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Potential of enhancing a natural convection loop with a thermomagnetically pumped ferrofluid

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ABSTRACT

The feasibility of using a thermomagnetically pumped ferrofluid to enhance the performance of a natural convection cooling loop is investigated. First, a simplified analytical estimate for the thermomagnetic pumping action is derived, and then design rules for optimal solenoid and ferrofluid are presented. The design rules are used to set up a medium-scale (1 m, 10–1000 W) case study, which is modeled using a previously published and validated model (Aursand et al. [1]). The results show that the thermomagnetic driving force is significant compared to the natural convection driving force, and may in some cases greatly surpass it. The results also indicate that cooling performance can be increased by factors up to 4 and 2 in the single-phase and two-phase regimes, respectively, even when taking into the account the added heat from the solenoid. The performance increases can alternatively be used to obtain a reduction in heat-sink size by up to 75%.

1. Introduction

Nanofluids are composed of a base fluid, such as water, oil or glycol, with suspended nanoparticles. Surfactants are often added to improve the stability of the particle suspension and prevent settling and clumping. Nanofluids have been heavily researched for the last two decades, and a number of potential applications have been proposed [2]. In 1995, Choi and Eastman [3] showed that nanofluids may have improved conductive and convective heat transfer properties compared to the corresponding base fluid. That is, nanoparticles increase the thermal conductivity and Nusselt number of the nanofluid. This increase has been confirmed by a number of authors [4–6].

If the nanoparticles are magnetizable, the fluid is known as a ferrofluid [7]. Such magnetic nanofluids have a number of interesting applications, one of which is its ability to be thermomagnetically pumped using only a static, inhomogeneous magnetic field and a temperature gradient. This is sometimes also called magnetocaloric pumping [8]. A static magnetic field cannot do any net work by itself. However, if a thermal gradient is present, a net pumping force can be achieved due to the temperature-dependence of the ferrofluid magnetization.

A cooling device using such a pump would require no moving parts, something which could provide enhanced reliability, simplicity and compactness. Additionally, the thermomagnetic pumping action may increase overall heat transfer performance in a given geometry, compared to conventional passive solutions such as natural convection. This may also be used to obtain more compact solutions with similar performance.

The improved reliability and compactness from replacing a mechanical pump with a thermomagnetic one may be useful for providing cooling in remote and hazardous environments, where deployment and maintenance is expensive and difficult. Examples include cooling of subsea, space and offshore equipment. Thermomagnetic pumping is particularly advantageous for space applications, since natural convection cooling systems are not possible in weightless environments.

Since the thermomagnetic pumping force increases with larger temperature differences, the pump will in some sense be self-regulating. If the magnetic field is set up by a solenoid or an electro-magnet, the pumping force may also be externally regulated by adjusting the wire current. Thus a thermomagnetically pumped cooling system can be externally controlled while also regulating itself, if necessary.

The concept of using magnetically pumped ferrofluids for heat transfer has been demonstrated by a number of authors, see e.g. Lian et al. [9] and Xuan and Lian [10]. In particular, Iwamoto et al. [11] built an apparatus for measuring the net driving force of a thermomagnetic pump for different heat transfer rates and pipe inclinations. Yamaguchi and Iwamoto [12] studied a magnetically driven system for cooling of microelectromechanical systems (MEMS). The same group has also studied the effect of magnetic field and heat flux on the flow rate and pumping power of thermomagnetically pumped devices [13]. They used a linearized

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magnetization model and account for the presence of vapor through a bubble generation rate. Karimi-Moghaddam et al. [14] considered a thermomagnetic loop with single-phase ferrofluid. They used a linearized model for ferrofluid magnetization and developed a Nusselt-number correlation for the heat transfer. Lian et al. [15] studied a similar system, and they too used a linearized model for ferrofluid magnetization and analyzed the effects of different factors, such as heat load, heat sink temperature and magnetic field distribution along the loop on the heat transfer performance.

While the thermomagnetic pumping effect is confirmed as real, it is an open question whether the effect is significant and useful in practice on macroscopic scales compared to conventional passive solutions such as natural convection. The purpose of this work is to investigate this with a simulated case-study.

We make use of a recently presented and validated model for thermomagnetic pumping and heat transfer [1]. This model treats phase change in the base fluid and the resulting multiphase flow in a rigorous manner. It uses thermodynamic equations of state and includes an advanced ferrofluid magnetization sub-model that is valid in the whole range from linear Curie regime to the saturation regime. The model is thus valid for a large range of parameters, e.g. a large range of applied external magnetic field strengths and a large range of ferrofluid temperatures. Having a general model enables systematic parameter studies of the thermomagnetic heat transfer performance, as well as optimization of a system design over a large range of parameters.

