

The Effect of Inhibitor on Wax Precipitation in Iranian Oil Fields Using Differential Scanning Calorimetry and Microscopy Methods

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Highlights

- The effect of EVA on wax appearance temperature (WAT) of crude oil was investigated;
- The WAT of crude oil was studied using differential scanning calorimetry (DSC);
- The morphology of crude oil wax crystals was examined;
- The most significant decrease in the WAT of crude oil was 26.13 °C.

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Abstract

This study investigated the effect of ethylene-vinyl acetate (EVA) as an inhibitor on wax appearance temperature (WAT) of crude oil in the Iranian oil field using the differential scanning calorimetry (DSC) method. The effect of EVA on the morphology of crude oil wax crystals was examined by a system equipped with an ocular microscope. The EVA inhibitor has an outstanding performance in reducing the wax appearance temperature of crude oil and prevents the crystallization process and the connection of the growing wax crystals to form a network structure by adsorbing on them. Adding 800 ppm of the EVA inhibitor caused the most significant decrease in the WAT of crude oil at a rate of 26.13 °C and formed smaller crystals and weaker structures at this concentration. Therefore, 800 ppm of the EVA inhibitor was selected as the optimal value.

Keywords: DSC, Ethylene-vinyl acetate inhibitor, Morphology, Wax appearance temperature, Wax precipitation

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1. Introduction

A large proportion of the sediments formed in most crude oil are waxes. Waxes are complex compounds of cycloalkanes, isoalkanes, and normal alkanes that are more abundant than the other components. In general, the number of carbons in waxes is 16–80 (Misra et al., 1995; Sadeghzad et al., 2000; Mansoori, 2009). At atmospheric pressure and room temperature, paraffins with 1–4 carbons are gaseous, paraffins with 5–15 carbons are liquid, and normal alkanes heavier than 15 carbons are solid (Firoozabadi, 1999). The structure of crude oil wax crystals combines different shapes, such as needle-shaped crystals and

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flat and shapeless plates. Amorphous crystals are immature crystals of small size usually joined together (Singh et al., 2000; Dirand et al., 1998). Normal alkanes are crystallized as plate-shaped crystals, aliphatic and cyclic hydrocarbons as needle-shaped crystals, and branched hydrocarbons as amorphous crystals (Buchler et al., 1927). The wax precipitation occurs when the operating temperature reaches or becomes less than the wax appearance temperature (WAT). Therefore, the most critical factor influencing the precipitation of wax sediment is temperature because it is directly related to the solubility of waxes (Erickson et al., 1993). Other factors cause wax precipitation when the temperature is below the wax appearance temperature (Eaton et al., 1976). Therefore, WAT measurement is a critical issue in the study of wax sediment. Of course, accurate prediction of WAT as a point is almost impossible, even using a thermodynamic model (Coutinho et al., 2005). Various methods, such as ASTM-D2500 (Lira-Galeana et al., 2000), viscometry (Speight, 2015), cross-polar microscopy (Lira-Galeana et al., 2000), cold finger (Speight, 2015), light transmittance (Speight, 2015; Kruka et al., 1995) and differential scanning calorimetry (Tiwary, 2002), are presented to measure the WAT of crude oil. All WAT measurement methods usually have difficulty in detecting the first crystals of a sample in thermal equilibrium, and a certain amount of solid wax must be formed to create a recognizable mark. Therefore, various methods are different in terms of detection (Hammami et al., 2003). Wax is precipitated by decreasing the temperature of crude oil during production, transport, and storage operations. The presence of wax causes a change in the behavior and composition of crude oil, reducing the effective diameter of the pipe and blocking the flow channels, additional pressure on the pumping equipment, and a decrease in production efficiency in oil fields (El-Ella et al., 2014; Jeirani et al., 2007; Zhu et al., 2008; Garcia et al., 2003; Garcia et al., 2001). The oil industry spends billions of dollars annually to remove wax deposits. Due to the particular importance of economics in the oil industry, wax separation has become an essential issue in the oil industry as operating costs increase with increasing wax deposits (Towler et al., 2004). Various methods have been developed to control, reduce, or remove heavy hydrocarbon sediment, such as mechanical, thermal, electromagnetic, microbial, and nonconventional methods. In this context, there is a strong tendency to the chemical method that is currently one of the most common methods to remove wax sediment and prevent its formation (Fan et al., 1996; Jafari Behbahani et al., 2008). Inhibitors and solvents are two major groups of chemical compounds used to eliminate, prevent, or reduce the adverse effects of wax deposits. Inhibitors are polymeric compounds consisting of two polar and hydrocarbon components. The hydrocarbon part of the inhibitors binds to the wax scale, but the polar part of the inhibitors affects the crystallization process of the wax scale and changes the structure of the wax crystals. By adsorbing substances on the surface of wax crystals or entering their structure, the rate of growth operations and formation of wax deposits are reduced (Dobbs, 1999). Figure 1 shows the mechanism of wax formation in the presence and absence of inhibitors.

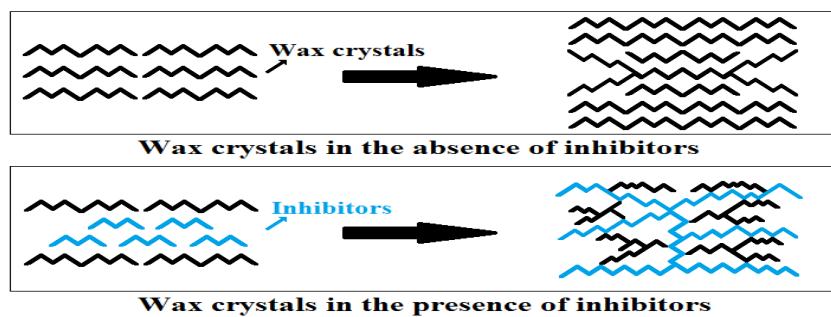


Figure 1

The mechanism of wax formation in the presence and absence of inhibitors.

Among the polymeric inhibitors, ethylene-vinyl acetate (EVA) is a suitable additive with high efficiency to prevent wax precipitation and improve oil flow (Hunt, 1962). Marie and Pedersen showed that EVA polymer had different crystal formation and growth mechanisms, depending on the type of solvent and the length distribution of the waxes. It could also act as a nucleating agent and a crystal growth inhibitor. Polymeric inhibitors act as a nucleating agent at temperatures above WAT (Marie et al., 2005; Pedersen et al., 2003). Facilitating nucleation increases WAT, and WAT decreases if tiny nucleation sites are not large enough to emerge (Wang et al., 2003).

