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Analysis of Vapor Compression Refrigerator System's Condenser using Simulation Approach

Sonam Singh[1]; Ghanshyam Dhanera[2]

[1]PG Research Scholar; [2]Asst. Professor

Department of Mechanical Engineering, B.M. College of Technology, Indore (M.P.) Bharat

Abstract:

Vapor compression refrigeration systems (VCRS) are among the most widely utilized refrigeration technologies worldwide, with significant research efforts dedicated to enhancing their performance. A key strategy for improvement lies in optimizing the efficiency of the condenser. This study focused on analyzing VCRS condensers by evaluating three critical properties: condenser exit temperature, pressure drop, and heat flux. The research tested condensers made from four different materials—aluminum, copper, steel, and nickel—using the refrigerant R134a. Based on the findings, a performance ranking of the materials was established.

Keywords: Refrigeration, Vapor compression refrigeration systems (VCRS), condenser, performance, condenser exit temperature, pressure drop, heat flux, materials.

1. Introduction

Silva Romero et al. (2024) emphasize the critical role of Vapor Compression Refrigeration Systems (VCRS) in various applications, including heating, ventilation, air conditioning, and refrigeration. These systems are integral to sectors such as food preservation, air conditioning, healthcare, and industrial processes. According to Salem et al. (2019), improving the thermal efficiency of refrigeration systems can lead to substantial energy, material, and cost savings. VCRS are prevalent across household, commercial, and industrial refrigeration systems, with She et al. (2018) noting their dominance in the refrigeration market, accounting for 80% of its share. Consequently, enhancing VCRS efficiency is vital for reducing energy consumption in refrigeration.

Since the early 1900s, numerous advancements have been developed to improve VCRS efficiency, such as radioactive cooling, cold energy storage, defrosting systems, independent temperature and humidity controls, ground source heat pumps, refrigerant sub-cooling, and condensing heat recovery. Among these advancements, efficient condenser design remains a key focus area for performance optimization.

The present research investigates VCRS condenser performance by evaluating three critical properties: condenser exit temperature, pressure drop, and heat flux. Four condenser materials—aluminum, copper, steel, and nickel—were tested, with R134a serving as the refrigerant. This study aims to provide insights into material performance to guide the design of more efficient refrigeration systems.

The objectives of the proposed research are as follows:

a) To evaluate the impact of different materials on the performance of the condenser in Vapor Compression Refrigeration Systems (VCRS).
b) To establish a performance-based ranking of the various material alternatives used in condensers.

2. Literature Review

This section highlights significant academic research efforts and their contributions to the advancement of refrigeration systems and condenser technologies. The following studies exemplify the depth and diversity of work undertaken by researchers in this domain:

- **Manyele (2025)**

The reference discusses the performance factors in a distillation process, which can be relevant to understanding the operational efficiency of condensers in vapor refrigeration systems. Although the primary focus is on ethanol-water distillation, the findings regarding the influence of feed thermal conditions on condenser duties can be extrapolated to vapor condensers in refrigeration systems. The study highlights how different feed conditions, such as feed at room temperature and superheated vapor, affect temperature profiles and composition, which are critical for optimizing condenser performance in refrigeration applications.

- **Chen (2025)**

The reference discusses the hydrothermal response of a grafted-PNIPAM system during the vapor condensation process, which is relevant to the study of condensers in vapor refrigeration systems. This research provides insights into the thermodynamic behaviors and efficiency improvements that can be achieved in condenser design, specifically focusing on the phase change dynamics and material properties that influence condensation performance. The findings may contribute to optimizing condenser systems for enhanced energy efficiency and operational effectiveness in refrigeration applications.

- **Eswaravelu et al. (2024)**

This study evaluates the performance of a thermoelectric cooling system integrated with a vapor compression refrigeration (VCR) cycle using SES36 as the working refrigerant. The combined system demonstrates enhanced efficiency, achieving a coefficient of performance (COP) of 3.2, indicating its effectiveness in improving refrigeration performance.

- **Riahi and Shafi (2023)**

This research conducts a detailed parametric analysis of a VCR system incorporating a phase change material (PCM) storage tank. The primary objective is to enhance the condenser's sub-cooled temperature. Findings reveal that while this modification increases daily electrical energy consumption, it offers advantages over conventional systems by optimizing operational performance.

- **Sharif et al. (2023)**

The study examines a variety of performance-enhancing strategies for VCR systems utilizing the refrigerant R1234yf. These strategies include the implementation of internal heat exchangers, ejectors, and nanolubricants. The research highlights significant improvements in system performance, with the most notable results achieved using internal heat exchangers and precise sub-cooling techniques.

- **Hussein et al. (2023)**

This investigation focuses on improving the efficiency of VCR systems through the use of Polyol Ester Oil (POE) mixed with nano copper oxide (CuO) particles, alongside a fluidized bed for condenser cooling. The incorporation of nanolubricants not only enhances the overall system performance but also reduces power consumption significantly, showcasing the potential benefits of advanced refrigerant technologies.

- **Bilen et al. (2022)**

This comprehensive review explores the application of nanorefrigerants in VCR systems. The inclusion of nanoparticles in traditional refrigerants demonstrates substantial performance improvements, with experimental studies reporting enhancements of up to 56.32%. These findings underscore the potential of nanotechnology in revolutionizing refrigeration efficiency.

- **Ozsipahi et al. (2022)**

The research investigates the use of R290/R600a refrigerant mixtures in household refrigeration systems. Results indicate that increasing the proportion of R290 leads to higher power consumption. However, this adjustment also enhances the refrigerant mass flow rate and the coefficient of performance (COP), offering a balanced trade-off for improved system efficiency.

- **Shah et al. (2021)**

This paper reviews conventional condenser designs in vapor-compression refrigeration systems, focusing on innovations that improve system efficiency while conserving water. The study emphasizes the importance of optimizing condenser designs to address environmental and operational challenges.

- **Hu et al. (2021)**

To address cooling needs in permafrost regions, this study introduces an innovative active refrigeration method. This approach efficiently dissipates heat from permafrost during warmer seasons, ensuring stable cooling performance in extreme climatic conditions.

- **Gado et al. (2021)**

This research examines hybrid absorption-compression cooling systems by analyzing various configurations from energetic, exergetic, economic, and environmental perspectives. The findings highlight the potential advantages of hybrid systems in achieving sustainable and cost-effective cooling solutions.

2.1 Gaps in the Research

Following are the details of gaps in the research:

The literature review revealed that there is a limited number of research papers specifically focused on determining the various properties of condensers made from different materials. Additionally, these papers did not address the ranking of materials used in condenser construction.

3. Solution Methodology

The present section is devoted to details of analysis used, and the software, used to solve the research problem, the details of which are presented in upcoming sub-sections.

