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Hydraulic pressures generated in Magnetic Ionic Liquids by paramagnetic fluid/air interfaces inside of uniform tangential magnetic fields

Paul Scovazzo [a,*], Carla A.M. Portugal [b], Andreia A. Rosatella [c], Carlos A.M. Afonso [c], João G. Crespo [b]

[a] Department of Chemical Engineering, University of Mississippi, Oxford, MS, USA
[b] REQUIMTE-CQFB, Departamento de Quimica, Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal
[c] Research Institute for Medicines and Pharmaceutical Sciences (iMED.UL), Faculdade de Farmácia, Universidade de Lisboa, Lisboa, Portugal

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ABSTRACT

Hypothesis: Magnetic Ionic Liquid (MILs), novel magnetic molecules that form "pure magnetic liquids," will follow the Ferrohydrodynamic Bernoulli Relationship. Based on recent literature, the modeling of this fluid system is an open issue and potentially controversial.
Experiments: We imposed uniform magnetic fields parallel to MIL/air interfaces where the capillary forces were negligible, the Quincke Problem. The size and location of the bulk fluid as well as the size and location of the fluid/air interface inside of the magnetic field were varied. MIL properties varied included the density, magnetic susceptibility, chemical structure, and magnetic element.
Findings: Uniform tangential magnetic fields pulled the MILs up counter to gravity. The forces per area were not a function of the volume, the surface area inside of the magnetic field, or the volume displacement. However, the presence of fluid/air interfaces was necessary for the phenomena. The Ferrohydrodynamic Bernoulli Relationship predicted the phenomena with the forces being directly related to the fluid's volumetric magnetic susceptibility and the square of the magnetic field strength. [emim][$FeCl_4$] generated the greatest hydraulic head (64-mm or 910 Pa at 1.627 Tesla). This work could aid in experimental design, when free surfaces are involved, and in the development of MIL applications.

1. Introduction

Recently a "second generation" of paramagnetic fluids was produced [1,2] that differed on the molecular level from the "first generation" of paramagnetic fluids or "ferromagnetic fluids." The "ferromagnetic fluids" studied in the previous century were suspensions of nanometer to micrometer sized permanent magnets [2]. Instead the "2nd-Gen" paramagnetic fluids are magnetic molecules that incorporate their "magnets" on the atomic scale. The fluid molecules have functional groups that contain unpaired electrons, such as iron (Fe), manganese (Mn), and gadolinium (Gd). In the recent literature, the 2nd-Gen paramagnetic fluids are a subset of molten salts or room temperature ionic liquids (RTILs) [3]. For example, ethyl(methyl)imidazolium chloride ([emim][Cl]) can create a paramagnetic fluid if the chloride anion of the [emim][Cl] salt is replaced with an appropriate metal anion; such as, $FeCl_4$ [3]. This produces the paramagnetic fluid [emim][$FeCl_4$] (MP = 18 °C) [3]. "Magnetic Ionic Liquids (MILs)" refers to the paramagnetic fluid subset of RTILs. Note that MILs are pure molten salts not salt solutions. The result is that the magnetic susceptibilities are greater than paramagnetic salt solutions since they are not diluted by the solution solvent. For example, the MIL [emim][$FeCl_4$] has almost 2 times the magnetic susceptibility of a $FeCl_3$ salt solution (0.00084 vs. 0.00046 [4]). This, combined with the negligible vapor pressures of MILs, is a significant advantage for MILs over the magnetic salt solutions studied in the previous century.

A number of research groups have looked at potential applications for 2nd-Gen paramagnetic fluids ranging from magnetically fixed liquid catalysts [5] to separation agents [6]. Other future applications could include micropumping [7] or any of the applications previously considered for the first generation paramagnetic fluids. In order to develop the fundamental knowledge needed for 2nd-Gen paramagnetic fluid applications, research groups have

* Corresponding author. Address: Department of Chemical Engineering, University of Mississippi, 134 Anderson Hall, University, MS 38677-1848, USA. Fax: +1 662 915 7023.

E-mail addresses: scovazzo@olemiss.edu (P. Scovazzo), cmp@fct.unl.pt (C.A.M. Portugal), rosatella@ff.ul.pt (A.A. Rosatella), carlosafonso@ff.ul.pt (C.A.M. Afonso), jgc@fct.unl.pt (J.G. Crespo).

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started measuring physical properties such as surface tension and viscosity [8]. The quantitative and qualitative measurements need to occur both inside and outside of magnetic fields.

One interesting factor in the study of 2nd-Gen paramagnetic fluids is that the validity of the continuum magnetic fluid assumption is higher than it was for the dispersed magnetic particles of the 1st-Gen paramagnetic fluids. Therefore, a logical starting place for the studies is with those models developed for 1st-Gen fluids that rely heavily on the continuum assumption, such as the Ferrohydrodynamic (FHD) Bernoulli Relationship [4]. The FHD-Bernoulli Relationship predicts magnetic forces that might be unexpected to investigators not familiar with the field of ferrohydrodynamics and, therefore, is directly relevant to investigators trying to adopt conventional test procedures for 2nd-Gen paramagnetic fluid property measurements inside of magnetic fields. For example, conventional experimental set-ups may also create unexpected magnetic forces, when operated inside of magnetic fields, that could complicate the interpretation of force-based measurements such as measuring surface tension via capillary forces.

