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Design and Analysis of a Graphite-Filled Polymer-Based Heat Exchanger

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Abstract—

Polymer-based heat exchangers are of interest where corrosion resistance, low mass, and geometric flexibility are important. However, the relatively low thermal conductivity of unfilled polymers can limit their heat-transfer performance. This work presents the design and computational assessment of a tube intended for a graphite-filled polyether ether ketone (PEEK)-based heat-exchanger concept. A three-dimensional model was developed and analysed using ANSYS Fluent, with water assigned as the working fluid and thermal boundary conditions applied at the inlet. The study considers the coupled roles of tube geometry, fluid flow, and heat conduction through the polymer-composite wall. The current manuscript documents the modelling workflow and provides a framework for reporting temperature, velocity, pressure, and heat-transfer results. Quantitative performance claims are intentionally reserved for insertion after the final solver outputs and material-property data have been checked. The approach is intended to support an initial engineering assessment of a lightweight polymer-composite tube; experimental validation and material-specific characterization remain necessary before application-level conclusions can be drawn.

Key Words—ANSYS Fluent, heat exchanger, graphite-filled polymer, polyether ether ketone (PEEK), thermal analysis.

I. INTRODUCTION

Heat exchangers are essential in thermal-management systems because they transfer energy between fluids while maintaining the required operating conditions. In aerospace-related applications, mass, packaging, corrosion resistance, operating temperature, and reliability can all influence material selection. Metals provide high thermal conductivity, but polymer composites may offer lower density and improved resistance to selected corrosive environments. Their usefulness depends on the particular polymer, filler type, filler distribution, manufacturing route, and service conditions.

PEEK is a high-performance thermoplastic known for its mechanical and chemical resistance. Incorporating conductive fillers such as graphite can modify the effective thermal transport of a polymer matrix, although the resulting conductivity is dependent on filler concentration, orientation, interfaces, and processing. Research on graphite-filled thermoplastics has demonstrated the potential of polymer-composite heat-exchanger concepts, while also showing that performance must be evaluated for the specific geometry and material system. Studies of graphene-reinforced PEEK further emphasize that conductive pathways and microstructure influence heat transport .

The present project focuses on the design and numerical analysis of a graphite-filled polymer tube rather than a direct, general comparison between copper and polymer heat exchangers. The main objective is to document a reproducible modelling approach, identify the thermal and flow fields predicted by the selected simulation setup, and establish what must be measured before the design can be assessed experimentally.

II. OBJECTIVES AND SCOPE

The objectives of this work are:

To develop a three-dimensional tube geometry for a polymer-composite heat-exchanger concept.

To define the fluid region, solid wall, mesh, material properties, and thermal boundary conditions in ANSYS Fluent.

To evaluate the predicted temperature and velocity distributions and, where available, pressure drop and heat-transfer quantities.

To identify the data required for future experimental validation of the manufactured or machined prototype.

III. LITERATURE REVIEW

J.-H. Imholze and H. Glade, "Crystallization Fouling on Polymer Composite Heat Exchanger Tubes and the Effects of Surface Treatments," Heat and Mass Transfer, 2025.Summary: Experimental study comparing polymer composite and metal heat exchanger tubes in a falling film evaporator, showing that flame-treated polymer composite tubes exhibit lower fouling and thinner scale layers than metal tubes, indicating better resistance to crystallization fouling.

O. M. Hameed, H. A. Mohammed, and A. N. Abd, "An Enhancement of Double Pipe Heat Exchanger Performance Using Nanofluid and Refrigerant Vapor," Journal of Thermal Engineering, 2024. Summary: Investigates the use of Fe_3O_4–water nanofluid to improve heat transfer performance in a double-pipe heat exchanger.

[1] F. Tarannum, S. Danayat, A. Nayal, R. Muthaiah, R. S. Annam, and J. Garg, "Thermally Expanded Graphite Polyetherimide Composite with Superior Electrical and Thermal Conductivity," 2022. Summary: Study reports the development of expanded graphite/polyetherimide composites with significantly improved thermal and electrical conductivity, demonstrating their suitability for thermal management applications such as heat exchangers and electronic cooling systems.

