Analytical Design of Helical Coil Steam Generator for Hot Temperature Gas Reactor

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Abstract. Reaktor Daya Eksperimental (RDE) is a non-commercial Hot Temperature Gas Reactor (HTGR) which is currently being developed by National Nuclear Power Agency of Indonesia (BATAN). Integrated helical coil steam generator attached in the RDE is selected to generate 10 MW steam. In order to achieve the rated power, steam pressure of 62 bar, steam temperature of 798.15K and mass flowrate of 3.54 kg/s are required as the output parameters to be produced by the steam generator. A compact design of a once through counter-flow helical coil steam generator is proposed. Analytical design of the helical coil steam generator is conducted to check the heat transfer area required to achieve the rated power. A simple thermodynamic analysis combined with empirical heat transfer coefficient for convective and boiling process inside the steam generator at constant pressure was performed. It is shown that with inlet water temperature of 418.15K and helium gas inlet of 973.15K at 4.27 kg/s and 34.2 bar as the heating fluid produced output helium gas temperature of 511.42K. Based on comparison with available similar existing HTGR reactor, the calculation overestimate heat transfer surface area by around 20%. Hence, the required area to achieve the rated power for the proposed design is estimated around 60.2-75.3 m².

1. Introduction

Based on the results of the study in National Roadmap for Nuclear Power Programme 2017[1], reactor low power and medium, Small and Medium sized Reactor (SMR) is required to meet the need for electricity in remote areas, with minimum electricity grids. Low and medium power reactors is also needed to meet the thermal applications in various forms, such as seawater desalination, hydrogen production, enhanced oil recovery, application on smelter in Indonesia. In the development of RDE reactor type of Pebble Bed Reactor (PBR) with consideration of very safe, functioning for cogeneration, has flexibility fuel, proven, competitive price, multipurpose[2] is selected. This type of reactor is expected to be developed in all over the territory of Indonesia according to its needs, and to meet the needs of supply, especially for electricity.

The nuclear PBR reactor is connected to a steam generator. Once through counter-flow helical coil steam generator is selected for steam production. The steam will then be used for electricity generation. The helical-coil tube bundle design is selected because of its ability in accommodating...
thermal expansion without excessive mechanical stress, has high resistance to flow-induced vibrations, and good thermal performance second only to a straight-tube design[3]. A helium gas is selected as the hot fluid medium to transfer the heat from PBR reactor to the steam generator. The steam generator is targeted to achieve 10 MW thermal power.

In order to achieve the targeted power, the once through helical coil steam generator need to be analysed. A fast evaluation method is needed to be able to predict the required specification for the steam generation. In this case, heat transfer surface area is needed as an initial reference to design the tube bundle. In this study, a simple thermodynamic calculation combined with empirical heat transfer coefficient for convective and boiling process at constant pressure is conducted to perform that purpose.

2. Calculation Procedure

Analytical design of the helical coil steam generator is performed by dividing the helical coil into three regions. The three regions are economizer, evaporator and superheater. These regions are adopted from a common design of Heat Recovery Steam Generator (HRSG). The most significant different is, in HRSG, each region is separated and clearly visible. In this helical coil steam generator, the region is constructed in a once through counter-flow reactor. Each region poses different purpose and phenomena in producing the final superheated steam.

In the proposed design of helical coil heat generator, 49 number of coils are combined in one vessel as shown in figure 1. The coils are arranged in 7 columns with each column having a different number of coils. The outer column with helical diameter \( (D_{oh}) \) of 0.41 m is consist of 10 number coils. Meanwhile, the inner column with helical diameter \( (D_{ih}) \) of 0.17 m is consist of 4 number of coils. Each column is separated with a distance \( (S_T) \) of 20 mm. The helical coil tube outer diameter \( (d) \) is 16 mm, with thickness \( (t_c) \) of the helical coil tube is 1 mm. The pitch \( (p = H/n) \) of the helical coil tube is 0.199 mm. The inner diameter of vessel \( (D_{iv}) \) is 0.64 m. The length of the helical coil tube \( (L) \) can be calculated as

\[
L = n \sqrt{(\pi D_{hh})^2 + p^2}
\]  \quad (1)

where \( H \) is helical coil height and \( n \) is number of turns. Detailed design can be seen in figure 1.

