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WATER AND WASTEWATER TREATMENT SYSTEMS BY MAGNETIC FIELD

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ABSTRACT

This paper discusses application that employs magnetic field as an aid in wastewater treatment. The magnetically assisted wastewater treatments are presented and compared in terms of performances with those of conventional treatment systems. The advantages and limitations of magnetic field application are discussed in order to evaluate their environmental benefits. The main conclusion from the literature is that magnetic field application has the potential to improve the physical performance in terms of solid-liquid separation mainly through aggregation of colloidal particles. The application is also significant in influencing the biological properties through the improvement of bacterial activity. Both of these enhancements lead towards increase in efficiency of the water and wastewater treatment performances.

Keywords: *Magnetic field, water and wastewater treatment, solid-liquid separation, aggregation, performance efficiency*

Introduction:

Magnetic field applications have been known for centuries (Basset, 1993). The concept of induction was introduced by Michael Faraday as early as 1830, claiming that when a magnetic field flux is crossed by flow ions or a conductive material, electrical current is induced. Although magnetic field applications were rapidly pursued in order to prove Faraday's claim, attention from researchers and industrialists worldwide was lacking (Shepard etal.,1995) . Still, Faraday's results are the foundation of all electrical power

Systems, including motors and generators. For water applications, (Faunce etal., 1890) improved the findings later on by designing an electromagnetic device to be installed in the cooler system so as to recycle and treat hard water. As a result of the feedback regarding this device, magnetic field applications in this area have improved considerably. The first commercial magnetic device for water treatment was patented in Belgium by (Vermeiren, 1958). According to (Baker etal., 1996), the effectiveness of magnetic field for water treatment applications is still a controversial question, and the relevant phenomena cannot be clearly explained (Fathi etal., 2006).

Early evidence of possible magnetic applications in water treatment was obtained some decades ago by Russian scientists (Chhatwan, 2011). When water passed through the pipelines of a boiler or engine machinery, mineral deposits from the water adhered to the walls of the pipes. Over time, the passage became narrower and the delivery of water to the machinery was reduced. The efficiency, fuel consumption and mechanical strength of the machine were subsequently degraded. While studying this problem, the scientists noticed that the mineral deposits did not stick to the sides of those pipes carry- ing magnetized water. These observations agreed with those of (Hibben, 1973), (Raisen 1984), (Szostak etal.,1985), (Pandolfo et al. 1987), (Watt et al. 1993), (Hogan et al. 1994), (Paiaro etal., 1994), and (Hammond, 1996). The magnetization of water for industrial use was then established. Researchers also found that water or other types of fluids can become magnetically charged when they are kept in contact with a permanent magnet of the proper strength for a considerable time (Chhatwani,2011).

Magnetic field has also been successfully applied for separation purposes (Augustu etal., 2005 and Ali-zade etal., 2008).

Magnetism is a unique physical property that independently facilitates applications such as water purification by affecting the physical properties of contaminants in water. In combination with other processes, it can improve the efficiency of purification technology (Ambashta etal., 2010). This physical treatment helps to avoid the use of chemicals such as polyphosphates corrosive substances, which are expensive and can be harmful to human life or disruptive to the environment.

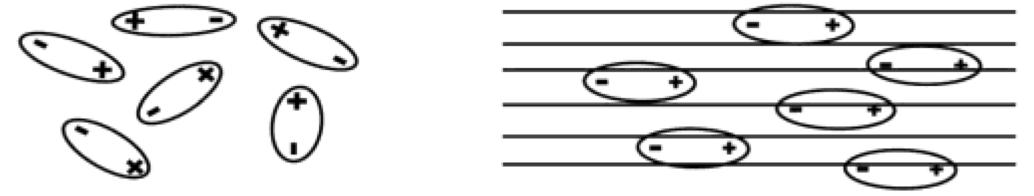
Magnetic technologies are currently being implemented in various ways through the application of either permanent magnets or high-gradient magnetic separation (HGMS) in combination with magnetic seeding, magnetic adsorption, or an electromagnetic device. The different approaches to magnetic applications have significantly different effects on the performance of each system. The use of permanent magnets normally creates a uniform magnetic field. However, the field can be varied by changing the orientation and arrangement of the magnets. Different shape of permanent magnet can also exhibit different magnetic field. Meanwhile, if an electromagnetic device is used, dynamic magnetic field is generally obtained. Hence, This article review magnetic field applications, particularly in environmental engineering to improve treatment systems or processes. The concepts of magnetization, such as magnetic gradient, Lorentz force, and magnetic memory are all considered. The implementation of magnetic field in various applications, particularly in the crystallization of calcium carbonate, water purification, coagulation and sedimentation of colloids particles, and wastewater treatment are presented. Then, the potential benefits and limitations of magnetic field applications in water and wastewater treatment systems.

