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A modified aggregation based model for the accurate prediction of particle distribution and viscosity in magnetic nanofluids

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A B S T R A C T

Magnetic nanofluids (MNFs) are suspensions comprised of a non-magnetic base fluid and magnetic nanoparticles. A possibility to induce and control the heat transfer process and fluid flow by means of an external magnetic field opened a window to a spectrum of promising applications. Particle distribution and viscosity are crucial parameters for the control of this smart fluid. However, few theoretical models have been reported that can satisfactorily predict the hydrodynamics properties of MNFs. In this study, modified population balance model of rheological law was employed to investigate the coagulation and fragmentation of magnetic nanoparticles in nanofluids. For the first time, both the effects of magnetic field and Brownian motion have been considered. The effect of shear rate, solid volume fraction and fractal dimension on final distribution of particle size and viscosity of nanofluids was studied in detail. For particle size distribution, it is found that the decrease of shear rate will lead to particle size increase. The effect of increasing solid volume fraction is similar to decreasing shear rate. Greater solid volume fraction could also contribute to the larger particle sizes. The increasing fractal dimension makes larger particle sizes and fluctuate geometry standard deviation. The viscosity of MNFS becomes increased with the increase of solid volume fraction. However, it would undergo decrease when shear rate increases. The calculation results considering Brownian motion showed good agreement with experimental results. Our model is expected to provide effective approach for the study of MNFs and contribute to their application in various industrial processes.

1. Introduction

Recent technological advancements in the field of electronics and thermal systems have led to an ever increasing demand for heat transfer systems with higher efficiencies. Both active and passive methods have been intensively investigated. Passive methods such as improvement of thermal conductivity and viscosity of the working fluid have the advantages of both energy conservation and high efficiency [1]. One of the passive methods attracting much attention in recent years is the employment and application of nanofluids [2–4]. Among various nanofluids, magnetic nanofluids (MNFs) are suspensions comprised of a non-magnetic base fluid and magnetic nanoparticles. The suspensions can be called smart or functional fluids because fluid flow, particle movement and heat transfer process can be controlled by applying magnetic fields [5]. A possibility to induce and control the heat transfer process and fluid flow by means of an external magnetic field opened a window to a spectrum of promising applications including magnetically controlled thermosyphons for technological purposes, enhancement of heat transfer for cooling of high power electric transformers, and magnetically controlled heat transfer in energy conversion systems [6,7].

The thermal conductivities for most of the nanofluids have been considered to have positive correlations with the particle volume fraction. However, the particle distribution and the viscosity with respect to the particle aggregation state in the nanofluids, especially in MNFs, remain unclear [8–12]. In a magnetic field, magnetic moments tend to align in the field direction and the nanoparticles in MNFS self-assemble into one dimensional chain/wire or rings, two dimensional magnetite particle aggregates and even three dimensional superlattices [13]. The created anisotropic feature in MNFS greatly affects the macroscopic properties of the fluid with its transport properties such as viscosity and thermal conductivity being significantly changed [14]. Moreover, it is difficult to transport magnetic nanofluids by traditional pumping due to their varied viscosity induced by imposed magnetic fields [15]. Obviously, the particle distribution and viscosity of the magnetic nanofluid are crucial for their application in heat and mass transfer processes. Duan et al. [16] found that the viscosities of Al_2O_3/water nanofluids showed a dramatic change before and after ultrasonication. Barthelmes et al. [17] found that the immobilization of matrix liquid renders the viscosity dependency on the particle aggregation state in concentration suspension. Both studies revealed that the viscosity of nanofluids could be attributed largely to a high level of nanoparticle aggregation. Unfortunately, the effects of particle aggregations on the apparent viscosity of the nanofluids have been overlooked in most of

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Nomenclature

i	The section of particles
V_i	The mass-equivalent volume of an aggregate in section I, cm^3
x_i	The number of primary particle in an aggregate in section i
N_i	Number concentration of flocs with volume V_i, $1/cm^3$
$B_{i,j}$	Collision kernel (collision rate) of particles or aggregates, cm^3/s
$\beta_{Si,j}$, $\beta_{Bi,j}$	Collision kernel of aggregates caused by shear deformation or Brownian motion, cm^3/s
G	Shear rate, 1/s
D_f	Fractal dimension
v_p	Volume of primary particle, cm^3
m	The effective mass of particles, kg
m_i, m_j	The mass of particle or aggregate in i_{th}, j_{th} section
d_i, d_j	Mass equivalent diameter, cm
σ	Equation collision diameter, cm
T	Kelvin temperature, K
k_B	The Boltzmann constant, J/K
ρ	Particle density, kg/m^3
η_0	Base fluid viscosity, Pa S
ϕ_0	Solid volume fraction
q	Exponent
τ^*	Shear stress
S_i	Fragmentation kernel (fragmentation rate) of particles or aggregates, 1/s
k_b	A factor to match the dimensions, $1cm^{-1}s^{-1}$
ϕ_{tot}	Effective or total volume concentration of the aggregates
ϕ_m	Maximum volume concentration
$v_{c,i}$	Collision volume of aggregate, cm^3
$\Gamma_{i,j}$	Fragment distribution function
$d_{c,i}$	Collision diameter, cm
d_i	Mass-equivalent diameter of an aggregate in section i, cm
R_s	Gyration radius of the aggregation, cm
r	Radius of primary particle, cm
r_i	The distance between the i_{th} particle and center of gravity of aggregation, cm
$(x_G y_G z_G)$	The center of gravity of aggregation, cm
N	The number of particles in an aggregate
R_s	Average gyration radius, cm
M_l	The Langevin magnetization
B	Magnetic induction
σ_{gn}	Number-based geometric standard deviation
$[\eta]$	Intrinsic viscosity
ϕ_A	Volume fractions of aggregates

