A Review: Enhancement of Heat Transfer with Nanofluids

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Abstract - The performance of industrial and practical appliances can be improved to perform some important heat transfer duty by heat transfer enhancement techniques. The enhancement of heat transfer using nanofluids have been used as one of the passive heat transfer techniques in several heat transfer applications. It is considered to have great potential for heat transafer enhancement and are highly suited to application in heat transfer processes. In recent years, several important research works have been carried out to understand and explain the causes of the enhancement or control of heat transfer using nanofluids. This review addresses the unique features of nanofluids, such an enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Browanian motion, etc. From the studies of literatures it has been found that the heat transfer coefficient increases with an increase in the concentration of solid particles. Certain studies with a smallerparticle size indicate an increase in the heat transfer enhancement when is compared to values obtained with a larger size. The significant applications in the engineering field explain why so many investigators have studied heat transfer with augmentation by a nanofluid in the heat exchanger. This article presents a review of the heat transfer applications of nanofluids to develop directions for future work. Future heat transfer studies can be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulence regions. There appears to be hardly any research in the use of nanofluids as refrigerants. Nanoparticle-refrigerant dispersions in two-phase heat transfer applications can be studied to explore the possibility of improving the heat transfer characteristics of condensers and evaporators used in refrigeration and air conditioning systems.

Keywords: Nanofluids, Heat transfer enhancement, Heat exchanger

1. INTRODUCTION

Nanofluids have become increasingly closer to an engineering reality starting from their initial vision originated more than decades ago [1]. In the last ten years, there has been more attention paid to enhance the convective heat transfer performance of nanofluids [2], due to the recognition in practical applications of nanofluids. Heat exchangers are widely used in many engineering applications, for example, applications in power production industry,

chemical industry, food industry, environmental engineering, waste heat recovery, air conditioning, and refrigeration. For decades, efforts have been made to enhance heat transfer of heat exchangers, reduce the heat transfer time and finally improve energy utilization efficiency. These efforts commonly include passive and active methods such as creating turbulence, extending the exchange surface or the use of a fluid with higher thermophysical properties [3].

The characteristics of flow and heat transfer in microchannels and microtubes have also attracted much attention of researchers because of the rapid developments of micro-electromechanical systems (MEMS) and micrototal analysis system. These developments have great impacts on the microelectronic cooling techniques, the microheat exchanger, bioengineering, human genome project, medicine engineering etc [4].

This aim of this review article is to summarize the heat transfer enhancement potential of nanofluids both experimental and numerical work and on the effect of the concentration and diameter of nanoparticles and the shape of cross sectional tubes.

2. EXPERIMENTAL WORK

The nanofluid has been found to be an important and attractive heat transport fluids for last two decades. It has got a significant potential for enhancement of heat transfer relative to the conventional fluids. From earlier research work, it has been found that the convective heat transfer of nanofluids has received very little attention in the literature. The numbers of published papers dealing with the enhancement of heat transfer with nanofluids are very limited. Enhancement in heat transfer has been studied earlier with the help of suspended micro-particles. Ahuja [5,6] has performed experiments on the heat transfer enhancement in the laminar flow of water with micro-sized polystyrene suspension. The results show a significant enhancement in the Nusselt number and heat exchanger effectiveness compared to that of a single phase liquid. Lee and Choi [7] have used a nanofluid as a coolant in a microchannel heat exchanger and compared the enhanced cooling rated with those of conventional water-cooled and liquid-nitrogen cooled microchannel. The effect of turbulence or eddy, suppression of the boundary layer, dispersion of the suspended particles, besides the augmentation of thermal conductivity and the heat capacity of the fluid are suggested to be the possible reasons for heat transfer enhancement. Esfahany et al. [8] have investigated the laminar flow convective heat transfer of Al_2O_3–water under constant wall temperature with $\varphi = 0.2$-2.5% for Reynolds number varying between 700 and 2050. The Nusselt number for the nanofluid is found to be greater that

