Vertical Flotation of particles in a paramagnetic fluid

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Abstract

Hirota et al. (2004) found that the magneto-Archimedes force could be used to levitate biological materials at different heights in pressurized oxygen, providing the possibility to separate them. However the magnetic levitation of mineral particles has not been widely explored. With this in mind some preliminary experiments were performed by levitating pure mineral materials in a paramagnetic solution manganese (II) chloride. Besides the report of levitation heights of various mineral particles in manganese (II) chloride solution, the lines obtained from the basic formula provided by previous researchers were compared with experimental data. The act of cryogenic paramagnetic fluid in the magneto-Archimedes levitation was also demonstrated. The obtained results are compared with the same particle levitation heights in manganese (II) chloride solution.

Keywords: magneto-Archimedes; levitate; shape; cryogenic

1. Introduction

As early as 1991, a water droplet, bismuth metal, antimony, plastic, wood, alcohol and acetone have been levitated successfully in air as the separation medium [2]. Among the levitated materials, the levitation of water needed the strongest magnetic field strength [2]. Graphite is one of the best choices for levitation because it has a larger diamagnetic susceptibility than most other materials and has a relative low density. Therefore a piece of graphite at room temperature can be levitated using powerful permanent magnets ($Nd_2Fe_{14}B$)

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in open air [3]. Copper has much higher density so it is very difficult to levitate in air even they were placed on as strong as the four blocks array permanent magnet [4]. When changing the magneto-Archimedes agent from air to dysprosium nitrate ($Dy(NO_3)_3$), a piece of copper could be levitated effectively [5]. Also it was found out that carbon, Si, and Ti were levitated at different positions in the separation medium 2.67 M $Dy(NO_3)_3$ using a standard laboratory electromagnet with magnet field strength 1.4T [5]. Hirota et al in 2004 successfully used magneto-Archimedes separation to separate biological materials [6].

In the presence of a background fluid, magneto-Archimedes levitation applies the buoyancy principle to the levitation in a magnetic field, which could be modified as shown by the following formula [7]:

$$\frac{\chi_0}{\mu_0} B \frac{dB}{dz} - \rho_0 g - \frac{\chi_f}{\mu_0} B \frac{dB}{dz} + \rho_f g = 0 \quad (1)$$

Where χ_0 and ρ_0 are the magnetic susceptibility and density of the levitating object respectively, χ_f and ρ_f are those of the background fluid. For the vertical direction magnet field gradient, the particle will endure four types of forces. Similar to wood in water, the particle in the media around it will receive a weight and buoyancy force provided by the media. Also the particle will be influenced by two further types of force, magnetic attraction and the magnetic levitation, which are related to the magnetic field strength. Here the levitation is known as the Magneto-Archimedes effect and the media called the Magneto-Archimedes agent [8-10].

Over the past decade a considerable amount of research has been conducted at the University of Nottingham on the levitation of particles under high magnetic fields and gradients [11-13]. This paper explores a new concept to separate particles with different density and magnetic susceptibility.

2. Experimental procedure

2.1 Materials

2.1.1 The preparation and properties of magneto-Archimedes agent fluid

The magneto-Archimedes solution used in this chapter is manganese (II) chloride solution. Different concentrations of manganese (II) chloride solution were prepared (ie, 2 M, 3 M and 4

M) by dissolving the manganese (II) chloride crystal in distilled water to get a clear pink solution.

The mass susceptibility of the manganese (II) chloride solution at 2 M, 3 M, 4 M can be obtained by calculation from Andres (1976) [14], which stated that the mass susceptibility of an aqueous solution of a paramagnetic salt could be obtained from the formula below[14]:

$$\chi_{total}=C_{salt}\chi_{salt} + (1-C_{salt})\, \chi_{water} \quad (2)$$

$$C_{salt} = \frac{m_{salt}}{m_{total}} \quad (3)$$

$$k = \rho\chi * 4\pi * 10^{-3} \quad (4)$$

The corresponding volume magnetic susceptibility of 2 M, 3 M and 4 M manganese (II) chloride solution were calculated and summarised in **Table. 1**.

2.1.2 The preparation and properties of pure mineral samples

In this research, various pure minerals and experimental materials were investigated. The minerals included pyrite, quartz, calcite, chalcopyrite, dolomite, galena, goethite, hematite, rutile, sphalerite and wolframite. Other materials were also used such as sand and glass. In **Table. 2**, the chemical form and mass magnetic susceptibilities were obtained from Gregory Bottley and Lloyd, [14] and [19]. The density were measured by Accupyc 1330 Helium pycnometer and the volume magnetic susceptibility were achieved by Formula (4). They were initially broken by a hammer, sieved to produce fine sized particles, and then dry screened to extract various size fractions for testing.

2.2 Superconducting Magnet

The experiments were performed using an Oxford Instruments Minimum Condensed Volume (MCV) superconducting magnet, which had a 5cm diameter open bore with the maximum magnet central field being about 17 Tesla in the magnet bore, and the maximum BdB/dZ field gradient about $\pm$ 1470 T^2m^{-1}. The picture of the superconducting magnet is shown in **Fig. 1a**. The maximum field strength position is about 19 cm down into the bore from the top plate of the superconducting magnet. The magnet field strength plot is shown in **Fig. 1b**.

2.3 Design of Experimental Procedure

2.3.1 Classical magneto-Archimedes levitation

To investigate vertical direction magnetic levitation, a small circular container was placed inside the superconducting magnet bore centre hole. The container was made of glass with an internal diameter of 23 mm and height of 85 mm and was filled with about 35 ml of manganese (II) chloride solution. This container was set on a small plate about 2 cm below the top surface of the superconducting magnet as shown in **Fig. 2** below.

2.3.2 Comparison of the levitation positions of different pure mineral particles

The levitation heights of the minerals in manganese (II) chloride solution were recorded using the same container for comparison under different magnetic field strengths. In addition the effect of solution density on levitation was assessed by adjusting the concentrations of the manganese (II) chloride solution.

