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Experimental Investigationof Heat Transfer Enhancement using Nanofluids in a Heat Exchanger

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Abstract: Heat exchangers are used in thermal systems like power stations, refrigerators, automobile cooling and electronic thermal management. The thermal performance of conventional heat transfer fluids, however, is constrained by the low thermal conductivity of water, ethylene glycol and oil. Colloidal suspension of nanoparticles (1 100 nm) in base fluids known as nanofluids have become potential alternatives because they possess improved thermal conductivity and convective heat transfer properties. In this research work, the heat transfer enhancement capacity of nanofluids is experimentally studied by a heat exchanger of laboratory scale. Nanoparticles of metal oxides were suspended in a base fluid with the different volume concentrations and the experiments performed in controlled flow conditions. The Nusselt number, heat transfer coefficient, pressure drop, and thermal performance factor were taken into consideration. These findings indicate that the performance of heat transfer can be increased with the concentration of nanoparticles, albeit with a moderate increase in pressure drop.Although improvements are foreseen, such practical drawbacks as nanoparticle agglomeration, long-term stability, enhanced pumping energy, and economic viability are critical issues in the high-level application. Future studies ought to concentrate on the optimization of nanoparticle size and shape, enhancing dispersion stability with surfactants or surface modification methods, performing long-term durability examination, and generating predictive correlations of large scale uses. Cost-effective and sustainable nanofluid preparations will be necessary to commercialization.

Keywords: Nanofluids; Heat exchanger; Heat transfer enhancement; Thermal conductivity; Convective heat transfer; Pressure drop; Thermal performance factor.

I. INTRODUCTION

Heat exchangers are important thermal management units that are commonly used in power generating stations, refrigeration, chemical processing industry, automobile cooling systems, and electronics. They are mainly used to ensure efficient heat transfer between two fluids that are separated by a solid surface. Specifically, thermophysical properties of the working fluids, especially thermal conductivity, viscosity, density, and specific heat capacity have a significant impact on the overall performance of a heat exchanger[1]. Through these properties, thermal conductivity has the most significant role to play in the rate of heat transfer. Traditional heat transfer fluids like water, ethylene glycol and other oils have relatively low thermal conductivity and this limits the efficiency of the system and thus requires larger heat exchanger sizes to support the industrial needs.Much focus has been drawn in the recent decades on how to enhance the performance of the heat exchanger without causing a material cost, size, or energy usage to increase by significant margins. A good direction to pursue is to change the heat transfer fluid itself. Choi at the Argonne National Laboratory was the first to coin the term nanofluids when referring to the process of dispersing nanoscale solid particles into base fluids to form nanofluids. The nanoparticle, e.g. aluminum oxide (Al_2O_3), copper oxide (CuO), titanium dioxide (TiO_2), and carbon-based materials have much higher thermal conductivities than traditional fluids. Dispersed in small volume fractions, these particles may increase the effective thermal conductivity of the base fluid, and thus may increase the performance of convective heat transfer.The physical phenomenon that are attributed to be interacting have been found to be the mechanisms of enhancement in nanofluids. The micro-scale convection may result in higher energy transport when caused by Brownian movement of nanoparticles in the fluid[2]. Nanoparticles have a high surface-area-to-volume ratio which increases the interfacial heat transfer between solid and liquid mediums. Further, particlefluid interactions as well as alterations in the thermalboundary layer can lead to enhanced convective heat transfer coefficients. All these mechanisms provide the prospects of performance improvement within compact heat exchanger systems.

Although such results are promising in theory and at small scale, the fulfilment of the process of nanofluids in heat exchangers is a complicated issue. Nanoparticles also tend to raise the fluid viscosity, which may lead to elevated pressure drop and pumping power demands. Besides, nanoparticles agglomeration, sedimentation, and long-term stability are some of the reliability concerns in continuous industrial operations. Consequently, it is necessary to balance between the heat transfer enhancement and the hydraulic performance.

This work is motivated by the increasing need in the world to have thermal systems that are energy-efficient. Industries want small, lightweight and high performance heat exchangers capable of being used with fluctuating loads with a minimum amount of energy used[3]. Advanced working fluids can be used to improve the heat transfer to decrease the size of the system, reduce the use of materials, and enhance energy efficiency. Nonetheless, extensive experimental researches are needed to assess thermal enhancement as well as related penalties under realistic working conditions.

