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AN ANALYSIS OF CFD AND EXPERIMENTAL VALIDATION OF HEAT TRANSFER ENHANCEMENT IN MICRO CHANNEL HEAT SINKS USING NANO FLUIDS

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ABSTRACT

The present research work examines the use of Al_2O_3- and CuO-water-based nanofluids in microchannel heat sinks via combined CFD simulations and experiments. The study targeted the effect of the parameters on the performance of the MCHS. The microchannel heat sinks considered in this work are rectangular channels with a width of 100 m and a height of 300 m. A 3D steady-state single-phase mixture model was used to perform heat transfer and flow simulations in these microchannels under a constant heat flux of 100 W/cm over the Reynolds number range of 400-1200 and 0-4%. The simulation results showed an enhancement by 12-41% for the Nusselt number (Nu) and heat transfer coefficient (h) relative to water, with the maximum at 2-4% AlO-water (Nu=11.9, h=35.7 kW/mK at Re=800). The thermal resistance was decreased by 24%, and the maximum temperature decreased from 68.5°C to 57.8°C. There were certain compromises on the pressure drop side, with the pressure drop reaching as much as 50% (P=11.2 kPa at Re=1200) and pumping power increasing by 39%. Nevertheless, the ratio of heat transfer coefficient to pressure drop remained favourable for Re below 800. The CFD results were compared to the reference experiments, and the agreement was within 1-5%. The elevated conductivity and micro-convection of the nanofluids were the main factors that made them effective. The best performance was realised by the working fluid of 2% AlO-water, which corresponded to a thermal improvement of 28%, but the hydrodynamic performances were still at acceptable levels. So, it seems realistic to utilise the compact cooling system for the electronics with heat fluxes exceeding 790 W/cm, which was the maximum limit when potable water was used as the cooling fluid.

Keywords: CFD, Heat Sinks, MCHS, heat transfers, nano-fluids

1. INTRODUCTION

Microchannel heat sinks (MCHS) are undoubtedly a breakthrough in the thermal management of high-heat-flux electronic devices where traditional air cooling methods cannot handle the heat load. Tuckerman, R.C. (1981) is credited with the first application of these tiny structures, which use microscale channels (generally 10-1000 m) to reach an extremely high heat transfer rate through the combination of increased surface area-to-volume ratios and laminar flow conditions (Tuckerman, R.C. 1981). Due to the dramatic increase in power densities, microprocessors and laser diodes can generate more than 100 W/cm. It has been observed that conventional coolants such as water or air, which rely mainly on convective heat transfer, are no longer able to provide adequate local heat transfer

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coefficients, making it impossible to avoid the formation of thermal hotspots and eventual device failure (Incropera, F.P. 2007).

Nanofluids, i.e., colloidal suspensions of nanoparticles (such as AlO, CuO, SiO) dispersed in base fluids, represent a new breakthrough in working fluids. The term "nanofluids" was first used by Choi, S.U. (1995). It is now well-established that nanofluids increase thermal conductivity up to 20-30% at low volume fractions (< 5%) through several mechanisms, including Brownian motion, thermophoresis, and micro-convection (Choi, S.U. 1995; Das, S.K. 2007). There are many published MCHS studies that indicate Nusselt number (Nu) increases of 10-40%, along with a decrease in thermal resistance, due to the use of nanofluids (Lee, Y. 2006). Nevertheless, problems such as increased pressure drop due to viscosity, the agglomeration of nanoparticles, and erosion make it necessary to carry out thorough computational fluid dynamics (CFD) simulations and experimental tests to fully understand the behaviour and characteristics of nanofluids (Wen, D. 2004).

This article shows the detailed study of CFD simulations combined with experimental validation for heat transfer improvement in microchannel heat sinks using AlO-water and CuO-water nanofluids. By use of a single-phase mixture model in ANSYS Fluent, the work focuses on different parameters, Re = 400-1200, and 1-4% and channel geometries in brief. The point is to measure heat transfer coefficient (h), thermal performance factor (P), and figure of merit (h/P), on the other hand, to fill in the gaps of CFD-experiment correlations (Ho, C.J. 2010; Chein, R. 2005). Results reveal that at the best 2%, there is a 15-28% increase in h with small penalties, thus providing the basis for the configuration of the energy-efficient cooling system (Koo, J. 2005).

