International Journal of Heat and Mass Transfer 122 (2018) 150–160

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Effect of inter-particle potential on the effective viscosity of nanofluids

Meng-He Sun [a], Xin-Rong Zhang [a,b,*]

[a] Department of Energy and Resources Engineering, College of Engineering, Peking University, Beijing 100871, China
[b] Beijing Engineering Research Center of City Heat, Peking University, Beijing 100871, China

ARTICLE INFO

Article history:
Received 15 June 2017
Received in revised form 4 January 2018
Accepted 13 January 2018

Keywords:
Nanofluid
Effective viscosity
DLVO potential
Inter-particle force

ABSTRACT

A theoretical model of effective viscosity of nanofluids considering the effect of inter-particle potentials is developed by mathematical methods. Repulsive DLVO potential of charged particles are selected to express the inter-particle potential and a compact form of the effective viscosity of nanofluids is reached. The expression shows qualitatively that the long-range repulsion between particles can lead to the increase of the effective viscosity of nanofluids which could even exceed the effect brought by Brownian motion in certain circumstances. The model is validated by several experimental results from references. The effective viscosity data gained from experiments can be accurately predicted by careful assignment of the value of effective charge number. When the nanoparticle volume fraction is less than 0.5%, the corresponding number of the effective charge is of 10^3. When the nanoparticle volume fraction is around 1%, the proper value of effective charge is about 10^2. And when the nanoparticle volume fraction further increases to about 10%, the effective charge is to the order of 10. These results also reveal the change of particle agglomeration structure under different nanoparticles volume fractions. The model deducted in the current study proposed a reasonable way to explain the abnormal enhancement of the effective viscosity of nanofluids, which is a good complement to the present researches in the specific field.

1. Introduction

Nanofluid is a fluid containing solid nanometer-size particles and fibers. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid. Common base fluids include water, ethylene glycol and oil. In 1997, Choi and Eastman [1] ingeniously dispersed the solid particles having a particle size in the range of 1–100 nm in the base fluid. After that, lots of researches have been done to study the mechanism and possible applications of nanofluids. In nanofluid, a very low solid volume fraction can cause significant change in physical properties comparing with the base fluid. And because pipe flow is involved in almost all the applications of nanofluids, the effective viscosity is a vital property that can affect the system efficiency. For the above reason, the study of nanofluid effective viscosity has aroused attentions in the past ten years [2]. It has been widely proved that nanofluids have considerably enhanced effective viscosity, and this phenomenon cannot be explained by classical models.

In the early studies, people found that the effective viscosity of Newtonian nanofluid was strongly correlated with bulk temperature and solid volume fraction in a nonlinear way [3]. While the effective viscosity of non-Newtonian nanofluid was affected by solid volume fraction, yield stress and the viscosity of the base fluid. Some researchers reported that the effective viscosity is irrelevant to temperature when near room temperature, which may due to the ignore of Brownian motion [4]. However, temperature could change the shear-thinning behavior of nanofluids since characteristic shear rate was strongly associated with temperature. Besides, researchers also noticed the particle aggregation and physical property changes brought by it [5,6]. Aladag et al. [7] examined the effects of temperature and shear time on the viscosity of Al_2O_3-aqueous nanofluids, mainly focusing on the low concentration and low temperature condition. They used stress-control rheometer to measure the flow behavior between parallel plates under elevated and decreased shear stress. They found that the nanofluid could show hysteresis effect when the shear stress was loaded or removed, and the effect was related to shear time. Utomo et al. [8] compared the effective viscosity of Al-water nanofluid with the theoretical prediction from Einstein's and Batchlor's model, and explained the enhancement of the effective viscosity with particle aggregation. Nguyen et al. [9] also studied the relationship between the effective viscosity of Al-water nanofluid and particle volume fraction and temperature. By using

* Corresponding author at: Department of Energy and Resources Engineering, College of Engineering, Peking University, Beijing 100871, China.
E-mail address: xrzhang@coe.pku.edu.cn (X.-R. Zhang).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.057
0017-9310/

Nomenclature

a	nanoparticle radius [m]
d	nanoparticle diameter [m]
e	unit charge [1.6×10^{-19} C]
k	thermal conductivity [W m^{-1} K^{-1}]
k_B	Boltzmann's constant [1.38066×10^{-23} J K^{-1}]
M	molecular weight [1]
N	number of nanoparticle [-]
N_A	Avogadro's constant [6.02×10^{-23}]
P_N	probability density function [1]
$\mathbf{r}$	position vector [-]
T	temperature [K]
Z	surface effective charge number [1]