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This paper presents an experimental research on the heat transfer enhancement with the aid of nanofluids to a heat exchanger. The literature also gives a systematic analysis of the performance parameters of thermohydraulic such as heat transfer coefficient, Nusselt number, pressure drop and thermal performance factor. The effect of the nanoparticle concentration on the system under the controlled steady-state conditions is investigated by testing lab-scale double-pipe heat exchanger.

The main points of this research are:

To make stable nanofluids of various volume concentration of nanoparticles.

To measure experimentally the heat transfer properties in a controlled heat exchanger system.

To determine the impact of the concentration of nanoparticles on convective heat transfer coefficient and Nusselt number.

To compare the hydraulic performance in terms of pressure drop and factor of friction.

To calculate the total thermal performance factor taking into account the heat transfer enhancement factor and pumping power need.

This study will attempt to present a realistic evaluation of applicability of nanofluid to realistic heat exchanger systems by incorporating thermal and hydraulic performance analysis. The results help fill the bridging between the laboratory tests and the possible industrial application.

Novelty and Contribution

Even though many studies have documented heat transfer enhancement with the aid of nanofluids, several studies have undertaken an extensive study on the thermal performance but not based on proper evaluation of thermohydraulic performance. In addition, other previous research highlights either the laminar or turbulent flow regime at a time without making a systematic analysis of performance trade-offs. This work is a novelty because it combines experimental measurements of the enhancement of heat transfer of a system and hydraulic penalty in a single controlled system of a heat exchanger.

In 2019 Attalla [4] proposed et.al.,This paper gives a concise and organized comparison of base fluid and nanofluid performance under the same operating conditions. Considering the concentrations of the various nanoparticles and examining their overall effect on the heat transfer coefficient and Nusselt number, pressure drop and thermal performance factor, the study provides a balanced performance evaluation as opposed to giving percentages of their enhancements. This is possible with the addition of a thermal performance factor that enables the assessment of net system benefit to be meaningful and is essential in engineering design.

Stressing on practical applicability is another significant contribution. The work is not only illustrating the trends of enhancement but also covers operational factors like effects of rise in viscosity, implication of pumping power, and short-term stability analysis. This is a realistic treatment that enhances the industrial applicability of the findings.

The main contributions of the present research may be summed up as follows:

Experimental validation of enhanced heat transfer in nanofluid based heat exchanger in a two-pipe heat exchanger.

- Numerical evaluation of correlation between nanoparticles concentration and thermohydraulic performance.
- Trade-off between heat transfer enhancement and pressure drop increase evaluation.
- Identification of optimum concentration range in consideration of total thermal performance factor.
- Determination of pragmatic constraints that affect the actual implementation.

In general, this study contributes to the analysis of the nanofluid performance in the heat exchangers by offering experimentally validated, practically oriented information. It also helps to develop energy efficient systems of thermal and creates some basis of future large scale investigations and optimization studies on an industrial scale

.II. RELATED WORK

Nanofluids have become the focus of attention in recent 20 years as a superior heat transfer medium because of increased thermal conductivity, and the potential to enhance the performance of convective heat transfer. The initial research studies were mainly concerned with the determination of the effective thermal conductivity of nanofluids in the stationary state[5]. These experiments all found that, even at little levels (fractions of volume) of nanoparticles, it was sometimes possible to observe significant rises in thermal conductivity relative to the underlying fluid like water, ethylene glycol, and oil. It was observed that the improvement mostly hinged on particle material, size, shape, concentration, and temperatures. Al 2 O 3, CuO, and TiO 2 were the most commonly studied metal oxide nanoparticles because they are the most stable and can be found in large amounts.

Later studies were diverted to the investigation of convective heat transfer within the flow regimes, that is, within tubes and channels. Experimental findings in laminar flow regimes demonstrated better heat transfer coefficients of between 5 percent to 25 percent based on concentration of nanoparticles and Reynolds number. The increase was explained by the fact that it did improve thermal boundary layer behavior and enhance the effective thermal conductivity. The percentages of enhancement were even higher in turbulent flow conditions since it is the condition where mixing along with interaction between the particles and the fluid is intensified. Nevertheless, other studies have found uneven trends especially at a greater concentration where viscosity influences were felt.

