Validation of helical steam generator design for the experimental power reactor

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Abstract. The steam generator is an important component in any commercial nuclear power plants to deliver required steam from the reactor heat. Different with the steam generator design of PWR, other design in a small modular reactor (SMR) with smaller thermal capacity incorporates the helical-coiled tubes having advantage of additional heat transfer surface to deliver a superheated steam. The purpose of this research is to model the helical-coiled steam generator in the experimental power reactor developed by BATAN using RELAP5/SCDAP/Mod3.4 code as thermal hydraulic code to obtain a validation of technical data in the conceptual design document. After a number of steady-state simulations, operational thermal hydraulic parameters such as outlet helium and steam temperature, tube pressure drop, and heat capacity have been calculated to be close with the design data. It has been found out, that the different heat transfer characteristics in the helical-coiled tubes need to be addressed specifically in the RELAP5 input data by considering the new estimated heat transfer coefficient or by modifying the heat transfer area. In general, the developed steam generator model is ready to be integrated with the experimental power reactor model that can be used for safety analysis purposes.

1. Introduction
Steam generator is an important component in any commercial nuclear power plants operated worldwide today, especially in the pressurized water reactor (PWR) and pressurized heavy water reactor (PHWR). Its basic design is not different than a heat exchanger to convert fluid into steam from the heat generated in a nuclear reactor core. The converted fluid is feedwater for the PWR and heavy water for the PHWR such as CANDU reactor, in which the steam generator design for each type is almost similar [1]. The steam generator design of PWR and PHWR is widely known, having a typical concept of straight tubes (vertically with U-shaped or once-through or horizontally installed) filled with a flowing heated water (primary side), which are submerged in the converted water (secondary side) inside a shell form of vessel. In that case, the primary side water flows with higher pressure than the secondary side water to deliver dry slightly saturated steam or super-saturated steam into the turbine generator. Such PWR and PHWR related designs have been assessed and analyzed in term of safety and performances since they are already used in the commercial operating nuclear power plants with large thermal capacity [2, 3, 4].

Other design of steam generator used in a small modular reactor (SMR) with smaller thermal capacity incorporates the helical-coiled tubes having advantage of highly efficient use of space with additional heat transfer surface to deliver a superheated steam [5]. Several SMRs using the helical-coiled steam
generator are NuScale, SMART, IRIS, and HTR. The HTR (high temperature gas-cooled reactor) is of interest in this research, since it is the similar type of reactor, which is being designed by BATAN under the name of experimental power reactor (EPR) [6]. Under current design, the EPR with 10 MWt will be integrated with the helical-coiled steam generator to deliver superheated steam into the turbine generator for producing electricity of 3 MWe. Currently, the design of EPR is entering the detailed design stage, in which results of analysis related to the technical data, performance and safety aspects of basic design have to be validated. One of the components of EPR to be considered is the design of helical-coiled steam generator that has been determined in the conceptual design document [7]. Instead of straight or U-tubes, the helical-coiled steam generator is characterized by tubes, which are wound into helical coils to form a large bundle. Its heat transfer coefficient can be 16 to 43 % higher than straight tube design [8, 9].

The EPR document related to the helical-coiled steam generator has described several technical specifications such as thermal capacity, primary coolant temperature, primary coolant flow rate steam output, superheated steam pressure and temperature and feedwater temperature. Related to the helical-coiled tube design, main design characteristics of the tubing system and other parts are also presented in the document. The purpose of this research is to model the helical-coiled steam generator using RELAP5/SCDAP/Mod3.4 code as thermal hydraulic code to obtain a validation of technical data related to the thermal hydraulic parameter specifications using the data of main design characteristic. Modelling a helical-coiled tubes will be the focus of this research since the steam generator model performed so far were only limited to the U-tube steam generator. Results of analysis can be found in the safety analysis of AP1000 and APR1400 reactor [10, 11]. Methodology of research refers to the use of RELAP5 in modeling the helical-coiled tubes in the Next Generation Nuclear Plant (NGNP) [12]. The design of NGNP helical-coiled steam generator is different than the EPR steam generator in term of the number of tubes wound in only one bundle. Another reference can be found in the modeling of IRIS steam generator having much more number of tubes and winding by RELAP5 for performance analyses [9]. The research does not discuss several disadvantages still existing related to steam generators in general such as tube fouling and plugging, which can decreases the efficiency of the steam generator. To manufacture the helical-coiled tube is also more costly than the straight tube type as also it is more difficult to be cleaned easily. Finally, the results of analysis will contribute to complement the detail design description of EPR helical-coiled steam generator as part of preparation EPR detail design documents.

