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Optimization design of micro-channel heat sink using nanofluid by numerical simulation coupled with genetic algorithm☆

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ABSTRACT

In this study, microchannel heat sink (MCHS) performance using nanofluid as a coolant is analyzed numerically and nanofluid is modeled using the single phase model and the two phase model. The computational domain is taken as the entire heat sink including the inlet/outlet plenums and micro-channels. Two different types (A type and B type) of MCHS are considered and their thermal resistance for a constant heat flux is compared. The predicted thermal resistance of the B type MCHS shows better than that of the A type MCHS. Furthermore, it is found that single and two-phase models predict almost identical hydrodynamic fields but very different in the thermal fields.

The multi-parameter constrained optimization procedure integrates the design of experiments (DOE), and the response surface methodology (RSM) is proposed to design parameters. Genetic algorithm (GA) method is coupled with CFD as an optimization tool. The objective function which is defined as thermal resistance has developed a correlation function with three design parameters. The thermal resistance predicted by regression function for A type and B type MCHS is in good agreement with the numerical results of CFD by the difference within 3.9% and 3.2%, respectively.

1. Introduction

In recent years, electronics are manufactured much smaller while the operating speed is faster. Therefore, enlarging power densities is needed. According to the International Technology Roadmap for Semiconductors (ITRS), the maximum heat dissipation for a single chip package will reach 108 W/cm^2 by 2016. As a result, how to dissipate heat efficiently matters so as to increase performance of electronics is a very important issue. With excellent heat transfer capacity, micro-channel heat sink (MCHS) has been a widely adopted technique. The micro-channel heat sink concept was first discussed in detail by Phillips [1], and he proposed the theoretical correlation of conventional MCHS (i.e., I-type MCHS). The geometry structure of a MCHS is the main reason affecting the performance of heat transfer. This has led to the development of MCHS with different inlet/outlet locations or different micro-channel shapes. For better uniformities in temperature for MCHS, Chein and Chen [2] have proposed six types of heat sinks with various inlet/outlet arrangements. Different inlet/outlet locations have an effect on uniformities. Among them, the computed results of I-type MCHS and theoretical results proposed by Phillips are in good agreement. In fixed pressure drop or Reynolds number, how to get better heat transfer is important for MCHS. Vinodhan and Rajan [3] kept going on the study with fixed velocity inlet in MCHS, and they proposed four new types of MCHS which are improved from I-type MCHS. Different micro-channel shape could be seen in the new types MCHS, and they have better heat transfer performance than I-type MCHS in fixed parameters. (i.e. inlet velocity and heat flux).

The nanoparticles are used to improve thermal efficiency in recent years. The nanofluids compared to the base fluid have better heat transfer, and many researchers have studied nanofluids including experiments and simulations. However, most prior studies assume nanofluids as a single phase flow which is much easier and faster, while the accuracy is low in terms of the results of simulation compared to the experimental data, due to a lack of consideration of nanofluids microscopic phenomena. Therefore, many scholars use the two-phase model to simulate nanofluids in order to improve the accuracy of simulations. Nanofluids were first used by Choi [4] at the Argon national laboratory. Eastman et al. [5] reported that with low nanoparticle concentrations (1–5 vol.%), the effective thermal conductivity of the suspensions can increase by more than 20% for various mixtures. Lee et al. [6] measured four kinds of nanofluids (CuO/water, CuO/EG, Al_2O_3/water, Al_2O_3/EG), and showed CuO/EG increases 20% heat transfer by 4% solid volume fraction. At a low solid volume fraction ($\phi < 5\%$), the thermal conductivity increased linearly with increasing solid volume fraction and the thermal conductivity was also found to be increased with decreasing particle size. Experimental results of Xie

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Nomenclature

a	acceleration(m/s^2)
C_p	specific heat (J/kg·K)
D_h	hydraulic diameter (mm)
g	gravity acceleration(m/s^2)
H	height (mm)
k	thermal conductivity $(W/m \cdot K)$
L	length (mm)
$\overline{Nu}$	average Nusselt number
p	pressure (Pa)
Δp	pressure drop (Pa)
Q	volume flow rate (m^3/s)
q''	heat flux
Re	Reynolds number
R_{th}	thermal resistance (km^2/W)
T	temperature (K)
u, v, w	velocity component (m/s)
V	velocity (m/s)
W	width (mm)
x, y, z	Cartesian x, y, z-coordinate (mm)

Greek symbols

ρ	density of the working fluid (kg/m^3)
μ	dynamic viscosity $(N \cdot s/m^2)$
τ	shear stress (Pa)
ϕ	volume fraction

Subscripts

b	bottom plate
bf	base fluid
dr	drift
eff	effective
in	inlet
f	fluid
m	mixture
nf	nanofluid
p	solid particle
s	solid
w	wall

et al. [7] showed that using the deionized water, ethylene glycol (EG), and pump oil as the base fluid, the heat transfer increased significantly after adding a few nanoparticles (Al_2O_3).