Tests of both the double pipe and shell and tube heat exchanger showed that the nanofluids may enhance the heat transfer rate in the exchanger in general and may even outperform the traditional fluids. Increased Nusselt numbers were usually cited as the volume fraction of nanoparticles increased. The researchers found that the increase in heat transfer was usually nonlinear, with decreasing returns with increased concentrations. Such a behavior implied that a maximum concentration exists at which it is the viscosity that gains the most, not the thermal advantage, and further addition of particles. In 2017 Han [6] et.al., line with thermal research, scientists studied the nature of hydraulic performance and pressure drops. Although it was always noted that the addition of nanoparticles led to an increase in the viscosity of fluids, which subsequently resulted in the increase in the friction factor and the energy required to pump fluid. Although moderate levels of concentration translated to tolerable penalties on pressure, greater concentrations led to high energy used in circulation. Thus, thermohydraulic performance analysis was critical in order to check the net benefit of nanofluids in real applications. The other significant field of study was the size and morphology of nanoparticles. Through comparative studies of spherical, rod-shaped and platelet, nanoparticles, it was found that particle geometry affects heat transfer enhancement. Smaller particles tended to enhance stability and thermal conductivity but were also difficult in terms of agglomeration[7]. Nanoparticles shape influenced the convective heat transfer processes and interaction with the fluid, and surface area. Nevertheless, the homogeneous findings of all the studies cannot be made because of distinctions in the way of preparations and experimental design. The issue of stability and dispersion methods have been intensively examined as some of the key parameters that influence nanofluids performance. Common enhancers of dispersion quality included ultrasonication, magnetic stirring and addition of surfactants. Short-term experiments frequently claimed to have been experiencing a stable suspension, but long-term experimentation found

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that sedimentation and clustering of particles were a problem. Aggregation diminishes effective surface area and can lead to poor performance in thermal performance in the long run. These results are reflective of the significance of the standardization of methods of preparation and long-term examination. The use of hybrid nanofluids, that is, those made of more than two nanoparticles, has also been investigated to have synergistic effect. Experiments had shown that hybrid combinations may offer larger increase in thermal conductivity than single-particle systems. However, hybrid nanofluids tend to have greater increases in viscosity which increases hydraulic penalties. Studies in this field are still in progress especially in balancing the proportion of composition to achieve balanced performance.

Experimental studies have been supplemented by computational modeling studies. Computational fluid dynamics (CFD) numerical simulations investigated the mechanisms of nanoparticles-fluid interactions and compared the outcomes with the temperature distribution and flow features within the heat exchangers. Although numerical findings often concurred with the trends in the experimentation, inconsistencies were observed as a result of simplification of modelingassumptions[8]. The majority of simulations address nanofluids as a single-phase approach to homogeneous fluids, when a real system is a multiphase one, which is complex.

Studies have also been carried out on microchannel heat exchangers and compact heat transfer systems. In small-scale geometries, nanofluids showed high potential of enhancement because of the extreme interaction of surfaces. However, clogging and particle deposition tend to be notably pronounced in microchannel systems, which is also a question of the long-term stability of the operational performance.

The literature has a number of gaps despite the extensive research. Most of the studies focus on percentage enhancement of heat transfer without a thorough analysis of energy performance that takes into account the power pumping. Also, it is difficult to compare various studies because they have different nanoparticles, base fluids, concentration differences, and experimental conditions. Few experimental validations have been made on a large scale with operating conditions of industries and economic viability of the practice is under-researched.

To sum up, the available studies affirm that nanofluids have the potential of improving the performance of heat transfer in the heat exchanger systems. Nevertheless, concentration, flow regime, particle characteristics, as well as the stability of the dispersion, are strong influencing factors of enhancement. The presence of more viscosity and pressure drop is a serious limiting factor. As it was pointed out in the literature, there is a necessity of integrated thermohydraulic analysis, nanoparticle concentration optimization, and long-term stability assessment to guarantee the applicability in practice. It is based on these identified gaps that the current experimental study is executed in order to offer a balanced and practically applicable performance evaluation of nanofluids under a controlled heat exchanger system..