The thermal power required for each of the region is calculated, along with temperatures of the input and output of helium gas and water/steam sides. Because of the pressure for each side is assumed to be constant, the calculation procedure is straight forward without any iterative process. The calculation steps for each of the region are as follows,

1. Calculate the thermal duty of the water/steam side \( Q_{duty} \) (W).
2. Calculate the helium gas output temperature $T_{o,H}$ (K).

3. Calculate the Log Mean Temperature Difference ($LMTD$) of the related regions.

4. Calculate the heat transfer coefficient $h$ (W/m$^2$/K) for helium and water/steam sides.

5. Calculate the overall outer heat transfer coefficient $U_o$ (W/m$^2$/K) of the region.

6. Calculate the surface area $A$ (m$^2$) required for the heat transfer process.

The thermal duty of the water/steam side can be calculated with $Q_{duty}$, where

$$Q_{duty} = m_w \Delta h,$$

where $m_w$ (kg/s) is the mass flow rate of the water/steam side and $\Delta h$ (J/kg) is the enthalpy difference between input and output of the related region. For superheated steam, enthalpy can be interpolated from the properties of superheated water vapor table, while for water, enthalpy can be interpolated from the properties of compressed liquid water one. The saturated enthalpy, included the enthalpy of vaporization can be interpolated from the properties of saturated water (liquid–vapor) pressure table[4].

The helium gas output temperature $T_{o,H}$ of the related region can be calculated from the temperature difference of the thermal duty of the helium gas side, where $Q_{duty}$ of the helium gas side is same as the $Q_{duty}$ of the water/steam side.

$$T_{o,H} = T_{i,H} - \frac{Q_{duty}}{m_{H,c_p,H}(1-h_l)},$$

where $T_{i,H}$ is the inlet temperature of the helium gas at the related region, $m_{H}$ (kg/s) is the mass flow rate of the helium gas side, $c_{p,H}$ is the specific heat of helium gas with a constant value of 5.195 kJ/kg/K[5] and $h_l$ is the heat loss with usual value ranging from 0.2% to 1%[6]. The heat loss is depended on the insulation of the steam generator vessel, ambient temperature and outside wind velocity. For convenience, the calculation in this study use 1% of heat loss. The thermal duty or energy transferred from the helium gas neglect the radiation energy because maximum helium gas temperature is below 973.15K[6]. Beyond this temperature, the radiation energy should be included in the $Q_{duty}$ calculation of the helium gas side.

After the helium gas temperature of the related region is acquired, counter-flow $LMTD$ temperature can be calculated as follows

$$LMTD = \frac{(T_{o,H} - T_{i,W}) - (T_{o,W} - T_{i,W})}{\ln \left( \frac{T_{o,H} - T_{i,W}}{T_{i,W} - T_{o,W}} \right)}.$$
where $T_{aw}$ is the average temperature of the related region. For superheated steam, $C$ value can be interpolated from table 1.

For evaporator region, the heat transfer coefficient for the water/steam side ($h_i$) can be calculated using boiling in sub-cooled water during flow up as follows[7]

$$h_i = \frac{(T_{wall} - T_{sat})P_w^{0.35}}{5.0625 \times 10^{-4}}, \quad (8)$$

where $T_{wall}$ is the wall temperature. The wall temperature is estimated as the average value of inlet and outlet temperatures of the helium gas and water/steam sides. $T_{sat}$ is the saturated temperature and $P_w$ is water/steam side pressure in MPa.

The heat transfer coefficient of the helium gas side $h_o$ can be estimated using[8]

$$Nu = \frac{h_o D_E}{k_H} = 0.6 Re^{0.5} Pr^{0.31} \text{ for } 50 < Re < 10,000$$

$$Nu = \frac{h_o D_E}{k_H} = 0.36 Re^{0.55} Pr^{0.33} \left(\frac{\mu_H}{\mu_{w,H}}\right)^{0.14} \text{ for } Re > 10,000 \quad (10)$$

where, $Nu$ is Nusselt number, $D_E$ is equivalent diameter of the helium gas side, $Re$ is Reynolds number, $Pr$ is Prandtl number, $k_H$ is helium gas thermal conductivity, $\mu_H$ is viscosity of the helium gas and $\mu_{w,H}$ viscosity of the helium gas at wall temperature. The equivalent diameter can be calculated as follows

$$D_E = \frac{D_{g,H}^2 P}{\sqrt{(\pi D_{g,H})^2 + P^2}} = Nd^2. \quad (11)$$

The Reynolds number is defined as follows

$$Re = \frac{D_{g,H} G}{\nu_H}, \quad (12)$$

where $G$ (kg/m²/s) is mass velocity of the helium gas, and for the proposed design configuration, the mass velocity of the helium gas can be estimated as follows

