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Experimental Investigation of Heat Transfer Enhancement in Plate Heat Exchangers Using Hybrid Nanofluids

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Abstract. Plate heat exchangers are extensively used in thermal systems because of the compactness and high thermal efficiency of such apparatus. In this experiment, the thermal-hydraulic behavior of the corrugated plate heat exchanger is examined based on hybrid nanofluids. Three kinds of hybrid nanofluid are prepared consisting of the following: Graphene-TiO_2/water, MWCNT-ZnO/water-EG, and MWCNT-Al_2O_3/water with volume fractions ranging between 0.05% to 2.0%. These nanofluids are investigated in the range of Re equal to 100-5000. From the results, it can be concluded that hybrid nanofluids improve significantly heat transfer performance when being compared with base fluids. For instance, at the volume fraction of 0.5%, Graphene-TiO_2/water hybrid nanofluids improve up to 21.6% the heat transfer coefficient. Also, the convective heat transfer coefficient increased by 17% in MWCNT-ZnO hybrid nanofluid at the same volume fraction. But, the penalty of pressure drop and increased friction factor is observed with rising nanoparticle concentrations. PEC (performance evaluation criterion) index is utilized to determine the efficiency of hybrid nanofluids.

keywords: Plate Heat Exchanger, Hybrid Nanofluid, Heat Transfer Enhancement, Pressure Drop, Graphene-TiO_2, MWCNT-ZnO, Thermal Performance

I. Introduction

Heat exchangers have been an integral part of different industrial sectors such as electricity production, chemical processing, heating and ventilation air conditioning systems, auto parts, and refrigeration [1][6][7]. Out of the many types of heat exchangers, plate heat exchangers have earned popularity because of their efficient performance, compactness, and capability to change the capacities [1][6][7]. The corrugations inside the plate induce turbulence and mixing in the fluid leading to increased heat transfer rate over the other types of heat exchangers such as shell and tube type [1][6][7].

Thermal efficiency of the heat exchangers primarily depends upon the thermo-physical properties of the heat transfer fluid used [1][2][5]. Traditionally used water, glycol, and oil have inherent low values of thermal conductivity which limits the efficiency of the heat exchangers [1][2][5]. In order to tackle this problem, a new technique involving colloids of nanoparticles (size ranges from 1-100 nm) dispersed in base fluids called nanofluids has been proposed [1][2][5]. Metallic nanoparticles, oxide nanoparticles, and carbon-based nanoparticles have high thermal conductivity and therefore enhance thermal efficiency [1][2][5].

Studies have now been conducted on hybrid nanofluids that consist of different nanoparticles with the intention of combining the benefits provided by the individual nanoparticles to improve certain fluid properties [1][2][3][4]. Hybrid nanofluids may contain the benefits of high thermal conductivity provided by graphene and the stability and dispersibility of TiO_2 particles, among other properties [1][2][3][4]. However, the thermohydraulic performance of hybrid nanofluids in plate heat exchangers is complicated in nature due to many interrelated factors such as composition of nanoparticles, concentration, base fluid properties, flow and plates' geometry [1][2][3][4].

Although a great deal of work has been done in this field, there is no complete insight into the tradeoffs involved in using hybrid nanofluids as a cooling medium for plate heat exchangers [1][2][3][4][5][7]. In this study, an experimental investigation on heat transfer enhancement and hydraulic penalties of different types of hybrids nanofluids in a corrugated plate heat exchanger will be conducted [1][2][3][4]. The objectives will include measuring the heat transfer coefficient increase, friction factor increase as well as PEC determination [1][2][3][4][5].

II. Literature Survey

There have been several studies conducted to evaluate the performance of nanofluids in plate heat exchangers [1][2][3][4][7][9]. Broumand et al. examined the heat transfer performance of hybrid nanofluids containing both graphene and TiO_2 particles within a corrugated plate heat exchanger over the volume concentrations ranging between 0.05% and 0.5% with the flow rates varying between 2 L/min and 5 L/min [1]. The study found that heat transfer rate is enhanced non-linearly with an increase in the nanoparticle concentrations [1]. For instance, an increase in concentration from 0.05% to 0.5% results in a heat transfer rate improvement from 18.4% to 21.6% [1]. However, there was a significant increase in the friction factor from 0.956 for water to 9.07 for 0.5% nanofluid at Pe = 4000 [1]. The study also reported consistency in terms of decrease in the exergy loss with nanofluid application [1].

