

Magnetic field generation in the water treatment perspectives: An overview

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ARTICLE INFO

Article history:

Received 19 September 2017

Received in revised form

28 November 2017

Accepted 2 December 2017

Keywords:

Iron

Ferrite

Magnetic field (MF)

Magnetic water treatment

Atom

Electron

ABSTRACT

In the last few decades, many researches on the effects of magnetic field (MF) on water have been reported; however, still many arguments and doubts are present. This review aims to focus on the basic properties implied in magnetic phenomena generation at the atomic and electronic level of matter. Fundamentals of magnetism and origin of magnetic effect will be discussed. Both paramagnetism and diamagnetism are very crucial in the examination of atomic and molecular structure; however, these effects are very weak and have no real practical importance. Large scale magnetic effects resulting in commercially important materials appear in atoms and ions of only a few metallic elements notably Fe, Co, Ni, and some of the rare earths. In alloys or oxides of some materials containing these elements and some neighboring ions such as Mn, there is a crucial improvement of the atomic spin effect. This enhancement comes about from the cooperative interaction of large numbers ($10^{13} - 10^{14}$) of these atomic spins producing a region where all atomic spins within it are aligned parallel (positive exchange interaction). These materials are called ferromagnetic. In spite of the achieved performances on MF technologies, there is a huge work to be performed for better understanding and controlling of magnetic water treatment.

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1. Introduction

Since the middle of the 20th century, several studies on examining impacts of magnetic field (MF) on water have been reported (Ghanati et al., 2015; Hosoda et al., 2004; Bogatin et al., 1999; Alimi et al., 2007; Chang and Weng, 2008; Osuga and Tatsuoka, 2009; Sueda et al., 2007; Maki and Ataka, 2004; Iwasaka and Ueno, 1998; Inaba et al., 2004; Iino and Fujimura, 2009; Ghauri and Ansari, 2006) with many paradoxical findings are noticed. As an illustration, Cai et al. (2009) have mentioned decrease in surface tension attributed to a MF during the time that viscosity of water augments. Toledo et al. (2008) have evaluated an augmentation in both surface tension and viscosity of water affected to MF. These inconsistencies are perhaps linked to the manner of tests such as water flow velocity in MF, soluble material in water, MF distribution and measurement errors on water evaporation. Regardless of these different disagreements, the augmented evaporation

quantity of water in presence of MF is a less denied process. Nakagawa et al. (1999) have mentioned an elevation in pure water evaporation in presence of a MF gradient. They proposed that augmentation in evaporation is affected to air convection above the water surface due to volume magnetic force (Nakagawa et al., 1999). Wu et al. (2006) have observed an augmentation in distilled water evaporation in presence of static MF of 0.25, 0.36 and 0.55 Tesla comparatively with the pure water evaporation out of MF. Szcześ et al. (2011) also have indicated an elevation in water evaporation and memory impacts after passing across a MF which is function of the flow velocity. Holysz et al. (2007) have examined impacts on pure water and electrolyte solutions in static MF and observed an augmentation in pure water evaporation and reduction in evaporation of some of the electrolyte solutions. Rashid et al. (2013) have tested water evaporation across a MF of 0.5 T, which was placed at changing point of examined water height (water-air interface, water mid height and bottom). They have detected a maximum rate of evaporation when location of MF is at the interface. While putting MF at the bottom of the water height they have not observed any variation in the rate of water

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evaporation (Seyfi et al., 2017; Little, 2011; Donaldson and Grimes, 1987; De Brito et al., 2012).

This review paper aims to focus on understanding the basic properties implied in magnetic phenomena generation at the atomic and electronic level of matter. Fundamentals of magnetism and origin of magnetic effect will be discussed. Since MF presence is usually related to magnetite (Fe_3O_4), a special interest is accorded to ferrites which know a growing attention to be studied and used as promising green products in water/wastewater treatment technologies.

2. Fundamentals of magnetism and origin of magnetic impact

This Section reviews basics of magnetism and the deduction of magnetic units from a physico-mathematical base. These units will be then applied to quantify the intrinsic magnetic characteristics of electrons, atoms and ions. Being intrinsic, these characteristics are only function of the chemistry and crystal structure at a certain temperature. After this discussion of intrinsic characteristics, those which, moreover, are function of physical properties like stress, grain structure and porosity will be treated. In the end, the already determined units will be linked with functional magnetic variables under dynamic conditions such as those utilized in electrical devices. Initially, the magnetic units are obtained firstly from the centimeter-gram-second (CGS) system that is the more classical one for fundamental magnetic characteristics. At what time the significance is moved to component and application consideration, both CGS and meter-kilogram-second-ampere (MKSA) units are employed (Goldman, 2006).

2.1. MFs

A MF is a force field analogous to gravitational and electrical fields; in other words, surrounding a source of potential, there is a contoured sphere of effect or field (Krzemieniewski et al., 2004; Xu et al., 2010). In the case of gravitation, the source of potential is a mass. For electrical fields, the source is a positive or negative electrical charge. Fields (magnetic or otherwise) may be revealed only by the usage of a probe, which is frequently another source of that type of potential. The principle that is employed is the measurement of a force, either repulsive or attractive, that is tested by the probe under the effect of the field. For gravitation, where the interaction is always attractive, the ruling equation is (Goldman, 2006; Trad, 2006):

$$F = G \frac{m_1 \times m_2}{r^2} \quad (1)$$

where, F = force (N); G = constant = 6.67×10^{-7} N.m²/kg²; m₁, m₂ = masses (kg); r = distance between masses (m).

In the case of an electrical field, the corresponding equation is (Goldman, 2006):

$$F = K \frac{q_1 \times q_2}{r^2} \quad (2)$$

where, q₁, q₂ = electric charges (C); K = electric constant = 9×10^9 N.m²/C²; r = distance between charges (m).

The force is repulsive if the two charges are of the identical sign and attractive if the signs are various (Goldman, 2006).

Primary workers studying MFs observed that the origin of the magnetic impact seemed to originate near the ends of the magnets. These sources of magnetic potential are known as magnetic poles. For the MF, there is one important difference compared to the other types of fields. In the gravitational or electrical analogs, the potential generating entities, mass or charge, may be present separately. Therefore, positive or negative electrical charge may be accumulated separately. In the magnetic situation, the two types of MF-producing species seem to be coupled together as a dipole. As a consequence, isolated magnetic monopoles have not observed (Goldman, 2006).

2.2. The principle of magnetic poles

The poles principle emerged a long time ago when the single manner of examining magnetic phenomena was founded on the interaction of permanent magnets. Even if related theories are now much more polished since then, the pole principle is yet a helpful tool in discussions and calculations on ferromagnetism. Poles are imaginary points near the end of a magnet where one might consider all the magnetic forces on the magnet to be concentrated. The strength of a pole is established by the force applied on it by another pole. In 1750, John Mitchell measured the forces between magnets and found, as an illustration, that the attraction or repulsion reduced in proportion to the squares of the distances between the poles of two magnets. Comparable to the gravitational and electrical examples, the force is given by Goldman (2006):

$$F = K' \frac{m_1 \times m_2}{r^2} \quad (3)$$

where, m₁, m₂ = strengths of the two poles; K' = a constant which has the value of = 1 in the CGS system, = $1/4\mu_0$ in the MKSA system (where $\mu_0 = 4 \times 10^{-7}$ Henry/m = permeability of vacuum) (Goldman, 2006).