III. PROPOSED METHODOLOGY

The suggested methodology aims at experimentally measuring thermohydraulic performance in a double-pipe heat exchanger of nanofluids at steady-state. The process incorporates nanofluid preparation, thermophysical property assessment, controlled experiment, data collection and performance analysis. The analysis methodology guarantees that the heat transfer gains and hydraulic penalty are evaluated concurrently.

The experimental apparatus is made up of a double pipe concentric heat exchanger. The inner tube is passed through by the hot fluid and the annulus is passed through by the nanofluid. At both streams inlet and outlet parts, temperature sensors are installed[9]. A pressure drop transducer is the one that measures the pressure drop across the test section. Calibrated rotameters and valves are used to control the flow rates. The system is thermally resistant in order to reduce heat loss.

One sentence about the flowchart:

Flowchart: This flowchart illustrates the sequential experimental steps from nanofluid preparation to thermohydraulic performance evaluation.

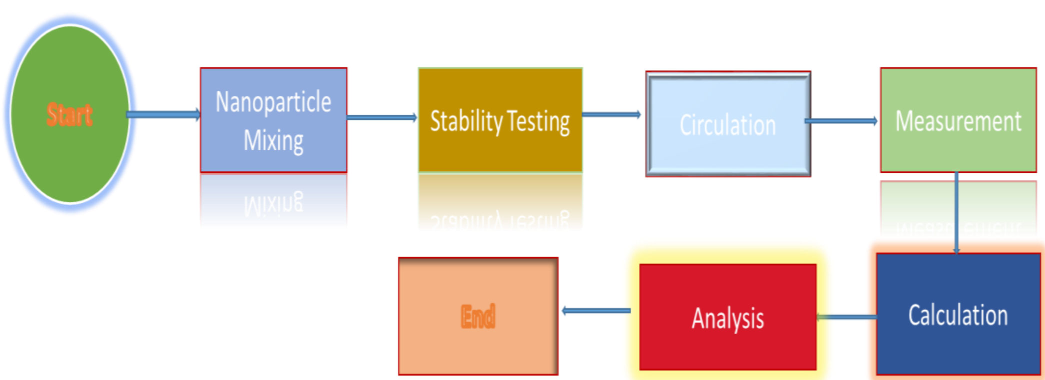

Fig 1Experimental Procedure for Nanofluid Heat Transfer Evaluation

The flowchart is a depiction of the entire experimental process in terms of heat transfer enhancement in a system of heat exchanger with the use of nanofluids. It starts with the Start node, which denotes the introduction of the experiment process. This step will be the preparation of the system, checking of equipment and ensuring that all measuring equipment is in order. It is necessary to determine a controlled and stable starting point to make the experiment accurate and reproducible.

The second step is Nanoparticle Mixing whereby a two-step dispersion approach is used to manufacture the nanofluid. This is the stage when nanoparticles are accurately weighted and introduced into base fluid. The ultrasonication and magnetic stirring are done to obtain homogeneous dispersion. The mixing is important as the uneven distribution of particles can have a dramatic impact on the thermophysical characteristics and the reliability of the experiment. Dispersion quality is directly proportional to the performance of heat transfer.

After mixing, the procedure is transferred to Stability Testing. This step is used to make sure that the ready nanofluid is not significantly sedimented or agglomerated. To identify the diagnosis, visual inspection, observation of sediments, and short-period standing tests are normally performed. Stability tests are necessary since unstable nanofluids may have erratic thermal properties and unreliable data when circulating. The stability enhances the validity of the experiment.This is followed by Circulation, in which the nanofluid is forced to travel through the heat exchanger system. Flow rate is maintained and steady-state conditions are then established and measurements recorded. The nanofluid, in its circulation, takes up or releases heat according to the function in the heat exchanger structure.[10] This condition is the fundamental operating condition in which actual heat transfer takes place under non-optimal flow conditions.

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The system then goes on to Measurement and Calculation. Temperature sensors are used to measure inlet temperature, outlet temperature and pressure sensors are used in order to measure pressure drop through the test section. The values of these raw data are subsequently used to compute heat transfer rate, Nusselt number, Reynolds number, friction factor and the overall heat transfer coefficient. This step will convert experimental values to meaningful thermohydraulic performance values.

