

Rheological behavior of magnetically treated petroleum samples Comportamiento reológico de muestras de petróleos tratados magnéticamente

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Abstract

Much of the oil deposits contain heavy hydrocarbons, the extraction of which is difficult due to their high viscosity. Magnetic technology has been one of the methods used to solve these problems. The objective of this research was to evaluate the rheological behavior and viscosity of several magnetically treated samples of Cuban oil. For this, oil samples with different physical-chemical characteristics were used to delve into the relationship between the nature of the fluid and the magnitude of the observed effect. A 0.47 T magnetic conditioner was designed and the experimental installation was validated as a prediction and diagnostic method for its application in oil handling. The magnitude of the effect observed in magnetically treated crude depends largely on the chemical-physical characteristics of the fluid, such as the content of water and asphaltenes, viscosity, density, among others. In this research, the greatest effects are associated with crude oils with high viscosity and high asphaltene content. The magnetic treatment used decreased the viscosity of several samples of Cuban crude oil from 7.6% to 98.17% at different velocity gradients. The rheological behavior of the crude oil samples studied does not change with the magnetic treatment used, but there are changes in the coefficients of the rheological models; decreasing the consistency index in all the analyzed samples, which corresponds to the decrease in the viscosity of the samples after the magnetic treatment.

Keywords: oil, static magnetic field, rheology, viscosity

Resumen

Gran parte de los yacimientos de petróleo contienen hidrocarburos pesados, cuya extracción se dificulta debido a su alta viscosidad. La tecnología magnética ha sido uno de los métodos empleados para solucionar estos problemas. El objetivo de esta investigación fue evaluar el comportamiento reológico y la viscosidad de varias muestras de petróleo cubano tratadas magnéticamente. Para ello se emplearon muestras de petróleo con diferentes características físico-químicas para profundizar en la relación entre la naturaleza del fluido y la magnitud del efecto observado. Se diseñó un acondicionador magnético de 0,47 T y se validó la instalación experimental como método de predicción y diagnóstico para su aplicación en el manejo de petróleos. La magnitud del efecto observado en crudos tratados magnéticamente depende en gran medida de las características químico-físicas del fluido, como pueden ser el contenido de agua y

asfaltenos, la viscosidad, la densidad, entre otras. En esta investigación, los mayores efectos se asocian a crudos con elevada viscosidad y con elevado contenido de asfaltenos. El tratamiento magnético empleado disminuyó la viscosidad de varias muestras de petróleo crudo cubano desde un 7,6 % hasta un 98,17 % a diferentes gradientes de velocidad. El comportamiento reológico de las muestras de petróleo crudo estudiadas no cambia con el tratamiento magnético utilizado, pero si se producen modificaciones en los coeficientes de los modelos reológicos; disminuyendo el índice de consistencia en todas las muestras analizadas, lo que se corresponde con la disminución de la viscosidad de las muestras después del tratamiento magnético.

Palabras claves: petróleo, campo magnético estático, reología, viscosidad

1. Introduction

Crude oil is one of the most demanded and traded primary energy carriers in the world. It is one of the most important raw materials and has been the main source of energy for society since 1950 [1]. Oil prices fluctuate constantly, depending on the global economic situation and the availability of this type of resource that affects supply and demand [2]. The oil industry plays a fundamental role in driving the economy and has a significant impact on the development of other types of industries [1]. However, it causes an adverse environmental impact as it affects the local environment, the community and the workers of these industries to a great extent [3].

In this type of industry, the rheology and transportation of crude oil are essential issues that must be studied, analyzed and updated periodically [4]. Oil transportation has become a complex and highly technical operation. One of the biggest difficulties in pipeline transportation is high viscosity fluids that require efficient and economical ways to transport heavy crude oil [2]. Viscosity reduction is important in the extraction operation, in the production process and even afterwards, in order to reduce the economic costs of the operations carried out in this industry [5]. Currently, different methods are used to reduce the viscosity of heavy crude oils in order to improve the pipeline transportation process, such as dilution with lighter crude oils or alcohols [6, 7], heating and the use of surfactants to stabilize emulsions [2, 8], among others. In the extraction process, the most used methods are steam injection and chemical injection, using combinations of substances [9]. Another method to reduce the viscosity of heavy crude oil is the formation of oil in water (O/W) emulsions, which has been widely studied [8, 10].

