THE VERIFICATION OF THE RSG-GAS REACTOR COOLING TOWER HEAT TRANSFER CAPACITY

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ABSTRACT

The RSG-GAS reactor has been replaced and the technical specifications for the new cooling tower specify that the heat transfer capacity from the secondary cooling water to the environment is 5500 kW per module. Therefore, this study aims to verify the theoretical calculations of the heat transfer capacity using performance test data collected on the 30 MW power operation on December 20, 2018, such as the temperature of the primary and secondary coolant entering and exiting the cooling tower, wet bulb and environmental dry bulb temperature, as well as the inlet and outlet air temperature. Furthermore, the data were used to calculate the heat transfer capacity from the secondary cooling water to the environment. The results showed that each cell of the RSG-GAS cooling tower reactor transfers the heat of approximately 5528.52 kW. This value is consistent with the technical specifications written in the revised RSG-GAS Safety Analysis Report 11.

Keywords: capacity, cooling tower, heat, specification, theoretical.
capacity to the environment. Furthermore, a test on the cooling tower carried out in terrace 96 on 18 May 2018 showed that at 30 MW of operation for 45 minutes, the primary coolant reached a temperature of 41.962 °C. The increasing trend of the primary coolant temperature tends to continue until a steady condition is reached. The reactor automatically SCRAM when used for a long time because the temperature of the primary coolant has exceeded the activation limit of the protection system which is 42 °C. Consequently, the RSG-GAS cooling tower after 30 years of operation no longer meets the safety criteria for reactor operation [2].

The seven cell cooling towers of the RSG-GAS reactor have been replaced, while the heat transfer capacity to the environment was tested on December 20, 2018. The results showed that at a steady state of 30 MW, the temperature of the primary coolant leaving and entering the core is 44 °C and 36 °C, while the inlet and outlet temperatures of the secondary coolant is 36.94 °C and 29.86 °C respectively. Additionally, 6 operating cooling towers were able to transfer heat to the environment. Furthermore, the temperature of the primary coolant entering the core did not exceed the activation limit of the protection system [3]. The project handover document stated that the cooling tower’s heat transfer capacity is 5500 kW per module. Therefore, this study aims to verify the cooling tower heat transfer capacity per module based on theoretical calculations using performance data.

METHOD

Heat Transfer in Cooling Towers

The cooling tower transfers heat from the water to the ambient air [4]. This process occurs due to direct contact in two ways, namely heat transfer from cooling water to air (sensible) and through evaporation (latent) [5]. Heat transfer from cooling water to air depends on the temperature and moisture content indicated by the Wet Bulb Temperature (WBT) parameter. Ideally, the cooling water might condense to WBT, but this has never been achieved given that the cooling water rarely has direct contact entirely with the air. Meanwhile, the Cold Water Temperature (CWT) depends on the contact time with the air and cooling water, the amount of surface area of the fill, and water that becomes droplets [6]. The smaller the difference between WBT and CWT, the better the cooling tower’s heat transfer performance.

Secondary cooling water with mass rate L and inlet temperature T1 enters and exits with outlet T2, while the environmental air with mass rate G and enthalpy h1 enters and exits with enthalpy h2. Heat transfer occurs from water to air and the cooling tower schematic is shown in Figure 1.

![Figure 1. Cooling Tower Schematic](image)

Figure 1. Cooling Tower Schematic [7]

Figure 2 shows the volume control of the heat and mass transfer processes in a cooling tower. The analysis of heat and mass transfer is as follows. Water enters at t and leaves the section at a lower temperature, i.e. t-dt, while air enters with ha and leaves with the enthalpy ha+dha. The rate of heat transfer from water is equal to the rate of heat received by air [9]. The equation is as follows [10]:

\[ dQ = G \cdot dha = L \cdot Cp \cdot dt \]

(1)

According to the principle of enthalpy potential, the heat transferred from the cooling water to the air over a wide interval is:
\[ dQ = \frac{hc}{Cpm} \cdot (hi - ha) \]  \hspace{1cm} (2)

To calculate the heat transfer rate in all parts of the cooling tower, equations 1 and 2 are integrated to obtain the following equations:

\[ L \cdot Cp \cdot \int_{t_{in}}^{t_{out}} \frac{dT}{h_i - ha} = \int_{0}^{A} \frac{hc \cdot dA}{Cpm} \]  \hspace{1cm} (3)

\[ L \cdot Cp \cdot \int_{t_{in}}^{t_{out}} \frac{dT}{h_i - ha} = \frac{hc \cdot A}{Cpm} \]  \hspace{1cm} (4)

\[ NTU = \frac{\frac{hc \cdot A}{Cpm}}{G} \]  \hspace{1cm} (5)

\[ Q = \frac{hc \cdot A}{Cpm} \cdot (hi - ha) \]  \hspace{1cm} (6)

where:
- \( dq \): heat transfer rate
- \( G \): air mass flow rate
- \( dha \): enthalpy change of air
- \( L \): water mass rate
- \( Cp \): the specific heat capacity of water
- \( Dt \): change in water temperature
- \( hc \): convection coefficient
- \( hi \): enthalpy of saturated air at the water temperature
- \( ha \): enthalpy of air
- \( Cpm \): humid air type heat
- \( t_{in} \): inlet water temperature
- \( t_{out} \): outlet water temperature
- \( A \): Heat Transfer Area
- \( NTU \): Number of Transfer Unit

The use of equations 1-6 is based on the assumption that the flow rates of water and air are constant.

