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INVESTIGATIONS ON BOILER TUBES WITH DIFFERENT MATERIALS: A SIMULATION APPROACH

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Abstract - The present research work is based on the evaluation of thermal properties for a boiler tube. For this purpose, using simulation approach, four different materials, aluminum, copper, steel and nickel were used and three properties, namely, pressure, temperature and inner wall temperature, were investigated, and rankings of different materials were declared.

Keywords: Boilers, tubes, simulation, materials.

1. INTRODUCTION

According to Magnus and Pardeshi (2024), the reliable operation of steam generation components is essential for maintaining uninterrupted power generation in these plants. Boiler steel tubes are prone to various types of failures, including fireside corrosion, waterside corrosion, hydrogen damage, fatigue-related fractures, and creep rupture. The main causes of these failures can be attributed to improper material selection, inadequate operational practices, such as maintenance deficiencies and insufficient water treatment, as well as design and fabrication defects. Notably, improper operations, evidenced by overheating and corrosion on both the water/steam side and fireside, are significant contributors to these challenges. According to Yon et al. (2023), tube overheating stands as the primary cause behind boiler tube failures, resulting in substantial replacement and maintenance expenses. The temperature of boiler tubes is influenced by both the heating effect of hot combustion gases in the furnace and the cooling effect of steam flow within the tubes. Hence, accurate prediction of tube temperature necessitates incorporating simulations of both gas and steam flows within the boiler model. Ranjeeth et al. (2024) also advocated that investigating failures of water tubes in boilers, particularly in thermal power stations, holds immense significance as it directly impacts the supply of energy to crucial processing units in refineries. Considering these facts, the present research work is devoted to the analysis of boiler tubes with different materials, investigating different properties and ranking them on the basis of obtained values of properties. For the purpose of research work, simulation approach was used. The targeted materials under research were aluminum, copper, steel and nickel.

Following points represent the objectives of the research work.

a) To investigate the performance of boiler tube with different materials; and
b) To investigate the ranking of different materials.

2. LITERATURE REVIEW

The present section is devoted to the academic aspects of the research work and presents the scenario of research in the field, and contributions of research, the details of which are presented in upcoming sub-sections.

2.1 Scenario of Research in the field of Steam Generator Tubes

Figure 2.1 presents the radar graph drawn on the basis of number of research publications offered by different researchers on boilers, in last five years.

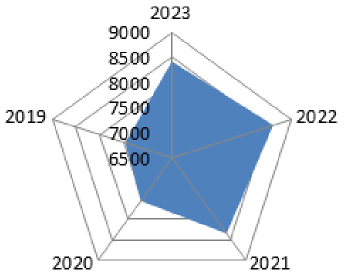


Figure 2.1: Research Publications on the search terms investigations on Boilers

2.2 Contributions of Researchers in the field of investigations on Boilers

Following are the summaries of selected contributions of researchers in the field of investigations on boiler tubes:

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

The current case study entails a comprehensive and systematic metallurgical examination of a defective water wall tube, aimed at pinpointing sulfidation corrosion as the underlying reason for its failure. Experimental findings indicate that the tube's failure stemmed from sulfidation corrosion occurring on its exterior. This corrosive reaction was instigated by sulfur originating from pyrite (FeS2) present in the coal-ash deposits accumulated on the tube's outer surface.

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

This manuscript aims to provide a comprehensive overview of the different causes of boiler failures, ranging from caustic embrittlement, oxygen pitting, fouling, agglomeration, hydrogen damage, stress corrosion cracking, slagging, fatigue failure, hot corrosion, oxidation, to erosion, among others. Furthermore, it discusses various preventive measures, including surface modification techniques. By exploring more advanced combinations of coating materials and implementing preventive measures, it is feasible to enhance the protective qualities of boilers for future applications.