Moreover, the added polymers may bind to the surface of the wax crystals and prevent them from increasing further, or they may attach to the surface of larger crystals and prevent them from accumulating. It should be noted that the effect of polymeric additives added as an inhibitor to the waxed solution does not change the amount of the deposited wax of the mixture but instead changes the growth and morphology of wax sediment crystals (Pedersen et al., 2003; Ronningsen et al., 1991). In a study by Chen et al., polymeric inhibitors did not completely prevent the formation of wax deposits and only delayed the formation of wax deposits, that is, they reduced WAT. They also showed that this was due to the change in the wax structure from orthorhombic to hexagonal (Chen et al., 2010). Venkatesan et al. observed that polymeric inhibitors prevented the accumulation and precipitation of wax crystals and eventually formed weaker structures of wax gel by producing smaller particles (Venkatesan et al., 2005). Jenings stated that inhibitors that created weaker structures were more effective and prone to wax precipitation. Jenings concluded that inhibitors reduced the adsorption power of wax on the surface by entering the structure of the wax deposit and changing its structure (Jenings et al., 2006). Jafari Ansaroudi et al. (2013) and Shuang et al. (2019) showed that wax crystals were formed as crystal lattices without inhibitors. However, in the presence of EVA polymer, the morphology of wax crystals varied. The reason for this result was that EVA could combine with growing crystals to prevent crystallization and growth of crystals. Lack of crystal growth and inability to connect and form crystal lattices caused a weaker structure. These results were also expressed by Ashbaugh et al. (2002) and Pedersen et al. (2003). Bilderback et al. (1969) observed that spherical crystals that formed a smaller surface area had a better effect on reducing the viscosity, formation, and sedimentation of wax often. Similar results were observed in the studies of Pedersen et al. (2003) and Ronningsen et al. (1991). Pedersen et al. (2003) observed that the WAT of crude oil was significantly reduced in the presence of EVA polymer, and a similar conclusion was expressed in the work of Shuang et al. (2019). Coto et al. (2014) found that in some cases, inhibitors did not change the amount of WAT but did change the morphology of the crystal wax. Coto et al. (2014) and Chrisman et al. (2019) concluded that a further decrease in temperature and an increase in the residence time increased the crude oil wax crystals. Yang et al. (2015) observed that wax crystals enlarged after the addition of EVA and concluded that polymeric inhibitors, in some cases, led to larger wax crystals with a spherical structure. Similar results were reported in the studies of Shuang et al. (2019), Pedersen et al. (2003), and Yang et al. (2015). Shuang et al. (2019) stated that the strong effect of EVA crystallization caused the further growth of the average size of crude oil wax crystals.

The primary purpose of this study is to evaluate the effect of EVA polymer inhibitor on the morphology of crude oil wax crystals in Iran's oil field using a designed system equipped with an ocular microscope. In addition, the effect of EVA polymer on the WAT of crude oil is investigated using the differential scanning calorimetry (DSC) method.

2. Materials and methods

2.1. Materials

a. Crude oil

The studied crude oil was from Iran's oil fields. According to the experiments, it was found that the studied crude oil has an API grade of 42.33, which is considered a light oil. The IP-143 and BP-237 methods have been used to determine the properties of the studied crude oil, such as asphaltene content and wax content, respectively (Wang et al., 2002; Kumar et al., 2017). Table 1 reports the properties of the studied crude oil.

Table 1
The properties of the crude oil studied herein.

Properties	Unit	Amount	Methods
Density	g/cm ³	0.805	ASTM-D287
API	-	42.33	ASTM-D287
Wax content	wt %	10.6	BP-237
Asphaltene content	wt %	<1	IP-143

b. Chemicals

This study used an ethylene-vinyl acetate (EVA) copolymer with a density of 0.926 g/l (Lotte Chemical Company, South Korea) to prevent the precipitation of crude oil wax. The chemical materials used in this study are presented in Table 2. The chemicals were used without further purification.

Table 2
The chemicals used herein.

Materials	Chemical formula	Purity	Company
Acetone	C ₃ H ₆ O	≥ 99%	Ghatran Shimi, Iran
Pentane	C ₅ H ₁₂	≥ 99%	Fluka, Switzerland
Toluene	C ₇ H ₈	≥ 99%	Ghatran Shimi, Iran
Heptane	C ₇ H ₁₆	≥ 99%	Merck, Germany
Xylene	C ₈ H ₁₀	≥ 99.8%	Merck, Germany

3. Methods

3.1. Differential scanning calorimeter

The disadvantages and advantages of each WAT measurement method depend on the amount, nature, and composition of used crude oil samples and the sensitivity of the equipment and measurement methods (Monger-McClure et al., 1999). The measured WAT using the ocular microscope method can be 10 to 20 °C higher than the WAT measured by the DSC and the viscometer (Ronningsen et al., 1991; Hammami et al., 1997). However, the DSC method can detect significant amounts of WAT in limited sample volumes compared to other methods (Monger-McClure et al., 1999; Tiwary, 2002). One of the advantages of this method is simplicity and fast and convenient response for typical analyses (Coto et al., 2010). Therefore, this study employs the DSC method (Jiang et al., 2001) to determine the WAT of crude oil DSC-3 (Mettler Toledo Stars, Switzerland), which uses air atmospheres and neutral gases in its chamber to measure the wax disappearance temperature (WDT) and WAT of crude oil.

The crude oil sample was first heated at 60 °C for 15 min to dissolve the wax crystals completely to determine the effect of EVA on the WAT of crude oil using the DSC method. The EVA inhibitor solutions were then added to the crude oil sample. After adding the EVA inhibitor to the crude oil sample, a certain amount (approximately 2–30 mg) of the sample (EVA + crude oil) was placed inside the DSC device. The sample was then cooled from 60 to –30 °C at a cooling rate of 5 °C/min.

3.2. Fourier transform infrared spectroscopy

The molecular structure of the extracted wax precipitate was identified and investigated by the Fourier transform infrared (FTIR) spectroscopy using the BP-237 method. The spectrometer model used in this research was Vertex 70 (Bruker, Germany), which can record Fourier transform infrared spectra of the samples using potassium bromide (KBr) tablets in a range of 400 to 4000 cm^{-1} .

3.3. Microscopic system

In order to study the morphological changes of wax crystals in crude oil, a system is designed that includes a laboratory chamber and an ocular microscope. The chamber of the laboratory system is made of plastic and can cool and heat crude oil samples in a temperature range of 0 to 60 °C. There is a fan inside the chamber to equalize the internal temperature of the chamber, a 12-inch cylinder equipped with a halogen light source, a sample container to place oil samples in, and a thermometer to report the temperature. On this chamber, a 2-inch glass with an area of 24 cm × 18 cm is placed to control the temperature. A schematic of the laboratory system chamber is shown in Figure 2.