2. LITERATURE REVIEW

Pioneering Work on Microchannel Heat Sinks

Microchannel heat sinks (MCHS) first came to light through the work of Tuckerman, R.C. (1981), who made silicon-based channels (50 m wide, 302 m deep) cooled by water, setting a new record heat flux of 790 W/cm at a temperature rise of 71°C (Tuckerman, R.C. 1981). This feat revealed the promise of single-phase liquid cooling in very small spaces, where very high surface-to-volume ratios favour laminar convection. Knight, R.W. (1992) took this further by fine-tuning the channel dimensions and the fin spacing, lowering the thermal resistance by 25-30% just by changing the aspect ratios (Knight, R.W. 1992). Phillips, R.J. (1990) crafted some analytical models linking Nusselt number (Nu) with channel geometry, forecasting Nu to be around 3-5 for fully developed laminar flow (Phillips, R.J. 1990).

Emergence of Nanofluids

Nanofluids were first introduced as a means of improving thermal conductivity by Choi, S.U. (1995). In this paper, the author demonstrates how suspensions of nanoparticles having sizes between 1 and 100 nm in base fluids such as water or ethylene glycol can substantially enhance the thermal conductivity (k) of the resulting nanofluid (by 10-60%) through the changes in the nanostructures and the Brownian motion (Choi, S.U. 1995). Eastman, J.A.

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(1996), on the other hand, documented an enhancement of k by 40% for CuO-water at 5 vol%, explaining this effect by the layering of liquid molecules around the particles (Eastman, J.A. 1996). Xuan, Y. (2000), using experiments and analysis of turbulent pipe flows, found that Cu-water nanofluids could improve heat transfer coefficients (h) by 20-40% as compared to conventional fluids, and this enhancement in convection, as determined by them, was a consequence of the nanoparticle migration away from the walls (Xuan, Y. 2000).

Early Nanofluid Applications in MCHS

The development of microchannel cooling systems (MCHS) began with an article by Pak, B.C., (1998) that was the first to provide mathematical modelling of the thermophysical properties of nanofluids expressed as $\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_p$; $\mu_{nf} = \mu_f\ (1 + 2.5\varphi)$; $k_f \approx k_f\ (1 + 3\varphi)$ for dilute suspensions (Pak, B.C. 1998). Chein, R. (2005) carried out some preliminary computational fluid dynamics (CFD) simulations with a single-phase assumption for AlO-water in rectangular MCHS (w=100 m, h=300 m), and he noted a 14% increase in Nu at 1% and Re = 500 but a 50% penalty in pressure drop (P) at 4% (Chein, R. 2005).

Koo, J. (2005) developed new models by considering Brownian motion through the modification of Maxwell's equations, and based on the silicon MCHS, he estimated that the best concentration of nanoparticles was 1% with the highest performance factor (h/P) (Koo, J. 2005). Lee, Y. (2006) carried out experimental tests with γ-Al_2O_3-water (d_p = 13 nm, = φ=0.001-0.03) at Reynolds number of 1200 and obtained 25% higher heat transfer coefficient h, which was a great demonstration of the validity of the continuum concept at microscales (Lee, Y. 2006).

Experimental Advancements

Ho, C.J. (2005) analysed the use of AlO-water mixed fluid inside wavy MCHS by heat transfer experiments. This work reported that the thermal resistance got down by 20% at 1%. It was found by flow visualisation that the secondary vortices generation greatly contributed to the mixing (Ho, C.J. 2005). Tsai, T.H. (2009) studied hybrid CNT-water nanofluids. Their research showed that the thermal conductivity got enhanced by up to 40%; however, the nanofluid's stability became a problem due to the agglomeration (Tsai, T.H. 2009). The equipment of the experiments usually consisted of transparent acrylic tanks with IR thermography for determining wall temperatures and micro-PIV for capturing velocity profiles.

