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A comprehensive review of experimental investigations of forced convective heat transfer characteristics for various nanofluids

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Abstract

Nanofluids are suspension of nanoparticles (less than 100 nm) in the conventional base fluids. The dispersed solid metallic or non-metallic nanoparticles change the thermal properties like thermal conductivity, viscosity, specific heat, and density of the base fluid. Past studies focused on measuring the thermal properties of nanofluids. These suspended nanoparticles effectively improve the transport properties and heat transfer characteristics of the base fluids. Recently, heat transfer augmentation using suspensions of nanometre-sized solid particles in base liquids have been investigated by various research groups across the world. This paper reviews the state-of-the-art nanofluid studies in the area of forced convection heat transfer enhancement. The results for the heat transfer characteristics in internal flow with constant heat flux and constant wall temperature boundary conditions reported by various researchers have been compiled and reviewed. Further, in heat exchangers, the real boundary conditions are different from the constant heat flux and constant wall temperature boundary conditions. Over a span of 2 decades, the literature in this field is widespread; hence, this review would be useful for researchers to have a precise screening of a wide range of investigations in this area.

Introduction

Energy concerns have come up as the most important problem for the world's scientists and engineers. Thermal loads are increasing day by day and have wide variety of use in electronics, transportation, power plants, food industry, air conditioning, refrigeration, etc. The conventional heat transfer fluids, such as water, oil, ethylene glycol, propylene glycol are mostly used in industries. These fluids contain poor thermal properties. In order to increase heat transfer rates, the use of extended-surface thermal control technologies such as fins and micro channels, vibration of heated surface, injection or suction of fluid and applying electrical or magnetic fields has reached to the bottleneck. Therefore, new technologies with the potential to improve the thermo-physical properties of the conventional cooling fluids have been an area of great potential for researchers. The solids have better thermal properties than fluids. Ahuja (1975) and Liu et al. (2999) carried experiments to enhance the thermo-physical properties of fluids by adding micrometre- and millimetre-sized solid particles in the base liquids. However, real-world applications of these fluids are fewer due to the reasons, i.e. large-sized particles tend to quickly settle out of suspension and thereby, in passing through micro channels, cause clogging and a considerable rise in the pressure drop. Furthermore, the abrasive actions of these particles cause erosion of components and pipelines. To overcome these problems, nanosized particles dispersed in the base fluid known as nanofluids, were firstly introduced by Choi (1995) at the Argonne National Laboratory. These novel fluids indicated improved heat transfer properties such as higher thermal conductivity, long-standing stability and uniformity along with the negligible obstruction in flow channels due to very small sizes and large specific areas of the nanoparticles. The nanoparticles used to prepare the nanofluids are basically metals (e.g. Cu, Ni, Al), oxides (e.g. Al_2O_3, TiO_2, CuO, SiO_2, Fe_2O_3, Fe_3O_4, $BaTiO_3$) and some other compounds (e.g. CNT, TNT, AlN, SiC, $CaCO_3$, graphene) with a size of 1 to 100 nm. The great quantum of research on heat transfer enhancement shows the appreciable growth and the

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necessity of heat transfer enhancement technology in the field of nanofluids.

This paper presents the comprehensive review of various experimental investigations in convective heat transfer with the use of nanofluids in laminar and turbulent flow regimes under constant wall temperature and constant heat flux boundary conditions. Further, a detailed review on the use of nanofluids in different types of heat exchangers has been presented. It is vital for reliable applications in engineering thermal systems.

Preparation of nanofluids

This section presents different methods used by researchers for the synthesis of nanoparticles and preparation of nanofluids. For making nanoparticles, the current processes for the synthesis include inert-gas condensation process, chemical precipitation, mechanical milling, chemical vapour deposition, micro-emulsions, spray pyrolysis and thermal spraying. The nanoparticles are mostly used in powdered form for making nanofluids.

In experimental studies, the preparation of nanofluids is the next most essential step. The nanofluids are not simply formed by mixing of solid particles in base liquids. Some special requirements are necessary including uniform, stable and durable suspension, minimal accumulation of particles, no chemical alteration of the fluid, etc. There are mainly two techniques used to produce nanofluids: the single-step and the two-step methods.

One-step method

Akoh et al. (1978) invented the single-step direct evaporation approach which is called the vacuum evaporation onto a running oil substrate (VEROS) technique. The original requirement behind this method was to produce nanoparticles, but it is not easy to subsequently separate the particles from the fluids to produce dry nanoparticles. Wagener et al. (1997) proposed a modified VEROS process. They put high-pressure magnetron sputtering for the preparation of suspensions with metal nanoparticles such as Silver (Ag) and Iron (Fe).

Lo et al. (2005) applied a vacuum-submerged arc nanoparticles synthesis system (SANSS) method to make nanofluid-based copper metal with various dielectric fluids including deionized water, with 30%, 50% and 70% volume ethylene glycol solution and pure ethylene glycol. They investigated that the various morphologies, which are achieved, are mainly affected and determined by the thermal conductivity of the dielectric fluids. Further, CuO, Cu_2O and Cu-based nanofluids can also be produced by this process efficiently. The advantages of this method are that the nanoparticles agglomeration is minimized and the stability of nanofluids is increased, while the disadvantages are that the high vapour pressure fluids are not suitable with such practices and residual reactants are left in the nanofluids due to incomplete reaction or stabilization. Recently, Lo et al. (2006) also made a nickel (Ni) nanomagnetic fluid by using the SANSS method.

Two-step method

The two-step method is largely used in the synthesis of nanofluids. In this method, nanoparticles, nanotubes or other non-materials employed are first produced as dry powders by chemical or physical methods. Then the nanosized particles are dispersed in a fluid in the second processing step with the help of ultrasonic agitation, high-shear mixing, homogenizing and ball milling. The two-step method is the most beneficial method to produce nanofluids in large scale, because nanoparticle synthesis processes have already been scaled up to industrial production levels. For example, Wang et al. (1999) used this method to produce Al_2O_3 nanofluids. Murshed et al. (2005) made TiO_2 suspension in water using this method. As compared to the one-step method, the two-step method works better for nanoparticles containing oxides, while it is not effective with metallic particles.

With the exception of the use of ultrasonication methods, certain additional processes are also coming into consideration, including pH control or addition of surface active agents (surfactants) to acquire stability of the nanofluid suspension against sedimentation. These techniques alter the surface properties of the dispersed particles and thus lower the affinity to form particle groups. It should be well-known that the selection of surfactants should rest mainly on the nanoparticles and fluid properties. Xuan and Li (2000) selected salt and oleic acid as the surfactant to increase the permanency of transformer oil - Cu and water - Cu nanofluids, respectively. Murshed et al. (2005) used oleic acid and cetyltrimethylammonium bromide (CTAB) surfactants to ensure better stability and proper dispersion of TiO_2/water nanofluids. Hwang et al. (2999) cast-off the sodium dodecyl sulphate (SDS) during the preparation of water-based multi-walled carbon nanotube (MWCNT) nanofluids since the fibres are entangled in the aqueous suspension. Xuan et al. (2013) studied the effect of surfactants on the heat transfer nature of nanofluids. They used Cu-water nanofluids with three volume fractions and two mass fractions of sodium dodecyl benzoic sulphate (SDBS). They showed that the surfactant remarkably affects transport properties and the convective heat transfer performance of nanofluids and suppresses heat transfer enhancement effect of suspended nanoparticles. Rashmi et al. (2011) reported that stability and thermal conductivity enhancement of carbon nanotube nanofluids using gum arabic surfactants showed considerable increment in same. In general, procedures including altering of pH value, adding surfactants, and ultrasonic vibration goals at changing the surface properties of dispersed particles and reducing the formation of particle groups to obtain uniform and constant suspensions.

Nanofluid properties and non-dimensional numbers

The convective heat transfer coefficient describes the effectiveness of heat transfer. It is a function of a number of thermophysical properties of the nanofluid - the most considerable ones are specific heat, thermal conductivity, viscosity and density. These various properties of the nanofluid are found out by using classical formulas derived from a two-phase mixture under concern as a function of the particle volume concentration and individual properties can be calculated using following respective equations:

Effective density:

$$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_{bf} \tag{1}$$

Specific heat:

$$(\rho Cp)_{nf} = \phi(\rho Cp)_p + (1-\phi)(\rho Cp)_{bf} \tag{2}$$

Dynamic viscosity:

$$\mu_{nf} = (1 + 2.5\phi)\mu_{bf} \tag{3}$$

However, these properties of nanofluid are not only dependent on the volume concentration of nanoparticles, but also extremely dependent on additional constraints, including particle shape (spherical, disk shape or cylindrical), size, mixture combinations and slip mechanisms, surfactant, etc. Studies demonstrated that the thermal conductivity as well as viscosity both increase by the usage of nanofluid compared to those of base liquid.

