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Design of Helical Type Steam Generator for Experimental Power Reactor – Helium Side

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Abstract: Previous research has not analyzed the helium temperature distribution in the RDE steam generator shell. This study aims to fill that gap by analyzing these thermal characteristics with empirical calculations and Ansys Fluent simulations. The validity of the RDE steam generator design is reaffirmed, having been successfully analyzed from both the water-flow perspective in previous research and the helium-side perspective in the present study. The analytical methods used herein showed strong consistency, with empirical and numerical simulation results differing by less than 10% across all parameters. Although the calculated shell height of 5.73 m exceeds the RDE design's 4.97 m, the overall design's validity is confirmed.

Keywords: HTGR, RDE, Steam Generator, Helium.

Abstrak: *Penelitian sebelumnya belum menganalisis distribusi temperatur helium pada bagian selubung (shell) steam generator RDE. Penelitian ini bertujuan untuk mengisi kekosongan tersebut dengan menganalisis karakteristik termal ini melalui perhitungan empiris dan simulasi Ansys Fluent. Validitas desain steam generator RDE ditegaskan kembali, setelah berhasil dianalisis baik dari perspektif aliran air pada penelitian sebelumnya maupun dari perspektif sisi helium pada penelitian ini. Metode analisis yang digunakan dalam penelitian ini menunjukkan konsistensi yang kuat, dengan hasil perhitungan empiris dan simulasi numerik memiliki perbedaan kurang dari 10% pada semua parameter. Meskipun tinggi selubung hasil perhitungan sebesar 5,73 m melebihi desain RDE sebesar 4,97 m, validitas desain secara keseluruhan tetap terkonfirmasi.*

Kata kunci: *HTGR, RDE, Pembangkit Uap, Helium.*

INTRODUCTION

The High Temperature Gas Reactor (HTGR) is a Generation IV nuclear reactor, distinguished by its high safety level. When the temperature increases suddenly, HTGR features negative temperature reactivity, the fission reaction will drop directly until the reactor temperature returns to its initial temperature. Many countries are considering HTGR since thermal efficiency is greater than PWR and BWR [1]. Development of High-Temperature Gas-cooled Reactor (HTGR) technology dates back to 1960. A key milestone was reached in 2000 when China built and operated the HTR-10, a 10 MW pilot plant designed to demonstrate the reactor's safety. This work culminated in the world's only commercially operating HTGR, the 210 MWth HTR-PM in China, which has been active since December 2023 [2]–[4].

Indonesia is preparing research on HTGR called the Experimental Power Reactor (RDE) with a capacity of 10 MW_{th} [5]. Helium and graphite function as coolants and moderators, with the inlet water coolant temperature being 250°C and the outlet at 750°C [6]. The high critical working temperature of HTGR requires thermal-hydraulic analysis because very large temperature differences can damage components and shorten their service life. An uneven temperature distribution within a steam generator can lead to some tubes operating at dangerously high temperatures [7]. To forecast these thermal patterns, a coupled heat transfer analysis, which models the thermal interaction between the primary and secondary circuits, can be conducted using Ansys Fluent [8].

In previous research, the conceptual design of a steam generator on RDE has been studied from the perspective of a helical pipe where feed-water flows. The study obtained that the steam generator height is 4.97 m by empirical analysis methods and fluid simulations using Ansys Fluent. The boundary condition was the helium temperature used as heat flux to simulate the heat transfer [9]. Previous research on the RDE set the inlet water temperature at 418.15 K. In those studies, helium gas was introduced at a temperature of 973.15 K and a pressure of 34.2 bar, flowing at a rate of 4.27 kg/s. The helium then exited the system at a temperature of 511.42 K [10].

A gap exists in the current research, as the temperature profile of helium within the RDE steam generator shell has not been previously investigated. To address this, the present study analyzes the thermal characteristics on the helium side of the generator, using both empirical methods and numerical modeling with Ansys Fluent. Analyzing the helium temperature distribution is critically important because uneven heating directly impacts safety by causing component-damaging hot spots and compromises performance by lowering the reactor's overall thermal efficiency. This specific analysis represents a research gap because prior studies logically simplified the problem by focusing only on the water-side dynamics, treating the complex helium flow as a simple, uniform boundary condition rather than modeling its actual distribution. Conducting a comprehensive and realistic simulation of the steam generator—one that fully couples the heat transfer of both water and helium—is challenging due to technological resource limitations. As such, this research builds upon previous work by focusing exclusively on the helium simulation component.