MATERIALS AND METHODS

The mechanism of magnetic applications has not been completely confirmed scientifically by researchers. Many papers describe different types of magnetic mechanisms, and several of them are even in conflict with each other. This is because most of the literature does not consider the entire effect of an application. According to (Kronenberg, 1983), the basic principle of magnetic applications is related to the existence of molecular nucleation. However, this principle does not explain how it can be achieved or why the effect of magnetism can differ depending on the media or application. This review article highlights four factors that contribute to the use of magnetic field: magnetization and exhibition of a magnetic field (Johan,2003), a magnetic gradient (Oshitani etal., 1999), Lorentz force (Spiegel,1998), and magnetic memory (Ellingsen etal.,1979). These factors determine a complete concept and mechanism for the effectiveness of magnetic field applications. Magnetization and Exhibition of Magnetic Field Particles or molecules can be categorized as positively charged (positive χ) or negatively charged (negative χ), where χ is their magnetic susceptibility. Their magnetization M can be expressed as

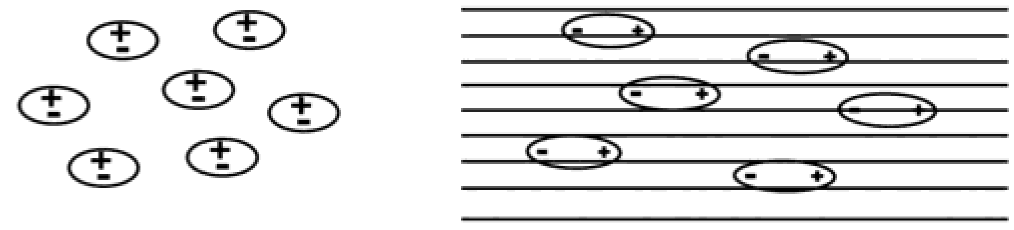
$$M = \chi v.H \qquad (1)$$

where H is an applied magnetic field in emu/cm3, M is magnetization of a particle after exposure to H , and χvis a measured magnetic susceptibility of the molecules' electrons due to the magnetization. Molecular substances can also be classified as polar or nonpolar. In a nonpolar molecule, the center of



Arrangement of polar molecules in the absence of magnetic field

Arrangement of polar molecules under influence of magnetic field



Arrangement of nonpolar molecules in the absence of magnetic field

Arrangement of nonpolar molecules under influence of magnetic field

FIGURE 1 Effect of a magnetic field on polar (top) and nonpolar (bottom) molecules.

Gravity of the positively charged nuclei and the electrons coincide, while in a polar molecule, they do not.

Both polar and nonpolar molecules are illustrated in Figure 1. In the absence of magnetic field, polar molecules are positioned randomly. Thus, their negative and positive charges are impossible to attach to each other, even though collisions between the molecules occur. However, when the samples are exposed to a magnetic field of certain intensity, the polar molecules are easily aligned in accordance with their positive and negative charges. Meanwhile, nonpolar molecules in the absence of a magnetic field move continuously at random because the positive and negative charges coincide in the centers of molecules.This inhibits coagulation. However, under the influence of a magnetic field, the positive and negative charges can be separated. The molecules are aligned in accordance with the direction of the magnetic field (Vick,1991). With the resulting alignment, as shown in Figure 1, the molecules are in an orderly arrangement, causing the particles to coagulate and aggregate. In addition, the number of dipoles pointing in the direction of the field increases with increasing field strength. This makes it more likely that the particles coagulate and that uncommon or unnecessary particles or pollutants can be removed.

