New Journal of Physics
The open–access journal for physics

Cryogenically enhanced magneto-Archimedes levitation

A T Catherall, P López-Alcaraz, K A Benedict, P J King and L Eaves
School of Physics and Astronomy, University of Nottingham,
Nottingham NG7 2RD, UK
E-mail: ppxatc@nottingham.ac.uk

New Journal of Physics **7** (2005) 118
Received 12 January 2005
Published 9 May 2005
Online at http://www.njp.org/
doi:10.1088/1367-2630/7/1/118

Abstract. The application of both a strong magnetic field and magnetic field gradient to a diamagnetic body can produce a vertical force which is sufficient to counteract its weight due to gravity. By immersing the body in a paramagnetic fluid, an additional adjustable magneto-buoyancy force is generated which enhances the levitation effect. Here we show that cryogenic oxygen and oxygen–nitrogen mixtures in both gaseous and liquid form provide sufficient buoyancy to permit the levitation and flotation of a wide range of materials. These fluids may provide an alternative to synthetic ferrofluids for the separation of minerals. We also report the dynamics of corrugation instabilities on the surface of magnetized liquid oxygen.

Contents

PII: S1367-2630(05)92829-2
1367-2630/05/010118+10$30.00

1. Introduction

The levitation of diamagnetic materials has recently become a topic of interest to a broad section of the scientific community. Diamagnetic levitation was first demonstrated using bismuth [1]. Later work included the lifting of water [2] and, more famously, the stable levitation of a living frog [3, 4]. The levitation of common diamagnetic objects requires very large magnetic field-gradient products due to the small magnetic susceptibility of diamagnetic materials. Consequently, there are only a limited number of materials which can be diamagnetically levitated, in quantity, in the magnets commonly available in a research laboratory. Several groups working on magnetic levitation have recently used a paramagnetic fluid to provide additional buoyancy through the magneto-Archimedes effect. Biological materials including DNA and crystals such as NaCl have been levitated in compressed oxygen gas in a closed pressure vessel [5, 6]. Cooled oxygen gas in an open vessel at ambient pressure has also been used to enhance magneto-buoyancy, enabling levitation of denser materials such as diamond [7]. This method also provides quick and easy access to the samples under investigation. Additional magneto-buoyancy can be obtained by using liquid oxygen (LOX) due to its larger magnetic susceptibility and density. Heavy metals such as gold and platinum can be easily floated in LOX with commercially available superconducting magnets [7]. Interestingly, the magnetic susceptibility of LOX is so great that we would be able to float, in our own magnet (described below), a hypothetical material with a density of almost $400\,000\,\mathrm{kg\,m^{-3}}$, more than 15 times denser than the densest known material, osmium. The aim of this paper is to discuss the application of cryogenic oxygen, both in its gaseous and liquid forms for magneto-Archimedean levitation. Since LOX is a powerful combustion agent, we have investigated the use of less-reactive liquid nitrogen–oxygen mixtures (LNOX) as a safer alternative to pure LOX. We also compare the application of cryogenic oxygen for levitation with the use of synthetic ferrofluids.

2. Diamagnetic levitation

Earnshaw's theorem [8] implies that the stable levitation of a ferromagnetic or a paramagnetic object due to magnetic forces alone is impossible, since there can be no local maximum in the magnetic field intensity in free space, and hence no local minimum in the potential energy. Due to their negative susceptibility, diamagnetic objects require a local minimum in magnetic field intensity for stable levitation. Berry and Geim showed that such local minima can exist in free space [4]. Within a finite solenoid, the field strength is greater near the current-carrying coils than along the axis. This provides the necessary lateral stabilizing force for the levitation of diamagnetic objects.

Diamagnetic levitation is achieved when the magnetic force on a diamagnetic object exactly balances its weight due to Earth's gravity. To a good approximation, this condition is given by

$$\frac{\chi}{\mu_0} B \frac{\mathrm{d}B}{\mathrm{d}z} + \rho g = 0, \tag{1}$$

where χ and ρ are the magnetic susceptibility and density of the substance, μ_0 is the permeability of free space, B is the magnetic induction, z is the vertical coordinate and g is the acceleration due to gravity ($-9.81\ \mathrm{ms^{-2}}$). For diamagnetic materials, $|\chi| \ll 1$ and effects due to the distortion of the magnetic field by a levitating object are negligible.