The use of magnetic technology to reduce viscosity and even to prevent the formation of deposits in oil pipelines is one of the methods that has attracted the attention of various research groups today and for several years [11-13]. This method generally includes the use of magnetic devices or electromagnets to generate magnetic fields for the treatment of dispersed oil systems [14, 15]. With the application of this type of technology, satisfactory results have been obtained [16-19], and interesting effects have been observed on different properties of these hydrocarbons [15, 16, 20-22]. However, there is very little research on the effect of this type of magnetic treatment on the rheological behavior and viscosity of these complex fluids.

In this sense, the research carried out by Loskutov and collaborators between 2003 and 2008 stands out. In 2003, several samples of crude oil with different paraffin contents (more than 7%), with low density and with high freezing temperatures were analyzed. The magnetic treatment was carried out using a magnetic activator of the MAZh-T2 type and a magnetic induction of 0.6 to 0.8 T. After the magnetic treatment, changes in the activation energy of the fluid and variations in the degree of molecular association of the hydrocarbons were observed [20]. In 2006, these researchers demonstrated that in crude oils with different resin contents, the

alternating magnetic treatment significantly affected the particle size of the dispersed colloidal phase of these systems and, consequently, their rheological characteristics [23]. In 2008, it was concluded that the specific characteristics of the structural-rheological behavior of crude oils, their resin and asphaltene fractions indicate the occurrence of structuring processes, due to a change in the size and activity of associative entities of the oil-dispersed system as a whole, when passing through a magnetic field [12].

On the other hand, in the research carried out by Goncalves et al. in 2011, only one of the six crude oils used in the experimentation decreased its viscosity by 39%, as well as its viscoelastic properties, when subjected to magnetic treatment. In addition, they showed that the presence of large amounts of paraffinic compounds could not be the only factor responsible for the change in the rheological properties of crude oil samples caused by magnetic fields, as other authors previously suggested [24]. Likewise, these authors have also demonstrated the high selectivity of the magnetic treatment on the nature of the crude oils and the great importance of this factor in the magnitude of the effects or changes observed [25].

Due to the variety in the results obtained so far, it has not been possible to establish the mechanism of interaction between crude oil and magnetic fields [26], or its effect on the rheological behavior and viscosity of this type of oil-dispersed systems. Therefore, it is essential to propose strategies or experimental designs that allow us to continue delving into the effects caused by magnetic fields on the properties and rheological behavior of crude oil. In this way, contribute to the clarification of its possible mechanism of action, in order to take advantage of the technical and operational benefits of this new and promising technology.

The objective of this research is to evaluate the rheological behavior and viscosity of several magnetically treated oil samples. For this, crude oil samples with different physical-chemical characteristics were used to delve into the relationship between the nature of the fluid and the magnitude of the observed effect.

2. Materials and Methods

The experiments were carried out at the Fuels Laboratory of the National Center for Applied Electromagnetism (CNEA), of the Universidad de Oriente and at the Petroleum Research Center (CEINPET), in Havana, Cuba.

In this study, samples of five different types of oil (C1, C2, C3, C4 and C5) with a wide variety of physical-chemical characteristics were used. The main analyzes were performed according to the following standards: API gravity (ASTM-D-1298), viscosity (ASTM-D-445) and asphaltenes (ASTM-D-6560). The physical-chemical characteristics of the crude oils studied from C1 to C5 are shown in Table 1.

The physical-chemical characteristics of the analyzed crude oils confirm the heterogeneity of the oil samples. The asphaltene content varies from 0.97 to 16.3% and the water content from 0.2 to 50.67%; depending on their API gravity, heavy oils predominate.

