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Thermo-hydraulic Performance of Annular-Finned Double-Pipe Heat Exchanger: Numerical and Experimental Investigation of Metallic and Polymer Composite Tube Wall Materials

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Abstract

Double-pipe heat exchangers are central to the process industries — dependable, easily maintained, and straightforward to fabricate. Their conventional form relies on metallic tube materials, most often copper or stainless steel. Both metals conduct heat well, but they are dense, prone to corrosion in aggressive service environments, and increasingly at odds with the light-weighting goals that drive modern system design. Fibre-reinforced polymer composites, epoxy-based materials, and thermally enhanced thermoplastics such as GNP-filled PTFE and boron-nitride-loaded PEEK are attracting serious interest as tube-wall candidates — provided their lower thermal conductivity can be compensated geometrically. This study investigates that trade-off directly. A double-pass double-pipe heat exchanger fitted with annular fins on the inner tube outer surface was examined experimentally and through validated three-dimensional CFD in ANSYS Fluent 2025R1, using the realizable k–ε turbulence model with conjugate heat transfer. Cold water at 25°C passed through the inner tube; hot water at 50°C through the annular region, with equal flow rates on both sides. Against a plain-tube baseline, the finned configuration improved heat transfer rates by 25–30% and raised effectiveness consistently across flow rates from 1 to 15 LPM.Building on that validated model, inner-tube wall conductivity was varied parametrically from 0.2 W/m·K (neat polymer) to 20 W/m·K (near-metallic composite). Annular fins proved effective at compensating for reduced wall conductivity: a composite tube at k = 5 W/m·K achieves thermal performance within 8–12% of the metallic baseline, while offering 40–60% weight reduction and inherent corrosion immunity. Pressure drop remained governed by flow rate and fin geometry rather than wall material, changing negligibly across the full conductivity range. These findings define a practical material selection window for lightweight, corrosion-resistant polymer composite tube application in compact double-pipe exchangers.

Keywords: CFD simulation, double-pipe heat exchanger, annular fins, polymer composite tube, thermal conductivity parametric study, thermo-hydraulic performance, lightweight heat exchanger, sustainable thermal design

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INTRODUCTION

Heat exchangers remain among the most widely used thermal systems in industries such as power generation, chemical processing, refrigeration, automotive engineering, food processing, and HVAC applications because of their ability to transfer heat efficiently between fluids while maintaining compact system size and operational reliability. Among the various configurations available, the double-pipe heat exchanger continues to attract attention due to its simple construction, ease of maintenance, low manufacturing cost, and suitability for moderate heat-duty applications. Although the thermal design of conventional metallic heat exchangers has been extensively optimized over the years, current industrial trends toward lightweight systems, corrosion resistance, energy efficiency, and sustainable manufacturing have encouraged researchers to explore alternative materials and enhanced surface geometries for improved thermo-hydraulic performance.

Several studies have demonstrated that passive heat transfer enhancement techniques can significantly improve the performance of double-pipe and shell-and-tube heat exchangers. Pachegaonkar et al. [1], Nawale et al. [2], and Dhumal et al. [3] reported that twisted tape inserts improve turbulence intensity and thermal boundary layer disruption, thereby enhancing convective heat transfer. El Maakoula et al. [4] investigated helical baffles and observed improved thermal performance due to stronger secondary flow development inside the exchanger. Similarly, Bhuiyan and Islam [5] studied wavy fin geometries and reported considerable enhancement in heat transfer area and fluid mixing. Hameed et al. [6] and Bhola et al. [7] demonstrated that annular fins can substantially improve thermal effectiveness by increasing the available heat transfer surface while maintaining relatively simple fabrication requirements. Recent studies have also explored hybrid enhancement methods combining geometric modification with advanced working fluids. Assaf et al. [8] experimentally demonstrated that the combined use of ring inserts and twisted tapes produced significant improvement in heat transfer performance compared with conventional enhancement methods. Hasan et al. [9] further showed that integrating nanofluids with finned exchanger configurations enhances convective transport and overall thermal efficiency. These investigations confirm that surface enhancement techniques continue to play an important role in improving exchanger performance, particularly under compact design requirements.

Despite these advancements, the majority of existing investigations assume metallic tube-wall materials such as copper, stainless steel, or aluminum, where wall conduction resistance is comparatively negligible due to high thermal conductivity. However, this assumption becomes invalid when polymeric or composite tube materials are introduced. Conventional thermoplastics such as PTFE, HDPE, and PVC possess thermal conductivity values typically between 0.2 and 0.5 W/m·K, which are significantly lower than those of metallic materials. Consequently, conduction resistance through the tube wall becomes a dominant factor affecting exchanger performance. Xu et al. [10] and Chen et al. [11] reported that thermally conductive polymer composites reinforced with graphite nanoplatelets, graphene, boron nitride, or carbon fibers can increase thermal conductivity substantially while retaining advantages such as low density, corrosion resistance, and manufacturing flexibility. The growing interest in polymer composite heat exchangers is largely driven by industrial demand for lightweight and corrosion-resistant thermal systems. Tükenmez and Yalçın [12] observed that polymer-based exchangers are particularly attractive for marine, desalination, and chemical processing applications because they eliminate corrosion-related degradation commonly encountered in metallic systems. Khoshvaght-Aliabadi et al. [13] further highlighted the potential of composite materials in low-temperature heat recovery and compact HVAC systems. Studies by Burger et al. [14], Liu et al. [15], and Wang et al. [16] demonstrated that boron nitride and graphite-based fillers can improve polymer thermal conductivity by several times depending on filler loading, orientation, and dispersion quality. These studies collectively indicate that thermally enhanced polymer composites may provide a realistic alternative to metals for selected heat exchanger applications.

Although research on polymer composite thermal systems is increasing, significant gaps remain in understanding the interaction between exchanger geometry and composite wall conductivity. Most available investigations are limited to simplified one-dimensional models, flat-plate exchangers, or shell-and-tube configurations without detailed analysis of fin-induced flow behavior. Zaheed and Jachuck [17] investigated polymer heat exchangers experimentally, but their work did not address three-dimensional fin–fluid interactions or parametric conductivity variation. Mehendale [18] discussed compact exchanger enhancement strategies; however, systematic CFD-based studies involving annular-finned double-pipe exchangers with polymer composite tube walls remain limited in the open literature. Previous investigations on fin-enhanced double-pipe heat exchangers have consistently demonstrated that surface modification plays a significant role in improving thermo-hydraulic performance. Rao and Levy [19] developed a semi-empirical methodology for predicting the performance of finned double-pipe heat exchangers and highlighted the importance of fin geometry in enhancing convective heat transfer. Experimental work by Shewale et al. [20] further confirmed that helical fins substantially improve thermal effectiveness by promoting secondary flow formation and increasing turbulence intensity within the flow domain. Similarly, Ameen and Mahmood [21] carried out both numerical and experimental investigations on externally finned double-pipe heat exchangers and reported noticeable enhancement in heat transfer characteristics compared with plain tube configurations. Hussein [22] investigated the use of semi-circular disc baffles and observed that flow disturbance mechanisms significantly improve heat transfer, although accompanied by an increase in pressure drop. Narayanan et al. [23] examined helical fluid motion in a double-start screw-type heat exchanger through modeling and simulation, demonstrating that induced swirl flow improves thermal transport due to stronger fluid mixing. Kundu et al. [24] focused on beneficial design methodologies for shell-and-tube heat exchangers and emphasized the need for optimized geometrical configurations to achieve better thermal performance with acceptable hydraulic losses. Patil et al. [25] experimentally studied heat transfer enhancement liners in double-pipe heat exchangers and reported improved heat transfer coefficients owing to intensified flow interaction near the tube walls. In addition, Debtera, Neme, and Prabhu [26] performed CFD simulations of double-pipe heat exchangers and demonstrated the effectiveness of numerical methods in accurately predicting temperature distribution, pressure variation, and overall exchanger performance. Collectively, these studies establish that fins, inserts, baffles, and flow-modifying geometries can effectively enhance heat transfer; however, most of the existing investigations remain limited to conventional metallic tube materials. The influence of thermally conductive polymer composite tube walls, particularly in conjunction with annular fin geometries, remains comparatively unexplored and forms the primary motivation for the present investigation.

