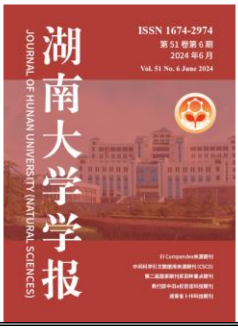

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Experimental Analysis of Heat Transfer Enhancement of Nanofluids in a Pipe Flow

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Abstract: This research explores the thermal enhancement potential of nanofluids in a pipe flow system through a series of experimental tests. This research investigates the impact of nanofluid concentration, flow rate, and other operational parameters on the heat transfer coefficients of pipe flows. Experiments were conducted in a controlled pipeline system to compare the heat transfer performance of nanofluids and traditional fluids. Heat transfer coefficients, thermal conductivity, and convective heat transfer were measured at various concentrations, flow rates, and temperatures. The results provide valuable insights into the potential of nanofluids to enhance heat transfer in various applications. The experimental data clarified the complex relationships between heat transfer and fluid properties in nanofluid-based systems. Experiments on the data suggest that the highest heat transfer coefficients are achieved for 0.20 vol% GO/water and GO/methanol nanofluids at a heat load of 30 W and fill ratios of 30%, 50%, 70%, and 90%. Conversely, a reduction in the heat transfer coefficient is observed at a heating power of 10 W. The findings are intended to provide insights into the design and optimization of nanofluid-based heat transfer systems, with potential applications in a range of thermal engineering fields.

Keywords: heat transfer, base fluid, nanofluid, Nusselt number, flow rate, viscosity.

管流纳米流体强化传热的实验分析

摘要：本研究通过一系列实验测试探索了纳米流体在管道流动系统中的热增强潜力。本研究调查了纳米流体浓度、流速和其他操作参数对管道流动传热系数的影响。在受控管道系统中进行实验，以比较纳米流体和传统流体的传热性能。在不同浓度、流速和温度下测量了传热系数、热导率和对流传热。结果为纳米流体在各种应用中增强传热的潜力提供了宝贵的见解。实验数据阐明了基于纳米流体的系统中传热和流体特性之间的复杂关系。对数据进行的实验表明，在热负荷为30西和填充率为30%、50%、70%和90%时，0.20体积百分比/水和去/甲醇纳米流体的传热系数最高。相反，在加热功率为10西时观察到传热系数降低。该研究结果旨在为基于纳米流体的传热系统的设计和优化提供见解，并可能在一系列热工程领域得到应用。

关键词：传热、基流体、纳米流体、努塞尔特数、流速、粘度。

1. Introduction

The concept of energy efficiency is paramount in modern industrial processes, with increasing emphasis on maximizing energy conversion and minimizing waste. In today's industrial landscape, heat exchangers and heat pipes play a crucial role in the thermal energy transfer, enabling the efficient movement of thermal energy between different materials [1], [2]. Heat pipe systems have emerged as a front-runner in the heat transfer arena due to their impressive characteristics, such as thermal performance, compact and lightweight design, and low cost of setup and maintenance. These features make heat pipes an attractive and efficient solution for a variety of industrial applications [3], [4], [5]. Heat pipes are widely recognized as the preferred method for heat transfer in industrial settings due to their exceptional rapid response times and capacity for effectively conveying substantial quantities of thermal energy. These characteristics allow heat pipes to address an extensive range of heat transfer challenges, making them an ideal solution for numerous industrial processes. According to [6], [7], [8], heat pipes are vacuum-sealed devices that leverage the temperature variations within a copper tube to transfer heat between two areas. These devices rely on evaporative and condensation processes to transport thermal energy with remarkable efficiency [9], [10]. In essence, a heat pipe comprises three essential components: an evaporation section, a condenser, and an adiabatic section. The evaporation section functions as heat intake, the condenser acts as heat release, and the adiabatic section resides in the center of the heat pipe, where heat transfer is absent.

