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Design of Helical Type Steam Generator for Experimental Power Reactor

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A B S T R A C T

Reaktor Daya Eksperimental (RDE) is a high-temperature gas-cooled reactor (HTGR) for electricity generation, heat generation, and hydrogen production by BATAN. Empirical and numerical calculations are needed to strengthen the existing design. The numerical method by computational fluid dynamic (CFD) analyzes temperature distribution and pressure drop along the pipe. The BATAN RDE steam generator design has a seven-layer helical pipe model, while this research uses a one-layer helix pipe. In empirical calculations, the heat transfer region has three sections; single-phase liquid, two-phase, and single-phase vapor heat transfer. In numerical calculations, applied constant heat flux and constant working fluid properties. The results of empiric calculations data showed that the helical pipe height was 3.98 m, shorter than the BATAN design, which is 4.97 m. This considerable difference is due to empirical calculations, which did not cover the safety factor. The results of numerical calculations show that in the single-phase, empiric calculation data were acceptable since the different values of numerical calculations for empiric calculation data were below 10%. Meanwhile, the case of the two-phase numerical calculations is not satisfactory and needs further research to obtain optimal results.

1. INTRODUCTION

The high-temperature gas-cooled reactor (HTGR) has the characteristics of the fourth-generation reactor considering its level of safety. HTGR is a steam generator or heat exchanger customized using helical pipes with the aim of heat transfer rising without increasing the turbulence value or adding to the heat transfer surface area. BATAN designed HTGR by benchmarking The 10 MW High-Temperature Gas-Cooled Test Reactor (HTR-10) from China using the numerical method with the Reactor Excursion and Leak Analysis Program (RELAP)[1].

The analysis of the helical coil heat exchanger using the computational fluid dynamics (CFD) method has been a research topic for years. Various researchers have implemented their study on heat transfer through the helical coils with the assumption of constant heat flux and constant working fluid properties, which are idealized ones[2]. Geometrical and thermal-hydraulic deviations in an HTGR steam generator will result in temperature deviations from the ideal design cases[3]. The helical coil heat

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exchanger should use a small diameter coil and large diameter pipe because it gives desirable pressure and temperature drop[4]. After all, the temperature drop is inversely proportional to the mass flow rate, while pressure drop is directly proportional to the flow rate[4]. Furthermore, the tube temperature distribution is much higher in the copper tube than in aluminum, and the heat transfer rates also much higher in the copper tube than in aluminum[5].

BATAN keeps improving the HTGR to get optimal results. This research aims to study empirically and numerically heat transfer in helical type steam generators, analyze numerically using CFD with ANSYS Fluent then the results of the empirical and numerical analysis compared to the results of the calculation of the steam generator by RELAP. If the BATAN design is good enough, then the empirical and numerical value will be comparable with the Batan design. The empiric method has two cases; the single-phase case (liquid or vapor only) using the internal heat transfer correlation and the two-phase case using the Chen correlation. While the numerical methods using the CFD with ANSYS Fluent by assuming constant heat flux.

NOMENCLATURE

A	=	area (m^2)
c_p	=	specific heat (J/kg·K)
D	=	diameter helical coil (m)
d	=	diameter pipe (m)
F	=	enhancement factor
f	=	friction factor
G	=	mass velocity (kg/m^2·s)
h	=	convection coefficient (W/m^2·K)
k	=	thermal conductivity (W/m·K)
L	=	length pipe (m)
l	=	length pipe on coil (m)
$\dot{m}$	=	mass flow rate (kg/s)
Nu	=	Nusselts number
Pr	=	Prandtls number
p	=	pressure (MPa or bar)
q	=	heat transfer rate (W)
Re	=	Reynolds number
S	=	suppression factor
T_m	=	mean temperature (K or °C)
T_s	=	surface temperature (K or °C)
U	=	overall heat transfer coefficient (W/m^2·K)
X_{tt}	=	Martinelli parameter
x	=	vapor quality
μ	=	dynamic viscosity (kg/m·s)
ρ	=	density (kg/m^3)
σ	=	surface tension (N/m)
Δp_{coil}	=	pressure drop helical pipe (MPa or bar)
ΔT_{lm}	=	log mean temperature difference (K or °C)

2. THEORY

In this study, the HTGR steam generator uses two working fluids that flow in opposite directions (counter flow). Empirical calculations have two parts; single-phase liquid or vapor and two-phase. Water as a cold fluid flow inside the helical pipe, while helium as a hot fluid flow outside the helical coil. The design of this steam generator is similar to that of the shell-and-tube heat exchanger.