previous study [17]. For MNFs in particular, Goharkhah et al. [18] studied the effect of magnetic field on the heat transfer performance of convection nanofluid and they found that a magnetic field with alternating magnetic intensity is more efficient than a constant one to enhance heat transfer. It is assumed that the varied intensities of the imposed magnetic field will significantly affect the particle distribution and viscosity of the magnetic nanofluid which, in turn, results in various heat transfer performances. Although experimental results have been frequently reported, mathematic model that can satisfactorily describe and predict the particle distribution and viscosity of MNFS under a varied magnetic field, is still highly desired.

Hatami et al. [19] have investigated the natural convection of a non-Newtonian nanofluid flow between two vertical plates using Least Square Method (LSM) and Differential Transformation Method (DTM). Also the effects of the nanoparticles volume friction, Prandtl number and nanoparticle materials on velocity and temperature profiles are considered. It is observed that the results of DTM and specially LSM are in excellent agreement with numerical ones. Ahmadi et al. [20] conducted a comprehensive performance of flow and heat transfer of nanofluid in a stretching flat plate. The unsteady flow and the related heat transfer of a nanofluid caused by linear motion of a horizontal flat plate have been analyzed and the nonlinear differential equations governing on the presented system have been reduced to a set of ordinary differential equations and obtained equations have been solved by Differential Transformation Method. These findings could be of valuable guidance for finding simple but effective analytical solutions in the study of the science and engineering problems of nanofluid.

Malvandi et al. investigated the effects of Brownian motion, thermophoresis motion and magnetic field on particle migrations, Nusselt number and pressure drop of nanofluids in a channel for non-symmetrical [21] and symmetrical heat fluxes by Modified Buongiorno's model [22,23]. It was found that both symmetrical and non-symmetrical heat fluxes can cause the lower particle concentration near hot wall. The work motivates us to consider whether the heterogeneous concentration distribution can result in different processes of aggregations in nanofluids and to find a mathematic model to precisely describe this process based on above theoretical findings.

As to the description of the aggregation of particles in fluid, population balance model of rheological law has been employed by Barthelmes et al. and Spicer et al. [17,24] to study coagulation and fragmentation of suspensions. The method can provide particle size distribution at any time and only needs to solve the group of ordinary differential equations (ODE). Barthelmes et al. [17] introduced the effect of shear rate on the processes of coagulation and fragmentation and they also built the relationship between particle size distribution and viscosity. Unfortunately, the effect of Brownian motion on particle size distribution has been neglected in these studies. In our opinion however, the Brownian motion in such suspension should not be overlooked especially when the particles in the nanofluids are of nanoscale.

In the present study, a modified population balance model of rheological law has been established by introducing the effect of magnetic field and Brownian motion. To our knowledge, we are the first that introduce the magnetic field effect when modeling the aggregation process in nanoparticle suspension. What's more, the effect of thermal motion (Brownian motion), shear deformation, initial solid volume concentration and magnetic field on the transient behavior of particle size distribution and suspension viscosity has been investigated. The proposed modified aggregation based model for particle distribution and viscosity prediction of the magnetic nanofluids is expected to provide effective approach for the study of MNFS and contribute to their application in various industrial processes.

2. Physical model description

The primary goal of the present work is to propose a suitable mathematic model to describe the coagulation and fragmentation of nanoparticles and the relationship between the particle size distribution and the manifested viscosity, under a varied magnetic field. A schematic illustration of the physical model under consideration is shown in Fig. 1. It is an enclosed annular space including two cylinders of different radii with top and bottom surfaces covered. The two cylinder surfaces satisfy the non-slip boundary condition and the top and bottom surfaces are smooth. This enclosed space is filled by nanofluid. The large and small cylinders correspond to the outer wall and inner wall of nanofluid, respectively. The outer wall is fixed and the inner wall is rotating with a tunable rotating speed of w. The radii of two cylinders are R_1 and R_2, respectively, with the same height H. Magnetic field of intensity B is parallel to the