$$G = \frac{\dot{m}_H}{2D_{g,H}^2 \pi} \sum_j \left( \frac{1}{2} (D_{inh,d} + (j-1)S_T)^2 - \frac{1}{2} (D_{inh,d} - (j-1)S_T)^2 \right) \left(\frac{1}{2} D_{inh} + (j-1)S_T\right)^2$$

where $j$ is the number of helical column in the vessel, in this study, $j = 7$. The helium gas properties of $k_H$ and $\mu_H$ are correlated dependent on the helium gas side average temperature ($T_{ave,H}$)[5].

$$k_H = 2.687 \times 10^{-3} (1 + 1.123 \times 10^{-3} P_H T_{ave,H}^{0.71} (1 - 2 \times 10^{-4} P_H)) \quad (13)$$

$$\mu_H = 3.674 \times 10^{-7} T_{ave,H}^{0.7} \quad (15)$$

where $P_H$ is helium gas side pressure in bar.

| Pressure, bar | 10    | 20    | 35    | 50    | 70    | 100   |
|--------------|-------|-------|-------|-------|-------|-------|
| 473.15K      | 255.4 | -     | -     | -     | -     | -     |
| 523.15K      | 248.0 | 274.0 | 337.0 | -     | -     | -     |
| 573.15K      | 250.7 | 264.5 | 291.5 | 328.4 | 404.9 | -     |
| 623.15K      | 256.8 | 265.6 | 281.1 | 300.0 | 332.0 | 402.5 |
| 673.15K      | 264.5 | 270.6 | 281.0 | 292.7 | 310.8 | 344.5 |
| 723.15K      | 272.8 | 277.5 | 285.0 | 293.3 | 305.4 | 326.3 |
| 773.15K      | 281.5 | 285.3 | 291.1 | 297.4 | 306.3 | 321.0 |
Plain tube overall heat transfer coefficient is selected. Both side heat transfer coefficients are correlated with\[6\]

\[
\frac{1}{U_o} = \frac{d}{h_{i,d_i}} + f f_i \left( \frac{d}{d_i} \right) + \frac{d}{2k_{wall}} \ln \left( \frac{d}{d_i} \right) + f f_o + \frac{1}{h_o} \]  

(16)

where \(f f_i\) and \(ff_o\) are the inside and outside tubes fouling factor, respectively. The fouling factors are estimated to be 0.000172 \(\text{m}^2\text{K}/\text{W}\) at clean condition\[6\].

After all the necessary parameters are estimated, the heat transfer area can be calculated with

\[
A = \frac{Q_{duty}}{U_o \Delta T_{LMTD}} 
\]

(17)

This is the outer area of the heat transfer surface. The value of \(A\) can be used to calculate the length and height of helical coil.

3. Results and Discussions

3.1 Proposed Design

To separate the regions, the saturation temperature need to be calculated since during evaporation the temperature inside the evaporator region is constant. From the properties of saturated water (liquid–vapor): pressure table\[4\], with the assumption of constant pressure at 62 bar of water/steam side, the saturation temperature is 550.8 K. The calculation of the state properties for each of the region is started from the known properties of superheater region as the target output of superheated steam. The target superheated steam is 798.15K at 3.54 kg/s and 62 bar. The counter-flow input of the helium hot gas is 973.15K at 4.27 kg/s and 34.2 bar.

Thermal duty or energy absorbed by the water/steam for each of the region is calculated. From table 2, The highest thermal duty of 5.52 MW is for evaporation process, the thermal duty is more than double of that for the economizer and superheater ones. Evaporation energy is highest since the enthalpy of evaporation of 1557.9 kJ/kg is higher than that of the enthalpy difference for increasing the water (609.6 kJ/kg) and steam (695.2 kJ/kg) temperatures in economizer and superheater, respectively. Second highest thermal duty is 2.46 MW for increasing steam quality into superheated one. The lowest thermal duty is 2.16 MW for the economizer, but not far difference from the superheater one.

