Non-conducting magnetic fluids and their application for heat removal in micro-gravity conditions

Sergey A. Suslov[1], Alexandra A. Bozhko[2] and Gennady F. Putin[2]
[1] *Swinburne University of Technology, Melbourne, Australia*
[2] *Magnetic Fluid Laboratory, Perm State University, Perm, Russia*

Summary

We propose a comprehensive theoretical and experimental investigation (including ground-based studies and experiments conducted on board of the International Space Station) with the aim of understanding and quantifying transport properties of nonconducting ferroluids and physics of their flows. The specific emphasis is on using such fluids for safe and reliable heat removal in micro-gravity conditions of a realistic spacecraft. Our preliminary investigation indicates that compact magneto-convection heat removal systems can operate in zero-gravity conditions and deliver better efficiency than their conventional convection-based counterparts operating at normal gravity.

Background

One of the most serious problems which designers of spacecraft equipment currently face is ensuring reliable heat removal in low and micro-gravity conditions. Due to the lack of natural convection even equipment (such as various electronic devices) that was found to operate faultlessly in ground conditions may be subject to thermal strain and even failure due to overheating on board of a spacecraft. **Using conventional methods of cooling such as convective heat transfer that is mechanically forced by fans is highly undesirable** due to parasitic vibrations and noise they generate, as well as due to the safety concerns which are caused by fast moving fan blades and long-range air drafts inside a confined body of a spacecraft. Therefore there exists a pressing need for reliable and safe alternative methods of equipment cooling in spacecrafts. **Using non-conducting nano-ferrofluids, which respond to externally applied magnetic field, as a heat carrier offers such an alternative.**

Common non-conducting artificial magnetic fluids consist of magnetite colloids which contain ferro-magnetic (e.g. magnetite) nano-particles suspended in a carrier fluid, usually synthetic oil, water or kerosene. To prevent formation of magnetite aggregates and their subsequent sedimentation a surfactant such as oleic acid is frequently used. The industrial production of such fluids began in the 1960s [1]. By now their manufacturing technology is significantly improved which enabled the range of ferrofluid applications to widen significantly [2]. However due to the complexity of their composition physical properties of ferrofluids depend not only on the type of components used to make them, but also on the conditions of their storage and use and on the hydrodynamics of flows they are subject to [1, 3, 4, 5]. **Understanding of these dependencies is currently far from being complete and will be subject of the proposed studies.**

Artificially manufactured ferrofluids respond to an external magnetic field similarly to natural paramagnetic and diamagnetic fluids (e.g. water, protein solutions, paramagnetic melts) and gases (e.g. oxygen). However the degree of the magnetization which can be achieved in artificial ferrofluids is many orders of magnitude higher than that in natural magnetic fluids. Therefore noticeable magnetic effects on fluid flows can be observed in magnetic fields created by ordinary permanent or electro-magnets, which makes these fluids **suitable** for a wide range of technological applications and, in particular, **for their use as a heat carrier in heat exchangers operating in reduced gravity conditions on orbital stations** where cooling by natural gravitational convection cannot be achieved [4, 6].

Nonuniform heating results in a nonuniform magnetization of ferrofluid placed in an external magnetic field: colder particles are magnetized stronger. Subsequently, a ponderomotive force arises which drives these cool fluid particles to the regions with a stronger magnetic field. Therefore by focusing the external magnetic field around heat sources a non-mechanically controllable flux of a cooling agent can be created to ensure optimal thermal conditions for equipment operation. The so-created flow is known as magneto-convection which is not associated with gravitational buoyancy forces. It is therefore of primary interest in micro-gravity conditions. We have shown [7, 8] experimentally and theoretically that **the enhancement of the heat transfer rate of up to 5 times in comparison with a pure conduction state can be achieved via magneto-convection.** This is a larger increase than that caused by buoyancy convection in normal gravity conditions. We also discovered that the magneto-convective heat transfer enhancement similar in magnitude to that caused by conventional gravitational convection is achieved in much thinner fluid layers. Therefore properly designed magneto-convective heat exchangers should be more compact than their buoyancy-based counterparts operating in normal gravity conditions.

