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Experimental Investigation on Heat Transfer Enhancement in Shell and Tube Heat Exchanger Using Graphene Nanofluids

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Abstract

The paper focuses on the dispersion of Graphene nanoparticles in a water–ethylene glycol based fluid to investigate their impact on the convective heat transfer performance of the resulting nanofluid. Various concentrations of graphene nanoparticles were prepared, and the nanofluids were subjected to different ultrasonication durations to ensure proper dispersion and stability of the nanoparticles within the base fluid. The study involved extensive experimental evaluation to systematically analyze how the nanoparticle loading concentration and the time of sonication affected the convective heat transfer coefficient, a critical parameter influencing heat exchanger performance. The results demonstrated a substantial enhancement in the heat transfer coefficient, with improvements reaching up to 27% when the nanoparticle concentration and sonication duration were optimized. This enhancement is attributed to the excellent thermal properties of graphene and the improved nanoparticle dispersion achieved through ultrasonication. The findings highlight the significant potential of graphene-based nanofluids in improving heat exchanger efficiencies, leading to more compact and energy-efficient thermal management systems. These improvements can contribute to reduced operational energy consumption and facilitate the design of smaller, cost-effective heat exchangers, offering both economic and environmental benefits in various industrial applications. Thus, graphene nanofluids represent a promising avenue for advancing thermal fluid technologies.

Keywords: Graphene nanofluid, shell-and-tube, heat exchanger, ultrasonication, thermal performance

INTRODUCTION

Efficient heat transfer is fundamental to modern industrial operations, influencing productivity, energy efficiency, and system longevity in sectors such as automotive, electronics, chemical processing, power generation, and food manufacturing [1]. As global industries move toward higher performance and sustainability standards, effective thermal management has become increasingly vital. Among the various heat transfer components, the heat exchanger plays a pivotal role by facilitating the exchange of thermal energy between two fluid streams without direct contact, forming the backbone of numerous systems including power plants, refineries, refrigeration units, and air-conditioning systems [2]. The performance of these systems is strongly governed by the thermophysical properties of the working fluid, particularly its thermal conductivity and convective heat transfer coefficient. Conventional fluids – such as water, ethylene glycol, and oil, are widely used due to their

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availability and chemical stability but are inherently limited by low thermal conductivity, which restricts the efficiency and compactness of heat exchangers [3].

Extensive research has focused on developing advanced heat transfer techniques and materials to address these limitations. Modern approaches such as computational fluid dynamics (CFD) optimization, the integration of extended surfaces, and the use of phase-change materials have yielded notable improvements [4]. However, one of the most significant advancements in recent years is the introduction of nanofluids, which are engineered colloidal suspensions of nanoparticles (1–100 nm) in traditional base fluids [5]. Owing to their superior thermophysical properties, nanofluids exhibit enhanced thermal conductivity, increased convective heat transfer coefficients, and improved system efficiency compared to conventional fluids. Studies have reported enhancements of 15–40% in thermal conductivity with the addition of nanoparticles such as metals (Cu, Ag), metal oxides (Al_2O_3, TiO_2), or carbon-based materials (graphene, CNTs), attributed to mechanisms such as Brownian motion, interfacial layering, and micro-convection effects [6, 7]. These attributes make nanofluids highly applicable in compact heat exchangers, electronics cooling, solar energy systems, and other high-performance energy systems.

Nevertheless, the practical implementation of nanofluids introduces challenges related to stability, viscosity, sedimentation, and increased pumping power at higher particle concentrations [8]. Therefore, optimizing parameters such as nanoparticle volume fraction, base fluid selection, and flow rate is essential to balance thermal enhancement with system efficiency. The present study aims to experimentally investigate the effect of nanoparticle concentration and flow rate on the thermal performance of a shell-and-tube heat exchanger using nanofluids as the working medium. This research focuses on comparing the heat transfer rates and convective heat transfer coefficients at various operating conditions to evaluate performance enhancement over conventional fluids. The findings of this work are expected to contribute to the development of more compact, energy-efficient, and environmentally sustainable heat exchanger designs for next-generation industrial applications.

LITERATURE REVIEW

L. Syam et al. [8] experimentally investigated Al_2O_3/water nanofluids in circular tubes fitted with twisted tape inserts under laminar flow. They observed that a 0.5% nanoparticle concentration with a twist ratio of 3 provided the highest heat transfer enhancement, though it increased the pressure drop due to higher flow resistance. This highlighted the trade-off between improved thermal performance and pumping power requirements.

O. Prakash et al. [9] analyzed MWCNT/water nanofluids in a shell and coiled tube heat exchanger using CFD simulations. The 0.5% nanofluid concentration showed the best performance owing to the high thermal conductivity of carbon nanotubes and the secondary flow effects of the coiled geometry, though with increased viscosity and pressure losses.

Mola et al. [10] studied $CuFe_2O_4$/water nanofluids in a helical coil heat exchanger and achieved up to 45% heat transfer enhancement compared to water, with 0.5% concentration giving optimal results. However, a 25% pressure drop increase was observed, emphasizing the need for balance between performance and energy consumption.

C. Prasad et al. [11] performed CFD analysis on three coiled tube-in-tube heat exchanger designs – helical, conical, and inclined rectangular – using Al_2O_3/water nanofluids. The conical coil showed the best performance with 15–25% higher Nusselt numbers and moderate pressure drops, making it suitable for compact, high-efficiency applications.

S. Perumal et al. [12] combined Al_2O_3/water nanofluids with air bubble injection in a shell-and-tube heat exchanger. This hybrid approach enhanced heat transfer by disrupting thermal boundary layers and improving fluid conductivity, with an optimal 0.3% nanoparticle concentration, though at an 18–22% higher pressure drop.

Overall, previous studies confirm that nanofluids substantially enhance heat exchanger performance, offering 20–45% improvement over conventional fluids. Optimal concentrations range between 0.3–0.75%, where heat transfer gains outweigh viscosity penalties. Passive methods such as twisted tapes and coils, and hybrid techniques like air bubble injection, further augment performance. However, long-term stability, cost, and pressure losses remain challenges, warranting further research for industrial adoption.

METHODOLOGY

The experimental study on the influence of volume fraction and ultrasonication duration on the heat transfer performance of graphene nanofluid followed a systematic approach. The process began with a comprehensive literature review to understand previous findings on graphene nanofluids, focusing on how nanoparticle concentration and ultrasonication time affect thermal conductivity and stability. A shell and tube heat exchanger was then designed using Fusion 360 software with a simple and modular configuration suitable for experimental variations. The required materials, including graphene nanoplatelets, base fluid, surfactant, ultrasonic bath, and measuring instruments, were collected, followed by fabrication of the heat exchanger through standard machining and assembly operations.

The graphene nanofluid was prepared using a two-step method—dispersing graphene nanoparticles in the base fluid with surfactant, then applying ultrasonication for varying durations to achieve uniform dispersion and stability. The prepared nanofluids were experimentally tested in a heat exchanger setup to evaluate parameters such as temperature difference, heat transfer coefficient, and pressure drop across varying volume fractions and sonication durations. Finally, all experimental data were analyzed, and a comprehensive report was prepared summarizing the methodology, observations, and conclusions regarding optimal parameters for enhanced heat transfer performance.

DESIGN OF HEAT EXCHANGER

Computer-Aided Design (CAD) plays a crucial role in developing thermal systems such as heat exchangers, ensuring accuracy, efficiency, and manufacturability. In this study, Autodesk Fusion 360 (2024) was used to design a shell and tube heat exchanger due to its integrated 3D modeling, simulation, and documentation capabilities.

The design process began by defining the objectives and operational specifications, including the type of heat exchanger, working fluids, flow arrangement, temperature, and pressure conditions. These parameters guided the determination of size, material, and performance requirements.

The modeling process involved creating the main shell by sketching and extruding a 200 mm diameter cylinder to a length of 680 mm. Tube sheets were designed at both ends with evenly spaced holes to accommodate 17 tubes, each extruded through the shell using a circular pattern. Inlet and outlet nozzles of 19.05 mm diameter were added for both the shell and tube sides, followed by flanges and bolt holes for assembly. Stainless steel was assigned as the primary material for the shell, tubes, and tube sheets, while rubber was used for gaskets. The final assembly was verified for alignment and exported for simulation and manufacturing purposes. The dimensions of heat exchanger components are given below in Table 1.