The five crude oil samples studied were characterized from the rheological point of view (flow and dynamic viscosity curves) before and after undergoing the magnetic treatment (MT). For the characterization of the samples, an Anton Paar MCR 301 concentric cylinder rheometer was used, which allows measurements to be made at low velocity gradients. The adjustment of the experimental data to the rheological models was carried out using the professional program

Microsoft Office Excel 2019. The average of the values of shear stress (τ) and the velocity gradient (γ) allowed the flow curves to be plotted and the flow to be characterized. rheological behavior of the samples.

Table 1. Physical-chemical characterization of the crude samples

Parameters	C1	C2	C3	C4	C5	Units
API Gravity 25°C	39,500	15,7	13,900	20,200	9,02	°API
Specific gravity 15°C	0,827	0,961	0,973	0,973	1,0064	g.cm^{-3}
Water and sediment	3,400	50,670	0,200	1,200	24,0	%, v/v
Kinematic viscosity 25°C	2,850	673,600	693,900	666,800	77 400,00	$\text{mm}^2 \text{s}^{-1}$
asphaltenes	0,970	4,560	16,300	12,000	13,62	%
API Classification*	Ligero	Pesado	Pesado	Pesado	Extrapesado	

* Classification according to American National Standard, 1995

The selection of the experimental conditions had as background previous studies carried out by Campos and collaborators from 2009 to 2010, which constituted the methodological reference of this research [15].

Description of the experimental installation for the magnetic treatment

An experimental installation was designed that allows maintaining the laminar flow regime characteristic of the extraction process, through the manipulation of the variables: height, internal diameter of the hose and fluid speed. The proposed installation (Figure 1) consists of a 500 mL graduated separating funnel. A 0.005 m diameter hose is adapted to it, through which the fluid is passed. The magnetic conditioner is placed in a horizontal position and the hose is passed through it to allow the passage of the fluid. Finally, the sample is collected in a container to carry out the corresponding analyses.

Characteristics of the AMF-L1 magnetic conditioner used for the treatment of crude oils

The magnetic conditioner used consists of two dipolar blocks of permanent magnets, connected to each other through a magnetic circuit formed by four CT-3 magnetic steel plates, in such a way that they generate a dipolar magnetic field in the air gap between them. The reference working region of this device is a 1 cm diameter cylinder, centered in the air gap and bounded by the ends of the dipole blocks of magnets, which is 15 cm long. The dipole blocks of magnets each contain three 33.7 MGOe NdFeB (Neodymium-Iron-Boron) permanent magnets, 1x3x5 cm in size.

Among the specifications for the design of the device, a nominal magnetic induction (mean value of the magnetic induction in the work region) between 0.4 and 0.5 T, and a length of exposure to the magnetic field of around 15 cm were considered. For this, the accumulated international

experience regarding the effective magnetic treatment of liquid fuels was taken into account, as well as the considerations for the subsequent use of this type of treatment in oil wells. Figures 2 and 3 show the results of the simulations and measurements performed on this magnetic device.

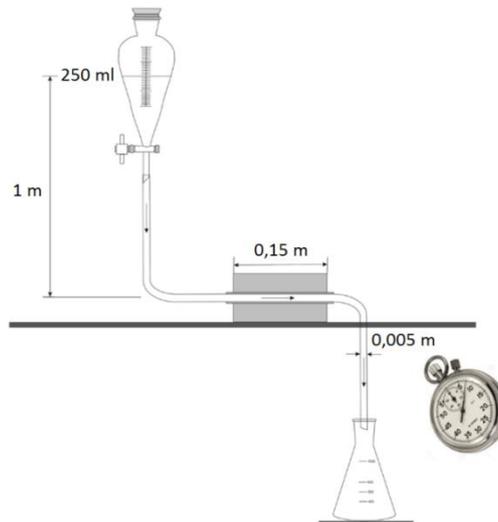


Fig.1 Scheme of the experimental installation proposed for the magnetic treatment of crude oil