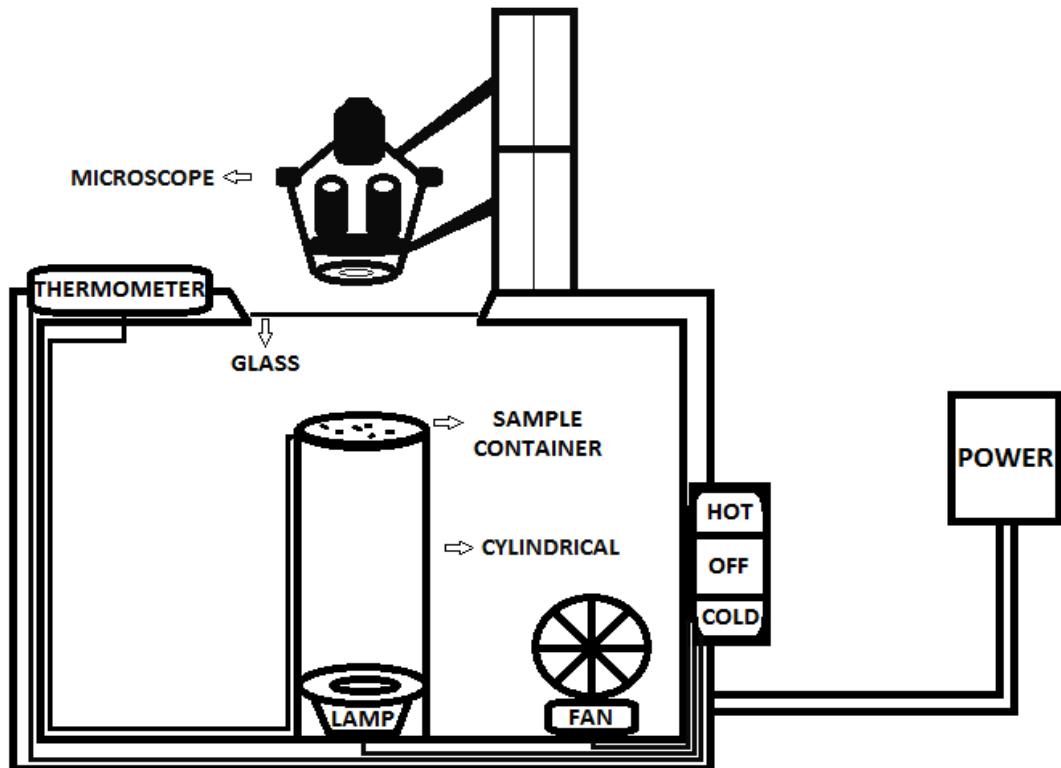


Figure 2

A schematic of the laboratory system chamber.

The ocular microscope is a stereo zoom microscope equipped with a Dino-Lite camera and is used to accurately observe and record images of wax crystals when crude oil wax forms on the sample

container. The focal length of this microscope is 45 mm, and its maximum magnification is $\times 200$. Prior to each test, the sample container of the laboratory system chamber was washed with distilled water and finally dried in an oven. Then, by placing the sample container on the cylinder inside the system chamber, the light source, fan, and heating system were turned on, and the chamber temperature was increased to 60 °C. First, the crude oil sample was heated at 60 °C for 15 min to dissolve the wax crystals completely to determine the effect of chemical inhibitors on the morphology of the crude oil wax crystals using the designed system. The chemical inhibitor solution was added to the petroleum sample at a concentration of 100, 200, 500, and 800 ppm. After that, 2 mg of the sample (chemical inhibitors + crude oil) was poured into the sample container of the system chamber.

It should be noted that the system chamber temperature was heated to 60 °C before the test. After pouring the sample on the sample container, the system chamber temperature was cooled from 60 to 0 °C. When the sample was cooled, the morphological changes of the crude oil wax crystals were recorded after 5, 10, 20, and 30 min using a built-in ocular microscope. In this method, all the experiments were performed at atmospheric pressure at a cooling rate of 5 °C/min. An overview of the designed system is shown in Figure 3.



Figure 3

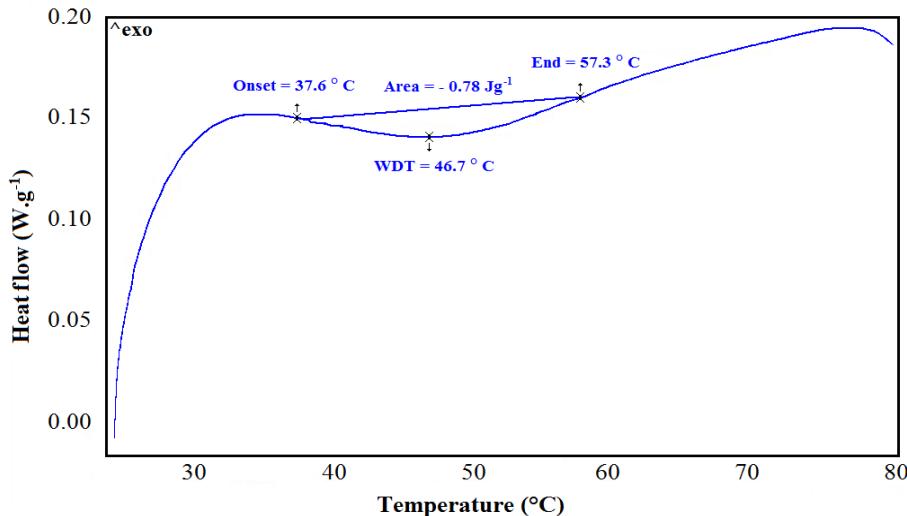
The designed system.

4. Results and discussion

4.1. Properties of wax

a. Wax disappearance temperature

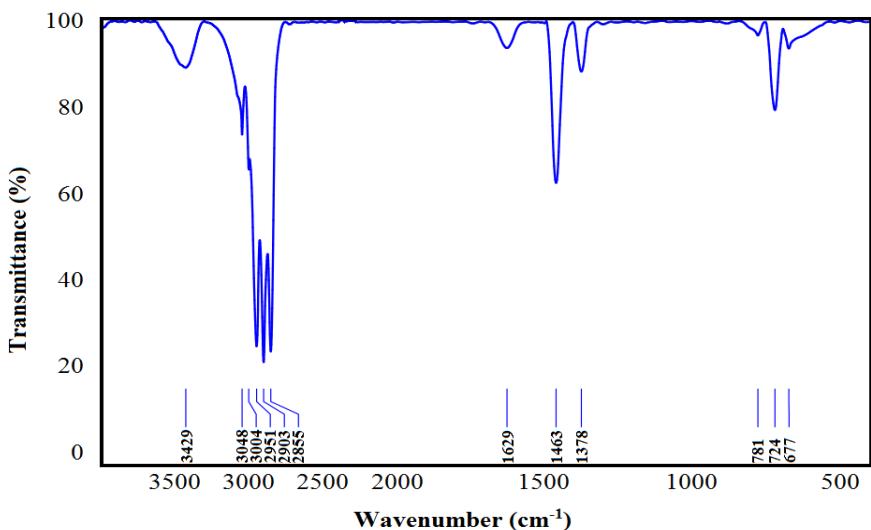
Figure 4 shows the wax disappearance temperature of the crude oil studied. This temperature was measured using the DSC method in a temperature range of 25 to 80 °C and a heating rate of 5 °C/min. It was found that the wax disappearance temperature of the studied crude oil wax was 46.7 °C. Therefore, to dissolve the crude oil wax crystals completely, the samples were first heated to 60 °C.

**Figure 4**

The wax disappearance temperature of the crude oil.

b. FTIR spectrum of crude oil wax sediment

Figure 5 shows the FTIR spectrum of the wax sediment extracted using the BP-237 method. According to the FTIR spectrum, in a wavenumber range of 400 to 4000 cm⁻¹, aliphatic CH functional groups (alkanes), with high tensile vibration in the regions of 2855, 2903, and 2951 cm⁻¹, and Ar–H functional groups (aromatics) and =CH (alkanes) with moderate tensile vibration appear predominantly. In addition, functional groups N–H₂, with flexural vibration, and NH, with tensile vibration, appeared with a weak intensity in the range of 1629 and 3429 cm⁻¹, respectively.