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

This study focuses on investigating the failure of superheater tubes within a sugarcane industry. Various failure mechanisms were observed on both the steam and fire sides of the ASTM A213-T11 and ASTM A213-T22 superheater tubes, which operate at temperatures of 240°C and 380°C, respectively. To discern these mechanisms, microstructural examinations were conducted on the damaged areas, along with characterization of corrosion deposits present on both tube surfaces.

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

In the present research work, a thorough analysis was conducted to investigate the causes of premature damage in broken tubes. The fractured surfaces of the failed tubes underwent non-destructive testing to examine their condition. Metallurgical investigation of the failed tubes was then conducted using optical and scanning electron microscopy, augmented with energy-dispersive X-ray spectroscopy and X-ray diffraction.

- **Rozmus-gornikowska et al. (2023)**

The primary objective of this study was to analyze the alterations in both the microstructure and chemical composition of the austenitic overlay, particularly focusing on the region near the interface where the overlay meets the base material.

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

This study examines the failure of superheater tubes within an air quenching cooler waste heat boiler at a cement plant. The tubes were constructed from material specified to ASTM SA210C. After three months of operation, a leak was discovered in one of the tubes along its bent section. Subsequently, additional leaks were detected in other tubes within the same boiler. To identify the root cause of these leaks, the failed tubes underwent investigation through visual inspection, optical emission spectroscopy, metallographic analysis, tensile testing, micro-hardness measurements, and SEM/EDS analysis.

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

After an extended period of service, a boiler tube in a power plant has experienced failure. By employing various characterization techniques including visual inspection, chemical analysis, dimensional and hardness measurements, fractography, and metallography, the likely cause of the failure has been determined. The analysis revealed that the failure occurred due to vibrational fatigue. Dynamic loading resulting from unstable fluid flow within the water wall tube caused hammering, inducing vibration that led to alternating stress. The presence of a defect in the fillet weld joint under continuous boiler operating conditions ultimately resulted in fatigue failure. Several preventive measures have been proposed to prevent similar failures in the future.

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

This paper examines the performance of different coatings deposited through various thermal spray processes. It then discusses the impact of various process parameters and heat treatments on the microstructure and mechanical properties of these coatings. Finally, recommendations are made regarding the most effective coatings for mitigating maximum hot corrosion of boiler tubes.

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

As per the findings of researchers, unexpected boiler failures within power plants can disrupt electricity generation processes. The primary factors influencing boiler failures include the material composition of the tubes, their positioning, operating temperatures and pressures, as well as the chemical composition of both the feed water and the coal used. This study aimed to elucidate the causes and mechanisms behind the failure of the fire-side boiler water-wall tubes, specifically due to perforation and corrosion.

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

This review initially elucidates the causes and mechanisms of corrosion to establish a foundation for minimizing losses caused by fireside corrosion. Subsequently, it introduces the preparation and characteristics of coatings that exhibit significant promise in resisting the intrusion of corrosive agents by bonding a fortified surface onto the tubes.

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

This paper discusses the failure mechanism and prevention strategies for TP347H stainless steel tubes utilized in the reheater of a coal-fired power plant boiler. By examining the detailed mechanical properties, microstructure, chemical composition, and magnetic behavior, the study identifies the causes of reheater tube failures. These failures are primarily attributed to prolonged overheating, the precipitation and coarsening of secondary phases along grain boundaries, and the development of a high concentration of deformation-induced martensitic structures.

- **Bhosale et al. (2020)**

This study encompasses an examination of the high-temperature solid particle erosion behavior of WC-Cr3C2-Ni coatings deposited via atmospheric plasma spray and high-velocity oxy-fuel processes. Using an air-jet erosion tester (ASTM G76), the effects of temperature and impact angle on the erosion performance of both uncoated and coated specimens were comparatively evaluated. The surface morphology of the eroded specimens was analyzed using a scanning electron microscope.

2.3 Gaps in the Research and Objectives of Research

During the survey of literature, it was found that very limited numbers of research papers were focused on the analysis of boiler tubes using different materials. Plus, very limited numbers of research papers were focusing on investigating more than one thermal property. Considering these facts, the research topic as well as objectives of the research work was finalized.