2. Descriptions of EPR helical-coiled steam generator

By design, EPR steam generator is object to generate superheated steam with around 520 °C and 6 MPa from heated feedwater by the heat of hot helium gas within the power of 50 % to 100 %. It has a form of vertically erected pressure vessel, tube bundles for heat-exchange surface, shells, feedwater charging tubes, superheated steam discharging tubes, and headers for steam and feedwater, which has a comparable design with the THTR-300 steam generator [13]. The tubing system has a type of once-through, helically coiled tubing in a single cylindrical bundle with vertical operating position. The tube bundle is placed in the internal shell of steam generator, in which helium gas flow from a hot duct enters the shell from in top-down direction as part of primary system to heat the feedwater flowing inside the tubes. The heat-exchanging tubes are filled with the feedwater with 145 °C via a feedwater charging tube of 3.45 kg/sec mass flow in the lower part of steam generator moving bottom-up to be converted into the superheated steam as part of secondary system. Figure 1 shows the general view of the EPR steam generator as proposed by the conceptual design document [7]. On the upper part of steam generator, a helium circulator is installed to maintain the helium flow in the primary system, which also acts as a primary gas blower. By looking at the hot duct connection and the position of the helium circulator, the EPR steam generator design is similar to the steam generator of HTR module with downrated dimension [14].
Figure 1. EPR steam generator general view (Left) and proposed pattern of tube bundles inside internal shell (Right)

The figure also illustrates the pattern of tube bundles in form of helical-coiled tubes around a central spindle placed in the internal shell. In the conceptual design, there are 7 layers of single cylindrical bundles with 7 helical-coiled tubes on each row. Therefore each cylindrical bundle has increased diameter starting from the innermost (1st bundle) to the outermost bundle (7th bundle) marked by D-1 to D-7. Another design uses an increased number of tubes starting from 4 tubes in the 1st layer, rising gradually up to 10 tubes in the 7th layer as showed in the Figure 1. That kind of increased number of tubes was also applied in the design of steam generator for SMART Integral test loop (ITL) [15]. In total, there are 49 heat exchange tubes installed in the steam generator with average coiling height of 4970 mm. All tubes have inside diameter (Di) of 12 mm with 2 mm thickness. Table 1 lists the main geometric data of helical-coiled tube bundle, which are used for the modelling using RELAP5.

The inclination angle $\varepsilon$ is a positive slope angle of the tube length to achieve a full helical circle. With increased tube bundle diameter, the inclination angle become bigger, causing the calculated tube length (L) becomes shorter as shown in the table. The values of $\varepsilon$ and L in the table are estimated by manual calculation by referring the tube pitch or the distance between the tubes. All of the dimensions in the Table 1 and Figure 1 are used in particular to calculate the equivalent feedwater flow area, average heat transfer area, and primary helium flow area and in the RELAP5 input deck. The primary helium flow area is the flow area of helium entering the internal shell of steam generator without the tube bundle cylinders, while the average heat transfer area is the area of all tube surfaces in the tube bundles, in which the heat transfer from helium to the feedwater takes place.
Table 1. Main technical parameter of EPR steam generator and geometric data of helical-coiled tube bundle

