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Multiphysics Simulation and Thermal Characterization of VVER-1200 Steam Generator for Optimized Heat Transfer and Structural Integrity

Shah Nusrat Jahan Shanta[1,*], Noor-Al-Din[2], Abdus Sattar Mollah[3]

Abstract

VVER-1200 is a Russian design reactor that consists of two circuits comprising the reactor core, piping, vertical steam generator, pressurizer, active and passive safety systems, turbine, and generator. This reactor involves single-phase flow from the reactor core to the steam generator, where high-pressure water exchanges heat with normal water, resulting in steam production. The flow is turbulent, which enables maximum efficiency in heat transfer. Using ANSYS Workbench's multiphysics simulation capabilities, a typical computational model of a VVER-1200 grade shell-and-tube steam generator and its thorough thermal analysis are presented in this study. Temperature distribution curves are created using MATLAB to improve thermal behavior visualization and validation. The findings of the thermal study offer a thorough understanding of the steam generator's temperature profile, axial and radial temperature distributions, and maximum and minimum heat flux values. The results assist safe operation and effective reactor performance by advancing knowledge of the thermal performance and heat transfer properties of the VVER-1200 steam generator. The heat steam generator is of the shell-and-tube type. This research demonstrates a typical model of a VVER-1200 grade shell-and-tube-type steam generator, along with thermal analysis using multiphysics software ANSYS Workbench. MATLAB is used to plot the temperature distribution curve. The thermal analysis depicts the temperature profile, axial and radial temperature distribution, as well as maximum and minimum heat flux of the steam generator of the VVER-1200 reactor.

Keywords: VVER-1200, ANSYS, steam generator, heat transfer, thermal analysis

INTRODUCTION

Nuclear energy is one of the best options for producing energy in the future. A nuclear power plant is a facility where power is generated using nuclear energy. This is a steam power plant where steam is produced by the conversion of nuclear energy to heat energy. Currently, many countries are adopting nuclear energy for power production owing to its cleanliness, low fuel cost, and good efficiency.

However, nuclear energy has several serious disadvantages. Some of these disadvantages include the production of harmful radioactive waste, tremendous fallout of ionizing radiation due to accidents, and high initial costs. However, nuclear energy is a blessing if utilized properly with regular monitoring and continuous training of nuclear power plant employees [1].

Research is ongoing to improve safety features, and as a result, new designs are being developed by skilled scientists and engineers. The design and

***Author for Correspondence**
Shah Nusrat Jahan Shanta
E-mail: shanta2024sh@gmail.com

[1]Student Department of Nuclear Science and Engineering Military Institute of Science and Technology Mirpur Cantonment, Dhaka, Bangladesh
[2]Student Department of Nuclear Science and Engineering Military Institute of Science and Technology Mirpur Cantonment, Dhaka, Bangladesh
[3]Professor Department of Nuclear Science and Engineering Military Institute of Science and Technology Mirpur Cantonment, Dhaka, Bangladesh

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development of two-circuit reactors are currently considered safe 3+ generation reactor designs. Under this concept, VVER-1200 reactors have been developed and are operating in several countries [2].

The Russian Federation is developing a VVER-1200 reactor. It has two circuits and a steam generator, where steam is produced and driven towards the turbine to generate electricity. Heat is transported from the primary circuit water that passes through the tubes to the secondary circuit water located on the shell side of the steam generator. The secondary water is transformed into steam by this heat exchange process, and the steam is then sent to the turbine to generate power. Radioactive contamination is reduced, and operational safety is improved by physically separating the reactor core from the steam-generating process. Effective heat transfer and dependable steam production are guaranteed by the efficient design and turbulent coolant flow of the shell-and-tube steam generator. Overall, the steam generator is essential for the VVER-1200 nuclear power plant's continued power generation, safety, and reactor efficiency. This steam generator is separated from the reactor core, where high-temperature and high-pressure water is circulated in a shell-and-tube-type steam generator to exchange heat with normal water, resulting in steam production [3].

The material attributes of each component must be specified in the ANSYS model, along with the geometry, mesh configuration, and applied thermal conditions. Thermal analysis evaluates mechanical parameters, including temperature and heat flux, under static boundary conditions [4].

