

Convective Heat Transfer in Heat Exchangers Using Nanofluids: A Review

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ABSTRACT

Enhancing the Convective heat transfer in the carrier fluids, by augmenting the thermal conductivity in fluids, with nano particles is one of the passive techniques. Enhancement in the thermal conductivity in the carrier fluids can be achieved by suspending particles of nano-size into the base fluids, such colloidal suspensions are called as nanofluids. Nanofluids are proven fluids which improve the convective transfer of heat in the base fluids in the heat exchangers. But still, there are lot of challenges that are existing in understanding the mechanisms of enhancement of convective heat transfer for large scale applications. In this work, an attempt is made to summarize recent advancements on augmentation of convective heat transfer in heat exchangers in turbulent flows using various nanofluids and present various setbacks for the development of nanofluids for critical applications.

Keywords: nanofluids, thermal properties, viscosity, thermal conductivity, turbulent flow.

INTRODUCTION

Intensifying the heat transfer relies on the thermo-physical phenomenon pertaining to the working fluid. It can be achieved by suspension of nano particles in the carrier fluids. Suspending solid nano particles (metallic and non-metallic) in the carrier fluids result in the improvement of thermo-physical characteristics of carrier fluids. Dispersing the solid particles in the fluids was primarily recommended by [Maxwell, 1891]. Later Liu [1988] dispersed solid particles of millimeter in size in the carrier fluids and used them as fluids for heat transfer. The suspended particles of millimeter in size led to an intensification in the heat transfer. However, the problems that were associated with the micro or millimeter sized suspensions lead to clogging of micro-channels and also have caused issues like erosion, fouling, increased pressure drops in the micro channels etc. This situation led to the hindrance in the development of

fluids for heat transfer using micro or millimeter sized solid suspensions. With the advent of latest technologies of materials, nano meter sized particles have emerged as potential materials for intensification of heat transfer phenomenon. Such nano meter sized particles suspended in the carrier fluids are termed as nanofluids. In fact, nanofluids which are made out of nano particles are the colloidal dispersions in the carrier fluids. Usage of suspension of nano particles in the carrier fluids was first coined by Choi [1995]. Based on his experiments, he proved that nanofluids portray enhanced thermal properties in contrast to the carrier fluids.

SYNTHESIS OF NANOPARTICLES

There are basically two strategies for synthesis of nano particles. Preliminary strategy is Bottom up strategy and the secondary one is the

top down strategy as mentioned by Wang and Xia [2004]. In top down approach, a ruinous approach is generally adopted. Larger molecules are broken down into smaller molecules. Methods like Grinding/milling, CVD, physical vapor deposition fall into this category. A planetary mill is generally used to synthesize nano particles in this method. Second type of approach of synthesis of nano particles is the bottom up approach. This approach is quite opposite to the earlier one. That is why this type of approach is called as building up approach. In this approach, nano particles are synthesized from smaller molecules. Sedimentation and reduction techniques fall into this category. Solgel, green synthesis, biochemical synthesis and spinning methods fall under this category of methods of synthesis of nano particles. A comprehensive review of different methods of synthesizing the nano particles was summarized by Ibrahim et al. [2019]. Ajitha et al. [2013] synthesized silver nano particles utilizing chemical reduction method. Ruchi Deshmukh et al. [2013] synthesized cobalt nano particles of needled shape using chemical reduction method. Chia Chang et al. [2015] synthesized CuO nano particles via precipitation method. Vander Walt [2015] synthesized poly sorbate stabilized and gold coated iron oxide nano particles using phase reaction method. Guzman et al. [2015] synthesized copper nano particles using polyol method. Humnic [2015] synthesized FeC nano particles using laser pyrolysis technique. Various equipments were used by various researchers to characterize the nano particles as well the nanofluids. Equipments like SEM (Scanning Electron Microscopy), XRD (X-Ray diffraction) and TEM (Transmission Electron Microscopy, are used for

characterizing the nano particles. Various equipments used for characterization of nano particles is pivoted in Table 1 SEM allows the imaging of nano particles below 10nm.