| Main technical parameter of EPR steam generator |  |
|-----------------------------------------------|--|
| Thermal capacity (MW)                          | 10.16 |
| Helium temperature at the steam generator inlet/outlet (°C) | 700.0 / 243.0 |
| Helium flow rate (kg/sec)                      | 4.27 |
| Helium pressure (MPa)                          | 3.42 |
| Feedwater / superheated steam temperature (°C) | 145.0 / 525.0 |
| Superheated steam pressure (MPa)               | 6.2 |

| Main geometric data of helical-coiled tube bundle |  |
|--------------------------------------------------|--|
| No. of bundle | Tubes number | D (mm)  | ε (°)  | L (m)  | Tube bundle height (m) |
|----------------|---------------|---------|--------|--------|------------------------|
| 1              | 4             | 251 (D-1) | 10.83  | 40.59  | 4.97                   |
| 2              | 5             | 308 (D-2) | 11.02  | 40.03  | 4.97                   |
| 3              | 6             | 365 (D-3) | 11.16  | 39.37  | 4.97                   |
| 4              | 7             | 422 (D-4) | 11.26  | 38.85  | 4.97                   |
| 5              | 8             | 479 (D-5) | 11.33  | 38.10  | 4.97                   |
| 6              | 9             | 536 (D-6) | 11.39  | 39.05  | 4.97                   |
| 7              | 10            | 593 (D-7) | 11.44  | 37.74  | 4.97                   |

* D : mean diameter of tube bundle cylinder
* ε : inclination angle

3. RELAP5 modelling of helical-coiled steam generator

The focus of modelling using RELAP5 is to obtain a representative heat exchange mechanism from the helium gas flow to the feedwater through the helical-coiled tube. Most of the RELAP5 model involves a straight heated tube, in which a heat transfer from primary fluid to secondary fluid occurs from a side-by-side parallel volume. In case of helical-coiled tubes with a multilayer bundles, the helical form is stretched to obtain a straight tube to be placed in an inclination angle calculated from the total tube length and helical height [12]. The heat transfer surface of the straight tube is calculated from all tube surfaces of the tube bundles as showed in Table 2.

Table 2. Estimation of tube flow area and heat transfer surface area of helical-coiled tube for RELAP5 model

| No. of bundle | Tubes number | D (mm)  | ε (°)  | L (m)  | Tube bundle height (m) |
|---------------|---------------|---------|--------|--------|------------------------|
| 1             | 4             | 251 (D-1) | 10.83  | 40.59  | 4.97                   |
| 2             | 5             | 308 (D-2) | 11.02  | 40.03  | 4.97                   |
| 3             | 6             | 365 (D-3) | 11.16  | 39.37  | 4.97                   |
| 4             | 7             | 422 (D-4) | 11.26  | 38.85  | 4.97                   |
| 5             | 8             | 479 (D-5) | 11.33  | 38.10  | 4.97                   |
| 6             | 9             | 536 (D-6) | 11.39  | 39.05  | 4.97                   |
| 7             | 10            | 593 (D-7) | 11.44  | 37.74  | 4.97                   |

The total flow area of tubes, in which feedwater flows, is 0.005541 m². From the surface area of inner tubes and outer tubes, an average of heat transfer area is estimated to be 84.269 m². This value is a validation of the heat transfer area described in the conceptual design document, which is 84.8 m² [7].
The second value to be estimated is the equivalent primary helium flow area flowing around the outer surface of tube bundles, which is calculated from the internal shell flow area subtracted by areas of multilayer tube bundle cylinders. On that case, the mean diameters of tube bundle cylinders on Table 1 and the internal shell diameter of 219 mm (inside) and 625 mm (outside) on Figure 1 are used, which results in $0.11478 \text{ m}^2$ of primary helium flow area.

Modelling of the steam generator components using RELAP5 is performed by defining the entire components into nodes (nodalization) [16]. Nodes in RELAP5 representing hydrodynamic components and heat structures, for which the nodalization of EPR steam generator is developed are shown in Figure 2.