For stable levitation to occur, equation (1) must be satisfied in a region of the magnetic field where both lateral and vertical stability are provided by the magnetic field configuration [4]. In our magnet, stable levitation can be achieved within the upper part of the magnet bore.

Diamagnetism is generally a very weak magnetic property and large magnetic field-gradient products are required for levitation. For water ($\chi = -9.0 \times 10^{-6}$, $\rho = 1000\,\mathrm{kg\,m^{-3}}$), a value of $B\,\mathrm{d}B/\mathrm{d}z = -1360\,\mathrm{T^2\,m^{-1}}$ is required for levitation. Denser materials such as KCl and diamond require even stronger magnetic fields due to their higher density.

3. Magneto-Archimedean levitation

In the presence of a background fluid, the condition for the levitation of an object is modified to

$$\frac{\chi_o}{\mu_0} B \frac{\mathrm{d}B}{\mathrm{d}z} + \rho_o g - \frac{\chi_f}{\mu_0} B \frac{\mathrm{d}B}{\mathrm{d}z} - \rho_f g = 0, \tag{2}$$

where χ_o and ρ_o are the magnetic susceptibility and density of the levitating object and χ_f and ρ_f are those of the background fluid. The third and fourth terms here represent the magnetic buoyancy and the usual Archimedean buoyancy provided by any fluid. If the background fluid is a gas, then the last term of equation (2) may usually be ignored due to the low fluid density.

Some magneto-Archimedean buoyancy is provided by the oxygen present in air. The paramagnetism of the O_2 molecule is due to the electrons in the $2\pi_{\mathrm{g}}$ anti-bonding orbital which form a spin triplet, a consequence of Hund's rules. Oxygen constitutes approximately 21% of air by volume, so the $B\,\mathrm{d}B/\mathrm{d}z$ required for levitation of water is reduced from $-1360\,\mathrm{T^2\,m^{-1}}$ in a nitrogen atmosphere to approximately $-1306\,\mathrm{T^2\,m^{-1}}$ in air at ambient temperature and pressure. The use of a background medium of higher paramagnetic susceptibility will further reduce the field requirements for levitation, enabling a wider range of materials to be levitated.

4. Cryogenic levitation

The experiments discussed here were performed using an Oxford Instruments superconducting magnet with closed-cycle cooling, a system specifically designed for experiments on levitation. The magnet has a 50 mm diameter open bore and is capable of producing a maximum central field of 17 T and a maximum $B\,\mathrm{d}B/\mathrm{d}z$ product of $-1470\,\mathrm{T^2\,m^{-1}}$ near the top of the bore. These values may be altered by changing the current in the superconducting coils.

The internal bore of the magnet was thermally lagged with a thin insulating layer, the remaining space being filled with oxygen gas. The temperature of the oxygen in the bore was measured using a thermocouple.

4.1. Oxygen gas

The magneto-Archimedean buoyancy provided by gaseous oxygen is greatly increased by reducing the temperature of the gas. Charles' law states that, at constant pressure, the density of a gas is inversely proportional to its temperature. Curie's law of paramagnetism states that the magnetic susceptibility of a paramagnetic material is proportional to its density and inversely proportional to its temperature. For oxygen gas at atmospheric pressure, the magnetic

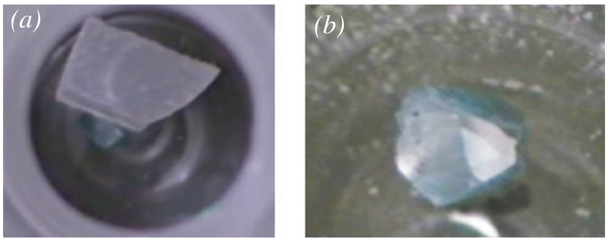

Figure 1. Objects levitating in cooled oxygen gas at atmospheric pressure and with $B\,\mathrm{d}B/\mathrm{d}z = -1470\,\mathrm{T}^2\,\mathrm{m}^{-1}$. (a) A KCl crystal levitating in oxygen at approximately 200 K (movie 1). In the background is a diamond which cannot be levitated at this temperature and field strength; (b) the same diamond levitating at a temperature of 150 K (movie 2).