Xuan and Li [8] explored the heat transfer phenomenon of nanofluid (CuO/water) flowing through a pipe with constant heat flux wall, and the Reynolds number ranged from 10,000 to 25,000. Their experimental results showed that nanofluid has a higher heat transfer coefficient than pure water while nanoparticle is less than 2% concentration. Murshed et al. [9] found that the heat transfer effects would be enhanced with the increase of volume concentration of TiO_2. Yoo et al. [10] discussed four kinds of nanofluids (TiO_2/water, Al_2O_3/water, Fe/EG, WO3/EG), the results displayed that the thermal conductivity of nanofluids is much better than that of pure water, but they also found that the surface-to-volume ratio was an important factor of influencing the thermal conductivity coefficient of nanofluids.

Vajjha and Das [11] experimentally determined the thermal conductivity of three nanofluids (CuO, Al_2O_3, ZnO) and developed new corrections. Duangthongsuk and Wongwises [12] studied the thermal conductivity and viscosity with temperature dependent of (TiO_2/water) by experiments. The parameters studied included solid volume (0.2%–2%) and temperature (15–35 °C). The results showed that heat transfer effect increased as solid volume fraction increased. Beck et al. [13] measured the thermal conductivity of alumina nanoparticles (20 nm) over a temperature range from 296 K to 420 K. They showed that the simple model was able to predict the effects of temperature, particle size, and particle volume fraction. Turbulent convective heat transfer performance and the pressure drop of very dilute CuO/water nanofluid (less than 0.24% volume) flowing through a circular tube were investigated experimentally by Fotukian and Esfahany [14]. Measurements showed that the addition of small amounts of CuO particles to the base fluid increased heat transfer coefficients considerably.

Maiga et al. [15] simulated the turbulence of Al_2O_3/water nanofluids in a tube with constant heat flux. The results showed that heat transfer increased as the solid volume fraction and Reynolds number increased. The wall shear stress increased with the increased in solid volume fraction. Maiga et al. [16] showed that heat transfer effect of γ-Al_2O_3/EG is better than γ-Al_2O_3/water. Heat transfer enhancement due to flow of copper–water nanofluid through a two-dimensional rectangular duct has been studied by Santra et al. [17]. The results showed that there is a little effect of nanoparticles on the flow structure but the isotherms changed and it moved toward the centerline of the channel with increasing in solid volume fraction. The turbulent forced convection flow of a water/Al_2O_3 nanofluid in a square tube subject to constant and uniform wall heat flux was numerically investigated by Vincenzo [18]. Heat transfer enhancement increased with the particle volume concentration, but it was accompanied by increasing wall shear stress values. The optimal Reynolds number was analytically determined and it decreased as particles' concentration increased.

The dimensions of the computational domain as well as the mixture of the nanofluid applied in the present study are based on the work of Gherasim et al. [19]. Results showed that the Nusselt number increased with the increase of Reynolds number and nanoparticle volume fraction, through the increase in pressure drop was more significant with the increase of particle concentration. Besides, under a fixed pumping power the nanofluid did not exhibit higher heat transfer rate than water at lower values of heat flux, while the enhancement using a nanofluid becomes more remarkable as the heat flux increased. Three kinds of nanofluids (Cu/water, Al_2O_3/water and CuO/water) in the two-dimensional wavy channel were numerically studied by Yang et al. [20]. The results showed that the heat transfer could be improved when using nanofluids. The genetic algorithm for multi-objective optimization was performed to obtain the optimal solutions. Akbari et al. [21] compared the CFD predictions of laminar mixed convection of Al_2O_3/water nanofluids by single phase and three different two-phase models (volume of fluid, mixture, Eulerian). They found that single-phase and two-phase models predicted almost identical hydrodynamic fields but very different thermal ones. The predictions of the three two-phase models were essentially the same. At low volume fractions, comparing with the experimental data, the results simulated by the two phase model were more precious than the single phase model. Kalteh et al. [22] numerically studied the forced convection of Al_2O_3 nanofluid in the wide rectangular microchannel heat sink by the single-phase model and the two-phase model, and it was found that two-phase model solution is closer to the experimental data than the value of single-phase model.

To simulate the heat transfer features of nanofluids, the properties of nanofluids such as viscosity should be evaluated. Brinkman [23] discussed the viscous force of mixing liquids and found that the particle volume concentration was not high, but the viscosity of the fluid would still improve. The equivalent dilute solution viscosity equation was proposed by Einstein [24]. The size of particle was accounted in the model of Graham [25]. Nguyen et al. [26] investigated the viscosity of Al2O3/water nanofluid, and it revealed that for higher particle fractions, viscosities of 47 nm particle-size were clearly higher than those of 36 nm size. Besides, the findings showed that the application of Einstein's formula