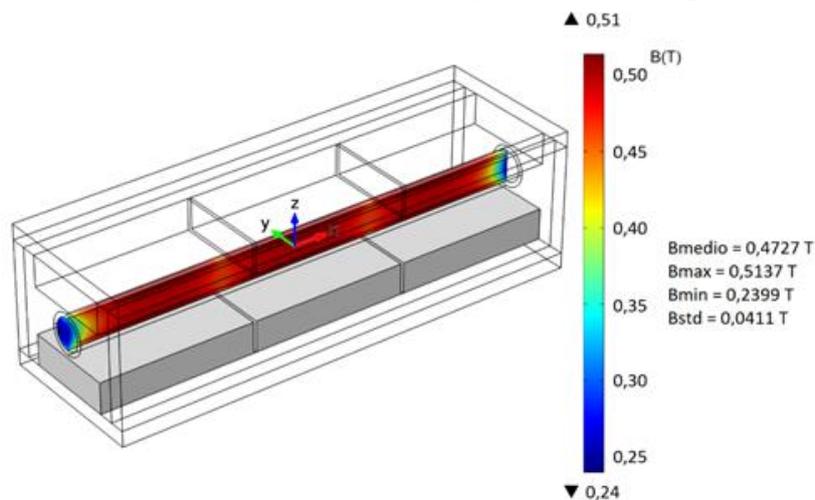


Fig.2 Magnetic induction distribution in the reference working region of the AMF-L1 device

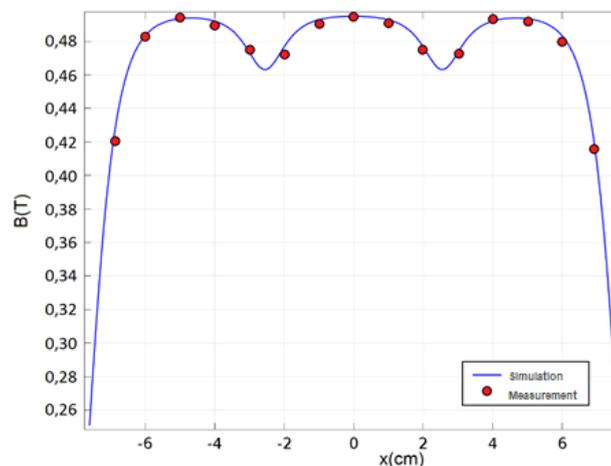


Fig.3 Variation of magnetic induction along the axis of the working region of the AMF-L1 device

For the simulation of the magnetic field, an open, non-linear, 3D magnetostatic problem was solved in the absence of electric currents. The solution domain was a 33.44 cm diameter sphere, inside which the magnetic conditioner is centered.

The equation corresponding to Gauss's law of magnetism was solved, written in the form $-\nabla \cdot (\mu_0 \nabla V_m - \mu_0 \vec{M}) = 0$, where V_m is the magnetic scalar potential; $\mu_0 = 4\pi \times 10^{-7}$ H/M is the magnetic permeability of vacuum and \vec{M} is the magnetization vector. Since the potential V_m is defined as $\vec{B} = -\mu \nabla V_m$, where μ is the magnetic permeability of the medium, the values and distribution of the magnetic induction \vec{B} are found from the post-processing of V_m . In order to obtain the best results, the approach used to model the open domains was the finite element technique. The proposed problem was solved by means of an adaptive mesh of 295 438 tetrahedral elements.

In the working region of the AMF-L1 device that would form a cylinder 15 cm long and 5 mm in diameter, centered in the air gap and limited by the ends of the dipole blocks of magnets, defined by the hose through which the fluid will be passed, the magnetic field simulations yielded the following values for magnetic induction: mean: 0.4711 T; maximum: 0.4999 T; minimum: 0.2478 T; standard deviation: 0.0429 T.

3. Results and Discussion

This section analyzes the experimental results related to the magnetic treatment of crude oil samples and its effect on the rheological behavior and viscosity of these fluids.

Effect of magnetic treatment on the viscosity of crude oil

For heavy oils, the characterization of viscosity and fluidity behavior are particularly important, as small changes can have large effects on the rate of production and the volume of recoverable oil. In certain heavy oil reservoirs the apparent viscosity of the oil can change when it is mixed with gas or water and an emulsion is created. The resulting viscosities are markedly different from those of heavy oil without water [27]. In this research, the viscosity curves were obtained for several crude samples (C1 to C5), at the temperatures corresponding to the extraction zone in the conditions of the wells or the place where the sample was obtained. In the oil samples analyzed after the magnetic treatment, a reduction in viscosity was obtained, which varies depending on the nature of the oil. The results of crude C1 and C2 are shown in Figure 4.

