Application of Carbon-based Nanofluids in Heat Exchangers: Current Trends

Adeola O. Borode 1, *, Noor A. Ahmed 1 and Peter A. Olubambi 2

1 Mechanical Engineering Department, University of Johannesburg, South Africa.
2 Department of Metallurgy, University of Johannesburg, South Africa.
Corresponding Author; aborode@uj.ac.za

Abstract-
The thermal performance of a heat exchanger can be enhanced by adding carbon nanostructured materials such as carbon nanotubes and graphene to the conventional working fluid. When nanomaterials are suspended in the working fluid, the fluid is known as Nanofluid. The enhancement in the thermal and rheological properties of the fluid is responsible for the augmentation in heat transfer performance. The influence of carbon nanomaterial on the thermophysical properties, heat transfer characteristics and flow properties are reviewed. The current trends on the utilization of carbon-based nanofluids in heat exchangers were reported. The study shows that carbon-based nanofluids have the potential to improve the performance of heat exchanger and reduce the cost of fabrication by reducing heat exchange area. The study identifies the scope for future study.

Key words: Graphene, Carbon Nanotubes, Nanofluids, Heat transfer, Performance, Radiator

1. Introduction
Over the years, the need to intensify heat transfer rates of heat exchangers by decreasing heat exchange time and improving energy efficiency led to the adoption of fins to augment heat exchange areas which in turn increases the weight and the volume of heat exchangers [1]. This led to the incorporation of nanofluids which are prepared by the suspension of nanomaterials to base fluids to augment the heat transfer characteristics of the base fluid. A lot of literature has reported that addition of specific concentration of nanoparticles in conventional fluids elevates thermal conductivity and improve thermal performance of the heat transfer systems [2]–[4]. Dispersion of Nanoparticles into a base fluid does not only improve the thermal conductivity of the fluid, but it also affects other properties such as viscosity and specific heat which influences the convective heat transfer [3], [5]. The other factors that remarkably alters the thermophysical properties of nanofluid include the nanomaterials used, the concentration of nanomaterials, purity level, morphology of nanomaterials and preparation method. Nanomaterials of various types such as metal oxides [6]–[8], carbon nanomaterials [9], [10], ceramics [11] etc. have been used in preparing nanofluids but none possess the exceptional thermophysical properties of carbon nanomaterials such as graphene and carbon nanotubes. Carbon-based nanofluids are mostly prepared either by one step method or two-step method [12]. The one-step method is the simultaneous synthesis of carbon nanomaterials and preparation of the nanofluid while two-step method which is frequently used involves the synthesis of the dry carbon nanomaterials and subsequent dispersion in conventional fluid [13]. Two-step method is less expensive and suitable for large scale production but achieves long-term stability is a major challenge due to the hydrophobic nature of nanomaterials. However, different physical and chemical treatments have been employed to solve this issue.
Some of the physical treatment includes homogenization and ultrasonication [14] while the chemical treatment includes covalent functionalization using acids or alkaline and non-covalent functionalization using surfactants or polymers such as sodium dodecyl sulfate (SDS), Gum Arabic, sodium dodecylbenzene sulfate (SDBS) etc. [9], [15]

This study reviews the development on the application of carbon-based nanofluids in heat exchangers. Effects of nanofluid concentration, fluid inlet temperature and mass flow rates on the thermal conductivity, viscosity, specific heat, heat exchanger efficiency and pressure drop have been reviewed. Scope for future study was also discussed.

2. Thermal and Rheological Characteristics of Carbon-based Nanofluids

Many authors have conducted experiments to measure the thermal conductivity, viscosity and specific heat of carbon-based nanofluids. Addition of nanomaterials in base fluids such as water, ethylene glycol and oil were reported to significantly improve thermal conductivity and viscosity while it reduces the specific heat.