The following dimensionless governing parameters are presented for the studies of various properties of nanofluids, namely:

Reynolds number:

$$\mathrm{Re}_{nf} = \frac{\rho_{nf} v D}{\mu_{nf}} \tag{4}$$

Prandtl number:

$$\mathrm{Pr}_{nf} = \frac{\mu_{nf} cp_{nf}}{k_{nf}} \tag{5}$$

Grashof number:

$$Gr_{nf} = \frac{{\rho_{nf}}^2 g\beta q'' D^4}{k_{nf}{\mu_{nf}}^2} \tag{6}$$

Rayleigh number:

$$Ra_{nf} = \frac{\rho_{nf} g\beta q'' D^4}{\alpha k_{nf}\mu_{nf}} \tag{7}$$

Peclet number:

$$Pe_{nf} = \mathrm{Re}_{nf}\,.\,\mathrm{Pr}_{nf} \tag{8}$$

where, the thermal diffusivity of nanofluid is given as

$$\alpha = \frac{k_{nf}}{\rho_{nf} cp_{nf}} \tag{9}$$

Reviews of nanofluid research

The state-of-the-art reviews have been published by different researchers on nanofluid applications in heat transfer research. The summary along with the various aspects reviewed have been presented in Table 1.

These evaluations have delivered the discussions of preparation and stability of nanofluid, theoretical and experimental studies on thermophysical properties and forced convective heat transfer characteristics of several nanofluids. Experimental and analytical studies showing various effects of particle size, shape, arrangement, volume concentration, dispersion and migration on convective heat transfer and thermo physical properties, nanofluid heat transfer and pressure drop correlations.

The above summary shows that a number of review articles are published on nanofluids but still there are many issues and matters to be fully investigated. So the present review provides the most recent studies of the convective heat transfer in order to provide database and suggestions for future works for the researchers in order to develop efficient and reliable thermal energy system.

Experimental studies on forced convective heat transfer of nanofluids

Constant heat flux boundary conditions

Tungsten oxide (TiO_2)

He et al. (2007) studied heat transfer and flow behaviour of aqueous suspensions of given nanoparticles (nanofluids) flowing upward through a vertical pipe. They observed that addition of nanoparticles into the base liquid increases the thermal conduction and the enhancement improves with increasing particle concentration and decreasing particle (agglomerate) size. The viscosity increased with increasing particle concentration and particle (agglomerate) size. For fixed flow Reynolds number and particle size of nanofluid, the convective heat transfer coefficient increased with nanoparticle concentration in both the laminar and turbulent flow regimes and it is also seemed that effect of particle concentration was more considerable in the turbulent flow regime.

Further, a study on convective heat transfer and pressure drop in a turbulent flow of aqueous solution of given nanoparticle (15 nm) through a constantly heated horizontal circular tube containing 0.1, 0.5, 1.0, 1.5 and 2.0% volume concentrations of nanoparticles was performed by Kayhani et al. (2012). Results indicated that

Table 1 Summary of the earlier evaluations on nanofluid research

Researchers	Aspects reviewed
Wang and Mujumdar (2007)	Augmentation of thermal conductivity, viscosity, free and forced convection transfer and boiling heat transfer
A. K. Singh (2008)	Thermal conductivity, heat transfer enhancement mechanism, application of the nanofluids
Kakac¸ and Pramuanjaroenkij (2009)	Forced convection heat transfer
Ghadimi et al. (2011)	Stability, characterization, numerical models and measurement methods, thermal conductivity and viscosity of nanofluid
Mohammed et al. (2011)	Types, properties, heat transfer characteristics of nanofluids and margins near the application of nanofluids. Fluid flow and heat transfer characteristics in microchannels heat exchanger
Mohammed et al. (2011)	Preparation of nanofluids methods, types and shapes of nanoparticles, base liquids and additives, transport mechanisms, and permanency of the suspension and heat transfer enhancement
Huminic et al. (2012)	Effective thermal conductivity, viscosity, Nusselt number and application of nanofluids in numerous types of heat exchangers
Ranakoti et al. (2012)	The basic mechanisms of improvement in heat transfer by addition nanoparticles
Philip et al. (2012)	An overview of recent advances in the field of nanofluids, especially the important material properties that affect the thermal properties of nanofluids and novel approaches to achieve extremely high thermal conductivities
Chandrasekar et al. (2012)	Study about thermophysical properties, forced convective heat transfer characteristics, the mechanisms involved and applications of several nanofluids
Daungthongsuk & Wongwises (2007)	Forced convective heat transfer of the nanofluids both of experimental and numerical investigation
Ding et al. (2007)	Forced convective heat transfer by experimental investigation, thermophysical properties, Reynolds number, particle migration effect on thermal boundaries
Godson et al. (2010)	Enhancement of heat transfer, improvement in thermal conductivity, increase in surface volume ratio, Brownian motion, thermophoresis of nanofluids
Murshud et al. (2011)	Various thermal characteristics such as effective thermal conductivity, convective heat transfer coefficient and boiling heat transfer rate of nanofluids
Sarkar et al. (2011)	Heat transfer characteristics of nanofluids in forced and free convection flows, for pressure drop prediction of the nanofluids conventional friction factor correlation of base fluid for both laminar and turbulent flows in minichannel as well as in microchannel is studied
Huminic et al. (2012)	Effective thermal conductivity, viscosity, Nusselt number, and application of nanofluids in numerous types of heat exchangers
Vajjha et al. (2012)	Due to variations of density, specific heat, thermal conductivity and viscosity, the effects on the performance of nanofluids are studied
Yu et al. (2012)	The comparison criteria of the thermophysical property-related heat transfer performance of nanofluids and their base fluids, the predictions of the heat transfer coefficients of nanofluids based on homogeneous fluid models by using nanofluid effective thermophysical properties, the enhancements of the heat transfer coefficients of nanofluids over their base fluids.
Sundar et al. (2013)	Heat transfer and friction factor for different kinds of nanofluids flowing in a plain tube under laminar to turbulent flow conditions, enhancement in heat transfer coefficient.
Suresh kumar et al. (2013)	Transport properties and heat transfer characteristics of base fluids in heat pipes
Corcione et al. (2012)	Heat transfer characteristics of nanofluid

heat transfer coefficients increased with increasing the nanofluid volume fraction but showed no change with changing the Reynolds number. At a Reynolds number of 11800, with 2.0% nanoparticles volume fraction the enhancement in the Nusselt number was observed to be about 8% for nanofluid.

Rayatzadeh et al. (2013) studied the convective heat transfer and pressure drop with and without continuous induced ultrasonic field in the reservoir tank containing nanofluid. Investigations were performed with volume concentration up to 0.25% for laminar flow regime. They noticed that the Nusselt number increased, by dispersing nanoparticles to the base fluid. It also showed that, when particle concentration increased more improvement in Nusselt number could be seen, except for volume concentration of 0.25%. The Nusselt number also showed dramatically increment with induced ultrasonic field as compared to the results obtained for without sonication. No considerable increment was observed in pressure drop.

Aluminium oxide (Al_2O_3)

Wen and Ding (2004) performed their experiments in the entrance region under laminar flow conditions. It has been observed that the convective heat transfer improved in the laminar flow regime by the using of Al_2O_3 nanoparticles which is dispersed in water. The convective heat transfer showed enhancement with Reynolds number, as well as particle concentration. In the entrance region, the improvement was particularly significant and decreases with axial distance. The sole reason for the enhancement of the convective heat transfer was the improvement of the effective thermal conductivity. For a non-uniform distribution of thermal conductivity and viscosity field, the particle migration was solely responsible and there was reduction in the thermal boundary layer thickness.

Anoop et al. (2009) conducted experiments using an aqueous solution of given nanoparticles in the developing region of pipe flow to calculate the convective heat transfer coefficient with the influence of particle size. It was observed that the nanofluid with 45 nm particles showed better heat transfer coefficient than with 150 nm particles. It was concluded that the observed increase in convective heat transfer with nanofluids was not only due to intensification in thermal conductivity but also because of the effects of particle migration and thermal dispersion. Mansour et al. (2009) investigated the problem of thermally developing laminar mixed convection flow inside an inclined tube. Results showed that with an increase of particle volume concentration from 0 to 4%, the heat transfer coefficient falls marginally.

Hwang et al. (2010) measured convective heat transfer coefficient and pressure drop of Al_2O_3 aqueous nanofluids in the fully developed laminar flow regime flowing through a consistently heated circular tube. There was more increment observed in convective heat transfer coefficient as compared to that of thermal conductivity. Based on scale analysis and numerical solutions, they had shown for the first time, the flattening of velocity profiles, induced from large gradients in bulk properties such as nanoparticle concentration, thermal conductivity and viscosity. They proposed that this flattening of the velocity profile is a potential tool for improvement of convective heat transfer coefficient higher than the thermal conductivity augmentation.

The effect of insert wire coil was reported by Chandrasekar et al. (2011) for heat transfer and friction factor characteristics for given nanoparticles with water as a base fluid. When nanofluid is used with wire coil inserts appreciable enhancement in the Nusselt number was observed. The heat transfer augmentation was credited to the thermal dispersion which flattens the temperature distribution and makes the temperature gradient between the fluid and wall steeper. There was no noteworthy increase in pressure drop for nanofluid.

Yu et al. (2012) investigated convective heat transfer and the thermophysical properties of specified nanoparticles in solution of polyalphaolefin (PAO) containing both spherical and rod-like nanoparticles. The effective thermal conductivity and effective viscosity of the nanofluids were measured and compared to predictions from various existing theories in the literature. It was noticed that, in addition to the particle volume fraction, other parameters, including the aspect ratio, the dispersion state and the aggregations of nanoparticles as well as the shear field have significant impact on the effective properties of the nanofluids, especially of those containing non-spherical particles. The convection heat transfer coefficient and pressure drop were also measured for the nanofluids in the laminar flow regime. The results indicated that, in order to correctly interpret the experimental data of nanofluids for a convective flow containing non-spherical nanoparticles, the shear-induced alignment and orientation motion of the particles must be considered.

