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Convective heat transfer performance of aggregate-laden nanofluids

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ABSTRACT

With the recent progress in nanotechnology, nanofluids are emerging as a new class of heat transfer fluids formed by adding nanometer-sized structures (e.g., particles, fibers, tubes) in conventional base fluids (e.g., water, ethylene glycol, engine oil). Due to attractive van der Waals forces, nanoparticles tend to agglomerate to form aggregates in nanofluids to form the so-called aggregate-laden nanofluids. Aggregation affects the nanofluid properties such as thermal conductivity and viscosity and further affects the heat transfer performance. The discrepancies regarding the influence of nanoparticles on thermophysical properties and heat transfer characteristics in the literature might arise due to nanoparticle aggregation. Firstly, three performance comparison criteria for nanofluids were proposed for thermally developing laminar flow, fully developed laminar flow and fully developed turbulent flow to evaluate the nanofluid efficiency as coolants. Secondly, parametric effects of aggregates on nanofluid viscosity and thermal conductivity were investigated. The cooling efficiency of the aggregate-laden nanofluids depends on aggregate parameters such as aggregate ratios, interfacial thermal resistance, volume fraction of aggregates in nanofluids and volume fraction of nanoparticles in the aggregates. One method to tailor the aggregate morphology is presented by dispersing nanoparticles of different size into a base fluid. By this method, the volume fraction of nanoparticles in the aggregates might increase, which thus enhances the nanofluid effectiveness due to reduction of viscosity.

1. Introduction

Nanofluids are engineered colloidal suspensions of nanometer-sized structures (e.g., particles, fibers, tubes) of a base fluid, which are more stable than microparticle colloids, with less particle setting, channel erosion and clogging [1]. Nanofluids generally provide higher thermal conductivity compared to their base fluids due to the relatively large thermal conductivity of the added nanoparticles. Thermal conductivity enhancement of nanofluids was illustrated in the open literature [2–4], but there are still some controversies about the underlying mechanisms for the increased thermal conductivity and even discrepancies on the magnitude of the nanofluid thermal conductivity enhancement, as indicated in Refs. [5–8] etc. Eapen et al. [3] and Evans et al. [9] concluded that the contributions of Brownian motion, micro-convection, the Soret effect (also known as thermodiffusion or thermophoresis) and the Dufour effect (an induced heat flow caused by the concentration gradient) can be neglected for nanofluids in most cases. However, aggregation, which can also be called as agglomeration or cluster, has been recognized as one of the important underlying mechanisms for the enhanced thermal conductivity [9].

Due to attractive van der Waals forces, nanoparticles tend to agglomerate to form aggregates. Aggregation affects the nanofluid properties such as thermal conductivity and viscosity and further affects heat transfer performance. Preparation methods such as addition of surfactants and ultrasonic vibration can reduce the size of the agglomerates substantially but are not able to break the agglomerates into primary particles. Existence of nanoparticle agglomerations has already been observed by dynamic light scattering and SEM/TEM observations in the literature, e.g., [10–16]. On one hand, agglomeration tends to enhance nanofluid viscosity due to the immobilized fluid trapped in the particle clusters and thus a higher effective volume fraction than the actual solid volume fraction. Anoop et al. [10] considered the viscosity increase to be primarily due to the agglomeration of particles in water-based and ethylene-based nanofluids. On the other hand, fractal agglomerations or aggregates can lead to thermal conductivity enhancement due to the ability of the heat to move rapidly along the backbone of the clusters [11]. Note that relatively large packed clusters may deteriorate thermal conductivity as it may induce sedimentation and therefore decrease the particle volume fraction. The increase in viscosity leads to thicker boundary layers and possible secondary flow mitigation, causing heat transfer deterioration. The thermal conductivity increase delays and disturbs the thermal boundary layer and thus is beneficial for heat transfer

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Nomenclature

Bi	particle Biot number, $2R_k k_f/d_p$
$c_{p,f}$	specific heat at constant pressure (J kg^{-1} K^{-1})
d	tube diameter (m)
d_a	agglomeration diameter (m)
d_p	particle diameter (m)
f	the ratio of $\varphi_{in,c}$ to φ_{in}
f_D	Darcy friction factor
Gz	Graetz number, RePrd/L
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
k_a	thermal conductivity of the aggregate (W m^{-1} K^{-1})
k_{nc}	thermal conductivity of the medium including base fluid and dead ends (W m^{-1} K^{-1})
k_x, k_z	thermal conductivities of line chains along transverse and longitudinal directions (W m^{-1} K^{-1})
L_x, L_z	geometrical factors defined in Eqs. (40) and (41)
L	tube length (m)
Nu	Nusselt number, hd/k
p	aspect ratio
Pr	Prandtl number, $c_p\mu/k$
q	heat flux (W m^{-2})
R_k	interfacial thermal resistance (m^2 K W^{-1})
Re	Reynolds number, $\rho ud/\mu$
T	temperature (K)
u	velocity (m s^{-1})
V	volume flow rate (m^3 s^{-1})

