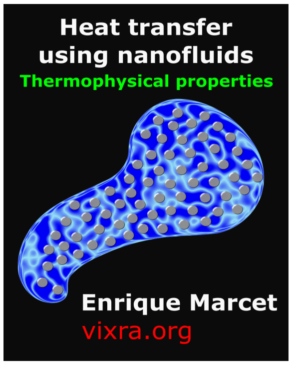

Thermophysical properties and heat transfer using nanofluids: a review

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Abstract

Nanofluids are considered to offer significantly more advantages in heat transfer than conventional fluids. Recently theoretical and experimental research papers appeared in the literature on thermophysical properties of nanofluids and enhancement of heat transfer using suspensions of nanoparticles. The aim of this review summarizes the results of research papers about thermophysical properties and forced convection heat transfer with nanofluids.

Keywords: nanofluids, heat transfer, nanoparticles, thermophysical, convection

NOMENCLATURE

ρ	Density	κ_B	Boltzmann constant
ϕ	Volume fraction	T	Temperature
Cp	Heat capacity	Nu	Nusselt number
k	Conductivity	h	Convection coefficient
μ	Viscosity	L	Large
Ψ	Esfericity	**Subscripts**	
Re	Reynolds number	np	Nanoparticle
Pr	Prandtl number	bf	Base fluid
v	Mean velocity	eff	Effective
D	Diameter		

1. Introduction

Heat exchangers are widely used in many applications, for example, power production, refrigeration, chemical and food industry, etc. Actually, high prices of energy motivate industry to apply energy saving methods. For years, efforts performed to save energy include passive and active methods such as creating turbulence, extending the exchange surface or to use a fluid with higher thermophysical properties [1].

Recent advances in nanotechnology have allowed the development of a new category of liquids termed *nanofluids*, which was first used by Choi [2] to describe liquid suspensions containing nanometer-size particles (*nanoparticles*).

In recent years, experimental and numerical investigation about nanofluids and associate technology has increased, showing the notable concern in relation to save energy. Thus, this paper presents a review on convective heat transfer of nanofluids.

2. Preparation Methods for Nanofluids

2.1 Two-Step Method.

Two-step method is the most widely used for preparing nanofluids. Nanoparticles, nanofibers, nanotubes and other nanomaterials used in the Two-step method are first produced as dry powders by chemical or physical methods. Then, the nanomaterials (nanosized powder), will be dispersed into a base fluid with the help of ultrasonic agitation, magnetic force agitation, etc. Due to the high surface area and surface activity, nanoparticles have the tendency to aggregate. The use of surfactants is an important technique to enhance nanoparticles stability. However, its use under high temperature is also a big concern [3].

2.2 One-Step Method.

To reduce agglomeration of nanoparticles, has been developed a one-step physical vapor condensation method to prepare Cu/ethyleneglycol nanofluids [4]. The one step process consists in simultaneously making and dispersing the particles in the fluid. In this process, stages as drying, storage, transportation and dispersion of nanoparticles are avoided. Thus, the stability of fluids is increased. The vacuum-SANSS (submerged arc nanoparticle synthesis system) is another one-step method to prepare nanofluids using dielectric liquids [5, 6].

One-step physical method can not synthesize nanofluids in large scale, and the cost is also high, so the one-step chemical method is developing rapidly. Zhu, et al. presented a novel one-step chemical method for preparing copper nanofluids by reducing $CuSO_4$. $5H_2O$ with NaH_2PO_2 . H_2O in ethylene glycol under microwave irradiation. Well-dispersed and stabled suspended copper nanofluids were obtained [7]. Silver nanofluids (mineral oil-based) have been prepared using Zhu Method. Other important methods for nanofluids preparation were reviewed by Yu and Xie [3], as well as Stability Evaluation Methods as Sedimentation and Centrifugation Methods, Zeta Potential Analysis and Spectral Absorbency Analysis.