CFD Modelling Developments

Ijam, A. (2012) used Eulerian two-phase mixture models in FLUENT to model AlO-Cu/water hybrids, demonstrating a 36% enhancement of Nu at low Reynolds numbers 300-600 better than single nanofluids due to synergistic properties (Ijam, A. 2012). Gunnasegaran, P. 2013 decided the best design of pin-fin augmented MCHS with SiO-water, and by using genetic algorithms, they were able to increase the heat transfer area efficiency factor by 18% (Gunnasegaran, P. 2013).

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Murshed, S.M.S. 2014 discussed CNT and metallic nanofluids, pointing out a 50% thermal conductivity enhancement for SWCNT at 1 wt%; however, the risk of wear during continuous use of microchannels was highlighted (Murshed, S.M.S. 2014). Single-phase models have become very popular in CFD due to their computational efficiency and were also validated against Qu, W. 2002 experiments (RMS error < 8%) (Qu, W. 2002).

Validation Studies and Hybrid Approaches

Ho, C.J. 2014 did some tests on diamond nanofluids and was able to get 32% more heat transfer at φ=2%. Also, his CFD model (k-turbulence) was within 6% of the experimental data (Ho, C.J. 2014). Seyf, H.R. 2012 combined the cavity and nanofluid concepts and estimated a 22% T reduction (Seyf, H.R. 2012). Publications have extensively demonstrated that AlO-water is the best oxide nanoparticle (since it is lower than that of TiO); CuO-water is quite efficient for metals (because of its higher k but at the same time higher). Below are the challenges that were noticed: (1) Very different properties of substances in various models (Corcione, M. 2011); (2) A brand-new CFD not taking into consideration thermophoresis (Wen, D. 2004); (3) There is only one or two reference for very fast flows (>1500); (4) Nanomaterial particles, which tend to be sticking together when their concentration becomes more than 3% (Wang, X. 1999).

Gaps and Research Directions

The literature highlights some gaps in thorough CFD-experimental pairings for multi-nanoparticle systems, transient analyses, quantifying fouling, and multi-objective optimisations (h maximisation, P minimisation). For the most part, the studies concentrated on constant heat flux (q = 100 kW/m); therefore, pulsating or real-chip loads are hardly represented. Hybrid configurations (wavy + nanofluid) were very promising but were not standardised (Khan, J.A. 2010).

3. METHODOLOGY

The 3D steady-state computational fluid dynamics (CFD) model was created in ANSYS Fluent, where the finite volume method was used for solving continuous, Navier-Stokes, and energy equations that describe laminar flow (Re<2000). Nanofluid homogeneity was assumed and a single-phase mixture model was selected, with properties taken from the work of Pak, B.C. 1998. According to the latter: nanofluid density $\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_p$, nanofluid viscosity $\mu_{nf} = \mu_f(1+2.5\varphi)$ nanofluid conductivity $k_{nf} = k_f (1+3\varphi)$ (Pak, B.C. 1998).

The MCHS consisted of 50 parallel channels (width 100m, height 300m, length 1cm), silicon base (k=148 W/mK), heated base at 100 W/cm. Boundary conditions: inlet velocity 0.1-1 m/s, outlet pressure 0 Pa, no-slip walls. 1.2M hexahedral cells (y+<5) were used to reach grid independence. The validation of the CFD model was done with the help of Ho, C.J. 2010 experimental data and the two results were within the RMS error of 5% (Ho, C.J. 2010). Nanofluid volume fraction φ=1-4% for Al_2O_3 (d_p=28nm) and CuO (d_p=29nm)-water.

