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Numerical and experimental investigation of heat transfer enhancement in a microtube using nanofluids☆

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ABSTRACT

Forced convective laminar flow of different types of nanofluids such as Al_2O_3 and SiO_2, with a nanoparticle size of 30 nm, and different volume fractions ranging from 0.5% to 1% using water as base fluids were investigated numerically and experimentally. This investigation covers the Reynolds number in the range of 90 to 160. The results have shown that SiO_2–water nanofluid has the highest Nusselt number, followed by Al_2O_3–water, and lastly pure water. The maximum heat transfer enhancement was about 22% when using the nanofluids and the numerical and experimental results agree well with the conventional theory.

1. Introduction

The fast growth of research in the heat transfer area was improved by using a new kind of heat transfer fluid called nanofluids which have nanosized particles. These particles can be metallic or nonmetallic such as Al_2O_3, CuO, SiO_2, TiO_2, Cu, Ni, Al and ZnO. Most of the recent studies showed that solid nanoparticles with high thermal conductivity when suspended in the base fluid would enhance the convective heat transfer coefficient and the effective thermal conductivity of the base fluid [1–11].

A large number of experimental and numerical studies focused on the flow and heat transfer behavior in a microtube have been reported by many researchers; Liu et al. [12] investigated experimentally the forced convective heat transfer characteristics in quartz microtubes with inner diameters of 242, 315 and 520 μm. The deionized water was used as the working fluid. The Reynolds number was ranged from 100 to 7000. The results indicate that the experimental Nusselt number tends to be in agreement with that of the laminar correlations when the flow state was laminar.

Zhou et al. [13] investigated experimentally and numerically the flow and heat transfer characteristics of liquid laminar flow in MT. They used smooth fused silica and rough stainless steel microtubes with the hydraulic diameters of 50–100 μm and 373–1570 μm, respectively. Deionized water was used as the working fluid. The Reynolds numbers were ranged from 20 to 2400. The results show that the Nusselt number along the axial direction do not accord with the conventional results especially when the Reynolds number is low and the relative tube wall thickness is high. Lelea [14] investigated numerically the conjugate heat transfer and laminar fluid flow in a stainless steel microtube. Three different fluids with temperature dependent fluid properties, water and two dielectric fluids, HFE-7600 and FC-70 were used. The diameter ratio of the MT was Di/Do = 0.1/0.3 mm with a tube length L = 70 mm. The Reynolds number range was less than 400. The results indicate that thermal conductivity has a significant influence on the local Nu number behavior as long as the Re number was low.

Celata et al. [15] investigated experimentally the influence of channel wall roughness and the channel wall hydrophobicity on adiabatic flow in circular microchannels. Different diameters of MT ranging from 70 μm to 326 μm were used with a Reynolds number of less than 300 for all diameters. The results indicate that, with degassed water, there was no effect of slip flow noted due to hydrophobic channel walls even at a 70 μm inner diameter. For roughened glass channels, an increase in friction factor above 64/Re was observed only at the smallest diameter of 126 μm.

Peng et al. [16] investigated water flow in a fused glass microtube with an inner diameter of 230 μm and an outer diameter of 500 μm. The Reynolds number was ranged from 1540 to 2960. The results indicate that the flow transition from laminar to turbulent occurs at a Reynolds number of 1700 to 1900, and the turbulence becomes fully developed at Re > 2500.

Mala and Li [17] investigated experimentally the effects of water flow in microtube. Fused silica (FS) and stainless steel (SS) of MT were used. The diameters used were ranged from 50 to 254 μm with Reynolds number up to 2500. The results revealed that as the Reynolds number increased, a significant deviation from the conventional theory was

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Nomenclature

Al_2O_3	Aluminium oxide
A	(m^2) Area of the test tube
c_p	(J/(kg·K)) Specific heat of water
D	(Mm) Diameter of test tube
D_h	(Mm) Hydraulic diameter of test tube
f	Darcy friction factor
h_x	(W/(m^2·K)) Local heat transfer coefficient
$\dot{m}$	(kg/s) Mass flow rate
Nu_x	Nusselt number
Δp	Pressure drop
q	(W/m^2) Heat flux
Q	(W) Heat transfer rate
Re	Reynolds number
R	Radius of test tube
SiO_2	Silicon oxide
T	(K) temperature
Tw_x	(K) Wall temperature along x-direction
$T_{b,x,int}$	Bulk temperature
ΔT_x	(K) Bulk temperature difference along x-direction
U	(V) Voltage supply
U_R	Uncertainty
I	(A) Electric current
τ_w	Wall shear stress

Greek symbols

P	(kg/m^3) Fluid density
Φ	(W) Power supply

Subscripts

ave	Average
B	Bulk temperature
C	Cross-section
I	Inner of test tube
In	Inlet
Int	Linear interpolation
L	Liquid
O	Outer of test tube
W	Wall surface

observed. In addition, the friction factor and the friction constant were higher than that predicted by the conventional theory.

