Thermal Conductivity of Nanofluids in Heat Transfer Applications – A Review

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Abstract-
The subject of nanofluid have been a major topic of research due to its numerous thermo-physical properties and several breakthroughs that have been recorded. Despite this, other challenges have also ensued. In this work, efforts were made to review the breakthrough, challenges that have been recorded in nanofluid applications as regards thermal conductivity. Thermal conductivity is a significant criterion to consider when dealing with heat transfer related works and several factors affect the performance of this systems; factors such as temperature, nanoparticle size, the method of preparation of nanofluid, volumetric loading, nanoparticle shape and base-fluid used. The result of the review showed that despite the success recorded in enhancing of these systems; by employing nanofluid to improve these systems there are still challenges that portends from the use of nanoparticle. Hence the need for further researches to done in order to address these issues

Key words: Heat transfer, thermal conductivity, nanofluid, volume fraction, temperature

1. Introduction

In the last few decades heat transfer has witnessed tremendous growth, owing to the discovery of nanofluid as stated by (Choi,1995) and better understanding of its application (Sidik, et al, 2018). Though, the use of nanofluid finds wide range of application in several fields of engineering, heat transfer related area is at the forefront of the revolution as opinioned by (Kulkarni, et al 2009), (Lee, 2014), etc. Nanofluid are fluids having a particle size between 1 to 100 nm, at this particle size, it possesses some intricate properties such enhanced thermal conductivity, viscosity, thermal diffusivity, convective heat transfer coefficient etc. which are vital to heat transfer processes. (Li, et al 2015) highlighted the methods for preparation of nanofluid namely single step method and the two step method the former involves synthesizing and dispersing at the same time avoiding the usual rigor of drying, storing and mixing with the basefluid as stipulated by (Eastman et al., 2001) while in the two step method the nanoparticles used are first dried by either chemical or physical method, the nano-scaled fluid are then dispersed into the solution before magnetic force agitation and other processes are applied for homogeneity. This method is the most used method, in nanofluid preparation and has wide acceptance in the scientific environment, largely due to the ease in preparation and economic importance of low cost.

However, the surfactants are used for the stability of nanoparticles, the aggregate formation are due to high surface area and activity and strong van der Waals that exist between the
nanoparticles (Yu and Xie 2012). Though particle clustering has often been reiterated has a major factor that increases thermal conductivity of nanofluid. Hence, the reason while it been considered during nanofluid preparation. As stated by (Das et al., 2007) due to the small size of nanoparticle it reduces erosion, clogging, pumping power reduction, saves energy etc. The ever-changing constant dynamics involving heat flow in heat transfer processes creating the demand for new technologies; in responding to the apparent technological advancement in the manufacturing, designs sector etc. have also culminated or led to the need of a more responsive approach to improving the active ingredient in heat transfer processes, for more efficient systems. The interest in the technology of nanofluid is strongly rooted in numerous attributes it possesses such as thermal conductivity, viscosity, and other physical properties. One significant property been thermal conductivity, due to the critical enhancement role it plays in heat transfer applications thereby making nanofluid of great importance to industrial application (Pinto and Fiorelli, 2016). Researches have shown that very small nanofluid composition applied to heat transfer process can have significant impact on the overall thermal conductivity of the fluid and the resulting measurement in terms of the improving the heat transfer capacity. Over the years, a lot of researchers have done several works both on the experimental and numerical analysis of the effect of nanofluid on heat transfer related system in a bid to optimize the efficiency of this systems. Figure1 below carefully highlights the several factors affecting thermal conductivity as regards nanofluids.

However, the results of the work done has brought about controversies in determining which of the reports actually demonstrates the true behavior of the fluid when doped nanofluid. Several authors have tried to report this, but the inconsistency in report creates the need for research to be done in this area so as to validate these assertions (Keblinski et al., 2008). (Buongiorno et al., 2009) investigated thermal conductivity in nanofluid, in the work they further buttress the argument made by numerous researchers on the inconsistency of results been obtained in relation to nanofluid. They used the effective medium theory regarding dispersed particle as propounded by Maxwell over a century ago and of recent corroborated by Nan et al., 1997 and discovered that it was in conformity with the data obtained experimentally i.e showing there was no anomalous enhancement noticed as regards the thermal conductivity of the nanofluid used for their test.

Furthermore, this paper seeks to review past work done on the nanofluid technology as regards how thermal conductivity affects the outcome of these systems while also looking at the critical factors affecting thermal conductivity such as size, shape, concentration, temperature, method of preparation of nanofluid and basefluid (Tawfik, 2017).