Magnetic Gradient

(Oshitani et al. 1999) claimed that the effectiveness of a magnetic application ultimately depends not only on the magnetic strength but also on the magnetic gradient or magnetic flux concentration, which changes frequently along the magnetic device. The energy E produced by the magnetization M of a material and the magnetic field H for a volume V of the material can be expressed as follows:

$$E = -VM.H = -V\ (\chi v.H)\ .H \qquad (2)$$

Eq. (2) can be simplified by assuming that the material load is parallel to the magnetic field and density when M is uniform. Thus, the magnetic interaction force F can be obtained as expressed in Eq. (3), where χo is the magnetic susceptibility of the material that accommodates the magnetized material.

$$F = -(dE/dx) = (\chi v - \chi o)\,VH\,(dH/dx) \qquad (3)$$

In Eq. (3), the most critical parameter that affects the effectiveness of magnetic applications is dH/dx, which indicates the rate of change of the magnetic field strength with distance and is called the magnetic gradient. When the magnetic field is uniform, $dH/dx = 0$, so the particles are magnetized and aligned with the magnetic field. However, the particles are not exposed to a magnetic force that would ensure their separation from the solution. The magnetic gradient also becomes more significant when the volume V of material that is separated is small. The highest magnetic gradient is required in order to produce the strongest magnetic force on the particles for separation purposes. In addition, existence of the magnetic gradient and a magnetic field of alternating strength become more effective than a static magnetic field for the aggregation such as CaCO3. The imple mentation results in more rapid crystallization occurrences, thus enhancing the de-scaling process in a shorter period of time. These significant effects were proven by (Kronenberg, 1983) and Oshitani et al. 1999).

Magnetic filtration can also be conducted by creating a magnetic gradient that can trap suspended solids (Radorenchik,1995) from a solution. In this case, the magnetic gradient can be developed by allowing a solution containing charged particles to flow through coils that are magnetized by permanent magnets located outside the pipes. The north and south poles of the magnets are arranged alternately in opposite directions to create an alternating magnetic field (Hirscbein etal.,1982). A combination of coil magnetization and the magnetic field produces magnetic gradient of higher intensity. This causes the flux lines to become considerably close to each other and more concentrated. The flux intensity increases with increasing coil concentration. When the solution flows through the coils, the charged particles are attracted thus separated from the original solution (Johan,2003). The intensity of the magnetic gradients therefore depends greatly on the magnetic strength and the characteristics of the coil magnetization.

Lorentz Force

Another significant factor that influences the mechanism of magnetic applications is the Lorentz force. This force affects charged particles moving through a magnetic field. The force increases linearly with particle charge, the particle velocity, and the orthogonal vector component of the magnetic field strength. As shown in Figure 2, when charged particles flow in the direction perpendicular to the direction of the magnetic field in the same plane, they produce a Lorentz force that is also perpendicular to the direction in which the charged particles flow and the magnetic field direction (Spiegel, 1998). The Lorentz force acts in the z-plane. Consequently, the charges on the surfaces of the particles are displaced from their original positions, causing the molecules to become unstable. The unbalanced particles move randomly and collide with each other, which cause them to aggregate (Bernardin etal.,1991). The Lorentz force has been proven to promote enhancement of water-related mechanisms, including dissolution enhancement (Basch etal., 1986), crystallization nuclei formation (Beleva, 1972), stabilization of coordinated water and double layer distortion (Gamajunuv, 1983).
Lorentz force is commonly exemplified by the phenomenon of electrical generators as shown in Figure 3. This figure indicates that when a wire carrying an electrical current I is placed in a magnetic field B, each of the moving particle charges comprising the current can experience the Lorentz force F . The force can also appear when both magnetic and electrical fields are acted on the moving particle charges. The induced Lorentz force creates a macroscopic force on the wire that is responsible for the motional electromotive force (EMF), the force underlying many electrical generators. When a conductor is moved through a magnetic field, the Lorentz force tries to push electrons through the wire, creating the EMF (Johan,2003). This phenomenon has been applied in the

development of a magnetic treatment device (MTD) in water applications to inhibit lime scale deposition on pipe wall (Basch etal.,1986).

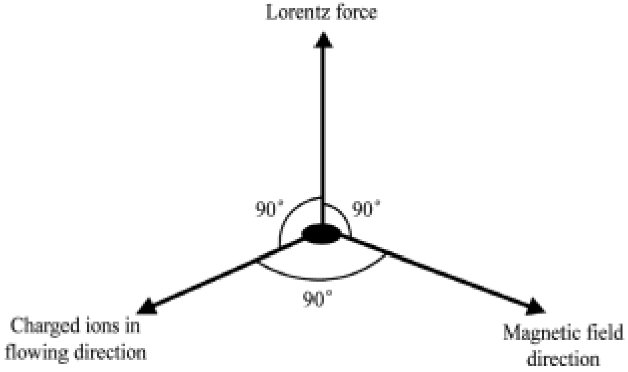


FIGURE 2 The Laplace-Lorentz force on a moving charged ion is at right angle of both the ion flowing direction and the magnetic field direction.

