
<th>$I_{\text{turbine}}$ (kW)</th>
<th>$I_{\text{condenser}}$ (kW)</th>
<th>$I_{\text{pump}}$ (kW)</th>
<th>$I_{\text{exhaust}}$ (kW)</th>
<th>$I_{\text{sum}}$ (kW)</th>
<th>Exergy Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>700</td>
<td>227709.62</td>
<td>89758.96</td>
<td>20864.50</td>
<td>780.80</td>
<td>13075.68</td>
<td>352233.53</td>
<td>64.20</td>
</tr>
<tr>
<td>250</td>
<td>700</td>
<td>221023.47</td>
<td>89763.38</td>
<td>19903.07</td>
<td>1508.77</td>
<td>13075.68</td>
<td>345274.38</td>
<td>64.97</td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>211425.09</td>
<td>89802.94</td>
<td>19769.80</td>
<td>1306.68</td>
<td>13075.68</td>
<td>335336.22</td>
<td>66.04</td>
</tr>
<tr>
<td>350</td>
<td>700</td>
<td>203348.12</td>
<td>89815.82</td>
<td>18814.05</td>
<td>1933.20</td>
<td>13075.68</td>
<td>326986.88</td>
<td>66.91</td>
</tr>
<tr>
<td>400</td>
<td>700</td>
<td>196858.58</td>
<td>89926.35</td>
<td>17897.62</td>
<td>2560.28</td>
<td>13075.68</td>
<td>320318.50</td>
<td>67.61</td>
</tr>
<tr>
<td>425</td>
<td>700</td>
<td>194510.66</td>
<td>89997.97</td>
<td>17872.25</td>
<td>2460.81</td>
<td>13075.68</td>
<td>317917.34</td>
<td>67.85</td>
</tr>
</tbody>
</table>

$E_A = 1003827.38 \text{ kJ}$

In the section 5.5.3., a detailed explanation was provided for the variation in the exergy efficiency with turbine inlet pressure and with turbine inlet temperature. Though the values are different for SCRC with DRH compared to SRH the reason provided there holds good in this case also. For the sake of verification the values of irreversibilities and exergy efficiency for SCRC with DRH are provided in the Table 6.4 for different values of turbine inlet pressure and Table 6.6 for different values of turbine inlet temperature.

The data of total irreversibility only at one value of turbine inlet temperature and at different turbine inlet pressure is tabulated in the Table 6.4. However, the values of total exergy loss at different values of turbine inlet temperature and turbine inlet pressure are plotted in Fig.6.15.
Fig. 6.15 Variation of total exergy loss of SCRC with DRH with different turbine inlet temperature

Figure 6.16 represents the variation of exergy efficiency with turbine inlet pressure at condenser pressure 0.05 bar and at a reheat pressure ratio of 0.25.

Fig. 6.16 Variation of Exergy efficiency of SCRC with DRH with different turbine inlet pressure of steam
The values of irreversibility in different components and exergy efficiency at different turbine inlet temperature have been tabulated in Table 6.5, which help in understanding the possible reason for this variation.

Table 6.5 Exergy efficiency at different turbine inlet pressures

<table>
<thead>
<tr>
<th>P bar</th>
<th>T (°C)</th>
<th>I_{boiler} kW</th>
<th>I_{turbine} kW</th>
<th>I_{condenser} kW</th>
<th>I_{pump} kW</th>
<th>I_{exhaust} kW</th>
<th>I_{sum} kW</th>
<th>Exergy Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>500</td>
<td>204112.52</td>
<td>93227.44</td>
<td>24341.24</td>
<td>2703.56</td>
<td>13075.68</td>
<td>337460.4</td>
<td>62.10</td>
</tr>
<tr>
<td>350</td>
<td>550</td>
<td>203992.58</td>
<td>92116.58</td>
<td>22687.49</td>
<td>2467.54</td>
<td>13075.68</td>
<td>334339.9</td>
<td>63.23</td>
</tr>
<tr>
<td>350</td>
<td>600</td>
<td>203348.12</td>
<td>91232.28</td>
<td>21255.66</td>
<td>2266.32</td>
<td>13075.68</td>
<td>331178.1</td>
<td>64.46</td>
</tr>
<tr>
<td>350</td>
<td>650</td>
<td>203149.50</td>
<td>90479.09</td>
<td>19975.04</td>
<td>2089.87</td>
<td>13075.68</td>
<td>328769.2</td>
<td>65.71</td>
</tr>
<tr>
<td>350</td>
<td>700</td>
<td>202425.05</td>
<td>89815.82</td>
<td>18814.05</td>
<td>1933.20</td>
<td>13075.68</td>
<td>326063.8</td>
<td>66.91</td>
</tr>
<tr>
<td>350</td>
<td>750</td>
<td>201356.31</td>
<td>89220.99</td>
<td>17756.21</td>
<td>1793.19</td>
<td>13075.68</td>
<td>323202.4</td>
<td>68.07</td>
</tr>
<tr>
<td>350</td>
<td>800</td>
<td>199562.86</td>
<td>88683.15</td>
<td>16789.90</td>
<td>1667.64</td>
<td>13075.68</td>
<td>319779.2</td>
<td>69.18</td>
</tr>
</tbody>
</table>

The data of total exergy loss only at one value of turbine inlet pressure and at different turbine inlet temperature is presented in the Table 6.5. However, the values of total exergy loss at different values of turbine inlet temperature and turbine inlet pressure are plotted in Fig.6.17.

