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Design Scenario and Analysis for Preliminary Specification of Steam Generator in the PeLUIt-40

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A B S T R A C T

The helical steam generator is connected to an HTGR-type nuclear reactor called PeLUIt-40 for steam production. Steam is used to generate electricity and hydrogen. A once-through helical tube bundle was employed because of its ability to endure mechanical stress due to thermal expansion, high resistance to flow-induced vibrations, and better thermal performance compared to a straight tube one. To produce the targeted steam, a design analysis of the once-through helical steam generator needs to be conducted. A quick evaluation method was used to predict the preliminary specifications required for steam production. Simple thermodynamic calculations combined with empirical heat transfer coefficients covering convective and boiling processes at constant pressure were used to carry out the analysis. Two scenarios were conducted to evaluate the design choice based on the previous design of RDE-10.

1. INTRODUCTION

Indonesia already has a plan to develop a High-Temperature Gas Cooled Reactor (HTGR) in collaboration with another country, where this reactor is named Reaktor Daya Eksperimental (RDE). A nuclear power reactor has a thermal power of 10 MWth and was previously designed by the National Nuclear Energy Agency (BATAN) [1]. Helium gas is used to extract heat from the reactor core, where the RDE is moderated with graphite and uses a spherical uranium fuel element (TRISO). In its development, the design and specification of the RDE refer to the Chinese HTR-10. [2–6]. The high-temperature gas-cooled reactor pebble-bed module (HTR-PM) with a capacity of 2 x 250 MWth is a Generation IV nuclear energy system developed by The Institute of Nuclear and New Energy Technology (INET) of Tsinghua University in China [7]. Generation IV nuclear energy system is designed to possess intrinsic safety and high efficiency, with many application opportunities as a high-temperature heat source [8], one of which is for hydrogen production.

The vertical heat exchanger using an inverted U-tube bundle configuration with a straight tube for a steam generator is usually used in pressurized water reactor (PWR) or pressurized heavy-water reactor (PHWR) with an overall steam generator height of 20-23 m and tube bundle height of 9.5-10.5 m [9]. The United Kingdom and the European

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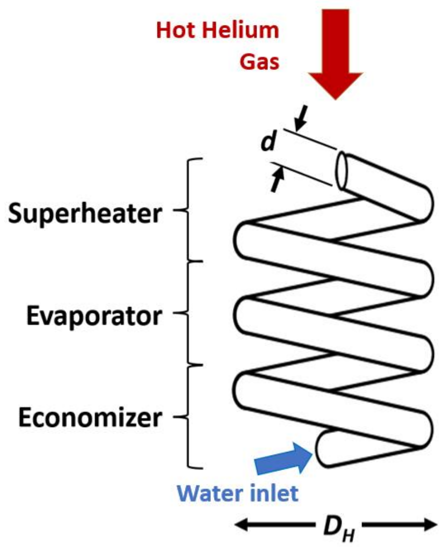

Fig. 1. Ilustration of the regions in the helical coil.

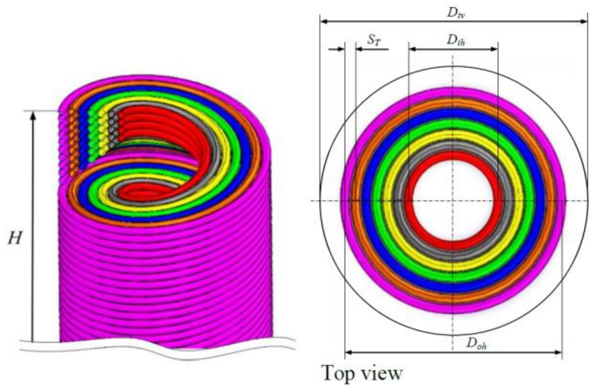

Fig. 2. The geometry of the helical coil steam generator [12]

Community in 1962 worked together to build the world's first HTGR with a thermal power of 20 MWth using fuel in the form of bundles of graphite rods and reached criticality in 1964. Subsequently, Germany successively built two pebble-bed nuclear plants, a 45 MWth test HTGR (AVR) and a 750 MWth HTGR power plant (THTR-300) [8]. THTR-300 utilized a once-though helical coil bundle for its steam generator [10]. The latest HTGRs that utilize a once-through helical coil steam generator are HTR-10 and HTR-PM from China [7-8].

