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Experimental studies on heat transfer and friction factor characteristics of Al_2O_3/water nanofluid in a circular pipe under laminar flow with wire coil inserts

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ABSTRACT

In this paper, fully developed laminar flow convective heat transfer and friction factor characteristics of Al_2O_3/water nanofluid flowing through a uniformly heated horizontal tube with and without wire coil inserts is presented. For this purpose, Al_2O_3 nanoparticles of 43 nm size were synthesized, characterized and dispersed in distilled water to form stable suspension containing 0.1% volume concentration of nanoparticles. The Nusselt number in the fully developed region were measured and found to increase by 12.24% at Re = 2275 for plain tube with nanofluid compared to distilled water. Two wire coil inserts made of stainless steel with pitch ratios 2 and 3 were used which increased the Nusselt numbers by 15.91% and 21.53% respectively at Re = 2275 with nanofluid compared to distilled water. The better heat transfer performance of nanofluid with wire coil insert is attributed to the effects of dispersion or back-mixing which flattens the temperature distribution and make the temperature gradient between the fluid and wall steeper. The measured pressure loss with the use of nanofluids is almost equal to that of the distilled water. The empirical correlations developed for Nusselt number and friction factor in terms of Reynolds/Peclet number, pitch ratio and volume concentration fits with the experimental data within ±15%.

1. Introduction

Thermal loads are increasing in a wide variety of applications like microelectronics, transportation, lighting, utilization of solar energy for power generation etc. Microelectromechanical systems (MEMS) technology and nanotechnology are also rapidly emerging as a new revolution in miniaturization. The thermal load control technologies with extended-surface such as fins and microchannels have already reached their limits. Hence, the management of high thermal loads in high heat flux applications offers challenges and the thermal conductivity of heat transfer fluid have become vital. Traditional heat transfer fluids such as water, engine oil, and ethylene glycol (EG) are inherently poor heat transfer fluids and thus major improvements in cooling capabilities have been constrained. To overcome this limited heat transfer capabilities of these traditional heat transfer fluids, micro/millimeter sized particles with high thermal conductivity suspended in them were considered by Ahuja [1]. Heat transfer fluids containing suspended particles of micro/millimeter sizes suffered from numerous drawbacks like erosion of the components by abrasive action, clogging in small passages, settling of particles and increased pressure drop. Hence, they were not accepted as suitable candidate for heat transfer enhancement and the search for new heat transfer fluids continued. Nanotechnology has come to rescue by providing opportunities to process and produce materials of sizes in nanometer range which can be suspended in traditional heat transfer fluids to produce a new class of engineered fluids with high thermal conductivity and elimination of the before mentioned problems associated with heat transfer fluids containing suspended particles of micro/millimeter size. This new class of heat transfer fluids with nanoparticles in suspension is called nanofluids. Nanofluids appear to be a very interesting alternative heat transfer fluids for many advanced thermal applications as listed in Table 1.

Nanofluids have emerged as an exciting new class of nanotechnology-based heat transfer fluids and have grown enormously in the past few years. Scientists and engineers are being challenged to discover the many unexpected thermophysical properties of these fluids, to propose new mechanisms and unconventional models to explain their behaviour. A comprehensive summary of the previous research works on the thermophysical properties of nanofluids is presented recently by Duangthongsuk and Wongwises [2].

Pak and Cho [3] experimentally investigated the convective heat transfer in the turbulent flow regime using Al_2O_3/water and TiO_2/water nanofluids, and found that even though the Nusselt number (*Nu*) was found to increase with the particle volume concentration and the Reynolds number, the heat transfer coefficient (*h*) actually decreased by 3–12%. Xuan and Li [4] investigated

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Nomenclature

A	cross-sectional area, m^2
c_p	specific heat, J/kg K
d	tube diameter, m
f	friction factor
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	length of the test section, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, hd/k
p	pitch ratio
P	perimeter, m
Pr	Prandtl number, $\mu c_p/k$
q''	actual heat flux, W/m^2
Re	Reynolds number, $\rho dv/\mu$
T	temperature, K
v	velocity, m/s
x	axial distance from the tube entrance, m
Greek letters	
φ	volume concentration
ρ	mass density, kg/m^3
μ	viscosity, kg/ms
Subscripts	
in	inlet
f	fluid
nf	nanofluid
out	outlet
s	solid phase
w	tube wall

