Journal of Cleaner Production 161 (2017) 908–921

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Characteristics and applications of magnetized water as a green technology

Ehsan Esmaeilnezhad [a], Hyoung Jin Choi [b, *], Mahin Schaffie [a, c], Mostafa Gholizadeh [d], Mohammad Ranjbar [a, e]

[a] Department of Petroleum Engineering, Shahid Bahonar University of Kerman, Kerman, Iran
[b] Department of Polymer Science and Engineering, Inha University, Incheon, 402-751, South Korea
[c] Department of Chemical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran
[d] Department of Chemistry, Ferdowsi University of Mashhad, Mashhad 91779-1436, Iran
[e] Department of Mining Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

ARTICLE INFO

Article history:
Received 22 March 2017
Received in revised form
21 May 2017
Accepted 27 May 2017
Available online 30 May 2017

Keywords:
Magnetized water
Surface tension
Green technology
Scale
Enhanced oil recovery

ABSTRACT

Water can be magnetized under an applied magnetic field, and some important properties of magnetized water have become useful in industries associated with its surface tension, pH, viscosity, electrical conductivity, and scale formation inhibition. The surface tension of water decreases upon the application of a magnetic field, while its pH increases. In addition, the shear viscosity of magnetized water increases and the magnetic field inhibits scale formation. This paper reviews the unique properties of magnetized water as well as its potential applications as a smart and more environmentally friendly fluid in the oil industry, e.g., as an injection fluid in enhanced oil recovery areas for producing oil.

Contents

1. Introduction

Magnetic field (MF)-treated water, so-called “magnetized water (MW)”, has been a challenging subject over the last several decades

---

* Corresponding author.
E-mail address: hjchoi@inha.ac.kr (H.J. Choi).

http://dx.doi.org/10.1016/j.jclepro.2017.05.166
0959-6526/

in both academia and industry, despite the controversy and the lack of a complete understanding. While many groups have confirmed the effects of MFs on water, some researchers still refute this effect (Algarra et al., 2008). Sophie (1953) reported the first attempt for the magnetic treatment of a liquid. Since then, the water magnetizing technique has developed rapidly in many areas, such as irrigation (Da Silva and Dobranszki, 2014), plant growth (Da Silva and Dobranszki, 2016), plant productivity (Hozayn et al., 2016), wastewater treatment (Zaidi et al., 2014), water purification (Ambashta and Sillanpaa, 2010), scale reduction (Simonič and Urbancl, 2017), animal science (Gilani et al., 2014), and medicine (Hafizi et al., 2014). This paper focuses on the properties of MWs that could be useful in industry, such as pH, hardness, scale formation, total dissolved solid, viscosity, surface tension, contact angle, and electrical conductivity. Owing to some controversial results, the direct application of MW properties to industry requires more study. This paper reviews the magnetization effects as well as the measuring tools (accuracy and precision), treatment conditions, and water solution properties. In addition, the effects of MF on the water properties depending on the test conditions are examined and a new method for enhanced oil recovery (EOR), which involves water flooding into oil reservoirs for extra crude oil recovery, is proposed. Overall, MW could have wide applications as a type of smart fluid.

The magnetization procedure of the water is simple without extra energy consumption when a permanent magnet is used. A permanent magnet can be installed on a previously established water tube system, resulting in no further energy requirements for water magnetization. This green technology is zero energy consumption and clean. Compared to other methods for EOR, which consume considerable energy and involve the addition of non-environmentally friendly materials to oil reservoirs, the oil production with this zero energy consumption technique is a clean production process.

Two main ways of making MW have been reported. The first is passing water through a MF and the other is using a static magnet near a certain volume of water. The MF strength and the time of magnetization have a great impact on the properties of MW. Furthermore, the MW treatment efficiency depends on the field–field gradient product (Nakagawa et al., 1999). Mosin and Ignatov (2014) introduced two main types of devices for a MW treatment based on either a permanent magnet or an alternating current solenoid electromagnet generating an alternating MF. Loraine and Huchler (2002) listed the devices currently available from a web-based search or contact with the manufacturers for water magnetizing purposes, and provided a brief review of the technologies and patents, evidence of efficacy, currently understood mechanism, and technology applications.