that of the base fluid; and heat transfer coefficient increases with an increase in particle concentration. The ratio of the measured heat transfer coefficients increases with the Peclet number as well as nanoparticle concentrations. Williams et al. [9] have investigated the turbulent convective heat transfer behaviour of alumina (Al_2O_3 – water and ZrO_2-water). The convective heat transfer and pressure loss behaviour of nanofluids under a fully developed turbulent flow, matches the correlations of a single-phase flow. Duangthonguk and Wongwises [10] have shown an enhancement of heat transfer at a lower concentration of TiO_2-water (φ = 0.2%) and claim that the convective heat transfer coefficient also depends on the experimental measurement system and calibration. Pak and Cho [11] have experimentally investigated the turbulent friction and convective heat transfer behaviours of water based nanofluids heated with constant heat flux boundary condition in circular stainless steel tube of 10.66 mm inner diameter and 4.8 m length. Two different metallic oxide particles, ν- alumina (Al_2O_3) and titanium dioxide (TiO_2) with mean diameters of 13 and 27 nm, respectively, are used as suspended particles. They have found that, the Nusselt number of the dispersed fluids for fully developed turbulent flow increases with increasing volume concentration as well as the Reynolds number. However, it is observed that the convective heat transfer coefficient of the dispersed fluid at a volume concentration of 3% is 12% smaller than that of pure water when compared under the condition of constant average velocity. Therefore, better selection of particles having higher thermal conductivity and large size has been recommended in order to utilize dispersed fluids as a working medium to enhance heat transfer performance. The experimental heat transfer coefficient values are more than predicted from conventional correlation. Jang and Choi [12] have shown an enhancement of the convective heat transfer coefficient of nanofluids (Al_2O_3 –water with φ = 0.3%) up to 8%. Lai et al. [13] have studied the flow behaviour of nanofluids (Al_2O_3- DI water; ν = 20 nm) in a millimetre-sized stainless steel test tube, subjected to constant wall heat flux and a low Reynolds number (Re<270). The maximum Nusselt number enhancement of the nanofluid of 8% to φ = 1% is recorded. Jung et al. [14] have conducted convective heat transfer experiments for a nanofluids (Al_2O_3 –water) in a rectangular micr-channel (50 µm × 50µm) under laminar flow conditions. The convective heat transfer coefficient increases by more than 32% for φ = 1.8% in base fluids. The Nusselt number increases with an increasing Reynolds number in the laminar regime (5<Re<300) and a new convective heat transfer correlation for nanofluids in microchannels is also proposed. Li and Xuan [15] have experimentally investigated the convective heat transfer and flow characteristics of the Cu-H_2O nanofluid under laminar flow in a straight brass tube of the inner diameter of 10 mm and the length of 800 mm. The effects of the volume fraction of suspended nanoparticles and the Reynolds number on the heat transfer and flow characteristics have been observed. The experimental results show that the suspended nanoparticles remarkably increase the convective heat transfer coefficient of the base fluid and the nanofluid has larger heat transfer coefficient of the base fluid and the nanofluid has larger heat transfer coefficient than pure water under the same Reynolds number. The heat transfer feature of a nanofluid increases with the volume fraction of nanoparticles. Considering some factors affecting convective heat transfer characteristics of nanofluids, such as the flow velocity, the transport properties, the volume fraction of nanoparticles, the microconvective and microdiffusion of the nanoparticles, a new convective heat transfer correlation for nanofluid suspending the nanoparticles under single-phase flow has been established. Eastman et al. [16] have conducted tests to assess the thermal performance of CuO-water with φ = 0.9% under turbulent flow conditions and the heat transfer coefficient is higher by 15% than that of pure water. Wen and Ding [17] have assessed the convective heat transfer of nanofluids in the entrance region under laminar flow conditions. Aueous based nanofluids containing ν- Al_2O_3 nano-particles (ν = 27-56 nm; φ = 06-1.6%) with sodium dodecyl benzene sulfonate (SDBS) as the dispersant, are tested under a constant heat flux boundary conditions. For nanofluids containing φ = 1.6%, the local heat transfer coefficient in the entrance region is found to be 41% higher than that of the base fluid at the same flow rate. It is observed that the enhancement is particularly significant in the entrance region, and decreases with axial distance. Particle migration is reasoned for the enhancement. Xuan and Li [18] have experimentally studied the single phase heat transfer of the Cu-water nanofluid in tubes in the turbulent flow regime (Reynolds number between 10000 and 25000) with φ = 0.3-2.0 % and have proposed a heat transfer correlation. The convective heat transfer coefficient increases remarkably with the volume-fraction and with the flow velocity, with a negligible penality in pumping power. Xuan and Li [19] have measures the convective heat transfer of the Cu-water nanofluid in a small hydraulic diameter flat tube under laminar flow conditions. The Nusselt number of the nanofluid with φ = 2% increases by more than 39% compared with that of pure water.

