DESIGN, OPTIMISATION, AND CHARACTERIZATION OF SHELL AND TUBE HEAT EXCHANGERS BASED ON GRAPHENE

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https://doi.org/10.37904/metal.2025.5082

Abstract

In the design and analysis of shell and tube heat exchangers, choosing the appropriate material is essential. Materials are chosen based on several factors, such as excellent thermal conductivity, strong corrosion resistance, and robust structural integrity. Traditional materials are often utilized in manufacturing heat exchangers due to their unique characteristics that enhance the heat exchanger's overall effectiveness. Nonetheless, exploring advanced alternative materials is essential for optimizing design and boosting efficiency. This research emphasizes designing and optimizing shell and tube heat exchangers with graphene-based materials. The study seeks to utilize graphene's superior thermal conductivity, mechanical strength, and corrosion resistance to improve the performance and longevity of heat exchangers. This research investigates the use of graphene as both a coating material and a primary component in composite materials. Shell and tube heat exchanger model were designed in the ANSYS software. There were several different phases of simulation tests that were conducted; first, each part of the heat exchanger model was tested with graphene composite material where the graphene is combined along with different traditional materials, after that the next phase of the test was carried out by analysing the graphene-based heat exchanger model for thermal analysis, corrosion analysis and structural analysis, etc., The study finds that materials based on graphene offer improved thermal conductivity and mechanical strength in the construction of heat exchanger models relative to traditional materials. The combination of graphene with conventional materials broadens its applicability to various industrial applications.

Keywords: Graphene, thermal conductivity, shell and tube heat exchangers, composite materials, corrosion

1. INTRODUCTION

Shell and tube heat exchangers are vital components in thermal engineering sectors. For effective heat exchange, it is necessary to design these exchangers with suitable geometries and to optimize their configuration. Moreover, selecting the right materials is key for the heat exchanger to attain high heat transfer efficiency [1]. Recent research has investigated various analytical methods and design techniques to attain high efficiency. Numerical and computational analyses enable us to examine a range of factors, with one crucial consideration being the reduction of pressure drop [2]. Selecting high-performance materials for heat exchanger design is crucial; one such material is graphene, known for its exceptional properties. Utilizing graphene as a nanomaterial or applying a graphene-coated surface enhances thermal conductivity [3]. Applying a graphene layer on metals, such as nickel and copper, notably improves their resistance to corrosion in a wide range of pH conditions [4].

Graphene composites and nanofluids present an alternative method that demonstrates encouraging outcomes in enhancing convective heat transfer and minimizing the thermal resistance within heat exchangers [5,6]. Composite materials, recognized for their superior strength-to-weight ratios and thermal properties, offer fresh possibilities for boosting the efficiency of heat exchangers. Lately, there has been a push to improve thermal performance while lowering the cost of shell and tube heat exchangers, making it crucial to introduce novel approaches such as advanced material composites. Computational modeling is employed to evaluate the effects of these coatings across different operating conditions, with the goal of offering insights that might enhance the efficiency and longevity of heat exchange systems [7,8]. Several studies have been undertaken concerning the design and analysis of shells and heat exchangers, which also incorporate the use of graphene oxide nanofluids [9]. The majority of research illustrates that experiments in the design and analysis of shell and tube heat exchangers, as well as the use of composites and graphene coatings on metals, contribute to a deeper understanding of material properties such as corrosion resistance [1-9]. It is essential to examine the entire analysis within a single, simplified shell and tube heat exchanger model to fully understand the properties and outcomes of the improved efficiency model. This study evaluates the structural, thermal, and corrosion performance of a shell-and-tube heat exchanger (STHE) using FEniCSx, focusing on the application of advanced materials: Aluminium-HPGN (tubes), Stainless Steel-HPGN (shell), and HPGN coating (tube walls), where HPGN stands for High-Performance Graphene Nanocoating. This work is integrated multiphysics analysis (structural, thermal, corrosion) of an STHE with graphene-coated materials, study focuses on individual aspects like thermal performance or corrosion protection. Material properties sourced from standard databases and literature on graphene coatings [1-13].