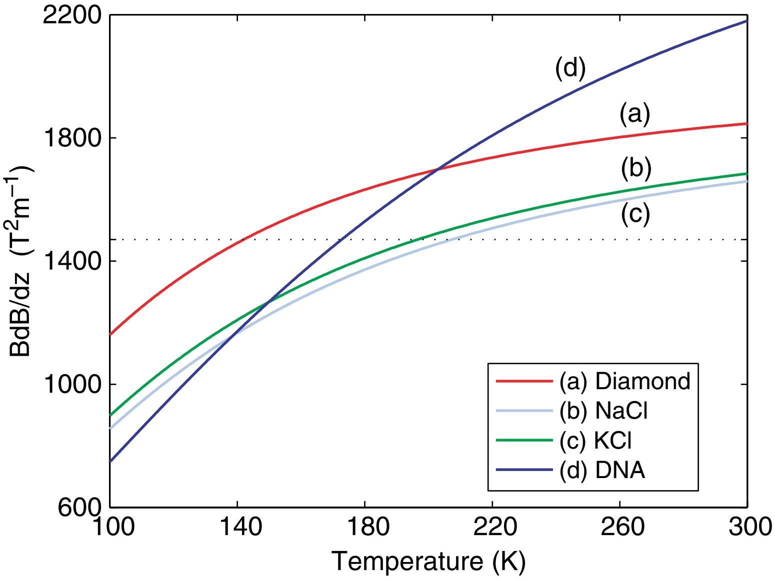

Figure 2. The magnetic field-gradient product required for magneto-Archimedean levitation of various materials in gaseous oxygen as a function of the temperature at atmospheric pressure. The broken line indicates the maximum $B\,\mathrm{d}B/\mathrm{d}z$ that our magnet can provide.

susceptibility is therefore approximately proportional to the inverse square of its absolute temperature, even close to the boiling point [9]. The resulting magneto-Archimedean buoyancy provided by gaseous oxygen is approximately an order of magnitude greater near its boiling point (90.1 K) than at room temperature.

The cryogenic enhancement of levitation provided by oxygen gas is demonstrated in figure 1 by the levitation of a crystal of KCl ($\chi = -13.0 \times 10^{-6}$, $\rho = 1984\,\mathrm{kg\,m^{-3}}$) and a diamond ($\chi = -21.7 \times 10^{-6}$, $\rho = 3513\,\mathrm{kg\,m^{-3}}$ at 90.1 K). At a temperature of 200 K the KCl crystal levitates, whilst the diamond does not, since the magneto-Archimedean force is not sufficient to counteract its weight at this temperature. By further decreasing the temperature to approximately 150 K, the increase in magnetic buoyancy is sufficient to levitate the diamond. In both cases, $B\,\mathrm{d}B/\mathrm{d}z = -1470\,\mathrm{T}^2\,\mathrm{m}^{-1}$. Figure 2 shows how cooled oxygen gas greatly reduces the

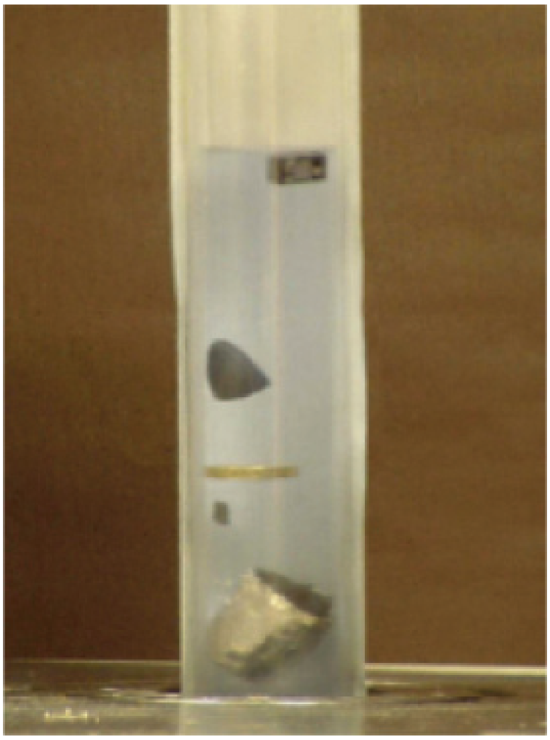

Figure 3. Various objects floating in liquid oxygen (LOX). From top to bottom these are: a silicon crystal; a gallium arsenide crystal; a British £1 coin; a small piece of lead; a platinum crucible (movie 3).

magnetic field requirements for levitation of a range of materials including DNA. The possible crystallization of DNA and of proteins in gravity-free conditions such as those provided by magnetic levitation is of much current interest [6, 10]. The levitation enhancement provided by cooled oxygen gas on DNA is much more apparent than for the other materials due to its relatively low density ($\rho = 1280\,\mathrm{kg\,m^{-3}}$) and susceptibility ($\chi = -4.99 \times 10^{-6}$) [6].