Fluid flow in the helical coil produces higher shear rates and turbulence as pressure drops, resulting in a 40% higher film coefficient and reduced fouling tendencies compared to the common shell and tube type. The helical coil shape eliminates the problems of thermal expansion and thermal shock that often occur during the starting of a heat-exchanging process, especially those involving high temperatures or cryogenics with the possibility of applying pressures exceeding 69 MPa [10-11]. Once-through helical tube bundles were selected in this study for their ability to endure unwanted mechanical stress due to thermal expansion, high resistance to flow-induced vibrations, and better thermal performance compared to straight tubes.

To achieve the targeted steam production, a once-through helical steam generator needs to be evaluated. Simple thermodynamic calculations combined with empirical heat transfer coefficients which include convective and boiling processes at constant pressure are employed to be able to predict the preliminary specifications required for the targeted steam production. This paper will explain the analysis of the steam generator of PeLUIt-40 to evaluate the design choices of the steam generator based on the previous design of 10 MWth RDE, in order to choose the best preliminary specification from two scenarios.

2. METHODOLOGY

Analysis of the helical steam generator design was carried out by dividing the helical coil into three regions as shown in Fig. 1. The three regions with different processes are called economizer, evaporator, and superheater. These regions adopt the design concept of the Heat Recovery Steam Generator (HRSG) but without any distinctive component boundaries. Each region has a different process or phenomenon in producing superheated steam as the final product. The economizer region is where the water temperature is increased to its saturated temperature. The evaporator region is where the water phase is converted into saturated steam. Lastly, superheater region is where the saturated steam properties are increased to superheated steam.

The proposed helical steam generator design is taken from the RDE design [12], 49 once-through coils as shown in Fig. 2 will be inserted in one vessel. The steam generator of 10 MWth RDE was estimated to have approximately 70 m^2 heat transfer area. Details of the design are shown in Fig. 2. The specification of the helical bundle is summarized in Table 1 where H is the height and n is the number of turns of the helical coil. The helical coil tube length (L) is calculated by Eq. 1.

$$L = n\sqrt{(\pi D_H)^2 + p^2} \tag{1}$$

The thermal power required for each region and the inlet and outlet temperatures of the helium gas and the water or steam sides is calculated simultaneously. The values of the targeted superheated steam and the hot helium gas are taken from the specification of the previous 10 MWth RDE but adjusted to produce 40 MWth-worth of steam. The helical tube is assumed to be made using Incolloy 625. The calculation procedure can be conducted directly due to the

Table 1. Specification of the Helical Steam Generator

Specification	Value
Number of columns	7
Outer Column Helical diameter (D_{oh})	0.41 m
Number of the helical coil in the outer column	10 tubes
Inner Column Helical diameter (D_{ih})	0.17 m
Number of the helical coil in the inner column	4 tubes
Column distance (S_T)	20 mm
Helical coil tube outer diameter (d)	16 mm
Helical coil tube outer thickness (t_c)	1 mm
Helical coil pitch ($p = H/n$)	0.199 mm
The Inner diameter of the vessel (D_{iv})	0.64 m

constant pressure assumption. The calculation procedure at each of the regions is as follows and described in detail in the previous study for RDE [12].

1. Thermal duty or load of the water or steam side Q_{duty} (W) calculation.
2. Helium gas output temperature $T_{o,H}$ (K) calculation.
3. Log Mean Temperature Difference (*LMTD*) calculation.

$$LMTD = \frac{(T_{o,H}-T_{i,w})-(T_{i,H}-T_{o,w})}{ln\left((T_{o,H}-T_{i,w})/(T_{i,H}-T_{o,w})\right)} \quad (2)$$

where $T_{i,H}$ is the inlet helium gas temperature, $T_{o,H}$ is the outlet helium gas temperature, $T_{i,w}$ is the inlet water temperature, and $T_{o,w}$ is the outlet water or steam temperature in the respective region.

4. Heat transfer coefficient h (W/m^2/K) calculation for helium and water or steam sides.
5. Overall outer heat transfer coefficient U_o (W/m^2/K) calculation.

$$\frac{1}{U_o} = \frac{d}{h_i d_i} + ff_i\left(\frac{d}{d_i}\right) + \frac{d}{2k_{wall}} ln\left(\frac{d}{d_i}\right) + ff_o + \frac{1}{h_o} \quad (3)$$

where ff_i and ff_o are the inner and outer tube fouling factors, respectively. The fouling factor is estimated at 0.000172 m^{2}K/W in clean conditions.