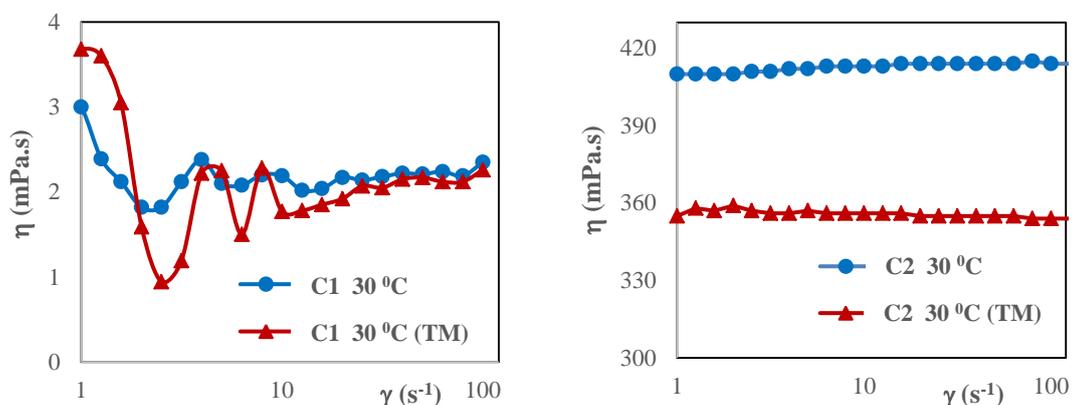


Fig.4 Viscosity curves of crude C1 and C2 before and after magnetic treatment (TM)

In crude C1 the behavior is variable with respect to the velocity gradient. At low gradients (1 s^{-1}) the viscosity increases by around 22.7%, then it decreases by 48.2% at 2.51 s^{-1} and around 100 s^{-1} the decrease is only 3.82% in the magnetically treated sample. Crude C2 behaves stable at the different speed gradients analyzed, because it is a fluid with Newtonian behavior, the viscosity after magnetic treatment is reduced by around 14%, although at low gradients the reduction can be around of 21%. This crude contains 38% emulsified water and an asphaltene content of 4.56%. The magnetic treatment used (0.47 T) has a greater incidence in the rearrangement and restructuring of the asphaltene molecules, which causes a decrease in the viscosity of the crude oil due to the weakening of the rigid asphaltene film around the water droplets. This facilitates the interactions between them and causes their coalescence. The foregoing shows that the value of the magnetic induction and the physical-chemical characteristics of the crude oil are determining factors in the result obtained. The behavior of the viscosity in crude oils C3 and C4 before and after magnetic treatment is shown in Figure 5.

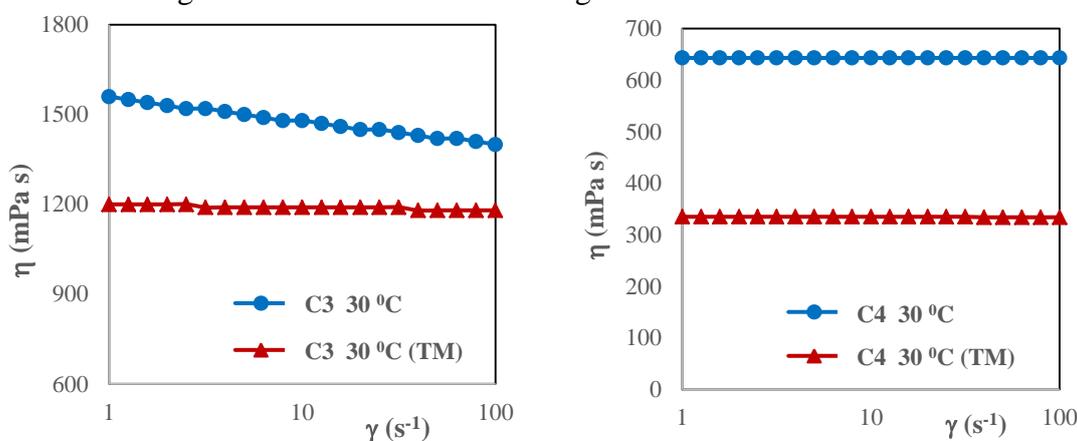


Fig.5 Viscosity curves of crude C3 and C4 before and after magnetic treatment (TM)