The available experimental results reveal that the convective heat transfer coefficients of nanofluids vary with the flow velocity and volume fraction and are higher than the base fluid under the same conditions as shown in Table 1. A hybrid nanofluid used to enhance the heat transfer and pressure drop in fully developed laminar flow through a uniformly heated circular tube is studied experimentally by Suresh et al. [20]. The nanofluid has composed of Cu-Al_2O_3 in water synthesised with a 0.1% concentration by volume. Experimental results show a maximum enhancement of 13.56% in the Nusselt number at a Reynolds number of 1730 when compared to the Nusselt number of water. The results also show that 0.1% Cu- Al_2O_3-water nanofluids have a slightly higher friction factor when compares to a 0.1% Al_2O_3-water nanofluid. The correlations of the Nusselt number and the friction factor are reported, and there is a good agreement with the experimental data reported elsewhere. Experimental results by Yang et al. [21] illustrate the convection heat transfer coefficient of graphite nanoparticles dispersed in a liquid for laminar flow in a horizontal tube heat exchanger. A study of laminar flow convective heat transfer of alumina nanoparticles in water with a constant surface temperature and various volume fractions is performed by Heris et al. [22]. The effect of the volume fraction of water- Al_2O_3 on the Nusselt number and friction factor in a circular tube with a twisted tape under turbulent flow has been studied by Sundar and Sharma [23]. Their results provide the heat transfer enhancement with the Reynolds number and the volume fraction of nanoparticles in water.

It has been shown in many literatures that the heat transfer behaviour of nanofluids and the application of nanofluids for heat transfer enhancement, are influenced by the effective thermo-physical properties of nanofluids and many other factors such as particle size, shape and distribution; Brownian motion, particle–fluid interaction and particle migration also have an important influence on the heat transfer performance of nanofluids. However, because of the lack of agreement between the experimental results report by various groups, most of the studies lack physical explanation for their observed results. All the convective studies have been performed with oxide particles. Besides, the experimental data available for convective heat transfer are limited and insufficient to exactly predict the trend for heat transfer enhancement. Maiga et al. [24] have reported that, with regard to the nanofluid thermal properties, the actual amount of experimental data available in the literature remains surprisingly small, and it is obvious that more works in this area will be published in the near future. Therefore, further research on the convective heat transfer of nanofluids is needed. Many researchers have focused on heat exchanger applications with nanofluids because of the wide range of applications for heat exchangers in the practical and industrial fields [25-34]. Forced convection heat transfer in a double pipe with turbulent nanofluid flow and plate heat exchangers is investigated experimentally by Zamzamian et al. [35]. The nanofluid consists of aluminium oxide and copper oxide in the ethylene glycol separately. The effects of volume fraction and operating temperature on the forced convection heat transfer coefficient of the nanofluids are evaluated. From this study, it has been concluded that the heat transfer coefficient of the nanofluid increases with increasing nanoparticles fraction and the temperature of the nanofluid.

3. NUMERICAL AND MATHEMATICAL MODELING

The mixture of nanoparticles and base fluid is a multiphase problem and could be approximated as either a homogeneous fluid or heterogeneous mixture. In the case of a homogeneous approach, because of the size of the nanoparticles, it has been suggested that these particles may easily be fluidized and consequently, can be considered to behave more like a single phase fluid. Further, by assuming a negligible motion slip between the particles and the thermal equilibrium conditions, the nanofluid could be considered as a conventional single-phase fluid with averaged physical properties of individual phases [36, 37]. However, because the effective properties of the nanofluids are not known precisely, the numerical prediction of this approach are not in good agreement with experimental results. Choi et al. [38] have first adopted a homogeneous model and used the conventional heat transport equations for pure fluids, such as the Dittus-Bolter correlation, to the nanofluids. In the case of a heterogeneous approach (two-phase), factors such as gravity, friction between the phases, Brownian diffusion, sendimentation, and dispersion are included in the flow model. The two phase approach provides the possibility of understanding the functions of both the fluid phase and the solid particles in the heat transfer process, and provides a field description of both the phases.