2.3.3 Experiments to confirm the magneto-Archimedes formula

As mentioned, the levitation of objects should satisfy the condition in formula (5).

$$V\rho_P g - V\rho g - \left(\frac{k_p VBB'}{\mu_0} - \frac{kVBB'}{\mu_0}\right) = 0 \qquad (5)$$

In this formula,

$$BB' = \frac{(\rho_p - \rho)g}{k_p - k}\mu_0 \qquad (6)$$

As the materials which can be levitated in the fluid always have much lower magnetic volume susceptibility so the k_p can be ignored in comparison to k**.** Then the formula (6) can be displayed as below.

$$BB' = \frac{\mu_0 g}{k}(\rho - \rho_p) \qquad (7)$$

So if BB' is set as the y-axis and ρ_p as the x-axis then the slope $\frac{\mu_o g}{k}$ and ρ can be determined from **Table. 1**. The line to satisfy Formula (7) can be achieved based on a known magneto-Archimedes fluid such as 2M manganese (II) chloride solution. The experimental data of BB' to allow the particles with different densities levitated in 2 M manganese (II) chloride solution were marked in the graphs and compared with the line obtained by the formula using 2M manganese (II) chloride solution as agent fluid.

2.3.4 Effect of the shape of the container

Based on the findings above that the particles were repulsed to the wall of the container, the shape of the container was changed to elliptical. The influence of the geometry on the vertical direction magnetic levitation experiment was recorded in **Fig.13**.

2.3.5 The liquid oxygen and the mixture of liquid oxygen and nitrogen

Because the oxygen molecule has two unpaired electrons in the anti-bonding $2\pi g$ orbitals and they form a spin triplet so that the oxygen has quite strong paramagnetic property [11]. Liquid nitrogen does not have any paramagnetic property. So in this section, the act of 100% liquid oxygen and the mixture fluid as magneto-Archimedes agent were investigated at vertical direction magneto-levitation. The composition of the mixture fluid is mainly based on the idea about the composition of the air. So the composition of the mixture fluid was set to 25% oxygen and 75% nitrogen in volume which is quite close to the air composition (22% oxygen and 78% nitrogen).

3. Results and Discussion

3.1 The classical magneto-Archimedes levitation

Initial observations, with a single particle size fraction (ie, 212 μm), indicated that the particles formed a ring against the container wall as shown in **Fig.3**.

When two different mineral particle species were present, according to their different mass magnetic susceptibility and/or different densities, they will be floating at different height positions in the tube so that can be separated clearly. A photograph of this is shown in **Fig.4**.

Fig.4 shows a top ring of quartz particles and a lower ring of pyrite particles, which are clearly separated. It was considered that this could provide a basic method to separate mineral particles in the vertical direction. The results were consistent with the conclusions obtained by previous work [2, 20, 7, 6]. The levitation positions of the particles remained static in relation to the top surface of the magnet even if the container was moved up or down. So the distance from the magnet top to the levitation position of the particles was fixed when the field strength was constant. The particles size range examined in this experiment was 212 µm - 1.2 mm and 53 µm – 106 µm in diameter. It was found out that the levitation positions were also independent from the particle size mentioned above. It only depended on the field strength, particles and agent fluid magnetic susceptibility.

The reason why the particles were repulsed to the tube wall is that the manganese(II) chloride solution is paramagnetic and stand a force which attracted them to the magnet bore centre which is a hole in our superconducting magnet equipment.

The particles in the fluid faced a corresponding opposite force and be repulsed to the tube wall (Fig.16)

3.2 Comparison of the levitation positions of different pure mineral particles

The results of the levitation positions of the different particles at different field strengths are shown in **Fig.5**, **Fig.6** and **Fig.7** below.

Because the platform which held the tube was about 2 cm below from the top of the magnet, the Y-axis, which states the height above the magnet, starts from -1 cm to almost the height of the bottle which is about 8 cm. As can be seen in **Fig.5** the higher the field strength, the higher the particles levitate. Also the particles with different mass susceptibility levitated at different positions in the bottle. For the dolomite and calcite materials, as the magnetic field strength increased, the difference between the two materials levitation positions seems decreased. For the pyrite and rutile materials, as the magnetic field strength increased, the two materials become separated more effectively. The same condition happened to dolomite and sphalerite particles.

It is shown in the **Fig.5** that the particles with similar density e.g quartz, calcite and dolomite, the levitation positions are the quartz particles occupy the highest position, calcite particles the second and dolomite particles the third. It follows that for particles with similar density, the magnetic susceptibility is the main factor to decide their levitation positions. These results are similar to results obtained by Ikezoe et al. (2002) [7].

Fig.6 and **Fig.7** are similar to the **Fig.5** using different concentrations of manganese (II) chloride solution (3M and 2M). They show as the concentration of the manganese (II) chloride solution decreased, the height of the particles float lower. And it was more difficult for the particles to be levitated at relatively lower B_c.

Fig.8 illustrates the positions in which the different minerals levitate in 4M manganese (II) chloride solution. Vertical direction magneto-Archimedes levitation can be applied to separate mineral particles. The densities of particles have bigger difference, the gaps of the levitation heights were bigger so that the separation is more effective.

From Formula (1) in this paper, we can see that the different mineral particles levitation positions depends on the combined effect of density and mass magnetic susceptibility (x). In **Fig.8** the particles with similar densities stay together e.g quartz particles (density 2644 kg/m^3) and calcite particles (density 2710 kg/m^3) or sphalerite particles (density 4000 kg/m^3) and rutile particles (density 4200 kg/m^3). Mineral particles whose density have the largest difference such as dolomite particles (density about 2974 kg/m^3) and sphalerite particles (density about 4000 kg/m^3) separate well and the levitation positions have the largest gap.

From **Table 2** in this paper, the particles with similar magnetic mass susceptibility (x) are quartz(χ_p = -5.7 X 10^{-9} (m^3.kg^{-1})) , calcite(χ_p = -3.8 X 10^{-9} (m^3.kg^{-1})), galena (χ_p = -4.4 X 10^{-9} (m^3.kg^{-1})) and sphalerite (χ_p = -3.3 X 10^{-9} (m^3.kg^{-1})) particles. In **Fig.8** , quartz and calcite particles were levitated at similar positions, because these two mineral particles still have similar densities (quartz density 2644 kg/m^3, calcite density 2710 kg/m^3). Galena, sphalerite particles were levitated at very different positions although they have similar magnetic mass susceptibility, because they still have different densities (galena density 7230 kg/m^3 , sphalerite density 4000 kg/m^3).