3. Properties of nanofluids

The most important properties of nanofluids are the thermophysical properties, in which specific heat, density, thermal conductivity and viscosity are very significant.

3.1 Effective density and specific heat.

Specific heat and effective density of nanofluids can be computed using classical equations derived for a two-phase mixture. Thus, the effective density of nanofluids is [8]:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_{np} \qquad (1)$$

Specific heat of nanofluids is calculated using the next equation [9]:

$$C_{p\,nf} = \frac{(1-\phi)(\rho C_p)_{bf} + \phi(\rho C_p)_{np}}{(1-\phi)\rho_{bf} + \phi\rho_{np}} \qquad (2)$$

The density and specific heat of the nanofluids are assumed to be a linear function of volume fraction due to lack of experimental data on their temperature dependence.

3.2 Thermal and effective thermal conductivity.

Keblinski et al. reported their idea on the possible mechanism of enhancing thermal conductivity, and suggested that the size effect, the clustering of nanoparticles and the surface adsorption could be the major reason of enhancement, while the Brownian motion of nanoparticles contributes much less than other factor [10]. Thermal conductivity and dynamic viscosity of the nanofluids are dependent not only the volume concentration of nanoparticle, but other parameters such as particle shape, size, slip mechanism, etc [1].

In the literature, the thermal enhancement ratio has been defined as the ratio of thermal conductivity of the nanofluid to the thermal conductivity of the base fluid (k_{eff}/k_{bf}). The effective thermal conductivity for a two-phase mixture k_{eff} is given by:

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

Maxwell derived his model based on the assumption that the discontinuous phase is spherical in shape and the thermal conductivity of nanofluids depend on the thermal conductivity of spherical particles, the base fluid and the particle volume fraction [11].

Hamilton and Crosser [12] extended Maxwell work to cover none spherical particles and introduced the shape factor (n) which can be determined experimentally for different type of materials. The Hamilton and Crosser equation is given by:

$$k_{eff} = k_{bf}\left[\frac{k_{np}+(n-1)k_{bf}-(n-1)\phi(k_{bf}-k_{np})}{k_{np}+(n-1)k_{bf}+\phi(k_{bf}-k_{np})}\right] \quad (4)$$

where the empirical shape factor (n) is defined by $n = 3/\Psi$ in which Ψ is sphericity defined as the ratio of the surface areas of a sphere with the volume equal to that of the particle. The Hamilton-Crosser model reduces to Maxwell model when $\Psi = 1$.

Yu and Choi [14] modified Maxwell equation with the assumption that the base fluid molecules close to the solid surface of the NP form a solid-like layered structure. Hence the nanolayer works as a thermal bridge between the liquid base fluid and the solid nanoparticles, and this will enhance the effective thermal conductivity (thermal conductivity of nanolayer (k_{layer}) is higher than thermal conductivity of the liquid). The Yu-Choi model (for the case $k_{layer} = k_{np}$) is given by:

$$k_{eff} = \frac{k_{np}+2k_{bf} + 2\phi\left(k_{np}-k_{bf}\right)(1+\beta)^3}{k_{np}+2k_{bf} - \phi\left(k_{np}-k_{bf}\right)(1+\beta)^3} k_{bf} \quad (5)$$

where $\beta = \frac{h}{r}$ is the ratio between the nanolayer thickness (h) and the original particle ratio (r).

3.2.1 Theoretical models.

A summary of selective theoretical models on thermal conductivity of nanofluids are reported in Table 1. The dimensionless numbers for these models can be computed using the next equations:

Reynolds number:

$$Re = \frac{\rho v D}{\mu} \quad (6)$$

Prandtl number:

$$\Pr = \frac{C_p \mu}{k} \quad (7)$$

Table 1. Theoretical models for effective thermal conductivity of nanofluids.