Recent investigations on compact and enhanced heat exchanger systems have increasingly combined experimental techniques with CFD analysis to better understand thermo-hydraulic behavior and optimize thermal system performance. Gadave and Kothmire [27] evaluated the thermo-hydraulic characteristics of shell-and-tube heat exchangers and demonstrated that exchanger geometry plays a critical role in determining heat transfer enhancement and pressure loss behavior. Extending the importance of material selection in thermal systems, Deshmukh, Shinde, and Kothmire [28] experimentally investigated heat transfer in composite vessels and highlighted the growing relevance of advanced materials in modern thermal engineering applications. Londhe et al. [29] examined the influence of economiser tube geometry on water heating performance and reported that geometric modifications significantly affect thermal efficiency and flow development. Similarly, Nagarhalli et al. [30] investigated natural and forced convective heat transfer from finned spheres and demonstrated that fin-assisted surfaces substantially improve convective heat transfer rates due to enhanced surface area and flow interaction. Several researchers have also employed CFD techniques to optimize thermal environments and fluid flow systems across different engineering applications. Tajane et al. [31] performed combined experimental and numerical investigations on radiative heat transfer for room cooling applications and confirmed the effectiveness of CFD in predicting thermal distribution patterns. Damdhar et al. [32] analyzed exhaust gas flow through mufflers using CFD and demonstrated the importance of flow path optimization for reducing pressure losses and improving flow uniformity. Narad et al. [33] conducted a numerical investigation on the positioning of air conditioning systems and showed how airflow distribution strongly influences cooling effectiveness within enclosed spaces. Pawar et al. [34] applied CFD techniques to greenhouse design optimization and reported improved thermal management through controlled airflow behavior. Powar et al. [35] investigated the effect of surface roughness on boundary layer development and established that wall surface characteristics can significantly alter near-wall heat transfer mechanisms. Likewise, Shindge et al. [36] studied catalytic converter flow behavior through CFD analysis and highlighted the role of internal geometry in governing pressure drop and thermal performance. Yadav and Kothmire [37] further demonstrated the capability of CFD tools in analyzing exhaust pipe flow behavior in diesel engines, emphasizing the importance of numerical methods in predicting complex thermo-fluid phenomena.

Recent developments in epoxy-based polymer composite thermal systems indicate that simultaneous advances in material engineering and heat exchanger geometry can substantially improve thermo-fluid performance while addressing limitations associated with conventional metallic systems. Lightweight construction, corrosion resistance, and tunable thermal conductivity have positioned polymer composites as promising candidates for next-generation compact thermal management applications. Recent investigations further demonstrate that combining thermally conductive polymer matrices with passive enhancement strategies can significantly improve heat transfer effectiveness without compromising structural advantages. Karlekar et al. [38] investigated annular-finned shell-and-tube heat exchangers fabricated using epoxy-based polymer composite materials and reported that the combined influence of conductive composite walls and fin-induced surface area enhancement substantially improved thermo-hydraulic performance while maintaining low structural weight. Similar observations were reported by Karkal et al. [39], who experimentally and numerically evaluated epoxy-based thermally conductive polymer composite U-tube shell-and-tube heat exchangers. Their findings demonstrated that carefully engineered polymer systems can approach metallic thermal performance while simultaneously providing advantages associated with corrosion resistance and reduced mass. Apart from material selection, geometric enhancement remains an equally important contributor to heat exchanger performance. Patil et al. [40] demonstrated that finned U-tube shell-and-tube configurations promoted stronger secondary flow development and localized turbulence generation, leading to enhanced thermal transport characteristics. Likewise, Patel et al. [41] observed that integrating thermally conductive polymer composites with finned helical coil geometries significantly improved thermal effectiveness due to intensified flow mixing and increased effective heat transfer area.

Surface modification strategies have also emerged as an effective pathway toward thermal enhancement in polymer-assisted thermal systems. Dhabade et al. [42] reported that corrugated shell-and-tube geometries incorporating epoxy-based polymer composite coatings enhanced convective transport behavior while simultaneously improving resistance to degradation mechanisms commonly encountered in metallic thermal systems. These findings suggest that combining material innovation with flow-path modification can provide synergistic thermo-fluid benefits. The application scope of polymer composite thermal systems extends beyond conventional heat exchangers. Dhanawade et al. [43] demonstrated improved thermal dissipation characteristics in metal–polymer composite heat exchangers developed for compact geyser systems, highlighting the growing relevance of polymer-assisted thermal management approaches in domestic energy applications. Hybrid polymer engineering concepts have also shown potential in broader multiphysics systems. Kapure et al. [44] optimized polymer–metal hybrid electrode configurations and reported enhanced electrostatic performance through improved field distribution behavior, whereas Mankar et al. [45] demonstrated thermo-electrical performance enhancement in lightweight polymer–metal hybrid systems through improved material integration strategies. The versatility of multifunctional polymer systems has further expanded toward sustainable engineering applications. Dixit et al. [46] investigated lignocellulosic–polymeric composite growth media for automated hydroponic systems and highlighted the broader potential of advanced polymer engineering toward environmentally sustainable thermal and process technologies. Collectively, these investigations demonstrate that integrating thermally conductive polymer composites with passive enhancement mechanisms such as annular fins, corrugated pathways, helical flow structures, and hybrid thermal architectures provides a viable route toward lightweight, corrosion-resistant, and energy-efficient thermal systems. These emerging developments establish a strong foundation for exploring polymer composite tube-wall integration in compact heat exchanger applications and motivate the present investigation on thermo-fluid characterization of corrugated U-tube shell-and-tube heat exchangers employing polymer composite materials.

The present work addresses this gap through a combined numerical and experimental investigation of an annular-finned double-pipe heat exchanger operating with both metallic and polymer composite tube-wall materials. A validated three-dimensional CFD model developed in ANSYS Fluent is coupled with experimental measurements to evaluate heat transfer rate, pressure drop, and thermo-hydraulic effectiveness over a flow-rate range of 1–15 LPM. Unlike earlier studies that treat tube-wall conductivity as a fixed property, the present investigation performs a systematic parametric analysis by varying wall thermal conductivity from 0.2 W/m·K to 20 W/m·K, thereby representing neat polymers, thermally enhanced composites, and near-metallic conductive systems. The novelty of the present research lies in the integrated evaluation of annular-fin enhancement and polymer composite wall conductivity within a validated conjugate heat transfer framework. The study not only investigates the thermal performance of annular-finned geometry experimentally and numerically but also establishes a practical conductivity-performance relationship for lightweight composite tube materials. The work further demonstrates how annular fins can compensate for reduced wall conductivity, enabling polymer composite tubes to approach the thermal performance of metallic systems while offering substantial reductions in weight and corrosion susceptibility. This combined geometric–material approach provides new design insight for next-generation compact heat exchangers intended for sustainable and corrosion-resistant thermal applications.