Greek symbols

β_x, β_z	parameters defined in Eqs. (36) and (37)
η	the ratio of heat removed to pumping power
μ	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})
φ	volume fraction
φ_a	volume fraction of aggregates in nanofluid
φ_{in}	volume fraction of nanoparticles in aggregates
$\varphi_{in,c}$	volume fraction of linear chains in aggregates
$\varphi_{in,nc}$	volume fraction of dead ends in aggregates
ΔP	pressure drop (Pa)
ΔT	temperature difference (K)

Subscripts

a	agglomeration
f	base fluid
m	maximum
nf	nanofluid
p	nanoparticles

performance. Therefore, the effects of aggregates on the overall heat transfer performance of aggregate-laden nanofluids in various applications need to be investigated.

The purpose of this work is to evaluate the performance or efficiency of aggregate-laden nanofluids as coolants for heat transfer applications. Basically, this work mainly focuses on the following three aspects.

- How to evaluate the performance or effectiveness of nanofluids as coolants?
- What are the main aggregate (agglomeration or cluster) parameters that affect the cooling efficiency of the aggregate-laden nanofluids?
- How to tailor the aggregates to enhance the cooling performance?

2. Performance comparison criteria for nanofluids as coolants

It is very important to choose appropriate performance comparison criteria (i.e., figures of merit) to compare the cooling performance of nanofluids over their base fluids. Inappropriate comparison criteria such as heat transfer coefficient ratios based on the constant Reynolds number may give misleading results because the net result for the constant Reynolds number basis is a combination of the nanofluid property effect and the flow velocity effect [17–21]. Due to the higher viscosity of the nanofluid, the flow velocity in the nanofluid is generally higher than that of the base fluid at the same Reynolds number, which provides an advantage for the nanofluid over the base fluid. Therefore, more appropriate figures of merit should be proposed to compare the heat transfer performances of nanofluids and their base fluids.

Three performance comparison criteria (i.e., figures of merit), denoted as FoM1, FoM2 and FoM3, respectively, are proposed as follows, mainly for nanofluids flowing in smooth and straight tubes. Now the flow and heat transfer are analyzed for a coolant passing through a smooth and straight tube under constant wall heat flux q with a volume flow rate of V, as shown in Fig. 1. Only a short section of the tube is considered. The coolant (base fluid or nanofluid) flows in at an inlet bulk temperature of T_{in}, and flows out at an outlet bulk temperature of T_{out}. The wall temperature at the section outlet is denoted by $T_{out,wall}$.

2.1. FoM1

The first one is the heat transfer ratio based on the same flow velocity, labeled as FoM1.

- For *fully developed laminar flow* in smooth and straight tubes,

$$\mathrm{Nu} = \frac{hd}{k} = \text{constant} \tag{1}$$

Therefore,

$$\frac{h_{nf}}{h_f} = \frac{\mathrm{Nu}_{nf}k_{nf}}{d_{nf}} \cdot \frac{d_f}{\mathrm{Nu}_f k_f} \tag{2}$$

If the nanofluid is beneficial as a heat transfer fluid, h_{nf}/h_f should be larger than unity. For both the base fluid and nanofluid flowing in the same straight tube with the same Nusselt number, one finds

$$\frac{h_{nf}}{h_f} = \frac{k_{nf}}{k_f} > 1 \tag{3}$$

The above formula is always true when the thermal conductivity of the nanoparticles is larger than that of the base fluid. The FoM1 for fully developed laminar flow is denoted as

$$\mathrm{FoM1}_{lam} : \frac{k_{nf}}{k_f} = 1$$

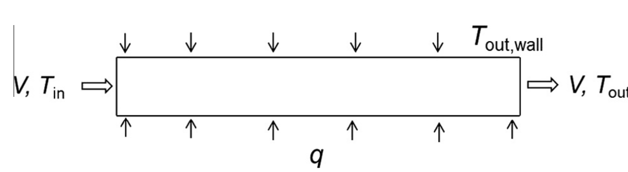

Fig. 1. Schematic of a coolant flowing in a smooth and straight tube under constant wall heat flux q.