3. SOLUTION METHODOLOGY

The present section is devoted to details of analysis used, and solution model along with 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 branch of fluid mechanics that uses numerical methods and algorithms to analyze and solve problems involving fluid flows. It's a powerful tool for simulating and understanding complex fluid flow phenomena in various engineering and scientific applications. CFD allows engineers and researchers to study fluid flow behavior, such as velocity, pressure, temperature, and turbulence characteristics, inside or around objects of interest without the need for physical prototypes. This capability is particularly useful in industries such as aerospace, automotive, energy, environmental engineering, and biomedical engineering, among others. The basic steps involved in a typical CFD simulation include:

a) **Problem Definition:** Defining the geometry of the domain of interest, specifying boundary conditions, and selecting appropriate fluid properties.
b) **Mesh Generation:** Dividing the geometry into discrete elements (meshing) to numerically represent the domain. The quality and resolution of the mesh greatly influence the accuracy and computational cost of the simulation.
c) **Numerical Solution:** Applying numerical methods, such as finite difference, finite volume, or finite element methods, to discretize the governing equations of fluid flow (Navier-Stokes equations) and solve them iteratively over the computational domain.
d) **Solution Convergence:** Iterating the numerical solution until a convergence criterion is met, ensuring that the solution is stable and sufficiently accurate.
e) **Post-processing:** Analyzing and visualizing simulation results to extract valuable insights into the fluid flow behavior. This may include generating velocity contours, pressure distributions, streamline plots, and other relevant data visualization techniques.

CFD simulations can range from simple laminar flow analyses to highly complex turbulent flow simulations involving multiphase flows, combustion, heat transfer, and chemical reactions. The choice of turbulence model, boundary conditions, and numerical methods depends on the specific characteristics of the flow and the goals of the analysis.

Overall, CFD has revolutionized the design process in many industries by providing engineers with predictive capabilities to optimize designs, improve performance, and reduce development costs and time-to-market.

3.2 k – ε Turbulence Model

The k – ε turbulence model is one of the most widely used models in computational fluid dynamics (CFD) to simulate turbulent flows. It's particularly popular due to its balance between accuracy and computational efficiency. In this model, two transport equations are solved: one for the turbulent kinetic energy and another for the turbulent dissipation rate. These equations provide information about the intensity and scale of turbulence in the flow.

The equation for turbulent kinetic energy represents the energy associated with the fluctuating velocity components in the flow, while the equation for dissipation rate represents the rate at which turbulence kinetic energy is dissipated into heat due to viscous effects. The k – ε model assumes that the turbulent viscosity is proportional to k and ε, which simplifies the calculation of the Reynolds stresses in the turbulence equations. However, it should be noted that the k – ε model has limitations, particularly in flows with adverse pressure gradients, separation, and swirling flows. Therefore, it may not always accurately predict complex turbulent behaviors, and more advanced turbulence models like Reynolds-averaged Navier-Stokes (RANS) models or Large Eddy Simulation may be necessary in such cases.

3.3 ANSYS R18.2

ANSYS R18.2 refers to a specific version of the ANSYS software suite, a collection of engineering simulation tools widely used for finite element analysis (FEA), computational fluid dynamics (CFD), electromagnetic, and other engineering simulations. Released in 2018, ANSYS R18.2 likely included various updates, bug fixes, and possibly new features compared to its predecessors. However, without specific release notes or documentation for that version, it's hard to pinpoint exact changes. ANSYS software is known for its versatility and robustness, offering engineers and researchers powerful tools for simulating and analyzing physical phenomena across a wide range of industries, including aerospace, automotive, electronics, and more.

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 boiler tube was created in ANSYS R18.2 software, with the following specifications.

a) Outside diameter (mm) = 100
b) Inside diameter (mm) = 80
c) Tube length (m) = 1

Figure 4.1 shows the mode of boiler tube.