Reference	**Year**	**Correlation**	**Details**
Maxwell [11]	1881	$\frac{k_{eff}}{k_{bf}} = \frac{k_{np} + 2k_{bf} + 2\phi(k_{np} - k_{bf})}{k_{np} + 2\,k_{bf} - \phi(k_{np} - k_{bf})}$	Liquid and solid suspensions. Spherical particles.
Bruggemann [14]	1935	$\frac{k_{eff}}{k_{bf}} = \frac{1}{4}\left[(3\phi - 1)\frac{k_{np}}{k_{bf}} + (2 - 3\phi)\right] + \frac{k_{bf}}{4}\sqrt{\Delta}$ $\Delta = \left[(3\phi - 1)^2(\frac{k_{np}}{k_{bf}})^2 + (2 - 3\phi)^2 + 2(2 + 9\phi - 9\phi^2)\frac{k_{np}}{k_{bf}}\right]$	Spherical particles. Applicable to high concentration.
Hamilton and Crosser [12]	1962	$\frac{k_{eff}}{k_{bf}} = \frac{k_{np} + (n-1)k_{bf} - (n-1)\phi(k_{bf} - k_{np})}{k_{np} + (n-1)k_{bf} + \phi(k_{bf} - k_{np})}$	$n = 3/\Psi$ $\frac{k_{np}}{k_{bf}} > 100$
Yu and Choi [13]	2003	$\frac{k_{eff}}{k_{bf}} = \frac{k_{np} + 2k_{bf} + 2\phi\left(k_{np} - k_{bf}\right)(1+\beta)^3}{k_{np} + 2k_{bf} - \phi\left(k_{np} - k_{bf}\right)(1+\beta)^3}$	$k_{layer} = k_{np}$ $\beta = \frac{h}{r}$
Bhattacharya [15]	2004	$\frac{k_{eff}}{k_{bf}} = \frac{k_{np}}{k_{bf}}\phi + (1 - \phi)$ $k_{np} = \frac{1}{\kappa_B T^2 V}\sum_{j=0}^{n}(Q(0)Q(j\Delta T))\Delta T$	Brownian dynamic
Prasher et. al [16]	2005	$\frac{k_{eff}}{k_{bf}} = (1 + ARe^m Pr^{0.333}\phi)Z$ $Z = \frac{k_{np} + 2k_{bf} + 2\phi(k_{np} - k_{bf})}{k_{np} + 2k_{bf} - \phi(k_{np} - k_{bf})}$	Effect of convection of the liquid near the particle included. A and m are constants. Nanospheres

Xue [17]	2005	$\frac{k_{eff}}{k_{bf}} = \frac{1-\phi\ + 2\phi\frac{k_{np}}{k_{np}-k_{bf}}X}{1-\phi\ + 2\phi\frac{k_{bf}}{k_{np}-k_{bf}}X}$ $X = \ln\frac{k_{np}+k_{bf}}{2k_{bf}}$	Nanospheres with interfacial shell.

Published reports of thermal conductivity enhancement as a function of nanoparticle loading are sumarizad in Fig. 1 [18-27] and compared with theoretical models (Maxwell and Bruggemann). The most important results were obtained by Chon et al. and Wang et al. in which thermal conductivity enhancement is greater than 40 %.