3.1 Computational Fluid Dynamics (CFD) Analysis

Computational Fluid Dynamics (CFD) is a specialized branch of engineering and physics focused on analyzing, simulating, and predicting fluid flow behavior through computational methods. In CFD, the mathematical equations that govern fluid behavior, such as the Navier-Stokes equations, are solved using numerical algorithms. The following steps outline the process of CFD:

- The initial step in CFD involves defining the problem to be solved, which includes specifying the geometry of the fluid domain, boundary conditions, and the properties of the fluid (e.g., viscosity, density).
- The governing continuous equations of fluid flow are discretized into algebraic equations using numerical methods. This typically requires dividing the fluid domain into a grid or mesh of discrete elements (such as cells or control volumes) and approximating the flow variables' derivatives within each element.
- The discretized equations are solved iteratively using numerical techniques, which may include finite difference, finite volume, or finite element methods. The solution process involves solving these equations for each discrete element in the grid to determine flow variables like velocity, pressure, and temperature.
- After obtaining the numerical solution, post-processing techniques are applied to analyze and visualize the results. This may include generating contour plots, streamlines, velocity vectors,

and other visual representations of the flow field. These results help engineers and scientists gain insights into fluid behavior and make informed decisions about design, optimization, or troubleshooting.

CFD is widely used in applications such as aerodynamics (e.g., aircraft and vehicle design), hydrodynamics (e.g., ship and submarine design), combustion, HVAC systems, environmental modeling, and biomedical engineering. Its ability to offer detailed insights into complex fluid flow phenomena makes it an essential tool for engineers and researchers in various industries.

3.2 ANSYS R18.2

ANSYS R18.2 is a version of the ANSYS software suite, released around 2018. ANSYS is a widely used engineering simulation software that supports various types of simulations, including finite element analysis (FEA), computational fluid dynamics (CFD), electromagnetic simulation, and more. The R18.2 release likely brought improvements in performance, new features, and bug fixes over previous versions, enhancing the capabilities of the software for engineers and researchers working on complex simulations in multiple domains.

4. Case Study

The present section is devoted to the details of model formulation and solution for the targeted research problem, the details of which are presented in upcoming sub-sections.

4.1 Model Formulation

As the first step of the research, as per the experts' opinions, the model of a VCRS condenser was created in ANSYS R18.2 software, with the following specifications.

a) Outside diameter (mm) = 12

b) Inside diameter (mm) = 10

c) Tube length (m) = 1

Figure 4.1 shows the mode of VCRS condenser.

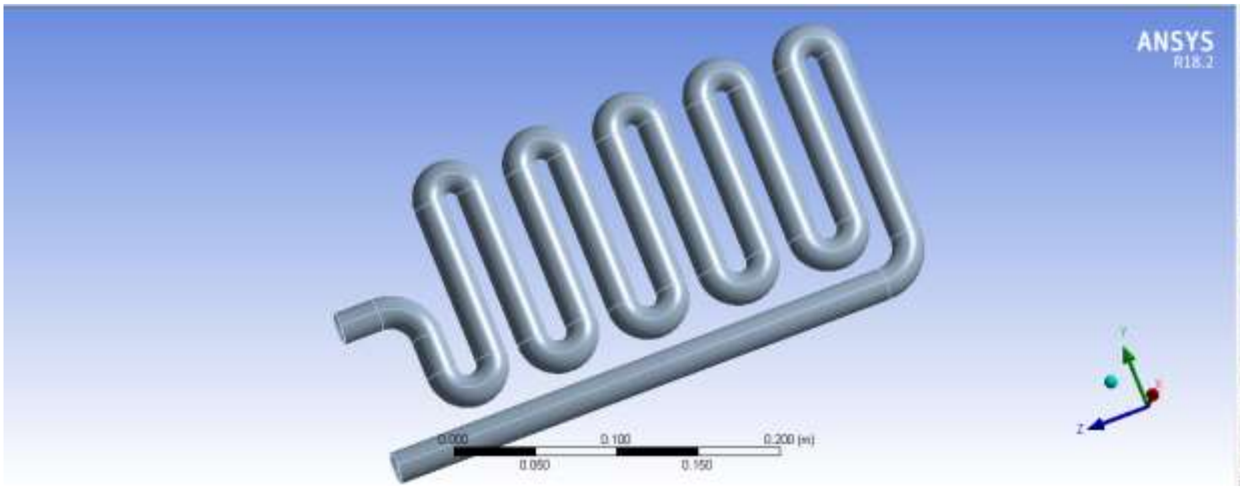
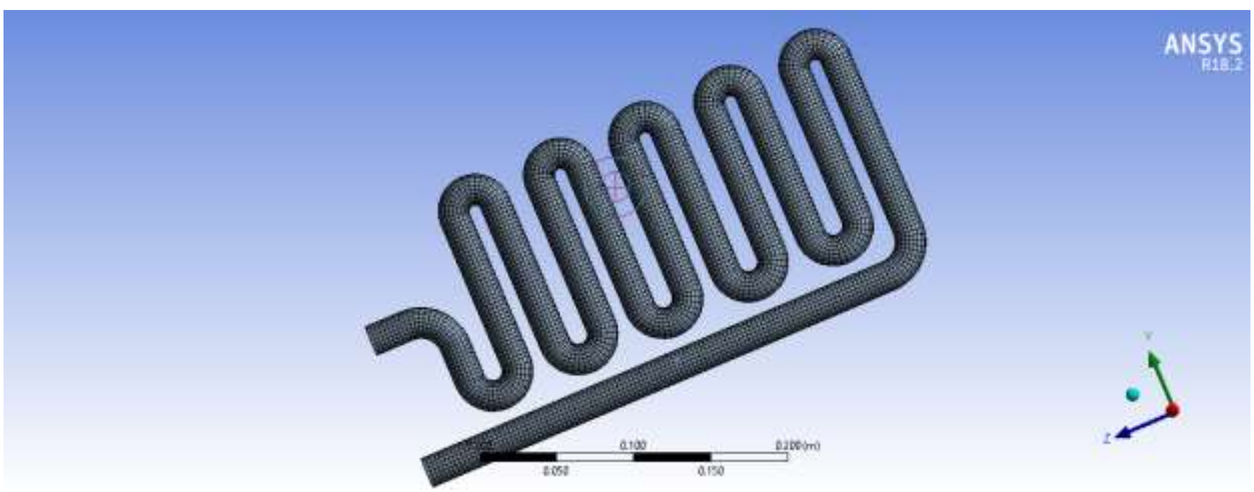


Figure 4.1: Model of VCRS Condenser

4.2 Solution of the Model

In order to solve the above model, computational fluid dynamics analysis was conducted in ANSYS R18.2, the details of which are presented as follows.

a) First of all, meshing of the model was performed. For the purpose of getting efficient mesh, conformal mesh was created, as shown in figure, given below.