![Fig. 6.17 Variation of total exergy loss of SCRC with DRH with different turbine inlet temperature](image-url)
6.5.4 Effect of turbine inlet temperature and pressure on fractional exergy loss

Figure 6.18 represents the variation of fractional exergy loss of all components of a supercritical cycle with double reheat with turbine inlet temperature.

![Graph of fractional exergy loss vs. turbine inlet temperature](image)

It may be observed from the result that the FEL of boiler increases marginally with an increase of temperature turbine inlet temperature. FEL of the turbine, condenser and pump slightly decreases with increase of inlet turbine temperature. Maximum FEL in boiler, turbine, condenser, pump and exhaust were found to be 72%, 28%, 7%, 0.8% and 4% respectively.
A similar variation in fractional exergy loss with turbine inlet pressure is presented in Fig. 6.19. FEL of boiler decreases with an increase of turbine inlet pressure.

![Fractional Exergy Loss vs Turbine Inlet Pressure](image)

Fig. 6.19 Variation of turbine inlet pressure of SCRC with DRH with fractional exergy loss of different components

FEL of boiler at 200 bar is 65.27%, at 250 bar is 64.01%, at 300 bar is 63.95%, at 350 bar is 62.19%, at 400 bar is 61.46% and at 425 bar is 61.18% respectively. FEL of the turbine varies from 24.29% to 28.31% and for condenser decreases from 5.95% to 5.62% as turbine inlet pressure varies from 170 to 425 bar. FEL of the exhaust increases from 3.53% to 4.11% as turbine inlet pressure varies from 170 to 425 bar and FEL of the pump less than 1%.
6.5.5 Effect of Condenser pressure on the performance

In the section 4.7.4, the effect of condenser pressure on the performance of supercritical cycle has been analyzed for the cycle without reheat at different turbine inlet pressures and turbine inlet temperatures. In order to carry out a similar analysis for supercritical cycle with double reheat, Fig 6.20 has been drawn. It may be observed that the energy efficiency decreases with increase in the condenser at a given turbine inlet temperature and the similar trend in the variation may also be observed at all value turbine inlet temperatures considered in the range of 500°C-800°C.

![Graph showing the variation of energy efficiency with condenser pressure](image)

Fig 6.20 Variation of energy efficiency of SCRC with DRH with double reheat pressure ratio of turbine inlet temperature

The effect of the condenser pressure on the performance of the cycle at different pressure on the performance of the cycle at different values of
turbine inlet pressure has been plotted in Fig.6.21. It is easy to conclude from the above figure that the variation in energy efficiency with condenser pressure is similar at all values of turbine inlet pressure in the range of 225 bar to 425 bar. The reason for this variation of energy efficiency with variation of turbine inlet temperature and turbine inlet pressure which is explained in the section 4.7.4 holds good in this case of supercritical cycle with double reheat.

![Graph showing variation of energy efficiency with condenser pressure](image)

Fig 6.21 Variation of energy efficiency of SCRC with DRH with double reheat pressure ratio of turbine inlet pressure

To analyze the trend in the variation of exergy efficiency of the cycle with condenser pressure, Fig.6.22 has been plotted for different turbine inlet temperatures from 500°C-800°C.
Fig 6.22 Variation of exergy efficiency of SCRC with DRH with double reheat pressure ratio of turbine inlet temperature

The possible reason for this trend in exergy efficiency of this cycle, the explanation offered in section 4.7.4 for the variation of exergy efficiency of supercritical cycle without reheat holds good for this case also.

It may be noted from this figure that, the exergy efficiency decreases with increase of condenser pressure at different turbine inlet temperatures as the total exergy loss increases with condenser pressure as shown in Fig.6.23.
Fig 6.23 Variation of total exergy loss of SCRC with DRH of different condenser pressure

Fig 6.24 shows the variation of exergy efficiency with condenser pressure at different turbine inlet pressures and at turbine inlet temperature of 700°C.

Fig 6.24 Variation of exergy efficiency of SCRC with DRH with double reheat pressure ratio of turbine inlet pressure
It may be observed that, the variation in exergy efficiency at all other values of turbine inlet pressure is similar to that of variation in exergy efficiency at 350bar. It may be noted that, the maximum energy efficiency occurred at a condenser pressure of 0.03bar at all turbine inlet pressures. At a turbine inlet temperature of 700°C, the values of energy efficiency at 225bar, 250bar, 300bar, 350bar, 400bar and 425bar are 65.26%, 65.70%, 66.24%, 66.79%, 67.35% and 67.04% respectively.