2. What is the water magnetizing mechanism?

Water, as a diamagnetic material, has a mass magnetic susceptibility of approximately -7.20×10^{-3} JT^{-2}/kg (Sueda et al., 2007). Pure water, as a polar and associative liquid, can alter its intermolecular bonds under a MF, transforming to a metastable state and retaining that state for some time (Golovleva et al., 2000). The MW treatment affects both the chemical and physical processes of dissolution and crystallization of water (Mosin and Ignatov, 2015). Nakagawa et al. (1999) reported essentially two different types of conceivable field effects. One is a direct field effect on the biochemical reactions; the other is indirect via changes in the surroundings. In the case of the former effect, the concern might be the possible genetic influence that a MF can have on living organisms. In the case of the latter, however, the MF effects can be considered like any other external parameter, such as temperature, pressure, or mechanical stirring.

Boichenko and Sapogin (1977) introduced the primary theory about MW treatments and Mosin and Ignatov (2014) then proposed three mechanisms of action of a MF on water. The first hypotheses assumes that the spontaneous formation and decay of colloidal complexes of metal cations occurs in MW, which accelerates their subsequent sedimentation. The second hypothesis is the polarization of dissolved ions in water and deformation of their hydration shells by the MF. According to the third hypotheses, the MF influences the structure of water directly, due to the dipole polarization of water molecules. H_2O molecules are bound together via low energy intermolecular van der Waals forces, hydrogen bonding, and dipole-dipole interactions. MF may deform the hydrogen bonds and cause some partial rupture.

Producing a weaker hydrogen bond in MF is also related to the Lorentz force, which makes the positive and negative ions rotate oppositely, thereby increasing the likelihood of ion collision. The movement of molecules then becomes more intense, its thermal motion increases and hydrogen bonding becomes weaker. Therefore, weaker hydrogen bonding is obtained with increasing magnetized time (Wang et al., 2013). A high MF (14 T) may affect the formation of hydrogen bonds of water molecules (Iwasaka and Ueno, 1998).

Based on the theory of magnetization of water (Pang and Zhong, 2016), the variation of the magnetization effect of water increases with increasing exposure time (in a fixed MF strength at 3000 Gauss) and with an increasing externally applied MF strength that can reach saturation at a higher MF strength (Fig. 1).

Weakly bound van der Waals complexes can be dissociated in a MF. The pre-dissociation of weakly bound van der Waals complexes contain atoms with a non-zero electronic orbital angular momentum in a MF when transitions to lower magnetic levels releases sufficient energy to break the van der Waals bonds (Krems, 2004).

In contrast to the third hypothesis, Hosoda et al. (2004) suggested that the hydrogen bond has greater stability in a MF that can be increased. As the diamagnetism of a molecule depends on the extent of the electron distribution, the electron delocalization of hydrogen-bonded molecules should increase its diamagnetism. Therefore, the hydrogen bond should become more stable under a MF, which is the main reason for some change in the water

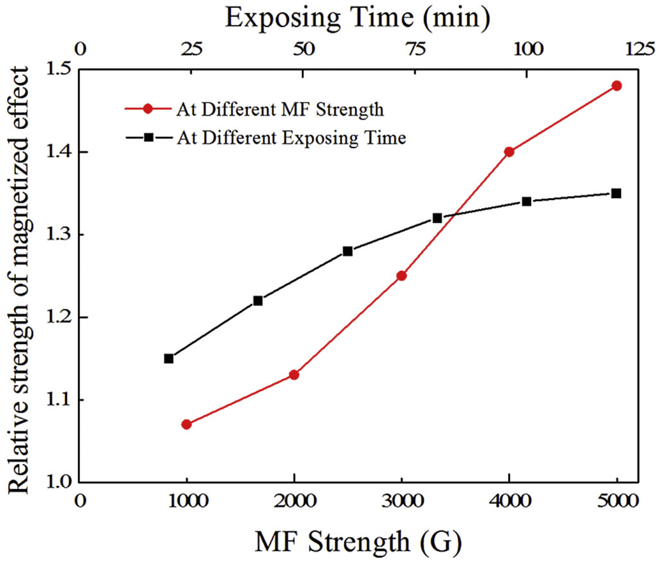

Fig. 1. Variations of the magnetized effect of water with increasing exposure time and MF strength (Reprinted from Pang and Zhong, 2016).