Xuan and Roetzel [39] has proposed a two-phase thermal dispersion model and is assumed that the convective heat transfer enhancement in nanofluids comes from two factors, (i) higher thermal conductivity, and (ii) the thermal dispersion of the nanoparticles. In this approach, the effect of the nanoparticle/base fluid relative velocity and temperature are treated as a perturbation of the energy equation. The thermal dispersion coefficient is introduced to describe the heat transfer enhancement. Khanafer et al. [40] have done study on the heat transfer enhancement in a two-dimensional enclosure utilizing the nanofluid. The effective thermal conductivity has been taken as the sum of the mixture of thermal conductivity evaluated from the conventional theory and a dispersion thermal conductivity. It is observed that in many of the numerical studies in convection, the effect of temperature on thermal conductivity is not considered. However, the effect of temperature on the thermal conductivity of nanofluid has been proved significant from studies made by das et al. [41]. Roy et al. [42] have modeled the hydrodynamic and thermal fields of a γAl_2O_3-water nanofluid (φ = 1-10%) in a radial laminar flow cooling system. Considerable increase in the wall shear stress is predicted on the account of the increase in the fluid viscosity. Overall, the study indicates that considerable heat transfer enhancement is possible and a maximum increase of twice the value of the base fluid in the case of φ = 10%. Maiga et al. [43] have modeled the forced convection flow of a nanofluid (γAl_2O_3 with water and ethylene glycol) in a straight tube of circular cross-section. A single –phase flow is assumed to derive the governing equations to calculate the heat transfer enhancement by the nanofluids in the laminar flow as well as the turbulent flow regime, with nanofluid concentrations ranging from 0 to 10%. For laminar flow, the results indicate an increase in the heat transfer rate, particularly at the walls, with the augmentation of φ (for φ = 10%, the product ρc_p and thermal conductivity, k increases by 18 and 33%, respectively). The heat transfer coefficient ratio also increases with particle loading and particularly at the tube end (by nearly 60%). Further, averaged heat transfer enhancement is clearly more pronounced for the γAl_2O_3-etylene glycol than for the γAl_2O_3-water nanofluid for φ> 3%. The wall shear stress is found to increase considerably with the particle volume fraction and along the tube length. For the turbulent flow regime, the heat transfer coefficient increases steeply for a very short distance from the inlet section. Buoniorno [44] has developed an alternative model that eliminates the shortcomings of the homogeneous and dispersion models. The homogeneous flow models are in conflict with the experimental observation and the pure-fluid correlations under predict that heat transfer coefficient. In this model, a detailed analysis of convective transport with seven slip conditions between particles and fluid are considered, for explaining the enhancement of heat transfer with nanofluids. In these mechanisms the Brownian diffusion and thermophoresis are the two most important nanoparticles/base fluid slip mechanisms. Convective heat transfer enhancement is obtained with a decrease in viscosity and consequent thinning of the laminar sub-layer. It is observed that the radial distribution of the particle concentration brings about by thermophoresis make the temperature profile flatten, thus giving a higher heat transfer coefficient and finally, a new correlation has been developed to predict the enhanced heat transfer coefficient of nanofluids. Palm et al. [45] have numerically investigated the enhanced heat transfer capabilities of