![Figure 2. Development of RELAP5 nodalization of EPR helical-coiled steam generator](image)
4. Results and discussion

4.1. Steady-state simulation based on standard input data

The first two parameter to calculate from the determined input data are the outlet helium temperature or \( T_{\text{H-Out}} \) (SV-480) and outlet steam temperature or \( T_{\text{S-Out}} \) (P-690) based on determined secondary mass flow rate of 3.54 kg/sec. The hydraulic loss inside the tube winding is first neglected. The calculation results in the \( T_{\text{H-Out}} \) of 263.6 °C and \( T_{\text{S-Out}} \) of 461.32 °C. Looking at the steam temperature of 6.2 MPa, the saturated steam temperature is 160.1 °C, so that the resulted steam is superheated, even it is still less than expected design value of 525 °C. By analyzing the pressure in the inlet and outlet helical-coiled tube, the calculated pressure loss in the water-steam line is 0.176 bar, which is also below the design value of 0.92 bar. The \( T_{\text{H-Out}} \) of 263.6 °C is higher than design value of 243 °C, whereas the pressure drop of helium calculated from inlet helium channel (P-420) and outlet helium annulus (SV-480) is 0.012 bar, slightly lower than minimum design value of 0.02 bar. From the preliminary results, the heat transfer from helium to water side is not optimum yet, since the average heat flux is 9.55 MWt. Therefore, the 2\(^{nd}\) calculation is conducted by considering the hydraulic loss of water inside the tube winding and in the helium flowing the internal shell to analyze its effect on the above parameter. It is found out that by adjusting the hydraulic losses (\( K_{\text{loss}} \)) on primary and secondary system the related pressure drops are close to the design values even they have no significant effect of the \( T_{\text{H-Out}} \) and \( T_{\text{S-Out}} \). Based on that, a third calculation is carried out by adjusting the secondary mass flow rate to obtain other parameter results. If the feedwater mass flow rate is increased, the resulted steam temperature \( T_{\text{S-Out}} \) will be decreased even it is still superheated. The increased feedwater mass flow rate will have effect on the average wall heat transfer to increase as shown in the decrease of the \( T_{\text{H-Out}} \). To raise the \( T_{\text{S-Out}} \), the feedwater mass flow rate can be lowered from the nominal value of 3.54 kg/sec resulting in the decreased heat transfer of the primary side. Table 3 shows the summary of the changes in the parameter input and output in the steam generator operational parameter.

| Parameter                  | No. of simulations | Design |
|----------------------------|--------------------|--------|
| K loss (P-440)             | 0.0                | 1.0    | 1.0  | 1.0  | 1.0  | -  |
| K loss (P-670)             | 0.0                | 1.0    | 1.0  | 1.0  | 1.0  | -  |
| \( T_{\text{H-In}} \) (°C) | 700.0              | 700.0  | 700.0| 700.0| 700.0| 700.0|
| \( T_{\text{H-Out}} \) (°C) | 263.6              | 265.32 | 250.72| 266.93| 241.54| 243.0|
| \( \Delta P_{\text{helium}} \) (bar) | 0.0117          | 0.0232 | 0.022 | 0.02326 | 0.02245 | 0.02 |
| \( M_{\text{helium}} \) (kg/sec) | 4.27               | 4.27   | 4.27 | 4.27 | 4.27 | 4.27 |
| \( T_{\text{W-in}} \) (°C)  | 143.5              | 143.5  | 143.5| 143.5| 143.5| 143.5|
| \( T_{\text{S-out}} \) (°C) | 461.32             | 449.42 | 285.32| 444.38| 511.53| 525.0|
| \( \Delta P_{\text{helical}} \) (bar) | 0.176             | 0.895  | 0.9055| 0.89051| 0.95471| 0.92 |
| \( M_{\text{feedw}} \) (kg/sec) | 3.54               | 3.54   | 4.5  | 3.54 | 3.54 | 3.54 |
| \( Q_{\text{wall av}} \) (average) | 9.547             | 9.508  | 9.688| 9.469075| 10.076695| 10.16|