Figure 3 shows the relationship between water and air and the driving potential of a counterflow cooling tower. AB is the line of work for water and is determined by the inlet and the cooling tower outlet temperature, while CD is the line for aerial work and starts from point C which indicates the enthalpy of air WBT. Furthermore, BC is the beginning of the enthalpy driving force, while the ratio of liquid to gas, L/G, is the line of action gradient. The air exits the cooling tower at point D, while the cooling range is the projection of the CD line to the temperature scale or the difference between the cooling tower inlet and outlet water temperature. Meanwhile, the approach is the difference between the outlet temperature and the WBT of the ambient air. The cooling tower characteristic, \( KaV/L \), is an integral value which indicates the area of ABCD and depends on the L/G ratio [11].

**Verification Method**

The data used for the calculations are records of reactor operations and the results of cooling tower tests conducted by HAMON Company on December 20, 2018 [12, 13]. These include:
1. Coolant flow rate entering the cooling tower
2. Air flow rate in cooling tower
3. Temperature of secondary coolant entering the cooling tower
4. Secondary cooling temperature out of the cooling tower
5. Dry bulb temperature
6. Wet bulb temperature
7. Cooling tower intake air temperature
8. Cooling tower exit air temperature

The verification steps include:
1. Calculating the mass velocity of air and water
2. Dividing the heat transfer area into 5 parts
3. Calculating the energy balance at the bottom of the cooling tower (where the air enters)
4. Calculating the average enthalpy of air
5. Calculating the enthalpy of saturated air
6. Calculating the value of \( hc \cdot A/Cpm \) (cooling tower characteristics)
7. Calculating the heat transfer capacity of cooling towers
RESULT AND DISCUSSION

A thermal performance test was carried out on the cooling tower of the RSG-GAS Reactor on December 20, 2018, and the results are shown in Table 1.

Table 1. Summary of Cooling Tower Thermal Performance Test Results [12]

| Parameter       | Unit  | Design | Test  |
|-----------------|-------|--------|-------|
| Inlet water     | °C    | 39.2   | 36.90 |
| Outlet water    | °C    | 32.00  | 29.92 |
| Range           | K     | 7.20   | 6.98  |
| Dry bulb        | °C    | 30.96  | 32.00 |
| Wet bulb        | °C    | 28.00  | 25.10 |
| Atmospheric pressure | mbar | 1013   | 1013.00 |
| Outlet air density | Kg/m³  | 1.115 | 1.124 |
| Air speed       | m/s   | 4.5    | 2.9   |
| Water flow rate | m³/hour | 3909  | 4148.00 |
| Tower Capacity  | %     | 107.1  |       |

The test carried out during operation with a power of 30 MW shows that the cooling tower transfers heat to the environment hence, the temperature of the primary coolant entering the core is at a steady-state of 36°C. This value is still far from the limit for the activation of the reactor protection system, which is 42°C. This situation shows that the replacement of the cooling tower has been able to meet the safety aspects of reactor operation.

The data used for the calculations are shown in Appendix 1 of Table 2. The first calculation performed was the mass rate of water and air entering the cooling tower and the results showed that the values were 179.98 kg/s and 115.28 kg/s respectively. Hence, the ratio of cooling water and air rate, L/G was 1.56. This value is the slope of the working air line passing through the cooling tower. The calculations for water and air mass rates are shown in Appendix 1 Table 3.

The heat transferred to the environment was determined by calculating the characteristics of the cooling tower using equation (4). This was carried out by dividing the cooling tower temperature area into 5 parts hence, the dT/n value is 1.396°C. The energy balance at the bottom of the cooling tower was then calculated and obtained a value of 9.13 kJ/kg. The next step was to calculate the value of $\frac{hc.A}{C_p m}$ as shown in Appendix 1 of Tables 4 to 6. The calculations obtained a value of 219.3098 kg/s which was then used to determine the characteristics of the cooling tower including the performance on inlet water temperature and WBT.

The NTU value was calculated using equation (5) and the results obtained a value of 1.9 which indicates the characteristics of the cooling tower, or in Merkel Theory referred to as the Merkel Number [6]. A large NTU value indicates that the outlet temperature is closer to the WBT of the inlet air and also a smaller approach. Meanwhile, the closer the approach value to WBT, the better the condition of the cooling tower. This value depends on the contact time between water and air, the surface area of the fill, and the amount of water that becomes a droplet.