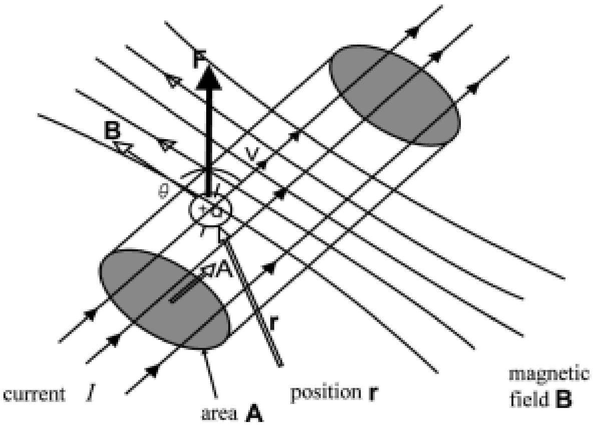


FIGURE 3 An electric wire with cross-section **A** flown by a current **I** is submitted to a force **F** when placed into a magnetic field **B.** Figure 2 gives the direction of

MagneticMemory

Magnetic memory can be defined as a period in which particles can sustain their magnetization properties after being exposed to magnetic field of certain intensity. Magnetic memory phenomena have been reported by (Kristiansen etal., 1979)and (Tombácz etal., 1991). The effects of magnetic memory on particles were recorded over time periods ranging from 10 minutes to 150 hours. (Higashitani etal.,1995) found that the magnetic memory can be observed until 6 days after the exposure of a CaCO3 solution to magnetic field.

In explaining magnetic memory, (Lychagin 1974) postulated that when a magnetic field affects water molecules, it changes their kinetic energy. These occurrences change the momentum of the dipolar molecules and thus cause particles aggregation. The formed aggregates are stable and sufficiently large, making it difficult for them to return to their original shapes even after the magnets are removed. This indicates that the magnetic memory stored by the aggregates can last almost permanently (Johan,2003). The results were also supported by (Colic etal.,1999), who claimed that changes in the molecular structure are caused by magnetic memory. However, the effects of magnetic memory on microorganisms or bacteria may differ from those on water molecules or other particles. For particles, higher magnetic memory is proven to improve the aggregation, but the condition is not so applicable for bacteria or microorganisms. Magnetic memory of either weak or high may improve or hinder their growth activity, thus influencing the performance of systems, especially the wastewater treatment system. Such consequences can be explained in terms of magnetic susceptibility. Different bacteria exist in a system and may have limitations on the susceptibility level towards the magnetic field. When the level is exceeded, the bacteria may die or exhibit growth reduction (Lebkowska etal.,2011 and Yavuz etal.,2000).

IMPLEMENTATION OF MAGNETIC FIELD

Magnetic technology has been used for decades in various applications. The following sections highlight application of magnetic technology in the field of water and wastewater treatment.

Crystallization of Calcium Carbonate (CaCO3)

CaCO3 precipitation has been the focus of numerous investigations because of its application in several industrial processes as pigment, brightener filler, and adsorbent (Heywood etal.,1991and Alimi etal.,2009).

However, CaCO3 scale deposition causes damages and operational issues such as pipe blocking, membrane clogging, and efficiency decay in heaters or heat exchangers. Various methods have been used to prevent scaling, which include water decarbonization through electrochemical processes, seeding or acid addition, and the addition of chemical inhibitors. However, these chemicals are deleterious to human health, and their use is forbidden in drinking water. Therefore, physical methods have been developed to avoid the addition of these chemicals; magnetic treatment of hard water is one of the methods currently used to prevent incrustation by these mineral salts (Alimi etal.,2009 and Bogatin etal.,1999).

CaCO3 can be categorized into three different polymorphs: calcite, aragonite and vaterite. Of these three, the most dominant polymorphs are calcite and aragonite. (Donaldson, 1988), proved that the existence of a magnetic field may cause occasional differences in the type of precipitated crystals. The initial ratio of calcite and aragonite was 80:20, but changed to 20:80 after magnetic treatment. This change promoted the precipitation of CaCO3 because aragonite seemed to be more easily precipitated as compared to calcite. Calcite in contrast, is the most thermodynamically stable form at standard temperature and pressure , and is likely to form dense layers that are difficult to be removed mechanically. Under normal conditions, aragonite seed crystals grow very little. When a magnetic field was applied, the aragonite grew significantly; the growth rate increased to a constant value after a certain period of magnetization. The pre-magnetization time to reach a steady growth rate was also shortened when applying higher magnetic field intensity or applying the magnetic field to the aragonite seed crystals.