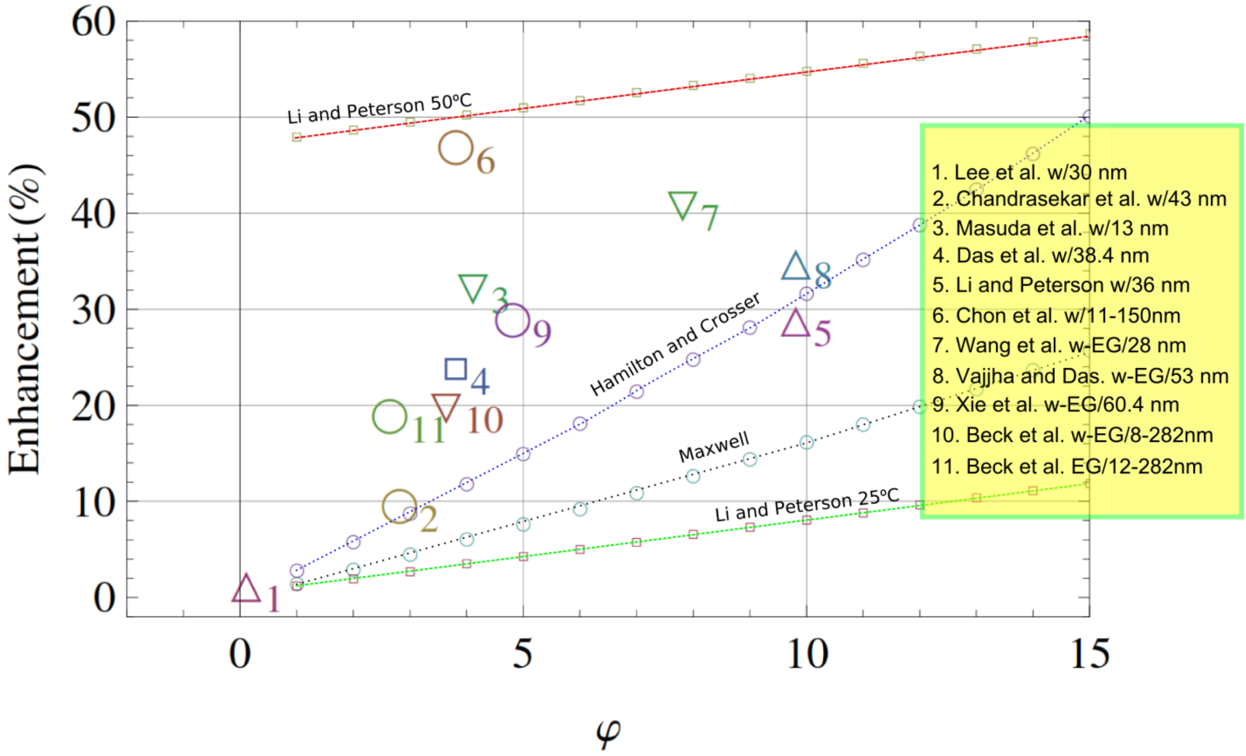

Figure 1. Thermal conductivity enhancement (%) as a function of the volume fraction of Al_2O_3 nanoparticles [18-27].

In the Fig. 1 we represented Li and Peterson model [16] which is an experimental correlation for Al_2O_3/water nanofluids. The Li and Peterson equation is given by:

$$\frac{k_{eff}-k_{bf}}{k_{bf}} = 0.764\phi + 0.0187(T - 273.15) - 0.462 \quad (8)$$

3.3 Viscosity and effective viscosity

Hypothetical analyses of the possible phenomena affecting the viscosity of nanofluids can be found in the literature, though they are very limited when compared with the depth of the theoretical models that can be found on thermal conductivity of nanofluids.

The Einstein's work [28] on infinitely diluted suspensions of uncharged hard spheres based on the vorticity of the particle shear field was the first theoretical work on viscosity of suspension. The Einstein equation is given by:

$$\frac{\mu_{eff}}{\mu_{bf}} = (1 + [\eta]\phi) \quad (8)$$

where $[\eta]$ is the intrinsic viscosity of the suspension. This lineal equation is based on the assumed absence of interaction between the particles, and the coefficient $[\eta]$ is a function of shape of the particle, which for hard spheres was given as 2.5. The Einstein model is valid for solid volume concentration $\phi < 2.5\%$.

Contrary to the uncharged particle Einstein model, Smoluchowski [29] presented an effective viscosity model for charged particles in electrolyte suspension given by:

$$\frac{\mu_{eff}}{\mu_{bf}} = \left[1 + 2.5\phi\left\{1 + \frac{1}{K\mu_{bf}a^2}\left(\frac{\zeta D_E}{2\pi}\right)^2\right\}\right] \quad (9)$$

where K is the specific conductivity of the electrolyte, a the radius of the solid particles, D_E the dielectric constant of the water and ζ the zeta potential of the particle with respect to the electrolytic medium.