Figure 6.25 shows the variation of fractional exergy loss of different components of the cycle with condenser pressure of the supercritical cycle with double reheat.

![Fractional Exergy Loss Graph](image)

Fig 6.25 Variation of fractional exergy loss of SCRC with DRH of different condenser pressure

It may be observed from the figure that, FEL of the boiler and turbine decreases with increase of condenser pressure. FEL of the boiler were found to vary 64.95% to 58.28% and from turbine 28.93% to 25.57%. In
this case, it is important to note that, FEL of the condenser increases rapidly from 1.29% to 11.63% with an increase of condenser pressure. FEL of the exhaust decreases marginally from 4.05% 3.85% with increase of condenser pressure from 0.03bar to 0.01bar.

6.5.6 Effect of boiler flue gas inlet temperature on exergy efficiency

As the energy efficiency of the cycle is independent of flue gas inlet temperature the effect of it on exergy efficiency, total exergy loss and fractional exergy loss at different turbine inlet temperature and turbine inlet pressure can be seen in Fig. 6.26 to 6.29.

In the section 4.8.5 the effect of boiler flue gas inlet temperature on exergy efficiency of supercritical Rankine cycle without reheat has been discussed. To carry out a similar analysis for SCRC with DRH, the data obtained has been plotted in Fig. 6.26 to Fig.6.29.

The trend in the variation of exergy efficiency and total exergy loss for a SCRC without reheat and with double reheat does not alter and the explanation provided in the chapter 4 in the section 4.7.5 for this variation holds good for this also.

The effect of boiler inlet flue gas temperature varied 900°C to 1400°C on exergy efficiency for the given flue gas boiler exit temperature of 100°C, turbine inlet temperature of 700°C, turbine inlet pressure of 350bar and reheat pressure ratio of 0.25 for the given capacity are shown in Fig. 6.26–Fig.6.29 respectively.
As the energy efficiency of the cycle is independent of flue gas inlet temperature, the effect of it on exergy efficiency, total exergy loss and fractional exergy loss at different turbine inlet temperature and turbine inlet pressure can be seen in Fig. 6.26 to 6.29.

Fig 6.26 Variation of exergy efficiency of SCRC with DRH with boiler flue gas inlet temperature

Fig 6.27 Variation of exergy efficiency of SCRC with DRH with boiler flue gas inlet temperature of turbine inlet pressure
Fig 6.28 Variation of total exergy loss of SCRC with DRH with boiler flue gas inlet temperature of turbine inlet temperature

Figure 6.29 represents the variation of fractional exergy loss of different component with boiler flue gas inlet temperature.
It may be noted that FEL of the boiler and turbine are slightly decreases with increase of boiler flue gas temperature. FEL of the boiler was found to be varying from 62.87% to 58.80% and FEL of turbine vary from 26.15% to 20.87%. FEL of the exhaust is increases significantly with increase of boiler flue gas inlet temperature. FEL in exhaust at 900°C is 4.24%, at 1200°C is 11.3% and at 1400°C is 14.88 % respectively for the given capacity.

**6.5.7 Effect of boiler flue gas outlet temperature on exergy efficiency**

In the section 4.7.6 the effect of boiler flue gas outlet temperature on exergy efficiency of SCRC without reheat has been discussed. To carryout the similar analysis for SCRC with DRH, the data obtained has been plotted in Fig. 6.30, Fig. 6.31 and Fig. 6.32.

The trend in the variation of exergy efficiency and total exergy loss for SCRC without reheat and with double reheat does not alter and the explanation provided in chapter 4 in the section 4.7.6 for this variation holds good for this also.
Fig 6.30 Variation of exergy efficiency of SCRC with DRH with boiler flue gas outlet temperature of turbine inlet temperature

Fig 6.31 Variation exergy efficiency of SCRC with DRH with double reheat pressure ratio of turbine inlet pressure
Boiler flue gas outlet temperature (°C)

Total Exergy loss (MW)

Fig 6.32 Variation of exergy efficiency of SCRC with DRH with boiler flue gas inlet temperature of turbine inlet pressure

Figure 6.33 shows the variation of FEL different components of supercritical cycle with double reheat.

Fig 6.33 Variation of fractional exergy loss of SCRC with DRH of different boiler flue gas outlet temperature
It may be observed from the figure that, the FEL of a boiler decreases with boiler flue gas outlet temperature. FEL of boiler and turbine were found to vary from 63.91% to 51.29% and from 29.21% to 17.72% with increase of boiler flue gas outlet temperature. However, FEL of the exhaust increases drastically from 1.55% to 26.9% with an increase of flue gas outlet temperature of FEL. Other components like, condenser and pump slightly decreases with an increase of temperature.