It is used for characterization of size as well as morphology of the nano particles. Sample preparation and acquiring the image is very easy with this equipment as said by Andros et al. [2020]. SEM images are obtained by the reflected electrons. Contrast to the SEM, TEM images are obtained by transmitted electrons. Moreover, SEM produces more precise 3D images, while TEM produces 2D images which require further interpretation. However, TEM produces an image of higher resolution. Depending upon the application, image resolution required one can select either SEM or TEM accordingly. XRD provides information related to crystal structure, composition and average size of the nano particles [Stefanos et al., 2018].

PREPARATION OF NANOFUIDS

Methods of preparation of nanofluids fall into two categories. They are single step technique and two step technique. In single step technique, particles are prepared and suspended in the fluid simultaneously. Eastman et al. [2001] developed and proposed single step technique of physical vapor condensation for synthesizing Cu/ethylene glycol based nanofluids. As the agglomeration of the nano particles is reduced, greater stability can be achieved by synthesizing the nano particles by this approach. Unnecessary processes like drying, storing, shipping and dispersion of nanoparticles can be avoided. Vacuum SANSS (Submerged arc nano particle synthesis system) is one

Table 1. Various equipments used for characterization of nano particles and nano fluids

No.	Parameter	Equipment to be used
1	Particle size determination	DLS, Zetasizer Nano ZS
2	Thermal conductivity	KD2 Pro Conductimetre
3	Specific Heat	Differential Scanning Calorimeter
4	Viscosity	Haake Rheo stress Rotational Rheo metre
5	Stability	Turbiscan Lab Expert, Nephelometer
6	Particle size (in conjunction with DLS)	TEM
7	Neuron Activation Analysis (particle concentration and contamination)	NAA
8	Loading and composition	Inductively coupled Plasma Spectroscopy
9	Analyzing components by weight	Thermo-gravimetric analysis
10	Particle size in conjunction with DLS/TEM	Scanning Electron Microscopy
11	Composition	Energy Dispersive Spectroscopy
12	Composition	X-Ray Diffraction

of the most efficient methods of this category. In this method, nano particles are synthesized using the dielectric fluids. Even though, there are certain advantages with one step method, there are certain disadvantages such as nano particles cannot be developed on large scale and it is not cost effective method. A comprehensive review was conducted on approaches of preparation of nanofluids by Wei Yu and Huaqing Xie [2012]. He also gave a brief description about novel approaches of production of nanofluids, in which the prepared nanofluids have more stability than the conventional methods. Second category preparation of nanofluids is two step approach. It is one of the most prominent methods of preparing nanofluids. In this approach, first powders are prepared. Then the powders are dispersed in the base fluids. In order to prevent from agglomerating of the nano particles within the base fluid, generally different methods are used. Magnetic stirring, use of ultrasonic bath sonicator, homogenizing, and ball milling are few of the methods that are used to avoid the agglomeration and for attaining of stable nanofluids. This is the most economical method of preparation of nanofluids and nano particles can be prepared on large scale using this method. Nanofluids prepared with this method are not much stable. Naser Ali et al. [2018] carried out a comprehensive review of different methods of preparation of nanofluids. Eastman et al. [1996], Wang and Xu [1999], and Lee et al. [1999] prepared Al_2O_3 nano fluids. Murshed et al. [2005] prepared Titanium nano fluids. Xuan and Li [2000] produced transformer oil and water based Cu nano particles using two step method. Mo et al. [2012] prepared two types of TiO_2 nanofluids. They also studied the effect of different dispersants (SDBS, PVP and CTAB) on the stability of TiO_2 nanofluids. Kamel et al. [2021] prepared Al_2O_3 and Cerium Oxide nanofluids and measured their thermal conductivity at various temperatures and observed that there is an intensification in thermal conductivity in contrast to the carrier fluid. They have developed correlations for thermal conductivity. Varma et al. [2017] prepared Fe_3O_4 nano fluids at low volume concentrations and evaluated their performance in a twin tube heat exchanger separately and along with the variable- cut radius twisted tapes. For preparing Nano fluids by two step method, initially, the quantity of the powder that has to be procured must be determined. For determining the amount of powder required for specific