The fluid selection can significantly influence crucial factors such as the heat transfer coefficient, pressure drop, and boiling point. These parameters play a vital role in optimizing the thermal efficiency and effectiveness of heat pipes. The choice and use of nanofluids are greatly influenced by their impact on the heat transfer coefficient. Nanofluids are fluid mixtures that incorporate nanoparticles into a base fluid, resulting in a significant increase in the heat transfer coefficient compared to traditional fluids. The nanoparticles alter the thermophysical properties of the base fluid, enhancing its heat transfer. The elevated heat transfer coefficient of nanofluids has a profound impact on the efficacy and efficiency of heat transfer processes. Due to this improved performance, nanofluids are often preferred for applications in which high thermal performance is a key requirement. In recent years, the incorporation of nanoparticles into working fluids has gained traction because this approach has been demonstrated to enhance the thermal conductivity and heat transfer properties of fluids [11]. Nanoparticles have been explored as potential additives in fuel formulations to ramp up performance [6], [12]. Incorporating fluids laden with nanoparticles can alter the thermophysical properties of the base fluid, including its viscosity, specific heat, and thermal conductivity, leading to improved combustion and engine efficiency [4], [13].

Studies have demonstrated, both through experiments and numerical simulations, that nanofluids can greatly enhance the energy exchange capabilities of a system [14]. The suspended nanoparticles within the fluid significantly enhance the thermal conductivity, resulting in improved system performance. The remarkable increase in heat transfer properties with the use of nanofluids has been consistently observed in various applications. In a pioneering study by [15], [16], an exploration combining experimental and computational methods was conducted to analyze the performance of a plate heat exchanger within a combi boiler. The primary objective was to enhance the heat transfer efficiency of the exchanger by creating and utilizing a specifically engineered nanofluid. Their findings indicate that using nanofluids in a plate heat exchanger improves thermal performance and increases energy efficiency. These results suggest that nanofluids can play a key role in optimizing heat exchanger performance and reducing energy consumption. In their experimental investigation [17], the authors delved into the thermal behavior of a custom-made heat pipe infused with a bentonite/deionized water nanofluid. Three distinct nanofluid mixtures were concocted with varying nanoparticle concentrations of 0.5%, 2%, and 4% to analyze the impact of the particle concentration on the heat pipe’s thermal properties. They examined the diverse thermal characteristics of the heat pipe and assessed the efficiency, thermal conductivity, and thermal resistance. This investigation compared the performances of deionized water and three distinct bentonite-infused nanofluid mixtures. They identified an optimal nanoparticle concentration that enhanced the heat pipe’s thermal properties, resulting in improved performance.

A meticulous evaluation (with an emphasis on experimental uncertainties) was conducted by [18] and [19], who revealed two key insights: the entrance region of a laminar nanofluid flow exhibits anomalous enhancement in heat transfer, and the turbulent flow regime of nanofluid, when subjected to empirical evaluation, yields data that adhere to established heat transfer correlation models, a phenomenon that can be ascribed to the heat transfer enhancement imparted by the unique characteristics of nanofluids. This intriguing finding has sparked their use as working fluids in various industrial sectors. Heat pipes, which are commonly utilized in cooling systems, offer a potential application for nanofluids. Phase change and convection are the mechanisms by which these ingenious devices transfer heat from the hotter interface to the colder interface, which is an inherently effective and efficient process. Here is how it works: vapor is produced at the heat source (evaporator), condenses at the heat sink (condenser), and the liquid is transported back to the evaporator through a capillary structure. Heat pipes are a highly sought-after technology due to their inherent traits, which include: (i) purely autonomous operation, independent of external intervention, (ii) exceptional capacity for thermal transport within a small physical footprint, and (iii) ease of implementation across a diverse array of engineering domains. They are ubiquitous in numerous thermal engineering applications, including solar energy collectors, central processing units, and small circuit transmission tools.

Zhang and Zhang [20] examined the impact of the filling ratio of working fluids on the neutron absorber capacity and thermal performance of an annular thermosyphon. The findings indicated an appreciable increase of 18% in the absorption threshold with a rise in the fill ratio. A comprehensive experimental analysis was conducted to investigate the impact of the operating parameters, such as the heat flux applied to the evaporator section, the tilt angle of the heat pipe, the working fluid filling charge ratio, and the nanoparticle volume concentration. The focus was on understanding their effects on the thermal efficiency and effectiveness of a thermosyphon heat pipe. Masood et al. [21] probed the heat efficiency of a closed-loop pulsating heat pipe using two disparate base fluids (ethanol and water) across a spectrum of filling ratios (28%, 41.3%, 63%, 82.5%, and 100%). The findings revealed that at lower and higher heat inputs, water exhibited lower thermal resistance, and the maximum heat transfer was achieved at a filling ratio of around 30%. Ethanol exhibited its best performance at low heat input when the filling ratio exceeded 50%. Cavazzuti [22] and Adeaga et al. [23] explored the impact of a silver nanofluid (with 20-mm-diameter particles) on the thermal efficiency of a copper pulsating pipe flow. The outcomes of the study revealed that at lower and higher heat inputs, water presented lower thermal resistance, and the apex heat transfer was accomplished at a fill ratio of roughly 30%. Osman et al. [24], Mukhtar et al. [25], and Constantinescu [26] introduced the idea of dispersing nanoparticles in base fluids. A range of materials, such as metals (aluminum and copper), carbides (silicon carbide), and oxides (aluminum oxide), were employed as nanoparticles, with water and methanol constituting the base fluids. Experimental studies have revealed that the thermal conductivity of nanofluids is contingent on the concentration, size, shape, and material of the nanoparticles.

Heat transfer enhancement in fluid systems has been a central focus of research for a considerable period, due to its fundamental importance in numerous industrial and technological applications. One particularly intriguing avenue of exploration in this field is the use of nanofluids, a class of engineered fluids infused with nanoparticles, to enhance heat transfer efficiency. This innovative approach has attracted interest due to its potential to significantly improve the thermal performance of conventional heat exchangers and cooling systems. This research delves into the fascinating realm of nanofluids, in which minute solid particles are dispersed in a base fluid, often water or oil. In this context, the pipe flow serves as a conduit for understanding how nanofluids interact with the thermal characteristics of the fluid as they move through a confined space. This research area has far-reaching implications for numerous industries, including electronics cooling, energy production, and HVAC systems. By investigating the behavior of nanofluids in pipe flows, scientists and engineers aim to unlock the full potential of these cutting-edge materials to improve heat transfer efficiency, reduce energy consumption, and ultimately contribute to more sustainable and efficient thermal management solutions. This experimental analysis provides valuable insights into the intricate mechanisms governing heat transfer enhancement in nanofluids within pipe flows, shedding light on the future of advanced heat exchanger technology and energy-efficient systems. This study made use of graphene oxide, which was dispersed in water and methanol to form a nanofluid, and utilized the same fluids as the working fluid in a copper pipe. In this study, graphene oxide nanofluids were used to assess the thermal transport properties of the aforementioned working fluids. The study investigated the impact of fluid composition on heat transfer characteristics, specifically, the convective heat transfer coefficient, thermal conductivity, and overall heat transfer coefficient.

2. Experimental Study Analysis

Fig. 1 shows the apparatus used to measure the heat transfer rate. It consists of a flowmeter, thermocouple, cooling component, data acquisition, and power supply. The test section is a straight stainless steel tube with dimensions of 2000 mm in length (L), 3.96 mm in inner diameter (D), and 0.17 mm in thickness. Both ends of the tube have electrodes attached to implement direct electric current heating. To facilitate precise heat flux control, a DC power supply is utilized, adjustable via a voltmeter. To prevent heat loss from the test section, a thick layer of insulation is placed around the test tube. The final result is a finely tuned, well-insulated test environment that allows accurate measurement of the convective heat transfer coefficient.

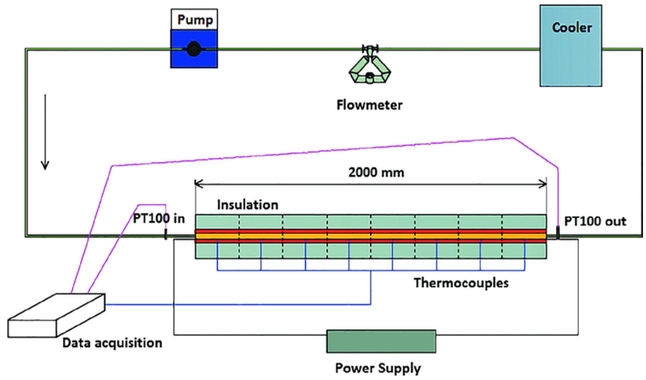

Fig. 1 Experimental apparatus (The authors)

The experimental setup includes the pipe flow system, heat source, thermometer, and pressure sensors. Twenty thermocouples, each with a diameter of 100 lm and welded to the outer surface of the test tube, are utilized to measure the exact temperature of the local wall along the heated portion of the tube with great precision. Additional thermocouples are situated at the inlet (Tin) and outlet (Tout) of the test section to measure the bulk temperature of the working fluid. The dynamics of the experimental apparatus are meticulous in this design, incorporating a magnetically driven fluidic pumping mechanism coupled with a sophisticated electromagnetic flow metering system. To maintain a pristine experimental environment, it is essential to clean the entire loop meticulously after each successive run of the experiment, even if the nanofluid composition remains unchanged.