(a) Mesh Model of the VCRS condenser

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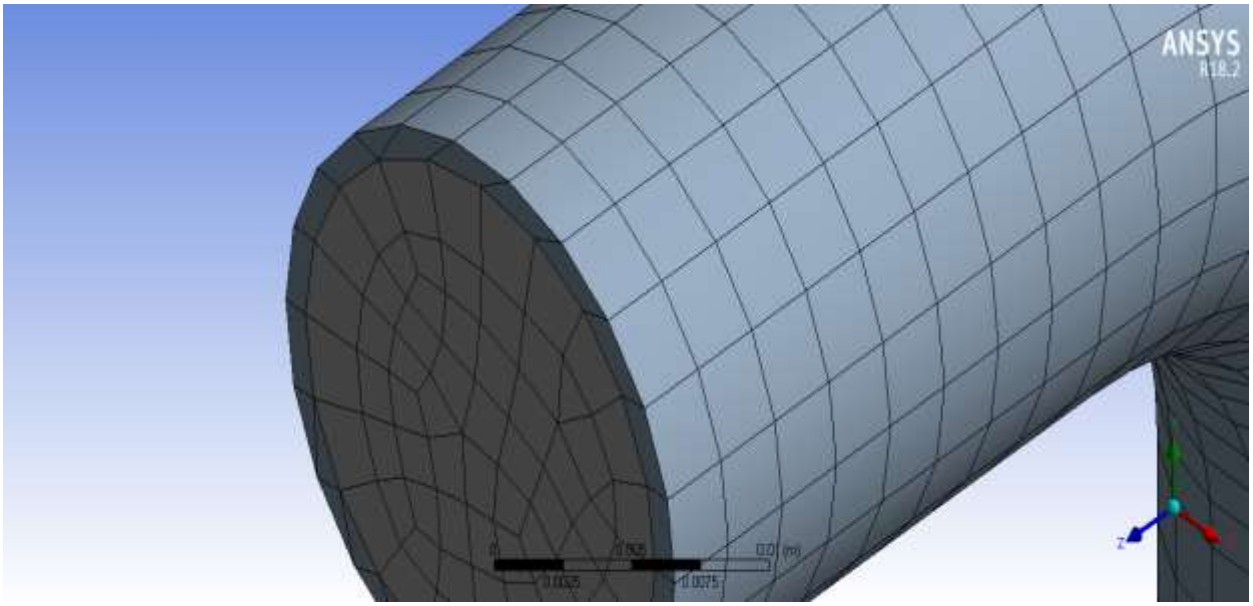

(b) Conformal Mesh Model for the VCRS condenser

Figure 4.2: Mesh Details for the VCRS condenser Model

Table 4.1 shows the details of mesh parameters.

Table 4.1: Details of Mesh

S. No	Entity	Details
1	Element type	Default
2	No. of nodes	64578
3	No. of elements	58996

b) In the next step, boundary conditions on the model were applied, as maximum temperature of 65 degree Calcius;

c) During the research work, calculations of pressure, temperature and heat flux were performed for the materials, shown below;

Table 4.2: Mechanical Properties of Materials

S. No	Mechanical Property	Unit	Materials			
			Aluminum	Copper	Steel	Nickel
1.	Young's modulus	Pa	69×10^{9}	1.2×10^{11}	2×10^{11}	21×10^{10}
2.	Poisson's ratio	-	0.32	0.33	0.28	0.31

3.	Density	Kg/m^3	2,710	8,960	7,850	8,908

d) In the research work, the refrigerant used in the model was R134a, whose properties are presented as follows.

Table 4.3: Mechanical Properties of Materials

S. No	Property	Unit	Value
1.	Density	kg/m^3	515.3
2.	Specific heat	j/kg-k	796.7
3.	Thermal conductivity	w/m-k	0.01409
4.	Viscosity	Kg/m-s	1.1687e-05

e) Following process parameters/equations were used to solve the research problem.

- Gravity in – y direction: 9.81 m/sec^2
- Energy equation: On
- Model used: k-epsilon model
- Inlet type: Pressure
- Outlet type: Velocity

5. Results and Discussion

The present section deals with the details of results obtained and the discussion made about the results, the details of which are presented, in upcoming sub-sections.

5.1 Results

Figure 5.1 represents the details of results obtained for pressure criteria.