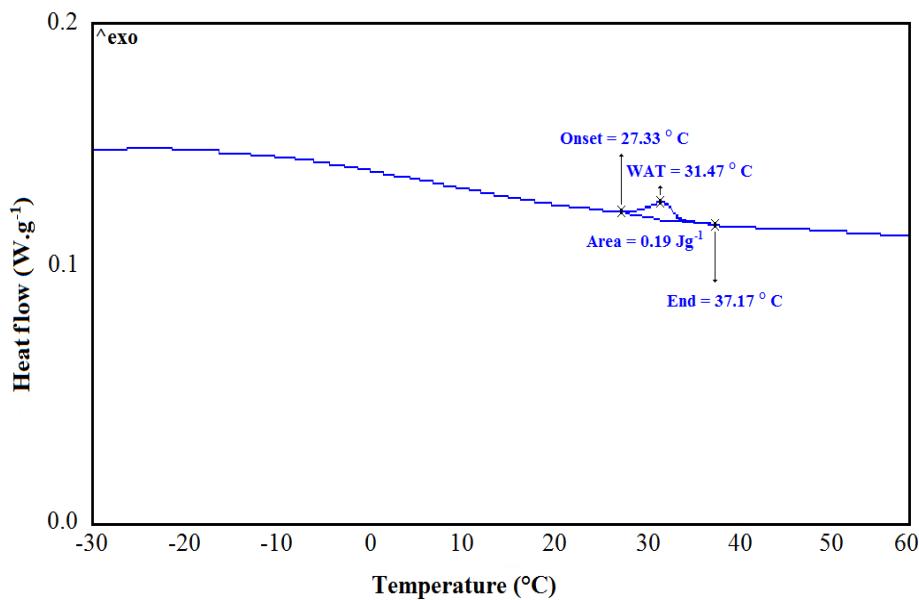
**Figure 5**

The FTIR spectra of the wax sediment.

4.2. Study of crude oil wax precipitation using the DSC method

a. Wax appearance temperature of crude oil without inhibitor

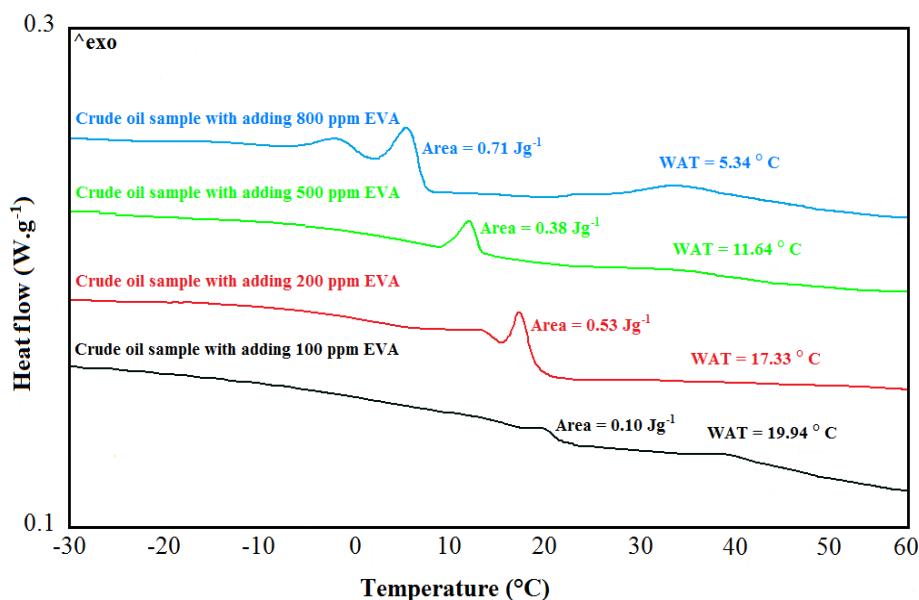
Figure 6 shows the WAT of the crude oil without inhibitor. The WAT of the studied crude oil is 31.47 °C, which is a high temperature, and there is a possibility of wax formation and blockage of pipelines.

**Figure 6**

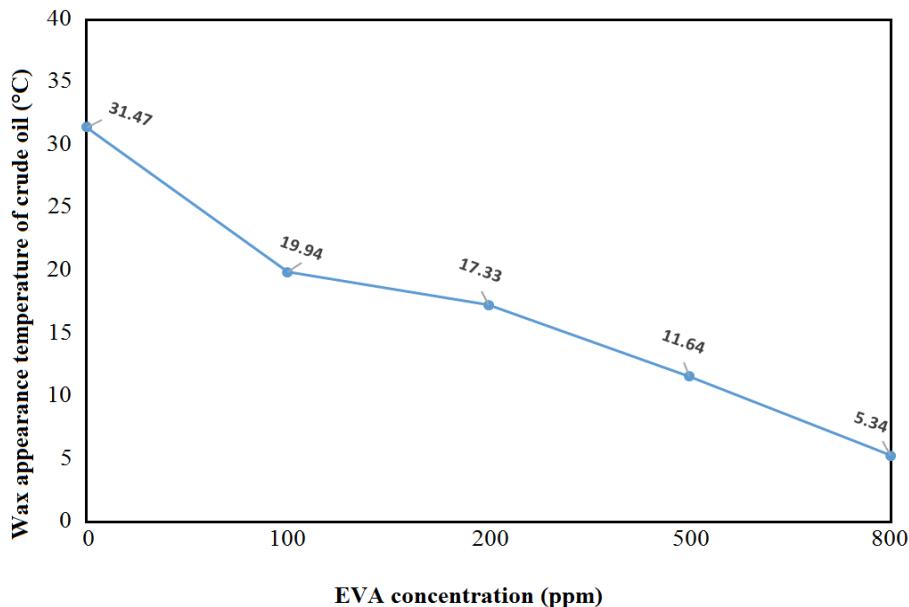
The wax appearance temperature of the crude oil.

b. Effect of EVA inhibitor on WAT

Figures 7 and 8 show the effect of the different concentrations of the EVA inhibitor on the WAT of the studied crude oil. The EVA inhibitor decreases the WAT of the studied crude oil, and this decrease increases with raising the concentration of the EVA inhibitor. Such a result was observed by Jafari Ansaroudi, who used a mixture of refined paraffin wax (concentration of 0.4 wt %) and kerosene as model oil and EVA polymer as the inhibitor (Jafari Ansaroudi et al., 2013).

**Figure 7**

The effect of different concentrations of the EVA inhibitor on the crude oil DSC curves.