In the CGS system, a unit pole is defined as one that applies a force of 1 dyne on a similar unit pole 1 cm away. The force is repulsive if the poles are alike or attractive if they are unlike. Around each pole is a region where it can apply a force on another pole. This region is named the MF. Each point in a MF is defined by field strength or intensity and a field direction which changes with location with respect to the poles. A visualization of the field directions may be performed if iron filings are sprinkled on a sheet of paper covering a magnet. The lines show the varying directions of the field emanating from the

poles. The direction is also that to which a North-seeking end of a compass needle placed at that spot would point. The field strength may be showed by the density of the lines in any one particular area. The density should fall off following the inverse square of the distance from the poles as predicted (Goldman, 2006).

The polarity of the magnet itself should be described, the assignment being such that the North-seeking pole is the North Pole of the magnet. Because opposite poles attract, the north-seeking pole of the magnet is in fact the same kind of pole as the South Pole of the planet. In other words, the north magnetic pole of the planet is the opposite kind of pole from the North Pole of all other physical objects with magnetic properties. The absolute direction of a MF outside of a magnet is from the North Pole to the South Pole. Because lines of MF should be continuous, the direction of the field inside the magnet is from south to north poles. The unit of MF intensity called an Oersted is defined as that exerted by a field located 1 cm from a unit pole. The MF intensity may as well be described in terms of current flowing across a wire loop. In the MKSA system of units, the unit of field strength is the ampere-turn per meter, which then relates the MF to this current flow (Goldman, 2006).

When a magnet of pole strength m , is brought into an external MF (such as that produced by another magnet), the force acting on each pole is given by Goldman (2006):

$$F = m \times H \tag{4}$$

where, m = pole strength (emu or electromagnetic units); H = MF strength (Oersteds) = m_2/kr^2 .

When a magnetic dipole such as a bar magnet is placed in a uniform MF at an angle, θ , each pole is acted on by forces illustrated by Fig. 1. The result is a couple whose torque is (Goldman, 2006):

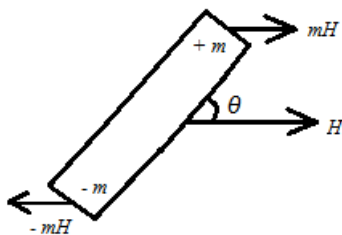


Fig. 1: Forces acting on a magnet at an angle, θ , to a uniform MF (Goldman, 2006)

$$L = \frac{m \times l}{H \times \sin \theta} \tag{5}$$

where, L = torque; l = distance between the poles (cm); θ = angle between the direction of the MF and the axis between the poles (direction of magnetization).

This torque will tend to rotate the magnet clockwise. By measurement of the torque and the angle, θ , we may evaluate the field strength (Goldman, 2006).

If the axis of a bar magnet is parallel to a uniform field, no force will act on it since the force on one pole will cancel the force on the other. However, a force will result if the field is non-uniform due to the difference in forces experienced by the individual poles. The force is (Goldman, 2006):

$$F_x = ml \frac{dH}{dx} \tag{6}$$

where, F_x = force in the x direction; $\frac{dH}{dx}$ = change in the MF per centimeter in the x direction.

Fig. 2 illustrates this action. The lengths of the arrows represent the field strengths at the two poles and also the difference in forces it generates. In addition to the translational force on the magnet due to its position in a non-uniform field, the magnet will also experience a rotational torque explained above if the magnet is at angle to the external field. Due to the dipolar nature and the combined action of the two poles, any force generated by the magnet in a field is proportional to the term, ml . This is named the magnetic moment that is equivalent to a mechanical moment. In magnetic materials, we are not as much concerned with m or l but with the product, ml , which is a measurable parameter as it was with the magnets. We will call this moment, μ , not to be confused with the permeability, μ (large μ) to be explained later (Goldman, 2006).

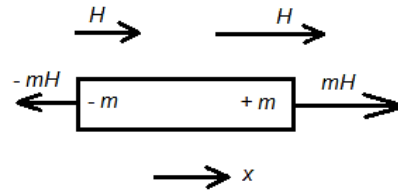


Fig. 2: Forces acting on a magnet in a non-uniform MF (Goldman, 2006)

To reveal this characteristic as a material property, we are interested in the magnetic moment per unit volume or the intensity of magnetization. Alternately, this parameter may be named the magnetic polarization or frequently, we shall just refer to it simply as the magnetization, M . The magnetization is given by Goldman (2006):

$$M = \frac{m \times l}{V} = \frac{\mu}{V} \tag{7}$$

where, V = volume (cm^3).

This definition is crucial in explaining the fundamental material characteristic that is clearly different from the magnetic circuit. When very precise research is performed, the magnetic moment per unit weight is usually utilized to avoid the problem of density changes with changing temperature or porosity (due to processing condition). In this situation, the term is σ , which is the moment per gram. The corresponding M or moment per volume is obtained by multiplying by the density (Goldman, 2006).

$$M = d \times \sigma \quad (8)$$

where, σ = moment per gram (emu/g); d = density (g/cm³).

It is simple to establish that M is as well equal to the number of poles per cross sectional area of the magnet (Goldman, 2006).

$$M = \frac{m \times l}{V} = \frac{m \times l}{A \times l} \quad (9)$$

$$M = \frac{m}{A} \quad (10)$$

where, A = cross sectional area (cm²).

As it will be seen later, M may be determined relative to a material (powder, chunk, etc.) or in some situations, electrically relative to a magnetic core. The significance of this alternate definition will become more obvious when the magnetic circuit is treated in terms of magnetic flux density of which M is a contributing (often a major) factor (Goldman, 2006).

The magnetization, M , (occasionally named the magnetic polarization) has CGS units called emu/cm² or frequently just electro-magnetic units (emu). The MKSA unit for the magnetization is the Tesla or Weber/m². There are 796 emu/cm³ per Tesla (or Weber/m²) (Goldman, 2006).

2.3. Electromagnetism

The actual birth of contemporary magnetism happened in 1819 when Hans discovered that a compass needle was deflected perpendicular to a current bearing wire when the two were placed close to one another. It was at this point that electromagnetism was born. Next, Faraday (1791-1867) discovered the opposite effect, namely that an electric voltage may be generated when a conducting wire cut a MF (Goldman, 2006).

2.4. Atomic magnetism

The research on electromagnetism in the early 1800's made clear the link between magnetic forces and electric currents in wires, but did little to interpret magnetism in matter, which was the older problem. The theories of that time had supposed that one or more fluids were existing in magnetic substances with some separation happened at the poles when the material was magnetized. In 1845, Faraday found that all substances were magnetic to certain level. Paramagnetic substances were weakly attracted, diamagnetic substances were weakly repelled and ferromagnetics were strongly attracted. The French physicist, Curie in 1895, today best known for his work on of radioactivity, measured the paramagnetism and diamagnetism in a great number of substances and established how these properties changed with temperature (Goldman, 2006).

Nineteenth-century scientists were still trying to find the link between electromagnetism and atomic magnetism. In taking into account the resemblance between magnets and current circuits, Ampère

(1775-1836) proposed the presence of small molecular currents which would actually make each atom or molecule an individual permanent magnet (Ampère, 1965). These atomic magnets would be pointed in all directions, but would arrange themselves in a line when they were placed in a MF. The expression "Amperian currents" is still employed today. The search for a source of these molecular currents ended with the discovery of the electron at the close of the 19th century and reported by Thomson in 1903. By 1905, there was general agreement that the molecular currents responsible for the magnetism in matter were due to electrons circulating in the molecules or atoms (Goldman, 2006).