The thermal results were used as inputs for the structural model when a steady-state thermal study was completed. To keep things brief, this study only considers the results of the structural analysis; however, ANSYS estimates for the temperature distribution are available and can be found in the investigation by Roman et al. [5].

The high-temperature and high-pressure water was circulated via turbulent flow. Turbulent flow increases vibration, noise, and pressure drop. This may lead to a decrease in the overall efficiency of the plant and a turbine trip if not properly monitored and regulated.

To avoid these consequences, an effective thermal analysis should be performed. Thermal analysis shows

- Areas of insufficient heat transfer
- Potential hotspots or areas of excessive thermal stress that could lead to component failure
- Components that are experiencing high thermal loads

These outcomes are important for enhancing efficiency, optimizing maintainability, and reducing costs, along with a deep understanding of the complex heat transfer processes associated with the steam generator. In addition, by performing a thermal analysis of the steam generator, new research can be conducted on

- Rod bundle design
- Secondary side flow distribution
- Transient analysis [6]

In this study, the steam generator of the VVER-1200 reactor was modeled, and a thermal analysis of the steam generator was performed using the multiphysics software ANSYS. This thermal analysis includes

- Temperature profile
- Axial and radial heat distribution
- Maximum and minimum heat flux

The main research gap is the lack of information regarding the reactor. Furthermore, there is insufficient enrichment in the scientific sector. Therefore, the goals of this study are to examine the sustainability of steam generators in high-pressure and high-temperature environments and to improve the knowledge of VVER reactors to address future issues [7, 8].

MATHEMATICAL MODELING

The time-dependent heat flow equation in the radial direction is expressed as follows [9]:

$$\frac{1}{r}\frac{\delta T}{\delta r} + \frac{\delta^2 T}{\delta r^2} = \frac{1}{\alpha}\frac{\delta T}{\delta t} \quad (1)$$

A set of algebraic equations for the temperature distribution at the nodal sites can be obtained by numerically solving Equation (3) using the forward difference method. The temperature distribution at an interior node is described as follows [10]:

$$T_m^{p+1} = F_0\left[\frac{r_{m-1}+r_m}{2r_m}T_{m-1}^p + \frac{r_{m+1}+r_m}{2r_m}T_{m+1}^p\right] + (1-2F_0)T_m^p \quad (2)$$

where p is an integer representing the elapsed time 't,' expressed as

$t = p\Delta t$

For the boundary nodes, specifically at the outer surface, the temperature distribution is described as follows [10]:

$$T_n^{p+1} = 2F_0\left[\frac{r_{n-1}+r_n}{2r_n}T_{n-1}^p + B_iT_0\right] + \left[1 - 2F_0\left(\frac{r_{n-1}+r_n}{2r_n} + B_i\right)\right]T_n^p \quad (3)$$

Here, Bi represents the Biot number. For a given spatial increment Δr and Fourier number F0, the time increment Δt can be calculated as

$$\Delta t = \frac{\Delta r^2 F_0}{\alpha}$$

For the solution to be stable, the following requirements must be fulfilled:

$$0.5 > F_0 < \frac{1}{[\frac{r_{n-1}+r_n}{r_n} + 2B_i]} \quad (4)$$

The temperature distribution through the thickness of the vessel wall is described by Equations (3) and (4).

$$\Delta t = \frac{\Delta r^2 F_0}{\alpha}$$

For the solution to be stable, the following requirements must be fulfilled:

$$0.5 > F_0 < \frac{1}{[\frac{r_{n-1}+r_n}{r_n} + 2B_i]} \quad (5)$$

The temperature distribution through the thickness of the vessel wall is described by Equations (3) and (4).