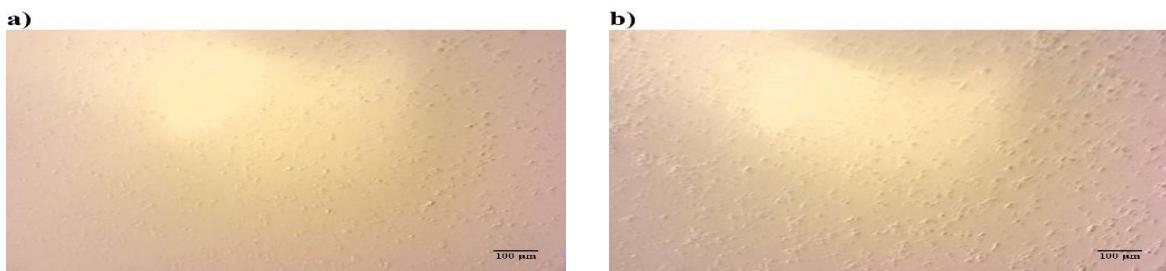
**Figure 8**

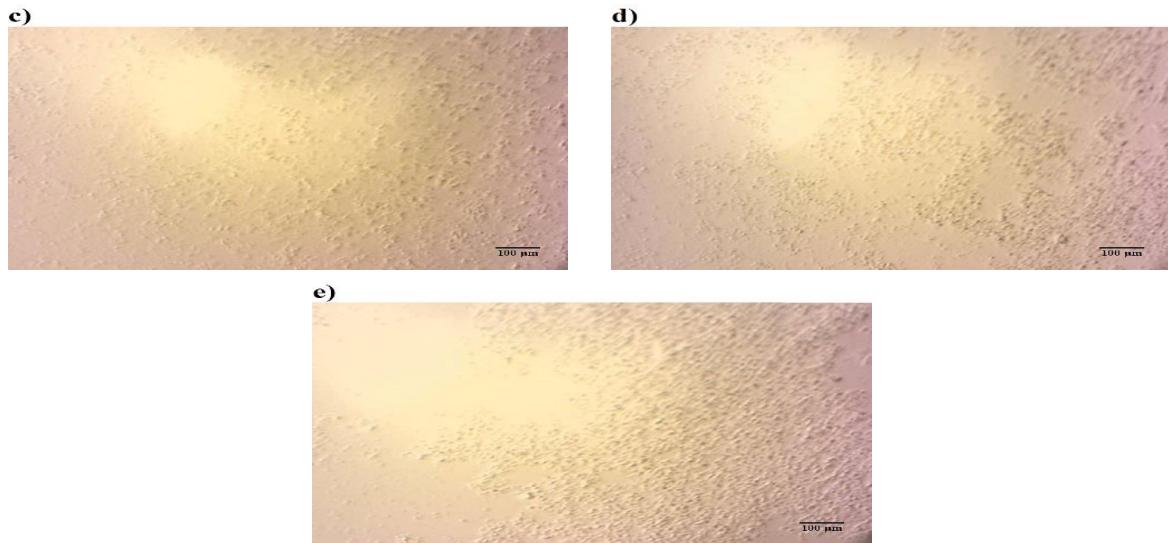
The changes in the WAT of crude oil at the different concentrations of the EVA inhibitor.

4.3. Study of crude oil wax precipitation using the microscopic method

a. Precipitation of crude oil wax without inhibitor

Figure 9 shows the microscopic structure of crude oil wax crystals without inhibitors. The changes in the wax crystals were recorded at 5, 10, 20, and 30 min after the first moment of formation to better understand how they grow. According to Figure 9, in the absence of inhibitors, the crude oil wax crystals are in the form of amorphous and needle-shaped crystals with small sizes (between 10 to 20 μm) and in large numbers. Shuang has also reported this finding. According to the FTIR result, the precipitate of crude oil wax contains aliphatic and cyclic hydrocarbons, which leads to the formation of needle-shaped crystals. Buchler also states such a finding. In addition, increasing the retention time and further decreasing the temperature increase the crude oil wax crystals and form crystal clusters, which is also expressed by Shuang et al. (2019), Buchler et al. (1927), Coto et al. (2014), and Chrisman et al. (2019). Finally, from joining these crystals, a network of crystals is created as a continuous plate-like structure, which can increase the volume of the solid phase and prevent the mobility of crude oil. Peng et al. (2019), Shuang et al. (2019), Chrisman et al. (2019), and Kane et al. (2003) have expressed such a conclusion. In this case, facilitating nucleation and creating a large nucleation site has increased the wax appearance temperature of crude oil. This finding is also expressed by Wang et al. (2003).

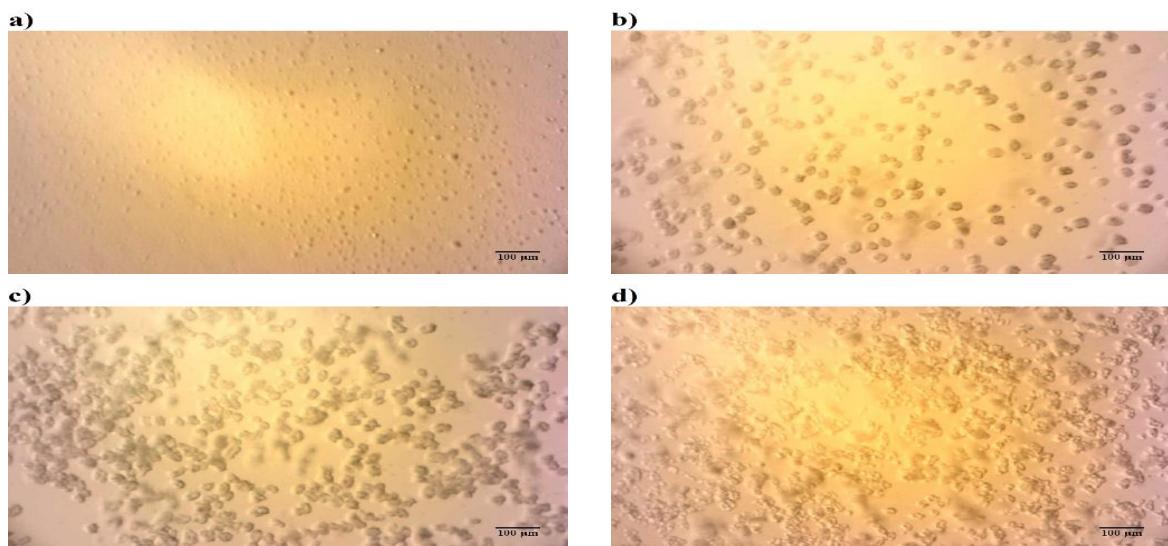


**Figure 9**

The microscopic images of the crude oil wax crystals without the inhibitor in a) the first moment of formation, b) 5 min, c) 10 min, d) 20 min, e) 30 min after the first moment of formation.

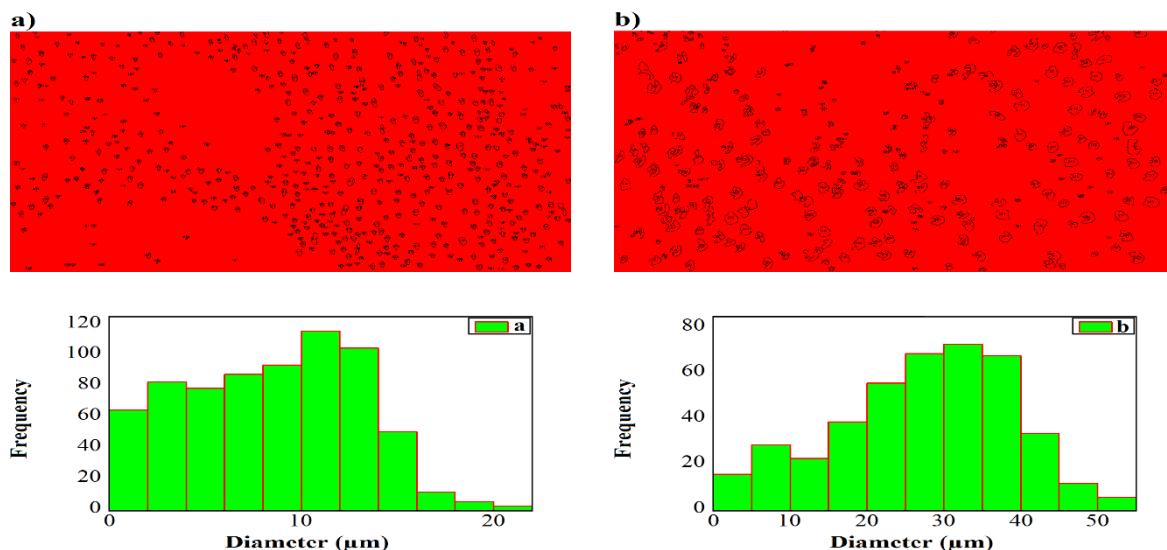
b. Precipitation of crude oil wax in the presence of EVA inhibitor

The EVA inhibitor at a concentration of 100, 200, 500, and 800 ppm was added to the crude oil sample to investigate the effect of the inhibitor on the morphology of the crude oil wax crystals, and the morphological changes of the wax crystals were recorded at 5, 10, 20, and 30 min after the first moment of formation. In addition, the size distribution of the crude oil wax crystals was reported in the early moments of formation to prove the mechanism of the EVA inhibitor. Figures 10 and 11 show the morphological changes and size distributions of the crude oil wax crystals in the presence of 100 ppm of the EVA inhibitor, respectively.