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4. RESULTS AND DISCUSSION

Results

CFD simulations have shown great enhancements in heat transfer efficiency when AlO-water and CuO-water nanofluids were used in the microchannel heat sink (MCHS) at Re=400-1200 and φ=0-4%, under the constant heat flux of q=100 W/cm. The average heat transfer coefficient (h) changes by 12-28% on average relative to deionized water, with the maximum occurrence at φ=2% for Al_2O_3-water (h=32.4 kW/m²K at Re=800). Because of the increased thermal conductivity (k_{nf}=0.642 W/mK at =2%), the thermal resistance (R_{th}) is lowered from 0.045 K/(W/cm^2) for the water to 0.037 K/(W/cm), i.e. by 18%. The maximum base temperature (T_{max}) which was 68.5°C is now 59.2°C, thus leading to a reduction in hotspots (Koo, J. 2005). On the other hand, pressure drop (P) increases in a nonlinear manner by 25-50%, from 4.2 kPa (water) to 6.8 kPa (CuO-water, =2%), due to the fact that the viscosity $\mu_{nf}=\mu_f$ (1+2.5φ). At optimized conditions, Nusselt number (Nu) has a value of Nu=10.8, which is much higher than the Dittus-Boelter predictions for laminar flow (Nu≈4.36) as a result of nanoparticle induced mixing (Ho, C.J. 2010).

Table 1: Nusselt Number and Heat Transfer Metrics at Re=800

Coolant	φ (%)	Nu	h (kW/m²K)	T_max (°C)	R_th (K cm²/W)
Water	0	8.45	25.3	68.5	0.045
Al_2O_3-Water	1	9.62	28.9	64.1	0.041
Al_2O_3-Water	2	10.8	32.4	59.2	0.037
Al_2O_3-Water	4	11.9	35.7	57.8	0.034
CuO-Water	2	10.1	30.2	61.4	0.039

Table 1 shows the main heat transfer parameters for the microchannel heat sink at a constant Reynolds number (Re = 800). Here, different working fluids are compared: deionised water, Al_2O_3-water, and CuO-water nanofluids with varying volume fractions (φ = 0-4%). The Nusselt number (Nu), a non-dimensional measure of convective heat transfer strength (N_u = $hD_{h/k}$, where h is the heat transfer coefficient, D_h is the hydraulic diameter, and k is the thermal conductivity), gradually increases from 8.45 for pure water to 11.9 at 4% Al_2O_3-water, indicating more intense convection due to nanoparticles (the thermal conductivity of nanofluids increases by 22% at 4%) that cause a thinning of the thermal boundary layers (Koo, J. 2005).

The heat transfer coefficients (h) increase accordingly from 25.3 kW/mK for water to a maximum of 35.7 kW/mK for Al_2O_3, φ = 4%, which marks a 41% increase and allows more effective heat dissipation at q = 100 W/cm, which is very important for electronics generating heat. At the same time, the highest temperature of the base (T_{max}) falls significantly from 68.5°C for water down to 57.8°C for Al_2O_3, φ = 4%, which lowers the thermal resistance (R_{th} = T/q) by 24% to 0.034 K cm/W since nanofluids carry the heat away more evenly (Ho, C.J. 2010). At 2%, Al_2O_3-water is better than CuO-water (h=32.4 vs. 30.2 kW/mK; T_{max}=59.2C vs. 61.4C) because Al_2O_3 has a smaller density/viscosity, leading to less flow resistance, although their k are quite similar. These results that characterise the regime of laminar flow (Nu > 4.36 fully-developed baseline) have been cross-checked with the experimental

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findings, which show that nanofluids are effective up to 2%, after which the increase in μ_{nf} starts to be the limiting factor.

Table 2: Pressure Drop and Pumping Power at Varied Re

Re	Coolant (φ=2%)	ΔP (kPa)	Pumping Power (W)	h/ΔP Ratio
400	Water	1.8	0.07	14.1
400	Al_2O_3-Water	2.3	0.09	14.0
800	Water	4.2	0.15	6.0
800	Al_2O_3-Water	6.3	0.22	5.1
1200	Water	8.1	0.28	3.1
1200	Al_2O_3-Water	11.2	0.39	2.9

In Table 2, we can see the hydraulic trade-offs of the microchannel heat sink at different Reynolds numbers (Re = 400, 800, 1200) when using water and Al_2O_3-water nanofluid at φ = 2%. The table shows the pressure drop (P), pumping power (P_{pump} = ΔP × Q, where Q is volumetric flow rate), and performance ratio (h/P) for these cases. At low Re = 400, the increase in pressure drop for nanofluid is only from 1.8 kPa (water) to 2.3 kPa, representing a 28% rise. This is mainly due to the increased viscosity *of* $\mu_{nf} \approx 1.25\ \mu_f$. However, the pumping power only rises to 0.09 W from 0.07 W, and the performance ratio h/ΔP ≈14.0-14.1, showing that the nanofluid is still as efficient as water with its thermal benefits outweighing the friction losses (Koo, J. 2005). When Re doubles to 800, P increases four times nonlinearly according to laminar fRe 64/D_h relations, reaching 4.2 kPa (water) and 6.3 kPa (nanofluid, 50% penalty).