6. Required outer pipe surface area A_o (m^2) calculation.

$$A_o = \frac{Q_{duty}}{U_o LMTD} \quad (3)$$

This calculation method has been compared to the existing Chinese HTR-10. It uses counterflow once-through helical steam generators with individual helical coloumn. It has 30 individual heat exchanger columns with an outer diameter of 18 mm helical coil tube. From that results, difference between the calculated area (66.6 m^2) and reported area (56 m^2) is in the value of 18.9% [12].

The design of the RDE will be used to develop PeLUIt-40 steam generator. There are two scenarios for the 40 MWth reactor configuration. The first scenario is by increasing the height of the single helical steam generator vessel of the RDE, and the second one is by dividing it into 3 (three) identical vessels with the same helical arrangement from the RDE but with an adjusted height as shown in Fig. 3. From these two scenarios, the required surface area to meet the target of 40 MW of thermal power is evaluated.

3. RESULTS AND DISCUSSION

3.1 *Scenario One: Single Vessel Steam Generator for 40 MWt*

The targeted superheated steam is 798.15 K at 14.16 kg/s and 62 bar with a counterflow input of hot helium gas of 973.15 K at 17.08 kg/s and 34.2 bar. These values are calculated from the RDE specification of 10 MW thermal output but with a thermal duty of 40 MW. In this scenario, the mass

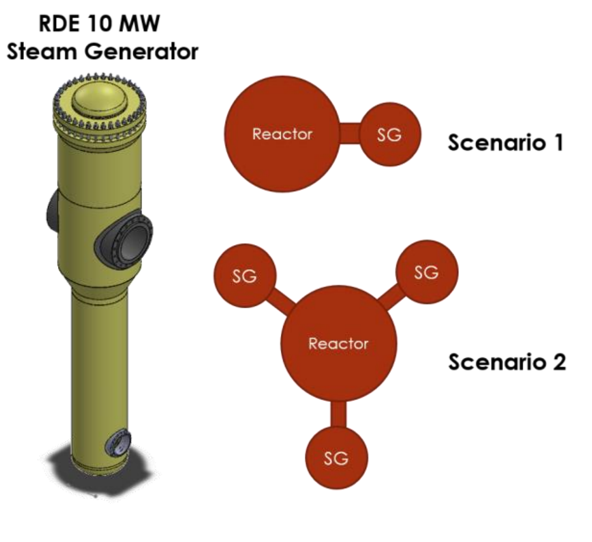

Fig. 3. Design scenarios for 40 MWt of steam generator (SG)

Table 2. Helical steam generator for scenario 1

	Economizer	***Evaporator***	***Superheater***
Water or Steam		14.16 g/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		17.08 g/s and 34.2 bar	
Inlet Temp. ($T_{i,H}$)	609.68K	860.74K	973.15K
Outlet Temp. ($T_{o,H}$)	511.36K	609.61K	860.74K
Thermal Duty (Q_{duty})	8.63 MW	22.06 MW	9.87 MW
LMTD	74.7 K	151.1 K	236.1 K
Overall Heat Transfer Coefficient (U_o)	1466.2 W/m^{2}K	1677.4 W/m^{2}K	1346.9 W/m^{2}K
Heat Transfer Area (A_o)	78.81 m^2	87.05 m^2	31.06 m^2
Total Heat Transfer Area		196.91 m^2	

flow rates of water and helium are four times greater than in the RDE because the target for thermal power is four times higher in this scenario.

From Table 2, the highest thermal load calculation result of 22.06 MW is for the evaporation process. This thermal load is more than double from that of the economizer or superheater. A similar result is also observed in the case of the RDE. The second highest thermal load is 9.87 MW for the superheater to improve the quality of the steam to become superheated steam. The lowest thermal load is 8.63 MW for the economizer, which is not much different from the superheater. It can be seen that the thermal load in this scenario is four times the thermal load in the RDE.

The outlet temperature for each region on the helium and water or steam gas sides can be determined from the thermal load as shown in Table 2. The temperature difference between the inlet and outlet for each region is used to calculate the overall heat transfer coefficient. The highest overall heat transfer coefficient of 1677.4 W/m^2.K is found in the evaporator region. The second highest overall heat transfer is 1466.2 W/m^2.K in the economizer region. To increase the inlet water temperature from 418.15K to 550.81K, a fourfold thermal load is required in this scenario compared to RDE since the mass flow rate also increases fourfold in this scenario as shown in Fig. 4.