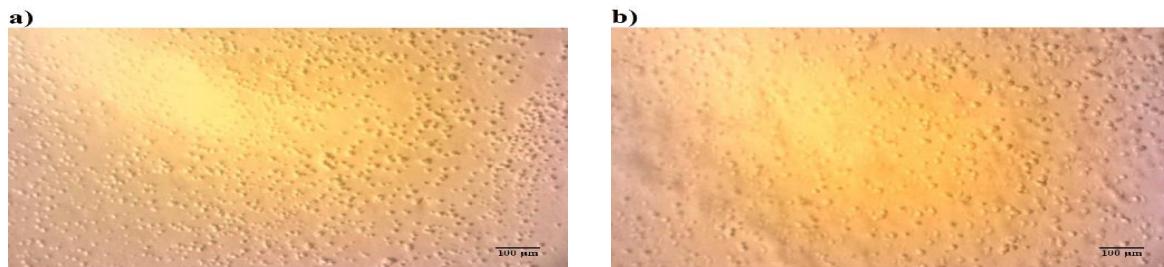
**Figure 10**

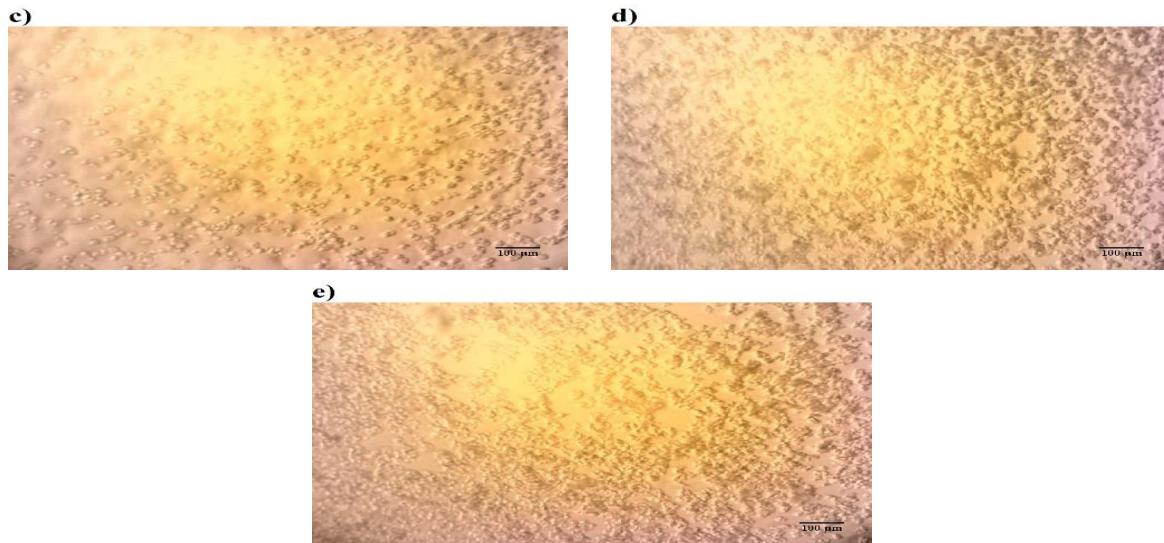
The microscopic images of the crude oil wax crystals in the presence of 100 ppm of the EVA inhibitor in a) the first moment of formation, b) 5 min, c) 10 min, d) 20 min, e) 30 min after the first moment of formation.

**Figure 11**

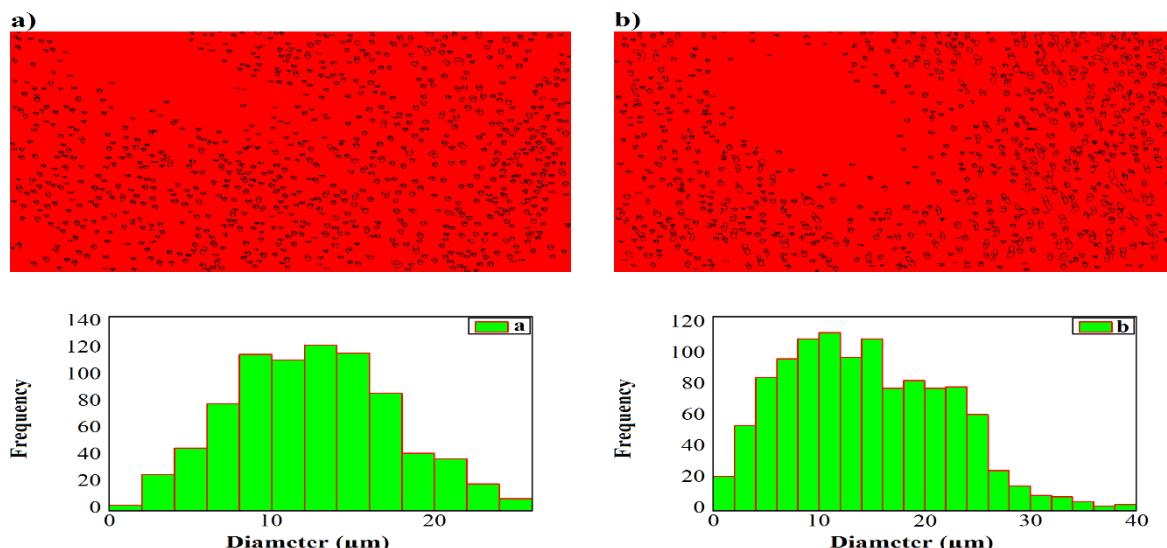
The size distribution of the crude oil wax crystals in the presence of 100 ppm of the EVA inhibitor in a) the first moment of formation and b) 5 min after the first moment of formation.

Figures 10 and 11 demonstrate that the presence of 100 ppm of the EVA inhibitor in the crude oil sample forms spherical crystals with sizes between 10 and 40 μm in the initial moments, the number of which increases after 10 min. After 20 min and with a decrease in the kinetic energy of the wax crystals, they are deformed as amorphous crystals and connected. After 30 min, the connection of the crystals to each other creates a network structure of amorphous crystals with more crystals and space than the plate structure of the wax crystals of the crude oil sample without the inhibitor. Figures 12 and 13 show the morphological changes and size distributions of the crude oil wax crystals in the presence of 200 ppm of the EVA inhibitor, respectively.