4.2. *Liquid oxygen*

LOX, whose zero-field boiling point is 90.1 K, provides far greater magneto-buoyancy than gaseous oxygen due to its higher magnetic susceptibility and density ($\chi = 3470 \times 10^{-6}$, $\rho = 1149\,\mathrm{kg\,m^{-3}}$ at 90.1 K). The density of LOX is slightly greater than water, so the last term of equation (2) cannot be ignored. Its high magnetic susceptibility means, however, that the diamagnetic force may be ignored in equation (2) to a good approximation. The levitation enhancement provided by LOX is demonstrated in figure 3 and movie 3. This shows various solids floating in pure LOX contained in a Dewar vessel. The top plate of the magnet cryostat is visible at the bottom of the figure. The materials are separated due to differences in their density, and float at vertical positions where the total Archimedean and magnetic buoyancy is equal to their weight. Since the bodies are photographed floating outside of the bore of the magnet, they experience a small horizontal magnetic force which displaces them to the walls of the vessel. All the bodies can be floated with lateral stabilitity, however, when positioned appropriately within the upper region of the bore of the magnet. Dense materials including platinum and lead are floated in fairly

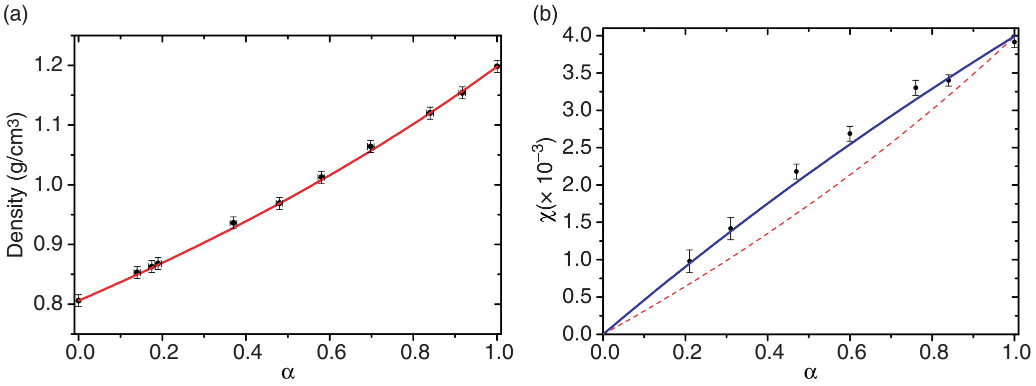

Figure 4. Properties of LNOX. (a) Density of the mixture as a function of the molar fraction of oxygen; (b) susceptibility of the mixtures as a function of the molar fraction of oxygen. All measurements were taken at 77 K. In (b), the dotted line shows the prediction assuming that Néel temperature of the mixtures is independent of oxygen concentration and equal to that of pure LOX and the solid line shows the result obtained using equation (4).

modest magnetic fields: $B\,\mathrm{d}B/\mathrm{d}z = -64\,\mathrm{T}^2\,\mathrm{m}^{-1}$ for platinum and $B\,\mathrm{d}B/\mathrm{d}z = -36\,\mathrm{T}^2\,\mathrm{m}^{-1}$ for lead, in good agreement with predictions made using equation (2).

4.3. LNOX mixtures

LOX is a very powerful combustion agent, widely used as a component of rocket fuel. We have therefore investigated the magnetic properties of mixtures of LNOX as a safer alternative.

The density and the susceptibility of LNOX were measured for a number of mixtures with different molar fractions of oxygen, α. The LNOX mixtures were placed on the top plate of the magnet and kept in a liquid nitrogen bath to maintain the mixture at 77 K, so that the effect of boiling was avoided. A modified precision balance was fixed to the ceiling above the magnet, at a sufficient distance to avoid the effects of magnetic fields on its operation. A small piece of very pure polycrystalline bismuth ($\rho = 9860\,\mathrm{kg\,m}^{-3}$ and $\chi = -166 \times 10^{-6}$ at 77 K) connected to the balance via a thin thread was immersed in the mixture. By measuring the apparent weight of the bismuth as a function of $B\,\mathrm{d}B/\mathrm{d}z$, the density and the susceptibility of a particular mixture were determined. The results are shown in figure 4.