METHODOLOGY

The present investigation adopts an integrated computational and experimental framework to evaluate the thermo-hydraulic performance of an annular-finned double-pass double-pipe heat exchanger operating with both metallic and polymer composite tube-wall materials. The methodology was intentionally structured so that the numerical model forms the primary analytical platform, while the experimental system serves as a validation benchmark for the CFD predictions. This approach enables detailed visualization of the flow field, thermal boundary-layer development, and conjugate heat transfer mechanisms that are difficult to access experimentally, while simultaneously ensuring that the numerical predictions remain physically reliable. Particular emphasis is placed on understanding how tube-wall thermal conductivity influences overall heat exchanger effectiveness when annular fins are employed to compensate for the inherently low conductivity of polymer-based materials.

GEOMETRY AND COMPUTATIONAL DOMAIN

The three-dimensional geometry of the annular-finned double-pipe heat exchanger was developed using CAD software and subsequently imported into ANSYS Fluent for numerical analysis. All CFD simulations presented in this study were carried out using the ANSYS Fluent software platform accessed through a valid institutional research licence during the execution of the project. The heat exchanger consists of two concentric tubes arranged in a double-pass counter-flow configuration. The inner tube, carrying the cold fluid, possesses an inner diameter of 18 mm and an outer diameter of 20 mm, while the outer shell has an inner diameter of 48 mm and an outer diameter of 50 mm. The total length of the hot-side tube is 600 mm and the shell-side flow passage extends over 500 mm. Uniformly spaced annular fins are mounted on the outer surface of the inner tube in order to increase the effective heat transfer area and disturb the thermal boundary layer within the annular flow region. Each fin has an outer diameter of 32 mm with a uniform axial pitch of 16.504 mm. The geometric configuration was selected to provide a balance between compactness, manufacturability, and enhanced heat transfer capability while maintaining moderate pressure losses. Figure 1 illustrates the computational geometry of the complete heat exchanger assembly, including the shell domain, tube-side passage, and annular fins. The computational domain included both fluid and solid regions to enable full conjugate heat transfer analysis. Separate domains were created for the tube-side fluid, shell-side fluid, inner tube wall, fins, and outer shell wall. This configuration allowed simultaneous prediction of fluid convection and heat conduction through the solid walls, which becomes particularly important when metallic materials are replaced by thermally conductive polymer composites. The geometric specifications of the heat exchanger components are presented in Table 1.

CFD FORMULATION AND NUMERICAL SOLUTION STRATEGY

The numerical simulations were carried out using the finite volume method (FVM), which is widely employed for heat exchanger simulations due to its strong conservation characteristics and suitability for complex three-dimensional geometries. The governing equations for conservation of mass, momentum, and energy were discretized over the computational domain and solved iteratively under steady-state conditions. Pressure–velocity coupling was handled using the SIMPLE algorithm, while second-order upwind discretization schemes were adopted for momentum, turbulence, and energy equations to improve numerical accuracy and minimize discretization error. The flow inside the annular-finned heat exchanger is characterized by recirculation, curvature-induced secondary motion, and localized turbulence generation near the fins. To capture these effects accurately, the realizable k–ε turbulence model with enhanced wall treatment was employed. Compared with the standard k–ε formulation, the realizable variant provides improved prediction of rotational flow structures, streamline curvature effects, and near-wall turbulence transport, making it more suitable for compact heat exchanger applications involving interrupted surfaces and annular fin geometries. Convergence was considered achieved when residuals for continuity, momentum, and turbulence quantities fell below 10^{-4}, while the energy residual was reduced below 10^{-7} to ensure thermal convergence. Water was selected as the working fluid for both shell-side and tube-side flow passages. Temperature-dependent thermo-physical properties of water were incorporated into the solver to improve physical realism over the investigated operating range. Radiation heat transfer was neglected because the operating temperatures remained sufficiently low for radiative effects to be insignificant compared with convective and conductive heat transfer mechanisms.

Table 1. Geometric specifications of the heat exchanger components.

Part	Dimension
Hot pipe (inner tube)	Inner Diameter = 18 mm; Outer Diameter = 20 mm
Cold pipe (outer tube)	Inner Diameter = 48 mm; Outer Diameter = 50 mm
Cold pipe inlet/outlet connections	Inner Diameter = 10 mm; Outer Diameter = 12 mm
Hot pipe length	600 mm
Cold pipe length	500 mm
Fin outer diameter	32 mm
Fin pitch	16.504 mm

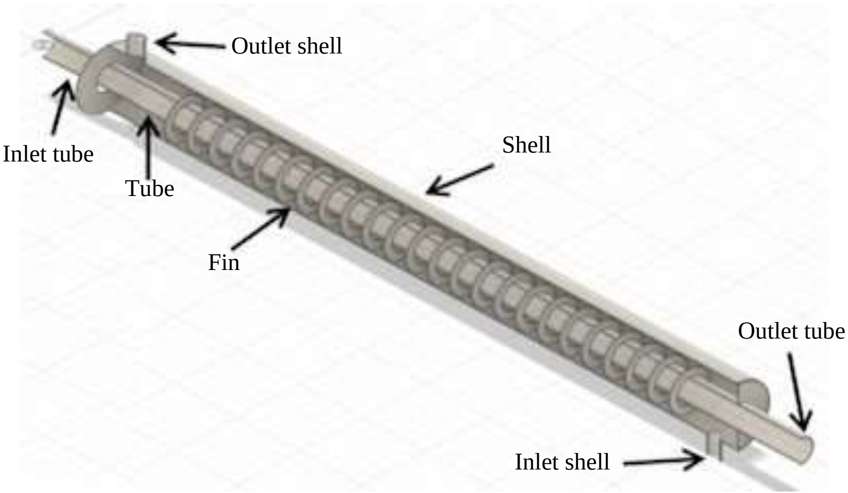

Figure 1. CAD model of the annular finned double pipe heat exchanger.

ADVANCED POLYMER COMPOSITE MATERIAL MODELLING

A major objective of the present work is to evaluate the feasibility of replacing conventional metallic tube-wall materials with lightweight thermally conductive polymer composites. Unlike metallic materials, polymer composites exhibit highly nonlinear thermal transport behavior governed by filler loading, filler orientation, interfacial resistance, and conductive network formation. Consequently, the thermal conductivity of the composite cannot be represented adequately using a simple constant-property assumption. To address this limitation, the present study incorporates a multi-regime thermal conductivity framework that combines effective medium theory, percolation behavior, and interfacial thermal resistance effects.

At low filler concentrations, conductivity follows a modified effective medium approximation:

$$k_{eff}=k_m\left(\frac{k_f+2k_m+2\emptyset\left(k_f-k_m\right)}{k_f+2k_m-\emptyset\left(k_f-k_m\right)}\right)$$

where k_{eff} represents the thermal conductivity of the epoxy matrix, $k_m$corresponds to the conductivity of the filler, and k_f is the filler volume fraction.