concentration, the weight of the powder required is given by law of mixtures. The equation for law of mixtures is given by Sundar et al. [2012]

$$\phi = \frac{\text{Volume of the nano particles}}{\text{Volume of the base fluid} + \text{volume of the nano particles}} \times 100 \quad (1)$$

$$\phi = \frac{\frac{\text{Weight of the nano particles}}{\text{Density of the nano particles}}}{\frac{\text{Weight of the base fluid}}{\text{Density of the base fluid}} + \frac{\text{Weight of the nano particles}}{\text{Density of the nano particles}}} \times 100 \quad (2)$$

where: ϕ is the concentration of the nanofluid.

THERMO-PHYSICAL CHARACTERISTICS

Nano fluids possess enhanced thermo-physical characteristics compared to the base fluids. Various thermo-physical features like specific heat (C_p), thermal conductivity (K), density (ρ) and viscosity (μ).

Thermal conductivity

The addition of nano particles to the carrier fluid improves the thermal conductivity in the carrier fluid [Naser Ali et al. 2018]. With the intensification in the thermal conductivity in the carrier fluid, there will be an intensification in the convective heat transfer. Intensification in thermal conductivity is apprehended to various factors. One of which is the influence of Brownian motion, which is attributed by the behavior of dispersion of nano particles in the carrier fluid. Other reasons are liquid molecules surrounding the nano layers, clustering of particles etc. Maxwell developed a correlation to assess the thermal conductivity in the nanofluid based on the thermal conductivities of the nano particles as well as the base fluid. Maxwell's model of thermal conductivity is stated as:

$$k_{nf} = k_{bf} \frac{k_{np} + 2k_{bf} + 2(k_{np} - k_{bf})\phi}{k_{np} + 2k_{bf} - (k_{np} - k_{bf})\phi} \quad (3)$$

where: k_{nf} is the thermal conductivity in the nanofluid, k_{np} is the thermal conductivity in the nano particles, k_{bf} is the thermal conductivity in the base fluid, ϕ is the particle volume concentration of the nanofluids.

The above equation is used for nano particles which are spherical, for low volume fractions and for randomly distributed particles. Majid et al. [2010] proposed a correlation for assessing the thermal conductivity in the nano fluids having non spherical shape and $n = 6$, at low volume concentrations, random distributed particles. Model of Hamilton and Crosser for assessing thermal conductivity is as stated below:

$$k_{nf} = \frac{k_p + (n - 1)k_f - (n - 1)(k_p - k_f)\phi}{k_p + (n - 1)k_f + (k_p - k_f)\phi} \quad (4)$$

Bruggeman [2004] proposed correlation for binary homogeneous mixture without any limitations on the concentration and for randomly distributed particles. Bruggeman’s model of thermal conductivity is as below:

$$k_{nf} = \left(\frac{k_p - k_f}{k_p + 2k_{nf}} + (1 - \phi) \left(\frac{k_f - k_{nf}}{k_f - 2k_{nf}} \right) \right) \quad (5)$$

Wasp model is also used for of predicting the thermal conductivity in the nano fluids. Wasp model is as shown below:

$$k_{nf} = k_{water} \left\{ \frac{k_{nanoparticles} + 2(k_{water} - 2\phi)}{k_{nanoparticles} + 2k_{water} + 2k_{nanoparticles} \left(\frac{k_{water} - k_{nanoparticles}}{k_{nanoparticles}} \right)} \right\} \quad (6)$$

Jang and Choi [2004] reported on a correlation for ascertaining the thermal conductivity for nanofluids based on kinetics, kapitzza resistance and convection. They have considered various means of energy transfer in nanofluids. They comprise of collision among carrier fluid molecules, thermal diffusion in nano particles in the fluids, collision among nano particles by virtue of Brownian motion as well as thermal communication of dynamic or jumping of nano particles with the carrier fluid molecules. The model proposed by Jang and Choi is as given below:

$$k_{eff} = k_{bf}(1 - f) + k_{nano}f + 3C_1 \frac{d_{bf}}{d_{nano}} k_{bf} Re^2 d_{nano} Pr f \quad (7)$$

where: C_1 is a proportionality constant, $Re_{d_{nano}}$ is the Reynolds number, f is the friction factor. K_{eff} is the effective thermal conductivity of the nano fluid, K_{bf} is the thermal conductivity of the carrier fluid.