It is known that LOX has a strong antiferromagnetic interaction between neighbouring O_2 molecules; thus its susceptibility obeys Néel's law [11]:

$$\chi = \frac{C}{T + \theta}, \tag{3}$$

where C is the Curie constant and θ is the Néel temperature. At 77 K, the density of LOX is $\rho_{lox} = 1198\,\mathrm{kg\,m}^{-3}$, the Curie constant is $C = 0.47$ K and the Neél temperature is $\theta = 40.6$ K [11], giving a magnetic susceptibility of $\chi = 4.0 \times 10^{-3}$. This is approximately 70% of the susceptibility that oxygen would have if there were no antiferromagnetic interaction present.

Since liquid nitrogen is diamagnetic, only the oxygen molecules are directly responsible for the paramagnetism of a mixture. Diluting LOX with liquid nitrogen (LN) reduces the number of

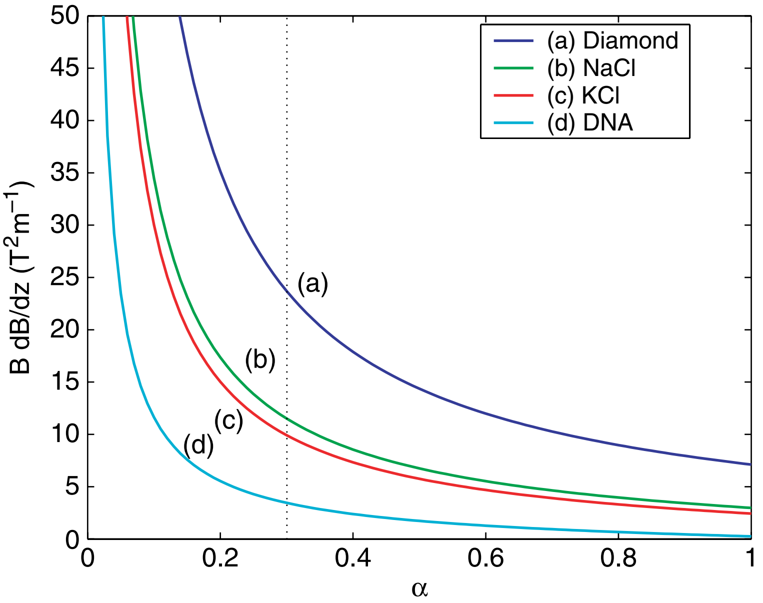

Figure 5. The $B\,\mathrm{d}B/\mathrm{d}z$ product required for magneto-Archimedean levitation of various materials in LNOX mixtures as a function of the molar fraction of oxygen molecules at 77 K. The dotted line indicates an oxygen molar fraction of 30%.

oxygen molecules per unit volume and increases the average intermolecular distance. However, the antiferromagnetic interaction is also suppressed since each oxygen molecule has fewer interacting neighbours. Hence the susceptibility of LNOX can be expressed by

$$\chi = \frac{\beta C}{T + \beta\theta}, \tag{4}$$

$$\beta = \alpha \frac{\rho_{mix}}{M_{mix}} \frac{M_{lox}}{\rho_{lox}}, \tag{5}$$

where ρ_{mix} is the density of the mixtures, M_{mix} is the mean molecular mass of the mixtures and M_{lox} is the molecular mass of oxygen.

Figure 4(b) shows the agreement between the predictions made using equation (4) and the experimental results for the susceptibility of the mixtures as a function of α. A nonlinear bowing effect of the susceptibility as a function of α is apparent, the theory and experimental results being in reasonable agreement.

We observed the flammability of several porous media including powdered sugar and biscuit fibre after being immersed in LNOX of various oxygen concentrations. We found no significant enhancement in the combustibility with LNOX mixtures whose oxygen fraction was below 30%. Figure 5 shows the effect of the oxygen concentration on the magnetic force requirement for levitation of a variety of materials. It can be seen that a oxygen fraction of 30% provides a susceptibility large enough to levitate most materials at modest magnetic fields.