The final procedure is to calculate the outer surface area of the tube that is needed for the heat transfer process. The largest surface area of 87.05 m^2 belongs to the evaporator region because the largest thermal duty needed is in the evaporation process. The second largest area of 78.81 m^2 belongs to the economizer region. The surface area of the economizer region is larger than the superheater one (31.06 m^2) even though the heat load for the superheater region is higher than the economizer one, this is because the *LMTD* temperature of the superheater region is higher than in the economizer, and the specific heat capacity of water is also higher than steam. For the economizer, evaporator, and superheater regions in this scenario, the overall heat transfer coefficient is larger than that of the RDE but not linearly four times the RDE, as can be seen in Fig. 5.

The total heat transfer area of the counterflow helical coil steam generator required for the design in this scenario is 196.91 m^2. This area is 180.54%

Table 3. Helical steam generator for scenario 2

	Economizer		Evaporator		Superheater	
Vessel Configuration	Total	Individual	Total	Individual	Total	Individual
Water or Steam	*Total* : 14.16 kg/s and 62 bar or *Individual* : 4.72 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	*Total* : 17.08 kg/s and 34.2 bar or *Individual* : 5.69 kg/s and 34.2 bar					
Inlet Temp. ($T_{i,H}$)	609.61K		860.74K		973.15K	
Outlet Temp. ($T_{o,H}$)	511.36K		609.61K		860.74K	
Thermal Duty (Q_{duty})	8.63 MW	2.88 MW	22.06 MW	7.35 MW	9.87 MW	3.29 MW
LMTD	74.7 K		151.1 K		236.1 K	
Overall Heat Transfer Coefficient (U_o)	1098.74 W/m^{2}K		1381.2 W/m^{2}K		910.27 W/m^{2}K	
Heat Transfer Area (A_o)	105.16 m^2	35.05 m^2	105.71 m^2	35.24 m^2	45.95 m^2	15.32 m^2
Total Heat Transfer Area	*Total* : 256.83 m^2 and *Individual* : 85.61 m^2					

larger than the RDE design as shown in Fig. 6. Since the total height of the steam generator vessel in the RDE design is about 11 meters, the height of the steam generator vessel will increase by at least 30.8 m. The height of these vessels can pose safety and manufacturing concerns.

3.2 *Scenario 2: Three Identical Steam Generators for 40MWt*

The calculation procedure is the same as scenario 1, namely the properties of water or steam for each region are calculated from the properties of the superheater region that has been previously determined as the target output of superheated steam. The superheated steam target is 798.15 K at 14.16 kg/s and 62 bar with hot helium gas counterflow input of 973.15 K at 17.08 kg/s and 34.2 bar. The total mass flow rates of water and helium are the same as in scenario one, but because three identical steam generator vessels are used, the mass flow rates for each vessel in scenario two are one-third of the total mass flow rates, namely 4.72 kg/s for water or steam and 5.69 kg/s for helium gas.

From Table 3, the highest calculated thermal load is 22.06 MW where this thermal load is used for the evaporation process much like the scenario one, but with three individual steam generator vessels. This thermal load is more than double from that of the economizer or superheater region, similar result is also observed in scenario one as shown in Fig. 4. The second highest thermal load is 9.87 MW with a total of three individual vessels to increase the quality of steam to superheated. The lowest thermal load is 8.63 MW for the economizer region but not much different from the superheater one. The thermal load of this scenario is the same as the total in scenario 1. For each vessel, the thermal load of the evaporator region is 7.35 MW, the superheater region is 3.29 MW, and the economizer region is