Water Purification

Water management techniques can be categorized according to the source of water and can be further classified as natural, domestic and industrial wastewater management. Depending on the water quality, Each scheme requires a separate plan of action for reuse or disposal, and water purification is one of the commonly adopted approaches. The possible techniques of purification are adsorption, biotechnology, catalytic processes, membrane processes, ionizing radiation and also magnetically assisted processes. Of all the techniques, a review on the role of magnetization in water purification to date is apparently lacking. Hence, this article discusses the applications of magnetic technology in water purification.

HGMS is a commonly used magnetic particle separation technique, in which a magnetically susceptible wire bed is placed inside an electromagnet. When a magnetic field is applied across the column, the wires dehomogenize the magnetic field, producing large field gradients around the wires that attract magnetic particles to their surfaces and trap them there. The collection of particles depends strongly on the creation of these large magnetic field gradients, as well as the particle size and magnetic properties. For successful collection of magnetic particles by HGMS, the magnetic force attracting particles toward the wires must dominate the fluid drag, gravitational, inertial, and diffusion forces as the particle suspension flows through the separator.

(Ha et al.2011) claimed that a superconducting HGMS system has advantages in removing pollutants and paramagnetic substances such as iron oxides due to the generation of a higher magnetic field strength. A cryocooled Nb–Ti superconducting magnet is an example of an HGMS system that can generate field strength of up to 6 T. The efficiency of HGMS was demonstrated by its use in the steam condensers of thermal power stations . The study found that contaminants consisting of α-Fe2O3 (hematite) and γ-Fe2O3 (maghemite) were effectively removed.

As the magnetic field strength increased, the turbidity of the condenser water was reduced. In addition to the increase in magnetic strength, the removal of turbidity in the condenser water was also enhanced as the wire diameter of the magnetic filter decreased and the mesh size increased. This is the rationale for determining the magnetic gradient at which changes in the mesh size and magnetic filter diameter cause changes in the magnetic field strength with distance (dH/dx). A higher magnetic gradient leads to efficient purification of a contaminated water source.

The use of iron oxide was also implemented and a combination of magnetic separation and maghemite (γ-Fe2O3) nanoparticles successfully adsorbed arsenic pollutants, As(V).

Besides the usefulness of HGMS, other studies have used high-temperature superconductivity bulk magnet systems that exhibit a higher susceptibility level. Using single pass, the adverse effect can be minimized. However, trial runs should be able to assist in the selection of the flow types.

As for magnetite adsorbent, the limitation would be the adsorption capacity of the adsorbent. The application of magnetite has to be supported by the magnetic separator. Through such approach, the exhausted adsorbent can be easily removed from the wastewater. To prolong the efficiency of the magnetite, the surface area must be sufficiently large so that the life of magnetite can be extended. The capacity of magnetite to adsorb also depends on the regeneration frequency of the adsorbent.

Based on the advantages and limitations of the magnetic field applications, it can be indicated that this technology is reliable and beneficial for the enhancement of water and wastewater treatment systems.

CONCLUSIONS

Magnetic field technology is highly suitable for various types of environmental engineering applications. Significant outcomes of the magnetic applications have been demonstrated under various types of magnetic modes such as permanent magnets, direct or alternating current, magnetic adsorbent, HGMS, and superconducting magnets. It is evident that the implementation of magnetic field accelerates the crystallization of CaCO3, enhances both the purification efficiency of contaminated water and the synthesis of PHAs even under unfavorable conditions. Magnetic field is also proven to improve the physical properties of the particles for enhancement of precipitation, coagulation and sedimentation. The improvement occurs as the magnetic field positively influences the aggregation of the colloidal particles and enhances solid-liquid separation process. The improvement resulted in better performance of the treatment systems. Magnetic field application also significantly influences the bacterial activity and enhances the biological treatment processes. This indicates that a magnetic field has the potential to minimize the proliferation of filamentous microorganisms, thus reducing the occurrence of bulking sludge.

Bulking is a notable operating problem that occurred in the activated sludge process caused by the excessive proliferation of the filamentous. Due to the severity of these occurrences, bulking Application of magnetic field towards minimizing the bulking sludge is apparently problem represents a frontier area for future research.

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