Sadeghinezhad et al. [16] measured the thermal conductivity and viscosity of graphene nanoplatelet (GNP) based nanofluid of various concentrations ranging from 0.025 to 0.1 wt% and a temperature between 10 to 40°C. The result showed an increase in thermal conductivity owing to increase in GNP concentration and temperature. The thermal conductivity enhancement was between 7.96% and 25%. Also, viscosity was found to rise with increase in GNP concentration while it reduces when temperature is elevated. A viscosity enhancement of 9-38% was reported.

Askari et al. [17] carried out an investigation into the impact of multi-walled carbon nanotubes (MWCNTs) and nanoporous graphene on thermal conductivity and viscosity of water. Nanofluid samples were prepared by adding different concentrations of MWCNTs and nanoporous graphene in water with tween 80 as dispersant. The thermal conductivity, viscosity and density of the fluid was found to increase when concentration of the nanomaterial additives is raised at a constant temperature. Also, increase in nanofluid temperature was observed to intensify the thermal conductivity of nano fluid and decreases viscosity.

Shende and Ramaprabhu [18] evaluated the thermal conductivity of different concentrations (0.005, 0.01 and 0.03 vol%) of reduced graphite oxide (rGO) suspended to various base fluids (water and EG). The outcome revealed an intensification in thermal conductivity of the two base fluids when the concentration of rGO is increased and when the temperature is higher.

From the studies in this section, it can be established that increasing graphene or carbon nanotube (CNT) loading in a conventional fluid raises thermal conductivity, viscosity and density of the fluid and reduces specific heat. This enhancement in thermophysical properties at high nanomaterial concentration and a higher temperature is ascribed to the Brownian motion responsible for random movements of particles which enhances with increase in nanomaterials and at elevated temperature. Another mechanism responsible for this thermal enhancement is the layered structure of nanomaterial surface and liquid molecules which is the thermal bridge between the liquid and the nanomaterials.

The morphology of the nanomaterials was also reported to influence the nanofluids’ thermophysical characteristics. Xing et al. [19] studied the thermal conductivity of nanofluids of CNTs of different aspect ratios which include 1000-3000 (MWCNTs), 500-3000 (short SWCNTs) and 2500-30000 (long SWCNTs). The result revealed that nanofluids with CNTs of higher aspect ratio have the highest intensification in thermal conductivity. This is because
of the minimal resistance on the CNT-fluid interface due to its large contact area for base fluids.

Mehrali et al [20] researched the influence of graphene nanoplatelet (GNP) with various average specific surface area (SSA) on the thermal conductivity of nanofluids. A thermal conductivity increments of 14.8%, 25% and 27.64% at 35°C was reported for nanofluid with 0.1 wt% GNP with average SSA in the order 300, 500 and 750 m²/g. This indicates that a higher surface area presents a higher enhancement in thermal conductivity.

Chen and Xie [21] reported a thermal conductivity increment of 12.1%, 14.2% and 15.6% for nanofluids with 0.2 vol% CNTs of different diameters in the order MWCNTs, double-walled CNTs (DWCNTs) and single-walled (SWCNTs). In contrast, Martin-Gallego et al. [22] revealed that MWCNT/resin epoxy nanofluid produce a higher thermal conductivity augmentation in comparison to SWCNT/resin epoxy nanofluid. This indicates that the base fluid used also affects the thermal conductivity and viscosity of nanofluids.

The surfactant used in stably dispersing nanomaterials into base fluid was also found to impacts the thermal conductivity and viscosity of nanofluids. Sadri et al. [5] used 0.25wt% of different surfactants (GA, SDBS and SDS) to suspend 0.5wt% of MWCNT S in water. The results showed that nanofluids prepared with GA and SDBS surfactants have an elevated thermal conductivity in comparison to water while the thermal conductivity of SDS-dispersed nanofluid is lesser than that of water. The poor performance of SDS on the thermal conductivity agrees with the study by Assael et al. [23] They also reported that raising the loading of cetyltrimethylammonium bromide (CTAB) and Triton X-100 in MWCNT-nanofluid improved the thermal conductivity of nanofluid. Maliaud et al. [24] found an increment in the viscosity of CNT nanofluid with the addition of SDS and Triton X-100 surfactants.