METHODS

This research analyzes the thermal-hydraulic characteristics of helium gas within the RDE steam generator through a combination of simulation and empirical approaches. To facilitate the analysis, the steam generator's geometry, which consists of seven layers of helical pipes, is simplified into a model with a single helical pipe. This simplified representation assumes the pipe is positioned at the radial center, which results in a uniform temperature distribution. Furthermore, the heat transfer coefficient used in the model is set to the average value of the original seven-layer RDE design. In the RDE steam generator, the working fluid flows in the opposite direction. The water flows through the helical pipe from bottom to top, while the helium gas flows in the shell from top to bottom, similar to a counter-flow heat exchanger. Figure 1 illustrates a schematic diagram of the steam generator.

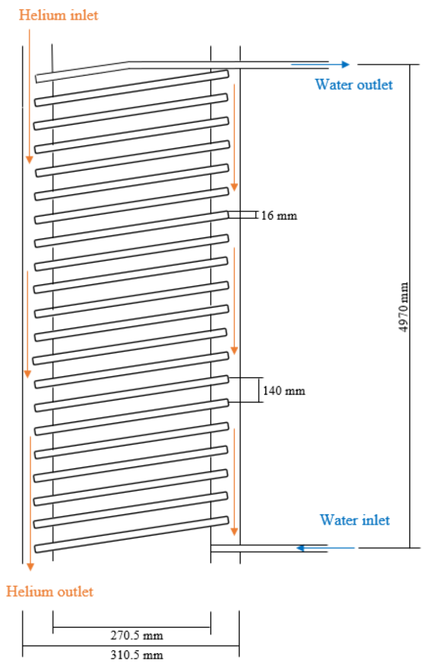

Figure 1. Schematic of Helical Pipe Steam Generator

The empirical analysis determines heat transfer throughout the system by calculating two key phenomena: convection in both the water and the helium, and conduction through the helical pipe's wall. For the helium side calculation, the flow is modeled as fully developed and turbulent within a smooth circular pipe. This assumption justifies using the classic Dittus-Boelter equation (1930), which is presented below:

$$Nu_D = 0.023 Re_D^{4/5} Pr^n \tag{1}$$

Where n = 0.4 for the heating process (Ts > Tm) and n = 0.3 for cooling (Ts < Tm), in the range:

$$\begin{bmatrix} 0.7 \leq Pr \leq 160 \\ Re_D \geq 10{,}000 \\ L/d \geq 10 \end{bmatrix} \tag{2}$$

The design and performance prediction of a heat exchanger requires the determination of several key parameters. These include the overall heat transfer coefficient (U), the total heat transfer surface area (A), and the fluid temperatures at both the inlet and outlet. These values are then used to establish the total rate of heat transfer (q), which is calculated with the equation that follows:

$$q = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o}) \tag{3}$$

$$q = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i}) \tag{4}$$

This analysis adapts Newton's Law of Cooling for the complex conditions within a heat exchanger. Specifically, the simple convection coefficient (h) is replaced by the overall heat transfer coefficient (U) to account for all thermal resistances (e.g., conduction through the wall and convection on both sides). Furthermore, the model acknowledges that the temperature difference (ΔT) between the fluids is not constant but varies at each position. Incorporating these modifications, the heat transfer rate is given by the following equation.

$$q = UA\Delta T_{lm} \tag{5}$$

For a counter-flow arrangement, where the two fluids flow in opposite directions, the Log Mean Temperature Difference (ΔT_{lm}) is given by the formula below:

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln[(T_{h,i} - T_{c,o})/(T_{h,o} - T_{c,i})]} \tag{6}$$

To calculate the pressure drop (Δp) across the system, the following formula is used [11]:

$$\Delta p = 4f \frac{L}{D_h} \frac{\rho u_m^2}{2} \tag{7}$$

For the purpose of this analysis, heat transfer to the surroundings, as well as any changes in kinetic and potential energy, are considered insignificant. The boundary conditions used are summarized in Table 1, where the inlet helium temperature is 973.15 K at a pressure of 3 MPa. In this study, the helium mass rate is 0.087 kg/s amid design simplifications that balance the actual design. Empirical calculations require fluid properties that are highly dependent on fluid temperature, so the CoolProp add-in in Microsoft Excel is used.