The effect of particle density has bigger influence than the effect of particle magnetic mass susceptibility.

For the quartz particles, the gap between the levitation positions at B_c=8 and 9T is the largest which can be seen from **Fig.9**. As the magnetic field strength increased, the gap between the levitation positions decreased. For the same particles the higher magnet bore centre field strength, the higher particle levitation position in the magneto-Archimedes agent manganese (II) chloride solution.

3.3 Experiments to confirm the magneto-Archimedes formula

To achieve the magneto-Archimedes levitation, the Formula (6) should be satisfied. The slope of the formula $\frac{\mu_o g}{k}$ and the y-axis intercept $\frac{-\mu_0 g \rho}{k}$ can be obtained based on the chosen fixed magneto-Archimedes agent fluid so that the line to the Formula (6) can be draw out.

In **Fig.10**, the circles or triangles mean the experimental data of the magnet field gradient BB' according to the different particle density ρ_{p} and the line is obtained from the magneto-Archimedes formula based on the fixed magneto-Archimedes agent solution. **Fig.10** shows that the formula line is quite close to the experimental data. **Fig.10** confirms that the Formula (5) and (7) are reasonable and can be used in future experiment and for design purpose. The similar results about 3M manganese (II) chloride and 4M manganese (II) chloride which are **Fig.11** and **Fig.12** are showed below.

3.4 The effect of the shape of the container

Fig.3 illustrates that streams of mineral particles with small size fraction were repulsed to the wall of the container when they were dropped into manganese (II) chloride solution. To confirm the phenomenon, the shape of the container was changed. **Fig.13** shows the influence of the geometry factor to the repulse of the particles to container wall.

It is confirmed again that the particles in magnet field got an outward centrifugal force so that can be repulsed to the wall of the container. At the same time, the particles with different density and magnetic volume susceptibility were levitated at different positions.

3.5 The cryogenic liquid acts as a magneto-Archimedes agent solution

Fig.14 shows the levitation positions of different pure mineral particles in 100% liquid oxygen. Compared with 4 M manganese (II) chloride solution, the levitation heights of the minerals in 100% liquid oxygen were much higher. Even the hematite and chalcopyrite particles which have relatively stronger paramagnetic properties can be levitated. It can be confirmed again that by increasing the paramagnetic properties of the surrounding magneto-Archimedes agent solution, paramagnetic objects in it can be levitated.

Fig.15 shows the levitation positions of different pure mineral particles in the mixture of 25% liquid oxygen and 75% liquid nitrogen. The levitation heights of the same minerals in mixture of 25% liquid oxygen and 75% liquid nitrogen were lower than in 100% liquid oxygen but still higher than in 4 M manganese (II) chloride solution. But the increase of the levitation heights of the particles from B_c=10 T to B_c=16 T in 4 M manganese (II) chloride solution is more significant than in the mixture fluid.

Liquid oxygen is paramagnetic, liquid nitrogen does not have any paramagnetic property, perhaps the liquid oxygen molecule moved following the magnetic strength line, accumulated and formed an enriched zone, so when $14<Bc<15$, glass or bronze particles levitation positions appeared a sharp increase.

But we still can conclude that for most particles, the increase in Bc cannot help the separation.

4. Conclusions

In this paper, mineral particles were levitated in the magneto agent manganese (II) chloride. And the mineral particles with different density and magnetic volume susceptibility were levitated at different heights similar to the results obtained previously by others [2, 20,7,6].

It was confirmed that the difference of the particle densities is more significant, the more effective the separation will be. It is concluded the particles levitation heights were higher when the magnetic field strength is stronger. Besides that, the formula line obtained from previous researchers and experimental data were compared as well. It proves that the Formula (5) can be used for later check and design purpose for the object levitation in the magneto-Archimedes agent solution.

Compared with other chemical solutions, the manganese (II) chloride solution is stable, cheap and has a stronger paramagnetic property. However, this solution is toxic, so a new kind of cryogenic liquid which is composed of liquid oxygen was investigated. It is found out that the pure liquid oxygen has a stronger paramagnetic property than the mixture of liquid oxygen and liquid nitrogen. The levitation positions of particles were higher in pure liquid oxygen than the mixture fluid at corresponding magnet bore centre field strength.

Compared with the solution 4 M manganese (II) chloride, the levitation positions for the same particles are much higher in pure liquid oxygen. The levitation positions are somewhat lower in 4 M manganese (II) chloride than the mixture of liquid oxygen and liquid nitrogen. The cryogenic liquid which is similar with the composition of liquid air, can effectively separate most kinds of pure mineral particles. It has low viscosity, strong paramagnetic property, and is atmosphere friendly. As the cryogenic liquid was easy to be vaporized so the particles separated from the liquid were very dry. In conclusion, the liquid air provides a potential possibility to act as the magneto-Archimedes agent in future.

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NOMENCLATURE

Variables

B	the magnetic induction field strength	(T)
B'	vertical direction magnetic field gradient	(T/m)
C_{salt}	mass percentage of salt in the total mass	(-)
g	the acceleration of gravity	(m/s^2)
k	volume magnetic susceptibility	(-)
k_1 (or k_p)	mass susceptibility of the levitating substances	(-)
k_2 (or k_l)	mass susceptibility of the medium gas (or liquid)	(-)
m	the mass of the particle	(kg)
V	particle volume	(m^3)
X	mass magnetic susceptibility	(m^3/kg)
μ_0	the permeability of free space	(H/m)
ρ	mass density	(kg/m^3)
ρ_1	the density of the levitating substances	(kg/m^3)
ρ_a	the apparent density of liquid	(kg/m^3)
ρ_2 (or ρ_l)	density of medium gas (or liquid) around it	(kg/m^3)
ρ_L	actual density of liquid	(kg/m^3)
$\frac{dB}{dz}$	vertical direction magnetic field gradient	(T/m)

Table.1: The density and volume magnetic susceptibility of different concentrations manganese (II) chloride solution

Solution	Density ($kg.m^{-3}$)	k X 10^{-6}
2 M Manganese(II) Chloride	1227	345
3 M Manganese(II) Chloride	1301	502
4 M Manganese(II) Chloride	1395	660