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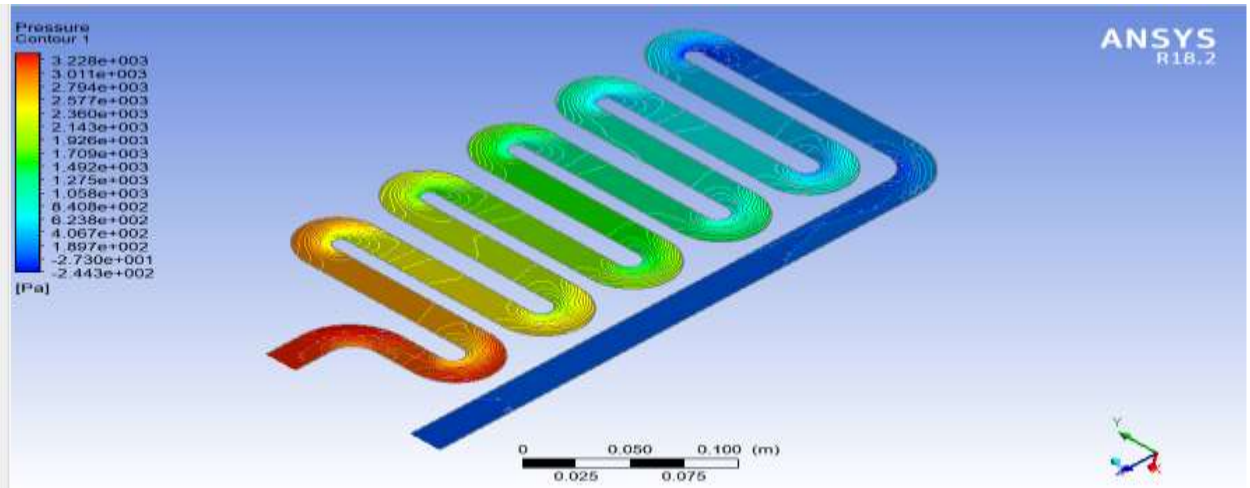
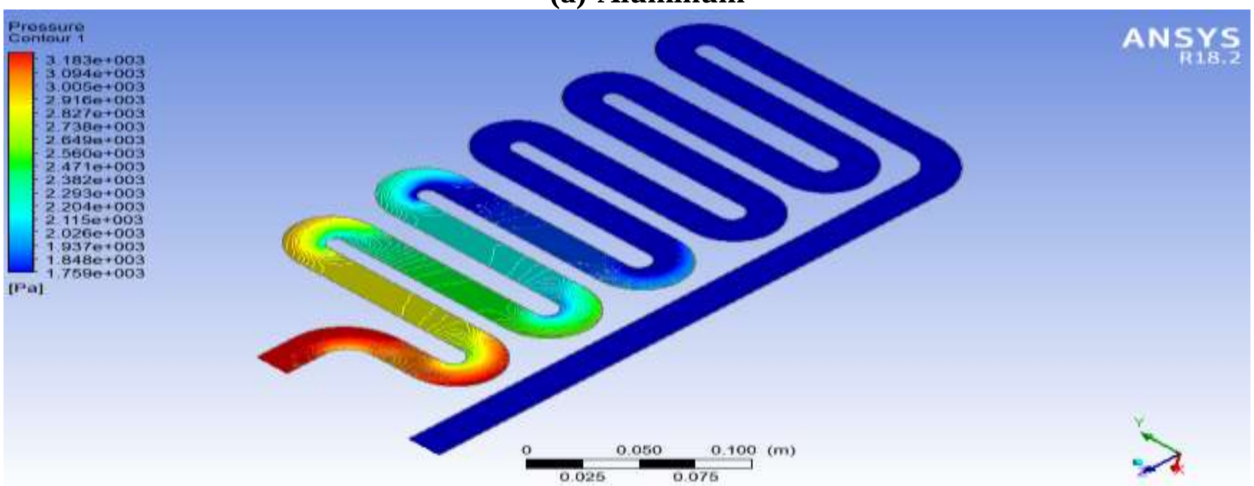
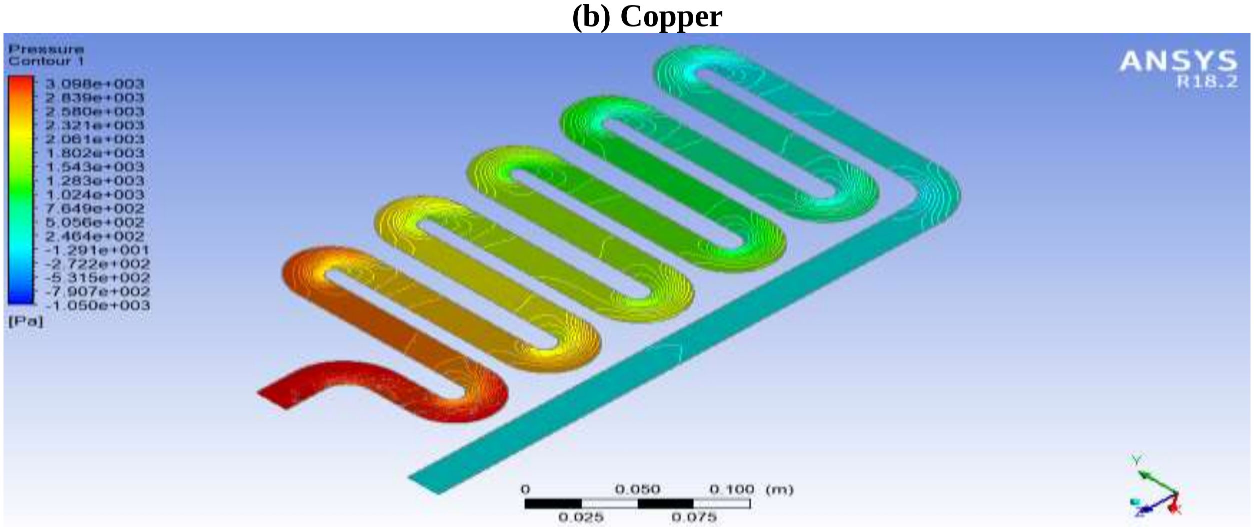