From all the studies reviewed in this section, it can be established that factors such as the concentration of nanomaterials, the morphology of nanomaterials, the temperature of nanofluid, base fluid and surfactants significantly influence the thermal and rheological characteristics properties of nanofluids of graphene and CNTs.

3. Performance of Heat Exchangers using Carbon-based Nanofluids

Heat exchangers are devices employed in industries to transport heat from one fluid to another. The parameters to evaluate the performance of a heat exchanger includes heat transfer coefficient (HTC), friction factor, pressure drop and pumping power. Numerous investigations have been carried out to evaluate the heat transfer performance of heat exchangers using MWCNTs and graphene nanofluids. Different works of literature on use of nanofluids in heat exchangers such as automobile radiator, plate-type heat exchanger, shell and tube heat exchanger and double-pipe heat exchangers are reviewed in this section.

Teng et al. [25] measured the heat transfer capacity of different concentrations of MWCNT-nanofluid flowing in a heat exchanger at volumetric flowrates ranging 0.6 to 2.0 L/min. The outcomes revealed a 7.77% maximum augmentation in heat transfer capacity of the heat exchanger using 0.25% MWCNT nanofluid flowing at 2L/min in relation to water.

Selvam et al. [26] assessed HTC and pressure drop in an automobile radiator using various concentrations of GNP nanofluid under laminar flow condition. The effect of flow rate, fluid inlet temperature and nanofluid concentration was studied. The outcome revealed that the convective HTC increases when the mass flow rate, inlet temperature or the concentration of GNP is raised. Meanwhile, the pressure drop was found to increase with an increase in GNP
concentration but decreases with increase in temperature. The increase in convective HTC and decrease in pressure drop at elevated temperature could be attributed to the corresponding increase in thermal conductivity and decrease in viscosity at a higher temperature. A maximum enhancement of 20% and 51% was reported was GNP nanofluid with a concentration of 0.4 vol% at a mass flowrate of 100 g/s at an inlet temperature of 35°C and 45°C respectively. The pressure drop was found to decrease by 1kpa for a similar increase in the fluid temperature.

Chougule and Sahu [27] utilized different concentrations (0.15-1.0 vol%) of CNT nanofluids in an automobile radiator at different mass flow rates of 2 to 5 L/min. Results revealed an increase in Nusselt number owing to increase in nanofluid concentration and mass flowrates. The biggest enhancement in Nusselt number is 90.76%. In another study, the authors [28] found that pH of nanofluid affects the performance of radiator. The performance of radiator using acid-functionalized based nanofluid with a pH of 5.5 was reported to be better that nanofluid with a pH between 6.5 to 9. This is because a more acidic nanofluid is more stable and exhibit less agglomeration due to the higher charges on the CNT surface. In addition, CNT nanofluid dispersed with SDS was found to exhibit poor performance at high temperature. This is because the CNT nanofluid loses its stability at high temperature where the bonding between SDS and CNTS is weakened.

M’hamed et al. [29] conducted an experiment to evaluate thermal characteristics of a vehicle radiator utilizing MWCNT/EG-water nanofluid. The test was carried out at different Reynolds number (430-1400) and mass flow rates (2, 4 and 6 L/min). The HTC was found to increase from 986.8 to 2951W/m2K when the Reynolds number of 0.5vol% MWCNT nanofluid was raised from 430 to 1400. This enhancement in HTC is due to a greater blend of nanofluid at higher Reynolds number. an augmentation in HTC was also observed with an increase in the volumetric flowrates. This is ascribed to intensification in Brownian motion with amplification of collision between particles and particles with the radiator wall. This Brownian motion induced movement means more energy exchange and thermal conductivity which presents HTC intensification.