The water is an internal flow and is considered a turbulent flow. For fully developed (hydro-dynamically and thermally) and turbulent flow in a smooth circular pipe, the Nusselt local number acquires from the Dittus-Boelter (1930) equation as follows:

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

Where $n = 0.4$ is for heating ($T_s > T_m$) and $n = 0.3$ for cooling ($T_s < T_m$) process. Equation (1) has been confirmed experimentally over a range of conditions

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

and can be used for small to moderate temperature differences ($T_s - T_m$), with all properties evaluated by T_m.

Another correlation valid for smooth pipes with a lower Reynolds number range, is given by Gnielinski (1976). Gnielinski correlation on the range $0.5 \leq Pr \leq 2{,}000$ and $2{,}300 \leq Re_D \leq 10^4$ is

$$Nu_D = \frac{(Re_D - 1.000) Pr (f/2)}{1 + 12.7(Pr^{2/3} - 1)(f/2)^{0.5}} \tag{3}$$

The friction factor f is given by the following equation:

$$f = [1.58 \ln(Re_D) - 3.28]^{-2} \tag{4}$$

all properties are evaluated in T_m.

The water in the pipe undergoes forced convection to allow heat transfer from helium to water. Internal forced convection boiling is commonly referred to as two-phase flow and has characteristics of rapid change from liquid to vapor in the directional flow. Chen (1966) presented one of the most successful and well-known correlations for heat transfer in flow boiling, based on the simple addition of two postulated heat transfer mechanisms as expressed in the following equation[6]:

$$h_{TP} = h_{FC} + h_{NB} \tag{5}$$

$$h_{TP} = F h_l + S h_b \tag{6}$$

The component of the single-phase convection heat transfer coefficient h_l represent using the Dittus-Boelter equation. Chen found the relationship between F and $1/X_{tt}$ using a graph shown in Fig. 1. Butterworth (1979) completed the graph relationship using the equation

$$F = 2.35\left(0.213 + \frac{1}{X_{tt}}\right)^{0.736} \quad (7)$$

When $1/X_{tt} < 0.1$ then the value of $F = 1$. Then it is known that X_{tt} is the Martinelli parameter given by the following equation

$$X_{tt} = \left[\frac{(dp/dz)_l}{(dp/dz)_g}\right]^{0.5} \approx \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_g}\right)^{0.1} \quad (8)$$

The contribution of nucleate boiling using the Forster-Zuber (1955) correlation for pool boiling is

$$h_b = 0.00122\left[\frac{k_l^{0.79} c_{p,l}^{0.45} \rho_l^{0.49}}{\sigma^{0.5}\mu_l^{0.29} i_{lg}^{0.24} \rho_g^{0.24}}\right]\Delta T_{sat}^{0.24}\Delta p_{sat}^{0.75} \quad (9)$$

and S is the suppression factor as Chen correlated using the graph as a function of the result $Re_l\, F^{1.25}$. The graphic correlation for S is depicted in Fig. 1 and calculated using the equation

$$S = \frac{1}{1 + 2.53 \times 10^{-6}(Re_l F^{1.25})^{1.17}} \quad (10)$$

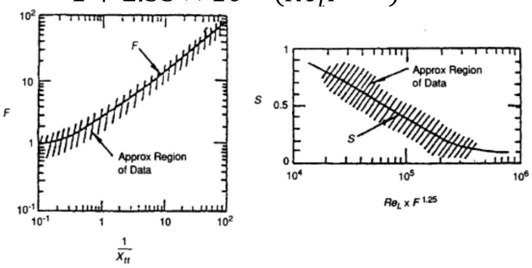

Fig. 1. Chen graphic correlation for convection factor F and suppression factor S (Chen et al. 1966)

Next, based on the heat transfer coefficient in the straight pipe ($h_{straight}$) is applied to calculate the heat transfer coefficient for the helical pipes (h_{coil}) with the following equation[2]:

$$h_{coil} = h_{straight}\left(1 + 3.5\frac{d}{D}\right) \quad (11)$$

Helical Coil Heat Exchanger (HCHE) provided more excellent heat transfer performance and effectiveness than straight tubes or other heat exchangers since the secondary flow development inside the helical pipe improves heat transfer rates[7]. Fig. 2 shows the formation of secondary flow from the primary flow. The secondary flow is induced by centrifugal force while the main flow hits the curved surface[8].