In this paper, we suggest a procedure for designing an optimal solenoid and optimal ferrofluid for a particular application, and we derive a simple approximation for the expected thermomagnetic pumping action. Then we apply the suggested optimization procedures to set up a case study using the full model from [1]. We consider a 1 m long natural convection cooling circuit and show how thermomagnetic pumping can be used to improve its performance. The natural convection case will serve as a reference case to which any improvements obtained by using ferrofluids and/or thermomagnetic pumping will be compared.

In [1], it was found that the predicted effect of thermomagnetic pumping was sensitive to heat transfer coefficients, which have high uncertainties. In the present paper, we eliminate much of this uncertainty by comparing thermomagnetic performance with natural convection, an effect which is also driven by heat transfer. Any error in heat transfer should then have little effect on the relative performance enhancements.

In Section 2, we briefly present the flow model equations that were introduced in [1]. We describe how these equations are solved numerically with periodic boundary conditions for a convection loop. Section 3 derives some analytical estimates of the optimal geometric dimensions of a solenoid and the optimal properties of a ferrofluid for thermomagnetic pumping. A simplified analytical estimate for the thermomagnetic pumping action is also presented here. In Section 4, we describe the application case that we consider in this paper, with the dimensions of the rig, solenoid, heater and cooler, as well as the properties of the base fluid and particles. The results from the model with and without thermomagnetic pumping are presented in Section 5. These are further discussed in Section 6. The focus of the discussion is on how the driving forces vary with temperature, and how nanoparticles and thermomagnetic pumping may improve heat transfer or compactness compared to natural convection of a conventional fluid. Finally, Section 7 summarizes to what extent thermomagnetic pumping can improve a natural convection circuit and outlines further work.

2. Flow model

In [1], we presented a steady-state model for ferrofluid flow in a pipe section. The model includes gravity, magnetic and friction forces and a thermodynamic equation of state. Here we make use of that model to study a heat transfer loop.

2.1. Flow model

The one-dimensional steady-state flow of a ferrofluid may be described by

$$\frac{\mathrm{d}}{\mathrm{d}x}(\alpha_\mathrm{p}\rho_\mathrm{p}v) = 0, \tag{1}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}(\alpha_\mathrm{bf}\rho_\mathrm{bf}v) = 0, \tag{2}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}(p) = f^\mathrm{mag} + f^\mathrm{fric} + f^\mathrm{grav}, \tag{3}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}(\rho v h) = v f^\mathrm{grav} + \dot{q}, \tag{4}$$

where α_k (–) and ρ_k (kg/m^3) are the volume fractions and densities of the indicated phases, respectively. The subscript p describes the particle phase, while the subscript bf describes the base fluid phase. Without a subscript, quantities are total for the phase mixture, such as the flow velocity v (m/s), mixture density ρ (kg/m^3), and the mixture specific enthalpy h (J/kg).

The terms on the right–hand sides of (1)–(4) are called the *source terms*. They are described in detail in [1]. The most novel and important one, the magnetic force term, is given by

$$f^\mathrm{mag} = \mu_0 M \frac{\partial H}{\partial x}. \tag{5}$$

Here μ_0 (N/A^2) is the vacuum permeability, H (A/m) is the magnetic field, and M (A/m) is the magnetization of the ferrofluid,

$$M = \chi(H, T)H. \tag{6}$$

The factor χ (–) is the susceptibility of the ferrofluid, and it generally depends both on the magnetic field and the temperature T (K).

(Eqs. (1) and 2) state the conservation of particle and base fluid mass, respectively. (Eqs. (3) and 4) describe momentum and energy conservation expressed as ordinary differential equations (ODEs) in pressure and enthalpy flux.

These equations allow us to integrate along a pipe from an inlet position (subscript “in”) to an outlet position (subscript “out”). In other words, they allow the mapping of an inlet condition $\boldsymbol{u}_\mathrm{in} = [p_\mathrm{in}, (\rho v h)_\mathrm{in}]$ to an outlet condition $\boldsymbol{u}_\mathrm{out}$. The integration is performed along a pipe which may have a variety of components and orientations. The components and orientations affect the right hand side of the ODEs. The mass fluxes $\dot{m}_\mathrm{p} = \alpha_\mathrm{p}\rho_\mathrm{p}v$ and $\dot{m}_\mathrm{bf} = \alpha_\mathrm{bf}\rho_\mathrm{bf}v$ of particles and base fluid are constant along the pipe and need to be supplied as parameters to the integration procedure.

2.2. Finding periodic solutions

In order to describe a loop, we need to add the requirement that the solution is periodic, i.e. $\boldsymbol{u}_\mathrm{in} = \boldsymbol{u}_\mathrm{out}$. While searching for such solutions, the constants are chosen to be the pressure and particle volume fraction at the inlet (p_in, $\alpha_\mathrm{p,out}$), along with the pipe