The key components of the design include the shell, tube plates, tubes, end covers, bolts, nuts, and gaskets, as listed in Table 1. This CAD-based design approach ensures precision and enables further thermal and structural analysis for performance optimization.

FABRICATION SUMMARY

The fabrication of the heat exchanger was carried out through a systematic sequence involving material selection, fabrication, assembly, testing, and finishing. Stainless steel 316 was chosen for its superior strength and corrosion resistance. The tubes and shell were cut, rolled, and welded to the specified dimensions using TIG welding to ensure leak-proof joints. Baffles were positioned inside the shell to guide fluid flow, and the tube bundle was securely assembled and welded to the tube sheets. After assembly, the unit underwent dimensional inspection and leak testing to verify its integrity. Finally, surface finishing and painting were performed to enhance corrosion resistance and appearance, resulting in a durable and fully functional heat exchanger ready for experimental use.

Table 1. Heat exchanger specifications.

S.N.	Design Parameters	Dimensions (mm)
1	Length of shell D_t	680
2	Diameter of shell D_s	200
3	Shell thickness S_t	1
4	Length of tube L_t	610
5	Diameter of tube L_s	12.5
6	Tube thickness T_t	2
7	Inlet/outlet nozzle length L_i	50
8	Inlet/outlet nozzle diameter Di	19.05
9	End cover diameter D_c	250
10	End cover thickness D_t	1
11	Gasket thickness G	3

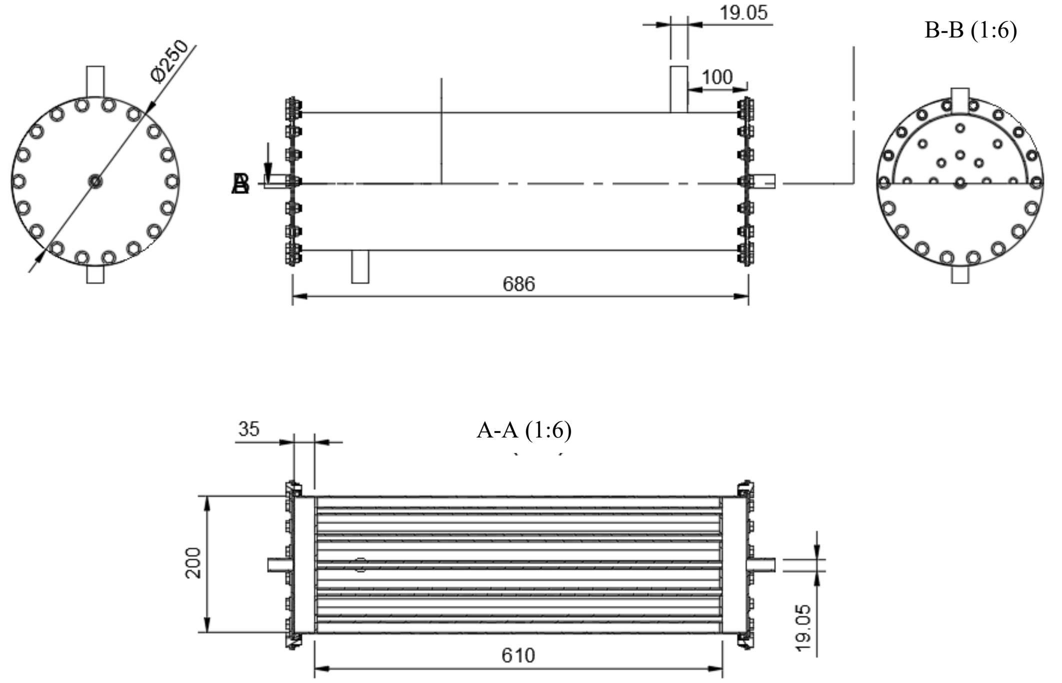

Figure 1. Cross-sectional view of shell and tube heat exchanger.