For the reasons given above, in our paper we examine the forces generated by imposing a tangential uniform magnetic field parallel to a paramagnetic fluid/air interface, also known as the Quincke Problem [4]. Such a situation could occur during a number of physical property measurements such as surface tension or viscosity (via capillary viscometers). Also, a fundamental understanding of this situation could aid in the development of 2nd-Gen paramagnetic fluid applications with free surfaces; such as, crystal growth, heat transfer enhancement, spin-up flow and mass-exchange apparati [9].

In our paper, we obtained data on the magnetic forces in a system where the capillary forces (surface tension) are negligible compared to the magnetic forces. The system had a uniform tangential magnetic field with a negligible vertical gradient and minimized edge effects. The data evaluation tested the hypothesis that magnetic molecules that form "pure magnetic liquids" follow the FHD-Bernoulli Relationship. Based on recent literature, we are aware that the modeling of this fluid system is an open issue and potentially controversial [10,11].

2. Theory

2.1. Basic terms and relationships

To develop the theoretical foundation needed to evaluate the FHD-Bernoulli Relationship and the data reported in our paper, we will start with basic magnetic physics and follow the development in the text book by Kraus and Fleish [12], unless otherwise noted. A magnetic field, **H**, is a vector quantity with SI-units of amp/m. If generated by an electrical current, I, traveling in a conducting wire coil or "solenoid," then the magnetic field inside of the solenoid, assuming no edge effects, is:

$$\mathbf{H} = \frac{NI}{L}\boldsymbol{\delta}_\mathbf{z} \tag{1}$$

where N is the number of turns, I is the current in amps, L is the solenoid length, and $\boldsymbol{\delta}_\mathbf{z}$ is a unit vector in the direction of the solenoid's axis. Magnetic flux density, **B**, is a vector that has the same vector direction, in an isotropic material, as the existing magnetic field, **H**. The definition of **B** comes from the force, **F** (in Newton), exerted on a moving charged particle in a magnetic field, as defined by the Lorentz Force Law:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{2}$$

where q is the charge, **E** is the electric field, and **v** is the charge velocity (m/s). This results in **B** having SI-units of Newton/(amp * m) or Tesla. The strength of the force generated depends on the medium through which the magnetic field, **H**, is permeating and the charged particle is moving. The permeability of the medium, μ, is a property that measures this dependence resulting in the following relationship, in an isotropic material, between **B** and **H**:

$$\mathbf{B} = \mu\mathbf{H} \tag{3}$$

where μ is the permeability of the medium in Newton/amp^2.

Energy is required to generate a magnetic field (i.e. current in a wire) and the energy is stored in the generated magnetic field. The amount of energy stored depends both on the size of the magnetic field generated, **H**, and the ease at which the field can "permeate" the medium, μ. If we consider the simple case of a uniform magnetic field, the energy stored in a magnetic field per volume, in J/m^3, is w_m [12]:

$$w_m = \frac{1}{2}\mu H^2 = \frac{1}{2}BH \tag{4}$$

2.2. Atomic-scale magnets and fluid magnetic susceptibility

The spin of an unpaired electron in an atom can be viewed as a moving charged particle that generates a magnetic field similar to an electric current in a wire coil (Eq. (1)). For some atoms; such as iron, and cobalt; the spin creates the equivalent of an atomic size bar magnet whose magnetic strength per volume can be reported as its magnetization, **M**, in units of amp/m.

In MILs the atomic bar magnets are randomly aligned until an external magnetic field is applied. A measure of the effect of applying an external magnetic field is the Volume Magnetic Susceptibility, χ_v, in SI-units of m^3/m^3:

$$\chi_v = \frac{M}{H} \tag{5}$$

Inside of a magnetic field, the alignment of these atomic bar magnets changes the medium's magnetic permeability:

$$\mu = \mu_o + \mu_o\chi_v \tag{6}$$

where μ_o is the permeability of a vacuum. By combining Eq. (6) with the energy storage equation (Eq. (4)), we see that the process of aligning the atomic "bar magnets" has resulted in the increase of energy stored in the magnetic field by a factor of $\mu = \mu_o + \mu_o\chi_v$.

The preceding discussion of the effects of imposing an external magnetic field on a paramagnetic fluid used the property of Volume Magnetic Susceptibility, χ_v. There are other common methods of reporting the magnetic susceptibility of a paramagnetic fluid, such as the effective moment, μ_{eff}, which can be estimated from the number of unpaired electrons, S, in the molecule:

$$\mu_{eff} \approx 2.0[0.5S(0.5S + 1)]^{1/2} \tag{7}$$

The effective moment, μ_{eff}, in units of Bohr Magnetons, has the following relationship to the Volume Magnetic Susceptibility, χ_v:

$$\mu_{eff} = 797.8(\chi_v T V_m)^{1/2} \tag{8}$$

where T is temperature (K) and V_m is the fluid molar volume (m^3/mol).

2.3. Modeling magnetic forces in linear polarizable fluids

There are two different approaches to modeling electromagnetic forces in magnetic materials [13]. The first formulates relationships using the conservation of energy principle. The second one uses material–field interactions such as the Lorentz Force Law (Eq. (2)) or Coulomb's force. While the two approaches produce different formulations, the total forces calculated agree with