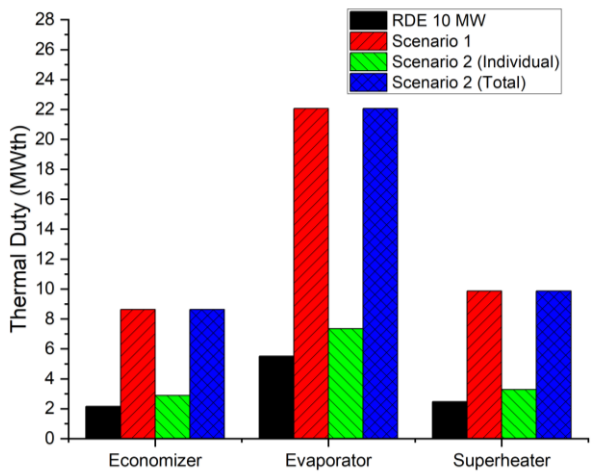

Fig. 4. Comparison of Energy Absorbed

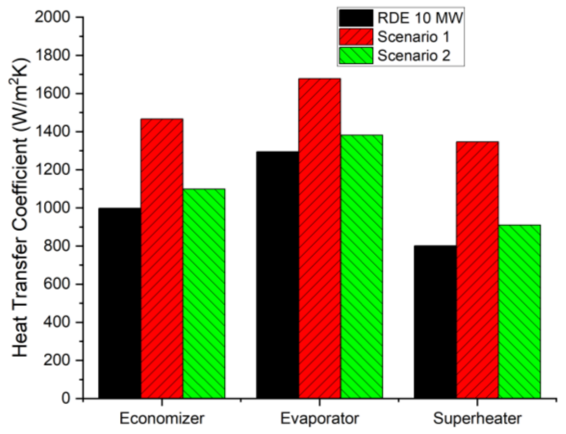

Fig. 5. Comparison of Overall Heat Transfer Coefficient

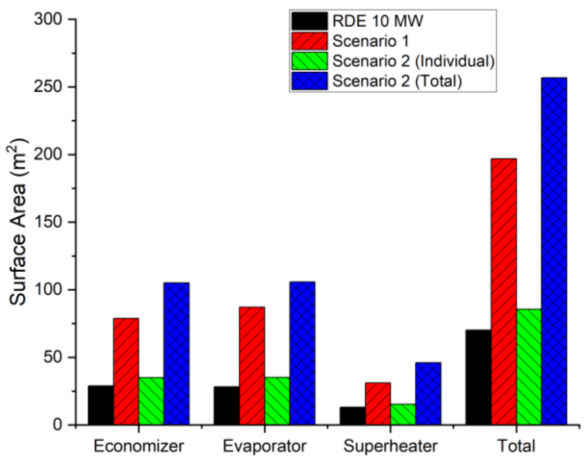

Fig. 6. Comparison of Heat Transfer Surface Area

2.88 MW, or one third of the total thermal load of each region.

The outlet temperature for each region on the helium and water or steam gas sides can be determined from the thermal load as shown in Table 3. The temperature difference or *LMTD* for each region is used to calculate the heat transfer coefficient. The highest overall heat transfer coefficient of 1381.2 W/m^2.K is found in the evaporator region. The second highest overall heat transfer coefficient of 1098.74 W/m^2.K is observed in the economizer region which is used to increase the inlet water temperature from 418.15K to 550.81K. It can be seen that even though the temperature rise is the same as in scenario 1, only one third of the thermal load is required because the mass flow rate is also one-third of the mass flow rate in scenario 1. For the economizer, evaporator, and superheater regions in scenario two, all of the overall heat transfer coefficients are lower than in scenario one but still larger than RDE as shown in Fig. 5.

Next, the final procedure is to calculate the outer surface area of the tube for the heat transfer process. Similar to scenario one, the evaporator region requires the largest surface area, namely 35.05 m^2 for each vessel (total of 105.71 m^2 for three vessels). The second largest surface area of 35.05 m^2 for each vessel (total 105.71 m^2 for the three vessels) is required in the economizer region. The surface area of the superheater region is the smallest even though the thermal load for the superheater region is larger than that of the economizer one which has a value of 15.32 m^2 for each vessel (total of 45.95 m^2 for the three vessels). This is because the *LMTD* temperature for the superheater region is higher than that for the economizer one, and the specific heat capacity of water is also higher than that of steam, similar to the previous scenario.

The total heat transfer area of the counterflow helical coil steam generator required for design in scenario two for each vessel is 85.61 m^2 and a total of 256.83 m^2 for three vessels. This area increases to 265.91% larger than the RDE. If the total height of the steam generator in RDE 10 MW is around 11 meters, then approximately the height of one individual steam generator in scenario 2 will increase by at least 21.97% or around 13.4 m. This is much lower than scenario one with an estimated height of 30.8 m. From a manufacturing perspective, a larger surface area or higher vessel height will result in more materials needed to manufacture the parts and more effort in terms of energy and costs for the production of the steam generator. A taller steam generator vessel also means a stronger foundation is needed thus definitely will be more costly. In addition, the steam generator with a height of 30.8 m in scenario 1 is above the existing common steam generator that is within the range of 20-23 m [9]. Steam generator tubes are the main pressure retaining boundary up to 60% in nuclear power plants [13], thereby increasing the risk of damage, failure, and operational safety due to internal and external loads.