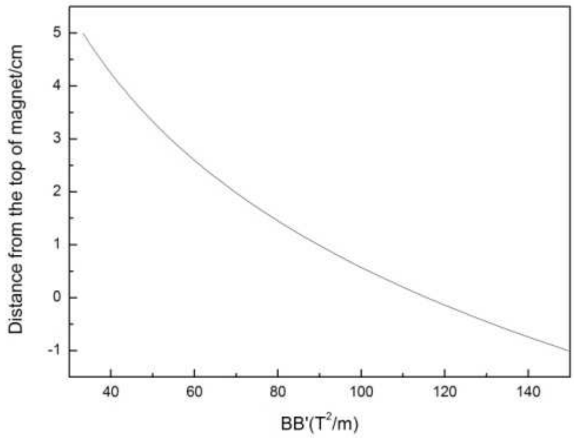
Table.2: The density, volume susceptibility and mass susceptibility of different materials (Andres, 1975; Hunt et al., 1995; Gregory Bottley and Lloyd)

Materials	Chemical Form	Density ($kg.m^{-3}$)	k_pX10^{-6}	χ_p X 10^{-9} ($m^3.kg^{-1}$)
Pyrite	FeS_2	4654	314	67.5
Quartz	SiO_2	2650	-15.1	-5.7
Calcite	$CaCO_3$	2710	-10.3	-3.8
Chalcopyrite	$CuFeS_2$	4250	6783	1596
Dolomite	$CaMg(CO_3)_2$	2974	45	15.1
Galena	PbS	7230	-31.8	-4.4
Goethite	$HFeO_2$	4300	1075-1634	250-380
Hematite	Fe_2O_3	5245	2622-19931	500-3800
Rutile	TiO_2	4200	50-210	12-50
Sphalerite	ZnS	4000	-13.2	-3.3
Wolframite	$(MnFe)WO_4$	7000	2660-8400	380-1200
Glass/Sand	(-)	2650	(-)	(-)

List of Figures

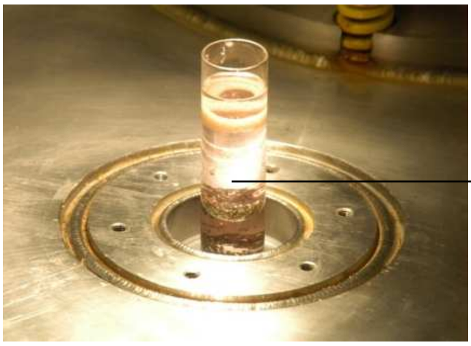
All the colour figures are intended for colour reproduction on the web and black-and-white in print.

a. MCV magnet system



b. BB' Vs distance from the top of magnet

Fig. 1: MCV magnet system used in experiments



The vessel on the platform in the magnet bore hole

Fig. 2: The vessel in the magnet bore centre hole

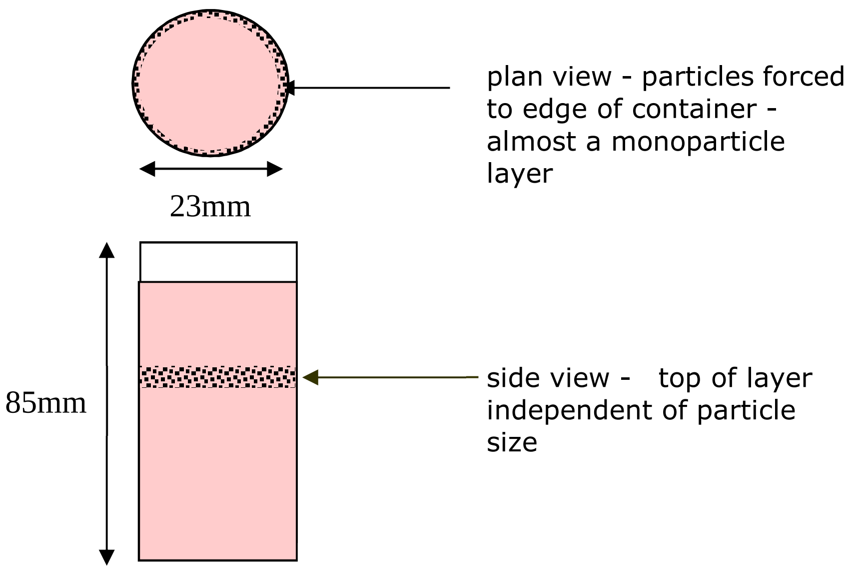


Fig. 3: Schematic of ring formation of pyrite particles levitating in a manganese (II) chloride solution

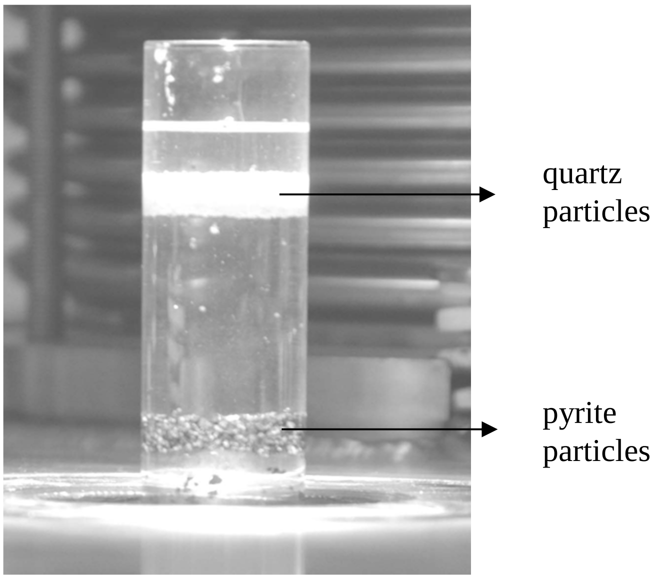


Fig.4: The photograph of quartz and pyrite particles levitated in 4 M $MnCl_2$ solution in a column container under B_c=16.5 T