Additionally, according to Fourier's law of heat transfer [11],

$$q = -k\nabla T \quad (6)$$

Where,
q = local heat flux density, $W.m^2$
k = Conductivity, $W.m^{-1}.K^{-1}$
∇T = temperature gradient ($K.m^{-1}$)

MATERIAL

The main components of the stream generator were made of 10GN2MFA steel [12]. The 10GN2MFA steel is widely used in the production of large-scale power units for nuclear plants. This steel is known for its excellent strength and ductility, which result from the optimal alloying of its solid solution and significant deep-hardening capabilities [13, 14]. It contains C, Mn, Si, Cu, Ni, Cr, Mo, and V. Its composition by mass includes 0.10% carbon (C), 0.84% manganese (Mn), 0.27% silicon (Si), 0.011% phosphorus (P), 0.008% sulfur (S), 0.06% copper (Cu), 1.90% nickel (Ni), 0.23% chromium (Cr), 0.48% molybdenum (Mo), and 0.03% vanadium (V) [15]. The thermal properties are listed in Table 1.

MODELING

The flowchart of the analysis in ANSYS Workbench is shown in Figure 1.

The required measurements of the pressure vessel are listed in Table 2, and to simplify the calculation, some data are assumed. The assumed data are listed in Table 3.

Sketch

The sketch is based on the 2D figure in Figure 1, and the detailed operation of the modeling is shown in Figure 2. In this sketching, various operations are used, such as revolving, extruding, Boolean operations, and patterning.

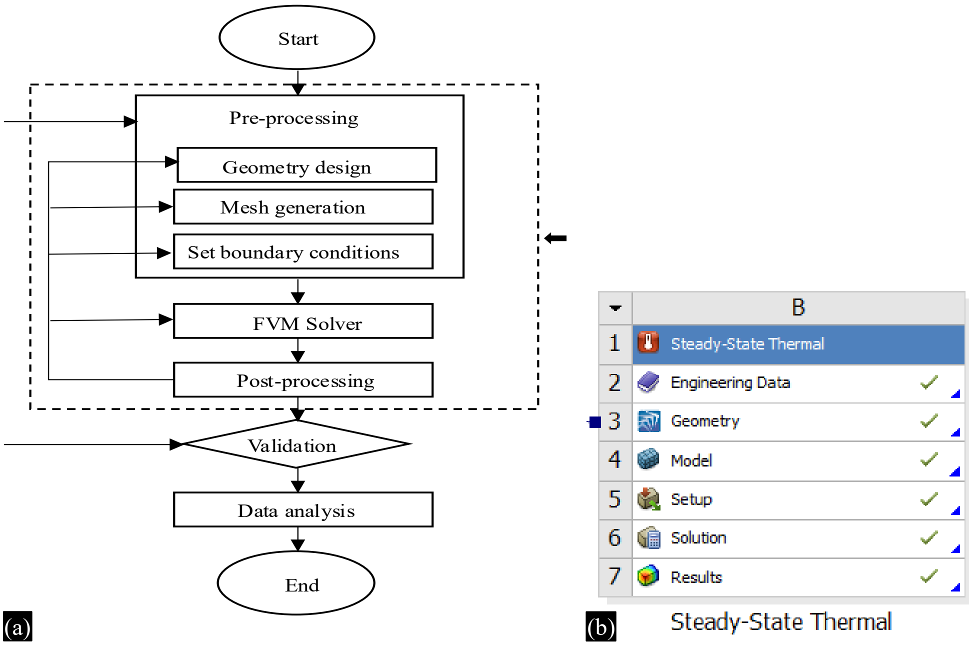

Figure 1. (a) and (b) Flowchart of analysis in ANSYS Workbench.

Table 1. Properties of 10GN2MFA [15].

Density, kg/m^3	7.85
Thermal Conductivity(k), W·m^{-1}·K^{-1}	67.92
Thermal diffusivity(α), mm^2 ·s^{-1}	18.97

Table 2. Dimensional measurements of the steam generator voltage error regulator (VER).

Name	**Value, mm**
Steam generator vessel length	13820
Internal diameter	4200 mm
Wall thickness	171

Table 3. Assumed data.