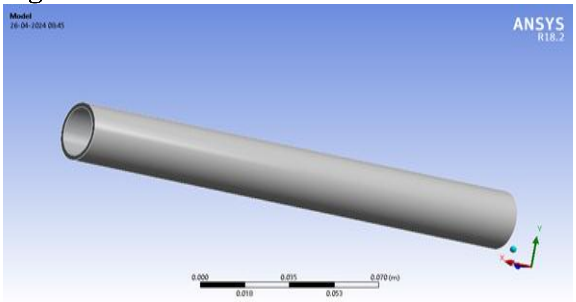
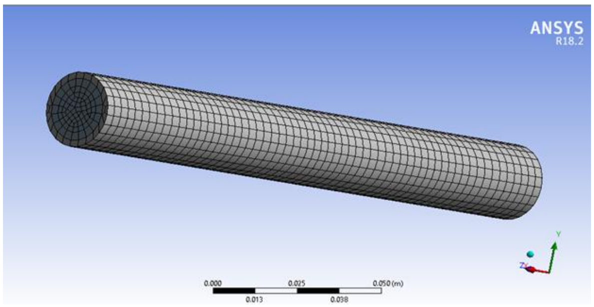


Figure 4.1: Model of Boiler Tube

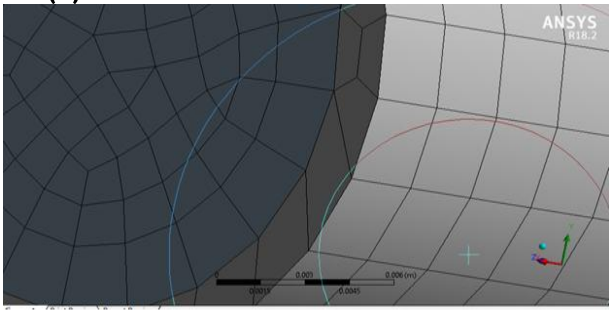
4.2 Solution of the Model

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 Boiler Tube



(a) Conformal Mesh Model for the Boiler Tube

Figure 4.2: Mesh Details for the Boiler Tube 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	7130
3	No. of elements	6344

b) In the next step, boundary conditions on the model were applied, as maximum temperature of 350 degree Calcius and minimum temperature of 35 degree Calcius;

c) During the research work, calculations of pressure, temperature and inner wall temperature 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) Following process parameters/equations were used to solve the research problem.

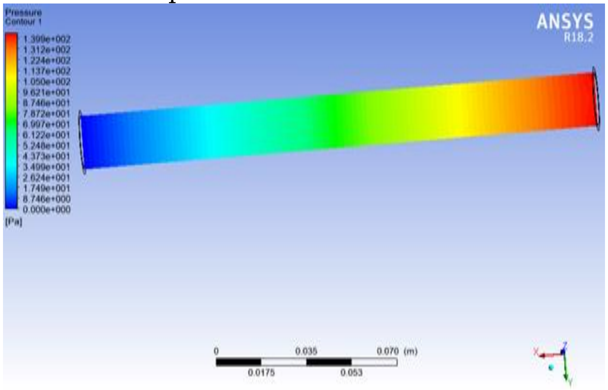
- Gravity in – y direction: 9.81 m/sec^2
- Energy equation: On
- Model used: k-epsilon model
- Inlet type: Pressure
- Outlet type: Velocity

5.RESULTS AND DISCUSSION

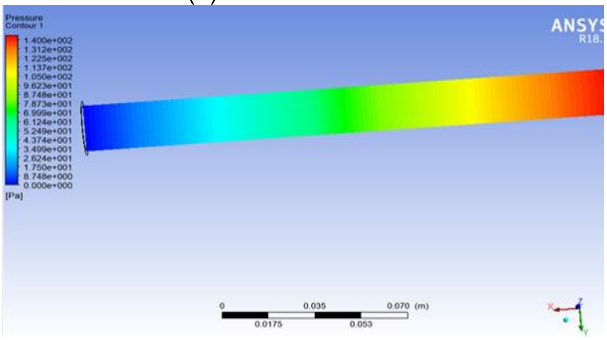
The present section deals with the details of results obtained and the discussion made about the results, the details of which are presented, in upcoming sub-sections.

