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Combined effect of physical properties and convective heat transfer coefficient of nanofluids on their cooling efficiency☆

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ABSTRACT

The advantages of using Al_2O_3, TiO_2, SiO_2 and CeO_2 nanofluids as coolants have been investigated by analysing the combined effect of nanoparticles on thermophysical properties and heat transfer coefficient. The thermal conductivity and viscosity of these nanofluids were measured at two leading European universities to ensure the accuracy of the results. The relative thermal conductivity of nanofluids agreed with the prediction of the Maxwell model within +/− 10% even at elevated temperature of 50 °C indicating that the Brownian motion of nanoparticles does not affect thermal conductivity of nanofluids. The viscosity of nanofluids is well correlated by the modified Krieger–Dougherty model providing that the effect of nanoparticle aggregation is taken into account. It was found that at the same Reynolds number the advantage of using a nanofluid increases with increasing nanofluid viscosity which is counterintuitive. At the same pumping power nanofluids do not offer any advantage in terms of cooling efficiency over base fluids since the increase in viscosity outweighs the enhancement of thermal conductivity.

1. Introduction

The term nanofluid was introduced by Choi [1] almost two decades ago to refer to a nanoparticle suspension in a liquid such as water, ethylene glycol or engine oil frequently used as a coolant. He reported that the presence of nanoparticles of high thermal conductivity in cooling fluids enhances the thermal conductivity of the resulting suspensions and improves their cooling performance [2]. Therefore the use of nanofluids as coolants for high power electronic devices, for example, might reduce pumping power and operating cost without compromising (or even with certain improvement) the cooling effect.

Since that time, numerous experimental studies have been conducted to investigate the thermal performance, especially thermal conductivity and heat transfer coefficient of nanofluids (referred further as NFs) containing metal or metal oxide nanoparticles (referred further as NPs) as well as carbon nanotubes dispersed in water, ethylene glycol, water/ethylene glycol mixture, engine oil, etc. However, results reported in the literature are not consistent [3,4] but recently the number of researches questioning the alleged improvement of heat transfer in the presence of NPs on thermal performance of suspensions increases.

Some researchers concluded that the heat transfer mechanism of NFs deviated from that of single-phase liquids since the enhancements of heat transfer coefficients they observed were higher than the enhancement of thermal conductivity. However, in the majority of works thermal performance of NFs was compared with thermal performance of base fluid at the same Reynolds number. Using this method of comparison, enhancements ranging from 350% for carbon nanotube (CNT) NFs [5] through 47% for alumina [6] and from 29% to 23% for Al_2O_3 and CuO [7] were reported. Comparison of the heat transfer coefficient of NFs at constant Reynolds number could be misleading [8–12] because the addition of NPs increases the apparent viscosity therefore to keep the same Re number of NFs and for base fluids flow rate (velocity) of the former one has to be increased. Recent experimental data show that the thermal performance of NFs is practically the same as their base fluids and that heat transfer coefficient of NFs can be predicted (within ± 10%) from correlations developed for base fluids using thermophysical properties of NFs [13,14]. In other words, NFs behave like homogeneous mixtures and therefore, the heat transfer coefficient of NFs can be predicted/calculated based on their effective thermophysical properties [10].

To calculate the heat transfer coefficients in NFs accurately thermal conductivity, viscosity, specific heat and density are necessary. The thermal conductivity of NFs is the most widely studied; however, the results reported in the literature vary from one researcher to another. Several researchers reported that thermal conductivity enhancements of NFs

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Nomenclature

A	cross sectional, m^2
A_p	perimetrical area, m^2
a	radius of primary particles, nm
a_a	radius of aggregates, nm
c_p	specific heat capacity, J/kgK
d	pipe diameter, m
D	fractal index, –
f	friction factor, –
h	heat transfer coefficient, W/m^2 K
IAPWS	the International Association for the Properties of Water and Steam
k	thermal conductivity, W/m K
L	length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, $h\,D_{in}/k$
Pr	Prandtl number, $(C_p\,\mu)/k$
Re	Reynolds number, $(\rho ud)/\mu$
Δp	pressure drop, Pa
Q	heat flow, W
P	pumping power, W
T	temperature, °C
u	velocity, m/s
$\dot{\nabla}$	volume flow rate, m^3/s