Sahin et al. (2013) studied the convective heat transfer, the pressure drop characteristics and heat transfer augmentation of water based nanofluid with volume concentration of 0.5%, 1%, 2% and 4% inside a circular tube in the turbulent flow regime. For the events, in which the particle volume fractions were lesser than 2 vol.% addition nanoparticles into pure water heat transfer enhanced. The Nusselt number improved with the rise in the Reynolds number as well as the particle volume fraction up to the particle volume concentration of 1 vol.%. It was concluded that for the concentrations of Al_2O_3 particles higher than 1 vol.% were not appropriate for heat transfer enhancement. For the particle volume concentrations larger than 1 vol.%, the viscosity growth of the nanofluids was much more dominating than the thermal conductivity of the nanofluids on heat transfer enhancement. The friction factor amplified with rise in the particle volume concentration, due to increase in the viscosity. The highest heat transfer enhancement was achieved at Reynolds number of 8000 and 0.5 vol.%.

Esmaeilzadeh et al. (2013) considered hydrodynamics and heat transfer characteristics of γ-Al_2O_3 nanoparticles (15 nm) with distilled water as a base liquid inside a circular tube in laminar flow regime. It was observed that by increasing the particle volume fraction leads to enhancement of convective heat transfer coefficient. Results revealed that the average heat transfer coefficient increased by 6.8% with 0.5% volume concentration and enhanced by 19.1% at 1% volume concentration in comparison with distilled water. The heat transfer coefficient increases with the increase in the heat flux.

Copper (Cu) and copper oxide (CuO)

Suresh et al. (2012) studied the convective heat transfer and friction factor characteristics of the plain and helically dimpled tube under turbulent flow using CuO/water nanofluid as working fluid. It was revealed that there was an appreciable growth in heat transfer rate with the use of nanofluids in a helically dimpled with negligible increase in friction factor compared to plain tube. The experimental results depicted that the Nusselt number with dimpled tube and nanofluids was about 19%, 27% and 39% (for 0.1%, 0.2% and 0.3% volume concentrations respectively) higher than the Nusselt number obtained with plain tube and water under turbulent flow. The experimental results showed that the dimpled tube friction factors were about 2–10% higher than the plain tube of isothermal pressure drop.

Razi et al. (2011) studied the pressure drop and heat transfer characteristics of nanofluid flow inside horizontal flattened tubes. When nanofluids flow in flattened tubes, they have superior heat transfer characteristics rather than in the round tube. Highest heat transfer enhancement of 16.8%, 20.5% and 26.4% was achieved for nanofluid flow compared to pure oil flow with 2% weight concentration inside the round tube and flattened tubes with internal heights of 8.3 mm and 6.3 mm, respectively.

Saeedinia et al. (2012) investigated the heat transfer and pressure drop characteristics of CuO/Base oil nanofluid in a smooth tube with different wire coil inserts in the laminar flow regime. An average, 45% increase in heat transfer coefficient and 63% penalty in pressure drop was observed at the highest Reynolds number inside the wire coil inserted tube with the highest wire diameter (WC3).

Hashemiand Akhavan-Behabadi (2012) performed an empirical study on heat transfer and pressure drop characteristics of CuO–base oil nanofluid flow in a horizontal helically coiled tube. Nanofluids showed better heat transfer characteristics when flowing in a helical tube rather than in the straight tube. Compared to base oil flow, maximum heat transfer enhancement of 18.7% and 30.4% was obtained for nanofluid flow with 2% weight concentration inside the straight tube and helical tube, respectively.

Selvakumar and Suresh (2012) showed the performance of convective heat transfer of aqueous nanofluid in an electronic heat sink. As volume flow rate and nanoparticles volume concentration increases, the convective heat transfer coefficient of water block was found to be increased and the maximum rise was 29.63% for the 0.2% volume concentration compared to deionized water. Based on the pressure drop in the water block, pumping power for the deionized water and nanofluids were evaluated and an average increase was 15.11% for the nanofluid volume concentration of 0.2% compared to deionized water.

Yu et al. (2013) performed the experiments on convective heat transfer with Therminol 59 based nanofluids under turbulent flow regime, containing copper nanoparticles at particle volume concentrations of 0.50% and 0.75%. The heat transfer coefficients calculated from the predicted thermophysical properties of the nanofluids, have enhanced as much as 18% with the introduction of low concentrations (<2.00 vol.%) of nanoparticles for high temperatures conditions. Because therminol-59 is a commonly-used high-temperature heat transfer fluid, that made copper in therminol-59 nanofluids very attractive for many commercial applications.

Ferrous oxide (Fe_3O_4)

Sundar et al. (2012) performed experiments for horizontal circular tube with and without twisted tape inserts for convective heat transfer and friction factor characteristics of magnetic nanofluid under turbulent flow regime. Heat transfer and friction factor enhancement of 0.6% volume concentration of nanofluid in a plain tube with a twisted tape insert of twist ratio H/D = 5 is 51.88% and 1.231 times compared to water flowing in a plain tube under same Reynolds number.

Carbon nanotubes (CNT)

Ding et al. (2006) showed the heat transfer behaviour of aqueous suspensions flowing through a horizontal tube. The flow condition, CNT concentration and the pH level have significant impact on heat transfer behaviour and the effect of pH was observed to be small. The augmentation was mainly dependent on the axial distance from the inlet of the test section; the augmentation showed rise, reached to the highest, and then fell with growing axial distance.

Chen et al. (2008) investigated heat transfer and flow behaviour of aqueous suspensions of titanate nanotubes (nanofluids). The results showed a small thermal conductivity enhancement of ~3% at 25°C and ~5% at 40°C for the 2.5 wt. % nanofluid. Despite the small thermal conduction enhancement, an excellent enhancement was observed on the convective heat transfer coefficient, which was much higher than that of the thermal conductivity enhancement.

Garg et al. (2009) studied with the effect of ultrasonication on viscosity and heat transfer performance of multi-wall carbon nanotube-based aqueous nanofluids. The maximum percentage enhancement in thermal conductivity was a 20% increased considerably after 24°C. At Reynolds number of 600 ± 100, the largest percentage improvement in heat transfer coefficient was 32%. There was continuous increment in heat transfer coefficient with axial distance. The contribution of significant increase in thermal conductivity with the rise of bulk temperature with axial distance was the reason behind this phenomenon.

Amrollahi et al. (2010) measured the convective heat transfer coefficients of water-based FWNT nanofluid through a uniformly heated horizontal tube in entrance region under both laminar and turbulent regimes flowing. For the first time, effective parameters such as Reynolds number, mass fraction and temperature, altogether in entrance region has been compared to calculate the convective heat transfer coefficients for functionalized MWNT nanofluid. The experimental results indicated that at a concentration of 0.25 wt. %, the convective heat transfer coefficient of these nanofluids increased up to 33–40% compared with pure water in laminar and turbulent flows respectively at 20°C.

Liu and Liao (2010) presented the forced convective flow and heat transfer characteristics of aqueous drag-reducing fluid with the carbon nanotubes addition. A new kind of aqueous drag-reducing fluid with carbon nanotubes (CNTs) was developed. The new working fluid was an aqueous CTAC (cetyl trimethyl ammonium chloride) solution with CNTs added and has both special effects of drag-reducing and heat transfer enhancement. Results indicated that there were no obvious differences of the drag-reducing characteristics between conventional drag-reducing fluid and new drag-reducing nanofluid. However, there were obvious differences of the heat transfer characteristics between both fluids. The heat transfer characteristics of new drag-reducing nanofluid have strong dependencies on the liquid temperature, the nanoparticles concentration and the CTAC concentration.

Further, experiments were performed by Behabadi et al. (2012) on heat transfer improvement of a nanofluid flow inside vertical helically coiled tubes in the thermal entrance region. If nanofluid was used instead of the base fluid, the results showed that the Nusselt number increased up to 45% in the tested straight tube. The heat transfer coefficient enhancement was calculated about 80%. The heat transfer rate increases noticeably on implementation of a helical coil instead of a straight tube. The Nusselt numbers acquired 3 to 7 times higher for the base fluid inside tested helical coils than the values evaluated for the base fluid inside straight tubes with a similar length of the coils. Finally, it was observed that the combination of the two enhancing methods has a noticeably high capability to the heat transfer rate.

Wang et al. (2013) reported the heat transfer and pressure drop of nanofluids containing carbon nanotubes (CNT) in a horizontal circular tube. A considerable enhancement in the average convective heat transfer was also observed compared with the distilled water. For the nanofluids with volumetric concentration of 0.05% and 0.24%, the heat transfer enhancement are 70% and 190% at Reynolds number of about 120 respectively, while the enhancement of thermal conductivity was less than 10%, therefore, it was concluded that the large heat transfer increase cannot be solely attributed to the enhanced thermal conductivity.

Silicon oxide (SiO_2)

Azmi et al. (2013) determined the forced convection heat transfer and friction factor with SiO_2 nanofluid in the turbulent flow regime. The Nusselt number and friction factor at 3.0% nanofluid particle concentration was respectively greater than the values of water by 32.7% and 17.1%. The pressure drop increased with particle concentration up to 3.0% and decreases thereafter. The nanofluid friction factor decreased with increase in Reynolds number at any concentration.

