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# Effects of variable particle sizes on hydrothermal characteristics of nanofluids in a microchannel

Tehmina Ambreen, Man-Hoe Kim *

*School of Mechanical Engineering & IEDT, Kyungpook National University, Daegu 41566, South Korea*

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This study investigates the influence of nanoparticle size on the heat transfer and pressure drop characteristics of nanofluids for laminar forced convection in a microchannel subjected to constant heat flux. Aqueous nanofluids containing spherical shaped particle dispersions of $Al_2O_3$ and $TiO_2$, have been simulated by employing discrete phase model (DPM) for a range of ten particle sizes 20–200 nm. Analysis has been carried out by considering two particle weight concentrations (0.1% and 2%) at Reynolds number of 1000, 1200 and 2000. Results demonstrate that for constant nanofluid compositions and flow conditions, convective heat transfer and friction factor are in inverse association with the particle diameter. With the reduction in particle size, the heat transfer coefficient of nanofluids escalates because of particles' enhanced effective particle surface area and uniform distribution along the channel radial direction. However, this improvement in heat transfer coefficient is compensated by undesirable increase in pressure drop as a consequence of higher viscosity. The variation in hydrothermal characteristics of nanofluids with particle diameter is more significant at higher particle concentration. The maximum heat transfer and friction factor difference of 11% and 20% respectively has been observed between particle sizes 20 nm and 200 nm for the particle concentration of 2%.

## 1. Introduction

The paradigm shift in mechanical designs to satisfy the appetite of energy as well as miniaturization requires adequate heat transfer techniques for efficient operations while existing design solutions have already attained their ultimate limits. In addition, the growth of carbon emitting processes i.e. heating, ventilation and air-conditioning, has adversely intensified global warming [1]. A possible solution is adaptation of eco-friendly heat transfer fluids with enhanced thermo-physical properties and nanofluids can be a possible avenue in this pursuit. Nanofluids, the conventional thermo-fluids comprising nano-sized metallic and nonmetallic suspended particles with enhanced thermal conductivity, were first introduced by Choi [2] in 1995. The infinitesimal particles exhibit high suspension stability, improved microchannel heat transfer capacity with least particle clogging, flexible properties and enlarged particle effective surface for maximum inter-phase heat exchange. Moreover higher thermal conductivity, negligible pressure drop and mechanical deterioration make nanofluids highly feasible for numerous industrial applications including microelectronics, transportation, space technology, nuclear and solar systems. Fully understood.

For the last two decades, an exponential increase in the nanofluid related studies has been observed, yet the underlying physical mechanism responsible for the elevated thermal efficiency of these innovative fluids is not well-established [3]. Nevertheless, the thermal conductivity and viscosity of nanofluids have been enormously attributed as key parameters defining their hydrothermal characteristics. These properties are the function of multiple factors including nanoparticle morphology (size and shape), material and concentration, base fluid properties and pH value, fluid temperature and additives [4–8]. However, literature statistics considering the sensitivity of nanofluids' thermal conductivity and viscosity towards particle size always remained inconsistent to draw any commonly accepted conclusion. Few studies demonstrated that reduction in particle size results in thermal conductivity escalation as a result of the enlarged effective surface to volume ratio, enhanced stability, particle-particle and particle-fluid interactions [9–15], while others presented antithetical trends [16–19]. Furthermore, Calvin and Peterson [20] reported the nonlinear relationship between particle size and thermal conductivity. On the other hand, the discrepancies in the studies reporting nanofluid viscosity as a function of particle size are even more striking [4,5,21,22]. The possible reasons for such conflicts can be explained

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* Corresponding author.
*E-mail addresses:* tehminaambreen91@gmail.com (T. Ambreen), manhoe.kim@knu.ac.kr (M.-H. Kim).

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**Nomenclature**

| | |
|---|---|
| $Al_2O_3$ | aluminum oxide (alumina) |
| $C_p$ | specific heat ($J/kg \cdot K$) |
| $C_c$ | Cunningham correlation (–) |
| $D_h$ | channel hydraulic diameter (mm) |
| $d_p$ | nanoparticle diameter (nm) |
| $d_{ij}$ | deformation tensor (–) |
| *DPM* | discrete phase model (–) |
| $F$ | force ($N/kg\ m^3$) |
| $f$ | Darcy friction factor (–) |
| $F_{drag}$ | Drag force ($N/kg\ m^3$) |
| $F_{gravity}$ | gravity force ($N/kg\ m^3$) |
| $F_{lift}$ | Saffman lift ($N/kg\ m^3$) |
| $F_{pressure}$ | pressure gradient force ($N/kg\ m^3$) |
| $F_{thermophoresis}$ | thermophoresis force ($N/kg\ m^3$) |
| $F_{virtual}$ | force due to virtual mass ($N/kg\ m^3$) |
| $g$ | gravitation acceleration ($m/s^2$) |
| $h$ | convective heat transfer coefficient ($W/m^2\ K$) |
| $m$ | mass (kg) |
| $k$ | thermal conductivity (W/mK) |
| $K_B$ | Boltzmann constant ($m^2\ kg/s \cdot K$) |
| $K_n$ | Knudson number (–) |
| $Pr$ | Prandtl number (–) |
| $Re$ | Reynolds number (–) |
| $S_u$ | source term (energy equation) |
| $S_E$ | source term (momentum equation) |
| $T$ | temperature (Kelvin) |
| $t$ | time (s) |
| $TiO_2$ | titanium dioxide (–) |
| $V$ | fluid total velocity (m/s) |
| $Y+$ | dimensionless wall distance of first node (–) |