To create graphene oxide nanofluids, GO nanoparticles must be carefully mixed with either pure water or methanol as the base fluid. These nanoparticles are fabricated through an intricate process known as the modified Hummers method, whereby natural graphite powder is subjected to a complex chemical transformation to obtain graphene oxide nanostructures [26], [27]. Graphite fine powders (45 lm) are purchased from pure chemical industries in Ibadan Oyo State, Nigeria. Concentrated sulfuric acids (H_2SO_4), sodium nitrate ($NaNO_3$), potassium permanganate ($KMnO_4$), hydrogen peroxide (35% H_2O_2), hydrochloric acid (10% HCL), deionized water, and methanol serve as the non-reactive media in the Hummers method, playing a pivotal role in facilitating the precise chemical reactions that give rise to the coveted graphene oxide nanostructures. The intricate thermal behavior of low-concentration nanoparticle-infused fluids is meticulously examined through stringent experimental methodologies. To obtain accurate thermal conductivity data for nanofluids, a sophisticated testing apparatus is developed, incorporating the transient hot-wire technique, a methodology widely adopted for the determination of thermal conductivity. This technique has proven to be a reliable and effective tool for measuring nanofluid thermal conductivity because of its ability to precisely measure thermal diffusion processes at the microscopic level. To quantify the thermal conductivity of nanofluids, a state-of-the-art KD2 thermal property meter is employed. Thermal conductivity measurements are carried out for nanofluids and base fluids at 20^0C. Before each measurement, the KD2 meter is calibrated using distilled water and methanol to ensure the maximum accuracy of the acquired data. The precision of the probe is meticulously verified through thermal conductivity measurements of pure water, benchmarked against values obtained from existing literature. Subsequently, viscosity measurements of the nanofluids are conducted using a rotary viscometer encompassing multiple temperature points.

In this study, a spectrum of graphene oxide nanofluid volume fractions was evaluated to gain insights into their thermal properties. The exploration encompasses a range of volume fractions, each examined in detail. The Reynolds number was systematically varied from 3050 to 10100, as depicted in Fig. 6. A thorough uncertainty analysis [28] revealed the following findings: (1) estimated flowrate uncertainty is 1.6%; (2) less than 1.2% of physical attributes are thought to be unknown; (3) the degree of measurement uncertainty is 1.6%. Under the specified experimental conditions, the uncertainty in the acquired data was estimated as 3.3%.

2.1. Heat Transfer in the Pipe Flow

The intricate apparatus used in this investigation is illustrated in Fig. 2. The setup comprises various elements: (1) a test section; (2) a heating coil; (3) a thermostatic bath serving as the cooling unit; (4) a data logger; (5) a flow meter; (6) a variable transformer; (7) a vacuum pump; (8) an electronic multimeter; (9) a pressure gauge. The copper-crafted heat pipe has a total length of 180 mm, an outer diameter of 12 mm, and a thickness of 1 mm. The evaporator, adiabatic section, and condenser have lengths of 55, 50, and 75 mm, respectively. An acrylic cylinder cooling jacket with an outside diameter of 80 mm and a thickness of 5 mm surrounds the condenser portion. The vital coolant fluid used in this experiment was base fluid, which was pumped from the thermostatic bath. A flow meter was used to precisely measure the cooling water flow rate. A vacuum pump was used to completely drain the heat pipe before starting the experiment, and the carefully prepared working fluids were then carefully inserted. To create vacuum pressure inside the heat pipe, a vacuum pump and a vacuum gage are coupled together. A heater coil was looped around the evaporator and connected to a variable transformer to provide heat input. A digital multimeter was used to measure the voltage and current of the heater coil. To prevent heat loss to the surroundings, the evaporator and adiabatic portion were insulated with a layer of glass fiber insulation. To measure the temperature distribution along the wall of the heat pipe, eight K-type thermocouples were carefully attached to its outside. As indicated in Fig. 3, four of these are placed strategically on the evaporator, four on the condenser, and one thermocouple is placed on the adiabatic section to capture the complex thermal gradients with unmatched accuracy.