After obtaining the hc.A/Cpm value, the heat transfer capacity to the environment was then calculated using Equation (6). The Q value which represents heat transferability is indicated by the inlet air or the water falling into the cooling tower pool, namely Q1. The calculation of the heat transfer capacity is shown in Appendix 1 of Table 7. A Q value of 5528.52 kW was obtained based on the theoretical calculations from the cooling tower test results at a nominal power of 30 MW.

CONCLUSION

The heat transfer capacity of the cooling tower to the environment is 5528.52 kW per module. This value is consistent with the specifications and contract requirements for the RSG-GAS cooling tower revitalization and cooling tower design data in the Revised 11 LAK.

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Table 2. The Calculation Data

| Data                        | Value | Unit | Description       |
|-----------------------------|-------|------|-------------------|
| Water flow rate             | 651,44| m3/h | Design            |
| Air flow rate               | 104,8 | m3/s | Design            |
| Inlet water to the cooling tower | 36,90 | °C  | Measurement       |
| Outlet water of cooling tower | 29,92 | °C  | Measurement       |
| Dry Bulb Temperature        | 32,00 | °C  | Measurement       |
| Wet Bulb Temperature        | 25,10 | °C  | Measurement       |
| Tb1 (inlet air)             | 32,00 | °C  | Measurement       |
| Tb2 (outlet air)            | 38,00 | °C  | Measurement       |

Table 3. The Calculation of Water Mass Rate and Air Mass Rate

| Data                        | Value | Unit |
|-----------------------------|-------|------|
| Range                       | 6,98  | °C   |
| Approach                    | 4,82  | °C   |
| T water average             | 33,42 | °C   |
| P water at T mean           | 994,62| kg/m3|
| L (water flow rate x p water)| 647933,10| kg/h|
| L                           | 179,98| kg/s|
| T air average               | 35,00 | °C   |
| ρ air at T mean             | 1,11  | kg/m3|
| G (flow rate x ρ air)       | 6916,8| kg/m |
| G                           | 115,28| kg/s |
| L/G                         | 1,56  |      |
| Cooling Tower divided by 5, dt/n | 1,396| °C |
| The bottom of the energy balance, d(ha,n - ha,n-1)=ha,1-ha,0 | 9,13 | kJ/kg|

Table 4. The Calculation of Mean Value of Air Enthalpy

| ha,n=ha,n-1+L/G x 4,19 x dt/n | Value | Unit | ha, mean |
|-------------------------------|-------|------|----------|
| ha,0= ha(TWB, TDB)=h inlet air | 76,29 | kJ/kg |
| ha,1=ha,0+L/G x 4,19 x dt/n   | 85,42 | kJ/kg |
| ha,2=ha,1+L/G x 4,19 x dt/n   | 94,55 | kJ/kg |
| ha,3=ha,2+L/G x 4,19 x dt/n   | 103,69| kJ/kg |
| ha,4=ha,3+L/G x 4,19 x dt/n   | 112,82| kJ/kg |
| ha,5=ha,4+L/G x 4,19 x dt/n   | 121,95| kJ/kg |

Table 5. The Calculation of Enthalpy of Saturated Air

| T water (°C) | T mean (°C) | ln Pws | Pws | Ws | hi, mean |
|--------------|-------------|-------|-----|----|----------|
| 29,92        | 31,32       | 30,62 | 8,43| 4577,53| 0,02943  | 106,06   |
| 32,71        | 32,01       | 8,51  | 4953,52| 0,03197| 114,05   |
| 34,11        | 33,41       | 8,59  | 5356,04| 0,03471| 122,57   |
| 35,50        | 34,81       | 8,66  | 5786,60| 0,03767| 131,65   |
| 36,90        | 36,20       | 8,74  | 6246,84| 0,04087| 141,36   |

Table 6. The Calculation of hc.A/Cpm

| hi-ha       | (kJ/kg) | 1/(hi-ha) |
|-------------|---------|-----------|
| h1-ha,1     | 25,21   | 0,0397    |
| h2-ha,2     | 24,06   | 0,0416    |
| h3-ha,3     | 23,45   | 0,0426    |
| h4-ha,4     | 23,40   | 0,0427    |
| h5-ha,5     | 23,97   | 0,0417    |
| Total       | 0,2083  |           |

hc.A/Cpm = L x 4,19 x dt x Σ 1/(hi-ha)

hc.A/Cpm (kg.d.a/kg) = 219,3098
Table 7. The Calculation of Heat Transfer Capacity

| Q = hc/A/Cp.m.(hi,n-ha,n) | Value | Unit  |
|---------------------------|-------|-------|
| Q1 = hc/A/Cp.m.(hi,1-ha,1) | 5528.524 | kW    |
| Q2 = hc/A/Cp.m.(hi,2-ha,2) | 5277.460 | kW    |
| Q3 = hc/A/Cp.m.(hi,3-ha,3) | 5142.384 | kW    |
| Q4 = hc/A/Cp.m.(hi,4-ha,4) | 5132.333 | kW    |
| Q5 = hc/A/Cp.m.(hi,5-ha,5) | 5257.116 | kW    |