At higher filler loadings, where conductive pathways begin to form, a percolation-based relation is employed:

$k_{eff} \propto (\phi - \phi c)^t$ for $\phi > \phi c$

where ϕcis the percolation threshold and t is an empirical exponent dependent on filler geometry and distribution.

To further improve physical realism, interfacial thermal resistance, commonly referred to as Kapitza resistance, was incorporated into the conductivity model. This effect becomes especially important for nano-scale fillers such as graphite nanoplatelets (GNPs) and boron nitride (BN) platelets, where phonon scattering at matrix–filler interfaces significantly influences overall heat conduction. The model therefore accounts not only for filler conductivity but also for interface-dominated transport mechanisms that govern practical composite performance.

The present simulations considered effective thermal conductivity values ranging from 0.2 W/m·K to 20 W/m·K. This range spans neat polymer systems, partially filled composites, and highly conductive percolated composite networks reported in recent literature for BN- and GNP-filled epoxy systems. The density and specific heat capacity of the polymer composite were assigned representative values of 1400 kg/m³ and 1100 J/kg·K, respectively. Unlike previous simplified approaches, the present methodology therefore captures the inherent anisotropic and network-dependent thermal behavior of advanced polymer composites in a physically meaningful manner.

The present study assumes isotropic effective thermal conductivity for polymer composite domains despite the known anisotropic transport behaviour observed in highly aligned graphene nanoplatelet and boron nitride filler systems. This assumption reflects practical manufacturing conditions where extrusion, compression moulding, or injection moulding frequently produce partially random filler orientation rather than fully directional conductive pathways. Under these conditions, experimentally reported conductivity values generally represent effective bulk conductivity rather than tensorial conductivity components. Although preferential filler alignment could improve radial heat spreading and locally modify fin efficiency, the present investigation focuses on system-level thermo-hydraulic sensitivity to achievable effective conductivity ranges representative of commercially manufacturable composite systems.

The present conjugate heat transfer framework assumes ideal thermal contact between polymer composite tube walls and annular fin structures to isolate conductivity-driven thermo-fluid interactions.

In practical manufacturing environments, interfacial resistance, imperfect bonding quality, residual stress development, and differential thermal expansion may influence local thermal transport pathways. These effects are expected to become increasingly important under cyclic thermal loading conditions encountered in marine, HVAC, and corrosive industrial service environments. Consequently, the present predictions represent an upper-bound thermo-hydraulic performance estimate under ideal composite integration conditions, while future work may incorporate thermo-mechanical degradation and interface resistance models for long-term durability assessment.

MESH GENERATION AND GRID INDEPENDENCE ANALYSIS

The computational mesh was generated in ANSYS Meshing using an unstructured tetrahedral discretization scheme as shown in the Figure 2. Local mesh refinement was applied in regions characterized by steep thermal and hydrodynamic gradients, particularly near fin surfaces, wall boundaries, and flow recirculation zones within the annular passage. Inflation layers were introduced at all solid–fluid interfaces to accurately resolve the near-wall viscous sublayer and thermal boundary layer.

A systematic grid independence study was performed to eliminate mesh-related numerical uncertainty. Three mesh densities were examined, consisting of approximately 180,000 elements (coarse mesh), 430,000 elements (medium mesh), and 860,000 elements (fine mesh). Key output parameters including outlet temperature, pressure drop, and Nusselt number were monitored for convergence.

The medium mesh demonstrated less than 1.5% deviation from the fine mesh predictions while significantly reducing computational cost. Consequently, the medium grid was adopted for all subsequent simulations. The grid convergence behavior confirmed that the numerical predictions were independent of mesh density and therefore suitable for thermo-hydraulic performance analysis. Variation of Nusselt number with increasing mesh density demonstrating convergence of the numerical solution as shown in the Figure 3. Mesh details are presented in Table 2.

Table 2. Mesh details.

Parameter	Specification
Element Type	Tetrahedral
Element Size	3.0 mm

Figure 2. Computational mesh of the geometry.

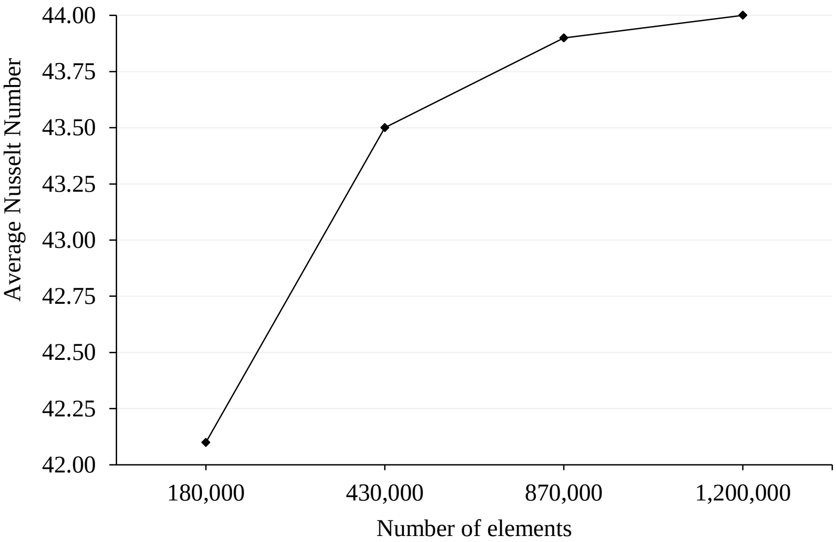

Figure 3. Mesh independence test.

BOUNDARY CONDITIONS AND CONJUGATE HEAT TRANSFER SETUP

Boundary conditions were defined to reproduce realistic operating conditions while maintaining consistency with the experimental validation setup. Mass-flow inlet boundary conditions were applied at both the shell-side and tube-side entrances, while pressure outlet conditions were imposed at both exits. The shell-side inlet temperature was maintained at 50°C, whereas the tube-side inlet temperature was fixed at 25°C. Simulations were performed over a flow-rate range of 1–15 LPM for both fluid streams in order to investigate the influence of Reynolds number on thermal and hydraulic performance. No-slip velocity conditions were applied at all solid–fluid interfaces. The external surface of the outer shell was treated as adiabatic to minimize environmental heat losses and isolate internal heat transfer behavior. Conjugate heat transfer was activated across all interfaces so that conduction through the tube wall and fins could interact directly with convective heat transfer in the fluid domains. For the baseline validation model, the inner tube and fins were assigned copper properties with a thermal conductivity of 401 W/m·K, density of 8978 kg/m³, and specific heat capacity of 381 J/kg·K, while the outer shell was modeled using stainless steel with a thermal conductivity of 16.3 W/m·K. Following validation, the metallic tube-wall properties were systematically replaced with polymer composite properties while maintaining identical flow and geometric conditions. This strategy enabled direct assessment of how reduced wall conductivity influences exchanger effectiveness when annular fins are present.

GOVERNING EQUATIONS

The numerical analysis was based on the steady-state conservation equations governing mass, momentum, and energy transport within the fluid and solid domains. The CFD simulations were performed under steady-state conditions by solving the conservation equations.