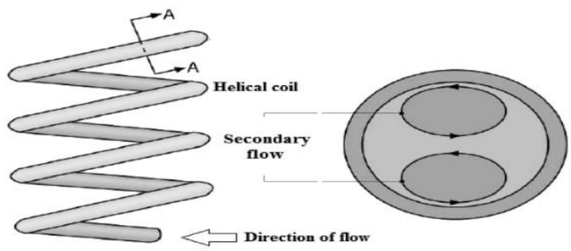

Fig. 2. Secondary flow formation[8]

Due to the curvature effect, the fluid streams on the outer side of the pipe move faster than the stream fluid on the inner side pipe[9].

In designing the performance heat exchangers, it is necessary to describe the total heat transfer rate of the fluid inlet and outlet temperatures, the overall heat transfer coefficient, and the total heat transfer surface area. The heat transfer rate is in the following equation:

$$q = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o}) \quad (12)$$

$$q = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i}) \quad (13)$$

The equation from the development of Newton's Law of cooling equations uses the overall heat transfer coefficient U instead of the single convection coefficient h, and because T varies at each position in the heat exchanger, the heat transfer rate has the following equation:

$$q = UA\Delta T_{lm} \quad (14)$$

The equation ΔT_{lm} for the counter-flow case is as follows:

$$\Delta T_{lm} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln\left[(T_{h,i} - T_{c,o})/(T_{h,o} - T_{c,i})\right]} \quad (15)$$

Empirical calculations using the energy balance equation can find the power generated in each part of the water temperature difference to know the unknown helium temperature. Afterward, finding the overall heat transfer coefficient will give the pipe height for each section.

3. METHODOLOGY

This research focuses on the heat transfer that occurs in the steam generator with empirical and numerical methods. The BATAN team has calculated the heat transfer of the steam generator by simulation using the RELAP software[1]. The empiric calculation process applies by simplifying the design of a seven-layer helical steam generator into a one-layer helix pipe, and the schematic is in Fig. 3. The heat transfer calculation is divided into three sections shown in Fig. 4. The calculation starts from the bottom to the top; single-phase liquid (section I) to two-phase (section II) to single-phase vapor (section III).

The assumption is to ignore the heat lost to the environment, the changes in potential, and kinetic energy. The second assumption is internal flow and fully developed conditions. Calculations are using Microsoft Excel software which includes an additional (adds-in) REFPROP application as a reference for fluid properties.

The design of the BATAN steam generator has seven layers of 49 pipes. In this research, using one helix pipe with the assumption to be in a radially centered position in the BATAN design in such a way that the radial temperature distribution has a constant value and the estimated value of the displacement coefficient is the heat transfer coefficient is equal to the average heat transfer coefficient in BATAN design. The effect of reducing from 49 pipes to one pipe is the mass flow rate and the generating power. Hence, mass flow rates and power are divided by 49 because they are related to the number of pipes in the BATAN design.