Al_2O_3-water (γ = 38nm; φ = 1-4%) in a radial laminar flow cooling system and is used temperature dependent nanofluid properties. The experimental results obtained using the single-phase approach indicate that property fluctuations are noticed near the injection inlet. Lower viscosities at higher temperature, decrease in wall shear stress for increase in wall heat flux and greater wall heat transfer rates are shown when compared to predictions using constant properties. Mansour et al. [46] have investigated the effect of the Hamilton-Crosser model and the Modified Maxwell model, to predict nanofluid (γAl_2O_3-water; φ = 1-10%) physical properties, on their thermal and hydrodynamic performance of both fully developed laminar and turbulent forced convection in a tube with uniform heat flux at the wall. Two models give substantially different results for thermal conductivity, specific heat and viscosity, and the differences are more profound for higher particle loading. The expression fails to account for the size disparity between the nanoparticles. The two models reveal in very different predictions and it is not possible to ascertain which is accurate. The study illustrates that the operational conditions or the design parameters varies significantly with the thermo-physical properties of the nanofluid. Kim et al. [47] have theoretically investigated the Thermo-diffusion and diffusion thermo effects on convective instabilities in binary nanofluids. Data from silver and copper nanofluids studies are used in this investigation, which shows that the particles causes a unique convective motion in binary nanofluids. The heat transfer enhancement by the Socet effect in binary nanofluids is more significant than that in mono-nanofluids. Further, the heat transfer coefficient of silver nanofluids is higher than that of copper, owing to the higher thermal conductivity of silver. Studies predict that the Soret and Dufour diffusions make the nanofluids unstable and this is more profound for denser nanofluids. Further, the convecvtive motion in nanofluids sets easily in both the effects as the concentration increases.

A numerical study has been conducted by Hyder et al. [48] for Al_2O_3 and TiO_2 nanoparticles in water under laminar flow in a circular tube. It is predicted that the pressure drops and Nusselt number increases with increasing of volume fraction and Reynolds number. Additionally, a comparison of the numerical results with experimental data is available and there is good agreement between them. Siva and Sivashanmugam [49] have numerically solved the governing equations for heat transfer of nanofluids inside a circular tube with helical inserts under laminar flow. The results show that the heat transfer increases with the Reynolds number and with decreasing twist ratio with a maximum at 2.93. Additionally, a comparison of the heat transfer rates of water and nanofluids shows an increase in the Nusselt number of 5-34% for different twists and different volume concentrations.

A number of investigators have studied the heat transfer and the pressure drop in a circular tube numerically [50-54]. A mathematical formulation and numerical method to determine the forced convection heat transfer and wall shear stress for the laminar and turbulent regions of Al_2O_3-water and Al_2O_3- ethylene glycol inside a uniform heated tube is introduced by Maiga et al. [55]. For the turbulent flow region, the averaged Reynolds number under the Navier-Stokes equation and the k-e turbulent model are adopted to describe the shear stress and heat flux of the nanofluids. In the area of laminar flow, the Reynolds number has been fixed at 250 with different heat flux from 10 to 250 W/m^2. For turbulent flow, the constant heat flux was 500000 W/m^2 and the Reynolds number varies in the range of 1×10^3 - 5×10^4. They have reported that ethylene glycol is better than water in hydrodynamic and heat transfer enhancement. The numerical results indicate that the heat transfer and the wall friction of nanofluids increase with increasing particle fraction and that the Al_2O_3–ethylene glycol give a greater heat transfer enhancement than the Al_2O_3-water. For the turbulent flow region, the heat transfer performance of the nanofluids is more pronounced with the increase of the Reynolds number. Fully developed forced convection of a nanofluid (water-Al_2O_3) is studied numerically by Mirmasoumi and Behzadmehr [56]. The results show that the convection heat transfer coefficient significantly increases with decreasing mean diameter of the nanoparticles; in addition, the hydrodynamics parameters do not change signigficantly. A simulation study of convection heat transfer enhancement in a circular pipe under turbulent flow is performed by Kumar et al. [57]. Forced convection under turbulent flow of an alumina nanofluid in a circular tube with a constant and uniform wall temperature is studied numerically by Bianco et al. [58]. These authors have found that the nanofluid's convective heat transfer coefficient is greater than that of water. The results show that the heat transfer enhancement increases with the Reynolds number and the volume fraction of the nanoparticles. Computational and numerical studies of nanofluid applications of heat exchangers are performed by [58-66], all of them have concluded that the heat transfer in enhanced in the heat exchanger when the solid particles are suspended in a base fluid. The potential mass flow rate reduction in an exchanger with a given heat exchange capacity using Al_2O_3-water nanofluids is studied by Bozorgan et al. [67]. The numerical study focused on turbulent flow in a horizontal double-tube counter flow heat exchanger. The results show that the nanofluid flow rate decreases as the volume fraction in the exchanger increases; on the other hand, the pressure drop of the nanofluid is slightly higher than that of water and increases with the increase of volume concentration. The louvered strip inserts in a circular double pipe heat exchanger are studied numerically by Mohammed et al [68]. The finite volume method is used to solve the governing equations and determine the thermal and flow characteristics. Four different types of naoparticles, Al_2O_3, CuO, SiO_2, and ZnO with different nanoparticle diameters and different volume fractions in the range of (20-50 nm) and (1-4%), respectively, are dispersed in water. From the numerical results, it is observed that the heat transfer increases by approximately 367% to 411%, but the friction factor of the enhanced tube is approximately 10 times that of the smooth tube. This results indicate that the Nusselt number of the SiO_2 nanofluid has the highest value, followed by Al_2O_3, ZnO, and CuO when compared with pure water. The results show that the Nusselt number increases with decreasing nanoparticle diameter, and it increases slightly with increasing volume fraction the streamline and isothermal line.