Comparative study among two or more nanoparticles

Kim et al. (2009) performed a study through a circular straight tube with stable nanofluids, i.e. water-based suspensions of alumina and amorphous carbonic nanoparticles prepared by two and one-step methods in the laminar and turbulent flow regime. The increment in thermal conductivity and convective heat transfer coefficient was 8% and 20%, respectively in alumina nanofluids containing 3 vol. % of suspended particles. For amorphous carbonic nanofluids, the thermal conductivity was similar to that of water, and the convective heat transfer coefficient increased by only 8% in laminar flow. The convective heat transfer enhancement at the entrance region was due to the movements of nanoparticles.

Rea et al. (2009) examined convective heat transfer and viscous pressure losses for alumina–water and zirconia–water nanofluids with a vertical heated tube in a flow loop laminar flow regime. For alumina–water nanofluid, the heat transfer coefficients obtained to rise by 17% and 27% in the entrance region and in the fully developed region respectively at 6 vol. % with respect to pure water. For zirconia–water nanofluid, at 1.32 vol.%, heat transfer coefficient increased by nearly 2% in the entrance region and 3% in the fully developed region. The calculated pressure loss for the nanofluids was in general much more than that of pure water.

Vajjha et al. (2010) presented the new correlations for the convective heat transfer and the friction factor developed from the experiments of nanoparticles comprised of aluminium oxide, copper oxide and silicon dioxide dispersed in 60% ethylene glycol and 40% water by mass. Heat transfer coefficient of nanofluids showed an increase with the particle volumetric concentration. For example, at a Reynolds number of 7240, the percentage increase in the heat transfer coefficient over the base fluid for a 10% Al_2O_3 nanofluid was 81.74%. The pressure loss of nanofluids also increased with an increase in particle volume concentration. The increase of pressure loss for a 10% Al_2O_3 nanofluid at a Reynolds number of 6700 was about 4.7 times than for the base fluid. This was due to the growth in the viscosity of the nanofluid with concentration.

Hybrid nanofluids

Suresh et al. (2011) showed the effect of a new type Al_2O_3–Cu/water hybrid nanofluid in heat transfer. They showed that Al_2O_3–Cu/water hybrid nanofluids have somewhat more friction factor when compared to Al_2O_3/water nanofluid at 0.1 vol.%. In a straight circular tube, heat transfer performance improved with Al_2O_3–Cu hybrid nanoparticles suspension when compared to that of pure water. The average enhancement in Nusselt number for Al_2O_3–Cu/water hybrid nanofluid was 10.94% in comparison with that of pure water. With growing Reynolds number, the convective heat transfer coefficient rises. The experimental results of hybrid nanofluid indicated highest enhancement of 13.56% in Nusselt number at a Reynolds number of 1730 when compared to pure water for laminar flow.

The summary of experimental studies based on forced convection for various nanofluids under constant heat flux boundary conditions and the contrivances suggested by the several researchers is given in Table 2. A graphical representation of Nusselt versus Reynolds number and heat transfer coefficient versus Reynolds number of various nanofluids at different volume concentrations for turbulent flow regime are depicted in Figures 1 and 2.

The constant wall temperature boundary conditions

Aluminium oxide (Al_2O_3)

Fotukian and Esfahany (2010a) worked on circular tube with γ-Al_2O_3/water nanofluid. They studied the convective heat transfer under turbulent flow regime with nanoparticles having volume fraction, less than 0.2% in the dilute nanofluids. It was observed that, at the Reynold number of 10,000, the heat transfer coefficient increased with 48% compared to pure water with 0.054% volume concentration. It was also noticed that, no further heat transfer enhancement occurred with increasing the nanoparticles concentration. The ratio of the convective heat transfer coefficient of nanofluid to that of pure water reduced with Reynolds number. When the nanofluid streamed in the tube, the wall temperature of test tube decreased considerably compared to the case related to water flowing in the tube. There was 30% intensification in pressure drop of nanofluid at Reynolds number of 20,000 with 0.135% volume concentration as compared to pure water. With increasing the volume fraction of nanoparticles, the pressure drop of nanofluid increased.

Heyat et al. (2012) explored convective heat transfer characteristics of Al_2O_3/ water nanofluids in the fully developed turbulent flow regime. The results showed that the heat transfer coefficient of nanofluid was higher than that of the base fluid and increased with increasing the particle concentrations. Moreover, the Reynolds number had a little effect on heat transfer enhancement. The experimental data were compared with traditional convective heat transfer and viscous pressure drop correlations for fully developed turbulent flow.

Copper oxide (CuO)

The CuO/water nanofluid convective heat transfer in turbulent regime inside a tube was investigated by Fotukian and Esfahany (2010b). The nanoparticles volume fractions less than 0.3% were used in the dilute nanofluids. As compared to pure water, the heat transfer coefficient improved by 25%. It was found that there was not so much effect on enhancement of heat transfer by increasing the nanoparticles concentration in the range of studied concentrations. Also the ratio of the convective heat transfer coefficient of nanofluid to that of pure water diminished with enhancing Reynolds number. When the nanofluid streamed in the tube, the wall temperature of test tube decreased considerably compared to the case of water flowing in the tube. With 0.03% volume concentration of nanofluid, the maximum increase in pressure drop was about 20%.

A steady state flow in helically coiled tubes was observed by Akbaridoust et al. (2013). In this study, heat transfer coefficient and pressure drop of nanofluid were compared to that of base liquid at same flow conditions in different helically coiled tubes. It was observed that, heat transfer and pressure drop was higher for tubes with greater curvature ratio. In various helical coiled tubes, nanofluid with larger values of particle volume concentration exhibited more heat transfer coefficient and pressure drop. Due to the low coil pitch, the coils with equal curvature ratio and different torsion ratio had the same results.

Silicon oxide (SiO_2)

Ferrouillat et al. (2011) examined the convective heat transfer of specified nanoparticles in base fluid water existing in colloidal suspensions (5–34 wt. %) in a flow loop with a horizontal tube test section whose wall temperature was imposed. Results indicated that the heat transfer coefficient values have increased from 10% to 60% compared to those of pure water. They also showed that the general trend of standard correlations was respected. In order to evaluate the benefits provided by the enhanced properties of the nanofluids studied, an energetic performance evaluation criterion (PEC) is defined. This PEC decreases as the nanoparticles concentration is increased.

The experiment was performed by Anoop et al. (2012) on forced convective heat transfer of nanofluids in a microchannel. The experimental results indicated that heat transfer increased with a flow rate for both water and nanofluid samples; however, for the nanofluid samples, heat transfer enhancements occurred at lower flow rates and heat transfer degradation occurred at higher flow rates (compared to that of water). Electron microscopy of the heat-exchanging surface revealed that surface modification of the microchannel flow surface occurred due to nanoparticles precipitation from the nanofluid. Hence, the fouling of the microchannels by the nanofluid samples is believed to be responsible for the progressive degradation in the thermal performance, especially at higher flow rates.

Table 2 Summary of forced convection experimental studies on nanofluids under constant heat flux boundary conditions

Researcher	Nanofluid	Method of nanofluid preparation	Particle size (nm)	Particle volume concentration %	Flow regime (Range of Reynolds number)	Heat transfer enhancement mechanisms
He et al. (2007)	TiO_2/water	Ultrasonication	95,145 and 210	1.0, 2.5 and 4.9 (wt.%)	Laminar and Turbulent (800–6500)	Increasing particle concentration and decreasing particle (agglomerate) size
Kayhani et al. (2012)	TiO_2/water	Two step	15	0.1, 0.5, 1, 1.5 and 2	Turbulent (7000–15000)	Particle volume concentration
Rayatzadeh et al. (2013)	TiO_2/water	Two step	30	0- 0.25	Laminar (800–2000)	Dispersion of suspended nanoparticles and sonication
Wen and Ding (2004)	γ-Al_2O_3/water	Ultrasonic bath	26-56	0- 4 (wt. %)	Laminar/entrance region (600–2200)	Non-uniform distribution of thermal conductivity due to particle migration effect and thermal boundary layer thickness reduced with effect of viscosity field
Anoop et al. (2009)	Al_2O_3/water	Laser evaporated physical	45 and 150	1, 2, 4 and 6 (wt. %)	Laminar/developing flow (500–2500)	Thermal dispersion and particle migration effects
Hwang et al. (2009)	Al_2O_3/Water	Two step method (ultrasonication)	30	0.01-0.3	Fully developed laminar flow (500–800)	Due to particle migration induced by Brownian diffusion there was flattening of velocity profile and thermopheris
Chandrasekar et al. (2010)	Al_2O_3/Water	Microwave assisted chemical precipitation method	43	0.1	Fully- developed Laminar flow (600–2400)	Flattens the temperature distribution due to the effects of dispersion or back-mixing which is attributed by wire coil insert and create the temperature gradient steeper between the fluid and wall
Mansour et al. (. 2011)	Al_2O_3/water	-	36	0-4	Laminar mixed convection flow (350–900)	Particle volume concentration and inclination of tube
Yu et al. (2012)	Al_2O_3-polyalphaolefin (PAO)	Ultra- sonication (spherical, nano-rods)	60 for spherical; d = 7, l = 85 for nano-rods	0.65	Laminar (100–500)	Particle volume concentration, other parameters such as dispersion state, aspect ratio and aggregation of nanoparticles as well as the shear field
Sahin et al. (2013)	Al_2O_3/water	Two step	-	0.5, 1, 2 and 4	Turbulent (4000–20,000)	Particle volume concentration and Reynolds number
Esmaeilzadeh et al. (2013)	γ-Al_2O_3/water	Ultrasonication	15	0.5, 1	Laminar (400–2000)	Particle volume concentration
Suresh et al. (2012)	CuO/ Water	Sol–gel method	15.7	0.1, 0.2 and 0.3	Turbulent (2500–6000)	Increasing volume concentration in plain tube, Reynolds number and dimpledtube in geometry
Razi et al. (2011)	CuO/oil	Chemical Analysis	50	0.2, 0.5, 1 and 2 (wt. %)	Laminar (10–100)	Flattening the tube profile
Saeedinia et al. (2012)	CuO/oil	Chemical Analysis	50	0.07 -0.3	Laminar (15–110)	Wire coil insert
Hashemi and Akhavan-Behabadi (2012)	CuO/oil	Ultrasonic processor	50	0.5,1 and 2 (wt. %)	Laminar (100–2000)	Helical tube curvature
Selvakumar and Suresh (2012)	CuO/water	Ultrasonication	27-37	0.1 and 0.2	Turbulent (2985–9360)	Increment in the volume flow rate and nanoparticle volume fraction
Yu et al. (2013)	Copper-in-Therminol 59	Sonication	50 to 100	0.50, 0.75 and 2.00	Turbulent (3000–8000)	Base fluid used as high temperature heat transfer fluid

