Combined cycle with detailed calculation of Cp in the HRSG

A large, light-oil fired gas turbine with an electrical power output of 171 MW is integrated with a steam cycle, forming a combined cycle.

Some gas turbine data:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical efficiency</td>
<td>36.1%</td>
</tr>
<tr>
<td>Exhaust gas flow</td>
<td>445 kg/s</td>
</tr>
<tr>
<td>Exhaust gas temperature</td>
<td>601 ºC</td>
</tr>
<tr>
<td>Heating Value Light Oil</td>
<td>42.3 MJ/kg</td>
</tr>
</tbody>
</table>

The steam cycle has a single pressure HRSG, without supplementary firing. The stack temperature has been measured to 138 ºC. Disregard approach temperature in the economizer outlet, i.e. assume that the temperature out from the economizer equals the drum temperature. The pressure at the steam turbine inlet is 40 bar and the temperature 550 ºC. The isentropic efficiency of the turbine is 0.88%. The mechanical and electrical efficiency of the steam turbine are each 0.98. Consider a steam cycle with a feedwater tank at 0.2 bar, which obtains steam from the steam turbine at the same pressure. Feedwater from this preheater is fed directly to the HRSG via a feedwater pump placed after the preheater. The pressure in the condenser is 0.05 bar.

a) Sketch the layout of the plant

b) Calculate the pinch point temperature difference
   *To obtain full score you have to determine Cp for the exhaust gas (i.e. not assume a value)*

c) Calculate the steam turbine power output

d) Calculate the combined cycle efficiency
SOLUTION

a) Power plant layout

b) Pinch point temperature

Pinch point temperature is $\Delta t_{pp} = t_{g3} - t_s$

where $t_s = \text{(saturation 40 bar)} = 250.4 ^\circ C$ and $t_{g3}$ is obtained from a heat balance over the superheater and the evaporator:

$m_{gt} \cdot c_{pg} \cdot (t_{g1} - t_{g3}) = m_{at} \cdot (h_1 - h_{S1})$  \[ A \]
But as both \( t_{g3} \) and the steam flow are unknown we have to find a way first to determine the steam flow. As we have been given the stack temperature, a similar heat balance considering this will give us the steam flow:

\[
m_{gt} \cdot c_{pg} \cdot (t_{g1} - t_{g4}) = m_{st} \cdot (h_1 - h_6) \quad \text{[B]}
\]

\( h_6 = \text{neglect pumpwork} = h_5 = \text{sat liq @ 0.2 bar} = 251.3 \text{ kJ/kg} \)

\( h_1 = 40 \text{ bar and 550°C} = 3560 \text{ kJ/kg} \)

\( t_{g1} \) and \( m_{gt} \) are given for the turbine. But we have to estimate \( c_{pg} \), which is dependent both on the temperature and on the composition of the exhaust.

The \( c_p \) chart we have available, considers average temperature of flue gases from light oil firing with a certain gas content, thus we have to determine both the gas content and the average temperature.

Average temperature is

\( t_{ave} = (t_{g1} + t_{g4})/2 = (601 + 138)/2 \text{ ºC} = 370\text{ ºC} \)

The gas content can be obtained from the gas turbine data given. We know that for light oil, the gas content is obtained from:

\[
\beta = (1 + 14.52) \cdot \frac{\beta}{1 + \beta}
\]

We thus have to find \( \beta \), which is defined as \( \beta = \frac{\dot{m}_{fuel}}{\dot{m}_{air}} \)

Here we need to find both the fuel flow and the airflow!

We know that \( \dot{m}_{gt} = 445\text{ kg} / \text{s} = \dot{m}_{fuel} + \dot{m}_{air} \rightarrow \dot{m}_{air} = \dot{m}_{gt} - \dot{m}_{fuel} \)

Furthermore \( \dot{Q}_{FUEL} = \dot{m}_{fuel} \cdot LHV \rightarrow \dot{m}_{fuel} = \frac{\dot{Q}_{FUEL}}{LHV} \)

But as we have both the power output and the efficiency of the gas turbine we get the fuel power as:

\[
\dot{Q}_{fuel} = \frac{P_{GTel}}{\eta_{GT}} = \frac{171}{0.361} \text{ MW} = 473.68\text{ MW}
\]

Now the fuel flow can be determined:
The airflow becomes
\[ \dot{m}_{air} = \dot{m}_{gt} - \dot{m}_{fuel} = 445 - 11.2 \text{ kg/s} = 433.8 \text{ kg/s} \]

The specific fuel consumption:
\[ \beta = \frac{\dot{m}_{fuel}}{\dot{m}_{air}} = \frac{11.2}{433.8} = 0.0258 \]

Finally the gas content can be determined:
\[ x = (1 + 14.52) \cdot \frac{\beta}{1 + \beta} = 15.52 \cdot \frac{0.0258}{1 + 0.0258} = 0.39 \]