5.1 Results

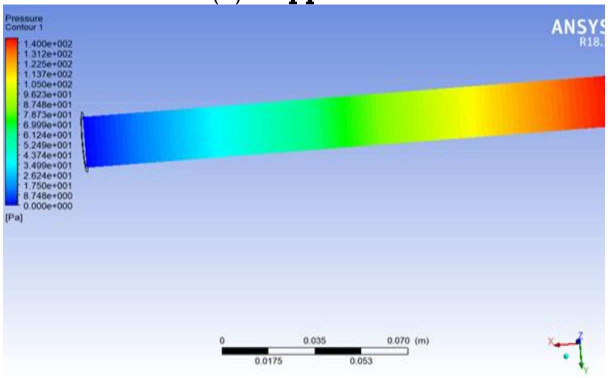
Figure 5.1 represents the details of results obtained for pressure criteria.



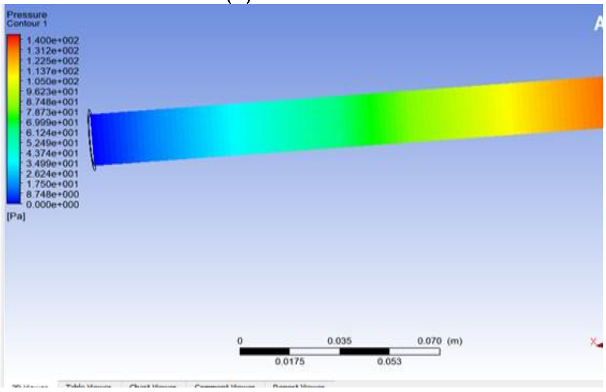
(a) **Aluminum**



(b) **Copper**



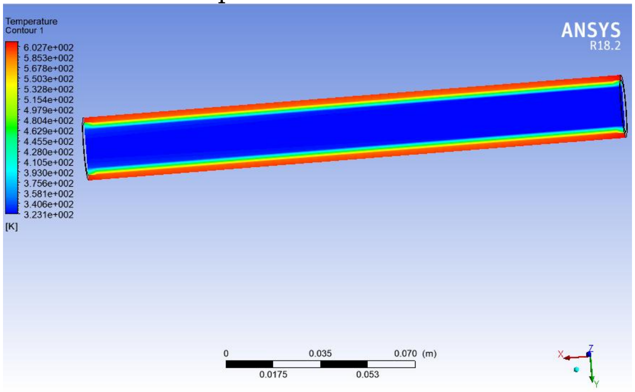
(c) **Steel**



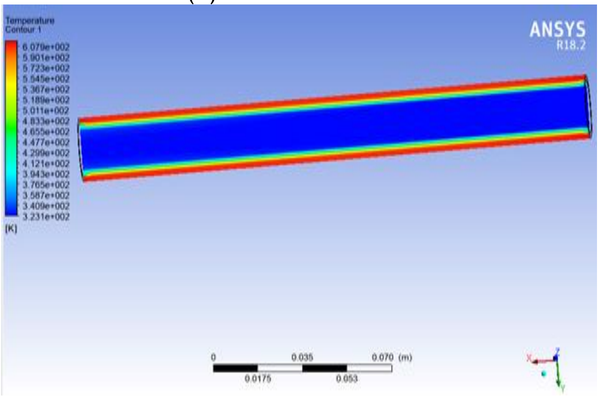
(d) **Nickel**

Figure 5.1: Results obtained for Pressure for different materials

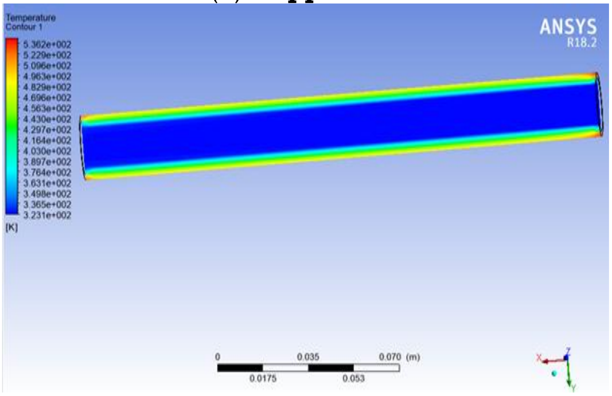