X. Li, Y. Chen, and Z. Wang, "Combined Heat Transfer Models and Dynamic Optimization Method for High-Pressure Feedwater Heat Exchanger in Nuclear Power Plant," Energy Engineering Journal, 2022.Summary: Proposes combined heat transfer models and optimization methods to improve accuracy and efficiency of feedwater heat exchangers.

J. Kasmir and S. M. Joshi, "Experimental Study of a Shell and Tube Heat Exchanger for Performance Enhancement," ICTSD Conference, 2015.Summary: Experimental study analyzing the performance of a shell-and-tube heat exchanger by varying inlet temperature and mass flow rate; results show that counter-flow configuration and higher flow rates significantly improve heat transfer coefficient and overall effectiveness.

Y. Zhang, L. Wang, and J. Liu, "Research on the Modeling and Simulation of Shell and Tube Heat Exchanger System Based on MPCE," International Journal of Modeling and Simulation, 2021. Summary: Develops a mathematical model and simulation of a shell-and-tube heat exchanger using MPCE for temperature control analysis

J. Li, J. K. Narayanan, X. Gao, and C. R. Kharangate, "An Experimental Study on the Local Heat Transfer Behavior of the Shell-Side Flow Condensation," IEEE ITHERM, 2025. Summary: Experimental investigation of shell-side condensation in a tube-in-tube heat exchanger showing that heat flux and heat transfer coefficient are highest near the inlet and decrease downstream due to liquid film thickening, while higher vapor and coolant flow rates enhance condensation heat transfer.

H. Chen, M. Wang, and T. Li, "Experimental Study of In-Tube Condensation and Evaporation Using Enhanced Heat Transfer Tubes," Energies, vol. 14, 2021. Summary: Experimental analysis demonstrating that enhanced heat transfer tubes (such as herringbone and 3D EHT tubes) significantly increase condensation and evaporation heat transfer coefficients compared with smooth tubes due to improved turbulence and fluid mixing.

IV. GEOMETRY AND MATERIAL DESCRIPTION

The heat exchanger domain is modelled as a straight tube featuring a nominal length of 450 mm, an outer diameter (D_o) of 24 mm, and a uniform wall thickness of 1.5 mm, deriving a nominal inner bore diameter (D_i) of 21 mm. The computational model, constructed in ANSYS, incorporates both the internal fluid passage and the solid composite wall region to perform conjugate thermal-fluid analysis. The computational setup encompasses the central tube domain along with its internal flow region.

The solid wall region of tube consists of a high-performance polymer-composite matrix based on polyether ether ketone (PEEK). The targeted baseline composition comprises approximately 65--70 wt%PEEK,10--15 wt%glass fibre, 10--15 wt%polytetrafluoroethylene (PTFE), and 5--10 wt%graphite filler. Liquid water serves as the working fluid within the primary internal flow domain.

Thermophysical parameters for the solid domain—specifically thermal conductivity, density, and specific heat—are assigned based on the verified grade properties of the multi-phase composite rather than generic unfilled PEEK values, ensuring accurate representation of directional heat transport across the tube wall.

The mesh was generated in ANSYS to discretize the fluid passage and the solid tube wall into smaller computational elements for numerical analysis. Appropriate boundary conditions, including fluid inlet temperature, outlet pressure, and thermal interaction between the fluid and the composite tube wall, were applied according to the simulation setup. The governing equations for fluid flow and energy transport were solved using ANSYS Fluent to obtain the temperature distribution, velocity field, and heat transfer behaviour within the tube. The resulting contours were examined to identify variations in fluid temperature and velocity along the tube length and to understand the thermal response of the graphite-filled polymer composite. This numerical approach provides an understanding of the potential application of the selected composite material in lightweight, corrosion-resistant heat exchanger systems.

