Effect of electromagnetic field on water-in-oil emulsion and calcium carbonate crystallization

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Abstract. The investigation was devoted to the effect of electromagnetic field on crystallization of calcium carbonate, structure of CaCO₃ crystals generated from oversaturated aqueous solutions, and water-in-oil emulsion (crude oil) properties. XRD demonstrated that electromagnetic field caused a decrease in mean size of CaCO₃ particles by 30 μm and prevalent aragonite formation. We detected that electromagnetic field application leads to decreased apparent viscosity of water-in-oil emulsion and inhibits influence of a non-ionogenic surfactant on stability and viscosity properties of crude oil. As a matter of practice, the method demonstrated its efficiency to prevent scale deposits in oil production wells.

1. Introduction

High-viscosity oil production requires development of advanced technologies to inhibit scaling in an oil/gas production well and to reduce viscosity of multi-phase flow of crude oil (i.e., a water-in-oil emulsion stabilized with asphaltenes, resins, naphthenic acids and other oil components [1-4]). Due to increasing amount of oil production and increase in its water cut that, in turn, causes reduced permeability of an oil-bearing bed, worse well capacity, higher operating costs, and deposit-associated failure of pumping equipment in a well, oilfield deposits found in most of actively produced oilfields recently became an especially burning issue [1-3,5]. Calcium carbonate, calcium and barium sulphates, corrosion byproducts, mechanical impurities and asphaltene-resin-paraffin compounds are primary components of most of these deposits [1].

Being the main method of addressing the issue of scaling in the oil production, scale inhibitors have a negative environmental effect [1]. In this respect, recent trends of natural management suggest developing advanced technologies to decrease the amount of oilfield reagents. Many studies dealing with effect of magnetic, electromagnetic, acoustic and electric fields on bulk crystallization in solution, nucleation and growth of crystals, as well as interaction between formed particles demonstrate evident opportunities of a physical field application to prevent the formation of oilfield scale [5-12]. For example, according to [6], the influence of electromagnetic fields on nucleation and growth rate of calcium carbonate crystals was assessed under dynamic conditions. A relationship between electromagnetic field effect on calcium carbonate crystallization and Ca²⁺/CO₃²⁻ ratio was detected. Application of electromagnetic field results in decreased crystal agglomeration rate and prolonged precipitation time.

As these methods do not eliminate a primary cause of crystallization (i.e., oversaturation) but modify nucleation and growth of crystals, they are supplemental ones. However, often that’s enough
to provide continuous operation of oilfield equipment. A distinct advantage is their potential application during primary oil production.

The paper presents findings of the study evaluating electromagnetic field effect on water-in-oil emulsion properties and calcium carbonate scaling in the mineral water model.

2. Experimental procedure

Electromagnetic field effect on inhibition of calcium salt crystallization was assessed in the mineral water model (ion composition - \( \text{Ca}^{2+} - 270.5\), \( \text{Mg}^{2+} - 30.3\), \( \text{Na}^{+} - 3120.2\), \( \text{Cl}^{-} - 4492.1\), \( \text{HCO}_3^{-} - 1525.5\) mg/l prepared from salts of \( \text{CaCl}_2\), \( \text{MgCl}_2\cdot6\text{H}_2\text{O}\), \( \text{NaCl}\), \( \text{NaHCO}_3\) [analytical reagent grade]).

Natural water-in-oil emulsion (Uzen Oilfield, Kazakhstan) and 29-(4-nonylphenoxy)-3,6,9,12,15,18,21,24,27-nonaoxanonacozanol-1 (neonol AF 9-10) (Nizhnekamskneftekhim PJSC) were used in this study. Tested oil was centrifuged from water-in-oil emulsion. The oil API (19.1) was calculated as per the formula (141.5\(\times \rho_w / \rho_o - 131.5\)), where \( \rho_w \) [1.01 g/cm\(^3\)] is oilfield water density. According to the American Petroleum Institute, this is heavy oil [13].

Density and viscosity of oil and water-in-oil emulsion were evaluated as per ASTM D1298 and ASTM D445-06 standard methods. Oil paraffins and asphaltenes were assayed as per ASTM D6560-12 and ASTM D5442-17. To assay resins, we used the method described in the collector [14]. Water level was determined as per ASTM D4006 method.