In crude C3, after magnetic treatment, the viscosity was reduced by around 21% compared to the untreated sample. In sample C4 there was a 48.06% reduction in viscosity after magnetic treatment. C3 and C4 crude oils are heavy oils with low water content and a high presence of asphaltenes. For this reason, it can be affirmed that the chemical nature of the analyzed samples influences the effects observed after the application of the magnetic treatment. In this case, the high content of asphaltenes is the property that prevails when considerable viscosity reduction effects have been obtained in these crude oils. The behavior of the viscosity for crude oil sample 5 is shown in Figure 6.

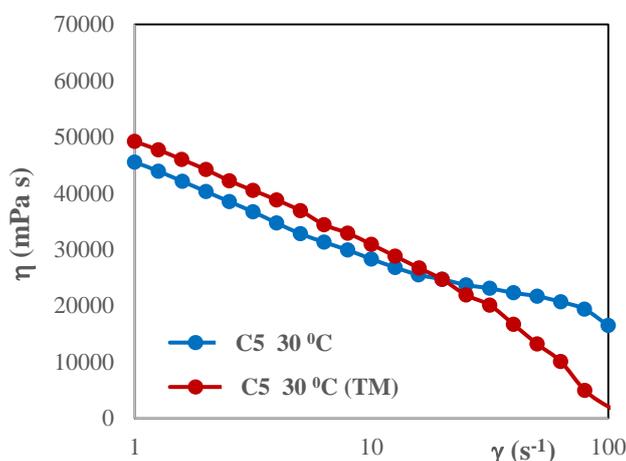


Fig.6 Viscosity curves of crude oil C5 before and after magnetic treatment (TM)

The C5 crude sample, when treated magnetically, at very low speed gradients, below 1 s^{-1} , increases its viscosity by 19%, compared to the untreated sample. From 25.1 s^{-1} the reducing effect of the magnetic treatment begins to be observed from 7.6%, which gradually increases until reaching a reduction of 98.17% at 126 s^{-1} , with respect to the untreated sample. The greatest reductions in viscosity are obtained in crude C5, which is the most viscous oil and has the highest asphaltene content of 13.62%; although this depends on the velocity gradient, since the behavior is not continuous.

The results show that the magnetic treatment has a viscosity-reducing effect on the crude oil samples studied, which depends on their characteristics and is more evident in heavy and extra-heavy oils with a high content of asphaltenes, which constitutes a novelty of this research for Cuban crudes. This result agrees with that reported by Musina [28], who obtained a reduction in viscosity for samples of Russian oils with higher viscosity and with a higher concentration of asphaltenes. These structural changes are related to the degradation of molecular associations and the formation of new paramagnetic centers under the action of the magnetic field. To assess the impact that the use of this type of treatment and its practical application could have, it is necessary to determine the effect that the magnetic treatment can have on rheological parameters such as the consistency index and the flow index.

Rheological behavior of crude oils with magnetic treatment

The equations of the adjustment of the flow curves of the crude oils allowed to establish the differences that the magnetic treatment produces in the oils studied. The model that describes the behavior of each one was selected from the regression coefficient (R^2), as shown in Table 2.