One purpose of the helical-coiled steam generator model is to be integrated with the RDE reactor having determined boundary conditions, in this case the \( T_{\text{H-In}} \), \( T_{\text{H-Out}} \), and helium mass flow rate. \( T_{\text{H-In}} \) is already set constant in the above calculation of 700 °C, which is the heat temperature coming out from the reactor. To keep the heat balance of the reactor, \( T_{\text{H-Out}} \), which is the helium temperature back to the reactor, is assumed to be maintained of 243 °C, with the constant helium mass flow rate of 4.27 kg/sec. Based on the simulation performed, one way to decrease the \( T_{\text{H-Out}} \) is by increasing the feedwater mass flow rate from its nominal value of 3.54 kg/sec. Table 3 (3\(^{rd}\) calculation) shows the results of simulation, that by increasing the \( M_{\text{feedw}} \) to 4.5 kg/sec, the resulted \( T_{\text{H-Out}} \) will approach the design value of 243 °C, at the expense of the lower produced superheated steam as shown by the \( T_{\text{S-Out}} \) of only 285.32 °C.

4.2. Effect of Heat transfer coefficient of the helical-coiled tube in RELAP5 model

The analyses related the output temperature described before might be misleading that the number of the helical-coiled tubes are not accurate. One factor to be considered in the heat transfer between two
fluids is the heat transfer coefficient, which in the RELAP5 model still assumes a straight pipe. Several literatures stated that the convective heat transfer coefficient in the helical-coiled tube is higher than in the straight tube [8, 12]. Literature review also reveals that not many researches are available related to the heat transfer coefficients of helical-coiled heat exchangers even several correlations have been proposed [18, 19]. Andrzejczyk et al [17] proposed a convective heat transfer coefficient for the coiled tube as:

$$\alpha_{io} = \alpha_{DB} \left\{ \left[ 1 + 3.6 \left( 1 - \frac{\delta}{0.5d_o} \right) \right] \left( \frac{\delta}{0.5d_o} \right)^{0.8} \right\}$$  (1)

In which, $\alpha_{DB}$ is the Dittus-Boelter heat transfer coefficient for straight tube, $\delta$ is tube thickness, and $d_o$ is tube inside diameter. By taking the $\alpha_{DB}$, which is calculated by RELAP5 for the 40 segments of P-670 (tube side), the multiplication factor can be calculated to obtain a new convective heat transfer for the helical-coiled tubes ($\alpha_{io}$) applied in the tube side (water-steam). The factor is calculated to be 1.411 to be multiplied with the $\alpha_{DB}$ on each segment. The obtained data are used as the new input data in the heat structure model to be run again by RELAP5. Results of calculation are shown in the 4th simulation of Table 3, in which the $T_{H\text{-Out}}$ and $T_{S\text{-Out}}$ are not changed significantly compared with the standard input data. The reason might be the heat transfer in the shell side, which is not yet adjusted. The heating helium has a characteristic to be circulated over the outer wall of the helically coiled tube fitted in the shell annulus [20], therefore its heat transfer coefficient should be also estimated again. V.C Momale et al [21] has reviewed several correlations for the outside heat transfer coefficient, for which an agreement among them is not found. Due to the general conclusion that the heat transfer coefficient in the helical-coiled tube is bigger than in the straight tube, it is then assumed that the heat transfer coefficient of the heating medium is multiplied with the similar factor as the heated medium, which is 1.411 for the 40 segments of the P-440. The results of simulation using the new heat transfer coefficient are shown in the 5th calculation of Table 3, in which the $T_{H\text{-Out}}$ and $T_{S\text{-Out}}$ are close with the design parameter. The effectivity of the heat transfer is also increased as shown in the average heat source from the tube wall, which approach the 10.16 MWt of the design. Figure 3 illustrates the results of the 2nd and 5th steady-state simulation for the $T_{H\text{-Out}}$ and the $T_{S\text{-Out}}$ calculation under design helium mass flow rate of 4.27 kg/sec and feedwater mass flow rate of 3.54 kg/sec after 2000 second.