Continuity Equation:

$$\nabla \cdot (\rho_{v}) = 0 \tag{1}$$

Momentum Equation:

$$\nabla \cdot (\rho_{vv}) = -\nabla p + \nabla \cdot \tau \tag{2}$$

Energy Equation:

$$\nabla \cdot (\mathbf{v}(\rho E + p)) = \nabla \cdot (k_{\text{eff}} \nabla T) \tag{3}$$

where k_{eff} represents the effective thermal conductivity, which, in the present study, incorporates polymer composite behavior.

The flow inside the annular-finned double-pipe heat exchanger is inherently complex due to the interaction between the moving fluid streams and the repeated fin structures mounted on the tube surface. As the fluid passes through the annular region, the fins disturb the developing thermal boundary layer and generate localized recirculation zones, secondary vortices, and flow separation effects, particularly at higher Reynolds numbers. To capture these flow phenomena with sufficient numerical stability and computational efficiency, the realizable k–ε turbulence model was adopted in the present study. Compared with the standard k–ε formulation, the realizable model offers improved prediction of rotational flows, streamline curvature, and separated flow behavior, which are commonly encountered in compact finned heat exchangers.

In addition, the model provides better estimation of turbulent viscosity and energy dissipation under moderate-to-high turbulent flow conditions. Enhanced wall treatment was employed together with inflation layers near the solid boundaries to accurately resolve the near-wall velocity and thermal gradients. The turbulence model was selected after careful consideration of previous literature related to shell-and-tube and finned heat exchanger simulations, where the realizable k–ε model has consistently demonstrated reliable prediction of heat transfer and pressure-drop characteristics while maintaining reasonable computational cost. The governing transport equations for turbulent kinetic energy (k) and turbulent dissipation rate (ε) were solved simultaneously with the continuity, momentum, and energy equations throughout the computational domain.

The realizable k–ε turbulence closure with enhanced wall treatment was selected owing to its established balance between computational robustness and predictive capability for internal thermo-fluid systems involving streamline curvature, recirculation, and conjugate heat transfer. Inflation-layer meshing was employed to maintain y+ values below 5, improving thermal boundary layer resolution near annular fins where secondary flow structures develop. While higher-fidelity approaches such as SST k–ω or Reynolds Stress Models may further resolve turbulence anisotropy, the present work prioritizes comparative thermo-hydraulic assessment across multiple polymer conductivity conditions requiring large parametric CFD datasets. Agreement with experimental measurements within 4.5% for heat transfer and 6% for pressure drop supports the suitability of the selected turbulence closure for the intended engineering analysis.

EXPERIMENTAL VALIDATION

Experimental testing was conducted primarily to validate the numerical model under realistic operating conditions. A physical double-pipe heat exchanger was fabricated corresponding to the baseline metallic configuration used in the CFD simulations. The system was arranged to operate in both counter-flow and parallel-flow modes, as illustrated in Figure 4. Temperature measurements were obtained using calibrated Type-K thermocouples positioned at the shell-side and tube-side inlets and outlets. The thermocouples possessed an operating range of −200°C to +1250°C with post-calibration accuracy within ±0.1°C, ensuring reliable thermal measurements throughout the investigation. Volumetric flow rates were controlled and measured using rotameters with a capacity range of 0–10 L/min. Hot-side inlet temperatures were varied between 50°C and 80°C, while cold-side inlet temperatures ranged from 20°C to 30°C.

Prior to data acquisition, steady-state conditions were verified through stabilization of thermocouples readings over consecutive five-minute intervals. Multiple measurements were recorded for each operating condition and averaged to reduce experimental uncertainty. The experimentally measured outlet temperatures, heat transfer rates, and pressure drops were compared directly with CFD predictions obtained for the baseline metallic configuration. The close agreement observed between experimental and numerical results confirmed the validity of the CFD framework and justified its subsequent application to the polymer composite parametric study.

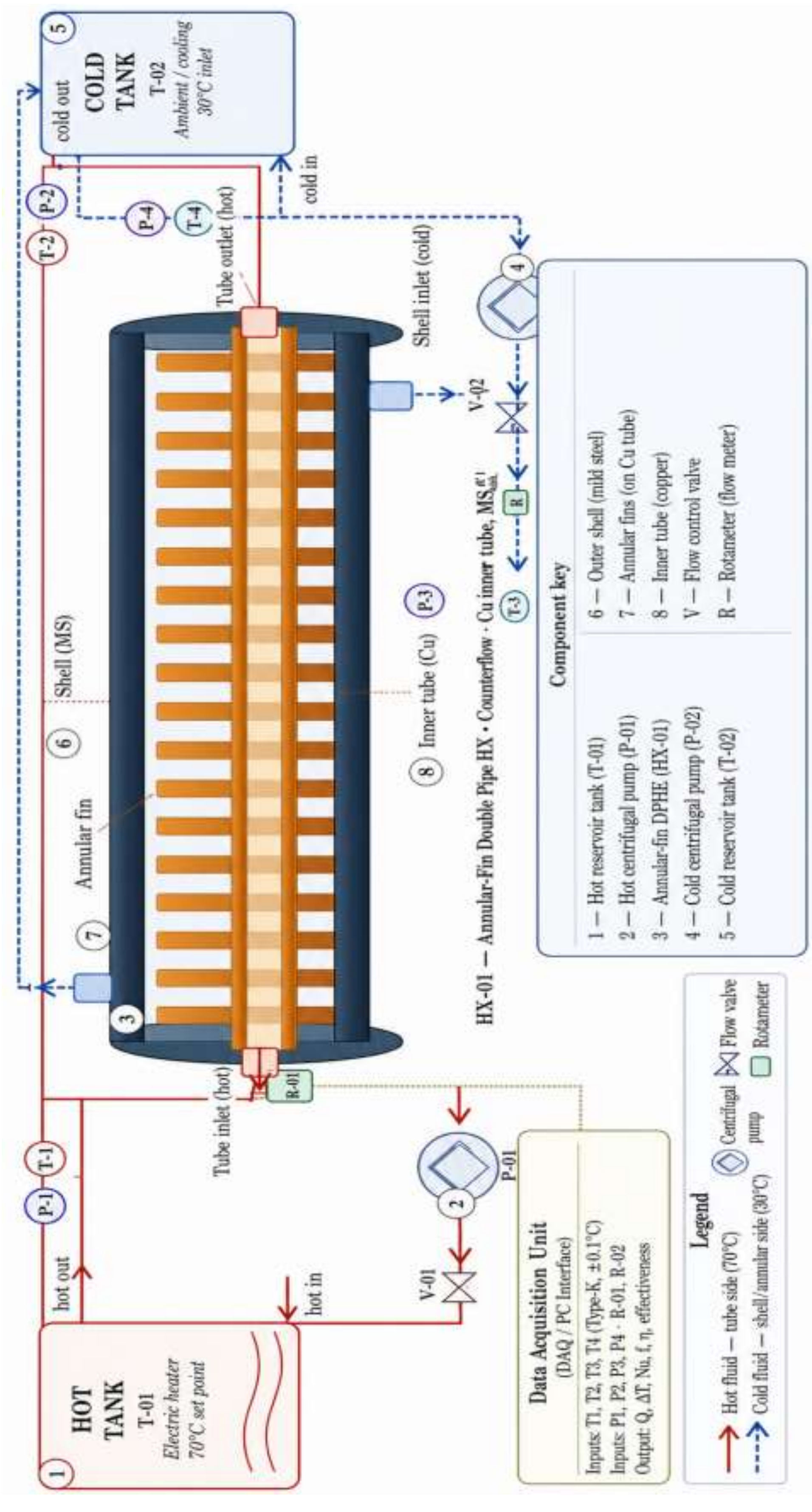

Figure 4. Schematic of experimental set up to test annular finned double pipe heat exchanger.