Figure 5.2 represents the details of results obtained for temperature criteria.



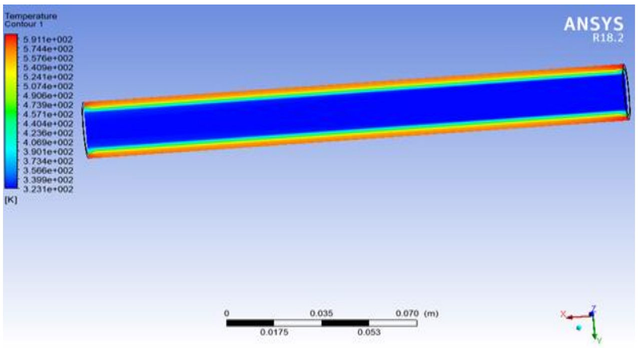
(a) **Aluminum**



(b) **Copper**



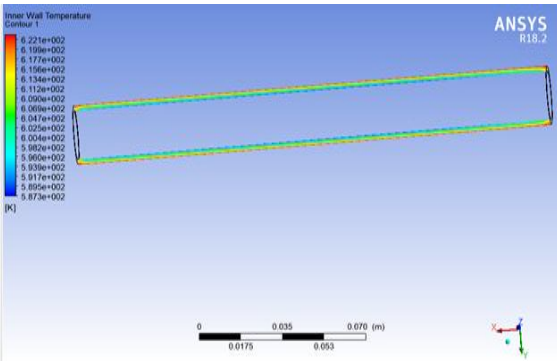
(c) **Steel**



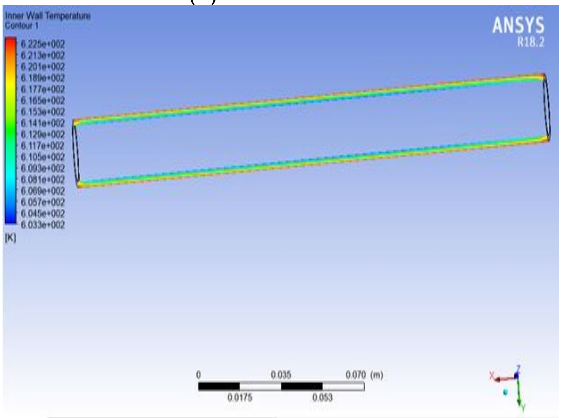
(d) **Nickel**

Figure 5.2: Results obtained for Temperature for different materials

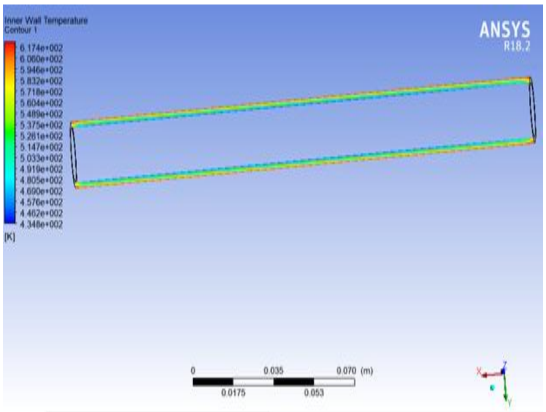
Figure 5.3 represents the details of results obtained for inner wall temperature criteria.