Finally, since the viscosity is important to the dynamics of particles moving within these fluids and to the rate of processes such as mineral separation, it is interesting to note that the dynamic viscosity of LOX and LN at their boiling points are 2.2×10^{-4} Pa s and 2.6×10^{-4} Pa s

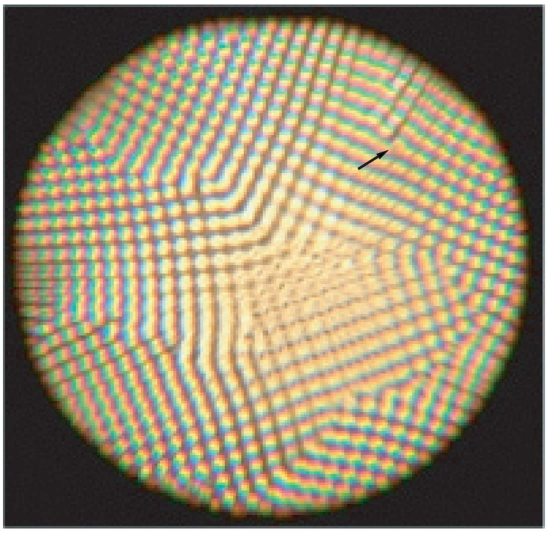

Figure 6. An image of the corrugation instabilities on the surface of LOX at $T = 90\,\mathrm{K}$ and $B = 17\,\mathrm{T}$ (movie 4). The arrow points to a dislocation in the crystalline pattern. The diameter of the image is 50 mm, corresponding to the bore diameter of our magnet.

respectively. These viscosities are considerably lower than the dynamic viscosity of water at 20°C, approximately 1×10^{-3} Pa s.

5. Surface patterning

When LOX is introduced into the bore of our magnet, it moves to the position of highest magnetic field, forming a horizontal disc-shaped membrane across the mid-plane of the bore. The upper and lower surfaces of the membrane are slightly concave. When a field exceeding a few Tesla is applied to the membrane, a regular pattern of corrugations appears on its surface. This effect was initially observed in conventional ferrofluids in the late 1960s [12]–[14], and has been explained in terms of the combined effects of the surface free energy, the gravitational energy and the magnetic energy associated with the ferrofluid [15]. The lattice of corrugations forms spontaneously when the decrease in magnetic energy exceeds the increase of the surface and gravitational energy terms. In a recent paper, we showed that this model can explain the appearance and form of the static corrugations on LOX [16].

In this section, we present new results describing the dynamics of the instability pattern on LOX. The instability first appears as a hexagonal lattice at a field of around 2.5 T at 90.1 K, and undergoes a transition to a square lattice at around 13 T. The photograph in figure 6 shows an array of simple square lattice crystallites extending over the surface of an LOX membrane in a field of 17 T. Due to the low viscosity of LOX and the convective turbulence of the slowly boiling fluid, the crystallites are in continual motion, and we observe shearing of the crystalline patterns along the grain boundaries, as shown in movie 4. As the crystallites approach the walls of the container they are destroyed. Simultaneously, however, new crystallites are created at the opposite side of the container conserving the total energy of the system. We often see dislocations in the crystalline pattern; such a dislocation is indicated in figure 6 by an arrow. These dislocations may be in motion with respect to the crystallites, travelling along the crystalline pattern and even across grain boundaries. The shearing and dislocation movement may be slowed and even suppressed by placing a square copper frame on the surface of the liquid; this is demonstrated in movie 5.

The good agreement between theory [16] and the properties of the instabilities on LOX suggest that the surface tension of LOX depends rather weakly on magnetic field strength up to a field strength of 17 T. Previous measurements of the surface tension of LOX in high magnetic fields were performed in narrow capillaries by observing the deformation of the meniscus [17, 18]. These measurements were hampered, however, since the meniscus deformed unexpectedly at field strengths above approximately 2 T for LOX at 77 K. Interestingly, this field value is close to the critical magnetic field for the onset of instabilities on LOX at 77 K. However, the length scale of the instabilities at this field strength is of the order of 10 mm, whilst the capillary diameters were in the range 0.507–1.531 mm. A detailed analysis would therefore be required to determine whether the instabilities and the meniscus distortion have the same origin.