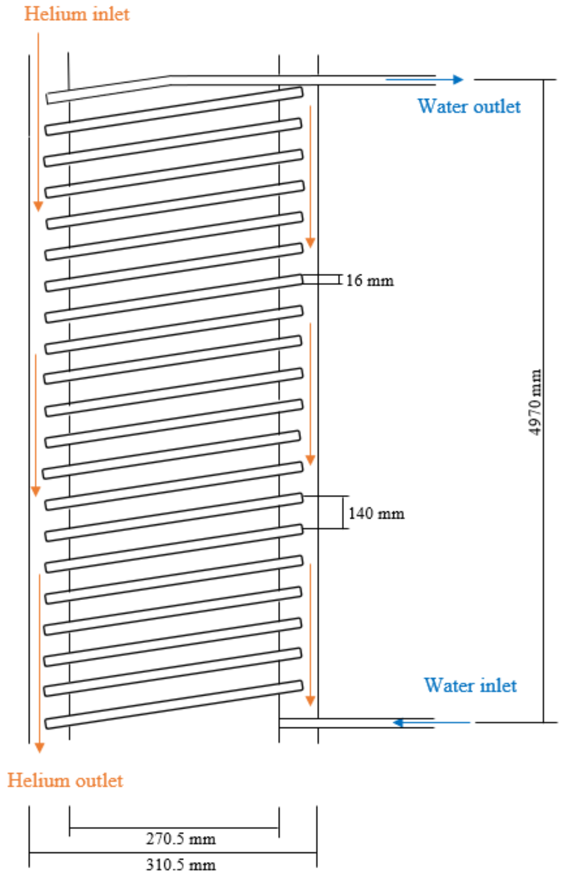

Fig. 3. Schematic of helical pipe steam generator

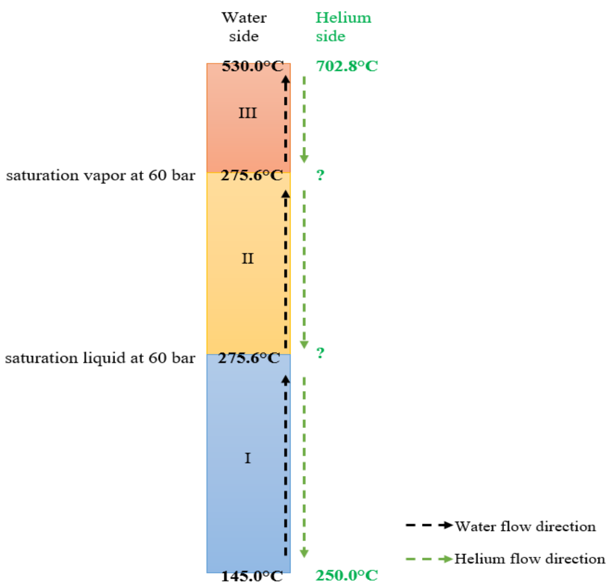

Fig. 4. Three sections of the heat transfer for the empirical calculation the steam generator design

The boundary conditions of the BATAN design steam generator and the boundary conditions used in this research are

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. BATAN design			3.57	4.27
2. This research			0.073	0.087

Numerical calculations use fluid properties that depend on water temperature. Meanwhile, CFD evaluates the fluid properties at cell temperature. In formulating a case in CFD, it is necessary to adopt a set of non-linear terms into the linear terms to reduce complexity in the computational method[10]. The property setting in ANSYS Fluent is done piecewise-linearly by using three values of each property (density, viscosity, conductivity, and specific heat) at three different temperatures to predict the dependence of the fluid on temperature. The heat flux is kept constant for any given heat transfer section on the winding wall of the pipe. Data or boundary conditions used in numerical calculations are data from the empirical method.

For velocity-inlet and pressure-outlet cases using the coupled algorithm method. Realizable k-epsilon to activate the turbulent model of water flow. Second order discretization for pressure and second order upwind scheme for equations of momentum, turbulent kinetic energy, turbulent dissipation rate, and energy. The convergence criterion is 0.001 for the continuity, speed (on axis x, y, z), k, and epsilon, while energy uses the convergence criterion 1e-06. The operating conditions are set at a pressure of 6 MPa, then activate gravity with a value of -9.81 m/s^2 on the z-axis.

Models for Eulerian multiphase and boiling in two-phase modeling employ Eulerian parameters. The Eulerian model activates the turbulent energy and flow model. Put the material properties in liquid and vapor states according to the desired value, then put boundary conditions for all states (liquid, mixed, and vapor). Set the coupling algorithm method to solve the pressure-velocity coupling case and default options for the discretization setting. The convergence criteria are set to local scaling so that all the convergence criteria are at a value of 1e-05. The operating condition is set at a pressure of 6 MPa and activates gravity with a value of -9.81 m/s^2 on the z-axis is still valid in the two-phase case.