EXPERIMENTAL SETUP

The experimental setup used for investigating heat transfer enhancement in a Shell and Tube Heat Exchanger (STHE) using graphene nanofluids is shown schematically in Figure 1. The system primarily consists of a shell and tube heat exchanger, a pump, a rotameter, an immersion rod water heater, a lithium-ion battery, and a thermal sensor with a digital display. The STHE serves as the core component, facilitating heat exchange between two fluids – hot water flowing through the shell side and nanofluid circulating through the tube side – without direct mixing. The pump circulates the working fluid through the system, maintaining a steady flow rate as measured and regulated by the rotameter. The hot water is generated using an immersion rod water heater, which heats the fluid to the desired inlet temperature before it enters the heat exchanger. Temperature readings at the inlet and outlet of both fluids are continuously monitored using thermocouple-based thermal sensors connected to a digital display, ensuring accurate data acquisition. A lithium-ion battery provides portable and stable power to auxiliary components like the sensors and display units. The setup is designed to ensure efficient thermal measurement, reliable flow control, and consistent performance, allowing precise evaluation of the nanofluid's effect on heat transfer characteristics under controlled experimental conditions. A schematic diagram of the experimental setup is shown in Figure 2.

NANOFLUID PREPARATION

The preparation of graphene-based nanofluids was carried out using the ultrasonication method, which is one of the most effective techniques for dispersing nanoparticles uniformly within a base fluid. In this process, high-frequency ultrasonic waves were applied to a mixture containing graphene nanoparticles, ethylene glycol, and distilled water, with sodium lauryl sulfate (SLS) serving as a surfactant to prevent particle agglomeration. Ultrasonication generates acoustic cavitation – rapid formation and collapse of microscopic bubbles – producing localized high temperatures, high pressures, and strong shear forces within the liquid. These intense conditions break apart clusters of nanoparticles into smaller, well-dispersed particles, ensuring a stable and homogeneous suspension. In this study, the mixture was subjected to ultrasonication for 60 minutes at a controlled temperature of 40°C to achieve optimal dispersion without damaging the graphene structure. The role of SLS was critical in stabilizing the nanofluid by reducing surface tension and minimizing re-agglomeration of nanoparticles. Ethylene glycol and distilled water acted as the base fluids, providing good thermal conductivity and specific heat capacity, respectively. The resulting graphene nanofluid exhibited enhanced stability and improved thermal properties, making it suitable for experimental investigation in heat transfer applications such as the shell and tube heat exchanger (Figure 3).