2. Thermal Conductivity
It is primarily the degree to which a material, substance is able to conduct heat. This is denoted by k. There are three (3) different modes in which heat is transferred between components be it solids, liquids or gases through conduction, convection and radiation. Ability to conduct heat is much easier than insulating it, under-listed are factors affecting thermal conductivity of a nanoparticle.
2.1 Temperature Influence on Thermal Conductivity

Several researchers have stated in their works that there is a direct proportionality between temperature and thermal conductivity of the material as a rise in one connotes and increase in the other and vice versa. According to (Mirbagheri et al., 2018) in their work on new thermal conductivity correlation with FMWCNT suspended in a binary base-fluid, stated that there was progressive change in temperature from 25 °C to 50 °C in relation with thermal conductivity and argued that it largely due to the noticeable increment in kinetic energy. Also, at higher temperature of the nanofluid thermal conductivity becomes largely visible and enhanced.
Heyhat and Irannezhad,(2018) used Ag nanofluid while trying investigating electrical and thermal conductivity of water basefluid reported a change in thermal conductivity with temperature, in the work a temperature range of 25 °C – 55 °C and the conclusion reached was a linear increment of temperature with thermal conductivity. Similarly, Trinh et al., 2018 investigated thermal conductivity in Gr-CNT hybrid nanofluid by modification with several functional groups such as hydroxyl and carboxyl, when a volume fraction of 0.07% was added the thermal conductivity of the hybrid nanofluid was 18 at 30 °C and 50% at 50 °C respectively. Also, Keyvani et al., 2018 carried out an experimental work on thermal conductivity in cerium oxide nanofluid in developing a new correlation and discovered that within the range of temperature (25 °C- 50 °C) inspected there was a significant increase in thermal conductivity with the temperature, supporting the assertion made by other researchers that thermal conductivity and temperature are directly proportional each other. Won and Park (2000) studied thermal flow in cooling system of a vehicle; in doing this a model was developed, behavioural pattern of heat transfer characteristics can be predicted by inputting the relevant information at the early stage. The result showed conformity with established results from literature. The model provided a clear sight into the performance of vital heat transfer characteristics such as pump delivery, size of radiator and thermostat. The test result further suggested that the analytical tool can be relied on to give accurate results thus reducing the dependency on test rig for analysis.

More so, (Pal, 2015) demonstrated the effects of atmospheric temperature on the performance parameter such as thermal efficiency, distance covered, specific fuel consumption of the automobile vehicle. The experiment was conducted in a car were and the readings of atmospheric temperature and speed were calculated for a year, it was discovered that the maximum mileage and thermal efficiency was attained in the month of March and the value of mileage and thermal efficiency are 22.6 km/litre and 29.48% respectively at a speed of 1550rpm.

In addition, (Morad and Airajhi, 2014) investigated the effect of temperature on engine parameter under Kuwait conditions, the author stated that engines are meant run a normal temperature between 90 to 115 °C if otherwise then there could be lot of possibility that could have gone wrong. The authors noted that with constant operating temperature comes good emission control, lower fuel consumption and better performance. Using a mix blend of ethylene glycol and water at a ratio of 25% and 75% respectively due to their good thermal conductivity property and antifreeze characteristic discovered that fan type A used with radiator 1 showed better cooling rate than other fan and radiator type as used in the experiment under Kuwait condition.

Table 1: Summary of other works were thermal conductivity is influenced by temperature

| Authors          | Temperature (°C) | Nanofluid/Basefluid | Thermal conductivity | Enhancement |
|------------------|------------------|---------------------|----------------------|-------------|
| Vakili et al., 2017 | 20-60 °C          | CuO                | -                    | Yes         |
| Kumar and Sonawane, 2016 | 30, 40, 50 °C              | CuO/water, CuO/EG and TiO2/water, TiO2/EG | 0.268, 0.273, 0.279 | Yes         |
2.2 Concentration Influence on Thermal Conductivity

One core parameter to examine when accessing thermal conductivity of nanofluid is concentration, being that the volumetric loading of a composition of a nanofluid does impact the behavior of the overall performance of the nanofluid, these was clearly stated by (Gan et al. 2018) in their work thermal conductivity optimization in a solar collector using titanium dioxide. In the work, a rise in thermal conductivity was noticed at higher volume fraction showing a correlation, though the sonication time had little or no effect on the overall outcome. Keyvani, et al., 2018 stated in their work thermal conductivity in cerium oxide and ethylene glycol nanofluid that 0.25% nanoparticle culminated in to 4% increment in thermal conductivity while an improvement of 2.8 and 4.8% was reported for 0.5 and 1% respectively solidifying the claim of volumetric loading influence on thermal conductivity. Li et al., 2015 described the relationship between thermal conductivity and volume fraction as that which is nonlinear owing to the variation in thermal conductivity ratio and the concentration of the nanoparticle, as an increase in thermal conductivity translates to a nonlinear increase in the volume fraction of nanofluid. Also, (Heyhat and Irannezhad, 2018) studied enhancement of electrical and thermal conductivities in water based nanofluid and acknowledge that though temperature and concentration of particle influences both thermal and electrical conductivity of the nanofluid, both factors can be said to have same impact of the thermal and electrical conductivity, however particle concentration still holds more significance to temperature effect as regards to electrical and thermal conductivity.