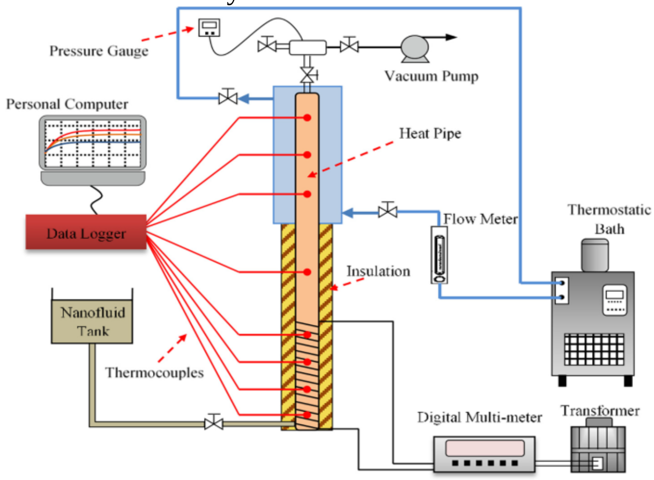

Fig. 2 Experimental setup diagram [14]

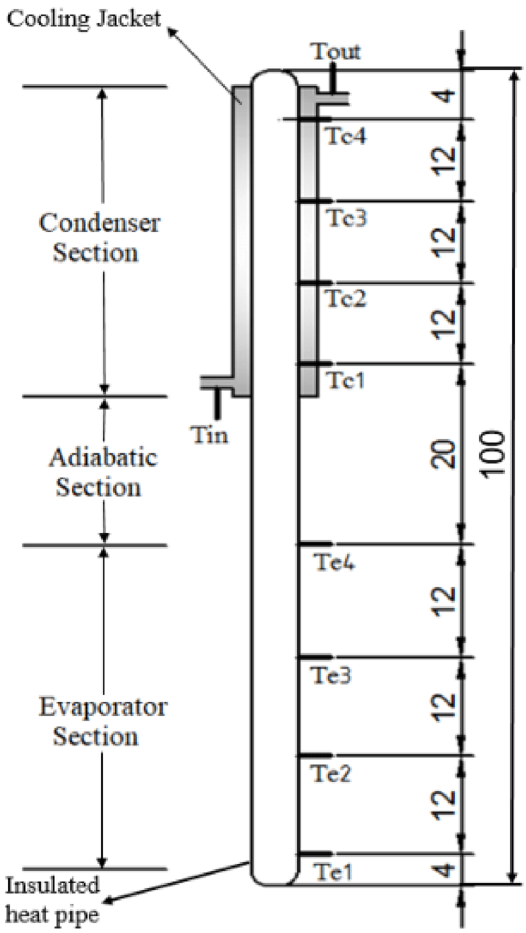

Fig. 3 Heat pipe's thermocouple mounting locations (The authors)

The placement of thermocouples along the heat pipe is depicted in Fig. 3, allowing a comprehensive assessment of the temperature distribution. Cold water was circulated to the condenser section at a constant temperature of 15^0C with a flow rate of 3/2 m^3/s for all testing scenarios. For each nanofluid concentration, the heat input was varied from 10 to 30 W. To ensure the best possible experimental conditions, the test area was evacuated using a vacuum pump to remove any non-condensable gases. The working fluid was carefully charged into the system when the test portion reached the ideal vacuum pressure. The filling charge ratios (FR), which are determined as the working fluid's volume relative to the internal evaporator volume, are set to 30, 50, 70, and 90% for each working fluid. In every case, the test section's vacuum pressure is precisely fixed at 10 kPa. After that, a steady condition was reached by progressively heating the test part.

3. Results and Discussion

A rotational viscometer was used to precisely measure the viscosity of the nanofluids over a wide range of volume fractions. The resulting viscosity data are plotted in Fig. 4 as a function of temperature. The figure elucidates the intricate interplay between temperature and viscosity at each nanofluid concentration. Fig. 4 reveals a noteworthy trend as the volume fraction of the nanofluid increases, and so does the viscosity. However, this trend was mitigated by a rise in temperature, which led to a decrease in the observed increase in viscosity with an increase in volume fraction.