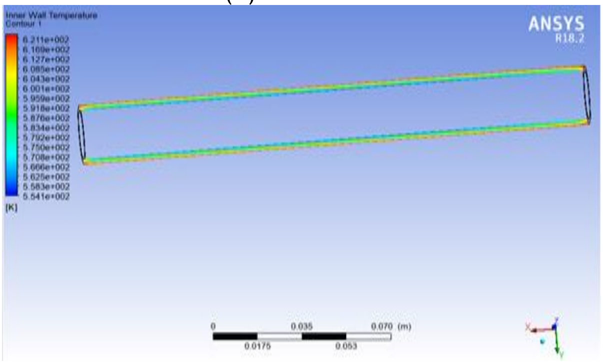
(a) **Aluminum**



(c) **Copper**



(d) **Steel**



(€)Nickel

Figure 5.3: Results obtained for Inner Wall Temperature 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	Inner wall Temperature
1.	Aluminum	1.399e+002	6.027e+002	6.221e+002
2.	Copper	1.400e+002	6.079e+002	6.225e+002
3.	Steel	1.400e+002	5.362e+002	6.174e+002
4.	Nickel	1.400e+002	5.911e+002	6.211e+002

5.3 Discussion

Figure 5.4 shows the graphical representation of above mentioned results.

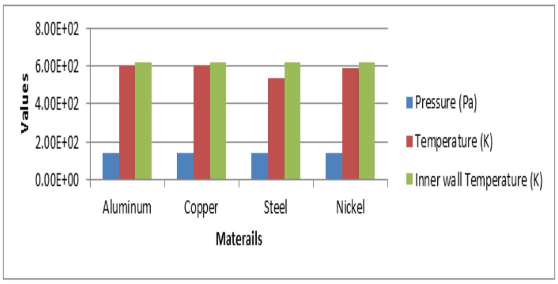


Figure 5.4: investigated Properties of Boiler Tube using Different Materials

Figures 5.5 to Figure 5.7 portray the results obtained for individual criteria.

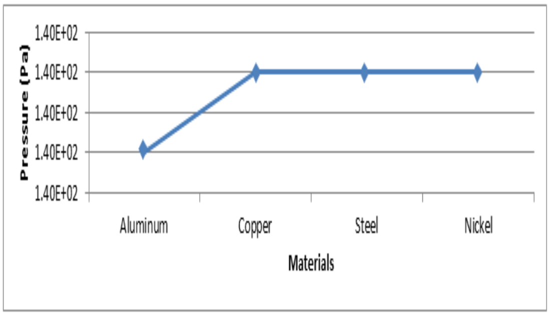


Figure 5.5: Values of Pressure for Different Materials

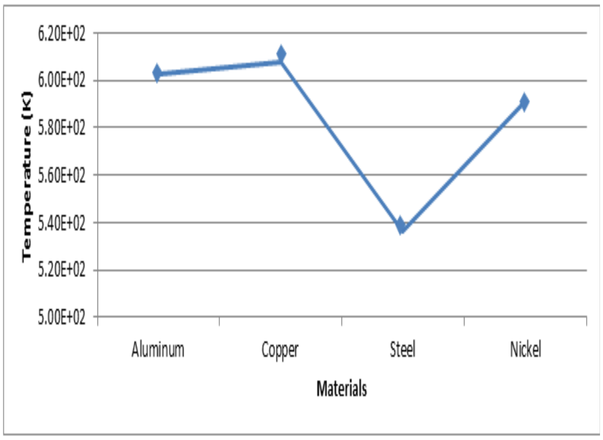


Figure 5.6: Values of Temperature for Different Materials

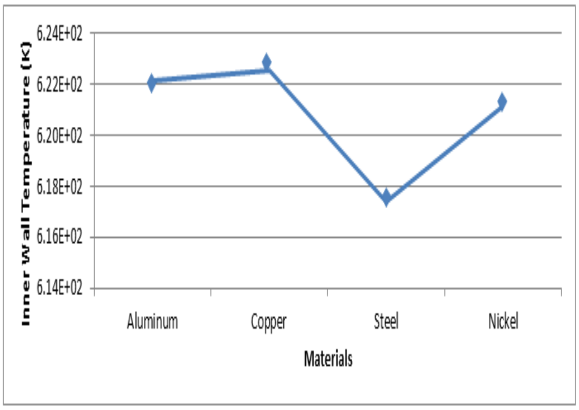


Figure 5.7: Values of Inner Wall Temperature for Different Materials

From Table 5.1 and figures 5.5 to 5.7, one can investigate the rankings of materials for different criteria, as follows.

Table 5.2: investigated Properties of Boiler Tube using Different Materials

S.No	Material	Material Properties & Rankings					
		Pressure (Pa)	Ranking	Temperature (K)	Ranking	Inner wall Temperature (K)	Ranking
1.	Aluminum	1.399e+002	2	6.027e+002	2	6.221e+002	2
2.	Copper	1.400e+002	1	6.079e+002	1	6.225e+002	1
3.	Steel	1.400e+002	1	5.362e+002	4	6.174e+002	3
4.	Nickel	1.400e+002	1	5.911e+002	3	6.211e+002	4

From Table 5.2, it may be noted that materials, copper, steel and nickel show the maximum values of pressure, 1.400e+002 Pa and score rank 1, whereas, aluminum scores rank 2 with the pressure 1.399e+002 Pa. On considering temperature criteria, it may be found that copper shows the maximum temperature of 6.079e+002 K and scores the rank 1, whereas, aluminum shows the temperature 6.027e+002 K and scores rank 2, whereas, nickel and steel, show the temperature values of 5.911e+002 K and 5.362e+002 K and score, rank 3, and 4 respectively. Proceeding in the same manner, on investigating the values of inner wall temperature, it can be found that copper, again, scores the rank 1 with the inner wall temperature value of 6.225e+002 K, whereas, aluminum, nickel and steel, show ranks 2, 3, and 4, by showing the inner wall temperatures, 6.221e+002 K, 6.211e+002 K and 6.174e+002 K.

On analyzing, above results, it may be found that, criteria temperature and inner wall temperature show similar kind of rankings, as compared to the pressure, the rankings may be considered to be declared as overall rankings, as presented below.

Table 5.3: Overall Rankings of Materials

S.No	Material	Material Properties & Rankings				Overall Ranking
		Temperature (K)	Ranking	Inner wall Temperature (K)	Ranking	
1.	Aluminum	6.027e+002	2	6.221e+002	2	**2**
2.	Copper	6.079e+002	1	6.225e+002	1	**1**
3.	Steel	5.362e+002	4	6.174e+002	4	**4**
4.	Nickel	5.911e+002	3	6.211e+002	3	**3**

6. Conclusion, Limitations and Future Scope of the Research

The present chapter is devoted to conclusion of the research, and limitations and future scope of the research work, the details of which are presented in upcoming sub-sections.

6.1 Conclusion

The present research work is devoted to the investigations on performance of boiler tubes with different materials. For this purpose, four different materials, aluminum, copper, steel and nickel were employed in the simulated model of a boiler tube, and different properties, pressure, temperature and inner wall temperature, were investigated. Based on the obtained values, rankings of materials on different criteria were investigated. Following points represent the conclusion of the research work:

- Copper secures rank one, and serves as the best material for boiler tubes;
- Aluminum scores rank second, and serves the second best material for the boiler tubes; and
- Nickel scores rank third, and acts as the third best option for boiler tubes.

6.2 Limitations and Future Scope of the Research

Following points represent the limitations of the research work:

- The research work is focused on a small set of materials;
- The research work is also limited to the investigations on limited number of properties;
- The research work is also limited to simulation approach only.

Following points represent the future scope of the research work:

- An extensive research involving a broader set of materials may be initiated;
- A broader research considering a larger set of properties may be called; and
- A greater research work, involving different research approaches may also be started.

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