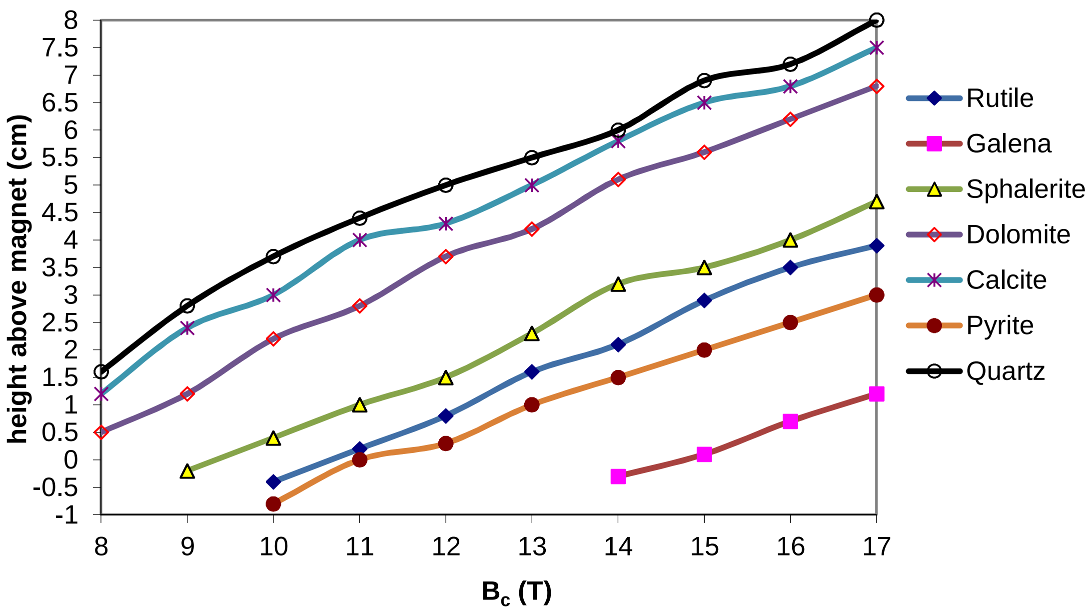


Fig. 5: The different levitation heights at different field strengths in 4M manganese (II) chloride solution

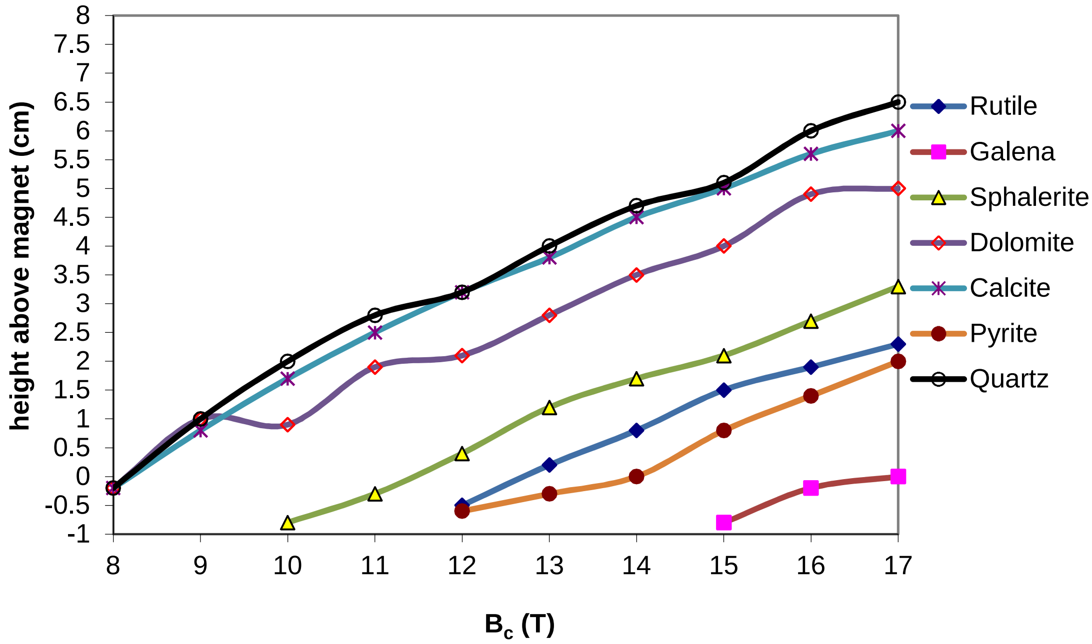


Fig. 6: Floating heights of minerals above the magnet bore in 3M manganese(II) chloride at various values of B_c

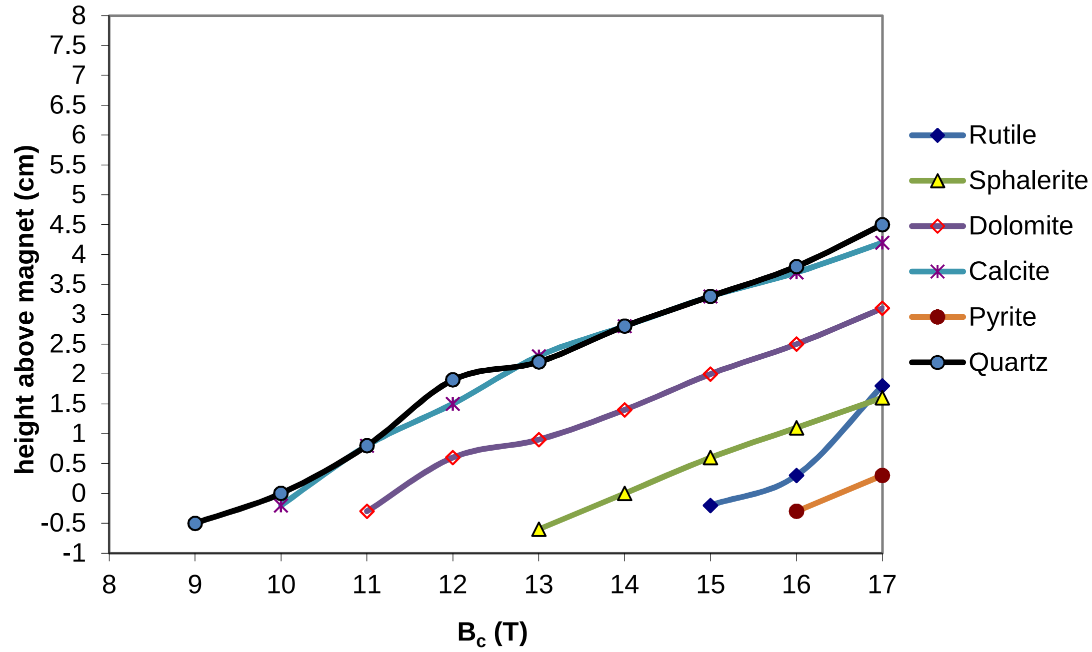


Fig. 7: Floating heights of minerals above the magnet bore in 2M manganese(II) chloride at various values of B_c