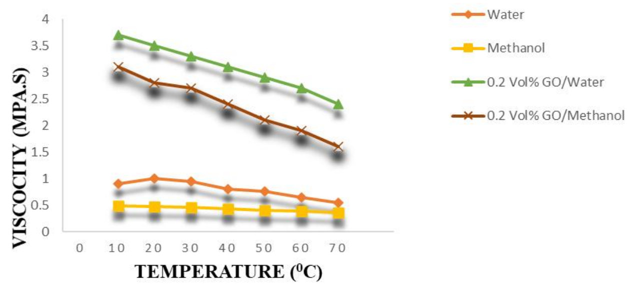

Fig. 4 Graphene oxide nanofluid's viscosity (The authors)

The pressure loss (Δp) experienced by the working fluid in the test section at a temperature of 293 K is plotted in Fig. 5 as a function of the flow rate for a nanofluid concentration of 0.1%. For comparison, the corresponding data for various nanofluids are superimposed on the same figure, elucidating the divergent behaviors of these nanofluids under similar operating conditions. Each line depicted in Fig. 5 can be described mathematically as $\Delta p = fLqU^2/(2D)$, where f denotes the friction coefficient, U is the mean velocity of fluid over the pipe's cross-sectional area, L is the length of the pipe, and D denotes the pipe's diameter. This equation elegantly encapsulates the interplay between fluid flow, pipe geometry, and friction forces and underpins the predictive power of empirical correlations in fluid flow analysis. A noteworthy finding in Fig. 5 is that the pressure drop in the nanofluids was slightly lower than that in methanol and pure water. This result can be attributed to the presence of nanoparticles in the pure fluid, resulting in increased frictional losses.

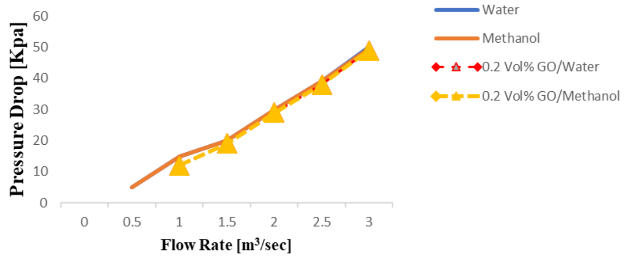

Fig. 5 Pressure decreases by 0.2 vol% for different nanofluids (The authors)

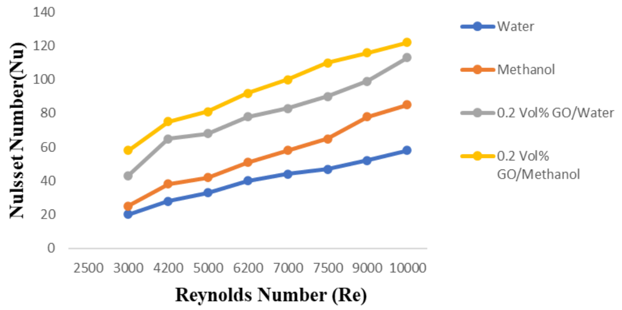

Fig. 6 Relationships between Nu and Re for graphene oxide nanofluid (The authors)

Fig. 6 provides a compelling illustration of the complex interplay between the Nusselt number (Nu), Reynolds number (Re), and volume fraction. The heat transfer coefficient at x/D = 200, where the flow is fully developed both hydrodynamically and thermally based on prior experimental results, is utilized to determine the Nusselt number. The exemplary Gnielinski equation [27], [28], traditionally employed to describe turbulent flows, is depicted as a solid line in Fig. 6 for comparison. This equation serves as a benchmark against which the experimental results can be evaluated, facilitating a more profound understanding of the hydrodynamic and thermal behaviors of the nanofluids under investigation.

$$H = \frac{q}{Ae(T_{w-}T_{b)}} \quad (1)$$

Where T_w is wall temperature

T_b is bulk temperature of the fluids

$$Nu = \frac{(0.125f)(re-1000)Pr}{1.07+12.7\sqrt{0.125f(Pr^{\frac{2}{3}}-1)}} \quad (2)$$

Where

$$f = [1.82\log_{10}(Re) - 1.64]^{-2} \quad (3)$$

The heat transfer performance of the nanofluids exceeded that of the base fluid, as anticipated. Notably, the Nusselt number increases with increasing nanoparticle volume fraction, particularly in the high Reynolds number regime. When the nanoparticle volume fraction is relatively low, the heat transfer enhancement is only modestly attributable to the nanoparticle suspension [29], [30], [31]. In contrast, for graphene oxide nanofluids, a significant heat transfer increase is achieved. These experimental findings demonstrate that a significant improvement in heat transfer occurs when a graphene oxide nanofluid is used as the working fluid in the convective heat transfer of a pipe flow. The heat transfer enhancement of graphene oxide nanofluids, on the other hand, is noticeably more substantial. According to the experimental findings, the use of graphene oxide nanofluids in convective heat transfer through pipe flow can significantly improve heat transfer, resulting in improved thermal performance and efficiency.