Table 1. Boundary Condition

Parameter	**Symbol**	**Unit**	**Fluids**	
			Water	**Helium**
Inlet temperature	T_{in}	°C	145.00	700.00
		K	418.15	973.15
Outlet temperature	T_{out}	°C	530.00	250.00
		K	803.15	523.15
Pressure	p	bar	60	30
		MPa	6	3
Mass flow rate	$\dot{m}$	kg/s		
1. RDE			3.57	4.27
2. This research			0.073	0.087

The empirical method was used to calculate several key parameters: the overall heat transfer coefficient (U), the total heat transfer area (A), the required height of the steam generator, and the pressure drop (Δp). The results are compared to previous research and shown in Table 2.

Table 2. Comparison of Results from the RDE (RELAP) Model and Empirical Analysis [9]

Parameter	RELAP	Empiric	Diff
$T_{h,i}$	700°C	702.8°C	+2.8
H	4.97 m	3.98 m	-0.99
A	1.60 m^2	1.32 m^2	-0.28
q	0.204 MW	0.205 MW	+0.001

The properties of helium gas in the simulation method in Ansys Fluent use a piecewise-linear setting with three temperature points for the properties of density, viscosity, conductivity, and specific heat. In the CFD case, the non-linear setting is converted into a linear form to ease the computational method [12]. Moreover, the heat transfer is more accurate to the actual property value. The simulation model was built using design dimensions and boundary conditions derived from the preceding empirical analysis. This included the setup for convection heat transfer, where the overall heat transfer coefficient (U) was based on the empirical results, and the free stream temperature was defined as the average water temperature in the helical pipe. Therefore, a schematic of the shell where the helium flows used in the simulation is presented in Figure 2.

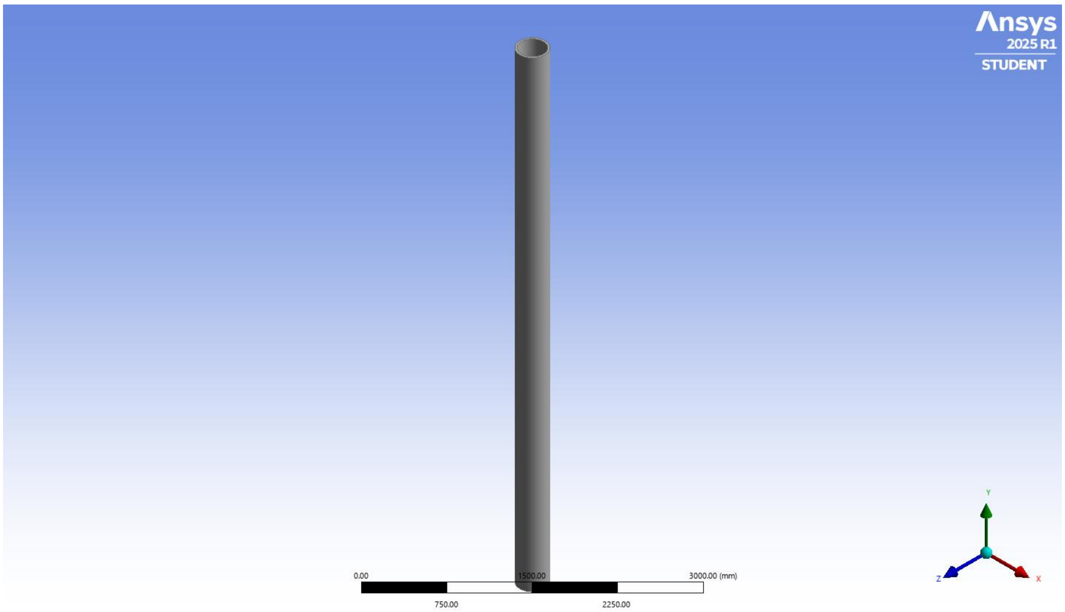

Figure 2. Design of Shell Steam Generator using Ansys DesignModeler

For the numerical simulation, the pressure-velocity coupling was handled using the Coupled algorithm, a method chosen for its suitability with the specified boundary conditions of a velocity-inlet and a pressure-outlet. To capture the effects of turbulence in the water flow, the realizable k-epsilon model was employed. High accuracy was sought by applying second-order discretization schemes; a second-order upwind scheme was used for the momentum, turbulent kinetic energy (k), turbulent dissipation rate (ϵ), and energy equations, while a standard second-order scheme was used for pressure. The solution was considered converged when residuals for continuity, velocity components, k, and ϵ dropped below 0.001, while the energy equation required a stricter convergence criterion of 1×10^{-6}. The simulation was configured with an operating pressure of 3 MPa and included a gravitational acceleration of -9.81 m/s^2 acting along the y-axis.