No. of tube	25
Diameter of tube	300 mm

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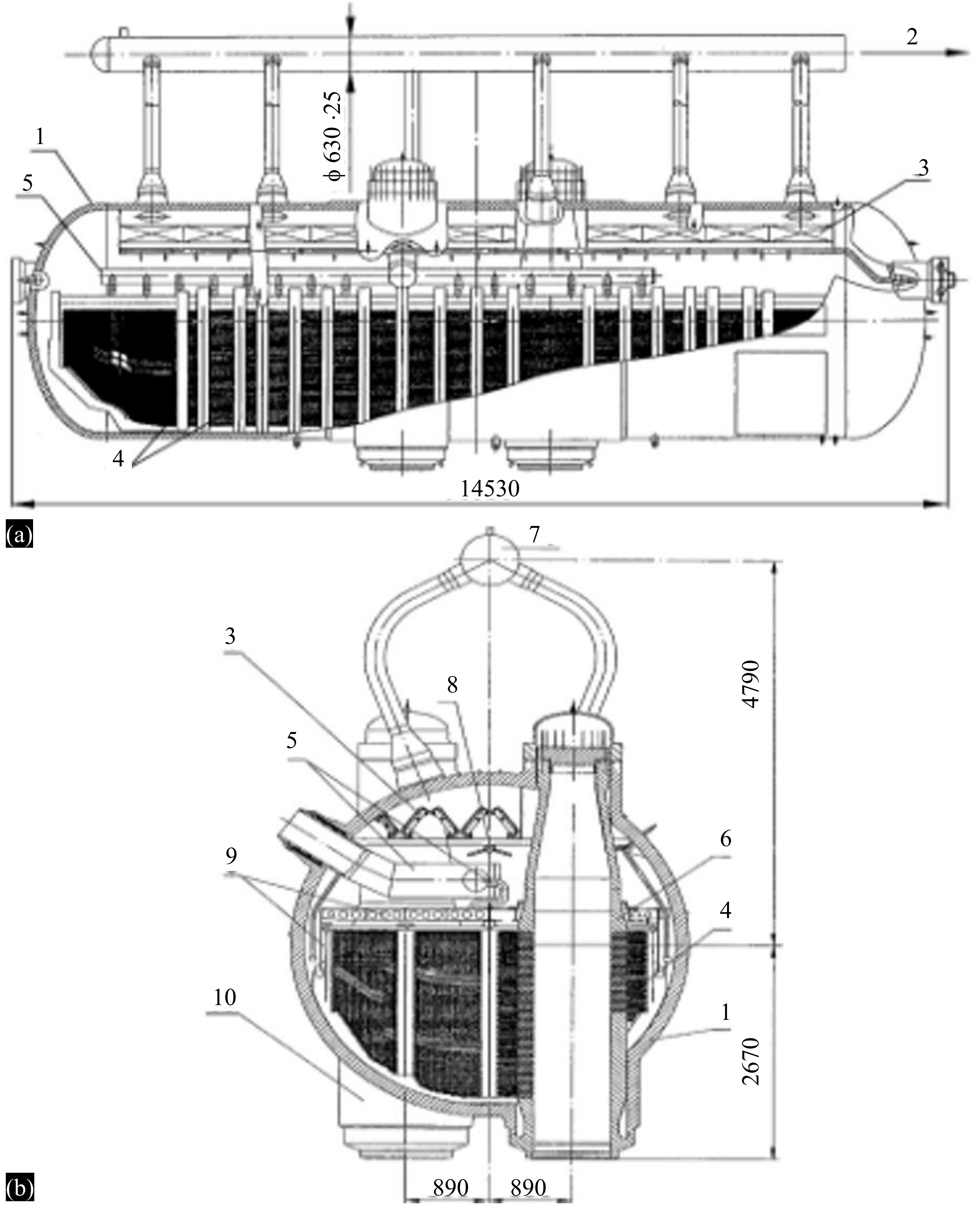


1. Vessel
2. Steam outlet
3. Chevrons of the separator unit
4. Heat exchange tube bundle
5. Supply of feed water
6. Outlet header
7. Outlet header
8. Supply of auxiliary feed water
9. Tube bundle support
10. Inlet header

Figure 2. Horizontal type steam generator for VVER-1000 [7]; (a) Longitudinal section; (b) Cross-section.