4. RESULTS AND DISCUSSION

The power generated in the single liquid phase is 0.04 MW, the helium inlet temperature is 345.2°C, and the required helical pipe winding height is 1.73 m. The power generated in the two-phase from the enthalpy difference is 0.11 MW, and the helium inlet temperature is 598.1°C. The total area required for the two-phase case is 0.55 m^2. Meanwhile, the helical coil height has an area of 1.65 m^2. The power generated in the steam phase is 0.05 MW, and the required helical pipe height is 0.60 m. The calculation result of the helium inlet temperature is 702.8°C, different from the initial assumption is 700°C. The summary of the calculation results of the steam generator design is in Fig. 5.

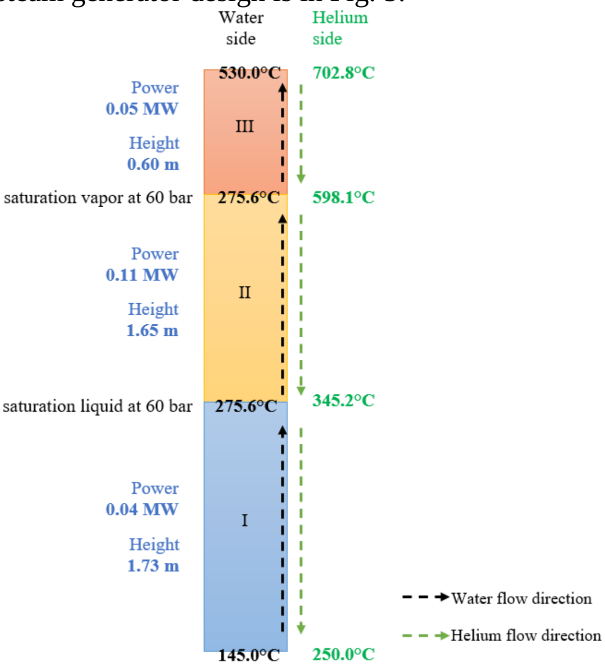

Fig. 5. Schematic of empirical calculation results in each heat transfer section

The height of the helical pipe coil is 3.98 m or about 0.99 m less than the pipe length designed by the Batan team, which is 4.97 m. The summary of the comparison between the Batan design and empirical calculations is in Table 2.

Table 2. Comparison of the Batan design (RELAP) and empiric.

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

This value is still acceptable due to several considerations. The pipe material used in the empiric calculations is aluminum, while in RELAP is not aluminum. The conductivity values of different materials will affect fully. Another factor is the crossflow flow and pipe slope, which are part of the simulation scheme with RELAP, while empiric calculation use counter-flow.

The value of the safety factor also affects the helical pipe height since BATAN designed the power generated as 11.02 MW considering the safety factor value is around 10.2%. Heat exchangers are often oversized by 70-80%, of which 30-50% for fouling[11]. Nevertheless, it depends on the type of heat exchanger. Safety factors are added to the heat exchanger design, considering its fouling, uncertainties in heat transfer methods and fluid properties, variable process or ambient conditions, and risks to the heat exchanger not found in the process requirements.

The results of numerical calculations in a single-phase liquid with ANSYS Fluent compared with the data from empiric calculation data are as follows:

Table 3. Comparison of empiric calculations and numerical (ANSYS) in single-phase liquid case.

Parameter	Empiric	ANSYS	Diff
T_{in}	418.15 K	418.15 K	0%
T_{out}	548.74 K	546.64 K	0.38%
$\dot{m}$	0.073 kg/s	0.077 kg/s	5.48%
Δp	0.0068 MPa	0.0069 MPa	1.47%

Based on Table 3, numerical calculations (ANSYS simulations) are close to the empirical calculations data because the difference is below 10%.