Table 2 Summary of forced convection experimental studies on nanofluids under constant heat flux boundary conditions *(Continued)*

Sundar et al. (2012)	Fe_3O_4/Water	Purchased from Sigma Aldrich Chemicals Ltd., USA	36	0-0.6	Turbulent (3000–22,000)	Use of twisted tape insert of twist ratio H/D = 5
Ding et al. (2006)	*MWCNT/water	Ultrasonication and high shear homogenization	-	0.5 (wt. %)	Laminar (800–1200)	Particle re-arrangement, due to the presence of nanoparticles there was reduction of thermal boundary layer, shear induced thermal conduction enhancement
Chen et al. (2008)	Titnate nanotube/ water	Shear homogenizing	*d = 10 l = 100	0.5, 1.0 and 2.5 (wt. %)	Laminar (1100–2300)	Particle re-arrangement under shear, enhanced wettability and particle shape effect and aggregation (structuring)
Garg et al. (2009)	*MWCNT/water,	Ultrasonication/ Power Law viscosity model	*d = 10–20 l = 0.5- 40 μm	1	Laminar (600–1200)	Increase in axial distance
Amrollahi et al. (2010)	FMWNT/water	Ultrasonication	150–200	0, 0.1, 0.12, 0.2 and 0.25 (wt. %)	Laminar and Turbulent (1500–5000)	Effective parameters includingmass fraction, Reynolds number, and temperature, altogether in entrance region
Liu et al. (2010)	*CNT/CTAC	Ultrasonic bath	*d = 10-20 l = 1–2 μm	0.5, 1.0, 2.0 and 4.0 (wt. %)	Turbulent (10^4 to 5×10^4)	A new kind of aqueous drag reducing base fluid
Behbadi et al. (2012)	*MWCNT/heat transfer oil	Ultrasonic processor	-	0.1, 0.2 and 0.4 (wt. %)	Laminar (100–1800)	Diffusion of particle in base fluid and helical tube profile
Wang et al. (2013)	*MWCNT/De-ionized water	Binary mixing	*d=20-30 l= 5-30 μm	0.0 and 0.24	Laminar (20 to 250)	Enhanced thermal conductivity and nature of nanoparticle
Azmi et al. (2013)	SiO_2/water	Mechanical Homogenisation	22	0- 4	Turbulent (5000–27,000)	Increment in particle volume concentration
Kim et al. (2009)	Alumina/water amorphous carbonic nanoparticles/ water	Two step and one step	20-50	0-3 0–3.5	Laminar (800–2400) and Turbulent (3000–6500)	Disturbances of thermal boundary layers
Rea et al. (2009)	Alumina/water Zirconia/water	Purchased Nyacol_ Nano Technologes Inc.	50	0- 6 0-3	Laminar- entrance and fully-developed region (432–1888); (333–356)	Due to various mixture properties of nanofluid
Vajjha et al. (2010)	*Al_2O_3/EG-water (60:40) CuO/EG-water(60:40) SiO_2/ EG-water (60:40)	Ultrasonication	45 29 20, 50 and100	0-0.1 0–0.006 0–0.1	Fully developed turbulent (2200–16000)	Particle volume concentration
Suresh et al. (2011)	Al_2O_3–Cu/water hybrid nanofluid	Two Step method	15	0.1	Fully developed laminar (700–2300)	Hybrid nanofluid has higher friction factor than Al_2O_3/water nanofluid

*CNT-Carbon nanotube, MWCNT-Multi-walled CNT, FWCNT-Functionalized CNT, d-diameter of nanoparticle, l-length of nanoparticle, CTAC-cetyltrimethyl ammonium chloride, EG- Ethylene Glycol.

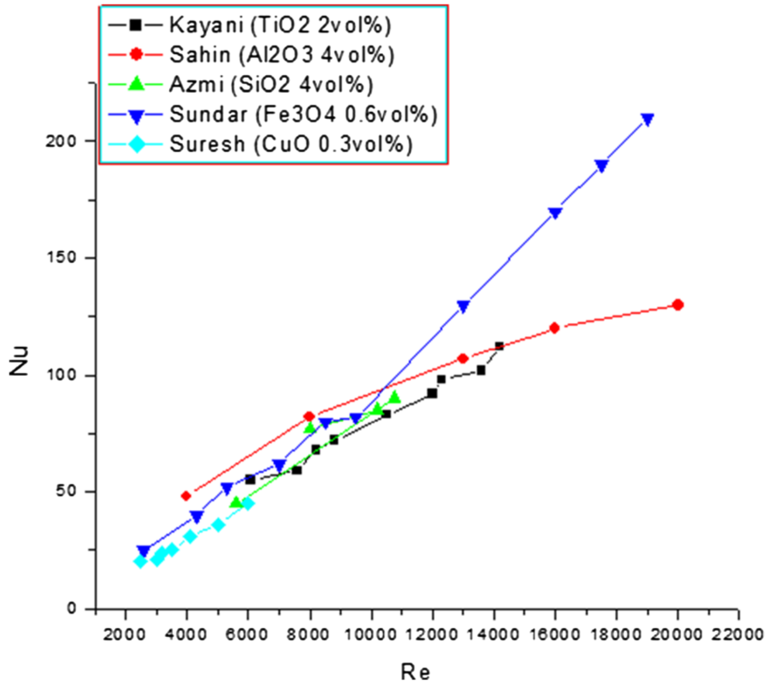

Figure 1 **Graphical representation of Nusselt and Reynolds number for various nanoparticles at different volume concentrations for turbulent flow regime.**

Carbon nanotubes (CNT)

Ashtiani et al. (2012) investigated heat transfer characteristics of MWCNT-heat transfer oil nanofluid flow inside horizontal flattened tubes. Nanoparticles weight fractions used were 0%, 0.1%, 0.2%, and 0.4%. In addition, the heat transfer coefficient increased at a constant volumetric flow rate as the tube profile became more flattened and the hydraulic diameter decreased. Increasing volumetric flow rate results in heat transfer enhancement for a given flattened tube at a constant nanoparticles weight fraction.

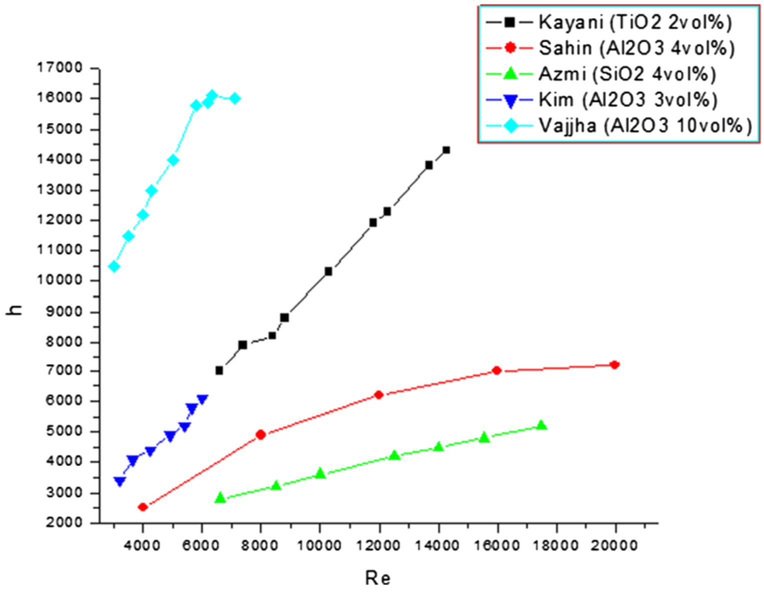

Figure 2 **Graphical representation of heat transfer coefficient and Reynolds number for various nanoparticles at different volume concentrations for turbulent flow regime.**

The heat transfer rate enhanced remarkably on utilizing nanofluids instead of the base fluid. As higher the nanoparticles weight fraction, the more the rate of heat transfer augmentation.