Mesh Generation

Table 4 shows the statistics of mesh generation, and Figure 3 shows the partial view of mesh generation.

Table 4. Statistical data of meshing.

Method	**Tetrahedrons**
Span angle center	Fine
Nodes	1124717
Element	636069
Element size	0.5 m

Table 5. Heat transfer rate [16].

Parameter	**Value, W/m^2 K**
Free convection of air	5 to 37
Hot water	1000–6000 (3000 W/m^2 K, I used)
Steam	6000–15000 (10,000 W/m^2 K, I used)

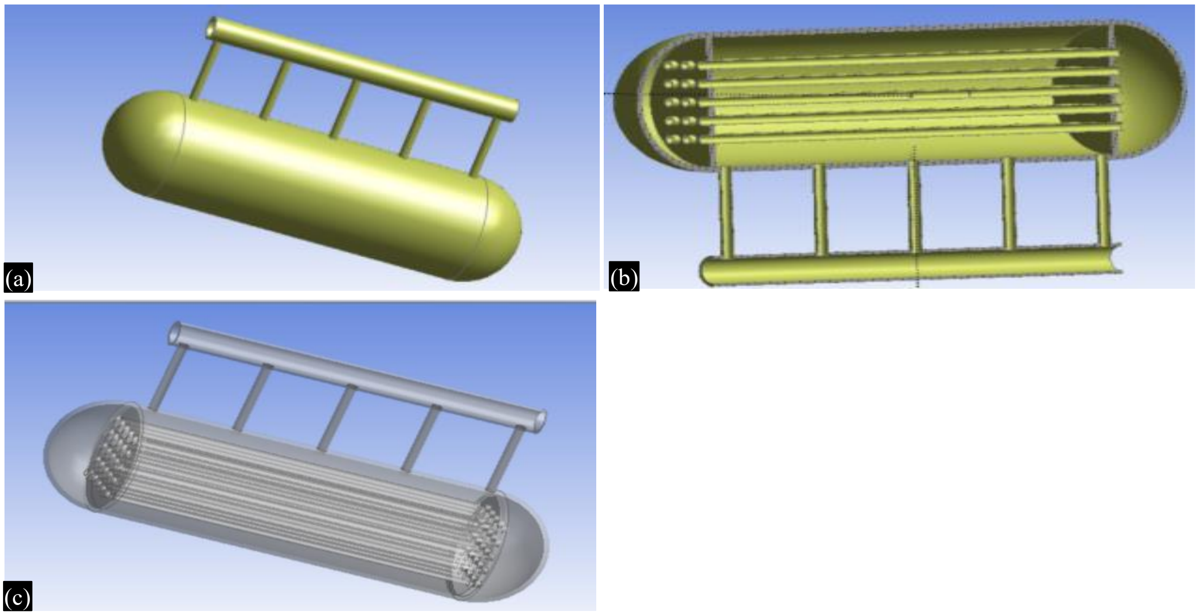


Figure 3. (a)–(c) Different points of view of modeling a geometry.

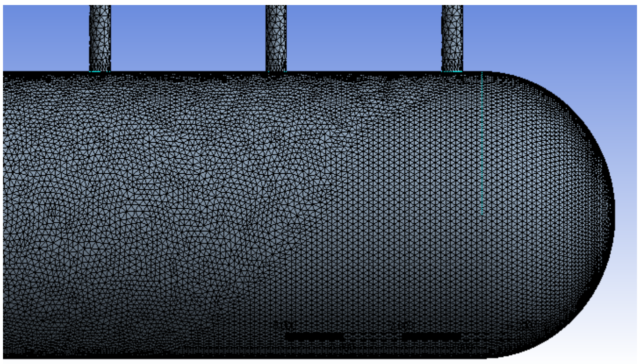


Figure 4. Partial view of mesh.

Boundary Condition

The temperature of hot water is 350°C and cold water 298.2°C [12], which is applied to the inner surface of the tube and the inner surface of the vessel. The maximum steam temperature in the steam generator pressure was approximately 300°C, which was applied to the inner surface of the steam outlet. The heat transfer rate by convection is presented in Table 5.