Outlet temperature for each of region in helium gas and water/steam sides can be determined from the thermal duty as can be seen in table 2. Temperature difference for each of region is used to calculate the heat transfer coefficient. The highest overall heat transfer coefficient of 1211.7 W/m²K is in the evaporator region. This high value of overall heat transfer coefficient, although usually driven

| Table 2. Results of the analytical design for helical coil steam generator. |
|---------------------------------|---------|---------|---------|
| Water/Steam                     | 3.54 kg/s and 62 bar |
| - Inlet Temp \((T_{i,w})\)       | 418.15K  | 550.81K | 550.81K |
| - Outlet Temp \((T_{o,w})\)      | 550.81K  | 550.81K | 798.15K |
| Helium gas                      | 4.27 kg/s and 34.2 bar |
| - Inlet Temp \((T_{i,H})\)       | 609.68K | 860.79K | 973.15K |
| - Outlet Temp \((T_{o,H})\)      | 511.42K | 609.68K | 860.79K |
| Energy absorbed by              | 2.16 MW  | 5.52 MW | 2.46 MW |
| Water/Steam \((Q_{duty})\)      |          |         |         |
| LMTD                             | 74.8 K   | 151.2 K | 236.1 K |
| Total heat transfer              | 942.5 W/m²K | 1211.7 W/m²K | 770 W/m²K |
| coefficient \((U_o)\)           |         |         |         |
| Heat transfer area \((A)\)       | 30.63 m² | 31.16 m² | 13.54 m² |
| Total heat transfer area         |          |         |         |
by the value of helium gas heat transfer coefficient side, is also driven by a high value of subcooled boiling heat transfer coefficient in this region. Second highest overall heat transfer is 942.5 W/m²K for increasing the inlet water temperature from 418.15 to 550.81K. This is due to the fact that water ability to transfer heat is higher than that of the steam.

The last step is to calculate the surface area for the heat transfer process. Knowing that evaporation process need the highest thermal duty makes no debate that it will need more surface area of 31.16 m². The surface area for the economizer of 30.63 m² as the second largest is not far different from the evaporator one because the overall heat transfer coefficient of the economizer is also high. The surface area of economizer is higher than that of superheater although the thermal duty for superheater is higher than that of the economizer. This is since the LMTD temperature for the superheater is higher than that of the economizer, and the specific heat capacity for water is also higher than that of the steam. The total heat transfer area for the once through counter-flow steam generator required for the design is 75.33 m². But this value need to be adjusted following the comparison of the existing similar design reactor.

3.2 Existing Reactor Design
A 10MW High Temperature Gas cooled Test reactor (HTR-10) was designed by INET of Tsinghua University[9-10]. The once through counter-flow steam generator employs helical coil with different configuration. The helical coil in this steam generator is separated individually while in our proposed design, it is combined in one tube bundle. Although it is different in configuration, the helical coil employed is similar, so it is comparable to be used as reference. HTR-10 has 30 number of once through helical coil bundle with helical coil tube outer diameter of 18 mm[9].

The same calculation procedure is conducted but with slightly different in the calculation of mass velocity and equivalence diameter in the helium gas side as follow

\[ G = \frac{m_H}{4(d_p^2-d_o^2)-(d_h^2-d_i^2)} \]

\[ D_E = \sqrt{\frac{N(p_{in})}{(\pi d_o^2)^2 + p^2} - d^2} \]

where \( d_o \) is the outer diameter of the inner cylinder, \( d_h \) is the outside diameter of helical coil and \( d_i \) is the inside diameter of helical coil.

From the calculation, the surface area for the heat transfer process required is 66.6 m². It is reported that the heat transfer surface area is 56 m²[10]. Around 18.9% difference is existed between the calculated and the reported one. This difference may exist because there is an increase in heat transfer coefficient at the helium gas side due to the support structure of the helical coil tube inside the tube bundle. So, based on this comparison, it will be naturally that the heat transfer surface area of the proposed design from the calculation also overestimated by around 20%. Improvement of the estimation can be achieved with involving the pressure drop estimation. However, this estimation is useful to fast predict the surface area required for helical coil tubes steam generator design reference. Further analysis such as Computational Fluid Dynamics should be employed to confirm the surface area requirement, especially because of flow distribution of the working fluids.

4. Conclusions
Design of once-through counter flow steam generator with helical coil tubes for Nuclear HTGR is proposed in this study. The helical coil tubes are arranged in one vessel to reduce the reactor volume. Heat transfer surface area is estimated at constant pressure in this study. Simplify thermodynamic analysis with region separation of the helical coil is conducted. The surface area of an existing similar design of steam generator is estimated using the calculation procedure. It is found that the calculation overestimates the surface area by around 20%. Preliminary estimation heat transfer surface area of the proposed design shown that it required around 60.2-75.3 m² to achieve the targeted superheated steam output.
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