See physicochemical properties of a test oil sample, as well as paraffin, resin and asphaltene levels in extracted oil in table 1.

| Parameter                     | Value   |
|-------------------------------|---------|
| Water level in a sample, %    | 28.0    |
| Density (kg/m\(^3\)) at 20°C  | 949.1   |
| Density (kg/m\(^3\)) at 50°C  | 936.5   |
| Viscosity (mPa\(\times\)s) at 20°C | 1450   |
| Viscosity (mPa\(\times\)s) at 50°C | 250    |

Oil component levels

| Parameter | Value |
|-----------|-------|
| paraffins | 1.6   |
| resins    | 14.9  |
| asphaltenes | 0.1   |

Laboratory studies of electromagnetic unit effect on \( \text{CaCO}_3 \) crystallization were performed on a laboratory bench (at Pilot National Research Institute of Technologies and Communication) where electromotive force was generated by axial core coil of an electromagnetic radiator. Its resultant vector is directed along the axis of downhole equipment. Moreover, orthogonal coil leads to formation of magnetomotive force which resultant vector is directed along the motion axis of oversaturated aqueous solution in \( \text{CaCl}_2\) - \( \text{MgCl}_2\) - \( \text{NaHCO}_3\) - \( \text{NaCl}\) model system at 75°C (figure 1). When a radiator generates an electromagnetic field, flux density affecting solution (emulsion) is 1.5-1.8 T.

\( \text{CaCO}_3 \) crystal size was recorded by a Analysette 22 NanoTec Plus laser particle sizer.

Morphological properties of \( \text{CaCO}_3 \) particles formed under electromagnetic field conditions were evaluated by a Rigaku Ultima IV X-ray diffractometer. The test was carried out by Cu Kα radiation at 20 kV and 2 mA (\( \lambda = 1.5405\) Å). Imaging was performed in angular range of \( 2\theta = 15\text{-}115^\circ \) (sampling interval - 0.02°). XRD pattern and phase analysis were carried out in Match! software.
Figure 1. Distribution of flux density vectors in electromagnetic field generated by a radiator.

Microstructure of CaCO$_3$ samples was evaluated by field emission scanning electron microscopy (FE-SEM) with a Hitachi SU8000 electron microscope. Imaging was performed by secondary electron recording at acceleration voltage of 2 kV and working distance of 4-5 mm. Analytical measurements were optimized as per the method described above [15]. Before imaging, samples were placed on surface of an aluminium table ($\varnothing = 25$ mm) and attached by conductive adhesive. Then, metal (Pt/Pd, 80/20) conductive layer (thickness = 7 nm) was sprayed on them by previously discussed magnetron sputtering method [15]. Sample morphology was assessed considering correction for surface effects of conductive layer spraying [16].

Rheological properties of water-in-oil emulsions were evaluated by a Haake Viscotesteri Q rotary viscometer. To estimate relationship between shear stress, viscosity and shear rate, we applied a shear test altering shear rate in the range of 1-300 s$^{-1}$ for test samples.

Effects of electromagnetic field and neonol AF 9-10 on stability of water-in-oil emulsions were evaluated by a dispersion stability measuring tool suite (Turbiscan Tower, Formulaction SA).

3. Results and discussion

It is a known fact that effect of electromagnetic field on aqueous solutions leads to alteration of water structure, hydrated ions and solubility of inorganic salts [17-19]. Application of magnetic field on water-in-oil emulsion results in destruction of dispersion structure caused by cleavage of hydrogen bonds of weak paraffin dipoles and paramagnetic particle spin-flip that, in turn, results in alteration of oil viscosity properties and affects calcium carbonate scaling [20].

Calcium carbonate scaling occurs in water-in-oil emulsion during oil production. Hence, we assessed effect of electromagnetic field on crystallization of calcium carbonate, as well as stability and viscosity properties of crude oil.