RESULT AND DISCUSSION

The maximum temperature is 350.72°C, which is in the hot water inlet, and the maximum heat flux is 1.75×10^5 W/m^2, which is in the middle of the tube. Figures 4, 5 and 6(a) and (b) show the temperature distribution of a radial and axial axis. From the curve of Figure 6, on the axial axis, the maximum temperature is found at the starting point of the inlet tube at 0 distance.

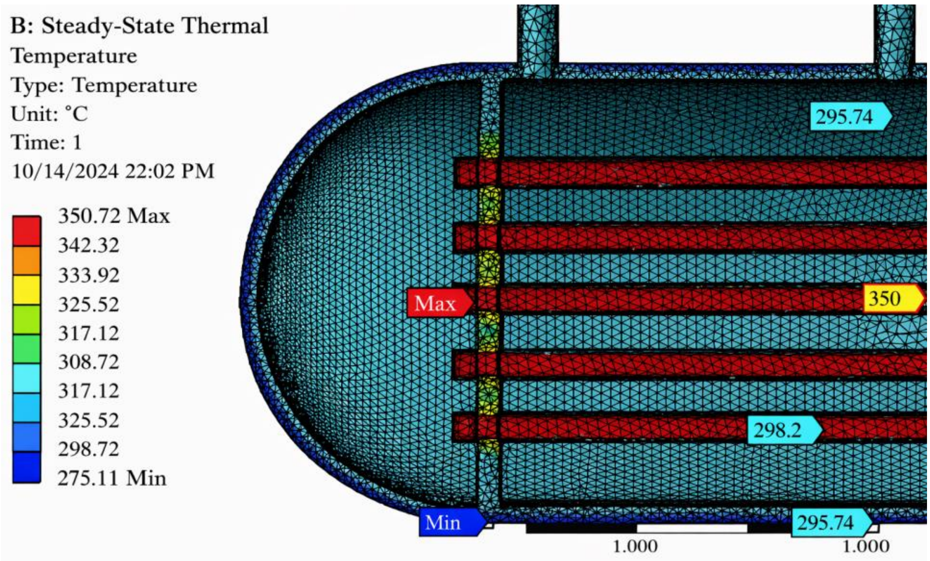
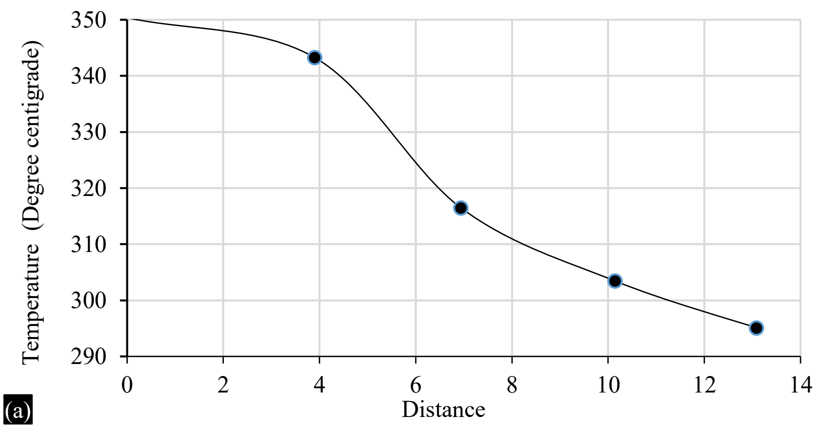
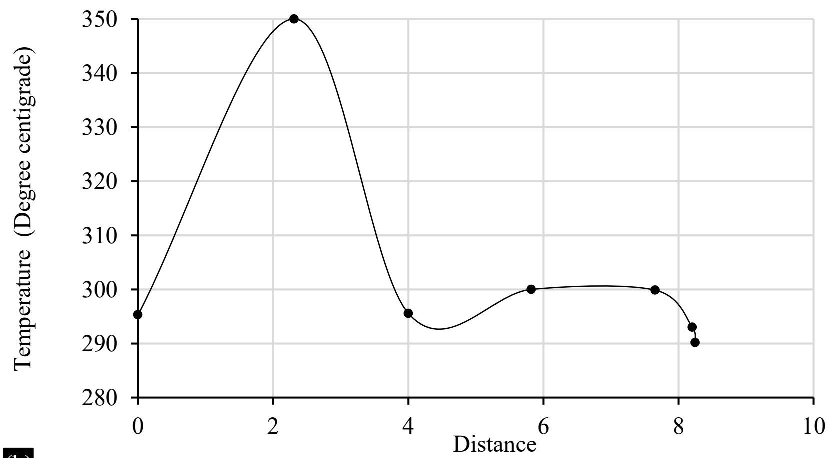