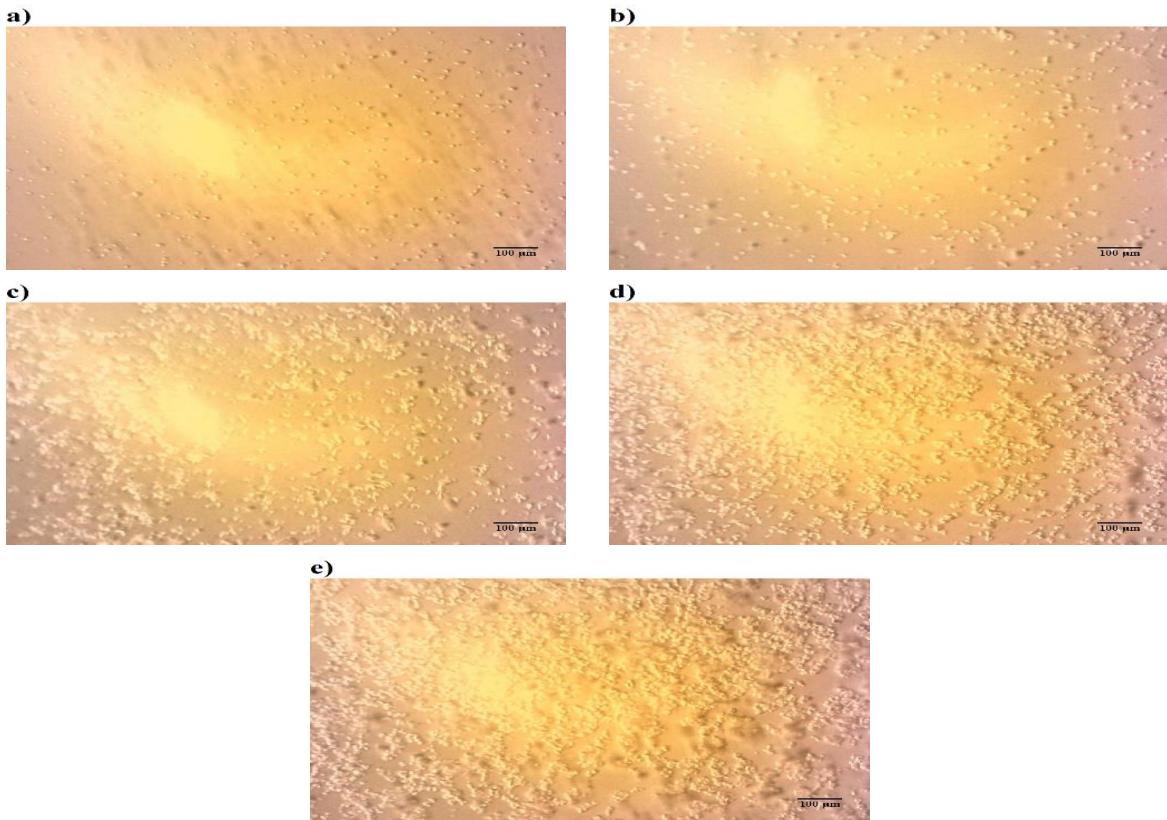
**Figure 12**

The microscopic images of the crude oil wax crystals in the presence of 200 ppm of the EVA inhibitor in a) the first moment of formation, b) 5 min, c) 10 min, d) 20 min, e) 30 min after the first moment of formation.

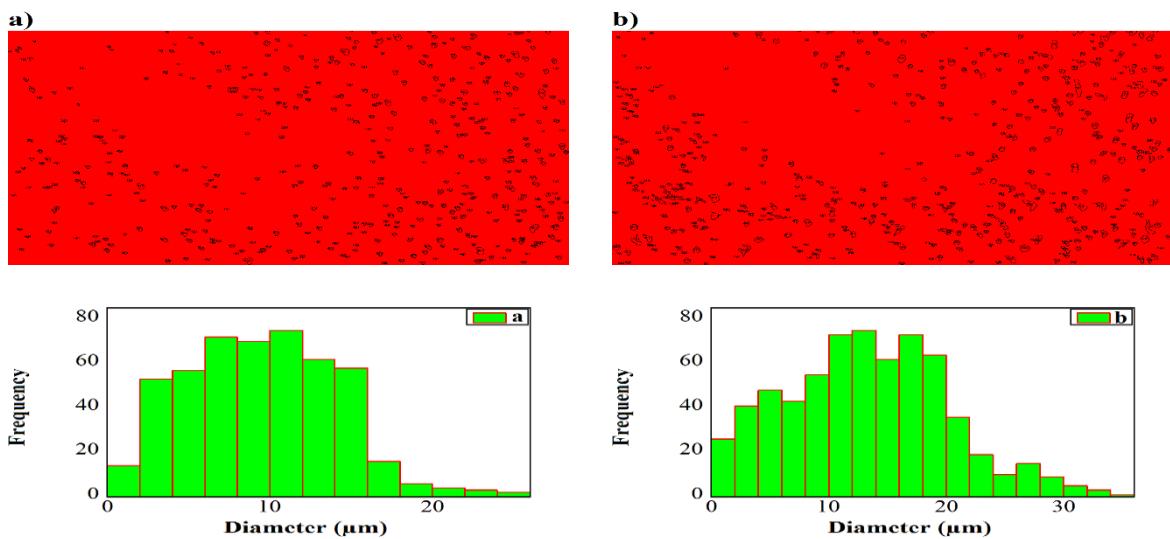
**Figure 13**

The size distribution of the crude oil wax crystals in the presence of 200 ppm of the EVA inhibitor in a) the first moment of formation and b) 5 min after the first moment of formation.

As shown in Figures 12 and 13, the presence of 200 ppm of the EVA inhibitor in the crude oil sample forms many spherical crystals with sizes between 10 and 25 μm in the early moments, the number of which increases after 10 min. After 20 min, the spherical crystals are deformed and become amorphous crystals, and the spherical crystals and amorphous crystals cover the sediment surface. After 30 min from the initial moments of the wax crystal formation, poor bonding of the crystals to each other results in a defective network structure of amorphous crystals having more space than similar conditions at a concentration of 100 ppm of the inhibitor. Figures 14 and 15 show the morphological changes and size distribution of the crude oil wax crystals in the presence of 500 ppm of the EVA inhibitor, respectively.

**Figure 14**

The microscopic images of the crude oil wax crystals in the presence of 500 ppm of the EVA inhibitor in a) the first moment of formation, b) 5 min, c) 10 min, d) 20 min, e) 30 min after the first moment of formation.

**Figure 15**

The size distribution of the crude oil wax crystals in the presence of 500 ppm of the EVA inhibitor in a) the first moment of formation and b) 5 min after the first moment of formation.

According to Figures 14 and 15, the presence of 500 ppm of the EVA inhibitor in the crude oil sample forms fine spherical and needle-shaped crystals with sizes between 10 and 20 μm in the initial moments, the number of which increases after 10 min. After 20 min and with a further decrease in the temperature, the crystals are very weakly connected and deformed as amorphous crystals. After 30 min from the initial moment of the wax crystal formation, poor bonding of the crystals in some areas of the wax

deposition leads to the formation of the clusters of amorphous crystals that are not critical enough to form a network structure. In this case, more space is observed than similar conditions at a concentration of 200 ppm of the inhibitor. Figures 16 and 17 show the morphological changes and size distributions of crude oil wax crystals in the presence of 800 ppm of the EVA inhibitor, respectively.