Mintsa et al. [2009] proposed a linear correlation for ascertaining the thermal conductivity in water/CuO and water/ Al_2O_3 nanofluids. Expressions proposed by them are given below.

$$k_r = 1.74\phi + 1 \quad (8)$$

$$k_r = 1.72\phi + 1 \quad (9)$$

where: K_r is the thermal conductivity of the nano fluids.

Ravi Babu et al. [2022] used Artificial Neural Networks for determining the viscosity as well as thermal conductivity in water based Aluminum oxide nanofluids of various concentrations. Levenberg–Marquardt algorithm was used for training the dataset. They estimated the mean square error for thermal conductivity as well as viscosity.

Specific heat

It is one of the crucial property in effecting the rate of transfer of heat in nanofluids. It is the quantity of heat essential for increasing the temperature of one gram of a nanofluid by one degree centigrade. Two models exist which are predominantly used to assess the effective specific heat capacity of the nanofluids. One model uses the law of mixtures. Specific heat capacity in the nanofluid can be assessed using the relation as shown below.

$$C_{nf} = (1 - \phi)C_{water} + \phi C_{np} \quad (10)$$

where: C_{nf} is the specific heat capacity of the nano fluid, ϕ is the particle volume concentration of the nano particles, C_{np} represents the specific heat capacity of the nano particles, and C_{water} denotes the specific heat of the carrier fluid.

The other model is established based on the thermal communication among the dispersed nano particles and the liquid phase. Xuan [2000] proposed the second model of correlation for specific heat capacity. The expression for finding out the specific heat capacity using this model is

$$C_{p,nf} = \frac{\phi(\rho C_p)_p + (1 - \phi)(\rho C_p)_f}{\phi\rho_p + (1 - \phi)\rho_f} \quad (11)$$

where: $C_{p,nf}$ represents the specific heat of the nano particles.

Viscosity

Viscosity which is a fluid property pertains to be a prominent factor which effects the convective transfer of heat. Next to thermal conductivity, viscosity plays a very important role in governing the transfer of heat phenomenon. Viscosity of the nanofluids is effected by two factors. One of the factors is the particle volume concentration of the nano particles. The other factor which affects the viscosity is the temperature. Increase in the particle volume concentration of the nano particles increase the viscosity of the nanofluids. Reduction in the temperature gradient of the nano fluids results in the increment in the viscosity of the nanofluids. Several correlations have been formulated for determining the viscosity of the nano fluids. [Drew and Passman, 1999] presented Einstein's expression for determining the effective viscosity of a viscous fluid comprising of suspended particles. This expression was extended by [Brinkman, 1952]. This expression is however restricted for concentrations less than 0.05%. The expression is depicted as follows:

$$\mu_{\text{eff}} = \mu_f (1 + 2.5 \varphi) \quad (12)$$

$$\mu_{\text{eff}} = \mu_f \frac{1}{(1 - \varphi)^{2.5}} \quad (13)$$

where: μ_{eff} is the effective viscosity of the nanofluid, μ_f is the viscosity of the base fluid.

Jang et al. [2007] proposed an expression for effective viscosity which consider the mean velocity and pressure drop of the nano fluids from his experiments. He found from his model that the viscosity enhancement is much larger than the viscosity anticipated from the Einstein's model of viscosity. The expression of effective viscosity from Jang is expressed as:

$$\mu_{\text{eff}} = \frac{D^2}{32U} \left(\frac{-dp}{dx} \right) = \frac{D_{\text{tube}}^2}{32U} \left(\frac{\Delta p_{\text{tube}}}{L} \right) \quad (14)$$

where: ΔP is the pressure drop in the tube, L is the length of the tube, D is the diameter of the tube and U is the velocity of the fluid in the tube.

Density

Density plays a crucial role in the convective transfer of heat of nanofluids. As the density of the nano particles is increased, due to the

distinction in the densities of the nano particles and the base fluid, the miscibility of the nano particles in the base fluid decreases. This entails in the reduction of transfer of heat and stability of the nanofluids. Munish et al. [2017]. Density have its effect on Reynolds number (Re), Nusselt number (Nu), pressure loss in terms of friction factor. From the law of mixtures, density of micro sized and nano sized particles of various concentrations, which is given by

$$\rho_{\text{nf}} = \varphi \rho_p + (1 - \varphi) \rho_f \quad (15)$$

where: φ is the particle volume intensity of the nano particles, ρ_f represents the density of the carrier fluid.

Nanofluids in a circular tube

Many studies were carried out to increase the convective transfer of heat by intensifying the thermal conductivity of the carrier fluids by dispersing the solid particles in the conventional fluids to intensify their poor thermal properties. Hwang et al. [2009] explored the convective transfer of heat as well as pressure loss with water based Aluminum Oxide nanofluids in the laminar flow regime under constant heat flux condition. They reported a minor improvement in the transfer of heat with low volume intensities of the nanofluids. Williams et al. [2008] analyzed the performance of Aluminum and Zirconia in a circular tube for turbulent flow. With their experiments, they didn't achieve significant enhancement in the heat transfer. Maiga et al. [2004, 2006] carried simulations to analyze the hydrodynamic and thermal effects forced convective transfer of heat of different nanofluids like copper, aluminum oxides and silicon dioxide in a colloidal solution of ethylene glycol and water mixture under turbulent flow conditions. They elucidated the significant improvement in the heat transfer. Zeinali et al. [2007] performed experimental investigations on intensification of convective transfer of heat in a circular tube using Aluminum Oxide nanofluids. Hojjat et al. [2011] dispersed three types of nano particles ($\gamma\text{-Al}_2\text{O}_3$, CuO and TiO_2 water based solution of CMC and investigated forced convection transfer of heat of these nano fluids under turbulent flow conditions. They proposed new correlations to predict Nusselt number as a function of Reynolds number and Prandtl number. Stalin et al. [2017] have investigated the effect of low volume concentrations of the water based cerium oxide nanofluid in a solar

Table 2. Correlations for determining Nusselt number (Nu) for turbulent flow of base fluids

Author	Correlation
Dittus Boelter (1930) [43]	$Nu = 0.02 \times Re^{0.8} \times Pr^n$ Where n = 0.3 for cooling and n = 0.4 for heating
Gnielinski (1976) [44]	$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.8} \left(\left(\frac{Pr}{3}\right)^{\frac{2}{3}} - 1\right)}$
Pak and Choi [45]	$Nu = 0.021 \times Re^{0.8} \times Pr^{0.4}$
Xuan and Li [46]	$Nu = 0.0059(1.0 + 7.6286\phi^{0.6886}Pe^{0.001})Re^{0.9338}Pr^{0.4}$
Buongiorno [47]	$Nu = \frac{\frac{f}{8}(Re - 1000)Pr}{1 + \delta_v^+ \sqrt{\frac{f}{8} \left(Pr_v^{\frac{2}{3}} - 1\right)}}$
Maiga et al. [38, 39]	$Nu = 0.085 \times Re^{0.71} \times Pr^{0.35}$

flat plate collector (SFPC). They have reported that the collector efficiency has improved by 21% with cerium oxide nanofluids when compared to the base fluids. They also proposed a correlation for anticipating the exit temperature of the collector with flat plate (FPC). Various correlations were proposed by various researchers for estimating the Nusselt numbers of the base fluids. correlations for predicting the Nusselt number, that are available in the literature are pivoted in Table 2.

Performance of convective heat transfer of nano fluids in heat exchangers

Various parameters like specific heat, viscosity and thermal conductivity greatly affect the performance of convective transfer of heat efficiency of the nano fluids in heat exchangers [Ibrahim et al., 2019]. Specific heat capacity is considered as a factor for analyzing the performance of the nano fluids in terms of exergy and energy. Numerous researchers have concluded that the volume concentration of the nano fluids effect the specific heat capacity [Babar et al., 2019, Lei et al., 2019, Sajid et al., 2019]. They have concluded that with the rise in particle volume intensity, there will be a decrease in specific heat. Viscosity is an important factor as far as pumping power is concerned. It has been proven that viscosity of the nano fluids depend on two factors. They are inclusion of nano particles in the carrier fluid and viscosity of the carrier fluid. Viscosity increases with the increment in size of the particles used, type of carrier fluid used and particle volume concentration of the nano fluid. Lee et al. [2008] and Sonawane et

al. [2014] dispersed aluminum oxide nano fluids in different base fluids and have reported that with the rise in volume concentration of the nano particles, there is a rise in the viscosity of the nano fluid. Various factors influence the thermal conductivity of the nano fluids. Those factors were identified as particle size, pH, shape, fluid type, temperature and volume fraction. Dasaroju et al. [2014] and Tawfik, [2017] has reviewed the various factor effecting the thermal conductivity and thermal properties of the nano fluids. In their review, they have discussed about various methods to measure the thermal conductivity. They have also discussed about the parameters that are effecting the enhancement of thermal conductivity.

Challenges and future scope

Even though, research on nanofluids has been carried to a great extent, still there are lot of challenges that are existing in the field of nanofluid research such as (a) complex methods that are existing for synthesizing of nanofluids (b) difficulties in preparation and characterization of nano particles and nanofluids (c) determining the thermo physical properties accurately (d) applications of nanofluids on large scale for typical applications (e) high cost of manufacturing of nano particles and manufacturing methods for industrial applications on large scale (f) long term stability of the nanofluids with different types of base fluids (g) lack of awareness of mechanisms accountable for improvement of the properties of convective heat transfer. Few of the issues which should receive greater attention for enhancement of convective

transfer of heat of nanofluids are intensification of thermal conductivity in nanofluids for super critical applications, mechanisms coupled with the Brownian motion and kinetics phenomenon of the dispersions, thermo-physical changes with the change in temperature, Use of nano fluids have shown considerable enhancement in the convective heat transfer. But, considerable attention has to be laid on the reduction of pumping power and friction losses, because the increase in particle volume concentration leads to augmentation in viscosity, and hence tending to the increase in pumping power. There are several issues which have to be resolved in the mechano-chemical synthesis of nano particles relative to solution phase techniques. They are related to reactivity of solid reductants, interaction of surfactants, growth species and true nature of the metallic precursors. Lot of awareness on knowledge of milling conditions, capping agents, salt precursors is needed to improve the synthesis procedures of nano particles [Paulo et al., 2020]. Shapes produced are mostly restricted to spherical by bottom up approaches. Novels methods are to be investigated to explore other morphologies to gain more knowledge of their properties and applications. Presence of defects in the nano materials is also one of the major challenge to overcome. Because of these defects, the efficacy of the nano fluids are not up to the mark. Particle clogging in the micro and mini channels is one of the major problem in the heat exchanging devices. Nano particle dispersions in single phase fluids is mostly investigated. Nano particle dispersions in two or multiphase should be given prominence to arrive at enhancement in the condensers, evaporators and refrigerators. So there are lot of challenges which have to be overcome in future, so that the nano fluids can be used in large scale in the industrial applications.

CONCLUSIONS

In this article, an attempt is done to summarize various methods of synthesis of nano particles, various equipments to characterize nano particles and nano fluids, various techniques of preparation of nano fluids, determining the thermo physical properties of nano fluids, correlations useful for estimating the convective heat transfer properties of nano fluids. The challenges existing in the synthesis, preparation and characterization of nano fluids have been depicted and

future scope has been elaborated. This article will be useful for researchers who wish to do research in the area of enhancement of convective heat transfer through nano fluids, enhancement of their thermo physical properties, chemical engineers working in enhancement of heat transfer for critical applications etc.

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