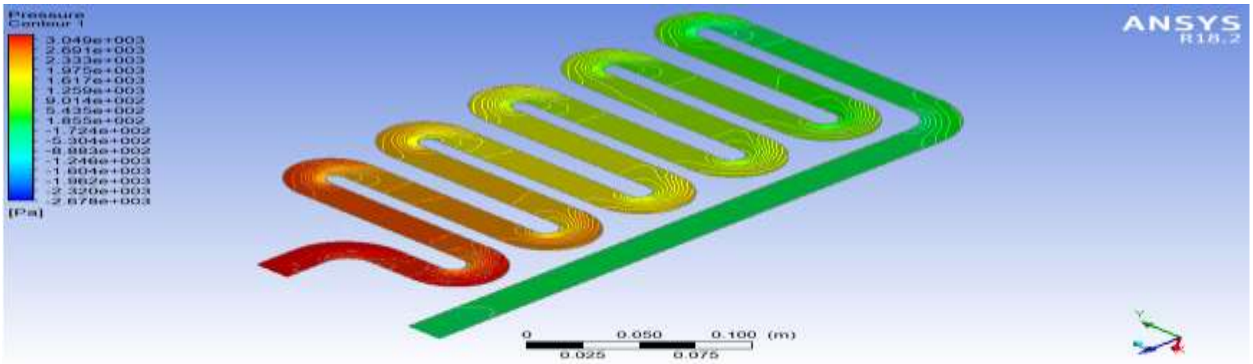
(a) Aluminum



(b) Copper



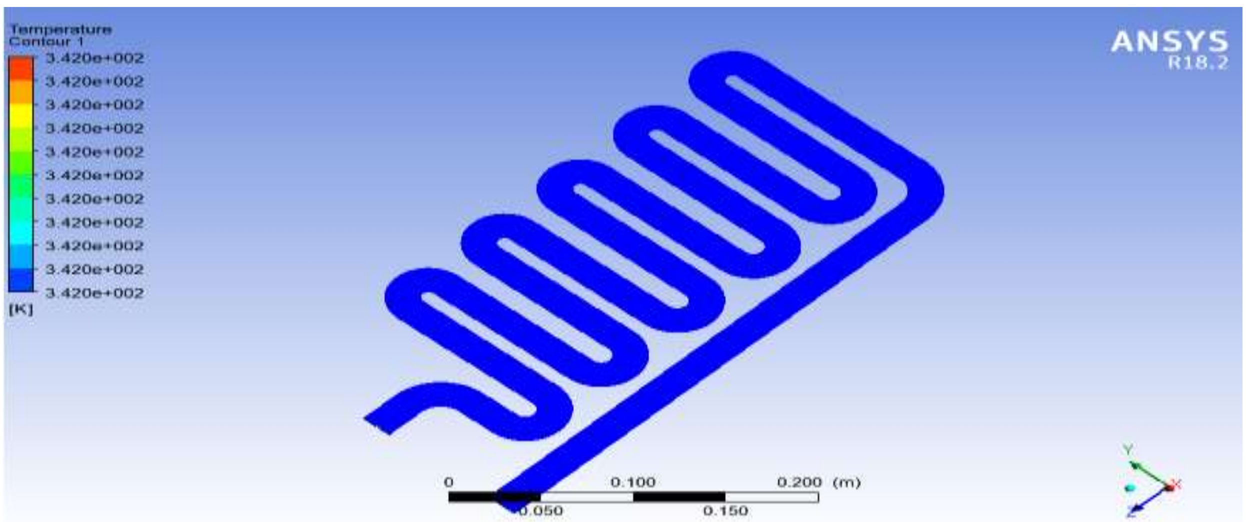
(c) Steel



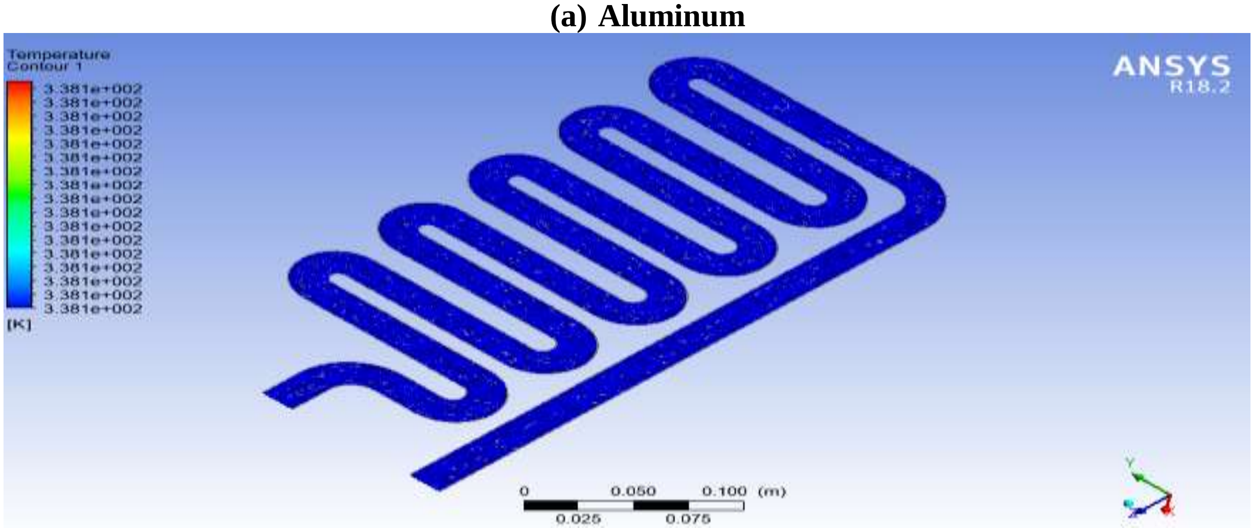
(d) Nickel

Figure 5.1: Results obtained for Pressure differences for different materials

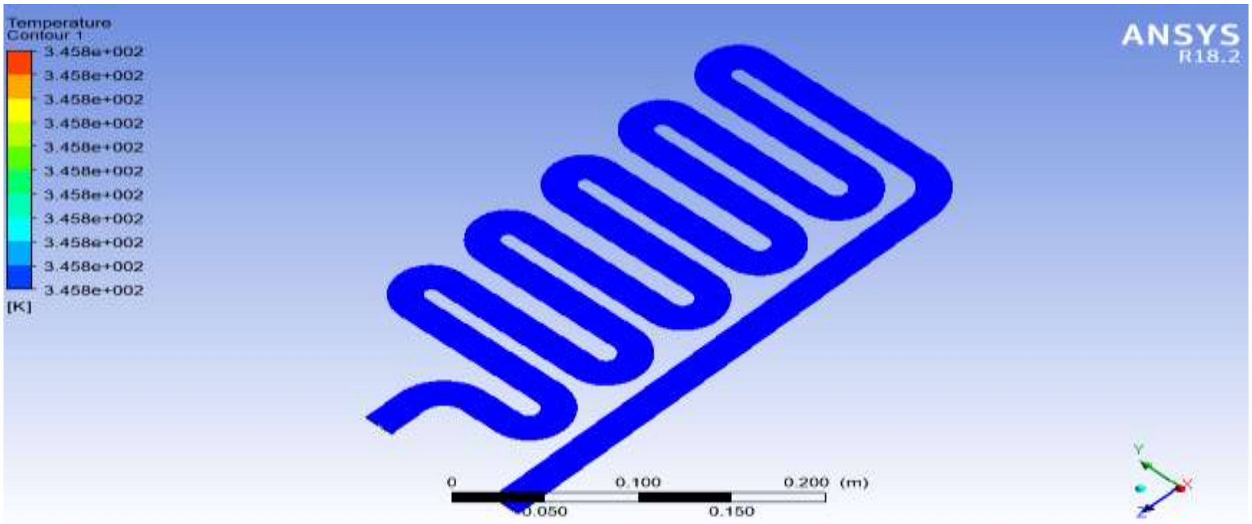
Figure 5.2 represents the details of results obtained for exit temperature criteria.



