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A practical evaluation of the performance of Al_2O_3-water, TiO_2-water and CuO-water nanofluids for convective cooling

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ABSTRACT

The convective heat transfer, pressure drop and required pumping power for the turbulent flow of Al_2O_3-water, TiO_2-water and CuO-water nanofluids in a heated, horizontal tube with a constant heat flux are investigated experimentally. Results show that presenting nanofluid performance by the popular approach of plotting Nusselt number versus Reynolds number is misleading and can create the impression that nanofluids enhance heat transfer efficiency. This approach is shown to be problematic since both Nusselt number and Reynolds number are functions of nanofluid concentration. When results are presented in terms of actual heat transfer coefficient or tube temperature versus flow rate or pressure drop, adding nanoparticles to the water is shown to degrade heat transfer for all the nanofluids and under all conditions considered. Replacing water with nanofluid at the same flow rate reduces the convective heat transfer rate by reducing the operating Reynolds number of the system. Achieving a target temperature under a given heat load is shown to require significantly higher flow rates and pumping power when using nanofluids compared to water, and hence none of the nanofluids are found to offer any practical benefits.

1. Introduction

Nanofluids have proved beneficial in a wide range of applications, such as in the chemical, electrical and nuclear industries, in cancer diagnosis, solar energy capture, high-powered lasers, drilling and in enhanced oil recovery [1–4]. They have also been widely promoted for heat transfer applications, where it has been claimed that they can offer significantly enhanced heat transfer [5–7], while alleviating the problems of clogging, erosion and sedimentation associated with suspensions that contain larger particles [8]. Despite much theoretical and experimental promise for energy-related problems there is still a need to transfer the research into a practical reality. Specifically this means increasing the convective heat transfer in a manner which outweighs the accompanying increase in viscous pressure drop [9]. The present study evaluates the performance of nanofluid coolants from this practical perspective.

The intense interest in the potential use of nanofluids in heat transfer applications has resulted in the thermal and hydraulic properties of nanofluids being widely investigated. Many previous studies have reported anomalous increases in thermal conductivity not predicted by the classical Maxwell model. Wu & Zhao [9] refer to a *spectacular improvement* in thermal conductivity. Sergis & Hardalupas [10] carried out a statistical analysis of nanofluid data and found enhancements of thermal conductivity typically between 1 and 24% (accounting for 45% of the data analysed) while 25% of the data indicated an enhancement over 29%, with some over 84%. This type of spread led to the proposal of new models and mechanisms, such as adaptations for non-spherical particles, surface layers and particle clustering [11–13]. Motivated by the uncertainty surrounding nanofluid properties, Buongiorno et al. [8] carried out the International Nanofluid Property Benchmark Exercise (INPBE) in which the thermal conductivities of nanofluids were measured by 34 organisations worldwide. A diverse range of nanofluids were investigated, including aqueous/non-aqueous base fluids, metallic and metal-oxide particles, near spherical and elongated particles and low-to-high particle concentrations. In contrast to previous studies the INPBE concluded that the conductivity could be well-modelled by standard effective medium theory. In fact the Maxwell model is based on an assumption that a

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Nomenclature

A	inside surface area of the test section tube (m^2)
C_p	specific heat (J/kg K)
D	diameter of the test section tube (m)
f	friction factor
H	heat transfer coefficient (W/m^2 °C)
L	length of test section tube (m)
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
Re	Reynolds number
T	temperature (°C)
$T_{s,in}$	inside surface test section temperature (°C)
$T_{b,m}$	average bulk temperature along the test section (°C)
$T_{b,in}$	inlet bulk temperature of the test section fluid (°C)
$T_{b,out}$	outlet bulk temperature of the test section fluid (°C)
$T_{s,out}$	outside surface test section temperature (°C)
V	average fluid velocity (m/s)

Greek letters

ϕ	volume fraction of nanofluids
β	ratio between the nanolayer thickness surrounding the nanoparticle and the nanoparticle radius
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)

Subscripts

av	average
bf	base fluid
nf	nanofluid
p	nanoparticle

single particle lies in an infinite medium, consequently as particle concentrations increase it becomes less accurate. Myers et al. [14] showed that a standard analysis of heat flow over a finite region can lead to a better agreement with data for higher volume fractions, but again this is without resorting to exotic physical mechanisms.

