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Heat transfer and flow of a dense suspension between two cylinders

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ABSTRACT

Concentrated suspensions, composed of solid particles and fluids, are used in many industrial applications. In this paper, we study the effects of temperature on the flow of a concentrated (dense) suspension between two long rotating cylinders. The viscosity of the suspension is assumed to depend on temperature and volume fraction of the solid particles. Based on these concepts, a generalized viscosity model is proposed and the model parameters are fitted with experimental data. The numerical results show good agreement with the available experimental measurements.

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1. Introduction

Concentrated suspensions are complex fluids composed of solid particles dispersed in a fluid, and are important in many industrial applications, such as drilling fluids [1,2], ceramics and reinforced polymer composites [3], coal slurries [4,5], and food engineering [6], etc. Successful operation of these suspensions requires a thorough understanding of the thermo-rheological properties of the suspension, such as its viscosity, the particle distribution, and the impact of the temperature field, etc. [7–10].

Suspensions composed of particles in a fluid can be considered as multiphase materials, and specifically two-phase flow approach can be used to study them. When the amount of the dispersed (particle) phase is very small, not impacting the motion of the continuous (fluid) phase, then a "dilute phase approach", sometimes referred to as the Lagrangian-Eulerian approach can be used. This is a one-way coupling. Alternatively, when the two phases are interacting with each other influencing the motion and the behavior of each other, a "dense phase approach", sometimes called the Eulerian-Eulerian (or the two-fluid) approach can be used. This is a two-way coupling. In either approach, governing equations are written for each component, and constitutive relations are needed before one can solve a system of coupled differential equations to obtain the velocity, temperature fields, etc. [see Soo [11] and Marcus et al. [12], Massoudi [13,14]]. In addition to these two approaches, a macroscopic (global) approach can be taken; here the suspension is considered as a complex fluid whose properties depend on the volume fraction of the particles, among other parameters. In this paper we take this approach.

There are many published studies involving flow and heat transfer in suspensions [7,8,15–18]. For example, Ahuja [19] studied heat transfer in suspensions of polystyrene spheres in aqueous sodium chloride or glycerine; it was found that the thermal conductivity of the suspensions can be three times as much as the thermal conductivity of stationary suspensions. Shin and Lee [16] experimentally investigated the rheological and thermal behavior of dense suspensions in a shear flow where the effects of particle size, particle concentration and shear rate were studied. In their paper, a shear-thinning viscosity was observed; the thermal conductivity was found to be strongly affected by particle concentration and particle size. Chen and Louge [17] theoretically explored heat transfer enhancement of dense suspensions in fluids; heat transfer enhancement is thought to be related to the agitation and movement of the solid particles. This was modeled by coupling the fluid and the solid phases through a particle concentration source term. It is worth mentioning that in recent years, nanofluids, which are suspensions composed of base fluids with different types of nanoparticles, have received much attention for their unusual performance on enhancing heat transfer efficiency [20–25]. In general nanofluids are usually considered to be dilute suspensions,

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and will not be discussed in this paper; for more details we refer to the recent review articles [23,26–29] and several important pioneering works [30–32].

In most situations, the suspension is modeled as a Bingham or as a power-law fluid model [33,34]. It is known that the rheological behavior of suspensions can be very complex. For example, the shear viscosity of a concentrated suspension, in addition to being dependent on the shear rate, could also depend on the volume fraction of the particles, the temperature, the pressure, etc. Krieger et al. [35], based on their experimental and theoretical studies for concentrated suspensions, suggested that the viscosity can depend on the shear rate and the volume fraction of the particles (with various sizes). According to their study, the shear-thinning property is dominant when the size of the (solid) particles is in the micro scale range, but this effect diminishes as the particle size increases. According to Briscoe et al. [36], the rheological behavior of concentrated suspensions, such as drilling mud, can also depend on pressure and temperature in applications, such as deep ocean drilling operations [37].

In this paper, we model the suspension as a non-linear fluid model where the shear viscosity depends on temperature and particle concentration, and particles migration is modeled by the concentration flux transport model proposed by Phillips et al. [38]. In Sections 2 and 3, the governing equations of motion and the constitutive relations for the stress tensor, the diffusive particle flux vector and the heat flux vector are provided. In Section 4, the numerical results are presented and analyzed. We first study the isothermal flow of a suspension between two concentric cylinders; we then consider effects of temperature and eccentricity.

2. Governing equations

If the effects of electro-magnetism and chemical reactions are ignored, the governing equations, for a suspension, are the conservation equations for mass, linear and angular momentum, particle concentration, and energy [7]. For a complete thermo-mechanical study, the entropy law should also be considered [see [39]].

2.1. Conservation of mass

$$\frac{\partial \rho}{\partial t} + div(\rho \boldsymbol{v}) = 0 \tag{1}$$

where ρ is the density of the suspension, $\partial/\partial t$ is the partial derivative with respect to time, and $\boldsymbol{v}$ is the velocity vector. For an isochoric motion, $div\boldsymbol{v} = 0$.

