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A multi-phase ferrofluid flow model with equation of state for thermomagnetic pumping and heat transfer

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ABSTRACT

A one-dimensional multi-phase flow model for thermomagnetically pumped ferrofluid with heat transfer is proposed. The thermodynamic model is a combination of a simplified particle model and thermodynamic equations of state for the base fluid. The magnetization model is based on statistical mechanics, taking into account non-uniform particle size distributions. An implementation of the proposed model is validated against experiments from the literature, and found to give good predictions for the thermomagnetic pumping performance. However, the results reveal a very large sensitivity to uncertainties in heat transfer coefficient predictions.

1. Introduction

Heat exchange is of key significance in a number of applications, such as process design and integration, waste heat recovery and collection, household heating and cooling, and cooling of engines, electronics and power electronics. Heat exchange concepts often use a fluid as the means of heat transport, and the rate of heat transfer to and from the fluid is a limitation.

In 1995, Choi and Eastman [1] proposed adding nanoparticles to a fluid to enhance its heat transfer properties. The particles are normally smaller than 100 nm, which ensures that they are suspended in the fluid by Brownian agitation. Surfactants are typically also added to improve the stability of the particle suspension. The term nanofluid is used for fluids that consist of a base fluid, such as water, oil or glycol, with suspended nanoparticles and possibly added surfactants.

While the theoretical potential of nanofluids has been known for some time, steadily improving nanofabrication techniques are opening more and more possibilities for practical use. Nanofluids have been shown to have quite novel properties, such as increased thermal conductivity and Nusselt number [2–4]. They have been heavily researched for the last 10–20 years, and a wide range of potential applications have been proposed (see e.g. [5]).

If a nanofluid is synthesized with magnetic particles, it is known as a ferrofluid [6]. Such magnetic nanofluids open up the possibility of pumping the fluid using an inhomogeneous magnetic field. A pump utilizing magnetic fields would require fewer moving parts, perhaps none whatsoever, which may lead to increased reliability.

Due to the symmetry of a static magnetic field, such a field cannot alone produce a net force on the fluid in steady-state, so another effect is needed to break the symmetry. The effect used here is the fact that the magnetic susceptibility of a ferrofluid depends on temperature. If the particles are engineered to have a particularly strong response to temperature, the fluids are called temperature-sensitive magnetic fluids (TSMF). A commonly used TSMF is composed of Mn–Zn ferrite particles with different kinds of base fluids [7].

The concept of using magnetically pumped ferrofluids, often referred to as thermomagnetic pumping, for heat exchange has been demonstrated by a number of authors, see e.g. Lian et al. [8], Xuan and Lian [9] and Lee et al. [10]. Iwamoto et al. [11] built an apparatus for measuring the net driving force of a thermomagnetic pump for different heat rates and pipe inclinations.

In this paper, we present a model for multi-phase ferrofluid flow that includes the effects of applied heat and a magnetic field on the fluid. We include a thermodynamic equation of state and vapor–liquid equilibrium calculations in order to accurately predict the thermodynamic properties of the base fluid. Equations of state enable the prediction of thermodynamic properties in a consistent way [12], across a wide range of pressures and temperatures, and common implementations include parameter databases for a large variety of possible mixtures. Taking advantage

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of the results of this large field of research adds flexibility to the model. To the best of our knowledge, including such thermodynamic models is novel work when it comes to simulation of thermomagnetic pumping.

An implementation of the model is then validated by comparing simulation results with the experimental results by Iwamoto et al. [11].

In Section 2, the equations for one-dimensional ferrofluid flow are presented, along with the source terms for magnetic, frictional, and gravitational forces, as well as heat transfer. The thermodynamic model and magnetization equations are also described. Section 3 briefly explains the numerical methods used to solve the model equations. The validation of the model against experimental results is described in Section 4. In Section 5 we discuss the results, and finally we draw conclusions and outline further work in Section 6.

2. Model

In this section, we present our multi-phase ferrofluid flow model. The model consists of a set of one-dimensional conservation equations with source terms that model the effects of heat transfer, friction, gravity, and magnetic forces. The equations are closed by a thermodynamic model that relates the primary flow variables to an equilibrium state. In addition, we present a model for the dependency of the ferrofluid magnetization on the magnetic field and temperature. The development of the flow model builds on ferrofluid dynamics models by Rosensweig [13], Müller and Liu [14], Tynjälä [15], though with significant simplifications expected to be appropriate for these applications.