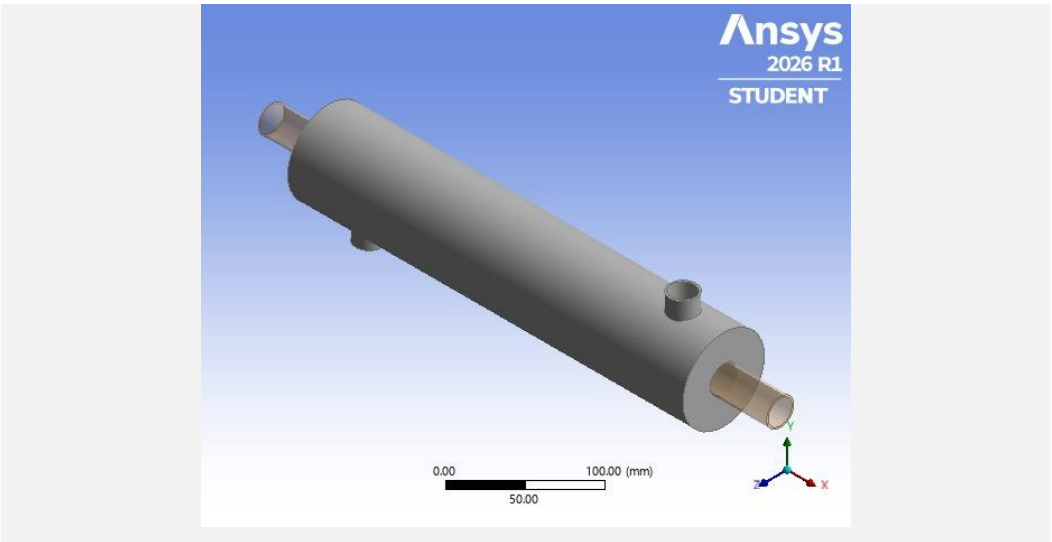


Fig. 1. isometric view of the final shell tube geometry.

V. NUMERICAL METHODOLOGY

A. Computational Domain and Mesh

The computational domain should distinguish the water passage from the polymer-composite wall wherever conjugate heat transfer is being solved. A mesh was generated for the model in ANSYS. For reproducibility, report the element type, total cell/element count, minimum orthogonal quality, maximum skewness, and any local refinement near the wall or inlet/outlet. Conduct a mesh-independence study by repeating the solution on progressively refined meshes and comparing a selected output such as outlet temperature or heat-transfer rate.

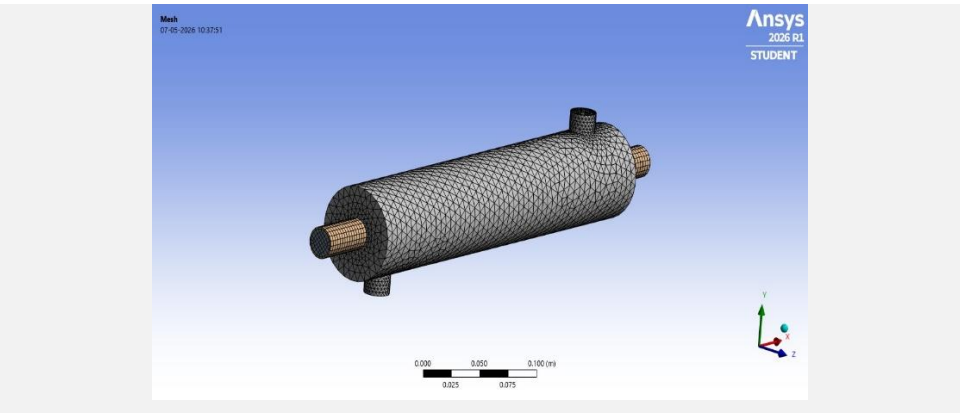


Fig. 2. mesh image

B. Materials and Boundary Conditions

The working fluid is water. The inlet temperatures used in the project setup were 299 K for the hot stream and 200 K for the cold stream. Confirm the exact domain assignment before publication: if the model contains only one internal water passage, do not describe both hot- and cold-stream inlets unless a second fluid domain was included. The inlet velocity or mass-flow rate, outlet pressure, wall thermal condition, turbulence model, and operating pressure must be reported from the actual ANSYS setup.

The solid wall should be assigned the verified properties of the actual graphite-filled PEEK-based composite. If a constant isotropic conductivity was used, state this assumption and explain its source. If the supplier provides anisotropic conductivity, an isotropic approximation may introduce error and should be acknowledged. The material data used in ANSYS must be listed in a table in the final version.