![Figure 3](image-url)

**Figure 3.** Steady-state simulations for $T_{H\text{-Out}}$ (outlet helium temperature) and $T_{S\text{-Out}}$ (outlet steam temperature) calculations under design helium and feedwater mass flow rate.
The effect of heat transfer coefficient in the 2nd and 5th calculation also appear in the produced steam along the helical-coiled tubes. Figure 4 shows the progress of steam production, which is described as the steam quality, looked from the bottom tube up to the highest part of the tube, where the saturated steam is established after 2000 second calculation. The steam quality is defined as the proportion of saturated steam (vapor) mass in a mixture of saturated liquid / steam masses. In the RELAP5 output, a steam quality of 0 indicates 100 % liquid or water in this case, while a steam quality of 1.0 indicates 100 % steam. From the figure, the water phase occurs in the similar tube position, which is the 16th segment, to be gradually switched over to the steam entirely in the 36th – 38th segment. In the 5th calculation with a better heat transfer coefficient, the steam is earlier developed than in the 2nd calculation.

**Figure 4.** Development of steam along the segments of helical-coiled tubes after 2000 second simulation

4.3. Steady-state simulation for the transient analysis

The steady-state results obtained above are based on the determined heat transfer coefficients, which are included in the RELAP5 input data for the validation of the helical-coiled steam generator model with the design data. For the transient analysis, in which thermal hydraulic parameters change constantly, a change in the heat transfer also takes place according to the time sequence. Therefore another input data is also prepared, which is based on the increased heat transfer area according to the following general correlation of heat exchanger [20]:

\[ Q = U \cdot A \cdot \Delta T_{\text{log}} \]  

By increasing the heat transfer area (A) and maintaining the overall heat transfer coefficient (U) to be calculated by RELAP5, the transferred heat load (Q) can be also increased. In the modified input data, it is assumed that the heat transfer area will be multiplied by the similar factor of the calculated heat transfer coefficient for the helical-coiled heat exchanger, which is 1.411 or 41 % higher than the original heat transfer area. Figure 5 shows the steady-state simulation to calculate \( T_{\text{H-Out}} \) and \( T_{\text{S-Out}} \) after modifying the value of heat transfer area in the model of the 2nd calculation.
Figure 5. Steady-state simulation for $T_{H\text{-Out}}$ (outlet helium temperature) and $T_{S\text{-Out}}$ (outlet steam temperature) calculations with modified heat transfer area in the helical-coiled tubes

From Figure 5, it shows that the effect of modified heat transfer area on the values of $T_{H\text{-Out}}$ and $T_{S\text{-Out}}$ is almost similar with the modified heat transfer coefficient as shown in Figure 4. By comparing with the input data without modification on 2nd calculation, the steady-state values are closer with the design data, in which $T_{H\text{-Out}}$ and $T_{S\text{-Out}}$ are 236 °C and 525.45 °C, respectively. The absorbed heat load ($Q$) is also therefore increased to 10.19 MWt from 9.50 MWt. Those results are approximation only having effect on the temperatures of helical-coiled tube walls, which might be different between the 2nd calculation, 5th calculation, and calculation with modified heat transfer area.

5. Conclusion

Modelling the helical-coil steam generator of experimental power reactor using RELAP5/SCDAP/Mod3.4 code has been performed to validate the proposed technical data with the main design characteristic as described in the document. The proposed technical data related to the helical tube pattern results in the calculated heat transfer area, which is close with the design specifications of 84.8 m$^2$. For the validation of thermal hydraulic parameter under steady-state condition such as the outlet helium and steam temperature, the resulted calculation closing to the design values of 243 °C and 525 °C is related to the determination of the heat transfer coefficient in the helical-coiled tubes, which needs to be addressed specifically in the RELAP5 input data. Another alternative is to increase the heat transfer area in the input data around 41 %, which results in the similar effect with the modified heat transfer coefficient. More analyses related to the heat transfer correlations in the inside and outside surface of helical-coiled tubes are required using other codes in order to obtain more representative results. In addition, the developed steam generator model is ready to be integrated with the experimental power reactor model that can be used for safety analysis purposes.

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