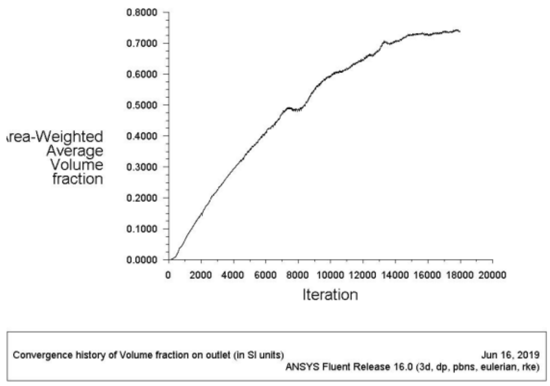

Fig. 6. Vapor fraction graph to simulation iteration

In the case of two-phase, the temperature is constant at the saturation temperature, then the ratio used is the density of the water fluid. If density at saturation liquid is 757.99 kg/m^3 and saturation vapor is 30.82 kg/m^3, both values are close to the upper and lower limits of the simulation results. After almost 20,000 iterations, the vapor fraction has not reached full steam (x=1). In Fig. 6, the vapor fraction only reaches about 0.75. If the vapor fraction does not attain one, then the exit density does not match the value of the vapor saturation density, which also applies to the pressure drop and mass flow rate values which are very much different from the empirical calculations for steam saturation.

Based on the empirical calculation of the phase change, the heat transfer coefficient h_{TP} of the working fluid is not constant and applies to the overall heat transfer coefficient U. The value of U varies along the pipe or varies with the amount of heat absorbed from the hot fluid. Therefore, the heat flux constant method can be assumed to be inappropriate in this case. Further research for the simulation of phase change heat transfer in helical pipes is needed to find a suitable method, to obtain optimal results. To adapt to empirical calculations utilizing heat transfer coefficients is the input simulation setup that uses the heat transfer coefficient as a heat source on the pipe wall. Therefore, it is impossible to compare the empirical calculation data and numerical simulation in phase change cases due to the inapt setting method.

The results of numerical calculations on a single vapor phase with ANSYS Fluent compared with the data from empirical calculation data are as follows:

Table 4. Comparison of empiric calculations and numerical (ANSYS) in single-phase vapor case.

Parameter	Empiric	ANSYS	Diff
T_{in}	548.74 K	548.72 K	0.004%
T_{out}	803.15 K	857.26 K	6.74%
$\dot{m}$	0.073 kg/s	0.072 kg/s	1.37%
Δp	0.066 MPa	0.066 MPa	0%

Based on the comparison data, the simulation is similar to the empiric calculation value since the difference is below 10%.

The results of numerical calculations or simulations with ANSYS Fluent helical pipes are in Fig. 7-12.

