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Effect of microtube length on heat transfer enhancement of an water/Al_2O_3 nanofluid at high Reynolds numbers

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ABSTRACT

In this paper, turbulent convective heat transfer in a two-dimensional microtube with 10 mm diameter and variable length with constant heating temperature was numerically investigated. The governing (continuity, momentum and energy) equations were solved using the finite volume method with the aid of SIMPLE algorithm on FLUENT commercial code.

Water–Al_2O_3 nanofluids with different volume fractions ranged from 1% to 4% were used. This investigation covers Reynolds number in the range of 10^4–10^5. The results have shown that convective heat transfer coefficient for a nanofluid is enhanced than that of the base liquid. Wall heat transfer flux is increasing with the particle volume concentration and Reynolds number. Moreover, a study on microtube length influence on heat transfer was attempted and few correlations were established.

1. Introduction

The characteristics of flow and heat transfer in microchannels and microtubes have attracted much attention of researchers because of the rapid developments of micro electromechanical systems. These developments have great impacts on the microelectronic cooling techniques, the micro heat exchanger, bioengineering etc. It is obvious that the understanding of the micro scale phenomena is very important for designing energy efficient micro devices.

To explore the fundamental physical mechanisms of fluid flow and heat transfer in microtube, many effects, including the size effect, surface roughness, viscous effect, axial heat conduction in the channel wall, surface geometry, the measurement errors, etc. should be taken into account [1]. One of the active techniques used to enhance the heat transfer is by using nanofluids. Nanofluids are fluids in which nanometer-size particles are suspended in conventional heat transfer base fluids like water or ethylene–glycol [2]. Most of the recent studies showed that the solid nanoparticles with a 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 [3–8]. Nevertheless, there is no uniform approach in this area and more experimental and numerical studies are still needed.

A large number of experimental and numerical studies focus on the flow and heat transfer characteristics in microtube have been reported by many researchers. Liu et al. [9] investigated experimentally the forced convective heat transfer characteristics in quartz microtubes with inner diameters of 242, 315 and 520 μm. The de-ionized water was used as the working fluid and 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.

Celata et al. [10] investigated experimentally the effects of compressibility for helium flow through fused silica microtubes. The microtube diameter was ranged from 30 to 254 μm. Reynolds number was from 0.8 to 500. Zhang et al. [11] studied numerically the effects of wall axial heat conduction and fluid axial conduction for simultaneously developing laminar flow and heat transfer in the wall of microtube with constant outside wall temperature. The results indicated that the heat transfer process is most sensitive to wall-to-fluid conductivity ratio and in condition when $30 \leqslant RePr \leqslant 11{,}560$.

Zhou et al. [12] investigated experimentally and numerically the flow and heat transfer characteristics of liquid laminar flow in microtubes with the hydraulic diameters of 50–100 and 373–1570 μm, respectively. Deionized water was used as the working fluid, and 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.

Yang and Lin [13] investigated experimentally the forced convective heat transfer performance of water flow through six micro

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Nomenclature

C	coefficient
c_p	specific heat (J/kg K)
D	hydraulic diameter (m)
f_{drag}	drag function
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	microtube length (m)
Nu	Nusselt number
p	pressure, Pascal
R^2	standard error
Re	Reynolds number,
T	temperature (K)
q	wall heat flux (W/m^2)
x, y	dimensionless Cartesian coordinates
v	velocity (m/s)

Greek symbols

α	thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
ε	dissipation of turbulent kinetic energy, m^2/s^3
φ	volume fraction of particles
ρ	density (kg/m^3)
ν	kinematic viscosity (m^2/s)
μ	fluid dynamic viscosity (kg/ms)
τ	wall shear stress (Pa)

Subscripts

0	refers to the reference (inlet) condition
av	average value
bf	refers to base-fluid
dr	drif
eff	effective
f	fluid
h	hot wall
k	the k-th phase
m	nanofluid/mixture
nf	refers to nanofluid property
p	particle
r	refers to “nanofluid/base-fluid” ratio
t	turbulent
w	value at wall channel

stainless steel tubes with inner diameters ranging from 123 to 962 μm. 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 were used. The diameter ratio of the tube was Di/Do = 0.1/0.3 mm with a tube length L = 70 mm and the Reynolds number was less than 400. The results indicate that thermal conductivity has an important influence on the local Nu number behavior as long as the Re number was low.

Salman et al. [15] concluded that the best setting of parameters that gave the best heat transfer enhancement through the microtube were by using silicon dioxide as the working fluid with percentage of concentration of 4%, diameter of particle of 25 nm, using Reynolds number of 1500.

Over the years, as a result of hard studies, the main focus of nanofluid research has gradually moved from effective thermophysical properties to heat transfer coefficients, an area connected more directly to nanofluid applications. This tendency is especially true for one of the most frequent nanofluid applications: the turbulent-flow, convective heat transfer of nanofluids cooling and heating. However, while a great number of original research papers concerning nanofluid heat transfer are available in the engineering literature, confusion exists in the nanofluid research community regarding appropriate nanofluid heat transfer coefficient comparison, nanofluid heat transfer coefficient prediction, and nanofluid heat transfer coefficient enhancement.

Also, to the best author knowledge, the number of studies reported in the literature related to microtube using nanofluids is quite limited, and this was a motivation for this analysis. Moreover, a consistent study on tube length variation was not registered yet, far as was noticed from the important scientifical databases. In this paper, turbulent convective heat transfer in a microtube with uniform heating temperature is numerically investigated using different water/alumina nanofluid with four different nanoparticle volume fractions. This investigation covers Reynolds number in the range of 10^4 to 10^5. Results of interests such as the heat transfer coefficient, wall heat flux, wall shear stress and the effects of nanoparticles volume fraction and Reynolds number are reported for different tube length.

2. Numerical model

2.1. Geometry and the governing equations

The 2-D Navier–Stokes and energy equations were used to describe the flow and heat transfer in the microtube. Fig. 1 presents the computational domain. The following assumptions are adopted: (1) the nanofluid is Newtonian and incompressible, (2) the flow is turbulent, (3) the nanoparticles are assumed to be spherical, (4) single phase model was used and (5) constant thermophysical properties were considered for the nanofluid.

Similar to any fluid mechanic and heat transfer problem, a numerical study for a nanofluid in a particular geometry is achieved by solving the main conservation laws for the flow. In general, a computational fluid dynamics (CFD) code follows three main steps when solving a problem [16]: first integrating the conservation equations over the generated control volumes; next changing the obtained integral equations into algebraic equations with the aid of discretization methods; and finally using numerical iterative methods to solve the algebraic equations. Incompressible flow, Newtonian behavior, Boussinesq approximation for buoyancy force in natural convection and steady-state condition seem to be reasonable simplifications when doing a numerical process. Nanoparticles and the basefluid are often assumed to achieve thermal equilibrium rapidly. Therefore, the assumption of thermal

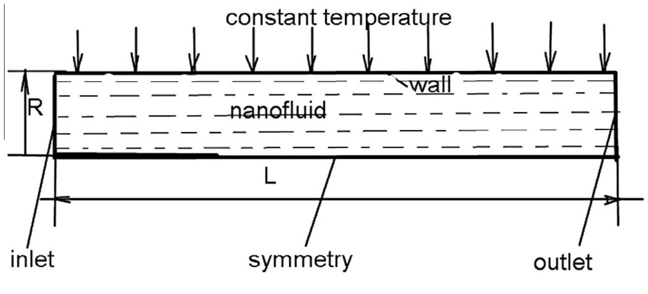

Fig. 1. The computational domain.