2.2. Conservation of linear momentum

$$\rho \frac{d\boldsymbol{v}}{dt} = div\boldsymbol{T} + \rho \boldsymbol{b} \tag{2}$$

where d/dt is the total time derivative, given by $d(\cdot)/dt = \partial(\cdot)/\partial t + [grad(\cdot)]\boldsymbol{v}$, $\boldsymbol{b}$ is the body force vector, and $\boldsymbol{T}$ is the Cauchy stress tensor. The conservation of angular momentum indicates that in the absence of couple stresses the stress tensor is symmetric, that is, $\boldsymbol{T} = \boldsymbol{T}^{\mathrm{T}}$.

2.3. Conservation of solid particles (particles flux)

$$\frac{\partial \phi}{\partial t} + \boldsymbol{v}\frac{\partial \phi}{\partial \boldsymbol{x}} = -div\boldsymbol{N} \tag{3}$$

The function ϕ is an independent kinematical field called the volume distribution or the volume fraction (related to concentration) with the property $0 \leqslant \phi(\mathrm{x},t) \leqslant \phi_{max} < 1$. Here the first term on the left hand side denotes the rate of accumulation of particles, the second term denotes the convected particle flux, and the term on the right hand side denotes the diffusive particle flux. Following [38], the diffusive particle flux $\boldsymbol{N}$ is composed of fluxes related to the Brownian motion, the variation of interaction frequency and the viscosity. Such a transport equation for the concentration of particles (convection-diffusion) has been widely used to study flow and heat transfer in suspensions [8,40,41].

2.4. Conservation of energy

For an incompressible fluid, the energy equation is,

$$\frac{\partial e}{\partial t} + div(e\boldsymbol{v}) = \boldsymbol{T} : \boldsymbol{L} - div\boldsymbol{q} + \rho r \tag{4}$$

where e is the internal energy, $\boldsymbol{L}$ is the gradient of velocity, $\boldsymbol{q}$ is the heat flux vector, and r is the specific radiant energy (which is not considered in this paper). Thermodynamical considerations require the application of the second law of thermodynamics or the entropy inequality. The local form of the entropy inequality is given by (Liu, p. 130):

$$\rho\dot{\eta} + div\boldsymbol{\varphi} - \rho s \geqslant 0 \tag{5}$$

where $\eta(\boldsymbol{x},t)$ is the specific entropy density, $\boldsymbol{\varphi}(\boldsymbol{x},t)$ is the entropy flux, and s is the entropy supply density due to external sources, and the superposed dot denotes the material time derivative. If it is assumed that $\boldsymbol{\varphi} = \frac{1}{\theta}\boldsymbol{q}$, and $s = \frac{1}{\theta}r$, where θ is the absolute temperature, then Eq. (5) reduces to the familiar Clausius-Duhem inequality

$$\rho\dot{\eta} + div\frac{\boldsymbol{q}}{\theta} - \rho\frac{r}{\theta} \geqslant 0 \tag{6}$$

Even though we do not consider the effects of the Clausius-Duhem inequality in this paper, for a complete thermo-mechanical study of a problem, the second law of thermodynamics has to be considered [39,42–44]. From the above equations, we can see that constitutive relations are needed for $\boldsymbol{T}$, $\boldsymbol{q}$, $\boldsymbol{N}$, and e. We ignore the effects of radiation. We will discuss these modeling issues in the next section.

3. Constitutive equations

3.1. Stress tensor

In general, we think, the constitutive equation for the stress tensor of a concentrated suspension should be given by a non-Newtonian (non-linear) model [see [45]] and it may include a viscous stress and a yield stress [see [7]]:

$$\boldsymbol{T} = \boldsymbol{T}_y + \boldsymbol{T}_v \tag{7}$$

where $\boldsymbol{T}_y$ is the yield stress and $\boldsymbol{T}_v$ is the viscous stress tensor. In this paper, we will not consider the effect of the yield stress and we assume that, in general, the viscous stress can be represented by a generalized power-law fluid model, where

$$\boldsymbol{T}_{\boldsymbol{v}} = -p\boldsymbol{1} + \mu_r(p,\theta)\left(1 - \frac{\phi}{\phi_{max}}\right)^{-\beta}\Pi^{\frac{m}{2}}\boldsymbol{D} \tag{8}$$

$$\mu_r = \mu_{r0} e^{\frac{C_{10}p\theta E_u - C_{20}p}{k_B(\theta-\theta_C)}} \tag{9}$$

$$\Pi = 2tr\boldsymbol{D}^2,\ \boldsymbol{D} = \frac{1}{2}(\boldsymbol{L} + \boldsymbol{L}^T),\ \boldsymbol{L} = grad\boldsymbol{v} \tag{10}$$

Here, $\boldsymbol{1}$ is the identity tensor, p is the pressure, θ is temperature, ϕ is the volume fraction, tr is the trace operator, Π is an invariant of $\boldsymbol{D}$ where $\boldsymbol{D}$ is the symmetric part of the velocity gradient, E_u is related to an "activation energy", k_B is the Boltzmann constant,