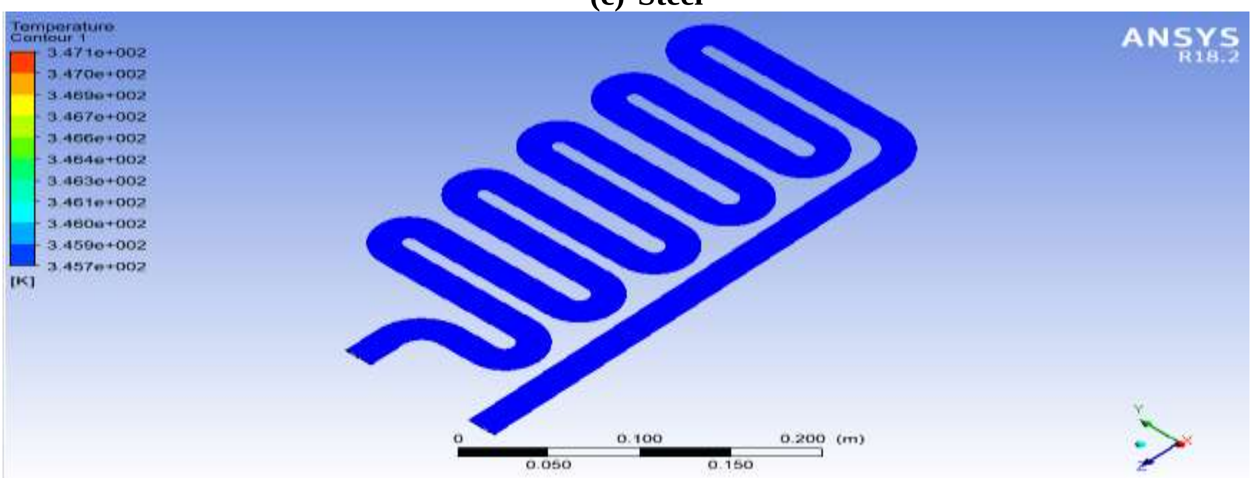
(a) Aluminum



(b) Copper



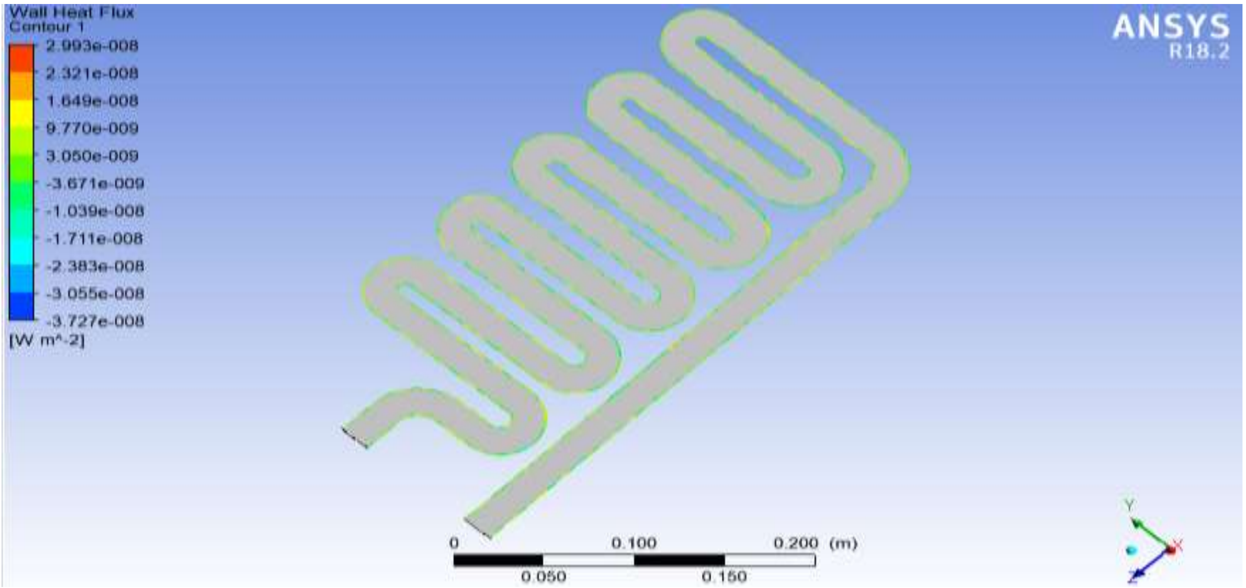
(c) Steel



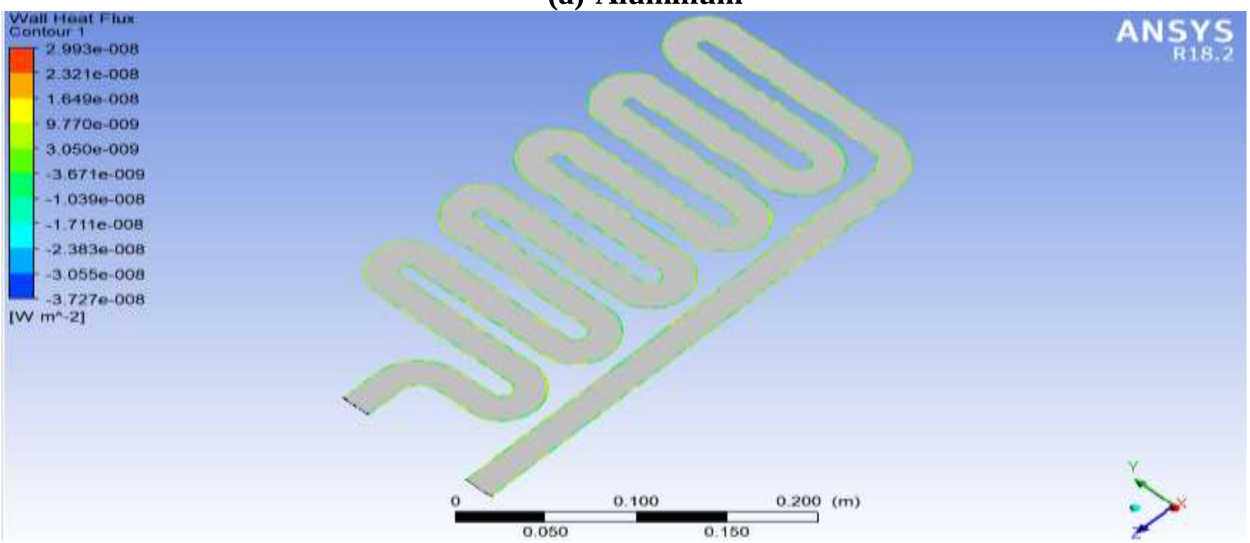
(d) Nickel

Figure 5.2: Results obtained for Exit Temperatures for different materials

Figure 5.3 represents the details of results obtained for heat flux criteria.