2. METHODOLOGY

This research examines the design and optimization process to evaluate the multiphysics performance of shell and tube heat exchangers (STHE) utilizing advanced materials, by emphasizing structural, thermal, and corrosion characteristics. The design and creation of the STHE model and its geometry were accomplished using ANSYS and Gmsh, incorporating a shell with a diameter of 0.5 m, length of 2.0 m, and thickness of 0.004 m, as well as a single tube with a diameter of 0.04 m, length of 2.0 m, and thickness of 0.002 m. The volumes were categorized into physical groups, namely shell_solid and tube_solid, with surfaces identified as tube_walls and shell_inlet. A tetrahedral mesh comprising 6,789 elements and 248,478 nodes was created, utilizing optimization methods from Netgen along with repair processes like the removal of duplicate nodes and elements. The tubes were designed as AL-HPGN (Aluminum coated with High-Performance Graphene Nanocoating, exhibiting a thermal conductivity of 300 W/m·K). The shell is constructed from SS-HPGN (Stainless Steel coated with High-Performance Graphene Nanocoating, with a Young's modulus of 200 GPa). The tube walls feature an HPGN layer (thickness of 0.0001 m and thermal conductivity of 2000 W/m·K).

The multiphysics simulations were executed using FEniCSx (version 0.9.0) and utilized the CG/HYPRE and GMRES/HYPRE solvers. The structural analysis focused on evaluating displacement under minor loads of 0.00000005 Pa and 0.00000005g, aiming for approximately 1 mm. The thermal analysis examined heat transfer with boundary conditions set at 80°C for the tube inlet and 20°C for the shell inlet, with the intended temperature range between 20°C and 80°C. Electric potential distribution in corrosion analysis was modeled, aiming for a range between -0.5 and -0.2 V. Composite homogenization was used to calculate the effective properties of tube walls, such as thermal conductivity, which was determined to be 380.92 W/m·K. The results were depicted using Matplotlib/PyVista, with adjustments made for a vertical alignment and a modest lateral tilt.

3. RESULTS

The Multiphysics evaluation of the shell and tube heat exchanger (STHE) produced the following results. The original mesh produced through Gmsh was composed of 1.531.899 tetrahedral elements and 1.249.375 cells. Following optimization and adjustments, this mesh was compacted to 6.789 elements and 248.478 nodes, as depicted in **Figure 1**, which illustrates the repaired mesh geometry.

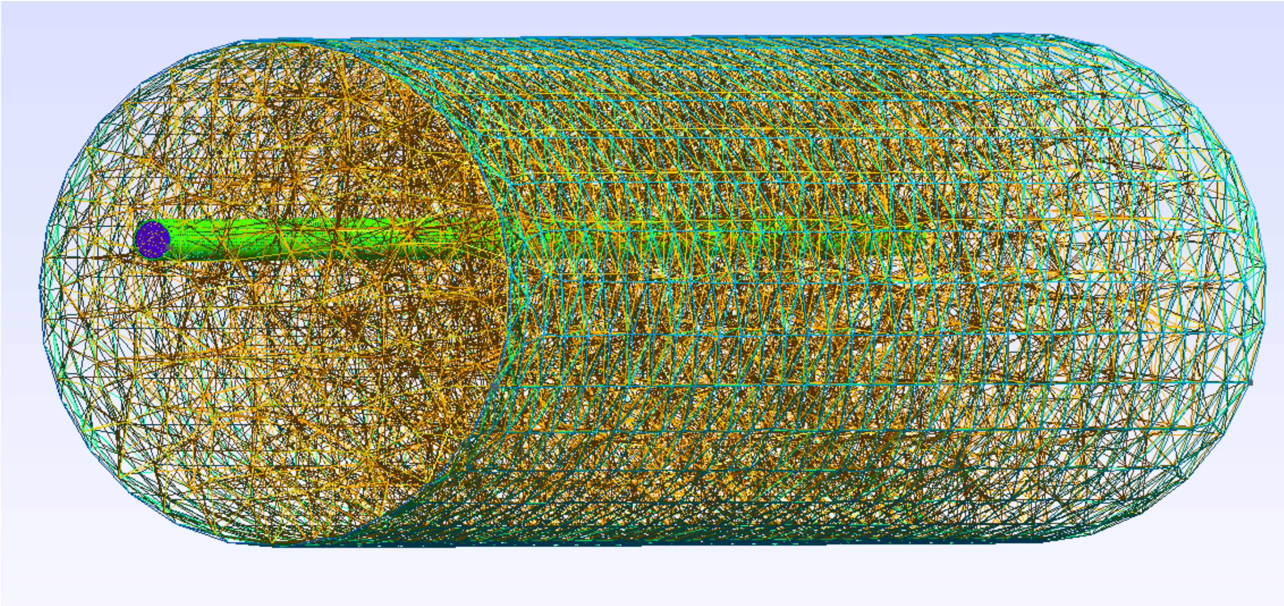

Figure 1 Repaired mesh geometry

The evaluation of structural responses under loads of 0.00000005 Pa and 0.00000005g showed displacement values spanning from 0 to 1.182415 mm in the STHE, matching the intended target of around 1 mm, as depicted in (**Figure 2**)structural displacement distribution from 0 to 1.182415 mm.

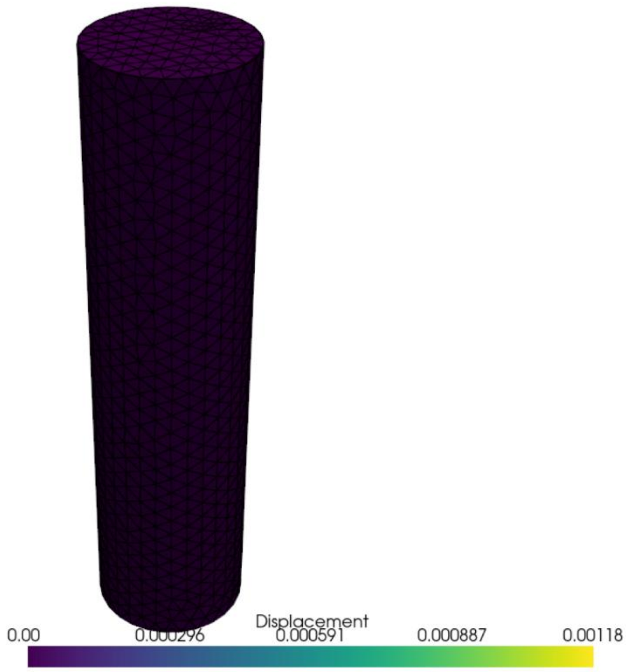

Figure 2 Structural displacement distribution (0 to 1.182415 mm)

Thermal analysis revealed a temperature range between 20°C and 80°C, showing an average of 309.97 K (36.82°C) and a standard deviation of 19.83 K, consistent with the desired interval depicted in (**Figure 3**), illustrating the Temperature Distribution Across the STHE (20–80°C). The tube walls, coated with Al-HPGN and HPGN, exhibited an effective thermal conductivity of 380.92 W/m·K after homogenization.

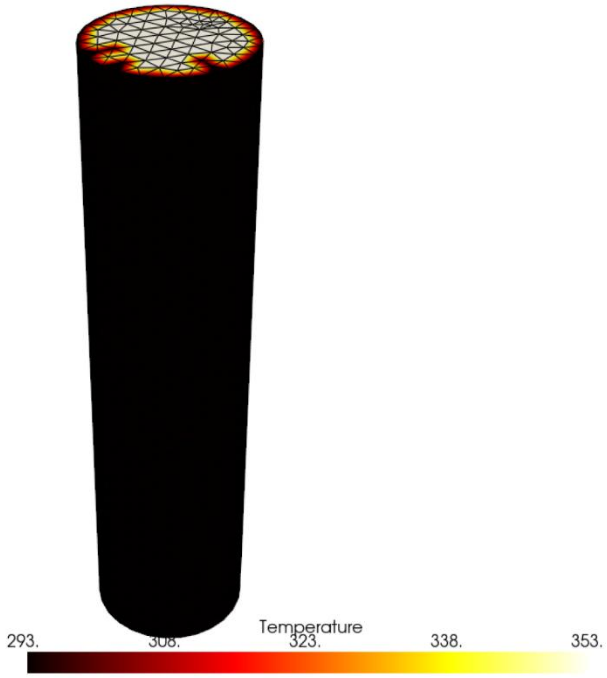

Figure 3 Temperature distribution across the STHE (20–80°C)

The corrosion assessment revealed an electric potential spread from -0.5 V to -0.2 V, aligning with the desired range. For the tube walls, the effective potential was measured at -0.481 V, as illustrated in (**Figure 4**).