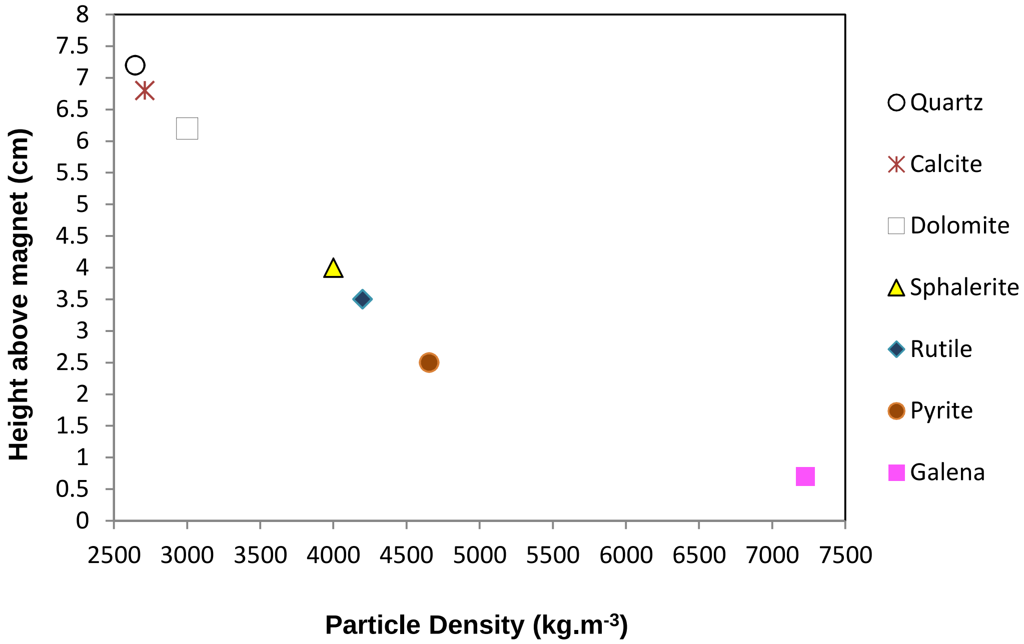


Fig. 8: The levitation positions of the particles with different density in 4M manganese (II) chloride solution at B_c=16 T

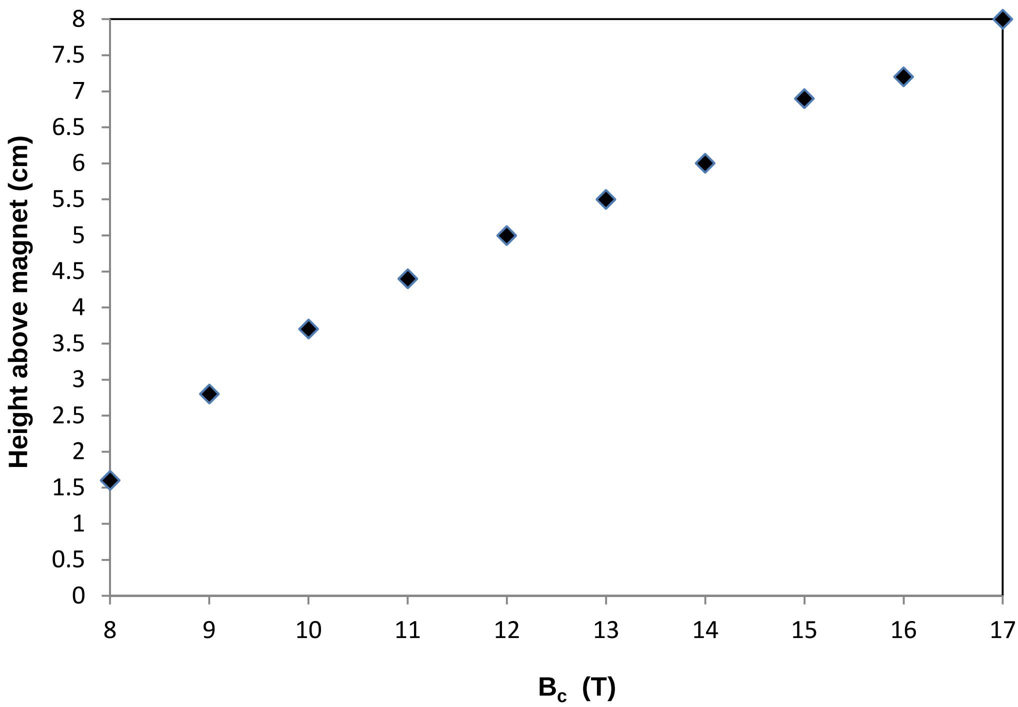


Fig. 9: The levitation positions of quartz particles at different B_c in 4 M manganese (II) chloride solution