*Greek symbols*

| | |
|---|---|
| $\lambda$ | molecular mean free path (m) |
| $\mu$ | viscosity (–) |
| $\rho$ | density of fluid ($kg\ m^{-3}$) |
| $\varphi$ | particle weight concentration (–) |
| $\nabla T$ | temperature change of the continuous phase |

*Subscripts*

| | |
|---|---|
| *avg* | average |
| *eff* | effective |
| *f* | fluid |
| *h* | hydraulic |
| *p* | particle |
| *T* | reference temperature |

as the difference in nanofluids' synthesis methods, nanoparticle and base fluid paring, surfactant and measurement techniques employed in multiple experimental investigations [21]. Consequently, the studied concerning particle size dependent hydrothermal characteristics of nanofluids have been also been greatly influenced by these deviations. Nguyen et al. [23] reported in their experimental study that 36 nm sized $Al_2O_3/water$ nanofluid exhibits higher heat transfer coefficient as compared to 47 nm sized particles. Mirmasoumi and Behzadmehr [24] observed significant enhancement in convective heat transfer coefficient of $Al_2O_3/water$ nanofluid as the particle diameter reduced from 120 nm to 10 nm for the mixed convective flow. However their calculated skin friction coefficient remained nearly insensitive to particle size. Anoop et al. [25] and Mostafa et al. [26] also reported inverse association between thermal performance and particle size of $Al_2O_3/water$ (45, 150 nm) for laminar forced convection in developing region of a tube. Analogues trend was observed by the Namburu et al. [27] in their numerical investigation on $SIO_2/Water - EG$ (20, 50, 100 nm) nanofluid by employing single phase model. Few successive studies further supported this behavior of the heat transfer coefficient reduction with particle average diameter of the nanofluids [28–33]. Contrarily, studies reported by Sonawane et al., Timofeeva et al. [34–36] represented exactly opposed results. In the experimental investigations on the $SiC/water$ and $SiC/W - EG$ (16–90 nm) nanofluids, Timofeeva et al. [34,35] concluded that large sized nanoparticle exhibit improved heat transfer characteristics as compared to smaller ones because of higher thermal conductivity and low viscosity. Later on Sonawane et al. [36] studied the thermal potential of $Al_2O_3/Aviation\ Turbine\ Fuel$ (ATF) nanofluid and concluded that nanofluids with 50 nm and 150 nm sized particles showed heat transfer coefficient enhancement of 36% and 47% respectively as compared to base fluid. Few researchers also recommended non-linear relationship between particle size and heat transfer characteristics of nanofluids. He at al. [37] explored three particle sizes (95 nm, 145 nm, 210) of $TiO_2/water$ nanofluids and stated that convective heat transfer coefficient is quite insensitive towards variation of average nano-particle diameter. Ji et al. [38] carried out experimental investigation on the performance of an oscillatory heat pipe by using $Al_2O_3/water$ nanofluid. Their results demonstrated that for $dp > 80$ nm, the heat transfer performance of $Al_2O_3/water$ nanofluids increase with reduction in particle size, however for $d_p < 80$ nm the reverse trend was observed. Seyf and Feizbakhshi [39] claimed that Nusselt number and particle size exhibited direct relationship for $CuO/water$ nanofluid while inverse relationship was observed for $Al_2O_3/water$ nanofluid. Abbasian et al. [40] considered both heat transfer and pressure drop parameters for their study on particle size of nanofluid. They summarized that the thermal performance of $TiO_2/water$ nanofluid escalates with reduction in particle size for $dp > 20$ nm, however for $d_p < 20$, particle size and heat transfer coefficient showed direct relationships. They also stated that pressure drop reduces with particle size increment.

In the context of the mentioned controversial results, recent review articles [3] summarized that the studies regarding particle size dependent hydrothermal characteristics are inadequate to establish any fundamental conclusion. Moreover, most of the studies considered few limited particle sizes and neglected hydrodynamic characteristics of nanofluids as a function of particle diameter. Therefore, the present manuscript is aimed at investigating particle size dependent laminar forced convective heat transfer as well as pressure drop characteristics of two types of nanofluids $Al_2O_3/water$ and $TiO_2/water$, in a microchannel subjected to constant heat flux. For this purpose, multiphase discrete phase model (DPM) has been employed because of its higher accuracy as compared to single phase model and other multiphase models [41–44]. Simulations have been carried out at three Reynolds number 1000, 1200 and 2000 for a series of ten particle sizes (20–200 nm). Nanoparticle concentrations of 0.1 wt% and 2 wt% have been selected for each nanofluid.

## 2. Problem description and modeling

In present study, the laminar forced flow of two aqueous nanofluids $Al_2O_3/water$ and $TiO_2/water$ in a horizontal circular