2.4.1. Bohr Theory of magnetism

In 1913, Bohr (1885-1962) described the quantum theory of matter to consider several of the impacts that physicists of the day could not interpret. In this theory, the electrons were said to revolve about the nucleus of an atom in orbits, similar to those of the planets around the sun. The magnetic behavior of an atom was suggested to be the consequence of the orbital motion of the electrons, an impact identical to a current flowing in a wire loop. The motion of the electrons could be characterized in fundamental units so that the magnetic moment accompanying the orbital moment could also be characterized. The fundamental unit of electron magnetism is named the Bohr magneton. Not only a fundamental electric charge but also a magnetic quantity is connected with the electron (Goldman, 2006).

The magnetic moment, μ , resulting from an electron rotating in its orbit can be given by Goldman (2006):

$$\mu = \frac{e \times p}{2m \times c} \quad (11)$$

where, e = electronic charge of the electron (C); p = total angular momentum of the electron; m = mass of the electron (g); c = speed of light (cm/s).

In the Bohr Theory, the orbital angular momentum is quantized in units of $h/2\pi$ (where h is Planck's constant). Thus, for the Bohr orbit nearest to the nucleus, the orbital angular momentum, p , can be replaced by $h/2\pi$. The resulting magnetic moment can be expressed as (Goldman, 2006):

$$\mu = \frac{e \times h}{4\pi \times m \times c} \quad (12)$$

If we substitute for the known values and constants, we obtain:

$$\mu_B = 9.27 \times 10^{-21} \text{ erg/Oersted} \quad (13)$$

This constant, known as the Bohr magneton, is the basic unit of magnetic moment in the Bohr Theory. It is that the result of the orbital motion of one electron in the lowest orbit (Goldman, 2006).

2.4.2. Orbital and spin moments and magnetism

The old Bohr Theory was incomplete in several aspects and even with the Sommerfeld in 1916 variation (the use of elliptical versus circular orbits) could not interpret several things. In 1925, George Uhlenbeck postulated the electron spin. At approximately the same period, Heisenberg in 1926 and Schrodinger in 1929 developed wave mechanics which was much more successful in taking into consideration magnetic phenomena. In quantum mechanics, the new source of magnetism is advanced-that of the spin of the electron on its own axis, similar to that of the earth. Because the electron carries electric charge, the spin conducts to movement of this charge or electric current that will generate a magnetic moment. Both theoretically and experimentally, it has been observed that the magnetic moment associated with the spin moment is almost identically equal to one Bohr magneton (Goldman, 2006).

The original equation for the Bohr magneton is varied slightly to comprise a term, g , known as the spectroscopic splitting factor. This factor denotes a ratio between the mechanical angular momentum to magnetic moment. The value of g for pure spin moment is 2 while that for orbital moment is 1. Nevertheless, the lowest orbital quantum number for orbital momentum is 1 (number of units of $h/2\pi$) whereas the quantum number linked with each electron spin is $\pm 1/2$. The new equation is (Goldman, 2006):

$$\mu = \frac{g \times e \times h}{2m \times c} \quad (14)$$

where, for orbital moment (lowest state): $g = 1$, $n = 1$; for spin moment: $g = 2$, $n = 1/2$.

The orbital and spin moment both turn out to be equal to $1 \mu_B$. There is a universal unit of magnetic moment that accommodates both the orbital and spin moments of electrons. The Bohr magneton is that fundamental unit. The magnetic moment was primarily described in relationships with permanent magnets. The electron itself may well be named the smallest permanent magnet (Goldman, 2006).

The net amount of magnetic moment of an atom or ion is the vector sum of the individual spin and orbital moments of the electrons in its outer shells. In gases and liquids, the orbital contribution to magnetism may be significant; however, in several solids, comprising those carrying the magnetically-important transition metal elements, strong electric fields observed in a crystalline structure destroy or quench the impact. Most magnetic materials are crystalline and thus would be influenced by this factor. In the great majority of the magnetic materials we will deal with (those involving the 3d electrons of transition metals), we will not be concerned with the orbital momentum except for small deviations of the g factor from 2. However, when we talk about the magnetic properties of the rare earths, we cannot ignore the orbital

contribution. In these cases, the affected 4f electrons are not outermost. Consequently, they are screened from the electric fields by electrons of outer orbitals. This is not the case for the 3d electrons which are in the outermost shell. For the present, however, we will consider the magnetic behavior of most common magnetic materials to be entirely the result of spin moments (Goldman, 2006).

2.4.3. Atomic and ionic moments

There are two modes of electron spin. Schematically, they may be represented as either clockwise or counter-clockwise. If the electron is spinning in a horizontal plane and counter-clockwise as viewed from above, the direction of the magnetic moment is directed up. If it is clockwise, the reverse is true. The direction of the moment is comparable to the direction of the magnetization (from S to N poles) of a permanent magnet to which the electron spin is equivalent. It is very frequent to schematically represent the two type's electron spin as arrows pointed up or down and this representation will be employed in the following discussion. A counter-clockwise spin in an atom (arrow up) will cancel a clockwise spin (arrow up) and no net magnetic moment will result. It is only the unpaired spins that will give rise to a net magnetic moment (Goldman, 2006).

In quantum mechanics, the atoms or ions are built up of electrons in orbitals identical to the Bohr orbits. These orbitals are as well classified following the shape of the spatial electronic probability density. This may be visualized as the superimposing of very many photographs of the electron at various times. The shape of the electron cloud that results is the shape of the orbital. As an illustration, for s electrons, this shape is the surface of a sphere. Discrete energy levels are associated with each of these orbitals. As we construct the elements of higher atomic numbers, the higher positive nuclear charge will need more outer electrons. As these are outer electrons are fed in to form the atom, the added electrons go into the lowest unfilled energy levels. Fig. 3 illustrates an example of an applicable energy level diagram. The electrons, like balls filling a stepped box would fill from the bottom up. Of interest to us in most magnetic materials, the 3d group of orbitals is particularly significant (Goldman, 2006). Each orbital is moreover divided into suborbitals each of which can accommodate one electron of each spin direction. The rules of quantum mechanics state when a 3d subshell is being filled, all the electron spins must be in the same direction (unpaired) until half of the subshell is filled at which time they can only enter in the opposite direction or paired. Fig. 4 shows this method in which the orbitals are filled utilizing a convention previously defined. The superscript indicates the number of electrons filling that orbital. The order of addition of subshells is generally from left to right with the exception that the $4s^2$ is added before the $3d^3$. Note that there are four unpaired electrons in the case of

the iron atom (Li, 2017). To form the Fe³⁺ ion from the iron atom, the two 4s electrons are removed first the one 3d electron giving rise to 5 unpaired electrons. In all these examples, unpaired electrons lead to a net magnetic moment. This classifies the atom or ion as paramagnetic, the degree being proportional to the number of unpaired electron spins. Each unpaired spin produced 1 Bohr magneton as previously mentioned. Table 1 shows the number of unpaired directions and thus the number of Bohr magnetons for each element or ion. In compounds, ions and molecules, account must be taken of the electrons used for bonding or transferred in ionization. It is the number of unpaired electrons remaining after these processes occur that gives the net magnetic moment. The spin quantum number, S, has unit multiples of +1/2 or -1/2 depending on orientation. The orbital moment, L, has unit multiples of 1, 2, etc. The vector coupling between L and S is quantized as combined moment, J (Goldman, 2006).

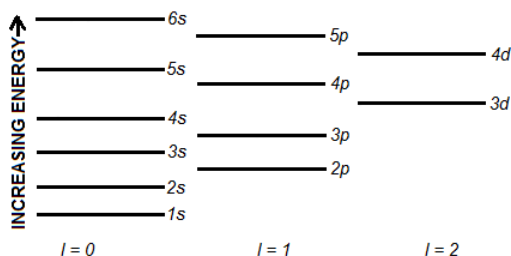


Fig. 3: Schematic diagram of electronic energy levels (Goldman, 2006)

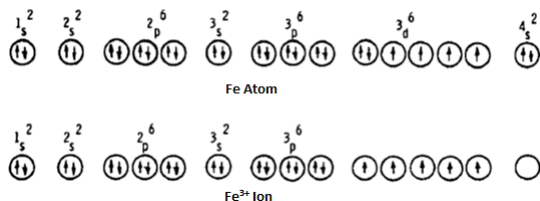


Fig. 4: Electronic configuration of iron atom (Fe) and ion (Fe³⁺) (Goldman, 2006)

Table 1: Numbers of unpaired electrons and Bohr magnetons in atoms and ions involved in ferro- and ferrimagnetic materials (Goldman, 2006)

Number of unpaired electrons (μ_B)	
Atom	
Fe	4
Co	3
Ni	2
Ion	
Fe ²⁺	4
Fe ³⁺	5
Co ²⁺	3
Ni ²⁺	2
Mn ²⁺	5
Mg ²⁺	0
Zn ²⁺	0
Li ⁺	0

2.5. Paramagnetism and diamagnetism

If an atom possesses a net magnetic moment (it is paramagnetic), this moment may be partially aligned

in the direction of an applied MF. Each atom therefore acts as an individual magnet in a field. The process of rotating these moments against thermal agitation is a difficult one and a large field is necessary to achieve only a small degree of alignment or magnetization (Goldman, 2006).

In several paramagnetic materials (Koktan et al., 2017) such as in hydrated salts, as the temperature is raised, the thermal agitation of the spins reduces even this small amount of alignment. In 1895, Curie established that in these cases, the susceptibility, χ , which is defined as (Goldman, 2006).

$$\chi = M/H \tag{15}$$

where, χ = susceptibility; M = magnetization or moment (emu/cm³); H = MF strength (Oersteds). Follows the Curie Law given as:

$$\chi = C/T \tag{16}$$

where, C = Curie constant; T = temperature (K). Moreover:

$$1/\chi = T/C \tag{17}$$

Fig. 5 illustrates the temperature function of the inverse of the susceptibility in a paramagnetic. The slope of the line is therefore 1/C (Goldman, 2006).

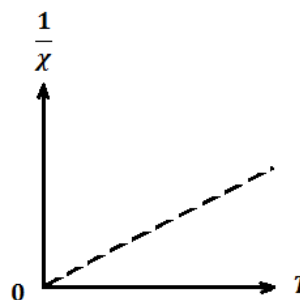


Fig. 5: Variation of susceptibility of a paramagnetic material with temperature (Goldman, 2006)

Diamagnetism is an inherent property of the orbital motion of the individual electron in a field. Since it is even a weaker effect than paramagnetism, it is only observed when the atom does not have a net spin or orbital moment. The orbital motion even though compensated sets up a field opposite to the applied field in a manner similar to the back emf of Lenz's Law (Goldman, 2006). The effect leads to a negative susceptibility or the actual lowering of the net moment in the material as an external field is applied. Diamagnetism is so weak an effect that a small paramagnetic impurity can offer mask out the effect (Goldman, 2006).

2.6. Ferromagnetism

Both paramagnetism and diamagnetism are very crucial in the examination of atomic and molecular structure; however, these effects are very weak and have no real practical importance. Large scale magnetic effects resulting in commercially important materials appear in atoms (and ions) of only a few metallic elements notably Fe, Co, Ni, and some of the

rare earths. In alloys or oxides of some materials containing these elements and some neighboring ions such as Mn, there is crucial improvement of the atomic spin effect. This enhancement comes about from the cooperative interaction of large numbers ($10^{13} - 10^{14}$) of these atomic spins producing a region where all atomic spins within it are aligned parallel (positive exchange interaction). These materials are called ferromagnetic (Goldman, 2006).

The regions of the materials in which the cooperative effect extends are known as magnetic domains. In 1907, Weiss first suggested the presence of magnetic domains to account for certain magnetic phenomena. He postulated the existence of a "molecular field" which produced the interaction aligning spins of neighboring atoms parallel Heisenberg in 1928 attributed this "molecular field" to quantum-mechanical exchange forces. Domains have been confirmed by many techniques and can be made visible by several means.

In ferromagnetic materials (as in paramagnetic materials), the alignment of magnetic moments in a MF at higher temperature is decreased. Since a much greater degree of alignment occurs in ferromagnetics, the effect is even more pronounced. With further temperature increase, the thermal agitation will exceed the exchange forces and at a certain temperature called the Curie point, ferromagnetism disappears. From complete alignment at 0 K to zero alignments at the Curie point, a curve of reduced magnetization, M/M_0 (where M_0 = magnetization at 0 K) plotted against reduced temperature, T/T_c (where T_c = Curie point) follows a similar pattern. Fig. 6 shows such a universal curve. For the ferromagnetic metals such as Fe, Co, and Ni, the general curve holds fairly well (Goldman, 2006).

Above the Curie point, the ferromagnetic material becomes paramagnetic, the susceptibility of which decreases with temperature. If the reciprocal susceptibility, $1/\chi$, is plotted against T, the curve obeys the Curie-Weiss Law:

$$1/\chi = 1/[C(T - T_c)] \tag{18}$$

where, C = Curie-Weiss constant; T_c = Curie point. Fig. 7 shows a typical plot (Goldman, 2006).

2.7. Antiferromagnetism

In ferromagnetism, the interaction of atomic spin moments was a positive one meaning that the exchange interaction aligned neighboring spins parallel in a magnetic domain. In his study of the paramagnetic susceptibility of certain alloys, Néel (Louis_Néel, 2017) noticed that they did not follow the Curie law at low temperatures but did obey the Curie-Weiss law at high temperatures;

$$\chi = C/(T + \theta) \tag{19}$$

where, θ = experimentally determined constant; also:

$$\chi = C/(T - T_N) \tag{20}$$

where, T_N = Néel temperature

Where the extrapolation of the high temperature linear slope of $1/\chi$ vs T resulted in a negative value or a negative Curie point. To accommodate these findings, he postulated a negative exchange interaction aligned the neighboring spins antiparallel. At very low temperatures, the negative exchange force prevented the normal paramagnetic alignment in a field so that the susceptibility was low. As the temperature increased, however, the exchange interaction was weakened. Thus, as the negative exchange diminished, the susceptibility actually increased until a point called the Néel point where the negative interaction disappears. Now the spin system behaves as a paramagnetic with the expected Curie-Weiss law dependence. For a polycrystalline material, the $1/\chi$ versus T curve is shown in Fig. 8.

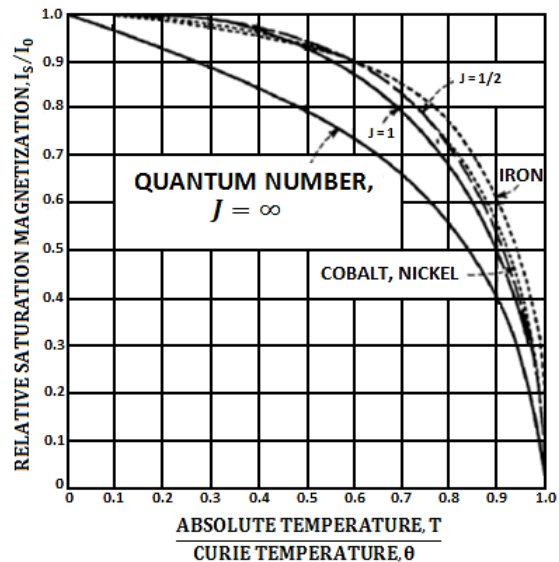


Fig. 6: Universal magnetization curve showing reduced magnetization, M_s/M_0 , or in this terminology, I_s/I_0 , versus reduced temperature, T/T_c . Curves for Co, Ni and Fe are shown with some theoretically drawn curves (Goldman, 2006)

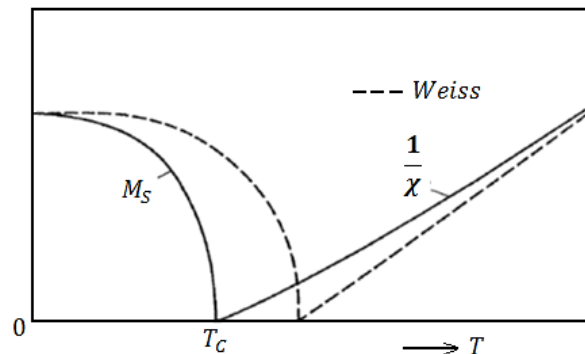


Fig. 7: Temperature dependence of the saturation magnetization of a ferromagnetic and inverse of the susceptibility above the Curie point (Goldman, 2006)

The negative exchange behavior of material of this type is called anti-ferromagnetism. Néel (Louis_Néel, 2017) then became concerned with the

magnetic behavior of oxides. Now, the magnetic ions in ferrites lie in the interstices of a close packed oxygen lattice (Jaafarzadeh et al., 2017; Reddy and Yun, 2016; Selvaraj et al., 2017, Huang et al., 2006). Because the distances between the metal ions are large, direct exchange between the metal ions is very weak. However, in 1919 Kramers postulated a mechanism of exchange between metal ions through the intermediary oxygen ions. Néel combined his theory on antiferromagnetism with Kramers ideas on indirect exchange and formulated his new theory for antiferromagnetic oxides and later for ferrites (Kefeni et al., 2017; Lou and Huang, 2009; Yang, 1994; Navratil, 2016; Ali, 2012; Ghernaout et al., 2009; Ghernaout et al., 2010). Later, this theory was put on a mathematical basis and called it super exchange. The mechanism assumed that one of the electrons in the oxygen ion could interact with or exchange with the unpaired electrons on one of the metal ions on what we call A sites. To be able to pair with the metal ion spin, the oxygen spin would have to be opposite to that on the metal ion. This would leave the other spin in the oxygen ion orbital free to pair with the unpaired spin of another metal ion preferably located opposite to the original metal ion. Since the second spin of the oxygen ion suborbital is opposite to the first, it can only couple with a spin which is opposite to the original metal ion. This, then, is the reason for the stability of the antiparallel alignment of the two metal ions adjacent to the oxygen ion. Many antiferromagnetic substances are oxides, the classic case being MnO. The theoretical basis of antiferromagnetism was formulated by Van Vleck (1924) and Nagamiya (1951) presented an excellent review on the subject.

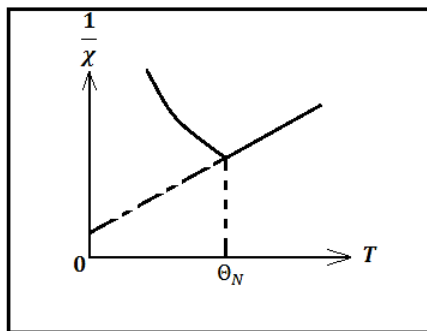


Fig. 8: Reciprocal of the susceptibility of an antiferromagnetic material showing the discontinuity at the Néel temperature and the extrapolation of the linear portion to the "negative Curie Temperature (Goldman, 2006)

Zener (1932) has proposed an alternative mechanism to superexchange called double exchange. In this case, the spins of ions of the same element of two different valencies simultaneously exchange electrons through the oxygen ion thereby changing the valences of both. Thus, $\text{Fe}^{2+}\text{O}^{2-}\text{Fe}^{3+}$ can change to $\text{Fe}^{3+}\text{O}^{2-}\text{Fe}^{2+}$. Although antiferromagnetic substances have no commercial value and, like paramagnetics, are mostly important in theoretical

studies, knowledge of antiferromagnetism is indispensable in the understanding of the magnetic moments in ferrites (Hencel et al., 1995; Tamaura, 1998; Ghernaout and Naceur, 2011; Irkia et al., 2017; Ghernaout, 2017).

2.8. Ferrimagnetism

About the same time that Néel was developing his theory of antiferromagnetism, Snoek (1947) in The Netherlands was obtaining very interesting properties in a new class of oxide materials called ferrites that were very useful at high frequencies. Now, a dilemma had arisen in accounting for the magnetic moment of a ferrite such as magnetite, Fe_3O_4 (or $\text{FeO}\cdot\text{Fe}_2\text{O}_3$) (Boczkaj and Fernandes, 2017; Cruz et al., 2017; Chella et al., 2017; Pan et al., 2017; Zhang et al., 2015). The theoretical number of unpaired electrons for that formula was 14, that is, 5 each for each of the Fe^{3+} ions and 4 for the Fe^{2+} ion. Theoretically, the moment should be $14 \mu_B$. Yet the experimental value was only about $4 \mu_B$. Néel then extended his theory to include ferrites. There were still two different lattice sites and the same negative exchange interaction. The difference was that in the case of antiferromagnetics, the moments on the two sites were equal while in the case of the ferrites (Mehrabi et al., 2017; Lee, 2004; Diodati et al., 2014) they were not and so complete cancellation did not occur and a net moment resulted; this moment was the difference in the moments on the two sites. This difference is usually brought about by the difference in the number of magnetic ions on the two types of sites. This phenomenon is called ferrimagnetism or uncompensated antiferromagnetism. Néel in 1948 (Louis_Néel, 2017) published his theory in a paper called Magnetic Properties of Ferrites; Ferrimagnetism and Antiferromagnetism. In the preceding year, Snoek (1947) disclosed the experimental magnetic properties of a large number of useful ferrites.

The interactions of the net moments of the lattice are continuous throughout the rest of the crystal so that ferrimagnetism can be treated as a special case of ferromagnetism and thus domains can form in a similar manner.

2.9. Paramagnetism above the Curie point

Ferrimagnetics also have a Curie point and one would expect the same type of paramagnetic behavior above the Curie temperature (Fig. 7). However, because of the negative interaction such as found in antiferromagnetics, the curve of $1/\chi$ vs T will be concave approaching an asymptotic value which would extrapolate to a negative value which again was found in antiferromagnetics. This type of behavior is strong confirmation of Neel's theory. The $1/\chi$ versus T curve is found in Fig. 9 for paramagnetic, ferromagnetic and ferromagnetic materials.

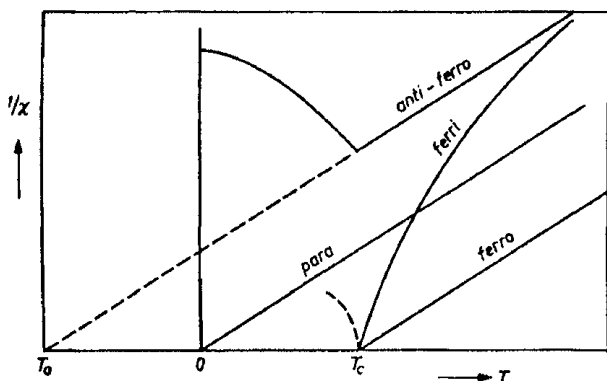


Fig. 9: Comparison of the temperature tendencies of the reciprocal susceptibilities of paramagnetic, ferromagnetic and ferrimagnetic materials

3. Conclusion

From this work, the following conclusions can be drawn:

1. A MF is a force field analogous to gravitational and electrical fields; i.e., surrounding a source of potential, there is a contoured sphere of effect or field. In the case of gravitation, the source of potential is a mass; for electrical fields, the source is a positive or negative electrical charge.
2. The poles principle emerged when the single manner of examining magnetic phenomena was founded on the interaction of permanent magnets. The pole principle remains a helpful tool in discussions and calculations on ferromagnetism. Poles are imaginary points near the end of a magnet where one might consider all the magnetic forces on the magnet to be concentrated.
3. In 1819, when Hans discovered that a compass needle was deflected perpendicular to a current bearing wire when the two were placed close to one another. It was at this point that electromagnetism was born.
4. In 1845, Faraday found that all substances were magnetic to certain level. Paramagnetic substances were weakly attracted, diamagnetic substances were weakly repelled and ferromagnetics were strongly attracted. In 1895, Pierre Curie measured the paramagnetism and diamagnetism in a great number of substances and established how these properties changed with temperature. Ampère (1775-1836) proposed the presence of small molecular currents which would actually make each atom or molecule an individual permanent magnet. By 1905, there was general agreement that the molecular currents responsible for the magnetism in matter were due to electrons circulating in the molecules or atoms (Ampère, 1965).
5. In 1913, Bohr (1885-1962) described the quantum theory of matter. The electrons were said to revolve about the nucleus of an atom in orbits. The magnetic behavior of an atom was suggested to be the consequence of the orbital

motion of the electrons. The motion of the electrons could be characterized in fundamental units so that the magnetic moment accompanying the orbital moment could also be characterized. The fundamental unit of electron magnetism is named the Bohr magneton. In 1925, George Uhlenbeck postulated the electron spin. Heisenberg in 1926 and Schrodinger in 1929 developed wave mechanics which was much more successful in taking into consideration magnetic phenomena. In quantum mechanics, the new source of magnetism is advanced-that of the spin of the electron on its own axis, similar to that of the earth. Because the electron carries electric charge, the spin conducts to movement of this charge or electric current that will generate a magnetic moment. It has been observed that the magnetic moment associated with the spin moment is almost identically equal to one Bohr magneton.

6. If an atom possesses a net magnetic moment (it is paramagnetic), this moment may be partially aligned in the direction of an applied MF. Each atom therefore acts as an individual magnet in a field. The process of rotating these moments against thermal agitation is a difficult one and a large field is necessary to achieve only a small degree of alignment or magnetization.
7. Both paramagnetism and diamagnetism are very crucial in the examination of atomic and molecular structure; however, these effects are very weak and have no real practical importance. Large scale magnetic effects resulting in commercially important materials appear in atoms (and ions) of only a few metallic elements notably Fe, Co, Ni, and some of the rare earths. In alloys or oxides of some materials containing these elements and some neighboring ions such as Mn, there is crucial improvement of the atomic spin effect. This enhancement comes about from the cooperative interaction of large numbers ($10^{13} - 10^{14}$) of these atomic spins producing a region where all atomic spins within it are aligned parallel (positive exchange interaction). These materials are called ferromagnetic.
8. In spite of the achieved performances on MF technologies, there is a huge work to be performed for better understanding and controlling of magnetic water treatment. Comparatively to electrochemical water treatment, magnetic water treatment remains more mysterious in terms of implied mechanisms and efficiency optimization.

List of symbols

A	Cross sectional area (cm ²)
c	Speed of light (cm/s) (Eq. (11))
d	Density (g/cm ³)
$\frac{dH}{dx}$	Change in the MF per centimeter in the x direction

e	Electronic charge of the electron (= 1.6×10^{-19} C)	results and application conditions. Environmental science and technology, 33(8): 1280-1285.
emu	Electro-magnetic units	Cai R, Yang H, He J, and Zhu W (2009). The effects of magnetic fields on water molecular hydrogen bonds. Journal of Molecular Structure, 938(1): 15-19.
F	Force (gravitation, electric field, MF) (N)	Chang KT and Weng CI (2008). An investigation into the structure of aqueous NaCl electrolyte solutions under magnetic fields. Computational Materials Science, 43(4): 1048-1055.
F _x	Force in the x direction (N)	Chella S, Ehsan D, Pratap K, Sirpa P, Andrews NG, and Amit B (2017). Magnetic SiO ₂ @CoFe ₂ O ₄ nanoparticles decorated on graphene oxide as efficient adsorbents for the removal of anionic pollutants from water. Chemical Engineering Journal, 322: 472-487.
G	Gravitational constant (= 6.67×10^{-7} N.m ² /kg ²)	Cruz DR, Santos BT, Cunha GC, and Romão LP (2017). Green synthesis of a magnetic hybrid adsorbent (CoFe ₂ O ₄ /NOM): Removal of chromium from industrial effluent and evaluation of the catalytic potential of recovered chromium ions. Journal of Hazardous Materials, 334: 76-85.
H	MF strength (oersteds) (= m_2/kr^2)	De Brito JF, de Oliveira Ferreira L, Pereira MCR, Da Silva JP, and Ramalho TC (2012). Adsorption of aromatic compounds under magnetic field influence. Water, Air, and Soil Pollution, 223(6): 3545-3551.
K	Electric constant (= 9×10^9 N.m ² /C ²)	Diodati S, Pandolfo L, Caneschi A, Gialanella S, and Gross S (2014). Green and low temperature synthesis of nanocrystalline transition metal ferrites by simple wet chemistry routes. Nano Research, 7(7): 1027-1042.
K	Constant which (= 1 in the CGS system, = $1/4\mu_0$)	Donaldson JD and Grimes SM (1987). Scale prevention in steel pretreatment by magnetic treatment. Steel Times International, 11(5): 44-45.
L	Torque	Ghanati F, Mohamadalkhani S, Soleimani M, Afzalzadeh R, and Hajnorouzi A (2015). Change of growth pattern, metabolism, and quality and quantity of maize plants after irrigation with magnetically treated water. Electromagnetic Biology and Medicine, 34(3): 211-215.
l	Distance between the poles (cm)	Ghauri SA and Ansari MS (2006). Increase of water viscosity under the influence of magnetic field. Journal of Applied Physics, 100(6): 066101-066101.
M	Magnetic moment per unit volume (or intensity of magnetization, or magnetic polarization or magnetization) (emu/cm ² or frequently just electro-magnetic units (emu). MKSA units for M is Tesla = Weber/m ² = 796 emu/cm ³)	Ghernaout D (2017). The Holy Koran revelation: Iron Is a "Sent Down" metal. American Journal of Environmental Protection, 6(4): 101-104.
m	Pole strength (emu or electromagnetic units); mass of the electron (g)	Ghernaout D and Naceur MW (2011). Ferrate (VI): In situ generation and water treatment: A review. Desalination and Water Treatment, 30(1-3): 319-332.
m ₁ , m ₂	Masses (gravitation) (kg), strengths of the two poles	Ghernaout D, Ghernaout B, Saiba A, Boucherit A, and Kellil A (2009). Removal of humic acids by continuous electromagnetic treatment followed by electrocoagulation in batch using aluminium electrodes. Desalination, 239(1-3): 295-308.
MF	Magnetic field	Ghernaout D, Mariche A, Ghernaout B, and Kellil A (2010). Electromagnetic treatment-doubled electrocoagulation of humic acid in continuous mode using response surface method for its optimisation and application on two surface waters. Desalination and Water Treatment, 22(1-3): 311-329.
p	Total angular momentum of the electron	Goldman A (2006). Modern ferrite technology. Springer Science and Business Media, New York, USA.
q ₁ , q ₂	Electric charges (C)	Hencel V, Mucha P, Orlikova A, and Leskova D (1995). Utilization of ferrites for water treatment. Water Research, 29(1): 383-385.
r	Distance (between masses, between charges) (m)	Holysz L, Szczes A, and Chibowski E (2007). Effects of a static magnetic field on water and electrolyte solutions. Journal of Colloid and Interface Science, 316(2): 996-1002.
V	Volume (cm ³)	Hosoda H, Mori H, Sogoshi N, Nagasawa A, and Nakabayashi S (2004). Refractive indices of water and aqueous electrolyte solutions under high magnetic fields. The Journal of Physical Chemistry A, 108(9): 1461-1464.

Greek symbols

μ	Magnetic moment (resulting from an electron rotating in its orbit)
μ ₀	Permeability of vacuum (= 4×10^{-7} Henries/m)
σ	Moment per gram (emu/g)
θ	Angle between the direction of the MF and the axis between the poles (direction of magnetization)

References

- Ali I (2012). New generation adsorbents for water treatment. Chemical Reviews, 112(10): 5073-5091.
- Alimi F, Tlili M, Amor MB, Gabrielli C, and Maurin G (2007). Influence of magnetic field on calcium carbonate precipitation. Desalination, 206(1-3): 163-168.
- Ampère AM (1965). On the mathematical theory of electrodynamic phenomena, experimentally deduced. In: Tricker RAR (Ed.), Early electrodynamics: The first law of circulation: 155-200. Pergamon, New York, USA.
- Boczka G and Fernandes A (2017). Wastewater treatment by means of advanced oxidation processes at basic pH conditions: A review. Chemical Engineering Journal, 320: 608-633.
- Bogatin J, Bondarenko NP, Gak EZ, Rokhinson EE, and Ananyev IP (1999). Magnetic treatment of irrigation water: experimental
- results and application conditions. Environmental science and technology, 33(8): 1280-1285.
- Cai R, Yang H, He J, and Zhu W (2009). The effects of magnetic fields on water molecular hydrogen bonds. Journal of Molecular Structure, 938(1): 15-19.
- Chang KT and Weng CI (2008). An investigation into the structure of aqueous NaCl electrolyte solutions under magnetic fields. Computational Materials Science, 43(4): 1048-1055.
- Chella S, Ehsan D, Pratap K, Sirpa P, Andrews NG, and Amit B (2017). Magnetic SiO₂@CoFe₂O₄ nanoparticles decorated on graphene oxide as efficient adsorbents for the removal of anionic pollutants from water. Chemical Engineering Journal, 322: 472-487.
- Cruz DR, Santos BT, Cunha GC, and Romão LP (2017). Green synthesis of a magnetic hybrid adsorbent (CoFe₂O₄/NOM): Removal of chromium from industrial effluent and evaluation of the catalytic potential of recovered chromium ions. Journal of Hazardous Materials, 334: 76-85.
- De Brito JF, de Oliveira Ferreira L, Pereira MCR, Da Silva JP, and Ramalho TC (2012). Adsorption of aromatic compounds under magnetic field influence. Water, Air, and Soil Pollution, 223(6): 3545-3551.
- Diodati S, Pandolfo L, Caneschi A, Gialanella S, and Gross S (2014). Green and low temperature synthesis of nanocrystalline transition metal ferrites by simple wet chemistry routes. Nano Research, 7(7): 1027-1042.
- Donaldson JD and Grimes SM (1987). Scale prevention in steel pretreatment by magnetic treatment. Steel Times International, 11(5): 44-45.
- Ghanati F, Mohamadalkhani S, Soleimani M, Afzalzadeh R, and Hajnorouzi A (2015). Change of growth pattern, metabolism, and quality and quantity of maize plants after irrigation with magnetically treated water. Electromagnetic Biology and Medicine, 34(3): 211-215.
- Ghauri SA and Ansari MS (2006). Increase of water viscosity under the influence of magnetic field. Journal of Applied Physics, 100(6): 066101-066101.
- Ghernaout D (2017). The Holy Koran revelation: Iron Is a "Sent Down" metal. American Journal of Environmental Protection, 6(4): 101-104.
- Ghernaout D and Naceur MW (2011). Ferrate (VI): In situ generation and water treatment: A review. Desalination and Water Treatment, 30(1-3): 319-332.
- Ghernaout D, Ghernaout B, Saiba A, Boucherit A, and Kellil A (2009). Removal of humic acids by continuous electromagnetic treatment followed by electrocoagulation in batch using aluminium electrodes. Desalination, 239(1-3): 295-308.
- Ghernaout D, Mariche A, Ghernaout B, and Kellil A (2010). Electromagnetic treatment-doubled electrocoagulation of humic acid in continuous mode using response surface method for its optimisation and application on two surface waters. Desalination and Water Treatment, 22(1-3): 311-329.
- Goldman A (2006). Modern ferrite technology. Springer Science and Business Media, New York, USA.
- Hencel V, Mucha P, Orlikova A, and Leskova D (1995). Utilization of ferrites for water treatment. Water Research, 29(1): 383-385.
- Holysz L, Szczes A, and Chibowski E (2007). Effects of a static magnetic field on water and electrolyte solutions. Journal of Colloid and Interface Science, 316(2): 996-1002.
- Hosoda H, Mori H, Sogoshi N, Nagasawa A, and Nakabayashi S (2004). Refractive indices of water and aqueous electrolyte solutions under high magnetic fields. The Journal of Physical Chemistry A, 108(9): 1461-1464.
- Huang J, Furukawa T, and Aoto K (2006). Thermodynamic evaluation of sodium ferrite Na₄Fe₆O₁₁. The Journal of Chemical Thermodynamics, 38(1): 1-4.

- Iino M and Fujimura Y (2009). Surface tension of heavy water under high magnetic fields. *Applied Physics Letters*, 94(26): 261902. <https://doi.org/10.1063/1.3167767>
- Inaba H, Saitou T, Tozaki KI, and Hayashi H (2004). Effect of the magnetic field on the melting transition of H₂O and D₂O measured by a high resolution and supersensitive differential scanning calorimeter. *Journal of Applied Physics*, 96(11): 6127-6132.
- Irkia S, Ghernaout D, and Naceura MW (2017). Decolourization of methyl orange (MO) by electrocoagulation (EC) using iron electrodes under a magnetic field (MF). *Desalination and Water Treatment*, 79: 368-377.
- Iwasaka M and Ueno S (1998). Structure of water molecules under 14 T magnetic field. *Journal of Applied Physics*, 83(11): 6459-6461.
- Jaafarzadeh N, Ghanbari F, and Ahmadi M (2017). Efficient degradation of 2, 4-dichlorophenoxyacetic acid by peroxymonosulfate/magnetic copper ferrite nanoparticles/ozone: A novel combination of advanced oxidation processes. *Chemical Engineering Journal*, 320: 436-447.
- Kefeni KK, Mamba BB, and Msagati TA (2017). Magnetite and cobalt ferrite nanoparticles used as seeds for acid mine drainage treatment. *Journal of Hazardous Materials*, 333: 308-318.
- Koktan J, Kráľovec K, Havelek R, Kuličková J, Řezanka P, and Kaman O (2017). Magnetic oxide particles with gold nanoshells: Synthesis, properties and cytotoxic effects. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 520: 922-932.
- Krzemieniewski M, Debowski M, Dobrzynska A, and Zielinski M (2004). Chemical oxygen demand reduction of various wastewater types using magnetic field-assisted Fenton reaction. *Water Environment Research*, 76(4): 301-309.
- Lee S (2004). Development of magnetic composite photocatalytic particles for environmental applications. University of Florida, Gainesville, Florida, USA.
- Li N (2017). Ferrate as a new treatment chemical for removal of effluent organic matter (EFOM) and emerging micropollutants in treated municipal wastewater for water reuse. Ph.D. Dissertation, Montclair State University, Montclair, New Jersey, USA.
- Little NH (2011). Assessing innovative zero-valent iron separation processes in an arsenic treatment scheme. University of New Hampshire, New Hampshire, USA.
- Lou JC and Huang YJ (2009). Assessing the performance of wastewater treatment with the combination of Fenton and ferrite process. *Environmental Monitoring and Assessment*, 151(1-4): 251-258.
- Louis_Néel (2017). In Wikipedia, The Free Encyclopedia. Retrieved 08:41, November 14, 2017. Available online at: https://en.wikipedia.org/w/index.php?title=Louis_N%C3%A9el&oldid=799192833
- Maki S and Ataka M (2004). Suppression and promotion of convection in water by use of radial components of the magnetization force. *Journal of applied physics*, 96(3): 1696-1703.
- Mehrabi F, Vafaei A, Ghaedi M, Ghaedi AM, Dil EA, and Asfaram A (2017). Ultrasound assisted extraction of Maxilon Red GRL dye from water samples using cobalt ferrite nanoparticles loaded on activated carbon as sorbent: Optimization and Modeling. *Ultrasonics Sonochemistry*, 38: 672-680.
- Nagamiya T (1951). Theory of antiferromagnetism and antiferromagnetic resonance absorption, II. *Progress of Theoretical Physics*, 6(3): 350-355.
- Nakagawa J, Hirota N, Kitazawa K, and Shoda M (1999). Magnetic field enhancement of water vaporization. *Journal of Applied Physics*, 86(5): 2923-2925.
- Navratil JD (2016). Chemistry of iron ferrites and their application for wastewater and acid mine water treatment. *Journal of International Environmental Application and Science*, 10(5): 697-702.
- Osuga T and Tatsuoka H (2009). Magnetic-field transfer of water molecules. *Journal of Applied Physics*, 106(9): 094311. <https://doi.org/10.1063/1.3247352>.
- Pan X, Yan L, Li C, Qu R, and Wang Z (2017). Degradation of UV-filter Benzophenone-3 in Aqueous Solution Using Persulfate catalyzed by Cobalt Ferrite. *Chemical Engineering Journal*, 326: 1197-1209.
- Rashid FL, Hassan NM, Mashot JA, and Hashim A (2013). Increasing water evaporation rate by magnetic field. *International Science and Investigation Journal*, 2(3): 61-68.
- Reddy DHK and Yun YS (2016). Spinel ferrite magnetic adsorbents: alternative future materials for water purification?. *Coordination Chemistry Reviews*, 315: 90-111.
- Selvaraj S, Moon H, and Kim DH (2017). Synthesis and photoelectrochemical properties of spinel-ferrite-coated hematite for solar water splitting. *Applied Surface Science*, 429: 42-47.
- Seyfi A, Afzalzadeh R, and Hajnorouzi A (2017). Increase in water evaporation rate with increase in static magnetic field perpendicular to water-air interface. *Chemical Engineering and Processing: Process Intensification*, 120: 195-200.
- Snoek JL (1947). *New developments in ferromagnetic materials*. Elsevier, Amsterdam, The Netherlands.
- Sueda M, Katsuki A, Nonomura M, Kobayashi R, and Tanimoto Y (2007). Effects of high magnetic field on water surface phenomena. *The Journal of Physical Chemistry C*, 111(39): 14389-14393.
- Szczęś A, Chibowski E, Hołysz L, and Rafalski P (2011). Effects of static magnetic field on water at kinetic condition. *Chemical Engineering and Processing: Process Intensification*, 50(1): 124-127.
- Tamura Y (1998). Ferrites for global environmental protection technology. *Journal of the Magnetics Society of Japan*, 22(S_1_ISFA_97_S1): 396-399. http://doi.org/10.3379/jmsjmag.22.S1_396
- Toledo EJ, Ramalho TC, and Magriotis ZM (2008). Influence of magnetic field on physical-chemical properties of the liquid water: insights from experimental and theoretical models. *Journal of Molecular Structure*, 888(1): 409-415.
- Trad TM (2006). Novel magnetic extractants for removal of pollutants from water. Ph.D. Dissertation, Oklahoma State University, Stillwater, Oklahoma, USA.
- Van Vleck JH (1924). The absorption of radiation by multiply periodic orbits, and its relation to the correspondence principle and the Rayleigh-Jeans law. Part I. Some extensions of the correspondence principle. *Physical Review* 24(4): 330-346.
- Wu SH, Sun YL, and Jia SY (2006). Effects of magnetic field on evaporation of distilled water. *Journal of Petrochemical Universities*, 19(1): 10-12.
- Xu YB, Duan XJ, Yan JN, and Sun SY (2010). Influence of magnetic field on Cr(VI) adsorption capability of given anaerobic sludge. *Biodegradation*, 21(1): 1-10.
- Yang K (1994). Removal of heavy metal ions from acid mine drainage by modified ferrite co-precipitation process. Ph.D. Dissertation, University of Nevada, Reno, USA.
- Zener C (1932). The exchange of energy between monatomic gases and solid surfaces. *Physical Review*, 40(3): 335-339.
- Zhang B, Jiang D, Guo X, He Y, Ong CN, Xu Y, and Pal A (2015). Removal of *Microcystis aeruginosa* using nano-Fe₃O₄ particles as a coagulant aid. *Environmental Science and Pollution Research*, 22(23): 18731-18740.