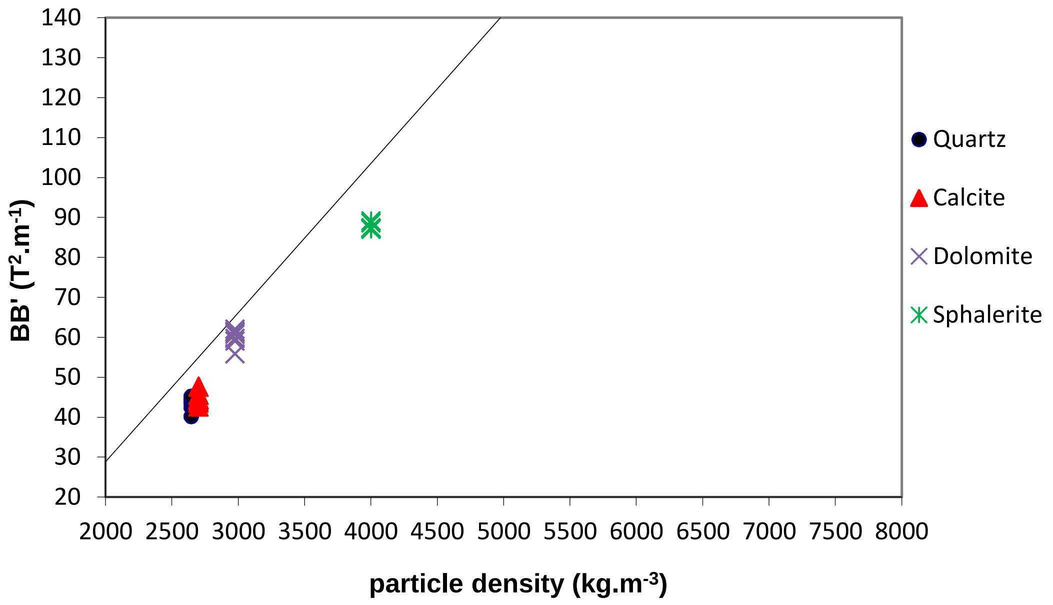


Fig. 10: The comparison of the line obtained from independently-measured values of ρ and κ and plot of experimental BB' against particle density for 2M manganese (II) chloride

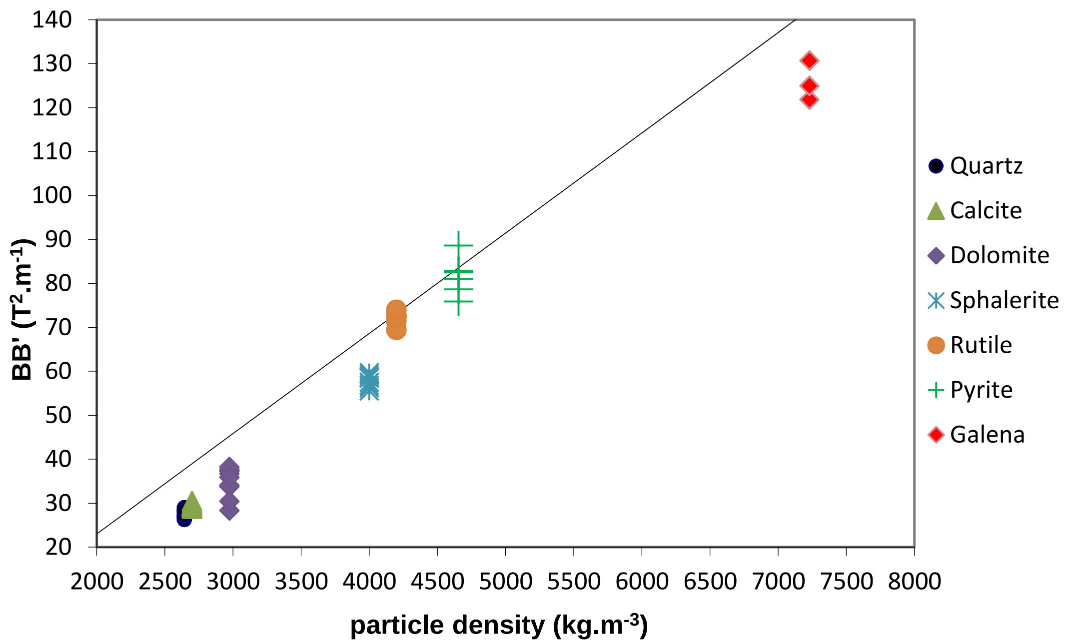


Fig. 11: Plot of experimental BB' against particle density for 3M manganese (II) chloride, compared with the line obtained from independently-measured values of ρ and κ

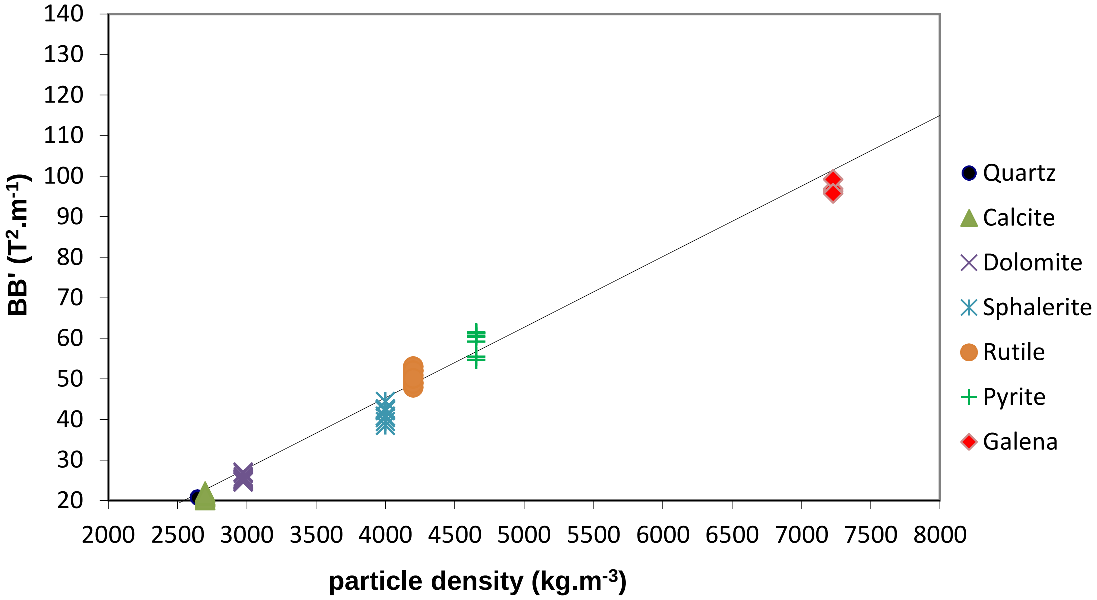


Fig. 12: Plot of experimental BB' against particle density for 4M manganese (II) chloride, compared with the line obtained from independently-measured values of ρ and κ