Booth [30] in 1950 studied the overprediction made by Smoluchowski's model obtaining the next equation:

$$\frac{\mu_{eff}}{\mu_{bf}} = \left[1 + 2.5\phi\left\{1 + \sum_{1}^{\infty} b_I \left(\frac{e\zeta}{\kappa_B T}\right)^I\right\}\right] \quad (10)$$

in which b_I is the characteristic of electrolyte and e is the electronic charge on particles.

A summary of selective theoretical models on effective viscosity of nanofluids are reported in Table 2.

Table 2. Theoretical models on effective viscosity of nanofluids.

Reference	**Year**	**Correlation**	**Details**
Einstein [28]	1906	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 2.5\phi$	Infinitely diluted suspensions of spheres.
Hatchek [31]	1913	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 4.5\phi$	Applicable for up to 40% solid concentration.
Saito [32]	1950	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + \frac{2.5}{(1-\phi)}\phi$	Spherical rigid particles. Brownian motion. Very small and spherical particles.

Brinkman [33]	1952	$\frac{\mu_{eff}}{\mu_{bf}} = \frac{1}{(1-\phi)^{2.5}}$	Spherical particles. Valid for highly moderated particle concentrations.
Lundgren [34]	1972	$\frac{\mu_{eff}}{\mu_{bf}} = \frac{1}{1-2.5\phi}$	Diluted concentration of spheres.
Batchelor [35]	1977	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 2.5\phi + 6.2\phi^2$	Spherical rigid particles. Brownian motion. Isotropic structure.
Thomas and Muthukmar [36]	1991	$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 2.5\phi + 4.83\phi^2 + 6.4\phi^3$	Applicable for up to 40% solid concentration.

For Al_2O_3/water (Eq. 11) and Al_2O_3/ethylene glycol (Eq. 12) nanofluids Maiga et al. determined the effective viscosity as a function of nanoparticle volume fraction [37]:

$$\frac{\mu_{eff}}{\mu_{bf}} = 1 + 7.3\phi + 123\phi^2 \quad (11)$$

$$\frac{\mu_{eff}}{\mu_{bf}} = 1 - 0.19\phi + 306\phi^2 \quad (12)$$

Gabiela and Angel Huminic reviewed important models for effective viscosity determination as Wang, Tseng and Lin, Song, Buongiorno and other models [1].

3.4 Convective heat transfer

The enhancement of the heat transfer coefficient is a better signal than the thermal conductivity enhancement for nanofluids used in the design of heat exchange equipment.

Pak and Cho performed experiments on turbulent heat transfer using Al_2O_3 and TiO_2/water nanofluids. The following model was obtained [9]:

$Nu = 0.021Re^{0.8}Pr^{0.5}$ (13)

In which $10^4 < Re < 10^5$, $6.5 < Pr < 12.3$ and $0 < \phi < 0.03$ (3 %vol).

The dimensionless Nu number is given by:

$$Nu = \frac{hD}{k}$$

Vajjha et al. [25] founded the next correlation (Eq. 14) for Al_2O_3, CuO and SiO_2/water nanofluids.

$Nu = 0.065(Re^{0.65} - 60.22)(1 + 0.0169\phi^{0.15})Pr^{0.542}$ (12)

In which $3000 < Re < 1.6.10^4$ and $0 < \phi < 0.1$ (10 %vol).

For Al_2O_3/water nanofluids Maiga obtained an important correlation [38, 39]. In Fig. 2 we represented Maiga [39] and Pak and Cho [9] models as a function of Pr and Re dimensionless number. The Maiga correlation results very important because the domain in which was obtained (Re and Pr) is applicable in the design of heat exchange equipment.