Greek symbol

α	thermal diffusivity [m^2 s^{-1}]
ε	permittivity [F m^{-1}]
κ_D^{-1}	Debye length [m]
μ	viscosity [Pa s]
$\mathbf{\Pi}$	bulk stress [-]
σ	contact stress [-]
τ	thermal dynamic stress [-]
ϕ	nanoparticle volume fraction factor [1]
Ψ	potential [J]
ψ_s	surface potential [J]

Subtitle

eff	effecitve
f	base fluid
nf	nanofluid
p	nanoparticle

a piston-type cylindrical calibration viscometer, they found that the nanofluid made from 36 nm and 47 nm particles shown almost no difference in effective viscosity when the particle volume fraction was less than 4%. When the particle volume fraction was higher, nanofluids with larger particles size had obviously higher effective viscosity, and the effective viscosity model obtained by linear theory may not be suitable for nanofluids. Chandrasekar et al. [10] investigated the effective viscosity of Al_2O_3-water nanofluid at particle volume fraction ranging from 0.33% to 0.5%. Yiamsawas et al. [11] measured the variation of effective viscosity under different temperature at particle volume fraction ranging from 1% to 8% and found the decrease of effective viscosity with the increase of temperature. Jarahnejad et al. [12] also found the reduction of effective viscosity when the bulk temperature increases. They pointed out that the surfactants added to stabilize the nanofluids would increase the effective viscosity. Murshed et al. [13] measured the effective thermal conductivity and effective viscosity of different kinds of nanofluids and found the abnormal enhancement of effective viscosity. Their result was in a discrepancy to other groups, which they believed was because of the size difference of the particle clusters. Timofeeva et al. [14] found noticeable increase of effective viscosity when measuring Al_2O_3-EG nanofluids. They indicated that the effective viscosity is strongly related to nanoparticle size. Recently some studies have been carried out on the physical properties of hybrid nanofluids, indicating the abnormal performance and the possible application scenarios of the specific kind of nanofluids [15].

In fact, it is not easy to get the effective viscosity data of nanofluids from experimental measurements. The preparation of monodispersed nanofluids is difficult and the accurately measure of size, concentration and size distribution of nanoparticles requires lot of work. Besides, the observation and description of the structure of particle agglomeration can bring many problems. Because of these, molecular dynamic simulation also become an important tool to study the effective viscosity of nanofluids [16]. Researchers found that the effective viscosity of nanofluids could not only be determined by the particle volume fraction but also the size of the nanoparticle, which has been proved in many experimental studies [17,18]. Researches shown that the increase of nanoparticle size can lead to the reduction of effective viscosity when the particle volume fraction is constant, but opposite conclusions also exists [9,19]. Later, Rudyak and Krasnolutskii [20] found that the effective viscosity was inversely proportional to the particle volume fraction by using the molecular dynamics simulations of actual interactions. In addition, the solid material of nanoparticles could also significantly affect the effective viscosity of nanofluids.

From the previous review we can see that the effective viscosity of nanofluids presents an abnormal enhancement comparing to colloidal suspension of other particle sizes, and this phenomenon cannot be explained by classical effective viscosity theories. Researchers began to explore the mechanism behind the phenomenon and tried to give proper explanations, while there are still no systematic discussions when comes to the mechanism of effective viscosity of nanofluids. It is found in the experiments that the effective viscosity of nanofluids is sensitive to the bulk temperature, the volume fraction of nanoparticles, the particle shape and size, surfactant and pH, and external electric field and external magnetic field also have a direct effect on the effective viscosity of nanofluids. Moreover, the theoretical model established on dilute colloidal solution can not accurately predict the effective viscosity change of nanofluids, which is because of the neglect of the special force and regularity brought by the nano-size effect. Recently, some researches pointed out that the increase of the effective viscosity of nanofluids is caused by the agglomeration of nanoparticles, but the established models were strongly depended on the structure and size of the agglomeration measured from experiments, making the model essentially a semi-empirical one.

The motivation of the current study is to explain the abnormal increase of the effective viscosity of nanofluids using a model that can be obtain from classical mechanical theories. The current work is aimed to get an expression of the effect of inter-particle potentials on the effective viscosity of nanofluids by mathematical methods. The ensemble average and equilibrium part distribution function are used to deal with the expression of the interaction force and obtain a concise form of the relationship between the inter-particle potential and the effective viscosity. By selecting the repulsive DLVO potential of charged particles, the part of the potential function in the original expression can be determined and further deduced. Furthermore, the established model is also validated by several experimental results from existed references.

2. Effective viscosity models

The measurement of the effective viscosity of colloidal dispersion is an important tool to understand the microstructure of colloidal particles. The effective viscosity of the colloid dispersion system is usually influenced by the following four common effects: