Role of air pressure in diamagnetism

Hamid V. Ansari
Department of Physics, Esfahan University, Esfahan, Iran
Personal address: No. 16, Salman-Farsi Lane, Laleh Street, Esfahan, Postal Code 8198636631, Iran
Email: hamid.v.ansari@gmail.com
Web Site: https://sites.google.com/site/scientificpapersofhamidvansari

January 23, 2012
KEYWORDS: Diamagnetism; Archimedes; Ferrofluid; Magnet; Levitation; Lenz' law
PACS: 75.20.-g; 51.60.+a; 75.20.En; 75.20.Ck

Abstract

In a gradient of magnetic field, magnetic dipoles of air are attracted toward the region of intense field. So, the air pressure is more in the regions of more intense field. The formed pressure gradient exerts a net force on a body placed in the air in this gradient of magnetic field toward the region of low pressure or the region having weaker field. This is like what takes place in the process of sink-float separation.

1 Introduction

As we know all substances have diamagnetic property, ie are repelled from a region of intense magnetic field. To show this interesting and nearly strange behavior, many experiments have been performed by the physicists [1] some of which have gained spectacular state (like the levitation of different substances, eg a frog, above an intense gradients of magnetic field [2].

This fact that a substance is attracted toward the region of intense magnetic field is easily justified by this assumption that the molecules of the substance are in fact magnetic dipoles which are attracted toward the region of intense field in a gradient of magnetic field. But, this fact that substances are repelled from the region of intense field in such a gradient is not justified with that ease. What is presented in all of the textbooks (eg see [3-12]) for justifying this phenomenon is applying Lenz' law in atomic scale. Shortcomings of this justification have been investigated in this article, but before that, a reason for this phenomenon has been presented which is based on the existence and role of the gaseous medium (eg air) in which the experiment is performed. This reason seems very evident and esp is easily verifiable by performing simple experiments.

2 Diamagnetism and air pressure

In a gradient of magnetic field in air, a net force is exerted on each molecular magnetic dipole of air toward the region of more intense field, because due to the torque exerted on the dipole, it turns and its axis will coincide with the line of magnetic field in such a manner that the force exerted on the pole placed in the region of more intense field is toward the region of more intense field and is bigger than the force exerted on the other pole which is toward the region of weaker field. In this manner, some net forces toward the region of more intense field will be exerted on the air molecules which pull them toward this region. These pulled dipoles (or molecules) will be pressed against the body of the magnet or will face, in a solenoid, the pressure of the dipoles pulled inward from the other end of the solenoid and in any case their pull will cease by reaction of the leaning surface and, in return, air molecules will be pressed, ie the air pressure will increase as we enter the region of more intense field. Such a pressure difference must be measurable by a proper pressure gauge.

The situation is quite similar to the gravity exerted on the water molecules which causes the water pressure to increase by going toward the region being pointed by the gravity exerted on the water molecules, ie the earth center. Therefore, as an upward force will be exerted on a body placed in a volume of water due to the difference in pressures at lower and upper parts of the body, in a gradient of magnetic field, there exists a force on a body placed in this gradient toward the region of low pressure or the region of weak field due to the above-mentioned pressure difference. If this is the real cause of diamagnetism, it is expected that by performing the experiment in a perfect vacuum, the mentioned pressure difference to disappear practically and in practice there exists no longer exertion of any net force on the body toward the region of weaker field. (For example the above-mentioned frog no longer will levitate over an air pad on the solenoid because there won't be any (pad) air in perfect vacuum.) Result of the performance of such an experiment can test the validity of this theory.

In summary, this article proposes that a fluid like air, when being attracted into a region of high magnetic field gradient, will create a net force on any material immersed in it which tends to expel it from the field gradient. This expulsion in such fluids is a well-known phenomenon (being used for some techniques of magnetic separation), but what is important here is that this article shows that the existence of such a fluid is necessary for such an expulsion while the current theory of diamagnetism doesn't see existence of it necessary for considerable repulsion of the materials from the region of high magnetic field. The above-mentioned well-known industrial phenomenon is sink-float separation by applying ferrofluids. Since the process used in this phenomenon is exactly the same one stated here for justifying diamagnetism, we explain it here:

One way to separate a mixture of fragments of different materials having different dimensions is pouring them into a liquid and applying Archimedes' law. According to this law, which is obtained easily, regardless of its volume, each fragment having density ρ will have an acceleration equal to $g - (\rho'/\rho)g$ when being immersed in a liquid having density ρ' in which g is the gravity acceleration. Thus, when pouring fragments of different materials into the liquid, all fragments having the same density will have the same acceleration when settling. This fact can be used in separation of different materials. But, in practice this method is not so useful for separation of heavy (metallic) materials, because for them ρ is considerably bigger than ρ' even if the densest usable liquid is used, and then $g - (\rho'/\rho)g$ will not be sufficiently smaller than g. A solution to this problem is substituting a greater acceleration for the g in the second term of $g-(\rho'/\rho)g$ instead of trying to increase ρ'/ρ considerably. In other words, suppose that there exists an additional constant force, other than the gravitational force, which is exerted on each molecule of the liquid in the same direction of the gravity, such that this force is not exerted also on the molecules of the bodies placed in the liquid. So, in the process of obtaining Archimedes' law for this new situation, we will have $g - (\rho'/\rho)g'$ for the acceleration of the fragments having density ρ in which g' is the acceleration due to both the gravity and the above-mentioned additional force. It is clear that depending on the largeness of this additional force, the acceleration $g - (\rho'/\rho)g'$ can be very smaller than g.

This procedure is an approximation to what takes place in sink-float separation. In this method, instead of common liquids we use a ferrofluid that firstly its density is more than many other liquids (because of the presence of tiny ferromagnetic metallic particles in it), and, much more importantly, secondly, when we set this ferrofuid on a solenoid in an intense gradient of magnetic field, separate from the gravity, it will pull strongly downwards the ferromagnetic tiny particles suspended in (and adherent to the molecules of) the liquid while this force won't be exerted also on the bodies (or fragments) inside the liquid which are not paramagnetic or ferromagnetic and we want to separate them from each other. In simple words, such a mechanism creates a considerable great pressure inside the liquid which can be observed by a simple pressure gauge.

An explanation about Ferrofluid: Presently, ferrofluids are produced industrially in such a manner that sufficiently tiny particles of ferromagnetic materials have been coated with sufficiently light materials such that the volume of the particle and its coat is so big that the weight of the particle and its coat equals the weight of the displaced liquid resulting in suspension of particles in the liquid. This suspension and the molecular attraction between the coats of these particles and the molecules of the liquid and that, due to their much smallness, these particles have thermal fluctuation, give ferrofluids the specifications of real physical liquids. Smallness of the particles and strong attraction between their coats and the molecules of the liquid have so much importance in giving the ferrofluid a homogeneous state as a real liquid, because if the particles are tinier we can increase the number of them used in the carrier liquid in order that fill all spaces empty of these particles and so decrease the distances between these particles and the surrounding molecules to such extent that, considering strong attraction between the molecules and the coats of the particles, all of the molecules of the liquid will be in the domain of attraction of the coats of the particles. Therefore, the situation will be such that we will have a pile of molecules attached to each particle under the influence of the strong attraction between each molecule and the coat the particle, and there will be no molecule not attached in this manner to a particle. In this manner, indeed we will have a new (real) liquid which each of its molecules is the above-mentioned complex consisting of a particle and a pile of molecules of the carrier liquid attached to it. It is clear that if the particles are tinier these new molecules (or in fact complexes) will also be smaller and so the whole fluid will be more similar to a real liquid.

3 Examination of the current theory

At first, let's see, in simple language, what Lenz' law is. Suppose that in an inertial right-handed cartesian coordinate system of xyz, a loop of narrow copper wire has been set in the xz plane such that its center is the center of coordinate system, O. Also, suppose that the N pole of a magnet is moving toward O on the positive section of the y-axis. A force in the direction of $-\hat{\imath}$ will be exerted on an electron in the wire at the intersection of the loop and the positive section of z-axis which makes it move in this same direction and electron will flow in the wire. Motion of the electron in the direction $-\hat{\imath}$ in the vicinity of the pole N, which we suppose it motionless for simplicity, will exert a force in the direction $-\hat{\jmath}$ on it. Since this force is normal to the loop plane and the loop is rigid, there will be no way for flowing of the electron in this direction and this force will be exerted on the whole loop in the direction of $-\hat{\jmath}$. Namely, by entrance of N into the loop, a force in the same direction of the motion of N will be exerted on the loop (and its reaction force is an opposite force being exerted on the pole N).

If, instead of the above situation, motion of N be at first in the direction of going away from the loop, the force exerted on the electron is in the direction of $\hat{\imath}$, and by flowing and motion of the electron in this direction in the vicinity of N a force in the direction of $\hat{\jmath}$ will be exerted on it which, because of the rigidity of the loop and that there is no way for flowing of the electron in this direction, this force will be exerted directly on the rigid body of the loop in the direction of $\hat{\jmath}$; ie when N moves away from the loop, there will be a force exerted on the loop in this same direction of moving away. It is obvious that if N is motionless relative to the loop, there won't be any force exerted on the loop.

What is considered at present for justifying diamagnetism is using this same Lenz' law in atomic scale. Namely, motion of the electron around the nucleus of atom is considered in a circuit similar to a circuit mentioned above, and it is said that according to the above analysis if N comes near to the loop, a force directed to getting away from N, ie in the direction of $-\hat{j}$, will be exerted on the loop (or in fact on the atom). But, this justification has some weaknesses:

Firstly, the circuit of the motion of electron about the nucleus is not rigid to cause the force to be exerted on the whole atom in the direction of $-\hat{j}$. In other words, the force exerted on the electron in the direction of $-\hat{j}$ in the above analysis in the atomic scale can make the electron flow in this same direction rather than being exerted on the rigid body of the loop in this direction repelling the body from N.

Secondly, as the above analysis shows, Lenz' law necessitates that when N is moving away from the loop, the loop is attracted to N, while in diamagnetism this is not the case that by making the magnetic pole away from the body the body is pulled toward the magnet.

Also, in Lenz' law, if N is motionless relative to the loop, no force is exerted on the loop, while in diamagnetism, always, even in a stationary state, there is a force, exerted on the body, toward the region of weaker field.

4 Experimental points

1. Select a powerful permanent magnet (eg from a drive of a computer). Select a small bit of every substance you like out of all substances categorized (presently) as diamagnet, for instance a bit of a narrow copper wire. Make each of these selected small bits of (diamagnet) substances near to a pole of the mentioned selected powerful magnet. You will observe easily that all of them will be attracted to the magnetic pole NOT be repelled form it! This is because firstly the molecules of every substance acts like a tiny magnetic dipole which is attracted toward the intense gradient of a powerful magnetic field and secondly the volume of each small bit is not sufficiently big to let the above explained repulsive Archimedes' force overcome this attraction.

2. To perform the experiment of diamagnetism in vacuum we must notice that if the intense magnetic field exists before creating the vacuum, it will cause the air molecules to be attracted to the poles (causing increase in the air pressure there) and even after evac-

uation of the container of the air molecules these molecules to remain attracted (or attached) to the poles (just like when the tiny particles of a ferrofluid remain attracted (or attached) to a magnetic pole as a pile, and by elimination of the magnetic field this pile flows downward due to its weight). In other words, by evacuation of the container of air, the air pressure near the poles will not decrease sufficiently, and this can cause insufficient and unnoticeable decrease in diamagnetism when the air of the container is pumped out. To avoid this situation, the air of the container is necessary to be evacuated first and afterwards the intense magnetic field is created and the phenomenon of diamagnetism is examined.

3. If you intend to verify diamagnetism by observing the speed of objects getting away from intense magnetic regions rather than observing levitation of objects over these regions, notice that existence of air molecules is an obstacle against objects in their getting away from intense magnetic regions. So, by reducing the air pressure (through evacuation), although the Archimedes' force, exerted on the objects, is also reduced, prevention of the air molecules against the movement is reduced too which this helps more acceleration of the objects. These two opposing factors may cancel each other or one overcome the other. To become sure that air resistance can not have practical effect on the experiment, the container of the experiment must become evacuated of air as much as possible.

4. According to theory presented here, the phenomenon of diamagnetism is expected to be more apparent for objects having less densities. (This is also the case for Archimedes' force.) So, it seems that if a small thin glass bulb is evacuated of air nearly completely, it will show this phenomenon better.

5 At the end

It is instructive to verify some experiments performed recently in the subject of diamagnetism and reported in a published article [13]. Let's repeat a part of the abstract of this article here: "Graphite has been known as a typical diamagnetic material and can be levitated in the strong magnetic field. Here we show that the magnetically levitating pyrolytic graphite can be moved in the arbitrary place by simple photoirradiation. It is notable that the optical motion control system described in this paper requires only NdFeB permanent magnets and light source." Performed experiments can be seen here [14]. Their relevant photos are shown in Fig. 1 and Fig. 2.

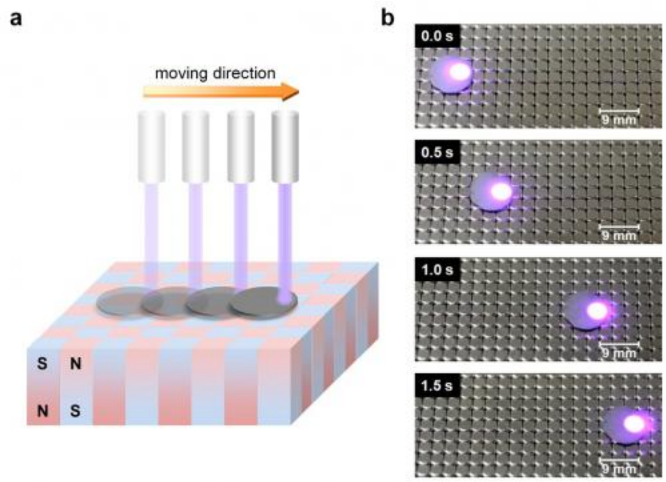

Fig. 1. (a) Experimental set-up of a 3-mm-diameter graphite disk levitating on NdFeB magnets arranged to face in alternate directions. (b) A laser moves the disk in the direction of the light beam (photographic frames from the video)

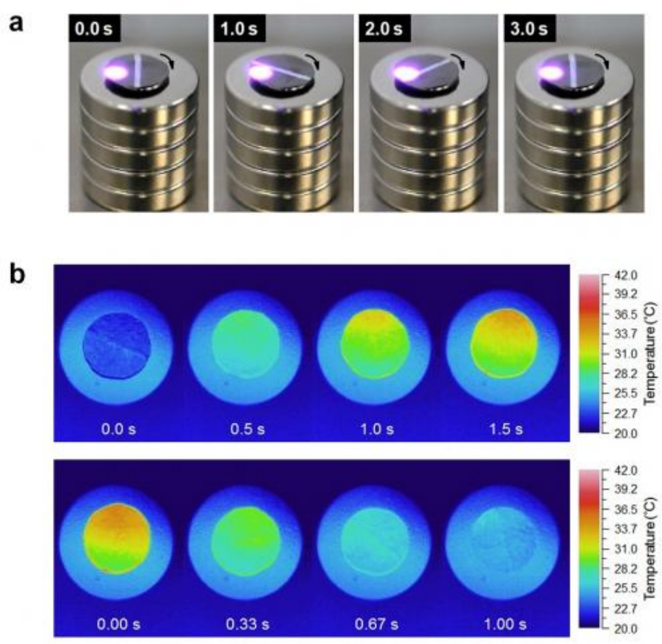

Fig. 2. (a) A laser causes a magnetically levitating graphite disk

to rotate (photographic frames from video). (b) The laser causes temperature changes in the graphite, as measured by infrared images of the disk when under laser irradiation (top) and after the termination of irradiation (bottom).

As we said, the real reason of diamagnetism is existence of a pressed pad of air molecules attracted to the strong magnetic poles. Based on this theory, we can justify the above-mentioned reported experiments well, as presented in the following. Arrange of the adjacent small permanent magnets in Fig. 1 is such that the air molecules make continuous strings of themselves each end of which is ended on a magnetic pole. In this manner, the above-mentioned air pad has a hilly structure above which the graphite disk can be placed with a stable equilibrium.

In Fig. 2, cylindrical magnet is used to give the mentioned air pad a circular symmetry, because we only want the disk to rotate about itself without any displacement. This air pad needs to have a bowl shape in order that the disk is placed in it to have a stable equilibrium.

A laser beam radiated on the center of the disk causes this center region to warm. This warmth is transferred to the adjacent air on the disk. This warmed air ascends. With its ascending, a partial vacuum is produced in this region into which cold air rushes from all surface regions around the center point. These (cold) air streams exert force on the disk due to their friction with the disk (top) surface. But, these forces cancel each other, because they have a uniform distribution around the center point of the disk. So, no acceleration is exerted on the disk. Such an acceleration will be created toward the laser spot, or the warmed spot, when the laser beam is radiated on a point near the edge of the disk (not on its center point), because in such a case the mentioned friction of the cold air will be exerted only on the bigger part of the disk (containing the center point) pushing it toward the laser spot.