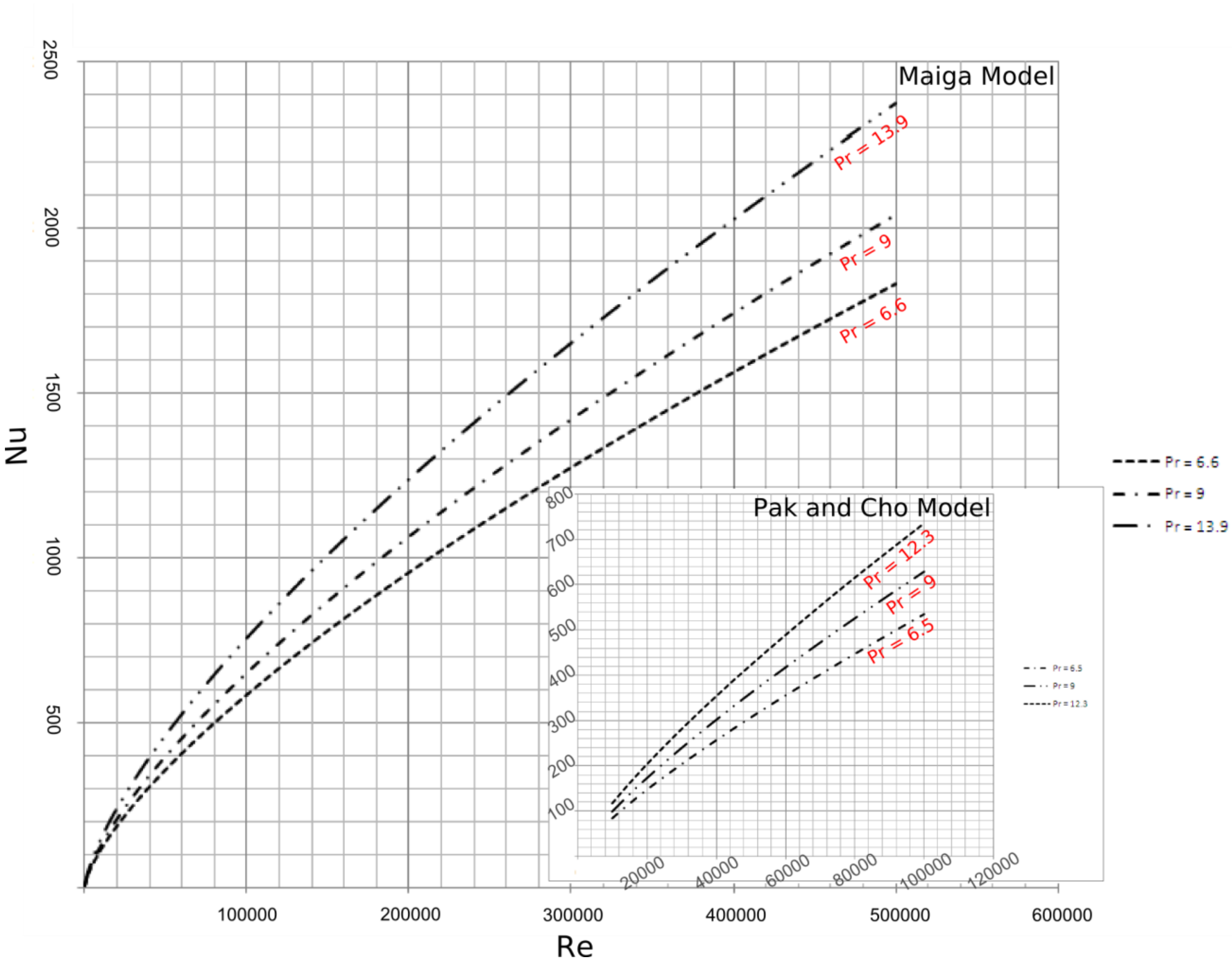

Figure 2. Maiga and Pak and Cho models. Maiga correlation [39] is valid for $0 < \phi < 0.1$ (10 %vol).