Greek letters

υ	kinematic viscosity, m^2/s
ρ	density, kg/m^3
α	thermal diffusivity, m^2/s
ϕ	solid particle volume concentration, –
ϕ_m	maximum particle packing fraction, –
μ	dynamic viscosity, cP

Subscripts

eff	effective
f	fluid
w	wall
in	inner
out	outer
p	nanoparticle

were significantly larger [15–17] than that predicted by conventional models based on the effective medium theory, such as the Maxwell model. Others found that the effective thermal conductivity of NFs agreed with the prediction of the Maxwell model [3] or was even lower [18,19]. Several mechanisms were postulated to explain reported enhancement. Some argued that NP Brownian motion enhanced the effective thermal conductivity of NFs [20–22], while others proposed models based on liquid layering [23–25] and NP aggregation [26,27]. Typically the predictions of those models agree well with carefully selected experimental results and fail with the majority of other data.

The experimental results have consistently shown that viscosity of NFs increases with particle loading [28–32] and that an increase of temperature usually caused reduction of the viscosity [30,33–36]; however, there are also contradictory results [37–39]. The effect of particle size and shape on the viscosity of NFs is not fully understood and only very few studies can be found in the literature. Some researchers reported higher viscosity for smaller particles [40–42]; others have shown that the viscosity of NFs increased with the increase of the particle size [28,29,43–45]. It was also reported that particle size does not affect viscosity of suspension [37]. Generally elongated particles showed higher viscosity of NFs [46,47]. A very good review paper by Mahbubul et al. [48] has summarised the latest experimental and theoretical works on the viscosity of NFs.

It is commonly accepted that the density and specific heat of NFs can be calculated as the weighted average of the densities and specific heats of the particles and the base fluids [49–51] and measured values agree well with these predictions [44,52–55]. However there are also claims that these methods cannot be used with NFs [56,57].

The aim of this work is to develop a method allowing estimation of the performance of NFs as a coolant prior to time consuming experiments involving measurements of heat transfer coefficients. The advantage of replacing simple fluid with NFs is analysed theoretically by considering critical temperature defined as the highest wall temperature in the cooling system. So far, the cooling performances of NFs were compared to those of base fluids in terms of heat transfer coefficients only. However, the additions of nanoparticles alter the thermophysical properties of the fluids and therefore the cooling performances of NFs cannot be compared based on this parameter alone. On the other hand, the critical surface temperature takes into account the heat transfer coefficient as well as the specific heat of NFs. To ensure the accuracy of thermophysical parameters used in this work, values were measured independently at two leading European Universities, the Royal Institute of Technology (KTH), Sweden and the University of Birmingham (UBHAM).

2. Material synthesis and characterisation

All the NFs tested in this study were water based and their properties are summarised in Table 1. The morphology and primary particle size shown in Fig. 1 were determined by using TEM. Except AA-AL particles which are spherical and AA-CI which are cubic, all other particles have irregular but approximately spherical shapes. The amounts of additives, used to improve shelf stability of these NFs are also shown in Table 1 but

Table 1
NF characteristics: pH, crystal phase, most common hydrodynamic particle size (by DLS), dry particle size range (by TEM), and additives.

NFs	Abbreviation	Solid concentration (wt.%/vol.%)	pH	TEM particle size range (nm)	Most common particle size (nm)	Additives (g surfactant/g solid)
Alumina						
ItN Nanovation	ITN-AL	3–40 wt.%/1–14 vol.%	9.1	100–200	200	1.5%
Evonik (Aerodisp 440)	EVO-AL	3–40 wt.%/1–17 vol.%	4.1	10–20	150	1.4%
Alfa Aesar (Nanodur X1121W)	AA-AL	3–40 wt.%/1–14 vol.%	4.0	10–80	160	12.7%
Titania						
ItN Nanovation	ITN-TI	3–20 wt.%/1–6 vol.%	7.8	15–50	220 nm or 140 nm (ultrasonicated)	20.8%
Evonik (Aerodisp W740X)	EVO-TI	3–40 wt.%/1–15 vol.%	6.7	15–50	130	3.0%
Silica						
Eka Chemical Levasil 100	LEVASIL-SI	3–45 wt.%/1–27 vol.%	10	30 nm spherical	90	0%
Ceria						
Alfa Aesar (Nanotek CE6042)	AA-CI	3–20 wt.%/0.5–3 vol.%	2.5	30 nm (cubic)	160	0.5%