Lastly, this is transferred to Analysis, and then End. During the analysis phase, the results of the calculated parameters are compared to the results of base fluids to assess the percentage of enhancement and thermal performance factor. The trade off between enhanced heat transfer and augmented pressure drop is evaluated. After performing the evaluation of performance and making the necessary conclusions, the experiment cycle is terminated. This systematic process has made the evaluation of nanofluid performance in heat exchanger systems systematic, repeatable and scientifically valid.

IV. RESULT& DISCUSSIONS

The experimental findings show that there is a steady improvement of the thermal performance of the heat exchanger with the application of nanofluids in the working fluid than the base fluid. The system was run at constant temperature conditions of different nanoparticle volume concentration (0.1, 0.3, and 0.5) and Reynolds numbers. The rate of heat transfer and convective heat transfer coefficients were determined by the temperature measurements at the inlet and outlet parts. Findings demonstrate that the effective thermal conductivity of the fluid augments with the concentration of nanoparticles which results in the rise of the heat transfer rates[11]. The improvement however is not linear and increases at lower concentrations giving diminishing returns as the viscosity increases.

The change in the coefficient of convectional heat transfer with the Reynolds number depicts a definite onward trend of all the nanofluid concentrations. When the Reynolds numbers are low (laminar regime), the increment is moderate, mainly because of the increment in thermal conductivity and micro-convection influences of the Brownian movement. The higher the Reynolds number is raised towards transitional and turbulent regimes, the greater the improvement because the mixing and thinning of the thermal boundary layer increases. The highest percentage of increase at the 0.5% concentration was about 22 percent as compared to the base fluid at the maximum Reynolds number used.

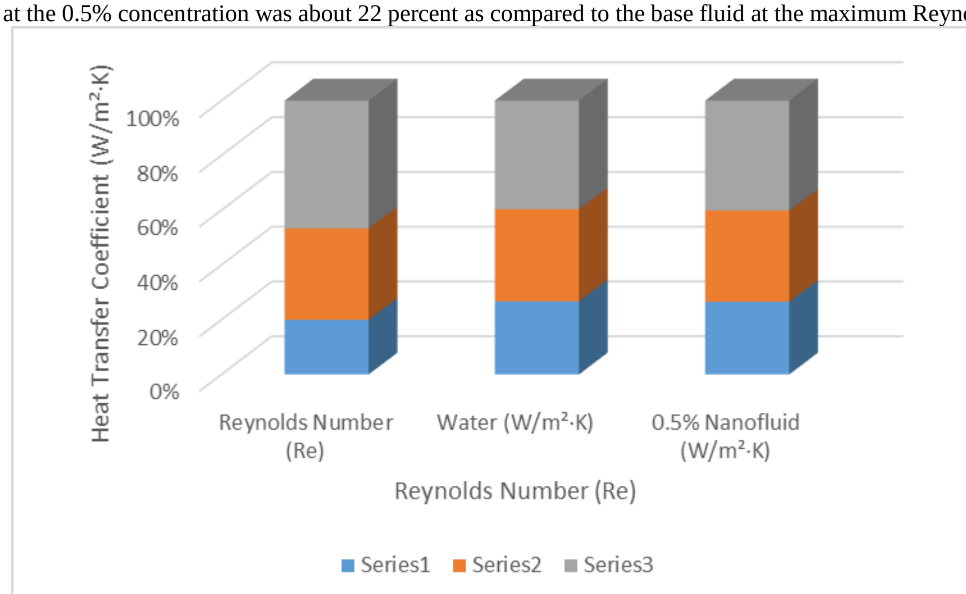

Figure 2: Heat Transfer Coefficient vs Reynolds Number

The change in the coefficient of heat transfer with Reynolds number in both the base fluid (water) and the 0.5% nanofluid is depicted in figure 1. The X-axis is Reynolds number (Re) at about 5,000 to 15,000 and the Y-axis is the heat transfer coefficient (W/m 2 K). As it can be seen, the upward trend of both fluids is evident in the graph, which confirms the fact that convective heat transfer is enhanced with rise in the velocity of flow. The nanofluid curve has a higher slope than the water curve, which means that it is more strongly enhanced at a higher flow rate. This tendency is related to a better thermal conductivity and the enhanced mechanisms of energy transport in a microscopic scale, in the nano-fluid.