Data on size distribution of CaCO$_3$ crystals obtained by the laser particle sizer demonstrated that effect of electromagnetic field (103 kHz) on calcium carbonate crystallization in oversaturated aqueous solution leads to decrease in mean crystal size by $\approx 30 \mu$, more narrow range of CaCO$_3$ particle size distribution (mean size $\sim 38 \mu$) as compared with crystals originated in the same conditions without electromagnetic field application (figure 2). A great number of simultaneous physical, chemical and hydrodynamic processes are running during bulk crystallization in solution. Along with this, nucleation and growth of crystals, as well as interaction of formed particles between each other cause polydispersity of calcium carbonate crystals [21].
Figure 2. Size distribution of CaCO₃ crystals exposed to electromagnetic field (103 kHz) over time.

Depending on temperature, pH value of solution, nature of organic and inorganic additives, produced calcium carbonate can crystallize in three crystallographic modifications (i.e., calcite, aragonite and vaterite) [22]. Considering our conditions, effect of electromagnetic field on oversaturated aqueous solution results in prevalent formation of aragonite (i.e., CaCO₃) in CaCl₂ - NaHCO₃ - NaCl model system at 75°C (figure 3).

Figure 3. Diffractogram of CaCO₃ crystals formed under electromagnetic field conditions. Calcite (C). Aragonite (A).

Since application of electromagnetic field results in the decrease of mean CaCO₃ particle size and prevalent formation of low-adhesive aragonite crystals [12], the produced calcium carbonate can be easily transferred by water-in-oil emulsion from a well instead of its precipitation on oilfield downhole equipment. As calcium carbonate (i.e., aragonite) particles have lower free superficial energy than calcite, they are low-adhesive to surface of oilfield equipment. Moreover, aragonite crystals demonstrate low agglomeration between each other [12].
Electron microscopic data comply with results of X-ray structure analysis. SEM images of aragonite crystals demonstrate their dendrite structure with crystallic radiate-fibrous pseudohexagonal aggregations (figure 4).

![Figure 4](image-url)  
**Figure 4.** Electron micrograph of CaCO₃ crystals formed under electromagnetic field conditions.

Oil is a disperse medium of oil-in-water emulsions in producing wells with low water cut at initial stages of oilfield development and exploitation. The review [23] describes a relationship between composition and structure along with advanced physicochemical, chemical and physical approaches to evaluation of emulsion structural features that determine their rheological properties. Due to relatively low bulk concentration of disperse particles in oil, the apparent viscosity of the disperse system is more than the oil viscosity [24].

Analysis of 'apparent viscosity-shear rate' curves demonstrated that at 20 °C crude oil flow follows the Newton's law, so the emulsion performance is equal to Newtonian fluid. Electromagnetic field exposure results in decrease in crude oil viscosity from 1,450 to 1,140 mPa·s without aqueous phase extraction. Turbiscan technology [25] that enables analysis of disperse system stability revealed that electromagnetic field (EMF)-induced decrease in apparent viscosity of crude oil results from loss of water-in-oil emulsion (WOE) stability confirmed by increased Turbiscan stability index (TSI) (figure 5).

It's a known fact that neonol AF 9-10 is an efficient reagent to reduce apparent viscosity of water-in-oil emulsions [24]. When we had detected that electromagnetic field exposure decreased apparent viscosity of crude oil, we electromagnetized a sample of crude oil containing 1% neonol AF 9-10 with a view to increase efficiency of the surfactant application. Contrary to our expectations, viscosity increased to 1,280 mPa·s, and influence of the surfactant on rheological properties of the emulsion was almost inhibited.

Pilot Corporate Group developed a scale-preventing resonant wave system which action is based on electromagnetic field [9]. Pilot testing of the electromagnetic unit demonstrated its anti-scale efficiency in wells equipped with electrical submersible pumps [5]. Application of the resonant wave system led to increase in mean time before failure by more than 6 times in scaled wells.

4. Conclusion
We presented results of laboratory testing of electromagnetic field effect on calcium salt crystallization that provide several opportunities for scale protection technologies. Also, we obtained experimental data on electromagnetic field effect on stability and rheological properties of oil. The electromagnetic unit prevents scale formation in downhole oil and gas equipment during oil production. The distinct advantage of the method is its potential application during oil production itself.
Figure 5. Electromagnetic field effect on stability of crude oil and oil containing neonol AF 9-10 at 20°C. TSI – Turbiscan stability index, τ – time (min).

Acknowledgement
The research is performed under the scope of the State Order of the subject №АААА-А17-1170011910021-8.

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