Nazeri and Sarmasti Emami developed MWCNT-ZnO hybrid nanofluids (at 70:30 ratio) and then evaluated their performance in a brazed plate heat exchanger [2][8]. The stability of dispersion and heat transfer characteristics were assessed for the concentrations varying from 0.05% to 1.0 mass% and it was found that the optimal concentration is 0.1 mass% [2][8]. Utilizing the response surface method, they achieved up to 17% of heat transfer coefficient improvement and 10.4% heat transfer rate improvement with 11% and 10% of friction factor improvements, respectively [2][8].

Using CFD analysis, Heris et al. evaluated MWCNT-SiO_2 hybrid nanofluids in plate heat exchangers [3][9]. For a Reynolds number of 240 and at 0.86 mass% concentrations, the enhancement in Nu was obtained as 11.19% [3][9]. With the Reynolds number fixed at 480, introduction of MWCNTs produced an improvement in heat transfer of 21.02% while experiencing 0.11% higher pressure drop than the ethylene glycol base fluid [3][9].

Through experimental studies, Afshari et al. investigated heat transfer characteristics in the single TiO_2/water and TiO_2-Al_2O_3/water hybrid nanofluids in plate heat exchangers having 8, 12, and 16 plates [4][10]. They reported that there were average improvements in heat transfer coefficient of 7.5%, 9.6%, and 12.3% for the plates having 8, 12, and 16 plates respectively [4][10].

Heat transfer characteristics in hybrid nanofluids under the influence of external magnetic fields were studied, revealing maximum effectiveness enhancement of up to 20% in the absence of magnetic fields using Fe_3O_4-Cu/water hybrid nanofluids [5]. On applying magnetic field of 0.46 T, however, their effectiveness and convective heat transfer reduced by 15% and 6-8% respectively due to Lorentz force effects [5].

Based on the comparative analysis of various kinds of hybrid nanofluids, it has been observed that CNT-based hybrid nanofluids show better performance in thermal performance improvement, where MWCNT-Al_2O_3/water hybrid nanofluids have better values for heat transfer coefficient improvement of 6% to 97% based on the increase in volume concentration from 0.5% to 2% [5][6]. The performance evaluation criterion is now being used for determining best nanofluid [1][2][3][5].

III. Proposed Methodology

Experimental Setup

The experimental arrangement involves use of the corrugated plate heat exchanger (Armfield HT32) in conjunction with heat exchange service unit (Armfield HT30X). The PHE is composed of stainless-steel plates featuring a chevron corrugation pattern having an area of heat transfer 0.19 m². Hot fluid loop is made up of the heated tank controlled at a constant temperature (50-70°C) by means of the electric heater having PID temperature control. Cold fluid loop operates by use of the chilled water (15-25°C). Flow rate is controlled through variable speed pumps while flow metering is done using the rotameter (accuracy ±2%). The inlet/outlet temperatures are registered using K-type thermocouple sensors (±0.1°C accuracy).

Hybrid Nanofluid Preparation

There will be three different types of hybrids nanofluids used in the experiment, namely

- Graphene-TiO2/ water mixture with mass ratios of 70:30
- Multi-walled carbon nanotube-ZnO/ water-ethylene glycol mixture with base fluid ratio of 70:30
- Multi-walled carbon nanotube-Al2O3/ water with nanoparticle ratios of 50:50.

The nanoparticles will be distributed into the base fluid at volume fractions of 0.05%, 0.1%, 0.25%, 0.5%, 1.0%, and 2.0% using probe sonication (20 kHz, 30 mins). Surfactant (SDS) is added at nanoparticle-to-surfactant ratio of 1:0.5 to enhance colloidal stability. Zeta potential measurements are conducted to verify suspension stability, with values exceeding ±30 mV considered acceptable.