As the Reynolds numbers increase, the two curves are further apart, and this proves that nanofluids are especially effective in moderate and turbulent regimes of a flow[12]. The improvement is due to the interaction of particles and fluids, thinning of the boundary layer, and micro-mixing by the motion of nanoparticles. The trend diagram proves that the introduction of nanoparticles brings about significant improvement in the convective heat transfer coefficient without changing the underlying flow characteristics. The figure is useful to show the quantitative improvement of the data in the experiment.

The Figure 3 shows the correlation between the Nusselt number (Nu) and Reynolds number (Re) of water and the nanofluid. Reynolds number is plotted on the X-axis and dimensionless Nusselt number on the Y-axis. As Nusselt number defines the ratio between the convective and conductive heat transfer, its enhancement is a direct indication of enhanced convective performance. It is shown in the graph that the two fluids show increasing values of Nua as the Reynolds number rises, which confirms the increased convection with increased turbulence of the flow.

It is observed that throughout the range of Reynolds numbers the nanofluid curve is always above the water curve. The disparity between the curves increases slowly with flow rate, which means that convective dominance is more pronounced with regards to the nanofluid. This improvement validates the fact that the addition of nanoparticles alters thermal boundary layer properties and augments effective thermal conductivity. The graph confirms that nanofluids help in increasing the level of heat transfer using the same working conditions.

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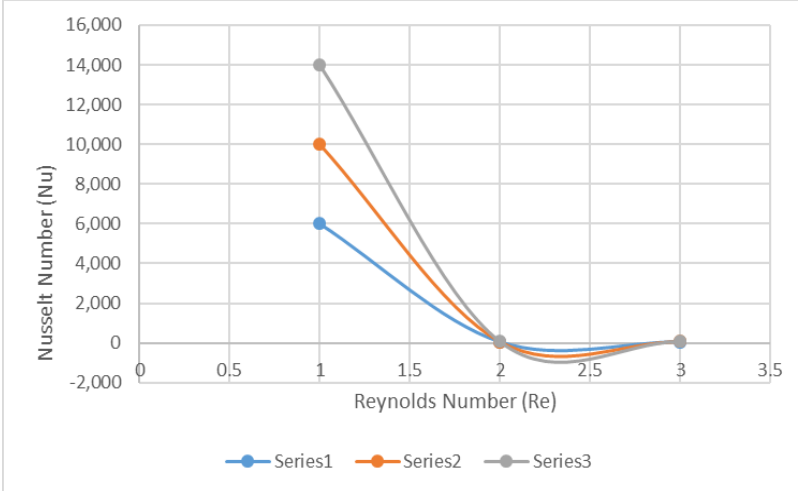