Al_2O_3/water nanofluid convention coefficient is greater than water fluid. This fact allows designing heat exchanger equipment of less heat exchange area. Recent technological developments, such as a microelectronic device are increasing thermal loads, requiring advances in cooling [40]. Other Nusselt correlations are listed in the next table (Table 3):

Table 3. Nusselt correlations for Al_2O_3/water, TiO_2/wate, graphite-synyhetic/oil, CuO/water and SiO_2/water nanofluids.

Reference	Year	Correlation	Details
Pak and Cho [9]	1998	$Nu = 0.021Re^{0.8}Pr^{0.5}$	Experimental study; turbulent flow. Al_2O_3/water nanofluids TiO_2/water nanofluids $0 < \phi < 0.03$ $10^4 < Re < 10^5$ $6.5 < Pr < 12.3$
Yang et al. [42]	2005	$Nu = aRe^b Pr^{\frac{1}{3}} \left(\frac{D}{L}\right)^{\frac{1}{3}} \left(\frac{\mu_w}{\mu_b}\right)^{-0.14}$	Experimental study; laminar flow; graphite-synthetic/oil nanofluid. $0 < \phi < 0.02$ $5 < Re < 110$
Maiga [38]	2005	$Nu = 0.28Re^{0.35}Pr^{0.35}$ For constant temperature $Nu = 0.086Re^{0.55}Pr^{0.5}$ For constant wall heat flux	Numerical study; laminar flow; Al_2O_3/water nanofluids $0 < \phi < 0.1$ $Re \leq 1000$ $6.0 < Pr < 753$

Maiga [39]	2006	$Nu = 0.085Re^{0.71}Pr^{0.35}$	Numerical study; turbulent flow; Al_2O_3/water nanofluids $0 < \phi < 0.1$ $104 < Re < 5 \times 10^5$ $6.6 < Pr < 13.9$
Vijjha et al. [25]	2010	$Nu = 0.065(Re^{0.65} - 60.22)(1 + 0.0169\phi^{0.15})Pr^{0.542}$	Experimental study; turbulent flow. Al_2O_3/water nanofluids CuO/water nanofluids SiO_2/water nanofluids $0 < \phi < 0.06$ For CuO and SiO_2 $0 < \phi < 0.1$ for Al_2O_3 $3000 < Re < 1.6 \times 10^4$

3.5 Specific heat capacity of nanofluids

Specific heat of material is an important property to define thermal performance of any material. Generally, specific heat remains constant for liquid and solid materials at constant pressure and wide range of temperatures. In the nanofluid case may vary depending upon type of material, base fluids and volume fraction of nanoparticles. In the Pak and Cho [9] investigation with

Al_2O_3/water nanofluids, they determined that 1.10-2.27% decrease in specific heat occurred for 1.34-2.78% volume fraction for nanoparticles size 13 nm. Zhou and Ni [42] determined that 47% maximum decrease in specific heat occurred for 21.7% volume fraction (Al_2O_3/water nanofluids and nanoparticles size 45 nm). Shahrul et al. [43] concluded that for most of nanomaterials in base fluids, specific heat decreases with increase in volume fraction. However, in Sonawane et al. investigation [44], specific heat of Al_2O_3/ATF nanofluids showed anomalous behavior of specific heat with volume fraction of nanoparticles. Experimental observations on various nanofluids showed increase in specific heat capacity [44-51]. Other investigations showed decrease in specific heat capacity of nanofluids [44,52,53].

4. Conclusions

The literature survey shows that nanofluids improve the heat transfer capability of conventional heat transfer fluids such as water by suspending nanoparticles in these base fluids. Important theoretical and experimental research on convective heat transfer show the significance of nanofluids to develop new technologies. Thus, this paper presents an overview of the recent investigation in the study of the thermophysical properties of nanofluids and their role in heat transfer enhancement. Theoretical and experimental correlation for the effective thermal conductivity, viscosity and Nusselt number of nanofluids are presented. Further studies are necessary to determine Nusselt number of nanofluids in more practical condition as jacked tanks, coils, etc.

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