Figure 5. Temperate profile.



(a)



(b)

Figure 6. (a) Axial and (b) radial temperature distribution.

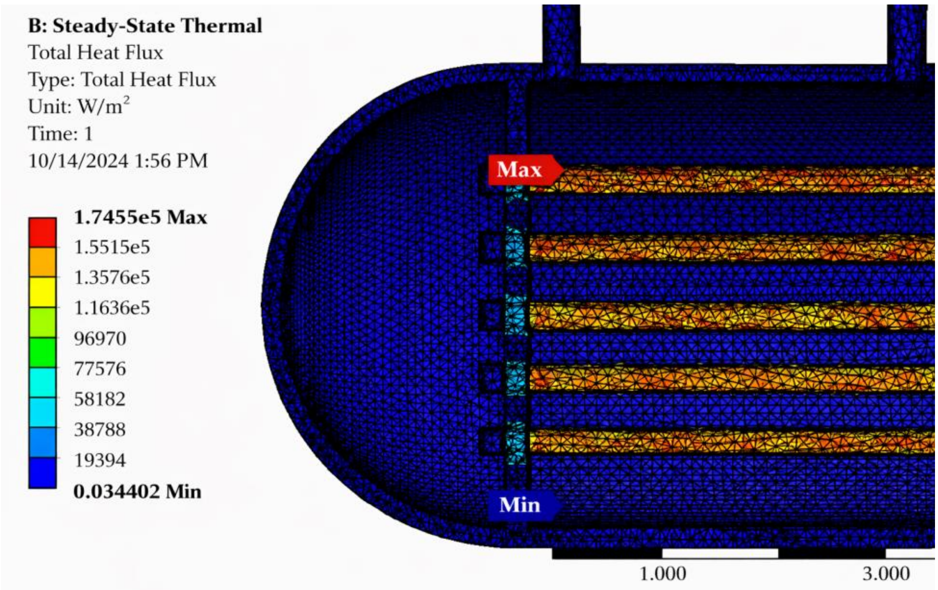


Figure 7. Heat flux profile.

With distance for the exchanging of heat, temperature gradually decreases, and the minimum value is found in the end point of the outlet, which is 295.3°C at 13.5 m distance. And in the radial axis, minimum temperature is found at the bottom of the vessel at 0 distance, and maximum temperature is found at the 2.3 m distance from the bottom point, which is the midpoint of the vessel. After that, the temperature decreased again in Figure 6.

Figure 7 shows the heat flux distribution in the body. The maximum and minimum values are indicated by color variation. The maximum heat flux was in the tube, and its value was 1.75×10^5 W/m^2. The minimum value was 19394 W/m^2.

CONCLUSION

This study reflects that analysis of mechanical phenomena in the VVER-1200 reactor is indispensable, as well as thermal analysis. This research might pave the way for more advanced steam generator designs for nuclear applications. This study is performed by simulation, so the results of this study may deviate from any physical experimental results. The results of this study could provide a basis for the creation of more sophisticated and effective steam generator designs for use in nuclear power plants in the future. Without requiring expensive and time-consuming experimental testing, the study offers insightful information about temperature distribution, heat flow variation, and structural response by utilizing simulation-based methodologies.

However, because the current study relies solely on numerical simulations, modeling assumptions, material property approximations, and boundary condition constraints may cause the conclusions to differ from the physical experimental data. Notwithstanding these limitations, the results enable further experimental validation and design improvement in nuclear engineering research and provide valuable information for enhancing steam generator performance.

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