Fig. 7 depicts the intricate relationship between the input heating power and filling ratio for the base fluid, GO/water, and GO/methanol nanofluids with respect to the evaporator heat transfer coefficient. The data show a startling trend: for all filling ratios, the evaporator heat transfer coefficient increases with increasing input heat power as a result of the increased rate of working fluid vaporization at high heat loads. Additionally, it is proposed that when heat loads increase, the number of nucleation sites and the rate of bubble formation noticeably increase, hastening the evaporation of the working fluid. The empirical data revealed that the evaporator heat transfer coefficient of pure water was consistently the lowest for a wide variety of fill ratios. This trend corroborates the proposition that the addition of GO nanoparticles to the base fluid augments the evaporator heat transfer coefficient of the heat pipe. Furthermore, it appears that the augmenting effect of the GO nanoparticles on the evaporator heat transfer coefficient is proportional to their concentration in the base fluid. The pinnacle of the evaporator heat transfer coefficient for the GO nanofluids was reached at a nanoparticle concentration of 0.20 vol%, accompanied by a thermal load of 30 W across an array of fill ratios. This optimal condition resulted in the highest evaporator heat transfer coefficient, indicating the potential of GO nanoparticles to enhance the performance of heat pipes across diverse fill ratios. The enhanced heat transfer performance attributed to the incorporation of nanoparticles in the base fluid can be ascribed to the formation of a nanoparticle coating on the inner surface of the pipe. In essence, this porous shape makes it easier for bubbles to form, which enhances the transmission of boiling heat to the evaporator section. This phenomenon has been elucidated in [32] and [33].

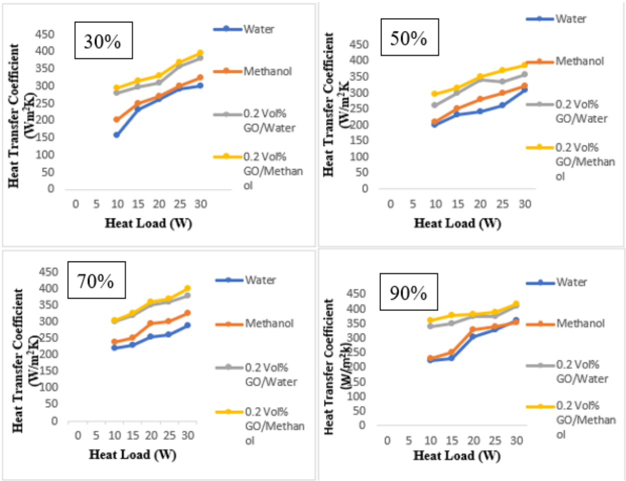

Fig. 7 Heat transmission coefficient dependent on the input heat load and percentage filling ratio, as demonstrated for different percentage filling ratios (The authors)

4. Conclusion

In conclusion, experimental analysis of the heat transfer enhancement of nanofluids in a pipe flow system revealed significant improvements in heat transfer properties compared to traditional base fluids. With an emphasis on their use in copper heat pipes, this work offers a complete investigation of the heat transmission properties of graphene oxide nanoparticles. The experiment included an evaluation of the heat pipe's ability to transfer heat under various heat fluxes, filling charge ratios, and volume concentrations when oriented vertically. The viscosity of the graphene oxide nanofluid increases with the increase in the concentration of nanoparticles. Despite the relatively small increase in pressure loss for GO nanofluids compared to pure water and methanol, the addition of nanoparticles was discovered to significantly enhance heat transfer performance in the circular tube flow. Additionally, it was discovered that adding GO nanoparticles to the heat pipe's working fluid had a noticeable improvement in its thermal performance. The findings of this research have important implications for various industrial applications, including cooling systems, heat exchangers, and thermal management. The use of nanofluids in these systems can lead to improved efficiency, reduced energy consumption, and improved overall performance. However, further investigation is needed to fully understand the mechanisms behind enhanced nanofluid heat transfer and overcome the challenges associated with their use, such as increased pressure drop and potential nanoparticle agglomeration.

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