An empirical study performed by Pakdaman et al. (2013) on pressure drop characteristics of nanofluid flow inside vertical helically coiled tubes for the laminar flow regime. Heat transfer oil was used as the base fluid, and (MWCNTs) were utilized as the additive to provide the nanofluids. Regarding the experimental study, application of helical coiled tubes instead of straight ones increased the pressure drop exponentially. As compared to the base fluid flow, nanofluid flows showed greater rates of pressure drop irrespective of the tube geometry in which the fluid flows. Finally according to the findings, the combination of the two processes used in this investigation causes the pressure of the fluid flow to drop considerably along the test section.

Comparison study among two or more nanoparticles

The experiment was performed by Heris et al. (2006) on convective heat transfer of oxide nanofluids under laminar flow regime. The results emphasized that the single phase correlation with nanofluids properties (homogeneous model) was not able to forecast heat transfer coefficient improvement of nanofluids. For the comparison between CuO/water and Al_2O_3/water nanofluids, the experimental results showed that heat transfer coefficient ratios for nanofluid to the homogeneous model are near to each other in low concentration but by enhancing the volume concentration, more heat transfer augmentation for Al_2O_3/water observed.

Hojjat et al. (2011) studied turbulent flow forced convective heat transfer behaviour of non-Newtonian nanofluids in a circular tube. By adding homogeneously γ- Al_2O_3, TiO_2 and CuO nanoparticles into the base fluid, three types of nanofluids were prepared. The rise in the convective heat transfer coefficient of nanofluids was more than the intensification in the effective thermal conductivity of nanofluids.

Meriläinen et al. (2013) showed the effect of particle size and shape on heat transfer characteristics and pressure losses in water-based nanofluids under turbulent flow regime. They found that on the basis of constant Reynolds number in range of 3000–10,000, average convective heat transfer coefficients of nanofluids improved up to 40% when compared to the base liquid. As compared to the base fluids, the rise in the dynamic viscosity of nanofluids indicated considerable pressure losses impact. To account for this, by matching the improved heat transfer performance to the augmented pumping power requirement, the convective heat transfer efficiency η was determined. Growing the nanoparticles volume concentration above 2% enhanced the heat transfer coefficient but at the similar time sinks heat transfer efficiency ‘η’ due to pressure losses, which outcome from the amplified fluid density and viscosity.

The summary of above experimental forced convection studies under constant wall temperature boundary conditions for various nanofluids is given in Table 3.

Heat exchangers

Tungsten oxide (TiO_2)

Duangthongsuk et al. (Duangthongsuk) showed the heat transfer enhancement and pressure drop characteristics of water based nanofluid in a double-pipe counter-current heat exchanger. The results showed that the convective heat transfer coefficient of nanofluid was 6–11% higher than that of the base liquid. With an increase in the mass flow rate of the hot water and nanofluid, the heat transfer coefficient of the nanofluid increased. Also, heat transfer coefficient of the nanofluid increased with the decrease in the nanofluid temperature, and the temperature of the heating fluid had no significant effect on it. Again, similar work was performed by Duangthongsuk et al. (2010). This time results showed that the heat transfer coefficient of nanofluid was much more than that of the base fluid and augmented with improving particle concentrations and the Reynolds number. The heat transfer coefficient of nanofluids was nearly 26% more than that of pure liquid. It was also emphasized that the heat transfer coefficient of the nanofluids was approximately 14% lower than that of base fluids at a volume concentration of 2.0 vol.% for given conditions. Increasing the volume concentrations, the pressure drop of nanofluids increased. It was also observed that the pressure drop of nanofluids was somewhat more than the base liquid.

Sajadi et al. (2011) investigated the convective heat transfer and pressure drop of aqueous suspension of nanofluid in a circular tube in the turbulent flow regime, where the volume fraction of nanoparticles in the base fluid was less than 0.25%. The results showed that heat transfer rate augmented significantly on the addition of small amounts of nanoparticles to the base fluid. There was no much effect on heat transfer enhancement by increasing the volume fraction of nanoparticles. The pressure drop of nanofluid increased with increasing the volume fraction of nanoparticles. The maximum pressure drop was about 25% greater than that of pure water which occurred in the highest volume fraction of nanofluid (0.25%) at Reynolds number of 5000.

Arani et al. (2013) investigated the convection heat transfer characteristics of water based nanofluid in fully developed turbulent flow. It was observed that all nanofluids, with particles size diameter (10, 20, 30 and 50 nm) showed better Nusselt number than the base liquid. It was further noticed that higher thermal performance was observed by the nanofluid with 20 nm particles size diameter. The

Table 3 Summary of experimental forced convection studies under constant wall temperature boundary conditions for various nanofluids

Researcher	Nanofluid	Method of nanofluid preparation	Particle size (nm)	Particle volume concentration	Flow regime (Range of Reynolds number)	Heat transfer enhancement mechanisms
Fotukian and Esfahany (2010a)	γ-Al_2O_3/water	Ultrasonic cleaning and mechanical mixing	20	0-0.2	Turbulent (5000–35000)	Dispersion of suspended nanoparticles
Heyat et al. (Heyhat et al. 2012)	Al_2O_3/water	Two-step	40	0.1-2	Turbulent (2500–17000)	Increasing the particle volume concentrations
Fotukian andEsfahany (2010b)	CuO/water	Ultrasonic mixing	30-50	0-0.3 %	Turbulent (5000–35000)	In presence of nanoparticles flowing in the tube, enhanced thermal energy transfer from the wall to the nanofluid
Akbaridoust et al. (2013)	CuO/ water	*EEW	68	0.1, 0.2 vol. %	Laminar (140–1000)	Higher values of particle volume fraction, greater curvature ratio (helical tube)
Ferrouillat et al. (2011)	SiO_2/water	Prepared from a commercial solution	22	5–34 (wt.%)	Laminar and turbulent (200–10,000)	Increase of particle volume concentration
Anoop et al. (2012)	SiO_2/water	Top-down approach	20	0.2, 0.5 and 1 (wt.%)	Laminar (2–23)	Applications of nanofluids have been explored in the literature for cooling of micro devices due to the anomalous enhancements in their thermo-physical properties as well as due to their lower susceptibility to clogging
Ashtiani et al. (2012)	*MWCNT/heat transfer oil	Electrical mixing and then ultrasonic cleaning	10-30	0, 0.1, 0.2 and 0.4 (wt. %)	Laminar hydrodynamically fully developed regime (lower than 1500)	Flattening tube at a constant nanoparticle weight fraction, particle volume fraction and increasing volumetric flow rate
Pakdaman et al. (2013)	*MWCNT-heat transfer oil	Ultrasonic processing	-	0, 0.1, 0.2 and 0.4 (wt. %)	Laminar flow in the thermal entrance region (0–2000)	Suspending nanoparticles in the base fluid enhances thermophysical properties
Heris et al. (2006)	CuO/water Al_2O_3/water	Ultrasonic vibration	50-60 20	0.2 – 3	Laminar (650–2050)	For low concentrations, heat transfer coefficient ratios for nanofluid to homogeneous model are close to each other but by enhancing the volume concentration, more heat transfer enhancement for Al_2O_3/water can be detected
Hojjat et al. (2011)	*γ- Al_2O_3/ CMC TiO_2/ CMC CuO/CMC	Ultrasonic vibration	25 10 30-50	0.1-1.5	Turbulent (8000–33000)	Peclet number and the nanoparticle concentration
Meriläinen et al. (2013)	Al_2O_3/water SiO_2/ water MgO/water	Ultrasound processing	41-53 15–47 28-110	0.5- 4 0.5 -4 0.5-2	Turbulent (3000–10000)	Use of small sized, spherical shape and smooth particles (less than 10 nm in size)

*MWCNT- Multi-walled carbon nanotubes, CMC- carboxymethyl cellulose, EEW- Electric Explosion of Wire.

average Nusselt number increased with the increase in the Reynolds number and particle volume concentration.

Aluminium Oxide (Al_2O_3)

Pandey et al. (2012) investigated effects of nanofluid (2, 3 and 4 vol. %) and water as coolants on exergy loss, heat transfer and frictional losses, and in a counter flow corrugated plate heat exchanger. It was noticed that the heat transfer characteristics enhance with intensification of Reynolds and Peclet number and with reduction in nanofluid concentration. For a given pumping power more heat could be extracted by the nanofluids relative to water, though with the lowest concentration of nanofluids, the maximum heat transfer rate was found. The non-dimensional exergy loss was observed to remain constant for water. Among the four coolants considered for the experiment, the non-dimensional exergy loss was the lowest with 2 vol. % nanofluid for a coolant flow rate up to 3.7 l lpm beyond which water gave the least value.

Wu et al. (2013) investigated convective heat transfer characteristics and pressure drop of water and five aqueous suspensions of nanofluids of weight concentrations from 0.78% wt. to 7.04% wt. inside a double-pipe helically coiled heat exchanger for both laminar flow and turbulent flow. Effect of nanoparticles on the critical Reynolds number was negligible. No anomalous heat transfer enhancement was found for both laminar flow and turbulent flow regimes. According to the constant flow velocity basis, the heat transfer enhancement of the nanofluids compared to water is from 0.37% to 3.43%.