RESULTS AND DISCUSSION

Before conducting the polymer composite parametric investigation, the numerical model was first validated against experimentally measured data obtained from the fabricated double-pass double-pipe heat exchanger. The comparison included outlet temperatures, overall heat transfer rate, exchanger effectiveness, and pressure drop over the investigated flow range of 1–15 LPM for the plain-tube metallic configuration. The CFD predictions showed strong agreement with the experimental measurements, with deviations remaining within 4.5% for heat transfer rate and below 6% for pressure drop across all operating conditions.

Such agreement confirms that the governing equations, turbulence closure, conjugate heat transfer formulation, and boundary condition assumptions adequately capture the thermo-hydraulic behaviour of the exchanger. Minor discrepancies between numerical and experimental values are attributed primarily to unavoidable experimental uncertainties associated with thermocouples response, rotameters calibration, and small thermal losses to the surroundings that are difficult to represent perfectly in numerical simulations.

The validation results establish confidence in the predictive capability of the CFD framework and justify its use for advanced material studies involving polymer composite tube walls. More importantly, the validated model demonstrates that the realizable k–ε turbulence model combined with conjugate heat transfer can accurately reproduce the complex interaction between annular flow structures, thermal boundary layer development, and extended-surface heat transfer generated by annular fins. This agreement is particularly important because the subsequent polymer conductivity analysis relies entirely on the ability of the CFD model to resolve the coupling between wall conduction resistance and convective enhancement mechanisms.

THERMO-HYDRAULIC PERFORMANCE OF PLAIN AND ANNULAR-FINNED METALLIC TUBES

The CFD results clearly demonstrate that annular fins significantly improve the thermo-hydraulic performance of the double-pipe heat exchanger when compared with the plain-tube configuration. Figure 5 illustrates the variation of heat transfer rate with volumetric flow rate for both configurations. In both cases, heat transfer increases continuously as the flow rate rises from 1 to 15 LPM. This behaviour is expected because increasing flow rate raises the Reynolds number, intensifies turbulence, and reduces thermal boundary layer thickness, thereby enhancing convective heat transfer coefficients on both shell and tube sides. However, the annular-finned configuration consistently outperforms the plain tube throughout the entire operating range, exhibiting approximately 25–30% higher heat transfer rates. The improvement produced by the annular fins arises from two simultaneous mechanisms. First, the fins increase the effective heat transfer area available for thermal exchange between the hot and cold streams. Second, the annular geometry generates secondary vortical structures in the shell-side flow field. These vortices periodically disrupt the developing thermal boundary layer between adjacent fins, promoting stronger fluid mixing and continuously exposing the fluid to higher temperature gradients. The resulting enhancement becomes increasingly pronounced at higher flow rates where turbulent transport mechanisms dominate energy transfer.

Exchanger effectiveness follows the expected thermodynamic trend with increasing flow rate, as illustrated in Figure 6. Pressure drop characteristics are presented in Figure 7. The temperature distribution inside the exchanger further confirms the effectiveness of the finned geometry. Figure 8 shows the temperature contours for the plain and annular-finned configurations. The finned geometry produces a more uniform thermal field along the annular region, indicating improved radial heat diffusion into the surrounding fluid. In contrast, the plain-tube configuration exhibits larger temperature gradients concentrated near the tube wall, suggesting weaker thermal penetration into the annular stream. The enhanced spreading of thermal energy in the finned exchanger demonstrates that the fins actively participate in transferring heat into the shell-side fluid rather than functioning merely as passive surface extensions.

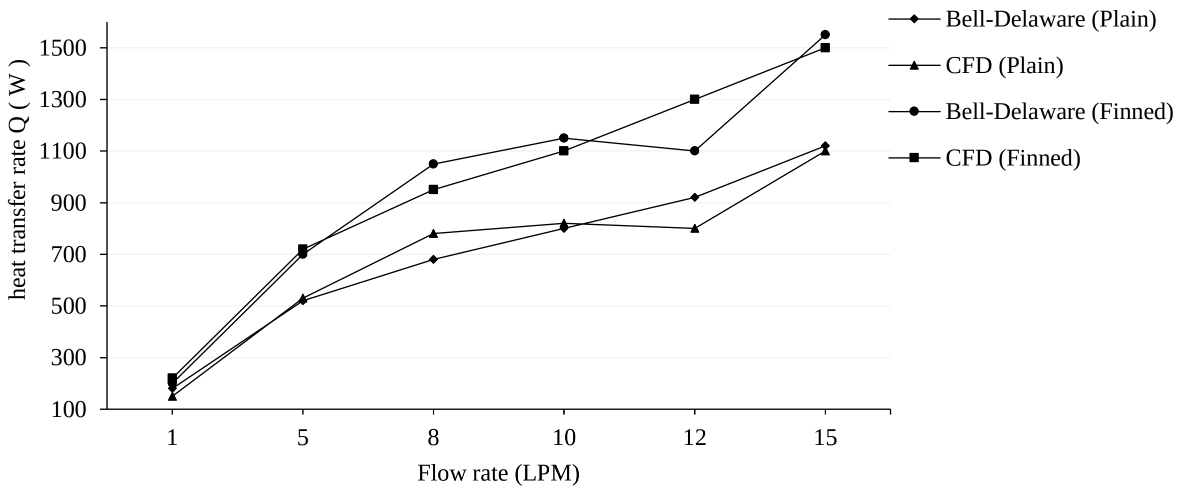

Figure 5. Comparison of heat transfer rate with flow rate for plain and finned tubes using bell–Delaware and CFD Methods.

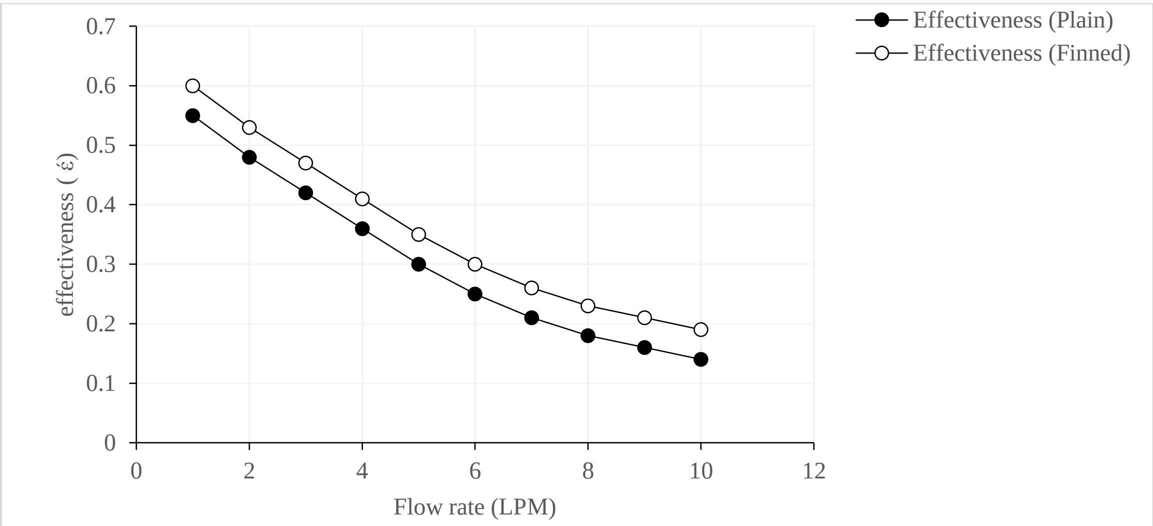

Figure 6. Pressure drop variation with flow rate for tube and annulus in plain and finned double-pass double-pipe heat exchanger.