Parameter	Current project information
Tube length	450 mm nominal
Outer diameter	24 mm nominal
Wall thickness	1.5 mm nominal

Parameter	Current project information
Nominal inner diameter	21 mm (derived)
Working fluid	Water
Inlet temperatures	299 K hot; 200 K cold
Composite composition	PEEK + graphite ranges supplied during planning
Thermal conductivity	45.17W/mK

C. Governing Equations

For steady, incompressible flow, the continuity equation is expressed as

$$\nabla \cdot (\rho u) = 0$$

where ρ is fluid density and u is the velocity vector. The momentum equation can be written as

$$\nabla \cdot (\rho u u) = -\nabla p + \nabla \cdot \tau + \rho g$$

where p is pressure, τ is the viscous stress tensor, and g is gravitational acceleration. For energy transport in the fluid, a common steady form is

$$\nabla \cdot [u(\rho E + p)] = \nabla \cdot (k_{eff} \nabla T) + S_E$$

where E is total energy per unit mass, k_eff is the effective thermal conductivity used in the energy model, T is temperature, and S_E represents any volumetric energy source. The exact equations and turbulence closure should be reported consistently with the selected Fluent models; the expressions above are general forms and are not a substitute for documenting the actual solver settings.

The heat-transfer rate may be calculated from a fluid energy balance as $\dot{Q} = \dot{m}\, c_p (T_{out} - T_{in})$, where $\dot{m}$ is mass-flow rate and c_p is the fluid specific heat. This relation requires consistent sign convention and sufficiently established inlet/outlet bulk temperatures. If both hot and cold streams are present, calculate the heat-transfer rate on both sides and report the energy imbalance.

D. Solver Procedure and Convergence

The model was set up and solved in ANSYS Fluent. In the final manuscript, specify whether the solution was steady or transient, the pressure–velocity coupling scheme, spatial discretization order, turbulence model, residual targets, and monitored quantities. Convergence should not be judged from residuals alone: outlet temperatures, mass balance, and heat-transfer rate should also stabilize. Include the final residual history or state the quantitative convergence criteria used.The numerical simulation was performed using ANSYS Fluent by defining the computational domain, material properties, and appropriate boundary conditions. The governing equations of mass, momentum, and energy conservation were solved to obtain the flow and temperature distributions. The domain was meshed to capture fluid flow and heat transfer through the graphite-filled polymer tube wall. Suitable solver settings and discretization schemes were applied based on the simulation requirements. Convergence was assessed by monitoring residuals and the stability of outlet temperatures, flow rates, and heat-transfer rate. The resulting temperature and velocity contours were used to understand the thermal behaviour and flow distribution within the model. These results provide a foundation for evaluating the design and planning future experimental validation.