The convective HTC of a shell and tube heat exchanger utilizing graphene nanofluid in a laminar flow regime was evaluated by Ghozatloo et al. [30]. The authors investigated the influence of graphene concentration and temperature on convective HTC. HTC enhancement was found to increase from 15.3% to 23.9% for nanofluid with GNP loading of 0.025 wt% and 0.1 wt% at 25°C and 38°C inlet fluid temperature respectively. Vasconcelos et al. [31] observed the superior thermal performance of a vapour compression refrigeration system with a counterflow brazed plate heat exchanger utilizing SWCNT/water nanofluid as the secondary fluid in comparison to water. Increase in the performance and refrigerating capacity of the system was reported with an increase in mass flow rate and inlet temperature of the fluid. This attribute is not specific only to nanofluid but also to water. This shows that thermophysical properties of nanofluid is what is responsible majorly for the intensification in heat transfer performance and not Reynolds number, mass flow rates or inlet temperatures.

Kumaresan et al. [32] conducted a study to determine the convective HTC of a tubular heat exchanger using CNT nanofluids. The nanofluids samples were prepared by adding different concentrations (0.15, 0.30 and 0.45 vol% of MWCNT) into a blend of water and EG (70:30). The highest augmentation in convective HTC was disclosed as 160% with MWCNT loading of 0.45% in the base fluid. Increase in MWCNT loading and Reynolds number gives an increase in the overall HTC, Nusselt number and pressure drop while the change in frictional
factor us negligible. Moreover, an increase in inlet temperature leads to an increase in overall HTC but have no significant effect on the friction factor and pressure drop. Goodarzi et al. [33] studied the impact of nitrogen-doped graphene (NDG) nanofluid on the convective HTC, pressure drop and pumping power of a counterflow double pipe heat exchanger. They observed that dispersing of NDG to the base fluid and/or increasing Reynolds number enhanced the HTC, friction factor, pressure drop and pumping power. However, for a low nanofluid concentration of 0.06 wt%, the increase in pumping power was found to be negligible while the augmentation in HTC is 15.86%.

4. Present State and Scope for future study

From the studies reviewed in the previous section, it was established that increasing Reynolds number, flow rates and inlet temperature does not only increase heat transfer for nanofluids but for any working fluid. Thus, the two major factors that affects the performance of heat exchanger using nanofluids are majorly thermal conductivity and viscosity. Thermal conductivity augmentation result to heat transfer intensification while higher nanofluid viscosity gives the unwanted increase in pumping power. Thus, it is recommended to use nanofluids at elevated temperature due to its high thermal conductivity which gives higher heat transfer and lower viscosity which consequently produce lower pressure drop and pumping power penalty. Also, nanofluids should not replace conventional heat transfer fluids but heat exchangers should be redesigned to accommodate the different challenges associated with the rheological properties of nanofluids. Moreover, there is no common standard for preparing carbon-based nanofluid for use in heat exchangers. More studies still need to be done to evaluate the optimum nanofluid concentration to produce the best heat transfer performance with an insignificant pumping power penalty.

Lastly, limited studies exist on specific heat of carbon-based nanofluids and how it influences the thermal performance of a heat exchanger. Further investigation needs to be done to close this gap.

5. Conclusion

According to this review, the application of carbon nanomaterials as additives to the conventional working fluid in heat exchangers has been successful without the need to extend heat transfer surface. Owing to the exceptional thermophysical properties of carbon-based nanofluids, they have huge prospects to replace traditional working fluids and consequently save energy.

The following conclusions are drawn:

- Raising concentration of carbon nanomaterials in the base fluid elevates the thermal conductivity, viscosity and density of the fluid
- At elevated temperature, the thermal conductivity increases while the viscosity lowers.
- The specific heat of nanofluid decreases with increase in the concentration and temperature.
- The friction factor, pressure drop and pumping power were found to increase with an increase in nanofluid concentration. This was attributed to the enhancement in viscosity.
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