Again the work is done on double tube heat exchanger by Darzi et al. (2013) on heat transfer and flow characteristics of water based nanofluid, and found out the effects of nanofluid with a mean diameter of 20 nm on heat transfer, pressure drop and thermal performance of a double tubes heat exchanger. The effective viscosity of nanofluid was measured in various temperatures ranging from 27°C to 55°C.

Khedkar et al. (2013) concentrated on the study of the concentric tube heat exchanger for water to nanofluids heat transfer with various concentrations of nanoparticles into base fluids and application of nanofluids as working fluid. It observed that, 3% nanofluids shown optimum performance with overall heat transfer coefficient 16% greater than water.

A study is reported by Tayal et al. (2999) on the forced convective heat transfer and flow characteristics of a nanofluid consisting of water and different volume concentrations of specified nanoparticles, nanofluid (0.3-2) % flowing in a horizontal shell and tube heat exchanger counter flow under turbulent flow conditions. The results showed that the convective heat transfer coefficient of nanofluid was slightly higher than that of the base liquid at same mass flow rate and at the same inlet temperature. The heat transfer coefficient of the nanofluid increases with an increase in the mass flow rate and with the increase of the volume concentration of the Al_2O_3 nanofluid. However, increasing the volume concentration caused increase in the viscosity of the nanofluid leading to increase in friction factor.

Carbon nanotubes (CNT)

The convective heat transfer characteristics were determined by Kumaresan et al. (2012) based CNT nanofluids in a tubular heat exchanger. The results indicated that the maximum enhancement in convective heat transfer coefficient was 160% for the nanofluid containing 0.45 vol. % MWCNT, which could not be attributed uniquely by improved thermal conductivity of the nanofluids. Further, there was a significant decrease in Reynolds number for a known velocity for all the nanofluids. The augmentation in the friction factor is minor at a greater velocity and greater temperature for the MWCNT nanofluids with 0.15 vol. %. Yet again, similar investigation was accomplished by Kumaresan et al. (2013) with the similar heat exchanger of several lengths for energy efficient cooling/heating system. In contrast to conventional heat transfer concept, the value of the Nusselt number for the nanofluids showed increment with the fall in the Reynolds number as the MWCNT concentration growths. The results revealed that in the entrance region, there was notable improvement in the convective heat transfer coefficient. Migration of the carbon nanotubes was the possible reason for the abnormal augmentation in the heat transfer coefficient for the smaller length of the test section. That migration of carbon nanotubes did not permit the thermal boundary layer to grow at the faster speed.

Copper Oxide (CuO)

Kannadasan et al. (2012) presented the comparison of heat transfer and pressure drop characteristics of CuO/water nanofluids in a helically coiled heat exchanger held in horizontal and vertical positions. Experiments were conducted using water and CuO/water nanofluids of 0.1% and 0.2% volume concentrations in the turbulent flow regimes. The experimental results showed that in the enhancement of convective heat transfer coefficient and friction factors of nanofluids, there was no much difference between horizontal and vertical arrangements compared to water. The enhancement in internal Nusselt numbers was high for higher concentration nanofluids at turbulent flow irrespective of the positions of the helically coiled heat exchanger.

Silver(Ag)

Godson et al. (2011) examined the convective heat transfer of nanofluids; experiments were performed using nanofluid made with given nanoparticles with water as base fluid in a horizontal 4.3 mm inner-diameter tube-in-tube counter-current heat transfer test section under laminar, transition and turbulent flow regimes. Experiments showed that convective heat transfer coefficient improved with the suspended nanoparticles by as much as 28.7% and 69.3% for 0.3% and 0.9% of silver content, respectively. Again same investigator Godson et al. [(Godson et al.)] performed their work by taking same nanofluid in a shell and tube heat exchanger. The results indicated an increase in convective heat transfer coefficient and effectiveness of nanofluids as the particle volume concentration was increased. A maximum enhancement in convective heat transfer coefficient of 12.4% and effectiveness of 6.14% was recorded.

Graphite

Further, investigation by taking graphite nanoparticles was performed by Yang et al. (2005) on heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in a laminar flow. At low weight fraction loadings, the graphite nanoparticles increased the static thermal conductivities of the fluid significantly. However, the experimental results revealed that there was less increase in heat transfer coefficient than predicted by either the conventional heat transfer correlations for homogeneous fluids.

Comparative study among two or more nanoparticles

Zamzamian et al. (2011) examined turbulent flow forced convective heat transfer coefficient in nanofluids of Al_2O_3/EG and CuO/EG in a double pipe and plate heat exchangers. They evaluated the effects of operating temperature and particle concentration on the forced convective heat transfer coefficient of the nanofluids. The outcomes showed significant enhancement in convective heat transfer coefficient of the nanofluids as compared to the base fluid, ranging from 2% to 50%. Furthermore, the outcomes showed that the convective heat transfer coefficient of nanofluid growths with increasing nanofluid temperature and nanoparticles concentration.

Further, the heat transfer characteristics of γ-Al_2O_3/water and TiO_2/water nanofluids were measured under turbulent flow condition in a shell and tube heat exchanger by Farajollahi et al. (2010). There was noteworthy improvement in heat transfer characteristics by adding nanoparticles to the base fluid as observed in results. When compared heat transfer behaviour of two nanofluids indicated that at a certain Peclet number and optimum nanoparticle concentration, heat transfer characteristics of TiO_2/water nanofluid were higher than those of γ-Al_2O_3/water nanofluid while γ-Al_2O_3/water nanofluid own superior heat transfer behaviour at larger nanoparticle concentrations.

The comparison of the thermal performances of two nanofluids at low temperature in a plate heat exchanger was given by Maré et al. (2011). The first was composed of oxides of alumina (γ-Al_2O_3) dispersed in water and the second one was aqueous suspensions of nanotubes of carbons (CNTs). The viscosity of the nanofluids was measured as a function of the temperature between 2° and 10°C. An experimental device, containing three thermal buckles controlled in temperature and greatly instrumented permitted to study the thermal convective transfers. The evolution of the convective coefficient was presented according to the Reynolds number, at low temperature from 0 to 10°C and for the two aforementioned nanofluids.

Additionally, Tiwari et al. (2013) investigated the heat transfer performance of the plate heat exchanger employing several nanofluids (CeO_2, Al_2O_3, TiO_2 and SiO_2) for various volume concentrations. The study depicted that CeO_2/water yielded best performance (maximum performance index enhancement of 16%) with comparatively minor optimum concentration (0.75 vol. %) within examined nanofluids.

The summary of above experimental forced convection studies of heat exchangers for various nanofluids is given in Table 4.

Discussions

The literature review reveal that nanofluids considerably enhance the heat transfer ability of conventional heat transfer liquids including oil or water or ethylene glycol or propylene glycol by dispersing nanoparticles in these fluids. It is understood that following mechanisms are responsible for enhancement of heat transfer coefficient in nanofluids

- Increasing particle volume concentration and decreasing particle (agglomerate) size.
- Dispersion of dispersed nanoparticles.
- Ultrasonication
- Non-uniform distribution of thermal conductivity and viscosity field due to influence of particle migration.
- Thermal boundary layer thickness reduction.
- Particle migration results in flattened velocity profile induced by Brownian diffusion and thermophoresis.
- Particle re-arrangement under shear, enhanced wettability and particle shape effect and structuring.
- Rise in value of thermal conductivity and Reynolds number of nanofluids.

One of the expected reasons of enhanced heat transfer performance of nanofluids is the reduction in boundary layer thickness by mixing effects of particles near the wall. The application of wire-coil inserts or dimpled tube can be a better option compared to twisted tape, longitudinal strip or spiral rod inserts because the wire-coil inserts or dimpled tube largely interrupts the flow near the wall while the twisted tape or longitudinal tape inserts interrupts the whole flow field. Additionally, wire-coil inserts

Table 4 Summary of experimental forced convection studies of heat exchangers for various nanofluids