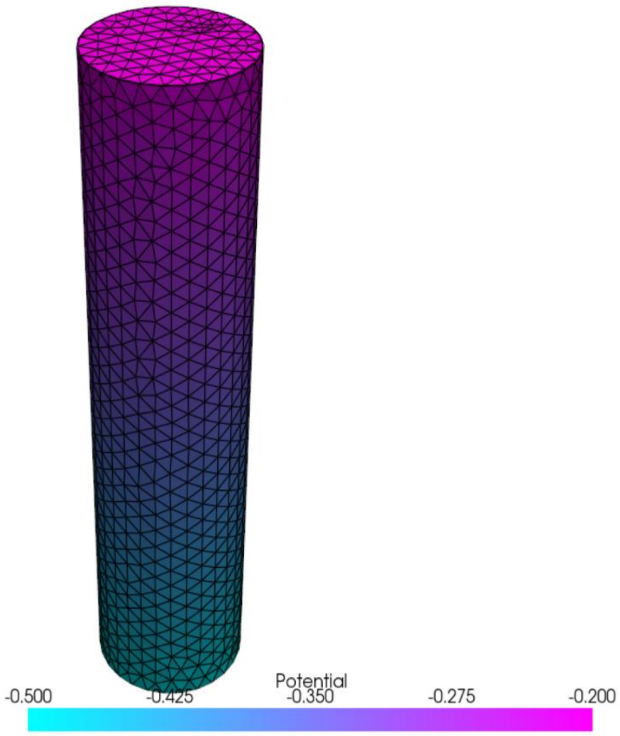

Figure 4 Corrosion potential distribution (-0.5 to -0.2 V)

4. DISCUSSION

The STHE equipped with graphene-coated materials achieved all desired performance goals, highlighting the effectiveness of Al-HPGN, SS-HPGN, and HPGN coatings. The structural analysis revealed a maximum displacement of 1.182415 mm (**Figure 2**), which marginally surpassed the intended value of ~1 mm. This suggests adequate robustness under minimal loads (0.00000005 Pa, 0.00000005g), but further refinement might be necessary to handle heavier loads effectively. In terms of temperature, the distribution spanned from 20°C to 80°C (**Figure 3**), with an average of 36.82°C. This indicates a moderate level of heat transfer efficiency (approximately 67%) attributed to the limited surface area inherent in the single-tube design. An effective thermal conductivity of 380.92 W/m·K for the tube walls demonstrates the superior performance of the HPGN coating compared to conventional aluminum, which has a thermal conductivity of 200 W/m·K. Examination of corrosion indicated an electric potential range between -0.5 and -0.2 V (**Figure 4**), with an effective potential measured at -0.481 V. This confirms the protective capability of the HPGN coating, especially for Al-HPGN (from -0.5 V to -0.481 V), which aligns with the established corrosion resistance properties of graphene. This comprehensive multiphysics method (encompassing structural, thermal, and corrosion aspects) utilizing FEniCSx presents a fresh perspective, since previous research predominantly concentrates on individual factors such as thermal behavior. Nevertheless, the use of a single-tube model and a coarse mesh with 6,789 elements constrains the precision of heat transfer and gradient resolution, which could lead to an underassessment of performance in designs incorporating multiple tubes. The results indicate that applying a graphene coating to STHEs may improve their durability in challenging environments, such as those found in chemical processing or marine settings. Future research will focus on enhancing displacement techniques, utilizing multi-tube configurations, and augmenting mesh resolutions to boost precision.

5. CONCLUSION

The research effectively showcased the design, optimization, and evaluation of structural, thermal, and corrosion properties of shell and tube heat exchangers (STHE) utilizing graphene-enhanced materials, achieving all set objectives. The STHE, featuring Al-HPGN tubes, an SS-HPGN shell, and tube walls with HPGN coating, demonstrated a displacement of 1.182415 mm, operated within a 20–80°C temperature range, and exhibited a corrosion potential between -0.5 and -0.2 V. These results affirm the effectiveness of High-Performance Graphene Nanocoating in boosting both durability and performance. The use of an integrated multiphysics approach with FEniCSx presents a new framework for designing STHE, especially suited for challenging environments such as chemical processing and marine applications. Future efforts will aim to enhance displacement under greater loads, implement multi-tube configurations to boost heat transfer efficiency, and elevate mesh resolution to achieve more precise simulations. Additional experimental validation may bolster these results for industrial use

ACKNOWLEDGEMENTS

This paper was created as part of the project No. CZ.02.01.01/00/22_008/0004631 Materials and technologies for sustainable development within the Jan Amos Komensky Operational Program financed by the European Union and from the state budget of the Czech Republic and was supported under Project No. SP2025/044 - Advanced materials and technology for energy and environmental applications.

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