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Original Research Paper

Heat transfer by nanofluids in wavy microchannels

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ABSTRACT

Pumping coolants through microchannels with well-defined structures along micro-electronic devices is a typical approach to remove the heat. It has been found recently that so-called nanofluids, i.e. dilute water-Cu or water-Al_2O_3 suspensions with a particle diameter of 100–150 nm, are highly efficient coolants. Numerical simulations can help to optimize the microchannel structures and typically homogenous single-phase models are applied. However, these underestimate the experimental results. An alternative approach is two-phase models based on an Eulerian approach for the base fluid and a Lagrangian description of the suspended particles. In this paper we follow that route and solve the three-dimensional governing equations including continuity, Navier-Stokes and energy equations with the well-known SIMPLE method. The governing equations for particles are solved by a 4th order Runge-Kutta algorithm. We focus on a wavy microchannel structure and demonstrate that the disagreement between the two simulation approaches is due to the non-homogeneous particle distribution in the domain. We also find that the Nusselt number increases with the increase in volume fraction and the decrease in particle diameter and that it. is about three times higher for a *nanofluid* in a *wavy* microchannels as compared to *water* in a *straight* microchannels.

1. Introduction

Adding metal nanoparticles to a fluid improves the thermal conductivity coefficient of the working fluid. However, the exact relation between fluid and particle properties, as well as parameters like particle volume concentration, the exact flow field, or the impact of geometrical constrains is still not fully understood [1,2]. Numerous approximate relations are available in the literature to predict the properties of a nanofluid such as its thermal conductivity and viscosity [1,2]. To date, none of them allows a precise prediction of the behavior of nanofluids for a wide range of parameters and flowing in arbitrarily shaped microchannel geometries. In particular, the theoretical results underestimate the experimentally found heat transfer characteristics of nanofluids [3].

We use a two-phase Eulerian-Lagrangian model to study. By treating the nanoparticles and the fluid separately, they can be described using their own governing equations and no assumptions about the combined system, the nanofluid, are needed. This is a strong advantage as compared to single phase models which assume that the particles are homogenously distributed and that the particle velocity and temperature are identical to the fluid velocity and temperature. These advantages come at the price of increased computing costs making an efficient parallelization and the use of parallel computers mandatory.

The current paper focuses on nanofluids in wavy microchannels. General flow and heat transfer characteristics in microchannels with wavy walls were numerically studied by Gong et al. [4]. They showed that the performance of microchannels increases with increasing Reynolds number and that channel with symmetric wavy walls perform better than asymmetric ones. They further expressed that wavy microchannels can be attractive candidates for cooling high heat flux micro-electronic devices in the future. Sui and Teo [5] studied fluid mixing and heat transfer enhancement in three-dimensional wavy microchannels. They used water as a coolant and concluded that the increase in mass flow rate increases the Nusselt number. Mohammed et al. [6] simulated heat transfer enhancement in heat sinks consisting of wavy microchannels. They demonstrated that wavy microchannels allow to enhance the heat transfer with only a small pressure drop and reported the optimum amplitude of the wavy structureto obtain

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Nomenclature

a	wall amplitude (m)
A_c	cross sectional area
b	power of volume fraction in Eq. (24)
c	power of particle diameter in Eq. (24)
Cp	heat capacity (kJ/kg K)
D_h	hydraulic diameter (m)
D_p	particle diameter (m)
d_p	nondimensional particle diameter
f	normalized pressure drop
F_b	buoyancy force (N)
F_{br}	brownian force (N)
F_D	drag force (N)
F_g	gravity force (N)
F_L	Saffman's lift force (N)
F_p	pressure gradient force (N)
F_T	thermophoretic force (N)
H	height of the microchannel (m)
J	jacobean of the coordinate transformation
k	thermal conductivity (W m^{-1} K^{-1})
$L_x.L_y.L_z$	micro device dimensions (m)
n	normal direction on the walls
Nu	Nusselt number
$Nu.A$	Nusselt number and area Multiplication
np	number of particles
$P.p$	dimensional and nondimensional pressure (Pa)
Pe	Peclet number
Pr	Prandtl number
q''	heat flux at the bottom of the micro-device (W m^{-2})
$q_{11}.q_{22}.q_{33}$ $q_{12}.q_{13}.q_{23}$	parameters defined in Eq. (8)
Re	Reynolds number
S	width of the microchannel (m)
t	wall thickness (m)
T	nondimensional temperature
$U.V.W$	velocity component in x,y,z directions (m s^{-1})
$u.v.w$	nondimensional velocity component in x,y,z-direction
$X.Y.Z$	x,y,z coordinate (m)
$x.y.z$	nondimensional X, Y, Z