(a) Aluminum



(b) Copper

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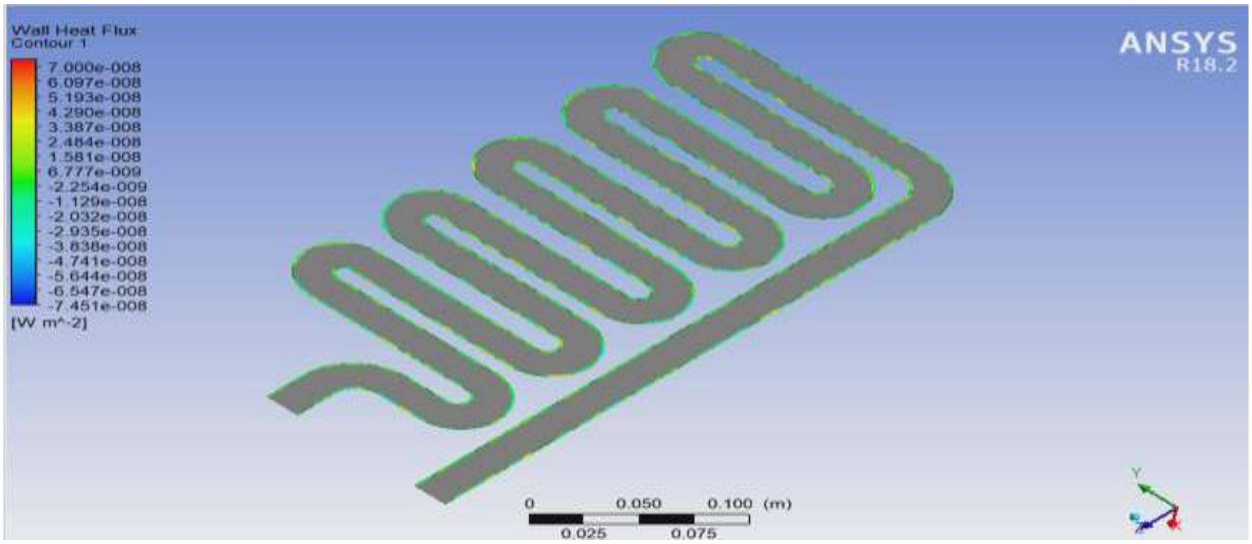
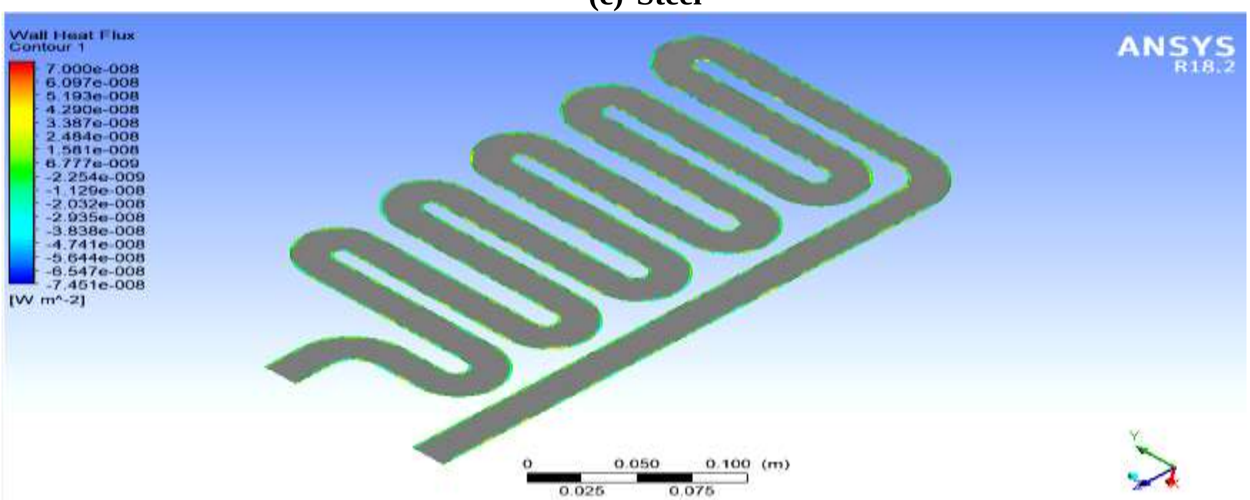


(c) Steel



(d) Nickel

Figure 5.3: Results obtained for Heat Flux for different materials

Table 5.1 presents the results obtained from the research work.

Table 5.1: investigated Properties of Boiler Tube using Different Materials

S.No	Material	Properties				
		Pressure			Temperature	Heat Flux
		P_{max}	P_{min}	P	T	
1.	Aluminum	3.228e+003	1.897e+002	3.04E+03	3.420e+002	-3.671e-009
2.	Copper	3.183e+003	1.848e+003	1.34E+03	3.381e+002	-3.671e-009
3.	Steel	3.098e+003	2.722e+002	2.83E+03	3.458e+002	-2.254e-009

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4.	Nickel	3.049e+003	1.855e+002	2.86E+03	3.457e+002	-2.254e-009

5.2 Discussion

Figures 5.4 to Figure 5.6 portray the results obtained for individual criteria.