In heat removal the goal is generally to achieve the required rate of cooling with a minimal power consumption. Since the latter depends on the nanofluid viscosity a number of studies have focussed on the viscous response of nanofluids. The Mahbubul et al. [15] investigation, for example, carried out a thorough review of studies into the viscosity of nanofluids and considered the effect of nanofluid preparation methods, temperature, particle size and shape and concentration on nanofluid viscosity. They found that concentration, particle shape and temperature all have significant effects on viscosity, whereas Azmi et al. [16] found that particle size was more influential than shape. In contrast to these studies, Sundar et al. [17] also found that the nanofluid preparation was also very influential. More recently, Bashirnezhod et al. [18], have considered that the existing experimental data on the thermophysical properties of nanofluids is neither sufficient nor reliable. They concluded that there is a pressing need for experimental studies which account for all the important factors including temperature, nanofluid concentration, nanoparticle size, pH, sonication time, aggregation and base liquid type to provide more accurate correlations for viscosity. They appear not to have been aware of the contemporaneous study of Meybodi et al. [2], who compiled an extensive database for water-based Al_2O_3, TiO_2, SiO_2 and CuO nanofluids and presented a formula to predict viscosity. They claim previous models have low accuracy while theirs, which involves only concentration, particle size and temperature, is superior.

The disagreements highlighted above have carried through to the primary goal of the research, namely the heat transfer performance. Many studies, both experimental and theoretical, claim that the addition of nanoparticles can lead to significant improvements in heat transfer performance compared to base fluids [2,16,19]. Fotukian & Esfahany [20] reported an average 25% increase in heat transfer coefficient and a simultaneous 20% reduction in pressure drop for very dilute CuO/water nanofluids. The statistical investigation of Sergis & Hardalupas [10] states that 19% of the papers studied showed an improvement in convective heat transfer between 10 and 18%, while 11% of papers show a deterioration (the remaining papers indicated unspecified enhancement). Haddad et al. [19] carried out a numerical study and stated explicitly that the presence of nanoparticles always leads to an enhancement in heat transfer. However, a paper by the same group, in the same year (Haddad et al. [21]), states that while numerical results mostly indicate an enhancement experimental studies show that nanoparticles lead to a deterioration in heat transfer.

Haghighi et al. [22] have recently considered the practical benefits of nanofluids by investigating the advantages of Al_2O_3, TiO_2, SiO_2 and CeO_2 on thermo-physical properties and heat transfer coefficient. They noted that the benefits reported in the literature may be due to their representation in terms of Nusselt number versus Reynolds number, which can be misleading because both are strong functions of the nanoparticle concentration. Also, since the viscosity of nanofluids increases with nanoparticle concentration, the flow rate must be increased to provide the same Reynolds number. As convective heat transfer rate increases with flow rate it is not appropriate to compare the performance of the base fluid (less viscous) with the nanofluid (more viscous) at the same Reynolds number. They proposed that it is more meaningful to compare the heat transfer rate for a given pumping power. When they did this, they found that the nanofluid performance was actually worse than water. The errors caused by comparison using non-dimensional parameters is discussed in greater detail in Myers et al. [23]: as stated above it does not make sense to compare Reynolds numbers which are scaled with concentration dependent properties, neither Nusselt numbers which are scaled with thermal conductivity. The authors continue with a critique of mathematical studies highlighting common errors, such as incorrect governing equations and parameter values that lead to the enhancements predicted by these theoretical studies.

Despite the wealth of literature concerning nanofluid properties and performance there remain many inconsistencies and much confusion, and consequently the current body of data is neither sufficient nor reliable for engineering applications. The purpose of the present study is to present results for the heat transfer properties and performance of standard nanofluids and to clarify a number of issues arising from previous studies. Specifically we undertake a comprehensive experimental evaluation of the heat transfer, pressure drop and power consumption for Al_2O_3, TiO_2 and CuO-water nanofluids for cooling applications. In the following section the nanofluid preparation methods are outlined. In Section 3 the experimental configuration and measurement techniques are described, and their validation against the literature is presented in Section 4. The experimental results are given in Section 5, together with comparisons against previous work and an