Greek symbols

ψ	general variable (u, v, w) in Eq. (6)
ϕ	particle volume fraction
λ	wall wavelength (m)
μ	viscosity (Pa s)
ρ	density (kg m^{-3})
θ	temperature (K)
τ	time (s)
$\xi.\eta.\varsigma$	curvilinear coordinate components
δV	volume of Eulerian cells

Subscripts

B	fluid bulk value
f	fluid
int	solid-fluid interface
nf	nanofluid
p	particle
r	ratio of Nusselt number of nanofluid to pure water
s	solid
sf	solid to fluid ratio

Superscripts

c	contravariant velocities

the maximum cooling performance. Rostami et al. [7] studied conjugated heat transfer in wavy microchannels to optimize the geometry for the maximum Nusselt number. They found that the intensity of secondary flows and the size of recirculation zones depend on geometrical parameters, so that there is an optimum geometry which has the maximum Nusselt number.

Another way to increase the heat transfer is the change in fluid properties. Adding nano-sized metal powder to the base fluid improves heat transfer properties of the working fluid, i.e. known that using nanofluids instead of traditional fluids in heat transfer applications results in an increase of the Nusselt number [9,10,12,13].

Jung et al. [13] experimentally studied forced convective heat transfer of nanofluid in a single microchannel. Together with the two base fluids water and Ethylene glycol, Al_2O_3 nanoparticles with a diameter of 170 nm and volume concentration between 0.6 and 1.8% were used. They found larger heat transfer coefficients for smaller channel cross sectionsand reported a 32% increase in the measured heat transfer coefficient for nanofluids with 1.8% particle volume fraction.

As stated above, single-phase simulations are based on empirical relations for properties such as the thermal conductivity or effective viscosity. In addition, they are known to under predict the experimentally measured enhancement of the heat transfer properties of nanofluids [8,9]. Therefore, two-phase models are a better choice. Kalteh et al. [8,9] performed two-dimensional simulations of heat transfer enhancement in a microchannel heat sink utilizing nanofluid. They modeled the nanofluid by the Eulerian-Eulerian method, where the particles and the fluid are described by continuous Eulerian fields. They found that two-phase modeling is suited to reproduce experimental data. Several authors have applied the two-phase Eulerian-Lagrangian model, where the fluid is described on an Eulerian grid and the particles follow Lagrangian trajectories, in circular microchannels using the FLUENT software package [10–12]. Bianco et al. [10] investigated two-phase nanofluid forced convection in a two-dimensional circular tube. The nanofluid was water with Al_2O_3 particles of 100 nm diameter. The maximum difference in the obtained heat transfer coefficient between single-phase and two-phase models is about 11% and the heat transfer coefficient for two-phase model was larger than that of the base fluid. Wen et al. [11] and He et al. [12] have done similar studies in pipe flow.

Most previous articles are limited to two dimensional problems, while there are only few publications on three-dimensional heat transfer problems. For example, three-dimensional natural convection heat transfer by nanofluids in an enclosure has been investigated by Purusothaman et al. [14,15].

Rebay et al. [16] and Bianco et al. [17] introduce the microscale and nanoscale heat transfer characteristics due to the presence of nanofluids numerically and experimentally.

In the case of nanofluid in wavy channels, Rashidi et al. [18] studied different methods including Eulerian-Eulerian, VOF and mixture methods in two phase models. They showed that the Eulerian-Eulerian method underestimates the heat transfer coefficient in comparison with other two phase models.

To the best of the author's knowledge, there is no study of two-phase modeling by means of an Eulerian-Lagrangian method of nanofluids in wavy microchannels available in the literature. We close this gap by studying three-dimensional conjugate heat transfer in nanofluid-filled wavy microchannels using the Eulerian-