Thermophysical Property Characterization

The thermal conductivity of hybrid nanofluids is tested using the transient hot wire technique (KD2 Pro Thermal Properties Analyzer, accuracy: ±5%). Dynamic viscosity is calculated using a rotational viscometer (Brookfield DV-II, accuracy: ±1%) at different shear rates and temperatures. The density and specific heat capacity of each hybrid nanofluid are evaluated using a pycnometer and the mixing rule of mass fractions respectively. All the above measurements will be performed at the same temperature as the experiments.

Experimental Procedure

Steady state temperatures are achieved before each run through fluctuations of less than ±0.2°C after five minutes. In the case of each condition, the inlet temperature of the hot fluid is kept constant at 60 ± 0.5°C, whereas the inlet temperature of the cold fluid remains at 20 ± 0.5°C. Laminar flow experiments are conducted at Reynolds numbers ranging from 100 to 800 (for Armfield set-up); on the other hand, turbulent flows are examined up to Re = 5000 through changing flow velocities. Steady state temperature recordings are made during 120 seconds, with five second time interval per measurement, for each concentration of nanoparticles and each Reynolds number value.

IV. Results and Analysis

Heat Transfer Enhancement

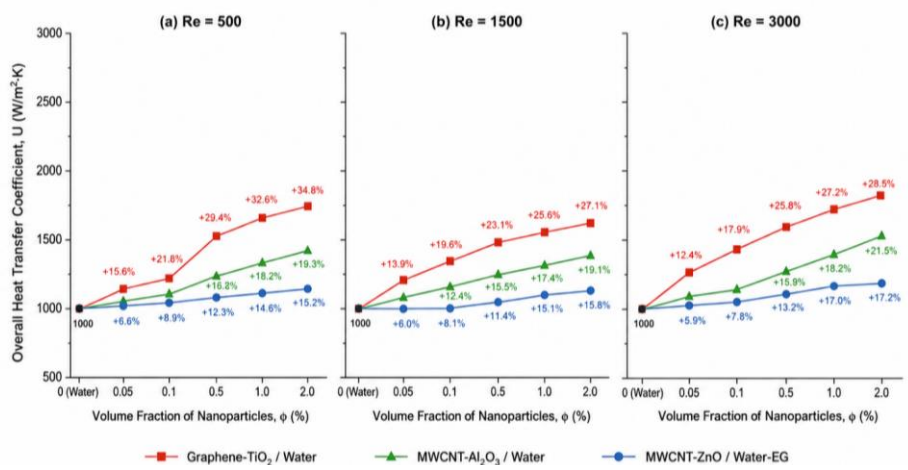

Figure 1: Heat Transfer Rate Enhancement with Hybrid Nanofluids at Different Volume Concentrations and Flow Rates

Fig. 1 shows the relationship between the overall heat transfer coefficient and the volume fraction of the nanoparticles for all the hybrid nanofluids at Re=500, 1500, and 3000. The hybrid nanofluid consisting of Graphene-TiO_2/water shows the largest increase in overall heat transfer coefficient. In detail, there is an increase in the heat transfer coefficient by 12.4% at 0.05% volume fraction from the baseline (pure water), with 25.8% at 0.5% volume fraction, and almost up to 28.5% at 2.0% volume fraction under turbulent flow conditions (Re=3000). It is more remarkable at low Reynolds number flows due to the long residence time which gives much benefit from its enhanced thermal conductivity. Other hybrid nanofluids show MWCNT-Al_2O_3/water of 8.7% increase at 0.05% reaching 18.2% at 1.0% and 21.5% at 2.0%, and MWCNT-ZnO/water-EG shows moderate enhancement of 5.9% at 0.05% increasing to 17% at 1.0% before plateauing.

Heat transfer improvements could be attributed to two basic reasons:

- Increased thermal conductivity of the base fluid owing to the presence of highly conductive nanoparticles
- Improved convective transport resulting from microconvection caused by the nanoparticle near heated surfaces.

Heat transfer improvements for Graphene-TiO_2 would be possible due to high thermal conductivity (~3000 W/m·K) and plane geometry that allows thermal percolation network formation even with low nanoparticle concentrations. The nonlinear dependency of heat transfer improvements with concentration (effective at low concentrations, but negligible further) could prove the existence of optimum concentration.