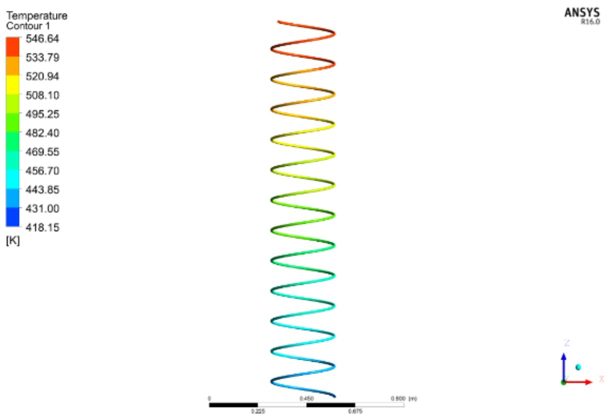

Fig. 7. Single-phase liquid temperature distribution

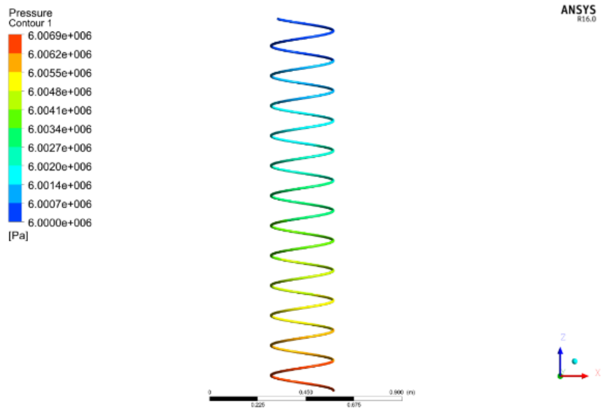

Fig. 8. Single-phase liquid pressure distribution

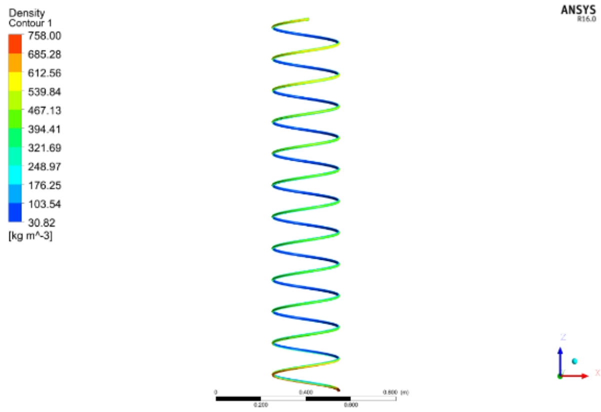

Fig. 9. Two-phase density distribution

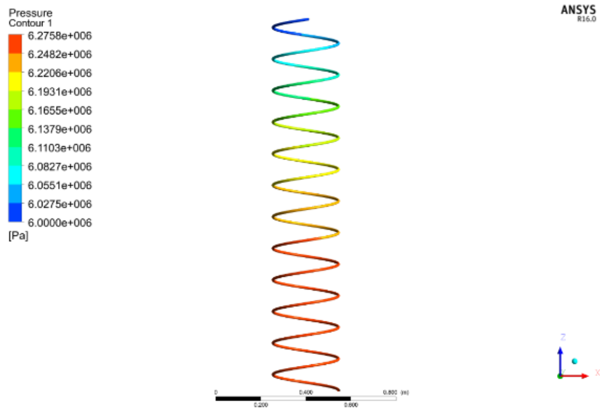

Fig. 10. Two-phase pressure distribution

According to Fig. 7 and 11, the temperature in the upper pipe is higher than in the lower part due to heat transfer from the helium, so the water temperature increases as the fluid flow upward. While Fig. 8, 10, and 12 show the pressure decrease, this indicates a pressure drop. And Fig. 9 shows that the fluid density distribution at the top of the pipe is still a mixture of liquid and steam fluids.

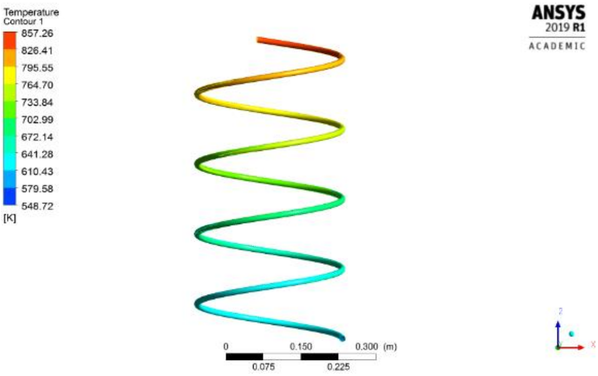

Fig. 11. Single-phase vapor temperature distribution

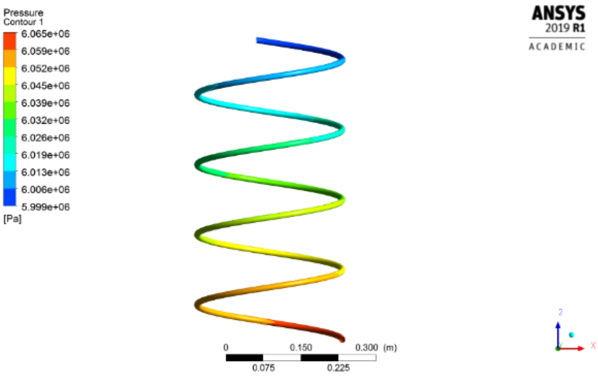

Fig. 12. Single-phase vapor pressure distribution

5. CONCLUSION

The results of empirical calculations with adjustments in the boundary conditions for one helical pipe, the height of the steam generator is 3.98 m or 0.99 m shorter than the BATAN design. The effect factors are the crossflow, pipe material, and safety factor. The results of numerical calculations with CFD using ANSYS Fluent are close to the empirical calculations data; the differences are below 10%. Meanwhile, further research is needed in two-phase simulations to obtain optimal results. The results of the steam generator design with empirical and numerical calculations in this study are almost close to the BATAN design. Several things need to be improved or updated in the empiric and numeric to approach the results following the BATAN design, or vice versa.

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AUTHOR CONTRIBUTION

This research was Sunny Ineza Putri thesis. Prihadi Setyo Darmanto and R. Mohammad Subekti were the promotor and co-promotor to this research.

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