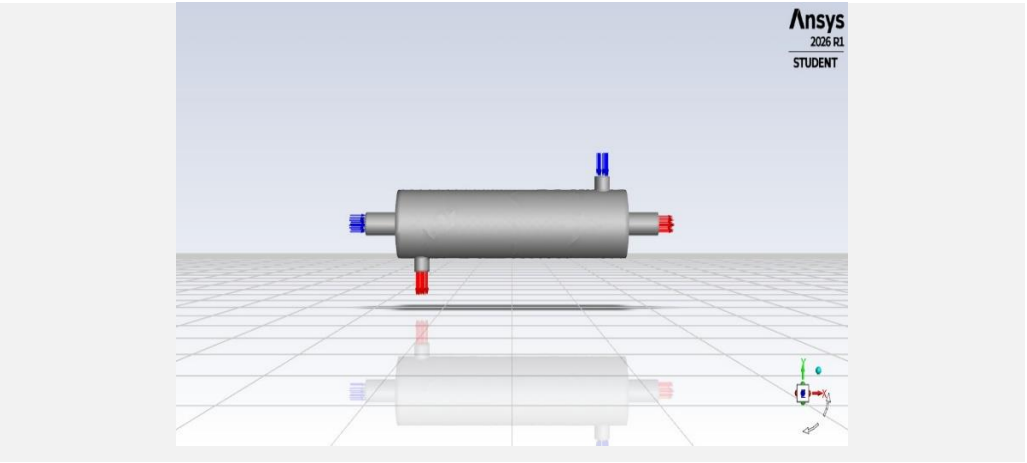


Fig. 3. ANSYS setup screenshot showing inlet/outlet

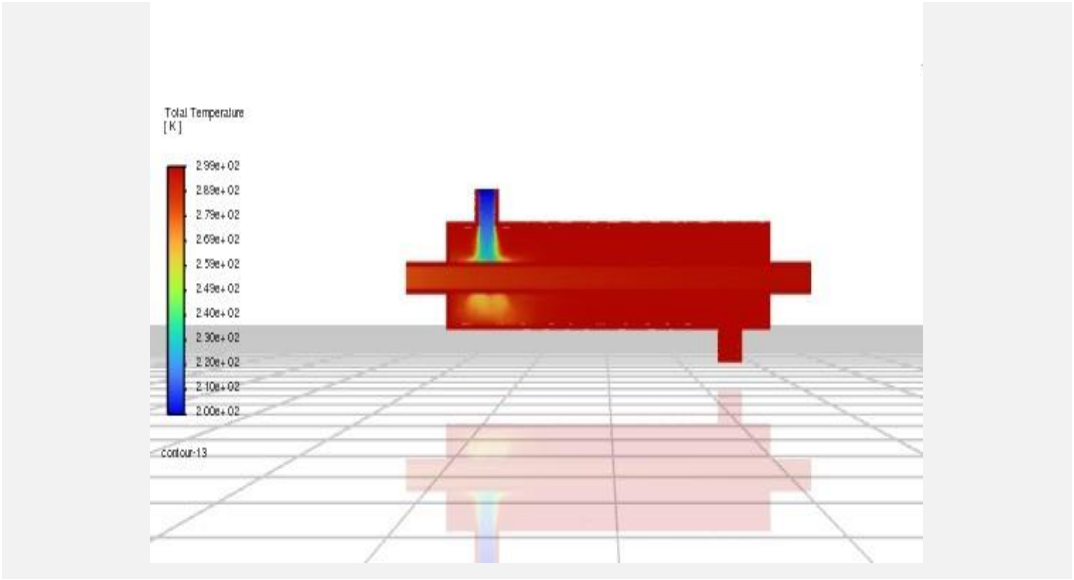


Fig. 4 temperature contour.

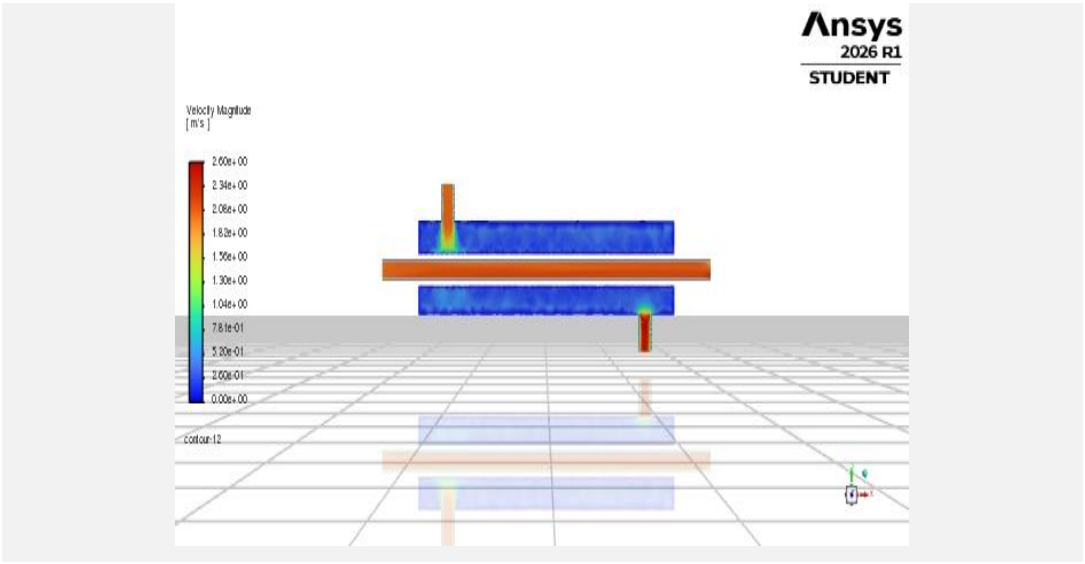


Fig. 5. velocity contour.