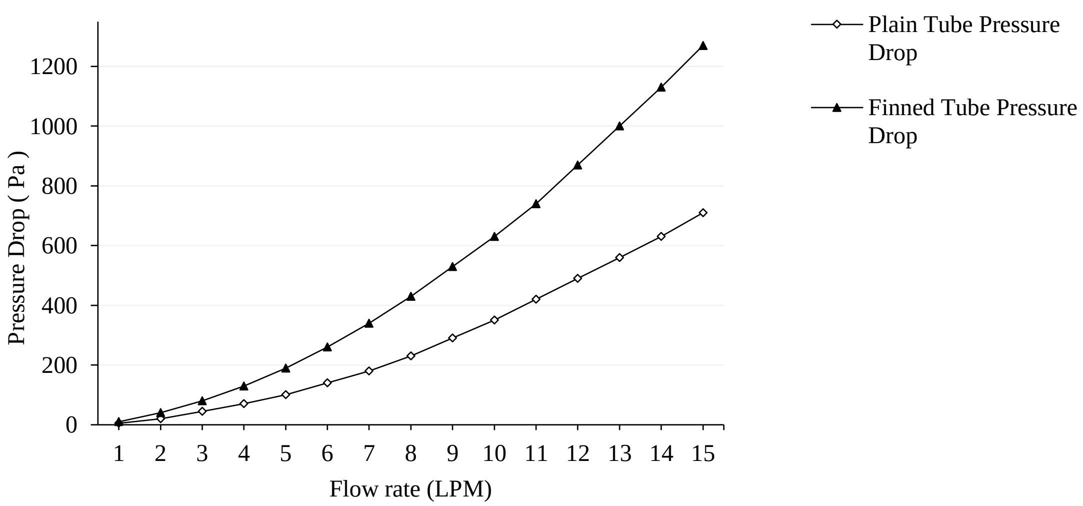

Figure 7. Pressure drop with respect to LPM for tube & annulus (plain and finned).

At lower flow rates, the residence time of the fluid inside the exchanger is longer, allowing greater energy exchange between the hot and cold streams. Consequently, effectiveness is highest at lower Reynolds numbers and gradually decreases as flow rate increases. Nevertheless, the annular-finned configuration consistently maintains higher effectiveness values than the plain tube across the entire operating range. The difference is especially significant at low-to-moderate flow rates, where the extended surface area has sufficient thermal interaction time to extract additional energy from the hot fluid.

A notable observation from the CFD analysis is the slight inflection in effectiveness around intermediate flow rates between approximately 7 and 9 LPM. This behaviour appears consistently in both metallic and polymer simulations, indicating that it originates from hydrodynamic flow restructuring rather than material properties. The phenomenon is associated with secondary recirculation development inside the inter-fin cavities, where local turbulence intensity increases sufficiently to alter the balance between convective enhancement and residence time effects. Such behaviour highlights the importance of three-dimensional flow analysis, which cannot be captured accurately using simplified one-dimensional exchanger models. As expected, pressure loss increases nonlinearly with increasing flow rate for both configurations because higher velocities intensify wall shear stresses and turbulent dissipation.

The annular-finned tube exhibits a substantially higher pressure drop than the plain tube due to the increased wetted perimeter and repeated obstruction of the shell-side flow path by the fins. At the highest investigated flow rate, the finned configuration experiences nearly twice the pressure penalty of the plain tube. This behaviour represents the classical thermo-hydraulic compromise associated with passive heat transfer enhancement techniques: improved thermal performance is inevitably accompanied by increased hydraulic resistance.

Despite this hydraulic penalty, the annular-finned exchanger demonstrates superior overall thermal performance because the gain in heat transfer significantly outweighs the additional pumping requirement. The CFD results therefore confirm that annular fins remain an effective passive enhancement strategy for compact exchanger applications where thermal performance is prioritised over minimal pressure loss.

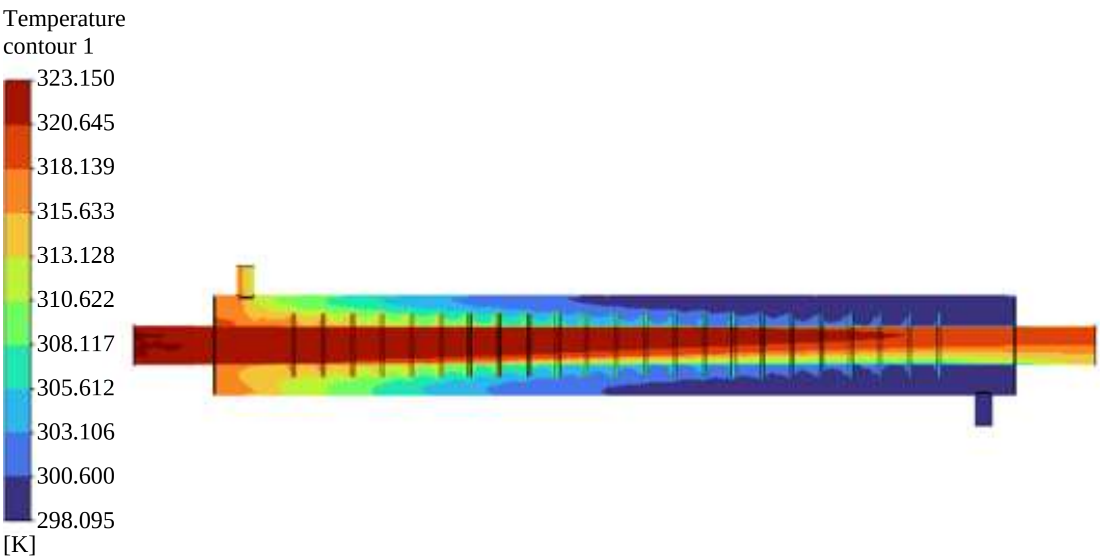

Figure 8. Temperature contours of plain and annular-finned tubes in a double-pass double-pipe heat exchanger.

POLYMER COMPOSITE TUBE PERFORMANCE UNDER VARIABLE THERMAL CONDUCTIVITY

Following successful validation of the metallic baseline, the CFD model was extended to investigate the effect of replacing the metallic inner tube with thermally conductive polymer composite materials. The effective thermal conductivity of the tube wall was varied parametrically from 0.2 W/m·K to 20 W/m·K to represent the transition from neat polymer systems to highly conductive graphene- and boron-nitride-filled composites. The results reveal that wall conductivity strongly influences exchanger thermal behaviour, particularly at lower conductivity values. At the lowest investigated conductivity of 0.2 W/m·K, representative of unfilled epoxy or PTFE, the annular-finned polymer exchanger exhibits approximately 38–42% lower heat transfer rate than the metallic copper baseline. The large reduction occurs because the tube wall conduction resistance becomes comparable to — and eventually larger than — the convective resistances on both fluid sides. Under these conditions, the wall itself becomes the dominant thermal bottleneck limiting energy transfer.