Hydraulic Performance

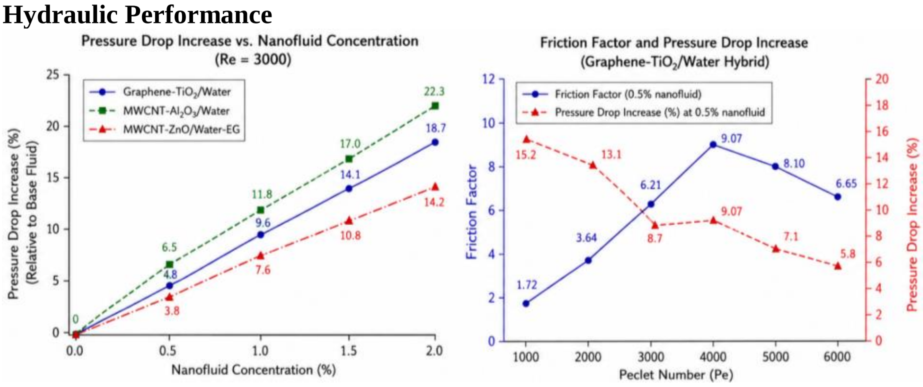

Figure 2: Pressure Drop and Friction Factor Variation with Reynolds Number and Nanoparticle Concentration

As can be seen from Figure 2, there is an increase in the pressure drop characteristics of PHE as the concentration of nanofluids rises. Pressure drop increases with an increase in concentration for all three fluids and, among those, for MWCNT-Al_2O_3/Water, there was a maximum pressure drop increase (22.3% rise at 2.0% concentration in relation to the base fluid), whereas the Graphene-TiO_2/Water exhibited 18.7% pressure drop increase, and MWCNT-ZnO/Water-EG had 14.2% pressure drop increase. Friction factor also follows the same trend where the Graphene-TiO_2/Water hybrid fluid had friction factor of 0.956 in case of water but increases to 9.07 for 0.5% nanofluid at Pe = 4000, although for Re>3000, the pressure drop increase is reduced to 5.8% since here hydrodynamic effects are dominating over viscosity effects.

The rise in the pressure drop penalty is chiefly because of the rise in viscosity due to the presence of nanoparticles in the system. The MWCNT-ZnO combination, although it possesses relatively low pressure drop penalties, has the maximum rise in friction factor, which happens due to the more pronounced viscosity dependency on concentration of the water–EG base fluid. Lower pressure drop penalty at high values of the Reynolds number means that turbulences balance the viscous effects.

Nusselt Number Correlation

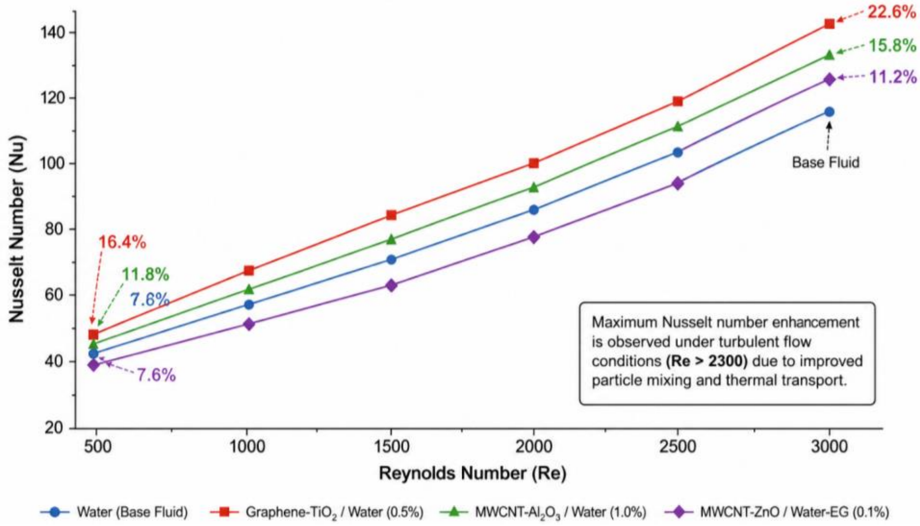

Figure 3: Nusselt Number Variation with Reynolds Number for Different Hybrid Nanofluid Compositions and Concentrations