Directions of the required research

In order to ensure comprehensive and accurate understanding of physics of ferrofluids to a degree enabling practical design of ferrofluid-based cooling systems and other applications the research needs to be conducted in three complimentary directions. This will ensure the most economical use of resources.

Ground-based experiments

While the emphasis of this investigation is on zero-gravity environment, in realistic spacecraft conditions the effective gravity is almost never zero due to various micro-accelerations associated with equipment vibrations (high frequency gravity modulation) or maneuvering of the ship (quasi-static gravity modulation) [9]. Therefore it is important to study combined convection caused by the competing gravitational and magnetic mechanisms. This is much easier and cheaper to do in a well equipped ground-based laboratory provided that the influences of gravitational buoyancy and magnetic effects are well distinguished [7, 10, 11, 12, 13, 14]. The major goal of ground based experiments should be the investigation of influences on the resulting flow patterns and heat transfer of: (a) the gravity vector orientation with respect to magnetic field and thermal gradient; (b) the shape of the boundaries (e.g. spherical cavity, flat layer or thin tube); (c) the non-uniformity and strength of external magnetic field. The ground-based experiments are also required to design and optimize the data acquisition equipment and methodology to be used during space-based studies.

Theoretical and computational investigation

The main pitfall of ground-based experimental investigations is that, while enabling direct observation and measurement of fluid and flow characteristics resulting from the combined action of gravitational buoyancy, magnetic ponderomotive force, magneto-phoresis, Soret effect, sedimentation and magneto-viscous effects, they cannot clearly distinguish which of these mechanisms contribute the most to fluid behaviour for a given set of experimental conditions. On the other hand such competing influences can be studied using careful analytical modelling. For example, it has been analytically discovered [15, 16] that when the coupling between gravity and magnetic mechanisms becomes too strong they tend to suppress each other. Therefore not all results of ground-based experiments can be easily extrapolated to zero-gravity conditions. Thus the major analytical effort should be focused on developing physically relevant tractable models which separate the influences of multiple physical mechanisms acting in a magneto-convective system, quantitatively explain their interaction and enable evaluation of practically important characteristics (such as heat transfer rate) as a function of governing parameters.

Space-based experiments

The intensity of magneto-convection flows and thus of the corresponding heat transfer depend on the magnetization gradient in ferrofluid. While the major reason for the existence of such a gradient is the non-uniformity of a thermal field, there are other contributing factors. The major one is the non-uniform distribution of magnetic particles. There exists an experimental and numerical evidence [17] that in ground conditions it may result from their gravitational sedimentation (i.e. the increase of particle concentration in the direction of gravity) and lead to a sudden reduction of convective heat transfer. Although various gravity-compensation methods are used in experimental studies (e.g. parabolic flight experiments) the time interval during which the reduced gravity can be maintained is limited to few minutes. Therefore it is virtually impossible to eliminate the sedimentation effect completely at the ground level when studying long-term fluid behaviour as would occur at an orbital station. The actual spacecraft-based experiments are the only reliable way to study magneto-convection which is not contaminated by particle sedimentation.

The other important mechanisms leading to the non-uniformity of magnetic particle distribution are thermo- and magneto-phoresis (thermal or magnetic Soret effects) which force magnetic solid particles to diffuse toward colder regions or regions with a stronger magnetic field. The theory of this effect is currently being developed, but its validation requires the knowledge of the fluids' constitutive Soret coefficients. Similarly to fluid's thermal diffusivity, it has to be measured experimentally in a non-isothermal fluid layer. Yet at normal gravity conditions such measurements are virtually impossible because of the buoyancy-driven convection and/or sedimentation which will inevitably occur simultaneously with thermo-magneto-phoresis and lead to a distortion of the experimental results up to several orders of magnitude.