RESULT AND DISCUSSION

The analysis determined that the thermal power transferred from the helium is 0.203 MW. This was achieved with a calculated overall heat transfer coefficient of 794.076 W/(m^2·K) across a heat transfer surface area of 1.897 m^2, corresponding to a required steam generator shell height of 5.73 m Therefore, a summary of the empirical calculation results in comparison to previous research is shown in Table 3.

Table 3. Comparison of Results from the RDE (RELAP) Model and Empirical Analysis

Parameter	RELAP	Empiric[1)]	Empiric[2)]
$T_{h,o}$	523.15 K	523.15 K	523.15 K
H	4.97 m	3.98 m	5.73 m
A	1.60 m^2	1.32 m^2	1.90 m^2
q	0.204 MW	0.205 MW	0.203 MW

[1)] prior research
[2)] this research

The analysis reveals a notable discrepancy in the steam generator's physical dimensions, where the calculated shell height of 5.73 m exceeds the established RDE reference design of 4.97 m by 0.76 m. This variance, while significant, is not indicative of a design flaw but is rather a quantifiable outcome stemming from a complex interplay between fundamental design assumptions, particularly in material selection and flow configuration, when compared to the reference model. Primarily, the material selection differs, as this analysis assumes an aluminum pipe while the RDE design utilizes a different material. This variation in material directly influences the thermal conductivity, which in turn alters the calculation of the overall heat transfer coefficient (U). Furthermore, the flow arrangement modeled in this study is a counter-flow configuration, which contrasts with the cross-flow scheme employed in the RDE's RELAP-based design.

Interestingly, both of these primary modeling differences—the use of a higher-conductivity material and a more efficient flow configuration—would individually predict a design that is more compact than the reference. The fact that the calculated shell height is nonetheless greater suggests that these advantages are outweighed by other implicit parameters or more aggressive assumptions within the RDE (RELAP) reference model. These could include significantly higher prescribed convection coefficients, a different geometric packing density of the helical tubes, or different target temperature approaches that were not replicated in the present empirical model. It remains crucial, however, to acknowledge the foundational design choice. The inherent superiority of the helical heat exchanger configuration, where secondary flow induced by the pipe's curvature actively enhances the convective heat transfer rate, underpins the viability of both the present design and the RDE reference [13].

The results of the Ansys Fluent simulation were validated against empirical calculations, with the comparison detailed in Table 4. The numerical model is shown to be accurate, as the deviation between the simulated and empirical results is less than 10%.

Table 4. Comparison of Results from the Empirical Analysis and Simulation using Ansys Fluent

Parameter	Empiric	Ansys	Diff
$T_{h,i}$	973.15 K	970.35 K	0.28%
$T_{h,o}$	523.15 K	536.68 K	2.58%
$\dot{m}$	0.087 kg/s	0.087 kg/s	0%
Δp	0.0013 MPa	0.0014 MPa	7.69%

The spatial distribution of key thermohydraulic parameters, as obtained from the numerical simulation, is presented in Figures 3 and 4. The simulation predicts a helium outlet temperature of 536.68 K. This minor, yet notable, overprediction can be attributed to a key idealization in the current computational model: the omission of inter-pipe thermal contact. In the simulation, each helical tube is treated as a thermally isolated entity interacting only with the surrounding helium flow. In a physical assembly, however, the packed helical tubes will have numerous points of contact, creating conductive pathways or thermal bridges between adjacent tubes. These pathways would allow heat to conduct directly from hotter tubes to cooler ones, facilitating a more effective thermal homogenization across the entire tube bundle. This additional mode of heat rejection from the hotter fluid streams is not accounted for in the model, likely leading to the slightly elevated average outlet temperature observed. Consequently, it is postulated that the model's predictive accuracy could be significantly enhanced by incorporating contact thermal resistance in future iterations. This refinement would likely lower the predicted outlet temperature, thereby minimizing the deviation from the RDE benchmark data.

In summary, while the thermal model exhibits a minor, explainable deviation due to a specific modeling simplification, the hydrodynamic model is well-validated. This provides overall confidence in the simulation's utility as a predictive tool, coupled with a clear understanding of its current limitations and a direct path for future refinement.