experimentally the convective heat transfer and flow characteristics for Cu/water nanofluid flowing through a straight tube with a constant heat flux under laminar and turbulent flow conditions. Cu nanoparticles with diameters below 100 nm were used in their study. The results of the experiment showed that the suspended nanoparticles remarkably enhanced the heat transfer performance of the conventional base fluid and their friction factor coincided well with that of the water. According to them, the convective heat transfer coefficient of Cu/water nanofluid is increased about 60% for the nanofluid at 2.0% volume concentration. In addition, they also proposed new convective heat transfer correlations for the prediction of heat transfer coefficients of the nanofluid for both laminar and turbulent flow conditions. As it is necessary to study the pressure drop of nanofluids besides the heat transfer enhancement in order to apply nanofluid to practical cases, they also conducted pressure drop studies for both the laminar and turbulent flow which revealed no significant augmentation in pressure drop for the nanofluid which indicates that the nanofluids will not cause extra penalty in pump power.

Wen and Ding [5] experimentally probed the convective heat transfer of Al_2O_3/water nanofluids in the laminar flow regime and showed that the use of Al_2O_3/water nanofluids can significantly enhance the convective heat transfer in the laminar flow regime, and the enhancement increases with Reynolds number and particle volume concentration. They also showed that (i) the enhancement is significant in the entrance region and decreases with axial distance (ii) the thermal developing length of nanofluids is greater than that of pure base liquid. They attributed the enhancement of the convective heat transfer to particle migration which may result in a non-uniform distribution of thermal conductivity and viscosity field which will reduce the thermal boundary layer thickness. Using the same experimental setup, Ding et al. [6] reported a maximum enhancement of convective heat transfer of CNT (carbon nanotubes) nanofluids over 350% at a Reynolds number of 800, and the maximum enhancement occurs at an axial distance of approximately 110 times the tube diameter. The observed large enhancement of the convective heat transfer was attributed to the enhancement of thermal conductivity, particle re-arrangement, shear induced thermal conduction enhancement, reduction of thermal boundary layer thickness due to the presence of nanoparticles and the very high aspect ratio of CNTs. The convective heat transfer performance of the graphite nanofluids were studied experimentally by Yang et al. [7] in laminar flow through a circular tube and showed that the nanoparticles increase the heat transfer coefficient of the fluid system in laminar flow, but the increase is much less than that predicted by the correlation based on static thermal conductivity measurements. Hence, they concluded that further investigation is needed to develop an appropriate heat transfer correlation for non-spherical nanoparticle dispersions.

He et al. [8] carried out experimental study on the flow and heat transfer behaviour of aqueous TiO_2 nanofluids flowing through a straight vertical pipe under both laminar and turbulent flow conditions. They observed that for a given Reynolds number and particle size, the convective heat transfer coefficient increased with volume concentration in both the laminar and turbulent flow regimes and the convective heat transfer coefficient was insensitive to the changes in particle size. Their measured pressure drop of nanofluids was very close to that of the base liquid for a given Reynolds number. With the same experimental setup, recently Chen et al. [9] with titanate nanotubes nanofluids concluded that, compared with thermal conduction, the enhancement of the convective heat transfer was much higher and the enhancement depends on nanotube concentration, Reynolds number and the axial position. Given the nanotube concentration and Reynolds number, the highest enhancement was observed at the entrance region; the enhancement decreased with increasing axial distance and approached a

Table 1
Applications of nanofluids in various fields.

Field	Applications
Electronics	Cooling of high performance computers and servers, high power lasers diodes, chip cooling, MEMS, NEMS, LEDs, integrated circuits, semiconductor devices
Automotive	Engine coolant, transmission fluid, power steering fluid, fan clutches, engine oil, brake fluid, lube oils, greases
Power generation/transmission	Transformer cooling
Nuclear application	Primary coolant in pressurized water reactors (PWR) and emergency safety systems
Renewable energy	To enhance heat transfer and energy density from solar collectors
HVAC	Energy efficient cooing/heating of buildings without increased pumping power in heating, ventilation and air conditioning (HVAC)
Production/fabrication	Cooling and lubrication of drill bits, grinding wheels, cooling of welding equipment
Defense	Cooling of power electronics, directed energy weapons, military vehicles, submarines
Space	Requires simplifying and lighter cooling systems which are feasible with nanofluids due to their low fluid inventory