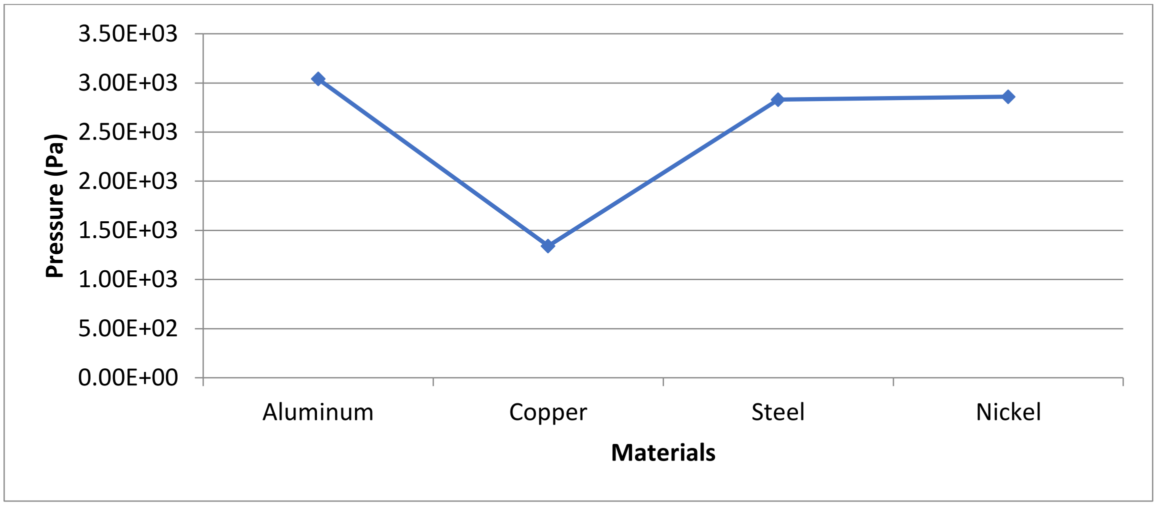

Figure 5.4: Values of Pressure Difference for Different Materials

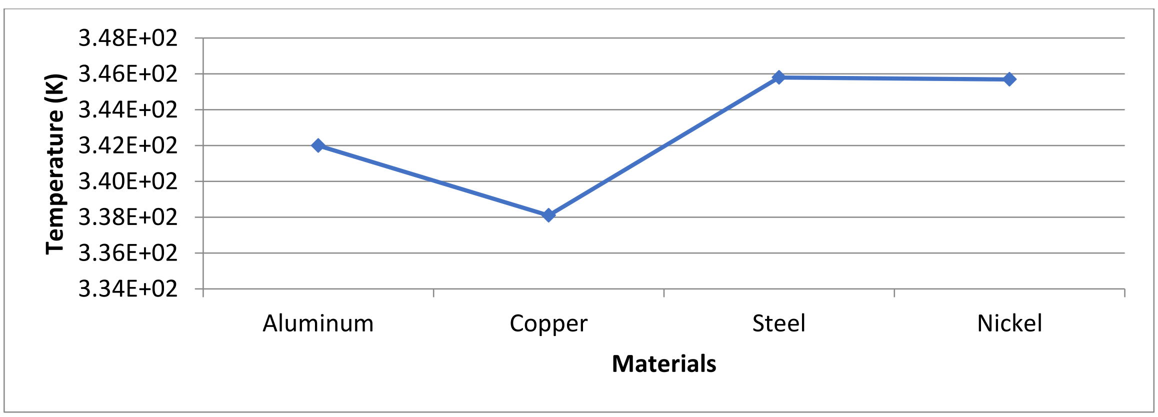

Figure 5.5: Values of Exit Temperature for Different Materials

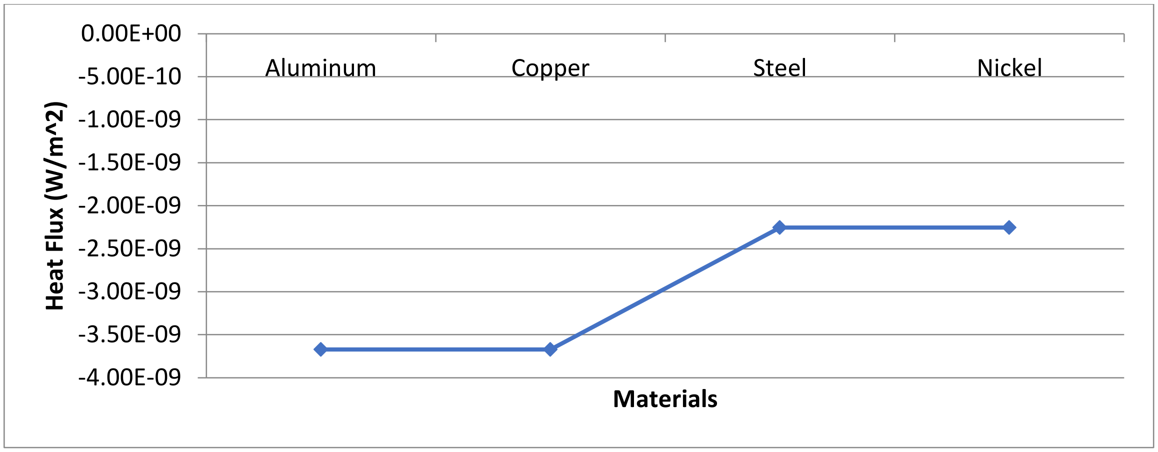

Figure 5.6: Values of Heat Fluxes for Different Materials

From Table 5.1 and figures 5.4 to 5.6, one can investigate the rankings of materials for different criteria, as follows.

Table 5.2: investigated Properties of VCRS Condenser using Different Materials

S. No	Material	Properties and Ranks							
		Pressure				Temperature			
		P_{max}	P_{min}	P	Rank	T	Rank	Heat Flux	Rank
1.	Aluminum	3.228 e+003	1.897e+0 02	3.04 E+03	4	3.420e+002	2	-3.671e-009	1
2.	Copper	3.183 e+003	1.848e+0 03	1.34 E+03	1	3.381e+002	1	-3.671e-009	1
3.	Steel	3.098 e+003	2.722e+0 02	2.83 E+03	2	3.458e+002	4	-2.25E-09	2
4.	Nickel	3.049 e+003	1.855e+0 02	2.86 E+03	3	3.457e+002	3	-2.254e-009	2

From Table 5.2, it can be found that copper shows minimum pressure drop of 1.34e+03 Pa and scores the rank 1. Proceeding in the similar manner, steel shows the second lowest pressure drop of 2.722e+002 Pa, and scores rank 2. Similarly, Nickel and Aluminum score the pressure drops of 1.855e+002 Pa and 1.897e+002 Pa, and earn the ranking scores of 3, and 4, respectively.

Table 5.2 also presents the details of exit temperatures for the condenser. It shows, that the copper is winner here, again, with the minimum exit temperature of 3.381e+002, which is similar to the entry temperature, which indicates, no gain or loss in the temperature of the condenser, when copper is used, which in other chases the temperatures change, and show minor modifications, which are due to the surface roughness, poor thermal conductivities as compared to the copper and turns in the condenser.

Again, on analyzing, the heat flux criteria, it was found that both copper and aluminum score rank 1 by showing the maximum amount of heat transfer (-3.671e-009 W/m^2), while nickel and steel score -2.254e-009 W/m^2, for ranks 2.

On the basis of above mentioned rankings, the overall rankings of materials may be declared as follows.

Table 5.3: Overall Rankings of Materials

S. No	Material	Properties and Ranks								
		Pressure				Temperature	Rank	Heat Flux	Rank	Overall Rank
		P_{max}	P_{min}	P	Rank	T				
1.	Aluminum	3.228 e+003	1.897e+002	3.04 E+03	4	3.420e+002	2	-3.671e-009	1	2
2.	Copper	3.183 e+003	1.848e+003	1.34 E+03	1	3.381e+002	1	-3.671e-009	1	1
3.	Steel	3.098 e+003	2.722e+002	2.83 E+03	2	3.458e+002	4	-2.254e-009	2	4
4.	Nickel	3.049 e+003	1.855e+002	2.86 E+03	3	3.457e+002	3	-2.254e-009	2	3

6. Conclusion, Limitations and Future Scope of the Research

This section focuses on concluding the research, discussing its limitations, and outlining future implications, the details of which are presented as follows.

6.1 Conclusion

The present research work was devoted to the investigations on the optimal material for condensers of a vapor compression refrigeration system. For this purpose, mode of an condenser was developed, and with the help of simulation approach, three properties, condenser exit temperature, pressure drop in the condenser as well as heat flux were determined for the four alternatives, namely, aluminum, copper, steel and nickel. The refrigerant used was R134a. Following concluding points were obtained from the research work.

- Copper serves as the best material out of all the available options; and
- Aluminum scores as the second best material for the condenser application.

6.2 Limitations and Future Scope of the Research

Following points represent the limitations of the research work:

- The research work was confined to limited number of condenser materials and refrigerants;
- Due to time and financial constraints, the research work was lacking in experimentation.

On the basis of above mentioned limitations, following research implications may be considered:

- An extensive research, considering of greater numbers of condenser materials as well as refrigerants may be called; and
- A vast research involving experimentation aspects may also be initiated.

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