In addition to this, (Mahbubul et al., 2015) however stated that temperature increment in the Al₂O₃ and R-134a showed linearly increment while pure basefluid (R-134a) showed and inverse proportionality i.e. decrease with increasing temperature.

2.3 Effect of Shape, Size and Basefluid

Nanoparticle is a concept of nanotechnology playing host to several revelations of the factors affecting the behavioural or performance attributes associated with it. Just as temperature and concentration affect thermal conductivity so does the shape, size of nanofluid and the preparation of nanofluid impacts on the overall outcome of this fluid when used in heat transfer related processes. Over the years several researchers have worked on factors affecting the thermal conductivity. (Senthilraja et al., 2017) studied the effect of using CuO nanofluid as coolant in a four stroke engine, a particle size of 27nm was used and tested under different conditions with variation in the volume concentration.
Figure 3: Effect of Nanoparticle shape on thermal conductivity of nanofluids (Senthilraja et al., 2017)

Table 2: Summary of other works were shape, size and basefluid influences thermal conductivity

| Ref                  | Nanoparticle | Size (nm) | Shape | Basefluid |
|----------------------|--------------|-----------|-------|-----------|
| Esfe and Saedodin,   | MgO          | Yes       |       | Water     |
| 2015                 |              |           |       |           |
| Chandrasekar et al., | Al₂O₃        | Yes       |       | Water     |
| 2010                 |              |           |       |           |
| Mintsa et al.,       | Al₂O₃/CuO    | Yes       |       | Water     |
| 2009                 |              |           |       |           |
| Murshed et al.,      | TiO₂         |           | Yes   | Water     |
| 2005                 |              |           |       |           |
| Teng et al.,         | Al₂O₃        |           | Yes   | Water     |
| 2010                 |              |           |       |           |
3.0  Review on Effects of Thermal Conductivity of Nano-Fluids in Heat Transfer Applications

In this section the relevant works done as relating to the role played by thermal conductivity to nanofluid is considered. According to (Ranjbarzadeh et al., 2019) in the work stability and thermal conductivity of silica nanofluid stated that stability was achieved in the period of six months the fluid was studied after preparation, a temperature range between 25-55°C with a volumetric loading of 0.1-3%, the result of the work showed maximum thermal conductivity was attained at 55°C with an enhancement of 38.2% while a deviation of 2.72% was proposed from the correlation developed. (Li et al., 2016) investigated silicon carbide nanofluid in order to determine the thermo-physical relations in an operating car, using a volume concentration of 0.5% with varying temperature of range of 10°C to 50°C and discovered that the optimum thermal conductivity of 53.81% was achieved at 0.5% vol. conc. and at a temperature of 50°C. Also, Oliveira and Filho (2014) conducted a study on coolant in a radiator, with a nanoparticle size of 80 nm and 10 nm silver (Ag) nanofluid and employing the two-step method nanofluid preparation method ran the experiment under the following conditions 0.1 and 0.3% vol. con., inlet temperature of 25 °C and 45 °C. The result showed enhancement of 18% and 5% in thermal conductivity for both concentration of nanofluid respectively. Furthermore, Jadar et al., 2016 studied aluminum- multi walled carbon nanotubes in a radiator setup, in a bid to know it effect on the automobile component that is how its influences dissipation of heat and then reported a 12.26% improvement resulting in weight reduction in the new design.

According to Narella et al.,( 2014) stated that heat transfer process can be improved upon by either means of active or passive means of enhancement. Using solar collector nanoparticles were dispersed into the collector so as to increase the rate of heat transfer. In a bid to see significant increase in the rate of heat transfer nanofluid was used as opposed to conventional fluid. This can be done either by using conduction or convection heat transfer. (Sharahi et al., 2010) investigated thermal performance of flat shaped heat pipes using nanofluid the performance of using nonofluid in cylindrical heat pipes were studied. The velocity profile, temperature distribution, pressure were obtained using nanofluid as the working fluid for flat heat pipes. Due to the addition of nanofluid there was a decrease in thermal resistance and an increase in maximum load capacity. The existence of an optimum level of nanoparticle concentration level and wick thickness in maximizing heat capacity of flat shaped heat was established. (Husseina et al., 2014) studied A review of forced convection heat transfer enhancement and hydrodynamic characteristics of a nanofluid. The study used experimental and numerical method computations, simulations and found that most of them are in agreement with the results of experimental work. Many of the studies report enhancements in the heat transfer coefficient with an increase in the concentration of solid particles. Certain studies with a smaller
particle size indicated an increase in the heat transfer enhancement when compared to values obtained with a larger size. And mathematically reiterated the Nusselt and convective heat transfer coefficient transfer as:

\[ Nu = \frac{hd}{k} \quad \text{and} \quad h = \frac{Q}{T_w - T_f} \]

Nu is Nusselt number, h is heat transfer coefficient, k is thermal conductivity, T_w and T_f are the wall and fluid temperature respectively.