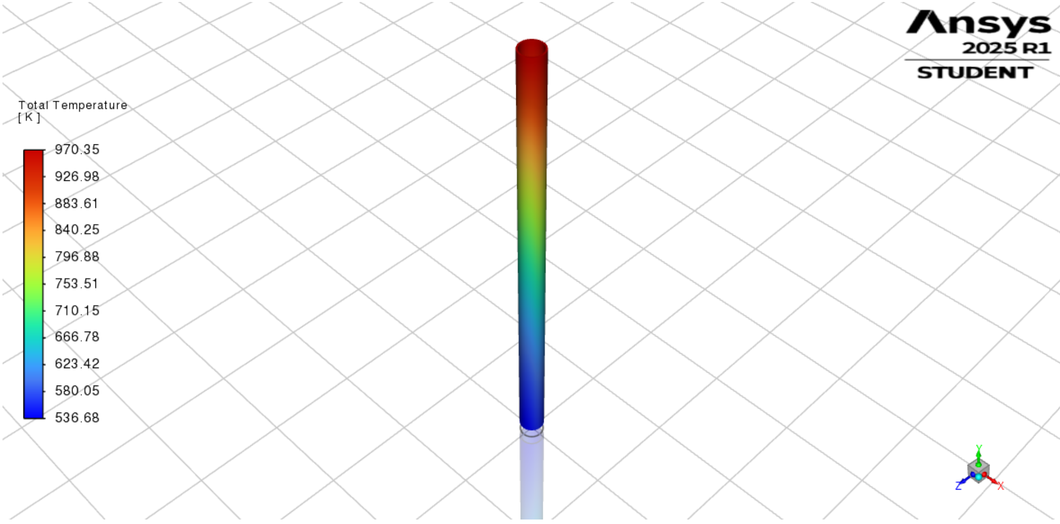

Figure 3. Temperature Distribution of Shell Steam Generator

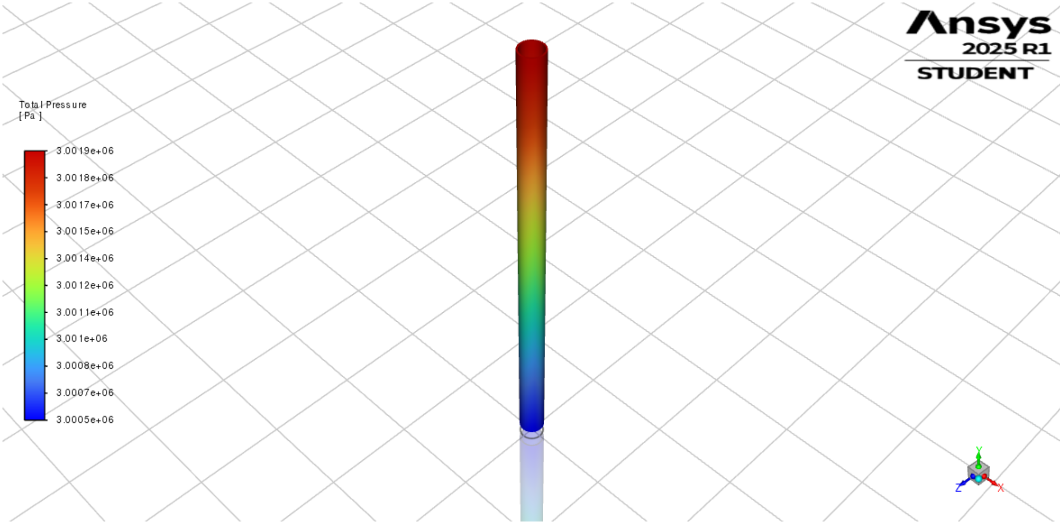

Figure 4. Pressure Distribution of Shell Steam Generator

CONCLUSIONS

In conclusion, the RDE design remains consistent within acceptable limits after empirical and numerical steam generator design studies from the water flow perspective in previous research and the helium perspective in this research. A key outcome of this work is the high degree of confidence in the analytical methods, established through a close agreement (<10% deviation) between empirical and numerical results. The analysis culminates in a design with a shell height of 5.73 m, a dimension understood to be influenced by the model's exclusion of inter-pipe contact heat transfer. Therefore, this research provides a reliable set of analytical tools and data that serve as a crucial consideration for future iterations and optimization of advanced steam generator designs.

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