VI. RESULTS AND DISCUSSION

The three-dimensional conjugate heat transfer simulation of the graphite-filled PEEK heat exchanger was systematically evaluated in ANSYS Fluent to resolve the coupled fluid dynamics and thermal energy transport within the system. Thermophysical properties for the working fluid (liquid water) and the solid domain (PEEK-graphite composite wall) were assigned according to the verified solver setup parameters (Table I).

A Design and Dimensional Analysis:

The shell-and-tube heat exchanger was designed directly in ANSYS by considering the required geometrical dimensions and thermal analysis requirements. The design consists of an inner tube surrounded by an outer shell, with separate fluid regions for the circulation of hot and cold fluids. The tube wall was assigned the selected graphite-filled PEEK composite material to investigate its thermal behaviour during the heat transfer process.

The shell and tube arrangement was developed to provide thermal interaction between the two fluid regions through the separating tube wall. The inner tube was designed with a length of 200 mm and a diameter of 20 mm, while the outer shell was designed with a length of 100 mm and a diameter of 60 mm. Both shell and tube regions were considered with a wall thickness of 5 mm. Separate inlet and outlet sections were also incorporated into the geometry to provide suitable flow passages for the fluids.

The shell inlet and outlet sections were designed with a length of 50 mm and a diameter of 23 mm. The complete geometry was divided into different regions, including the tube fluid domain, shell fluid domain, tube wall region and shell wall region. This separation was necessary to assign appropriate material properties and boundary conditions during the numerical analysis.

The final design provided a compact shell-and-tube configuration suitable for studying the thermal behaviour of the selected polymer-based composite material. The developed geometry was further used for meshing, material assignment and thermal analysis in ANSYS Fluent.

B Thermal Analysis:

The thermal analysis of the designed heat exchanger was carried out using ANSYS Fluent to investigate the temperature distribution and heat transfer behaviour of the graphite-filled polymer-based tube. The analysis was performed by considering hot and cold fluid regions separated by the tube wall. Water was selected as the working fluid, and suitable inlet temperature conditions were applied to study the thermal interaction between the fluid regions and the composite tube material.

The hot fluid inlet temperature was maintained at 299 K, whereas the cold fluid inlet temperature was maintained at 200 K. The temperature difference between the two inlet streams provides the driving force for heat transfer through the tube wall. The energy equation was considered during the simulation to evaluate the temperature variation within the fluid and solid regions.

The temperature contour obtained from ANSYS. The contour represents the temperature distribution throughout the developed heat exchanger geometry using different colour ranges. Red indicates the higher temperature region, while blue represents the lower temperature region. The intermediate colours, such as orange, yellow and cyan, indicate variations in temperature between the hot and cold regions. The temperature distribution varies across the fluid and tube wall regions. The red colour is predominantly visible in the higher-temperature region, while the blue and cyan colours appear near the lower-temperature fluid inlet region. This variation indicates the thermal interaction between the hot fluid, the composite tube wall and the surrounding cold fluid.

The temperature contour provides an understanding of the thermal behaviour of the designed heat exchanger under the applied boundary conditions. It also helps identify the regions where temperature variations occur during the heat transfer process. The numerical results provide an initial assessment of the proposed graphite-filled PEEK tube and can be used as a reference for further experimental investigation.

Parameters	**Temperature (K)**	**Temperature (°C)**
Hot fluid inlet	299	25.85
Hot fluid outlet	≈275	≈68.85
Cold fluid inlet	200	-73.15
Cold fluid outlet	≈290	≈16.85

Thermal Profile and Comprehensive Temperature Distribution

The solver setup imposed an inlet total temperature of 299 K(25.85˚C) for the hot fluid stream and 200 K(−73.15˚C) for the cold fluid stream, establishing an overall primary temperature difference of $\Delta T = 99$ K. As illustrated in the total temperature contours (Fig. 4), maximum thermal energy (299 K) remains concentrated at the hot stream inlet port, while the cold stream enters at 200 K. Smooth, continuous thermal gradients develop across the 1.5 mmthick composite tube wall, indicating uniform conjugate heat transfer between the inner core fluid passage and the surrounding outer shell stream.