5. CONCLUSION

The initial design of a once-through helical counterflow steam generator with the helical tube for a 40 MWth HTGR has been evaluated in this study. Two scenarios of the helical tube configuration are evaluated to select the best scenario based on the total heat transfer area and total steam generator vessel height. The heat transfer surface area is estimated at constant pressure in this study. The specification of the existing 10 MWth RDE steam generator is used as a reference for estimating the PeLUIt-40 steam generator. Preliminary estimation of the heat transfer surface area of the proposed design shows that approximately 196.91 m^2 is required in the first scenario using one steam generator vessel, and 256.83 m^2 in the second scenario using three identical steam generator vessels to achieve the targeted superheated steam. The height of the steam generator vessel for the first scenario is estimated at around 30.8 m, and for the second scenario is 13.4 m. Both are taller than the RDE 10 MW vessel which is 11 m. Therefore, to reduce production costs and lower safety risks, the best preliminary specification is the second scenario which is dividing the steam generator into three identical vessels to produce the targeted total termal load capacity of 40 MW.

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AUTHOR CONTRIBUTION

All the author are equally contributed as the main contributors of this paper. All authors read and approved the final version of the paper.

REFERENCES

1. T. Taryo, Rokhmadi, S. Bakhri, and G.R. Sunaryo, "The On-Going Progress of Indonesia's Experimental Power Reactor 10 MW and Its National Research Activities," *Prosiding Seminar Nasional Teknologi Energi Nuklir* (Makasar, Indonesia: SENTEN), p. 57–67, 2017.
2. F. Gou, F. Chen, and Y. Dong, " Dynamic Response of the HTR-10 Under the Control Rod Withdrawal Test Without Scram," Energy Procedia. 2017. **127**:247–254.
3. Z. Zuoji, Y. Dong, F. Li, Z. Zhang, H. Wang, X. Huang, H. Li, B. Liu, X. Wu, H. Wang, X. Diao, H. Zhang, and J. Wang, " The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation," Engineering. 2016. **2**(1):112–118.
4. C. Fang, X. Bao, C. Yang, Y. Yang, and J. Cao, “The R&D of HTGR High Temperature Helium Sampling oop: From HTR-10 to HTR-

PM," Nuclear Engineering and Design. 2016. **306**: 192 - 197.

5. S. Ding, C. Fubing, X. Bing, S. Lei, "Simulation of the HTR-10 Operation History With the PANGU Code," *Frontiers in Energy Research*. Vol. 9, Art. No. 704116, 2021. doi.org/ 10.3389/fenrg.2021.704116.
6. Y. Inaba, and T. Nishihara, "Development of fuel temperature calculation code for HTGRs," Annals of Nuclear Energy. 2017. **101**:383–389.
7. Z. Zhang, P. Ye, X.T. Yang, H.M. Ju, S.Y. Jiang, J.Y. Tu, "Supercritical Steam Generator Design and Thermal Analysis Based on HTR-PM," Annals of Nuclear Energy. 2019. **132**: 311-321.
8. W. Scheuermann, N. Haneklaus, and Fütterer M., editor(s), K. Kugeler, H. Nabielek, and D. Buckthorpe, "The High Temperature Gas-cooled Reactor: Safety considerations of the (V) HTR-Modul," EUR 28712 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-71311-8, doi:10.2760/270321, JRC107642.
9. J. Riznic, "Steam Generators for Nuclear Power Plants," Woodhead Publishing Series in Energy, p. 35 - 53, 2017.
10. J. Sun, R. Zhang, M. Wang, J. Zhang, S. Qiu, W. Tian, G.H. Su, "Multi-objective Optimization of Helical Coil Steam Generator in High Temperature Gas Reactors with Genetic Algorithm and Response Surface Method," *Energy*, Vol. 259, Art. No. 124976, 2022. doi.org/10.1016/j.energy.2022.124976.
11. M. Wang, J. Sun, J. Zhang, W. Tian, S. Qiu, and G. Su, "Thermal-hydraulic Characteristics Analysis Method of Helical Coil Steam Generator in High Temperature Gas Reactor," Atomic Energy Science and Technology. 2022. **56**(11): 2262-2271.
12. B.W. Riyandwita, M. Awwaludin, Krismawan, P. Zacharias, E. Siswanto, P.H. Setiawan and A. Nugroho, "Analytical Design of Helical Coil Steam Generator for Hot Temperature Gas Reactor," *Journal of Physics: Conference Series.* , Vol. 1198, No. 4, 2019. dx.doi.org/ 10.1088/1742-6596/1198/4/042014.
13. M.A. Bergant, A.A. Yawny, J.E.P. Ipiña, " Structural Integrity Assessments of Steam Generator Tubes using the FAD Methodology," Nuclear Engineering and Design. 2015. **295**: 457-467.