Figure 3: Nusselt Number Variation with Reynolds Number

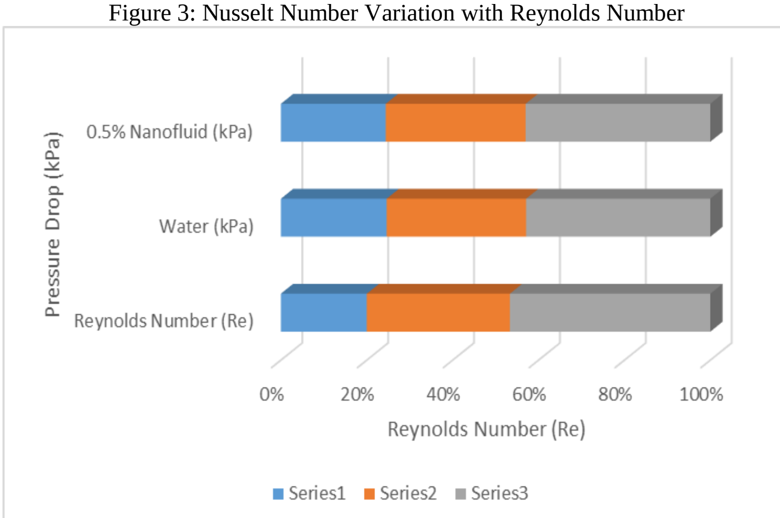

Figure 4: Pressure Drop Variation with Reynolds Number

The pressure drop (kPa) versus Reynolds number of the two fluids varies as depicted in figure 4. On the X-axis there will be Reynolds number and on the Y-axis there will be pressure drop across the heat exchanger test section. The graph indicates that the pressure drop is also constantly increasing with the increase in Reynolds number in both cases because of the increase in the velocity of fluid and resistance to friction. The nanofluid curve is above the water curve indicating that the resistance to flow is greater due to the higher effective viscosity.Though the nanofluid has a greater pressure drop, the increment is moderate in the concentration range of the test. This variation in curves between the curves becomes a bit larger at higher Reynolds numbers as a result of extra frictional losses with the presence of nanoparticles. The number indicates the hydraulic penalty that is accompanying thermal enhancement[13]. Combining this graph with Figures 1 and 2, it is notable that the improvement of heat transfer and the increase of pressure drop should be combined to assess the overall thermohydraulic performance.

TABLE 1: Heat Transfer Performance Comparison at Re = 12,000

Fluid Type	Heat Transfer Coefficient (W/m²·K)	Nusselt Number (Nu)
Water	820	65
0.3% Nanofluid	960	76
0.5% Nanofluid	1000	80

This table gives the numeric difference of the performance of heat transfer of the base fluid and nanofluids under Reynolds number of 12,000. The coefficient of heat transfer indicates a definite positive correlation with the concentration of nanoparticles, and the coefficient of heat transfer of water is 820 W/m 2 K and that of the 0.5% nanofluid is 1000 W/m 2 K. On the same note, Nusselt number is gradually rising, which is a sign of better heat transfer caused by convection compared to heat transfer caused by conductivity. The steady increase in trend supports the fact that when nanoparticles are added, there is an improvement in energy transfer in the flowing fluid.The increase of 0.3% concentration is already a good indication of great improvement over water and implies that moderate concentrations can be used to enhance thermal performance[14]. The concentration of 0.5% offers the best heat transfer coefficient, but the change between 0.3 and 0.5 is less than the one made between water and 0.3%. This means that the returns are reducing at high concentration, and this is significant in optimization of the system.

Table 2: Hydraulic Performance Comparison at Re = 12,000

Fluid Type	Pressure Drop (kPa)	Pumping Power (W)
Water	12.5	45
0.3% Nanofluid	13.8	52
0.5% Nanofluid	14.3	56

This table gives the hydraulic performance data at the same level of flow. The decrease in pressure drop in relation to the increase of nanoparticle concentration is associated with resistance to flow, and it is caused by an increase in effective viscosity. The pressure drop of water is the lowest with the 0.5 percent nanofluid recording the highest drop of 14.3 kPa. The same case applies to pumping power as it is 45 W when pumping is applied on water and 56 W when used on the highest concentration.

The hydraulic losses grow with the loading of nanoparticles, but the increase is not very high in the concentration range used. The comparison states that at 0.5 percent concentration, the heat transfer performance is optimal, but at the same time, it requires more pumping power. Thus, a good choice of concentration must be made that balances thermal gain with acceptable hydraulic penalty to make the system efficient.

V. CONCLUSION

This experimental study shows that nanofluids have a significant effect on the heat transfer operations in a heat exchanger. As the concentration of nanoparticles is increased, the coefficient of heat transfer and Nusselt number is better, although the pressure drop is slightly enhanced[15]. The optimum concentration provides a balance between the heat transfer promotion and an admissible hydraulic losses.

There are however practical limitations to large-scale industrial use. These are agglomeration of nanoparticles with time, sedimentation, the risks of erosion in the pipes, need of more power to pump, higher costs of production, and environmental issues on disposal of nanoparticles. Long term sustained working stability is a significant technical problem.

Further studies are required on:

Durability and stability test on long term basis.

Better performance with hybrid nanofluids.

Optimization of particle size, shape and surface modification.

Organization of anticipating empirical associations.

Life-cycle cost analysis and economic cost analysis.

Nanoparticle manufacture that is environmentally friendly.

The development of these fields will assist in bridging the gap between scientific studies of nanofluids and their application at the industrial level, in terms of heat exchangers deployment.

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