A simulation study of laminar forced convection between two parallel plates with a new model including a bi-partitioned solution domain has been introduced by Zhou et al. [69]. One section of the solution domain is modelled with bright meshes to solve the multicomponent flow and the other has a coarse mesh to characterise the single component flow. It seems that the validity and accuracy of this model is compared well with LBM using only one type of modelling for the entire flow. Laminar convection under constant heat flux boundary conditions using the finite volume method to find the effects of the solid volume fraction on thermal and hydraulic behaviours of nanofluid flow in elliptical ducts have been presented by [77-72]. The results show that for a given Reynolds number (Re), the Nusselt number (Nu) increases with the volume fraction of solid nanoparticles while the friction factor decreases. The effect of aspect ratio in elliptical tubes reduces the local friction factor, whereas it has no effect on the local Nusselt number. The laminar flow forced convection heat transfer of a CuO- water nanofluid in a triangular duct under a constant wall temperature condition is investigated numerically by Heris et al. [73]. This investigation has evaluated the effect of the nanoparticle volume fraction, size diameter, and type on heat transfer and has compared the results between the nanofluid and the pure fluid. A comparison of the convection heat transfer of a nanofluid in isosceles triangular ducts with various apex angle is also presented. The results show that an equilateral triangular duct has a maximum heat transfer compared with other types of isosceles triangular ducts. A numerical study of the heat transfer enhancement by internal longitudinal ribs and alumina water nanofluid in a stationary curve square duct has been performed by Soltanipour [74]. Table 2 shows the summary of published numerical and theoretical works of the convective heat transfer performance of nanofluids.

4. CONCLUSION AND FUTURE SCOPE

This review shows that nanofluids have great potential for heat transfer enhancement and are highly suited to application in heat transfer processes. Nanofluids are a new class of heat transfer fluid engineered by dispersing metallic or non-metallic nanoparticles less than 100 nm in size in a liquid. The understanding of the fundamentals of heat transfer and wall friction has a significant importance for developing nanofluids for a wide range of heat transfer applications. Although there are many research works available in the study of heat transfer with nanofluid, more experimental results and the theoretical understanding of the mechanisms of the particle movements are required to understand heat transfer and fluid flow behaviour of nanofluids. The use of nanofluids in a wide variety of applications appears promising. But the development of field is hindered by (a) poor characterization of suspensions (b) lack of agreement of results obtained by different researchers (c) lack of theoretical understanding of the mechanisms responsible for changes in properties. Many issues, such as thermal conductivity, the Browanian motion of particles, particle migration, and thermophysical property change with temperature, must be carefully considered with convective heat transfer in nanofluids. Future heat transfer studies can be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulence regions. There appears to be hardly any research in the use of nanofluids as refrigerants. Nanoparticle-refrigerant dispersions in two-phase heat transfer applications can be studied to explore the possibility of improving the heat transfer characteristics of condensers and evaporators used in refrigeration and air conditioning appliances. It is necessary to study the development of correlations of friction factor and heat transfer through tubes with nanofluids. Therefore, further studies are needed to develop a generalised hydrodynamic and heat transfer characteristic correlation for nanofluid in a tube. Additionally, a comparison among tube shapes for use in a car radiator can be performed experimentally and numerically. The more research in nanofluids which will define their future in the field of heat transfer is expected to grow at a faster pace in the coming future.