Wen and Ding [18] investigated experimentally the effects of convective heat transfer of nanofluids at the entrance region of the copper tube with a 970 mm length. The de-ionized water with Al_2O_3 nanoparticle was used as working fluids. The Reynolds number used was ranged from 500 to 2100. The results indicate that the use of Al_2O_3 significantly enhanced the convective heat transfer in the laminar flow regime and this enhancement increased with the Reynolds number and the particle concentration.

Koo and Kleinstreuer [19] investigated experimentally the effects of viscous dissipation on the temperature field and the friction factor in a microtube (MT) and microchannel (MC). Three working fluids were used, water, methanol and iso-propanol. The results indicated that the viscous dissipation effect on the friction factor was increased as the system size decreased. For water flow in a tube with a diameter of 50 μm, viscous dissipation becomes significant. For liquids, the viscous dissipation effects decreased as the fluid temperature increased.

Lelea and Cioabla [20] investigated numerically the effects of viscous dissipation on heat transfer and fluid flow in micro-tubes. Three different fluids, water and two dielectric fluids, HFE-7600 and FC-70 were used. The diameter ratio of the MT was 0.33 with a tube length L = 100 mm. Two different heat transfer conditions, cooling and heating, and three different Brinkman number, 0.01, 0.1 and 0.5, were used. The results revealed that the friction factor and Poiseuille constant Po are affected at Br = 0.5 for water and start with Br = 0.1 for highly viscous fluids HFE-7600 and FC-70. The Nusselt number for the cooling case for Br = 0.5 was about three times higher than for the heating case, regardless of the fluid type.

Minea [21] investigated numerically the turbulent convective heat transfer in a two-dimensional microtube with a 10 mm diameter and variable length with a constant heating temperature. Water–Al_2O_3 nanofluids with different volume fractions ranging from 1% to 4% were used. This investigation covers the Reynolds number in the range of 10^4–10^5. The results have shown that the convective heat transfer coefficient for a nanofluid is enhanced when compared to that of the base liquid. Wall heat transfer flux is increased with the particle volume concentration and the Reynolds number.

Minea [22] investigated numerically the effect due to the uncertainty in the values of the physical properties of water–Al_2O_3 nanofluid on their thermo hydraulic performance for laminar fully developed forced convection in a two zone tube. The results revealed that the heat transfer coefficient of Al_2O_3/water nanofluids is increased by 3.4–27.8% under a fixed Reynolds number compared with that of pure water.

Kang et al. [23] investigated experimentally the thermal performance using nanofluids and conventional fluids. The nanofluid used was an aqueous solution of 10 and 35 nm diameter silver nanoparticles. The results show that the temperature difference decreased from 0.56 to 0.65 °C when using the nanofluids compared to DI-water. Moraveji and Esmaeili [24] investigated numerically forced convection heat transfer with laminar and developed flow for water–Al_2O_3 nanofluid inside a circular tube with a diameter of 10 mm under constant heat flux from the wall. Nanofluids with particle sizes equal to 100 nm and particle concentrations of 1 and 4 wt.% were used. The result shows that the heat transfer was enhanced by increasing the concentration of nanoparticles in nanofluid and the Reynolds number.

Akbarinia et al. [25] investigated numerically the laminar mixed convection heat transfer in a circular curved tube with diameter 0.02 m with a nanofluid consisting of water and 1 vol.% of Al_2O_3 at different inclination angles. The results reveal that the heat transfer coefficient increases by 15% at 4 vol.% of Al_2O_3. Skin friction coefficient continually increases with the tube inclination, but the heat transfer coefficient reaches a maximum at the inclination angle of 45°. Wu et al. [26] investigated experimentally the pressure drop and heat transfer characteristics of alumina/water nanofluids in helical heat exchangers with a diameter of 13.28 mm at a Reynolds number ranging from 1000 to 15,000. The results reveal that the heat transfer enhancement of the nanofluids compared to water is from 0.37% to 3.43%.

Ahmed et al. [27–29] found that the Nusselt number is slightly affected by the type of nanoparticles. The nanofluid of SiO_2–EG provided the highest heat transfer rate and no increase in the friction coefficient was found when the volume fraction increases from 1 to 6%. They revealed that a remarkable enhancement in heat transfer rate was found when the base fluid (water) is replaced by a nanofluid such as SiO_2–water as the working fluid in non-circular channels. In addition, they reviewed the parameters that affect the thermophysical properties of nanofluids and one of them is the effect of base fluid type. They concluded that the highest improvement in the effective thermal conductivity was found with lowest thermal conductivity for the base fluid. Kherbeet et al. [30–32] presented a numerical investigation of the nanofluid effect of laminar flow on a mixed convection heat transfer over 2D microscale backward-facing step. The results reveal that the fluids with SiO_2 nanoparticles have the highest Nusselt number among other nanoparticles. In addition, the results show that the Nusselt number increases with the increment of the nanoparticle volume fraction.