Due to a very high cost of space-based experiments all experimental equipment needs to be designed and thoroughly tested in ground conditions. Methodical work in this direction is currently being conducted by the authors of this paper.

References

[1] V. G. Bashtovoy, B. M. Berkovsky, A. N. Vislovich, Introduction to thermomechanics of magnetic fluids, Hemisphere Co, Washington, D.C., U.S.A., 1988.

[2] S. Odenbach, Ferrofluids: magnetically controllable fluids and their applications, Springer Verlag, New York, 2002.

[3] R. E. Rosensweig, Ferrohydrodynamics, Cambridge University Press, 1985.

[4] E. Y. Blums, M. M. Maiorov, A. O. Tsebers, Magnetic Fluids, Zinatne, Riga, Latvia (in Russian), 1989.

[5] E. Blums, A. O. Cebers, M. M. Maiorov, Magnetic Fluids, Walter de Gruyter, 1997.

[6] A. A. Bozhko, G. F. Putin, Thermomagnetic convection as a tool of heat and mass transfer control in nanosize materials under microgravity, Microgravity Science and Technology 21 (2007) 89–93.

[7] A. A. Bozhko, G. F. Putin, Heat transfer and flow patterns in ferrofluid convection, Magnetohydrodynamics 39 (2003) 147–169.

[8] S. A. Suslov, A. A. Bozhko, G. F. Putin, Features of convection flows and heat transfer in magnetic colloids, in: Proceedings of the 7th International World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Krakow, Poland, June 28–July 3, 2009, pp. 1257–1264.

[9] G. Putin, I. Babushkin, G. Bogatyrev, A. Glukhov, E. Zilberman, A. Ivanov, M. Maksimova, V. Polezhaev, O. Bessonov, S. Nikitin, V. Sazonov, On the measurement of low-frequency microaccelerations on board of an orbiital station by sensor "Dacon", Advances in Space Research 32 (2003) 199.

[10] A. Bozhko, G. Putin, T. Tynjälä, P. Sarkoma, Experimental and numerical investigation of wave ferrofluid convection, J. Magn. Magn. Mater. 316 (2007) 433–435.

[11] A. Bozhko, G. Putin, T. Tynjälä, M. D. Meshin, P. Jalali, On pattern formation in ferrocolloid convection, J. Phys.: Conference Series 64 (2007) 1–8.

[12] A. A. Bozhko, G. F. Putin, Experimental investigation of thermo-magnetic convection in uniform external field, Izvestiya Akademii Nauk SSSR (Letters of the Academy of Sciences of USSR) (in Russian) 55 (1991) 1149–1156.

[13] A. A. Bozhko, G. F. Putin, E. N. Beresneva, P. V. Bulychev, On magnetic field control experiments of ferrofluid convection motion, Z. Phys. Chem. 220 (2006) 251–260.

[14] S. A. Bozhko, A. A. Suslov, G. F. Putin, Magneto-hydrodynamic interaction in a vertical slot filled with ferrofluid, in: Proceedings of the 7th International Conference on Fundamental and Applied MHD PAMIR08, Presquele de Giens, France, September 8–112, 2008, pp. 709–713.

[15] S. A. Suslov, A. A. Bozhko, G. F. Putin, Thermo-magneto-convective instabilities in a vertical layer of ferro-magnetic fluid, in: Proceedings of the XXXVI International Summer School—Conference "Advanced Problems in Mechanics", Repino, Russia, July 6–10, 2008, pp. 644–651.

[16] S. A. Suslov, Thermo-magnetic convection in a vertical layer of ferromagnetic fluid, Phys. Fluids 20(8) (2008) 084101.

[17] A. A. Bozhko, T. Tynjala, Influence of gravitational sedimentation of magnetic particles on ferrofluid convection in experiments and numerical simulations, J. Magn. Magn. Mater. 289 (2005) 281–285.