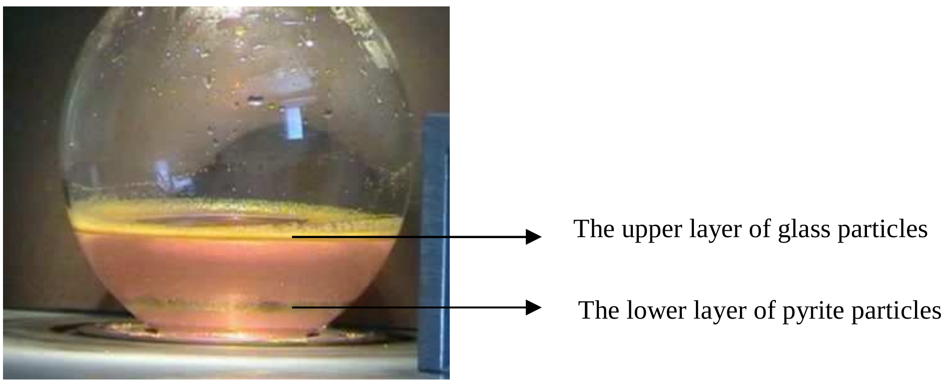


Fig. 13: The levitation of glass and pyrite particles in elliptical container in 4 M $MnCl_2$ solution

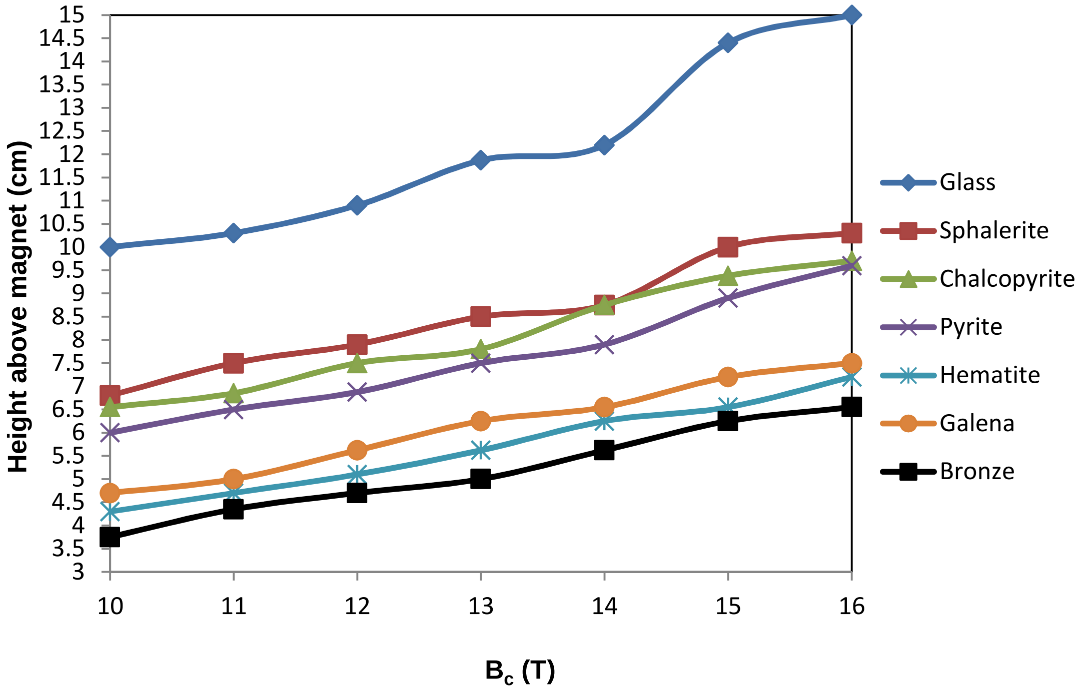


Fig.14: The different pure mineral particles levitated at different positions in 100% liquid oxygen at different B_c

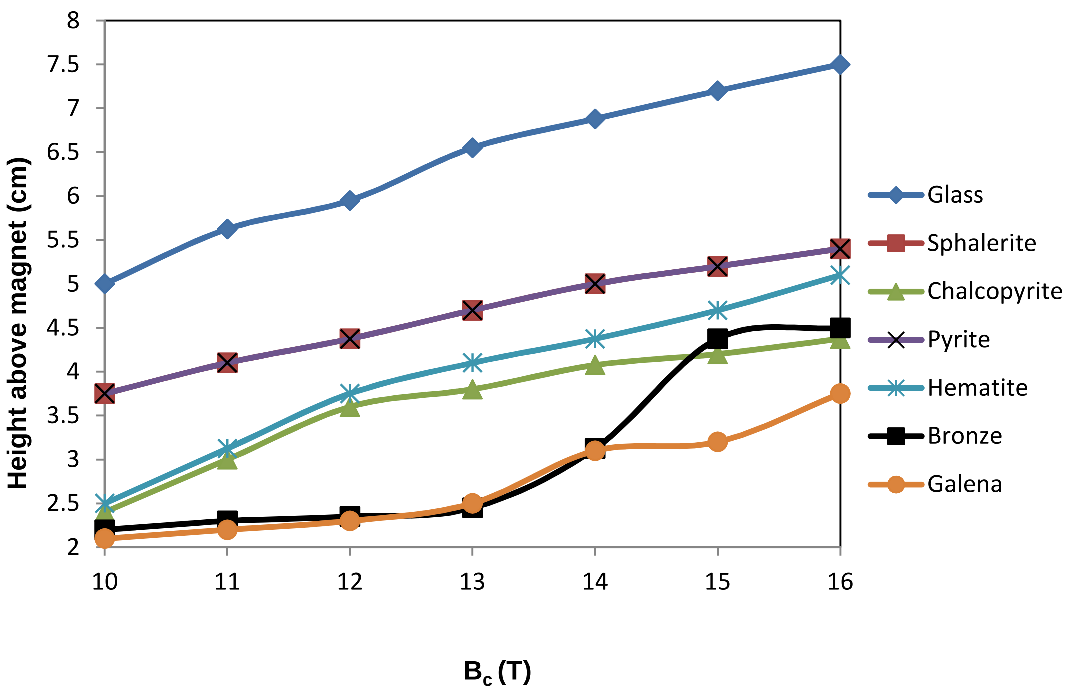


Fig. 15: The different pure mineral particles levitated at different positions in the mixture of 25% liquid oxygen and 75% liquid nitrogen in volume at different B_c