With \( x = 0.39 \) and \( t_{ave} = 370^\circ C \), we find \( c_p \) for equation \([B]\) as \( c_{pgB} = 1.10 \text{ kJ/kgK} \)

Equation \( B \) is now solved for the steam mass flow:
\[ \dot{m}_{st} = \frac{\dot{m}_{gt} \cdot c_{pg} \cdot (t_{g1} - t_{g3})}{h_1 - h_6} = \frac{445 \cdot 1.1 \cdot (601 - 138)}{3560 - 251.3} = 68.5 \text{ kg/s} \]

Before solving equation \([A]\) for the gas temperature \( t_{g3} \) we need to find a new \( c_{pg} \):
Assume \( t_{g3} \) to 260 \( ^\circ \text{C} \) (which is 10\( ^\circ \text{C} \) more than the water saturation temperature in the drum) then \( t_{ave2} = (601+260)/2^\circ\text{C} = 430^\circ\text{C} \) and with \( x = 0.39 \) we find that \( c_{pgA} = 1.117 \text{ kJ/kgK} \).

\( h_{s1} = \text{saturated water @ 40 bar = 1087.3 kJ/kg} \)

Equation \( A \) gives us \( t_{g3} \) as:
\[ t_{g3} = t_1 - \frac{\dot{m}_{st} \cdot (h_1 - h_{s1})}{\dot{m}_{gt} \cdot c_{pg}} = 601 - \frac{68.5 \cdot (3560 - 1087.3)}{445 \cdot 1.117} = 260.2^\circ \text{C} \]

We made a very good guess, so we do not have to iterate \( C_p \).

\[ \Delta t_{pp} = t_{g3} - ts = 260.2 - 250.4 = 9.8^\circ \text{C} \]

\( c) \text{ Steam turbine power output} \)
The steam power output is:

\[ P_{ST} = [m_{ST} \cdot (h_{s1} - h_x) + (m_{st} - m_x) \cdot (h_x - h_2)] \cdot \eta_M \cdot \eta_G \]

We need to find \( h_x, h_2 \) and \( m_x \).

The expansion line through the turbine in a h-s diagram is determined by the inlet and the outlet, that is \( h_1 \) and \( h_2 \). The steam extraction enthalpy is found on this expansion line on the given pressure 0.2 bar. Via a heat balance on the feedwater tank we find the steam flow in \( x \).

The enthalpy in turbine inlet is found in the intersection of 550ºC and 40 bar lines. The isentropic enthalpy in the turbine inlet is found by drawing a straight vertical line until intersected with the condenser pressure = pressure in the turbine outlet. Thus \( h_{2s} = 2210 \) kJ/kg

The real enthalpy of turbine outlet is found through the definition of the isentropic enthalpy of expansion:

\[
\eta_{\text{is}} = \frac{h_2 - h_2^s}{h_2 - h_1} = \frac{2210 - 2540}{3560 - 2210} = 0.3560
\]

\( h_2 = 2370 \) kJ/kg

Introduce the value of \( h_2 \) into the h-s diagram and connect \( h_1 \) and \( h_2 \) with a straight line to create the expansion line. The steam extraction in \( x \) is now found in the intersection between the extraction pressure, 0.2 bar and the expansion line:

\( h_x = 2540 \) kJ/kg

The steam flow in \( x \) is found through a heat balance on the feedwater tank.

Energy in = Energy out

\[ m_x \cdot h_x + (m_{st} - m_x) \cdot h_4 = m_{st} \cdot h_5 \]

\( h_4 \approx h_3 \) (neglect pumpwork) = sat liq water @ 0.05 bar = 137.5 kJ/kg

\( h_5 = \) sat liq w @ 0.2 bar = 251.3 kJ/kg

Rearrange the equation and solving for \( m_x \) we obtain:

\[
\dot{m}_x = \dot{m}_{st} \cdot \frac{(h_5 - h_4)}{(h_x - h_4)} = 68.5 \cdot \frac{(251.3 - 137.5)}{(2540 - 137.5)} \text{ kg/s}
\]

\( m_x = 3.24 \) kg/s

We are now able to calculate the turbine power output as:

\[ P_{STel} = [68.5 \cdot (3560 - 2540) + (68.5-3.24) \cdot (2540-2370)] \cdot 0.98 \cdot 0.98 \text{ kW} \]
\[ P_{Stel} = 77\ 758\ kW \]

d) The combined cycle efficiency

Finally the combined cycle efficiency is

\[
\eta_{CC} = \frac{\dot{P}_{GT} + \dot{P}_{ST}}{\dot{Q}_{fuel}} = \frac{171 + 77.76}{473.68} = 0.525
\]

\[ \eta_{CC} = 52.5\% \]