And now, the mechanism of the rotation of the disk in the experiment of Fig. 2 is presented. Suppose that the disk is motionless placed above the mentioned air pad formed on the cylindrical magnet. If, in this state, the laser beam is descended on the center point of the disk and warms that point and then the air adjacent to this point, and so, causes this air to ascend, rush of cold air from the around of the center point will not exert any net force and so any acceleration on the disk (because of a reason similar to one presented before (related to Fig. 1)). But generally, such a complete motionless state does not exist in practice. Since the disk is suspended on air pad, the least disturbances can stir the disk (even so little). Thus, suppose that the disk is gently rotating (due to the same mentioned disturbances) before turning the laser on. Now, it is shown that after turning the laser on, while its spot is sideward, this rotation will be amplified in the same first direction of (the gentle) rotation. For a simple explanation in this respect, notice Fig. 3.

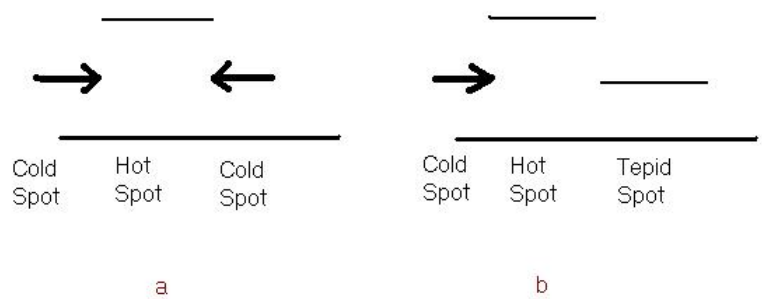

Fig. 3. The disk in Fig. a is motionless, while in Fig b, it is moving to right. Cold spot in Fig. b is the region that has not yet gone under the laser beam. (Arrow indicates cold wind.)

The place of the laser spot is warmed when the laser is turned on. Since the disk is gently rotating and passing beneath the laser beam, and since we also know the radiated point of the graphite holds the warmth gained during an (even small) interval of time without missing the whole of it immediately, after elapsing a time interval we will have an especial distribution of heat on that strip of the disk surface that has been passed beneath the laser beam. In this distribution we have the hottest point just under the laser beam while in adjacent points of the disk in the direction of rotation, the warmth is less (although is bigger than one of the cold points of the disk surface), because some heat has been missed when exiting the space just beneath the laser beam. Such a heat distribution causes the air adjacent to the laser spot, just under the laser beam, to be lighter than the air adjacent to other points of the disk while this lightness decreases gradually in the regions in the direction of rotation. So, it ascends more swiftly, and the partial vacuum created through this ascending is rushed by the cold winds blown chiefly from adjacent cold points that not yet have passed beneath the laser beam (rather than mild points that have passed recently beneath the laser beam). In this manner the (resultant) cold wind will push the disk in the same direction of its rotation.

References

[1] Edward M. Purcell, Electricity and Magnetism, McGraw-Hill, 1985

[2] David Halliday, Robert Resnick, Jearl Walker, Fundamentals of Physics, John Wiley & Sons, 2005

[3] John R. Reitz & Frederick J. Milford & Robert W. Christy, Foundation of Electromagnetic Theory, Addison-Wesley, 1993

[4] John David Jackson, Classical Electrodynamics, John Wiley & Sons, 1998

[5] Munir H. Nayfeh & Morton K. Brussel, Electricity and Magnetism, John Wiley & Sons, 1985

[6] Arthur F. Kip, Fundamentals of Electricity and Magnetism, McGraw-Hill, 1983

[7] I. S. Grant, W. R. Phillips, A. S. Grant, Electromagnetism, John Wiley & Sons, 1991

[8] David K. Cheng, Field and Wave Electromagnetics, Addison-Wesley, 1989

[9] Hugh D. Young & Roger A. Freedman, University Physics, Addison Wesley, 1996

[10] William H. Hayt & John A. Buck, Engineering Electromagnetics, McGraw-Hill, 2001

[11] Alvin Hudson & Rex Nelson, Saunders Colledge Pub., University Physics, 1990

[12] Marcelo Alonso & Edward J. Finn, Fundamental University Physics, Addison-Wesley, 1974

[13] Masayuki Kobayashi and Jiro Abe, Optical Motion Control of Maglev Graphite, J. Am. Chem. Soc., 2012, 134(51). pp 20593-20596, December 12, 2012

[14] http://www.youtube.com/watch?feature=player_embedded&v=AJ7fMVp_O5s