Table 2. Equations that describe the rheological behavior of crude oils

Crude oils	Ecuación: $\tau=K\gamma^n$	R^2
C1 (30°C)	$\tau=0,0023\gamma$	0,9985
C1-TM (30°C)	$\tau=0,0022\gamma$	0,9975
C2(30°C)	$\tau=0,4136\gamma^{0,9987}$	1,000
C2-TM (30°C)	$\tau=0,3512\gamma^{1,0014}$	1,000
C3 (30°C)	$\tau=1,5571\gamma^{0,9771}$	0,9981
C3-TM (30°C)	$\tau=1,1992\gamma^{0,99667}$	0,9999
C4 (30°C)	$\tau=0,64228\gamma$	1,000
C4-TM (30°C)	$\tau=0,3346\gamma$	0,9999
C5 (30°C)*	$\tau=41,937\gamma^{0,8423}$	0,998
C5-TM (30°C)*	$\tau=41,859\gamma^{0,8319}$	0,9984

*The adjustment was made at low velocity gradients

The flow index (n) increases in the crude oils: C2 and C3, when treated magnetically and the consistency index (K) decreases in the crude oils: C1 to C5, which is in correspondence with the reduction in viscosity obtained. after magnetic treatment. In general, there are no important changes in the rheological behavior with the application of the magnetic treatment under the

experimental conditions, except for heavy crude oil, in which a slight correction of the curve is obtained.

Similar results were reported by Loskutova (2006), who obtained rectification of the behavior of pseudoplastic fluids to Newtonian behavior in highly paraffinic crude oil samples [29]. This result is important from a practical point of view, since after establishing the operating conditions, if it is decided to apply the magnetic treatment at any stage, no modifications to the pumping conditions or any other operation that may be associated with it will be required. to the type of fluid being handled.

The results of this research confirm that the effects found under the action of the magnetic field depend, to a large extent, on the complexity of the dispersed oil systems, which is why they are difficult to explain. The structural transformations that occur under the action of a magnetic force can be followed by a restructuring of the associations of resins, asphaltenes and paraffins, due to the change in their dimensions or their decomposition, as well as the simultaneous association of some of these compounds [12, 16].

Several authors have attributed this behavior to the presence of acid resins in the crude oil, which act as surfactants and create a mechanical barrier on the surface of the dispersed phase particles, preventing their coagulation [20]. During the action of the magnetic field, the high activity of the polar acid resins favors the formation of smaller paramagnetic centers, which leads to a decrease in the viscosity of the oil. In the event that weakly polarized resins predominate, the interaction of those associated with the formation of larger structures and an increase in viscosity is favored. After a certain time interval, the partial or total reestablishment of the original dimensions of the associates and the relaxation of the rheological properties of the magnetically treated oils take place [29].

All this is closely related to the surface activity of the asphaltene molecules, which are natural surfactant agents that maintain the stability of the water emulsified in the oil. As these supermolecules decompose, during the rotational movement in the orientation process in the direction of the magnetic field, their surface action decreases. This weakens the interface and promotes the union of the water droplets due to the strengthening of the Van der Waals forces of attraction. In this way, the separation of the phases is favored in less time, with the consequent influence on the viscosity of the system.

Similarly, as a result of the magnetic treatment, the solubility of the salts present in the water is increased [30, 31], which could influence the pH of the system and cause a change in the hydrophilic-lipophilic balance at the interface level, also destabilizing the dispersed system. In addition, this increase in the solubility of the salts favors, during the water separation process, the elimination of the salts in the crude oil and which are the main cause of fouling.

All this depends on several factors, so the observed effect must be analyzed for each specific case, because even when some regularities could be established, the heterogeneity of the substances involved and the variables related to the magnetic treatment limits its explanation. For these reasons, a technological proposal for its application in oil wells must consider the effect of exposure time and magnetic induction, the percentages of water present in crude oil, the presence of surfactant agents and inorganic salts, among other variables.

4. Conclusions

The magnitude of the effect observed in magnetically treated crude depends largely on the chemical-physical characteristics of the fluid, such as the content of water and asphaltenes, viscosity, density, among others. In this research, the greatest effects are associated with crude oils with high viscosity and high asphaltene content. The magnetic treatment used decreased the viscosity of several samples of Cuban crude oil from 7.6% to 98.17% at different velocity gradients. The rheological behavior of the crude oil samples studied does not change with the magnetic treatment used, but there are changes in the coefficients of the rheological models; decreasing the consistency index in all the analyzed samples, which corresponds to the decrease in the viscosity of the samples after the magnetic treatment.

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Conflicto de Intereses

No existen conflictos de intereses entre los autores.

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