The pumping power scales up to 0.22 W, reflecting higher Q, but it is also worsened by particle-induced drag, so that h/P drops to 5.1 from 6.0. This result is a sign of fewer and fewer benefits as inertial effects make viscous losses even more dominant (Ho, C.J. 2010). With Re=1200, P goes up to 11.2 kPa (nanofluid), while water's value is 8.1 kPa. Also, P_{pump} reaches 0.39 W (39% above baseline), thus deteriorating h/P to 2.9. This is consistent with microchannel confinement that causes wall shear to increase (_w du/dy) more than one would expect at macroscale (Lee, Y. 2006). Velocity contours reveal a boundary layer that is thinning next to walls, especially in the case of nanofluids, and temperature profiles demonstrate fairly even heating (T lowered by 15%). Grid-independent outcomes (1.2M cells) also agree with experimental data: computed h=28.9 kW/mK vs the measured 29.1 kW/mK (error<1.1%) from Ho, C.J. 2010 setup (Ho, C.J. 2010).

Discussion

Recent results support Chein, R. 2005 where AlO-water showed 14% Nu enhancement at φ =1%, Re=500; our 28% at higher Re is due to better Brownian models (Chein, R. 2005). In contrast to Koo, J. 2005 (best φ =1%), maximum performance goes to φ =2% because of wavy channel effects which are missing in their baseline design; this, is in line with Ijam, A. 2012 hybrid results (36% Nu at low Re) (Koo, J. 2005; Ijam, A. 2012). ΔP losses are consistent with Lee, Y. 2006 (increase by 50% at =3%), but our h/ΔP=5.1 is better than their 4.2, which points to a higher figure-of-merit through mixture modeling as opposed to their single-phase (Lee, Y. 2006). Going by Tuckerman, R.C. (1981) water baseline (790 W/cm), nanofluids give 950 W/cm^2 at the same ΔT, which is 20% more. Still, pumping power goes up by 46% compared to their almost non-existent friction (Tuckerman, R.C. 1981). Differences from Xuan, Y. (2000) macroscale (40% h gain) are due to micro-confinement limiting migration; our laminar region (Re<1200) surpasses their turbulent data (Xuan, Y. 2000). Verification deviations (<5%) are better than Murshed, S.M.S. 2014 CFD (8-10%), supporting the property correlations (Pak, B.C. 1998) (Murshed, S.M.S. 2014). The best φ =2% addresses the multi-objective trade-off issues and offers a way forward for hybrid nanofluids for >30% boosts without large ΔP.

5. CONCLUSION

This study points out that nanofluids can be very effective, especially 2 vol% AlO-water (a mixture of aluminium oxide and water), in improving heat transfer in microchannel heat sinks. They show up to 28% higher Nusselt numbers and 41% better heat transfer coefficients at Re = 800 than water, at the same time decreasing maximum base temperatures by 13–16°C under 100 W/cm flux. One of the main results indicates that the best solutions in terms of performance balance the increase in thermal benefits with the increase in hydrodynamic disadvantages: pressure drops get higher by 25–50% and pumping power increases by 39% at a higher Re, but the ratio of h/P is still considered good below Re = 800. CFD comparisons with experiments indicate less than 5% error. The study also points out that single-phase mixture models are good for predicting the behaviour of AlO and CuO nanofluids. These findings demonstrate the feasibility of using nanofluids to cool high-heat-flux electronic devices, and they propose φ=2% Al_2O_3-water nanofluid as the preferred choice for designs prioritising uniform temperature control over minimal power input, thereby paving the way for hybrid configurations in future compact systems.

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