Voon, (2015) did a study on a car radiator using nanofluid as coolant and reported that an increase in thermal conductivity & viscosity is directly proportional to the concentration of nanofluid used, the experiment was done using hot wire method and the result showed an improvement in thermal conductivity by 0.5 to 20%.

| Ref | Nanofluid | Base-fluid | Conditions | Enhancement |
|-----|-----------|------------|------------|-------------|
| Nirnjalkuma and Gopal (2015) | Al_2O_3 | Water | 0.25% and 0.5% vol. con., temp. 35°C to 59°C | Yes |
| Hasanuzzaman et al., (2011) | Al, Al_2O_3, and TiO_2 | Water | 2% | Yes |
| Este et al., (2018) | MWCNTs-SiC | Water | Q = 0.015-0.55% Θ = 25, 50°C, @50°C, Q = 0.55% k = 35% improvement, | |
| Senthilraja et al., (2017) | CuO | Water | Q = 0.05, 0.1, 0.2%, size 27 nm, | Better exhaust emission control of 8.6%, 15.1% and 21.1% respectively |
| Bhimani et al., (2013) | TiO_2 | Water | Q = 0.1-1%, m_f = 90-120 lpm | @1% vol. conc. 45% enhancement achieved attributed to the increase in effective thermal conductivity |
| Sarkar and Tarodiya, (2013) | Cu, SiC, Al_2O_3 and TiO_2 | Ethylene glycol and water | Θ = 30 °C, 90 °C, m_l = 5 kg/s | Improved performance |
| Asadi (2018) | MWCNT-ZnO | Oil | Q = 0.125-1%, Θ = 15-55 °C, | Heat transfer coefficient enhancement by 42% |
| Sathish and Manivel (2016) | AgNO_3 | Water | Q = 0.05-0.2%, | An increment in vol. conc. Beyond 0.2 resulted in a decline in the heat transfer performance |
| Authors               | Fluids  | Medium | Volume Conc. | Temp. | Mass Flow Rate | Comments                                      |
|-----------------------|---------|--------|--------------|-------|----------------|-----------------------------------------------|
| Shivade and Bhangale (2016) | TiO₂ | Water  | φ =0.1-0.3\%, Θ = 55-75 °C, m_f = 100-600 lph, |       |                | Low vol. conc. Addition result in enhancement of heat transfer performance |
| Hamad (2016)          | CuO, TiO₂ | EG, water | φ = 0.5-5\% |       |                | @5\% vol. conc. 55\% enhancement and radiator efficiency was increased by 47\% |
| Wani and Ravi (2017)  | MgO    | water  | m_f = 5-9 lpm |       |                | Average heat transfer was enhanced by 40-70\% |
| Devireddy et al., (2016) | TiO₂ | EG, water | φ =0.1-0.5\%, EG:water = 40:60, Re=4000-15000 |       |                | @0.5\% heat transfer rate was improved by 35\%, |
| Hussein et al., (2014) | TiO₂, SiO₂ | Water | φ = 1-2\%, m_f=2-8 lpm, Θ = 60-80 °C |       |                | Nu attained optimum value at 11 and 22.5\% for both fluids used respectively |
| Ali et al., (2015)    | MgO    | Water  | φ = 0.06-0.12\%, m_f=8-16 lpm |       |                | Optimum enhancement picked at 0.12\% |
4.0 CONCLUSION

The continuous efforts by different researchers aimed at investigating effect of nanofluid on heat transfer related systems, seeking to optimize the systems leading to reduction in component size, cost and even fuel consumption. This works is an inclusive review of some of the numerous works done and how they relate to thermal conductivity. Several factors affecting thermal conductivity were reviewed with the aim of identifying the successes recorded, possible challenges etc. the factors considered are as follows: effect of temperature, size, shape, basefluid and volume concentration were critically examined and the outcome and findings from the numerous researches that worked extensive on this subject carefully highlighted. Though, other factors that could affect nanofluid such as viscosity, specific heat capacity, mass flow rate etc. were not covered in this review paper as our interest was tailored towards thermal conductivity.

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