To evaluate the heat transfer enhancement provided by the conductive filler, the conductive thermal resistance (R_{cond}) per unit length ($L = 0.45$ m) of the composite tube wall (with nominal outer diameter $D_o = 24$ mmand inner diameter $D_i = 21$ mm) was evaluated as follows:

$$R_{\text{cond}} = \frac{\ln(D_o/D_i)}{2\pi k_w L} = \frac{\ln(24/21)}{2\pi \times 45.17 \times 0.45} = \frac{0.13353}{127.71} = 1.045 \times 10^{-3}\ \text{K/W}$$

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Where $k_w = 45.17$ W/(m · K)represents the effective thermal conductivity of the PEEK-graphite composite.

For baseline comparison, neat (unfilled) PEEK typically possesses a low thermal conductivity of $k_{\text{neat}} \approx 0.25$ W/(m · K), which yields a conductive wall resistance of:

$$R_{\text{neat}} = \frac{\ln(24/21)}{2\pi \times 0.25 \times 0.45} = 0.1889\ \text{K/W}$$

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Comparing these two values reveals that incorporating graphite filler reduces the conductive resistance of the polymer wall by **99.45%**:

$$\text{Resistance Reduction (\%)} = \left(1 - \frac{1.045 \times 10^{-3}}{0.1889}\right) \times 100\% = 99.45\%$$

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This order-of-magnitude reduction in thermal resistance demonstrates that conductive filler network synthesis successfully converts an otherwise thermally insulating thermoplastic matrix into an effective heat-transfer interface.

VII. FUTURE WORK

The present work is a numerical design study and should be interpreted within the assumptions of the geometry, material model, boundary conditions, and solver setup. The exact composition and thermophysical properties of the supplied composite must be verified. If the material conductivity is based on a generic value rather than the actual grade, uncertainty in predicted wall temperatures and heat-transfer rate should be acknowledged. Manufacturing tolerances, surface finish, contact conditions, and possible anisotropy may also affect performance.

Future work should include (i) confirmation of the material certificate and temperature-dependent properties, (ii) a mesh-independence study, (iii) comparison with a second operating condition or validated reference case, (iv) experimental measurement of inlet/outlet temperatures and flow rate using the prototype, and (v) uncertainty analysis. Any proposed aircraft-engine use would additionally require evaluation of temperature limits, pressure integrity, vibration, fatigue, fire/smoke/toxicity requirements where applicable, and relevant aerospace qualification standards.

VIII. CONCLUSION

A modelling workflow for a graphite-filled PEEK-based polymer tube intended for heat-exchanger use has been presented. The study brings together three-dimensional geometry development, definition of fluid and solid regions, material assignment, mesh generation, and thermal-flow analysis in ANSYS Fluent. The approach provides a basis for examining the tube's predicted temperature and velocity fields and for planning prototype validation. Final conclusions about thermal performance must be drawn from verified solver outputs and the exact composite properties, not from qualitative contour appearance alone. Experimental testing is required before the design can be considered validated or suitable for a particular aerospace operating environment.

This project focused on the design and thermal analysis of a graphite filled polymer based heat exchanger using ANSYS. The heat exchanger geometry was successfully created and analyzed under specified thermal boundary conditions to study the heat transfer characteristics and thermal behavior of graphite filled PEEK composite material.

The thermal analysis results obtained from temperature contours, streamline plots, and temperature vector analysis indicated effective heat transfer between the hot and cold fluid regions. The graphite filled PEEK material showed improved thermal conductivity compared to conventional polymer materials, resulting in satisfactory thermal performance of the heat exchanger. The streamline analysis confirmed smooth fluid flow and stable thermal interaction within the shell and tube regions. The temperature distribution results demonstrated proper heat transfer through the graphite filled polymer walls under the applied operating temperatures of 90°C and 15°C. The study also highlighted the advantages of graphite filled polymer composites such as lightweight structure, corrosion resistance, reduced maintenance, and good thermal stability. These properties make graphite filled PEEK composites suitable alternatives to conventional metallic heat exchangers for industrial and engineering applications. From the obtained results, it can be concluded that graphite filled polymer based heat exchangers provide effective thermal performance and can be considered promising materials for future lightweight and corrosion resistant heat transfer systems.

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