Researcher	Nanofluid	Method of nanofluid preparation	Particle size (nm)	Particle volume concentration (vol.%)	Type of heat exchanger	Flow Regime (Range of reynolds number)	Heat transfer enhancement mechanisms
Duangthongsuk et al. (Duangthongsuk)	TiO_2/water	Ultrasonic vibration	21	0.2	Horizontal double tube counter-flow	Turbulent (4000–18000)	Increase with the increase of particle volume concentration and Reynolds number
Duangthongsuk et al. (2010)	TiO_2/water	Ultrasonic vibration	21	0.2, 0.6, 1.0, 1.5 and 2.0	Horizontal double tube counter-flow	Turbulent (4000–18000)	Increase with the increase of particle volume concentration and Reynolds number
Sajadi et al. (2011)	TiO_2/water	Ultrasonic cleaning	30	0.05, 0.1, 0.15, 0.20 and 0.25	Horizontal Tube	Fully-developed Turbulent (5000–30,000)	Dispersion of suspended nanoparticles
Arani et al. (2013)	TiO_2/water	Ultrasonic vibration	10, 20, 30 and 50	1, 1.5 and 2	Horizontal double tube counter-flow	Turbulent (9000–49,000)	Due to increase in particle volume concentration and Reynolds number, the Nusselt number was increased
Pandey et al. (2012)	Al_2O_3/water	Ultrasonic Processing	40-50	2, 3 and 4	Corrugated plate	Turbulent	Rise in Reynolds and Peclet number and with fall in nanofluid concentration
Wu et al. (2013)	γ-Al_2O_3/water	Ultrasonic vibration	40	0.78, 2.18, 3.89, 5.68 and 7.04 (wt.%)	Double pipe helical	Laminar and Turbulent (1000–10,000)	Nanofluid property and flow velocity effect
Darzi et al. (2013)	Al_2O_3/water	Ultrasonic vibration	20	0.25, 0.5 and 1	Double tube	Turbulent (5000–20,000)	Increasing the Reynolds number and concentration of nanoparticles
Khedkar et al. (2013)	Al_2O_3/water	Sonication, magnetic stirring	-	2- 3	Concentric tube	Laminar and turbulent (1000–5000)	Increase in particle volume concentration.
Tayal et al. (2999)	Al_2O_3/water	-		0.3, 0.5, 0.7, 1 and 2	Shell and tube	Turbulent (4×10^5-18×10^5)	Increase in mass flow rate and particle volume concentration.
Kumaresan et al. (2012)	*MWCNT/Water (70): EG (30)	Ultrasonication	*d=30-50 l=10-20 μm	0.15, 0.30 and 0.45	Tubular	Laminar and turbulent (1000–6000)	Particle rearrangement, the very high aspect ratio and postponing the boundary layer development due the movement of the carbon nanotubes at quicker frequency
Kumaresan et al. (2013)	*MWCNT/Water (70): EG (30)	Dispersion	*d=30-50 l=10-20 μm	0.15, 0.30, 0.45 and 0.1	Tubular	Laminar and turbulent (500–5500)	Particle migration effect not allow to develop thermal boundary layer at the faster rate
Kannadasan et al. (2012)	CuO/Water	Ultrasonic bath		0.1 and 0.2	Helical coil tube	Turbulent	(i)Helically coiled heat exchanger, (ii) For higher concentration of nanofluids, the enhancement in internal Nusselt numbers is higher
Godson et al. (2011)	Silver/Water	Ultrasonic vibration	80	0.3- 0.9	Tube in Tube	Laminar, transition and turbulent (900–12000)	Suspension of nanoparticles
Godson et al.	Ag/Water	Ultrasonic vibration	54	0.01, 0.03 and 0.04	Shell and tube	Turbulent (5000–25,000)	Increase in particle volume concentration
Yang et al. (2005)	Graphite/automatic transmission fluid	-	-	2, 2.5 (wt. %) 2 (wt. %)	Horizontal tube	Laminar (5–110)	Nanoparticles increased the static thermal conductivities of the fluid

Table 4 Summary of experimental forced convection studies of heat exchangers for various nanofluids *(Continued)*

	Graphite/synthetic base oil						significantly at low weight fraction loadings
Zamzamian et al. (2011)	$^*Al_2O_3$/EG CuO/EG	Magnetic stirring and ultrasonic irradiation	20	0.1, 0.5, and 1.0 (wt. %) 0.1, 0.3, 0.5, 0.7 and 1.0 (wt. %)	Double-pipe Plate	Turbulent	Effects of particle concentration and operating temperature enhancement
Farajollahi et al. (2010)	γ-Al_2O_3/water TiO_2/water	-	25 15	0.3, 0.75, 1, and 2 0.15, 0.3, 0.5, and 0.75	Shell and tube	Turbulent	Own superior heat transfer behaviorfor the smaller and greater volume concentrations
Maré et al. (2011)	γ-Al_2O_3/water *CNT/water	Purchased- nanotech A1121W, AquacylMSDS	37 *d=9-10, l=2 μm	1, 0.55	Plate	Laminar (20–200)	Effect of temperature on viscosity and effect of Reynolds number on convective heat transfer coefficient
Tiwari et al. (2013)	CeO_2/water Al_2O_3/water TiO_2 /water SiO_2/water	Ultrasonic vibration	30 45 - 10	0.5, 0.75, 1.0, 1.25, 1.5, 2.0 and 3	Plate	Laminar and Turbulent	Optimum volume concentration CeO_2/water nanofluid owns the superior performance followed by TiO_2/water, Al_2O_3/water and finally SiO_2/water for testing operating conditions.

CNT-Carbon nanotubes, MWCNT- Multi-walled CNT, EG- Ethylene glycol, d-diameter of nanoparticle, l- length of nanoparticle.

and dimpled tube have own benefits of lower pressure drop, less cost, easy installation and removal (Chandrasekar et al. 2010; Suresh et al. 2012; Saeedinia et al. 2012; Hashemi & Akhavan-Behabadi 2012; SyamSundar et al. 2012; Akbaridoust et al. 2013; Kannadasan et al. 2012). For augmentation of heat transfer rate MWCNT is a promising candidate in specified base fluid because it has shear thinning behaviour at boundary layers so it increases the thermal conductivity which is solely contributes to heat transfer rate (Garg et al. 2009; Amrollahi et al. 2010; Liu & Liao 2010; Akhavan-Behabadi et al. 2012; Wang et al. 2013; Ashtiani et al. 2012; Fakoor-Pakdaman et al. 2013; Kumaresan et al. 2012; Kumaresan et al. 2013). From the above review, the maximum enhancement of 190% in heat transfer as compared to de-ionized water was observed by Wang et al. (2013) at 0.24 vol.%. For non-spherical nanoparticles, some other parameters including the aspect ratio, the dispersion state and aggregations of nanoparticles as well as shear field have significant impact on effective properties of nanofluid, convection heat transfer coefficient and pressure drop observed by Yu et al. (2012). It is noticed by Yu et al. (2013) that therminol 59 shows very attractive features for many commercial applications. Applications of nanofluids have been explored in the literature (2013) for cooling of micro-devices due to anomalous enhancements in their thermophysical properties as well as due to their lower susceptibility to clogging.

Some of the contradictory behaviours were also observed in this study, Anoop et al. (2009) performed convective heat transfer experiments employing an aqueous solution of Al_2O_3 nanoparticles in developing region of pipe flow. They observed heat transfer coefficient falls marginally with rise in particle volume concentration from 0 to 4% range. It was noticed by Sahin et al. (2013) that concentration of Al_2O_3 particles higher than 1 vol.% were not suitable for heat transfer enhancement, in their study of convective heat transfer. Fotukian and Esfahany (2010a; 2010b) observed the other contradictory behaviour in their study that increasing nanoparticle concentration did not show much effect on heat transfer improvement in turbulent flow regime (5000–35000). The maximum value of 48% increase in heat transfer coefficient compared to pure water for 0.054 vol.% at Reynolds number of 10000. Sajadi et al. (2011) reported that there was no much effect on heat transfer enhancement by increasing the volume fraction of TiO_2 nanoparticles above 0.25%. A similar report was observed by Pandey et al. (2012), by increasing nanoparticles volume concentration above 2%, there is not so much effect on heat transfer enhancement.

Conclusions

A comprehensive review on forced convection heat transfer characteristics with different nanofluids based on experimental investigations with constant heat flux, constant wall temperature boundary conditions and in heat exchangers is presented in this review paper. Most of the experimental studies showed that nanofluids demonstrate an improved heat transfer coefficient compared to its base fluid. Further it increases significantly with increasing concentration of nanoparticles as well as Reynolds number. The use of nanofluids in a broad range of applications is promising but there is lack of agreement between experimental results from different research groups. Hence, experimental studies are desired to understand the heat transfer characteristics of nanofluids and recognize innovative and unique applications for these fields.

Future directions and challenges

Nanofluids revealed extensive ways in the applications of thermal management systems. Consequently, research efforts are essential to provide attention on the heat transfer applications of nanofluids in engineering, medical and space applications. Some plausible work which can be performed in coming future by researchers listed below:

- In future, further efforts are essential to give concentration on outcomes of new models and correlations to forecast accurately convective heat transfer with small deviation with the experimental results and general correlation equations should be developed for use in industrial applications.
- The high cost of the nanofluid is one of the major obstacles to employ nanofluids in wide spread range of applications. Efforts should be made to develop new methods for production of nanofluids to make them cost effective and be made use in use for commercial applications.
- The concept of hybrid nanofluid is emerging, so further systematic experimental studies should be performed in which a suitable combination of cost and quantity should be performed such that high cost of nanoparticles bearing good properties like thermal conductivity, viscosity, density, specific heat and surface tension etc. is suitably hybridized with nanoparticles bearing low cost and form nanoparticles having better and improved properties and control on an overall cost.

Many researchers have performed work in this field, yet it is emerging and developing and many investigations are still remaining to be performed. Nanofluid is a potential candidate in the field of enhancement of heat transfer rate.

Nomenclature

c_p Specific heat (J/Kg K)
D Diameter of copper tube (m)

k Thermal conductivity (W/m K)
h Heat transfer coefficient (W/m^2 K)
Nu Nusselt number
q'' Heat flux (W/ m^2)
Pr Prandtl number
Re Reynolds number
ρ Density (kg/m^3)
ϕ Volume fraction
β Ratio of nanolayer thickness
μ Dynamic viscosity (Pa s)
f Base fluid
nf Nanofluids
p Particle

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