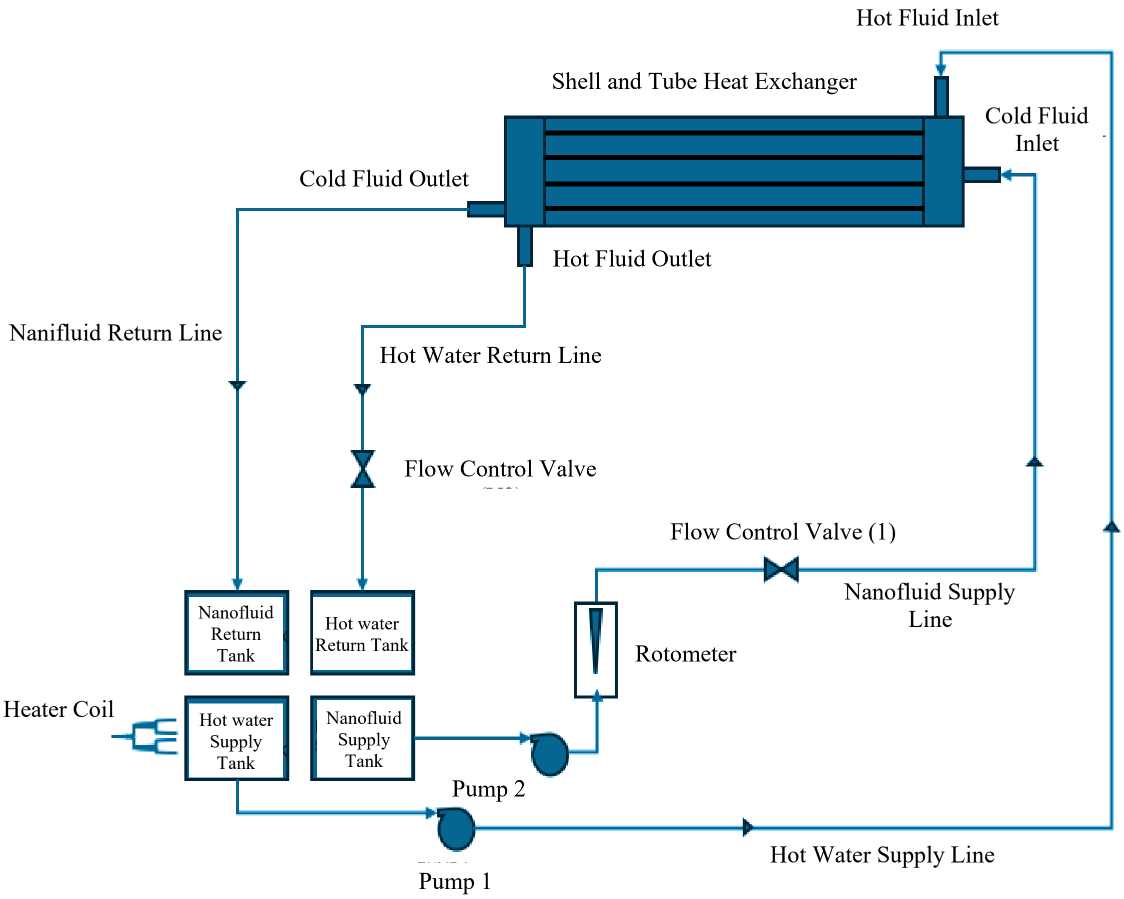

Figure 2. Experimental setup representation.

Density of base fluid, ρbf:

Distilled water (Dw): 997 kg/m³, 950 mL.
Ethylene Glycol (EG): 1113 kg/m³, 50 mL.

The density of the base fluid (ρbf) is calculated as:

$\rho bf = (\varphi Dw \times \rho Dw) + (\varphi EG \times \rho EG)$
$\rho bf = (0.95 \times 997\ \text{kg/m}^3) + (0.05 \times 1113\ \text{kg/m}^3)$.
$\rho bf = 1002.8\ \text{kg/m}^3$.

For 1 L volume:

Mass of base fluid (Mbf) = 1.0028 kg.

To find the weight of nanoparticles (Wp), we use the following equation:

$\Phi = (Wp / \rho p) / ((Wp / \rho p) + (Wbf / \rho bf))$

where:
Φ is the volume fraction (in percentage).
Wp is the weight of nanoparticles (g).
ρp is the density of nanoparticles (166 g/L, as derived from calculations).
Wbf is the mass of base fluid (1.0028 kg = 1002.8 g).

For $\Phi = 0.1\%$:

$(0.1 / 100) = (Wp / 166) / ((Wp / 166) + 1)$.
$Wp = 0.165$ g.

For $\Phi = 0.5\%$:

$(0.5 / 100) = (Wp / 166) / ((Wp / 166) + 1)$.
$Wp = 0.8318$ g.

For $\Phi = 1\%$:
$(1 / 100) = (Wp / 166) / ((Wp / 166) + 1)$.
$Wp = 1.657$ g.

RESULTS AND DISCUSSION

Graphene nanofluids exhibited a notable 27% increase in convective heat transfer coefficient compared to the base fluid during experimental testing, indicating superior thermal performance. The study observed that raising the concentration of graphene nanoparticles consistently enhanced the heat transfer capabilities of the nanofluid, leveraging graphene's excellent thermal conductivity. However, this increase in nanoparticle loading also led to a marginal rise in pumping power requirements due to higher fluid viscosity. Despite this, the overall benefit of improved heat transfer efficiency positions graphene nanofluids as a significant advancement in thermal fluid technology, particularly for optimizing industrial cooling systems where energy efficiency and compact design are critical.

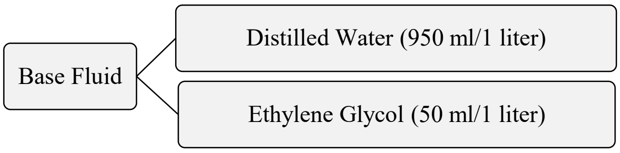

Figure 3. Base fluid preparation.

CONCLUSION

The study concludes that graphene nanofluids provide notable improvement in shell and tube heat exchanger performance. An optimal concentration of 0.5–0.75% graphene nanoparticles and controlled ultrasonication duration yielded the best results. The experimental approach verified the enhancement in convective heat transfer while maintaining acceptable pressure drops. Future work should focus on hybrid nanofluids and long-term stability analysis for industrial-scale applications.

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