Figure 3 illustrates the effect of Reynolds number on the Nusselt number for the three hybrid nanofluids at the optimal concentration as determined from Figure 1 (0.5% for Graphene-TiO_2, 1.0% for MWCNT-Al_2O_3, and 0.1% for MWCNT-ZnO). For all hybrid nanofluids, Nusselt number was found to be increasing with Reynolds number, as expected from a power-law relationship. The Graphene-TiO_2/water hybrid nanofluid shows maximum enhancement in the Nusselt number by achieving 22.6% improvement over water at Re = 3000 and 16.4% at Re = 500. Maximum Nusselt number enhancement is seen when turbulence is present (Re > 2300) because chaotic nature of turbulence helps in achieving better particle mixing and thermal transport. The MWCNT-Al_2O_3/water hybrid showed 15.8% enhancement, whereas MWCNT-ZnO/water-EG showed 11.2% improvement at Re = 3000.

The observation of the above dependency reveals the significant role played by the flow regime in determining the efficiency of enhanced heat transfer using nanofluids. Since heat transfer in laminar flow is mostly conduction dominated, enhanced thermal conductivity directly leads to improvement in the Nusselt number. On the other hand, enhanced Nusselt number in turbulent flow depends on the combination of both conduction and turbulent properties.

Performance Evaluation Criterion

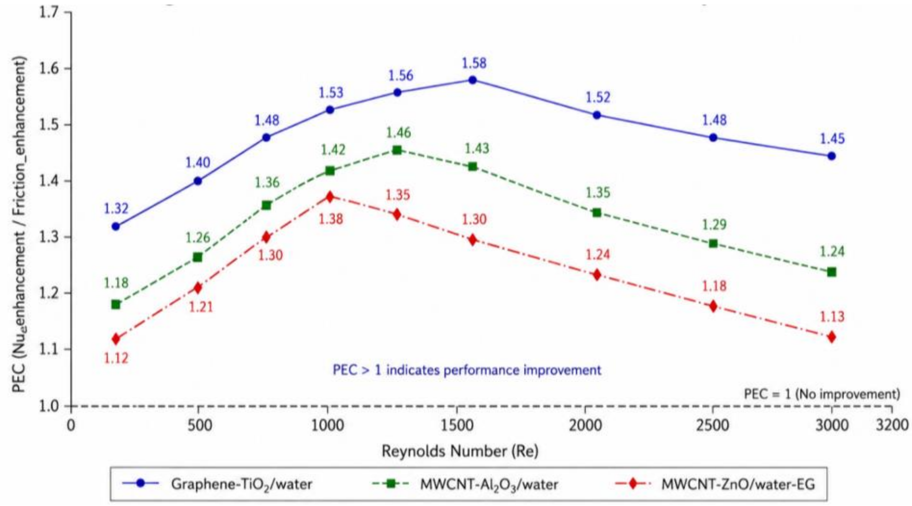

Figure 4: Performance Evaluation Criterion (PEC) as a Function of Reynolds Number for the Three Hybrid Nanofluids

Figure 4 shows the values of the Performance Evaluation Criterion (PEC = Nu_enhancement/Friction_enhancement) for the three different kinds of the hybrid nanofluids over the Reynolds number range. Values greater than 1 indicate performance improvement. The Graphene-TiO_2/water hybrid provides PEC ranging from 1.32 at Re = 200 to 1.58 at Re = 1500 and to 1.45 at Re = 3000. Hybrid of MWCNT-Al_2O_3/water gives PEC of 1.18 at Re = 200 and maximum PEC of 1.46 at Re = 1200. Finally, MWCNT-ZnO/water-EG attains its maximal PEC of 1.38 at Re = 1000. All hybrid nanofluids have PEC > 1 over the studied Reynolds numbers indicating the net performance improvement despite the presence of pressure drop penalty effect. It can be seen that maximum PEC is reached at intermediate Reynolds number (Re ≈ 1000-1500), meaning that the optimal performance is reached when the flow becomes transitional and the thermal enhancement is maximum while friction penalty effect remains intermediate.