2.1. Fluid description

We wish to describe the multi-phase flow (liquid/vapor/nanoparticles) of a ferrofluid in a pipe under the influence of external forces and heat sources/sinks. In this work, the system is described by a one-dimensional homogeneous equilibrium multi-phase flow model. In such a one-dimensional description, the actual sharp boundaries between phases are not resolved. Instead, the multiphase state at a given position along the pipe is described by the volume fraction of each phase at that position. The local volume fraction of phase k is given by α_k (–). The index k may be used to describe the three main phases, or different unions of them, as summarized in Table 1. The sum of the main volume fractions is unity, i.e. $\alpha_\ell + \alpha_\mathrm{v} + \alpha_\mathrm{p} = 1$.

Similarly, each phase has its own local average density, ρ_k (kg/m^3), which combines to the mixture density ρ in the following way:

$$\rho = \sum_k \alpha_k \rho_k \quad (k \in \{\mathrm{f}, \ell, \mathrm{p}\}). \tag{1}$$

The density is also defined for the combined phase indices f and bf, as the combined mass divided by the combined volume.

Table 1
Description of phase index subscripts.

Phase index	Description
k	Generic phase index
ℓ	Liquid phase
v	Vapor phase
p	Particle phase
f	Ferroliquid phase (ℓ and p)
bf	Base fluid phase (ℓ and v)
No subscript	The combined ℓ + v + p system

The volume fractions and densities of each phase must be found through some thermodynamic model, given the main flow-variables: mass fluxes, pressure, and enthalpy. A central assumption in enabling this is the homogeneous equilibrium model (HEM), which means that chemical, thermal and mechanical equilibriums between phases are locally reached instantaneously. In other words, it is assumed that chemical potential, temperature and pressure are equal in all phases at any given time and position (though they may vary in time and space). The model also includes the assumption that the friction between the phases is large enough to make the velocities equal.

The base fluid itself may consist of several chemical components, as is often the case with working fluids in heat transfer systems. However, in the homogeneous equilibrium model, the total composition of the base fluid will be constant. The compositions of the liquid and the vapor phase may vary, and be different from each other and the total composition, but this is not relevant for the flow model, which only requires the densities and phase fractions. However, the local compositions are relevant for the underlying thermodynamic model.

2.2. Flow equations

2.2.1. Transient

By considering the conservation of particle mass, base fluid mass, total linear momentum and total energy, while considering source terms deemed relevant, we may derive one-dimensional transient flow equations. These are essentially the fluid dynamic Euler equations with added source terms, which in this case become

$$\frac{\partial}{\partial t}(\alpha_\mathrm{p}\rho_\mathrm{p}) + \frac{\partial}{\partial x}(\alpha_\mathrm{p}\rho_\mathrm{p} v) = 0, \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_\mathrm{bf}\rho_\mathrm{bf}) + \frac{\partial}{\partial x}(\alpha_\mathrm{bf}\rho_\mathrm{bf} v) = 0, \tag{3}$$

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}(\rho v^2 + p) = f^\mathrm{mag} + f^\mathrm{fric} + f^\mathrm{grav}, \tag{4}$$

$$\frac{\partial}{\partial t}\left(\rho e + \frac{1}{2}\rho v^2\right) + \frac{\partial}{\partial x}\left(v\left(\rho e + \frac{1}{2}\rho v^2 + p\right)\right) = v f^\mathrm{grav} + \dot{q}, \tag{5}$$

where Eq. (2) represents the conservation of particles, Eq. (3) represents the conservation of base fluid (liquid + vapor) mass, Eq. (4) represents the conservation of total momentum, and Eq. (5) represents the conservation of total (internal + kinetic) energy. Here x (m) is the position along the pipe, t (s) is the time, v (m/s) is the flow velocity, p (Pa) is the pressure and e (J/kg) is the combined specific internal energy.

The terms on the right-hand side are *force terms* (N/m^3) and the *heat transfer term* (W/m^3), commonly called *source terms*, which will be explained in Section 2.3. The reason why the frictional force term is not present in the energy equation is that friction does not affect the total energy, it only converts kinetic energy to internal energy. In principle there is also an energy exchange with the fluid system when the magnetization changes (magnetocaloric effect), but this will locally be negligible compared to the other source terms, and in steady-state, the energy exchange will sum to zero across the thermomagnetic pump as a whole. It is assumed that this term will have a negligible effect on the results, and thus this term is excluded for model simplicity. Additional implicit assumptions in these equations include no mass transfer to or from the particle phase and no diffusion of particles.