Table 1
The heat transfer enhancement by a nanofluid under laminar flow [75]

Ref	Nanofluid	Re	Nu_{nf}/Nu_f
Lee and Choi [1996]	Cu-water 2 vol%	Laminar	100%
Li and Xuan [2002]	Cu-water 0.3-2 vol%	800-23000	60%
Xuan and Li [2003]	Al_2O_3-water 0.2-1.6%	Laminar	30%
Yang et al. [2005]	Al_2O_3-water 0.2-2.5 vol%	650-2050	350%
Heris et al. [2007]	Titanium nanotube-water	110	Enhancement of a with u and Pe
Chen et al. [2008]	(aspect ratio = 10) 0.5-0.5%	700-2050	Increase with aspect ratio (nanoparticle shape) increase
Rea et al. [2009]	Al_2O_3-water 0.6-6.0 vol% ZrO_2-water	1700	No abnormal heat transfer enhancement using measured properties of the nanoflid
Hwang et al. [2009]	Al_2O_3-water 0.01-0.3 vol%	Laminar	8% at 0.3 vol%
Mansour et al. [2011]	Al_2O_3/water nanofluids	550-800	Heat transfer enhancement
Sharifi et al. [2012]	Al_2O_3/water nanofluids	Laminar	Heat transfer enhancement
Sharifi et al. [2012]	Al_2O_3-Cu/water hybrid	Laminar	Enhancement of 13.56% in Nusselt no.

Table 2
Summary of numerical and theoretical investigations in convective heat transfer of nanofluids [76]

Author	Investigations	Approach	Results
Xuan and Li [2000]	Heat transfer characteristics of transformer oil-Cu and water-Cu nanofluids	Single phase fluid approach	The heat transfer coefficient improved dramatically with decrease in particle size and not only due to thermal conductivity increase
Xuan and Roetzel[2000]	Heat transfer of nanofluids	Single phase approach Dispersion model approach	Suspended particles increase the thermal conductivity.
Buongiono [2006]	Convective transport in nanofluids	Two-component non-homogeneous equilibrium model	Brownian diffusion and thermophoresis are the two most important nanoparticles/ basefluid slip mechanism
Behzadmehr et al. [2007]	Turbulent forced convection flow in a uniformly heated tube	Two phase mixture model	HTC increases with φ and Re. Higher Re resulted more uniform velocity profile
Maiga et al. [2003]	Forced convection flow of nanofluid (water/Al_2O_3 and ethylene glycol/ Al_2O_3) in a circulat tube	Single phase fluid approach	60% enhancement in HTC was found and turbulent flow enhancement increase with Re
Ding and Wen [2005]	Effects of particle migration in laminar flows of nanofluids	Mass conservation laws and momentum balance	Shear induced migration, viscosity gradient migration and self-dffusion. Highly non-uniform thermal conductivity profile obtained
Palm et al. [2006]	Heat transfer capabilities and temperature dependent properties of nanofluids in radial flow cooling systems	Single phase fluid approach	Temperature dependent properties lead to greater heat transfer performance with the decrease in wall shear stress
Kim et al. [2007]	Thermo diffusion, diffusion thermo effects in binary nanofluids	One fluid model	As the Soret and Dufour effects and φ increases the convective motion sets in easily
Mansour et al. [2007]	Thermal and hydrodynamic performance for both laminar and turbulent forced convection in a tube with uniform heat flux at the wall	Single phase fluid approach	Both the models predicted increased HTC with particle concentration
Prakash and Giannelis [2007]	Thermal conductivity of Al_2O_3 nanofluids		Dependence of the thermal conductivity on the size of

	using temperature and concentration dependent viscosity		the nanoparticle, temperature viscosity and particle concentration
Maiga et al. [2006]	Forced convection flow of nanofluid (water/Al_2O_3 and ethylene glycol/ Al_2O_3) in a circular tube and radial channel between a pair of parallel coaxial discs	Single phase fluid approach	HT increased by 63 and 45%. Increased heat transfer and dynamic viscosity resulted in increased wall shear stress with partial loading

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Nomenclature

Φ Volume fraction of nanoparticle

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