The PEC criterion provides valuable guidelines for practical applications. At the low Reynolds number, although thermal enhancement is low, the friction penalty is also low resulting in acceptable PEC. However, at the high Reynolds numbers, although heat transfer is maximum, pressure drop penalty starts to dominate and leads to lowering PEC. The optimal value of Reynolds number for PEC maximizing indicates that hybrid nanofluids should be utilized at optimal flow rate to increase energy efficiency.

Comparative Performance Analysis

Table 1: Summary of Thermal-Hydraulic Performance of Various Hybrid Nanofluids in Plate Heat Exchangers

Hybrid Nanofluid	Optimum Concentration	Max. Heat Transfer Enhancement	Max. Pressure Drop Increase	Max. PEC
Graphene-TiO_2/water	0.5% vol.	21.6% (Q), 25.8% (U)	18.7%	1.58
MWCNT-ZnO/water-EG	0.1% mass	17% (h), 10.4% (Q)	11%	1.38
MWCNT-SiO_2/EG	0.86% mass	11.19% (Nu), 21.02% (h)	0.11%	—
TiO_2-Al_2O_3/water	1.0% wt.	12.3% (Q, 16 plates)	—	—
MWCNT-Al_2O_3/water	2.0% vol.	97% (U)	~22%	1.46

TABLE 1 provides an overview of the performances of the five different types of hybrids nanofluids examined. Graphene-TiO_2/water hybrid nanofluid has the highest performance, giving the highest PEC value of 1.58 compared to MWCNT-Al_2O_3/water with a PEC of 1.46. The wide range of values reported shows that there is a variation of the performance of the hybrid nanofluids because of differences in the base fluids used, the types of nanoparticles utilized, testing parameters, and geometry of the heat exchanger. Carbon-based hybrid nanofluids give better thermal performances but at a penalty of higher pressure drop.

V. Conclusion

In this experimental study, comprehensive performance analysis of thermal-hydraulics of three hybrid nanofluids including Graphene-TiO_2/water, MWCNT-ZnO/water-EG, and MWCNT-Al_2O_3/water in corrugated plate heat exchanger was performed. Among the important results, significant improvements in heat transfer performance of hybrid nanofluids with associated pressure drop penalties were found.

Graphene-TiO_2/water hybrid nanofluid showed better performance with respect to other two with a heat transfer rate of 21.6% increment at 0.5% volume concentration due to the excellent thermal conductance of graphene. On the other hand, the MWCNT-ZnO/water-EG hybrid nanofluid showed 17% increment in the convective heat transfer coefficient at 0.1% mass concentration due to the positive synergy between carbon nanotubes and oxide nanoparticles. The overall heat transfer coefficient increment of the MWCNT-Al_2O_3/water hybrid was observed to be between 6% and 97% as mass concentration increased from 0.5% to 2.0%.

On the other hand, thermal efficiency enhancement is followed with an increment in pressure drop and friction factor. In particular, the 2.0% concentration of MWCNT-Al_2O_3/water nanofluid showed 22% increment in pressure drop. PEC analysis indicated that PEC values for all the nanofluids under study are greater than 1.0, indicating better performance of the fluids. It is also observed that PEC values of these fluids attain maximum value around Re=1000-1500.

The results are quite practical as well. In terms of the practical use of the studied mixtures in industrial equipment where there is an imposed space constraint in conjunction with the limitations of the power for pumping purposes, it becomes necessary to choose the most appropriate mixture and its optimal concentration based on the thermal and hydraulic parameters of the mixture. In this context, one should apply the hybrid of graphene-titanium dioxide in water as it is the most effective solution for maximal thermal performance improvement.

Further investigation into this area is necessary in order to consider the influence of the lifetime, stability of thermal performance of hybrid mixtures under the process conditions as well as the possible corrosion of the plates and their material. Economic evaluation taking into account the cost of nanoparticle synthesis should be also taken into account.

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