6. Conclusions

We have investigated the use of cooled oxygen gas, LOX and LNOX for magneto-Archimedean levitation and floatation. Oxygen gas provides a buoyancy force inversely proportional in magnitude to the square of the absolute temperature. This enables the levitation of many materials at ambient pressure, which cannot be levitated through their diamagnetism alone. The use of LOX, allows us to float very dense materials in greatly reduced magnetic fields. In view of the LOX's oxidizing power, we have studied combustion in LNOX and found that mixtures containing 30% of oxygen or less provide comparable levels of combustion to air but still provide strong magneto-buoyancy. On characterizing LNOX, we have studied the susceptibility as a function of composition and found a nonlinear behaviour as a function of the composition. We have applied molecular field theory to explain this phenomenon. The nonlinear bowing effect is somewhat advantageous, because it allows the use of relatively low concentrations of LOX, where oxidizing power of the mixture is low, whilst still retaining the ability to float a wide range of materials in fairly modest magnetic fields.

Synthetic ferrofluids have been previously used for a number of applications including mineral separation [19]. They possess a much greater magnetic susceptibility than LOX or gaseous oxygen, but have a number of important disadvantages for applications such as separation. Ferrofluids, which contain ferromagnetic nano-particles coated with a surfactant, are relatively expensive and present difficulties of removal, recovery and recycling. This is particularly true for the separation of porous materials which are easily penetrated by the ferrofluid. In contrast, LOX (pure or diluted with nitrogen) can be easily boiled off, leaving pure material behind. In addition, LOX has a far lower viscosity than most synthetic ferrofluids which permits faster settling and separation. LOX is a relatively cheap and environmentally friendly fluid, and as our experiments show, it does not present a combustion hazard when diluted with LN. The use of gaseous or LOX is also advantageous in a number of engineering and biological applications, where surfactant contamination is to be avoided or where the use of greatly reduced temperatures is desirable.

In our experiments, we have observed the formation of corrugation instabilities on the surface of LOX subjected to high magnetic fields. These studies reveal a rich range of phenomena such as the cubic or hexagonal crystallites shearing at grain boundaries, the result of convection and low viscosity of LOX.

Acknowledgments

We are grateful to RCUK for support. AC thanks Oxford Instruments for the sponsorship and PL-A thanks Rio Tinto plc. for financial support. We are grateful to Professor G Davies (King's College, London) for the loan of the blue diamond and to Professor A Geim for useful suggestions.

References

[1] Braunbeck W 1939 *Z. Phys.* **112** 735
[2] Baeugnon E and Tournier R 1991 *Nature* **349** 470
[3] Geim A K, Simon M D, Boamfa M I and Heflinger L O 1999 *Nature* **400** 323
[4] Berry M V and Geim A K 1997 *Eur. J. Phys.* **18** 307
[5] Ikezoe Y, Kaihatsu T, Sakae S, Uetake H, Hirota N and Kitazawa K 2002 *Energy Conver. Manag.* **43** 417
[6] Hirota N, Kurashige M, Iwasaka M *et al* 2004 *Physica* B **346** 267
[7] Catherall A T, Eaves L, King P J and Booth S R 2003 *Nature* **422** 579
[8] Earnshaw S 1842 *Trans. Camb. Phil. Soc.* **7** 97
[9] NIST Chemistry WebBook, Webbook.nist.gov.uk/chemistry 69 (2003)
[10] Maki S, Oda Y and Ataka M 2004 *J. Cryst. Growth* **261** 557
[11] Uyeda C, Yamagishi A and Date M 1988 *J. Phys. Soc. Japan* **57** 3954
[12] Cowley M D and Rosensweig R E 1967 *J. Fluid Mech.* **30** 671
[13] Zelazo R E and Melcher J R 1969 *J. Fluid Mech.* **39** 1
[14] Rosensweig R E 1985 *Ferrohydrodynamics* (Cambridge: Cambridge University Press)
[15] Gailitis A 1977 *J. Fluid. Mech.* **82** 401
[16] Catherall A T, Benedict K A, Eaves L and King P J 2003 *Phys. Rev.* E **68** 037302
[17] Takeda M and Nishiagi K 1992 *J. Phys. Soc. Japan* **61** 3631
[18] Takeda M and Nishiagi K 1994 *J. Phys. Soc. Japan* **63** 1345
[19] Rosensweig R E 1966 *AIAA J.* **10** 1751