However, the behaviour changes substantially as conductivity increases. At approximately 1 W/m·K, corresponding to lightly filled thermoplastic composites, the performance deficit decreases to nearly 22–26%. When conductivity reaches 5 W/m·K, representative of graphene nano-platelet or boron nitride reinforced epoxy systems, the exchanger operates within approximately 8–12% of the metallic baseline. Further increases to 10 W/m·K reduce the thermal performance gap to below 5%, indicating that highly conductive polymer composites can approach near-metallic thermal behaviour when combined with suitable fin-enhanced geometries. One of the most technically significant findings of the present study is that annular fins effectively compensate for the low intrinsic conductivity of polymer materials. In conventional plain-tube exchangers, the wall conduction resistance lies directly in series with the convective resistances, causing a severe reduction in overall heat transfer coefficient when conductivity decreases. In contrast, the annular-finned configuration redistributes heat transfer pathways by extending the conductive surface deep into the annular flow region. Heat transfer therefore occurs not only through the tube wall thickness but also through the fin surfaces and fin tips, which continuously interact with the surrounding turbulent fluid. Although fin efficiency decreases as wall conductivity is reduced, the fins still remain highly effective thermal transport structures even at moderate composite conductivities. The CFD results indicate that fin efficiency decreases from approximately 94% at 20 W/m·K to nearly 78% at 1 W/m·K, yet the total heat transfer enhancement produced by the fins remains substantially greater than that of a plain polymer tube. This finding demonstrates that geometric enhancement strategies can partially overcome material limitations, enabling lightweight polymer composites to achieve practical thermal performance levels previously associated only with metallic exchangers.

The Nusselt number trends further support this interpretation. At 5 W/m·K, the average Nusselt number remains nearly 85–90% of the metallic finned baseline across the investigated flow range. This relatively weak dependence on wall conductivity indicates that convective transport mechanisms remain governed primarily by flow structure, turbulence intensity, and fin geometry rather than by the wall material itself. Consequently, conventional heat transfer enhancement approaches such as fin optimization, pitch variation, and flow management remain equally effective when metallic materials are replaced with thermally enhanced composites. In contrast to heat transfer behaviour, pressure drop remains almost completely independent of wall conductivity. Across the full conductivity range from 0.2 to 20 W/m·K, pressure loss variations remain below 0.5%, which is effectively within numerical uncertainty limits. This behaviour confirms that pressure drop is controlled almost entirely by hydrodynamic flow resistance and geometric obstruction rather than by thermal transport properties. From an engineering perspective, this result is highly important because it indicates that switching from copper to polymer composite tubes does not introduce any additional hydraulic penalty. The designer therefore gains substantial weight reduction and corrosion resistance benefits without increasing pumping power requirements.

The temperature contour distributions provide additional physical insight into the conduction–convection interaction occurring inside the exchanger. At low conductivity values, strong thermal gradients develop across the polymer wall, and the shell-side fluid experiences slower temperature rise due to restricted heat penetration. The thermal contours appear more widely spaced near the tube surface, indicating reduced local heat flux. As conductivity increases toward 5–20 W/m·K, the wall temperature gradients diminish considerably, and the thermal field approaches that of the copper reference case. The annular fins remain thermally active in all cases, appearing as localized high-temperature regions extending into the annular fluid domain, thereby confirming their dominant role in sustaining thermal performance even when the base wall conductivity is reduced.

THERMODYNAMIC PERSPECTIVE AND PERFORMANCE EVALUATION

Heat transfer enhancement alone does not fully characterize exchanger performance because increased turbulence simultaneously increases hydraulic irreversibility. From a second-law perspective, entropy generation originates primarily from finite-temperature heat transfer and viscous dissipation associated with pressure losses. The annular fin configuration improves convective transport by increasing surface area and promoting secondary flow development; however, elevated turbulence intensity also increases pumping requirements. A thermo-hydraulic performance evaluation criterion (PEC), conceptually expressed as the ratio of heat transfer enhancement relative to frictional penalty, suggests that thermal improvement remains beneficial within the investigated operating range. The present results indicate that conductivity enhancement beyond approximately 5–10 W/m·K provides diminishing thermal returns while hydraulic losses continue increasing with Reynolds number, indicating an emerging optimization window for polymer composite heat exchanger design.

DESIGN SIGNIFICANCE AND NOVEL THERMO-HYDRAULIC INSIGHTS

The present investigation provides important design-oriented insights for the development of lightweight polymer composite heat exchangers. The results demonstrate that neat polymers with conductivity below approximately 0.5 W/m·K are unsuitable for compact high-duty exchanger applications because of excessive conduction resistance. However, once conductivity exceeds approximately 5 W/m·K, the thermal performance approaches near-metallic behaviour while still retaining the inherent advantages of polymer systems, including low density, corrosion immunity, and manufacturing flexibility. The study further establishes that annular fins play a critical enabling role in making polymer composite exchangers thermally viable. Rather than acting solely as area enhancement devices, the fins effectively redistribute heat transfer pathways and reduce the thermal sensitivity of exchanger performance to wall conductivity. This behaviour creates a practical conductivity window between approximately 5 and 10 W/m·K where polymer composite exchangers can realistically compete with metallic systems in terms of thermo-hydraulic performance. From a broader research perspective, the work introduces a novel combination of experimentally validated three-dimensional conjugate CFD, annular fin enhancement, and polymer composite conductivity parametrization over a wide conductivity spectrum. Unlike conventional studies that investigate either geometric enhancement or material substitution independently, the present work systematically captures the coupled interaction between turbulence generation, fin-assisted convection, and wall conduction resistance. The resulting thermo-hydraulic maps therefore provide directly applicable design guidance for next-generation lightweight and corrosion-resistant thermal systems intended for marine cooling, compact HVAC devices, chemical processing units, and portable energy systems.

CONCLUSIONS

This study combined physical experiments with validated three-dimensional CFD to characterize a double-pass annular-finned double-pipe heat exchanger, then extended the model across a parametric sweep of inner-tube wall conductivity from 0.2 to 20 W/m·K. On the geometry side, annular fins delivered a consistent 25–30% improvement in heat transfer rate over the plain-tube baseline across 1–15 LPM, at the cost of roughly doubled pressure drop at the upper flow range. CFD agreed with experiments to within 4.5% on heat transfer and 6% on pressure drop. On the materials side, fins proved to be the key enabler for polymer tube viability. At k = 5 W/m·K — achievable with 20–30 vol% GNP or BN-platelet loading in epoxy — the finned composite exchanger performs within 8–12% of the copper baseline while offering 40–60% weight reduction and full corrosion immunity. At k = 10 W/m·K the gap narrows below 5%. Pressure drop is insensitive to wall material throughout. The implication is clear: effective conductivity of 5–10 W/m·K unlocks near-metallic exchanger performance in a lighter, corrosion-resistant tube. Marine thermal management, chemical-process heat recovery, and low-temperature HVAC all stand to benefit. Experimental validation with fabricated composite tube sections is the logical and achievable next step.

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