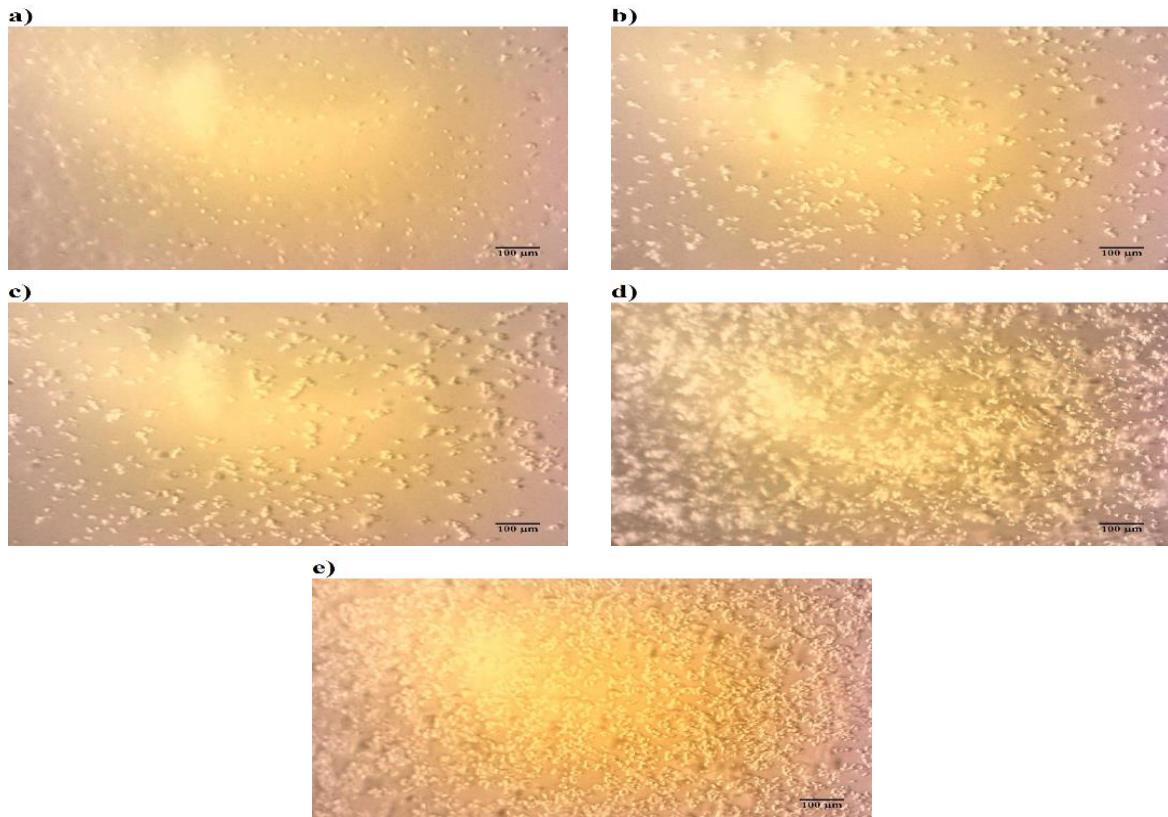


Figure 16

The microscopic images of the crude oil wax crystals in the presence of 800 ppm of the EVA inhibitor in a) the first moment of formation, b) 5 min, c) 10 min, d) 20 min, e) 30 min after the first moment of formation.

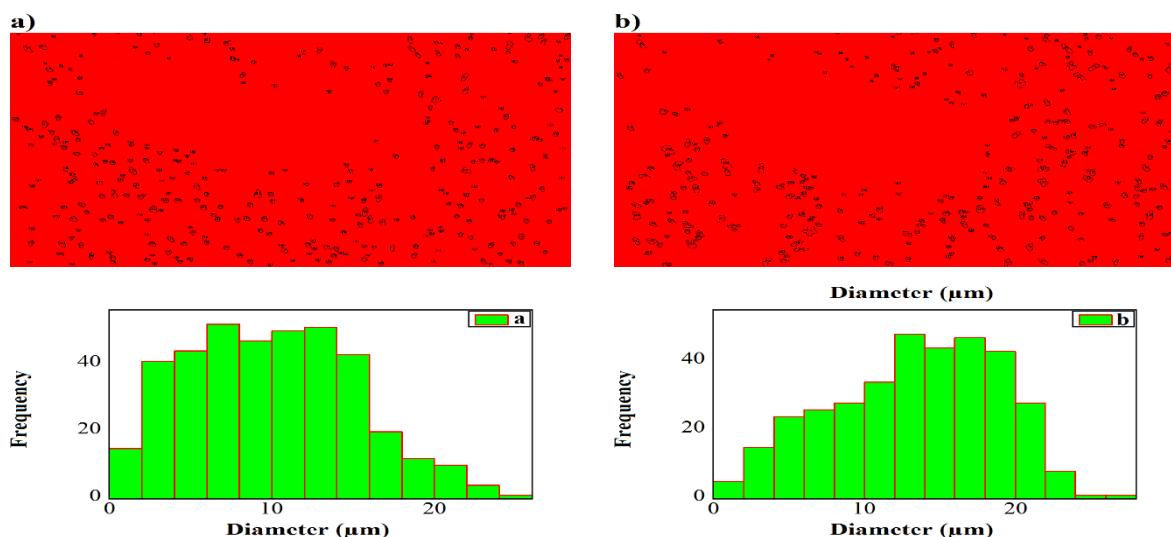


Figure 17

The size distribution of the crude oil wax crystals in the presence of 800 ppm of the EVA inhibitor in a) the first moment of formation and b) 5 min after the first moment of formation.

According to Figures 16 and 17, the presence of 800 ppm of the EVA inhibitor in the crude oil sample forms needle-shaped and amorphous crystals with sizes between 5 and 20 μm in the initial moments, and the number of crystals slightly increases after 10 min. After 20 min and with a further decrease in the temperature, the number of crystals increases. After 30 min from the initial moment of the wax crystal formation, the growth rate of the crystals and their ability to connect to form a network decrease, and the deposition surface is covered by amorphous crystals with smaller sizes (20 to 30 μm) and sizeable lateral space.

According to Figures 10–17, in the presence of small concentrations of the ethylene-vinyl acetate inhibitor (100–200 ppm), the strong effect of EVA crystallization causes the further growth of the average size of crude oil wax crystals and the formation of spherical crystals (with sizes between 10 up to 40 μm) in the initial moments. This finding has also been reported by Shuang et al. (2019), Pedersen et al. (2003), and Yang et al. (2015), who used crude oil and the EVA inhibitor in their studies. Over time, spherical crystals become amorphous crystals, deformed, and joined together to form an incomplete lattice structure of amorphous crystals with more space. The main factor determining the inhibitory effect of EVA on the morphology of crude oil wax precipitation is the amount of empty and unoccupied space by wax crystals because the space not occupied by wax crystals is larger and the amount of oil is higher, which can cause crude oil to flow. A similar conclusion has been expressed by Shuang et al. (2019). In this case, the EVA inhibitor delays the formation of wax deposits to lower temperatures, and this effect (the reduction of the WAT) is due to the change in the structure of the wax crystals from orthorhombic (needle-shaped) to hexagonal (spherical). Shuang et al. (2019) and Chen et al. (2010) have also reported the same findings. However, large concentrations of the ethylene-vinyl acetate inhibitor (500–800 ppm) form tiny, spherical, needle-shaped crystals (between 5 and 20 μm in size) in the early moments that change into amorphous crystals over time. Finally, amorphous crystals with sizes between 20 to 30 μm are scattered with a sizeable lateral space relative to each other that do not have the necessary ability to connect and form a network. The reason for this result is that increasing the EVA inhibitor leads to the nucleation of a larger number of wax crystals, which have slowed their growth rate and prevented them from crystallizing and accumulating by adsorption on the growing crystals. The lack of the growth of crystals and their lack of connection to each other to form crystal lattices lead to weaker structures. This finding has also been expressed by Jafari Ansaroudi et al. (2013), Ashbaugh et al. (2002), Pedersen et al. (2003), Venkatesan et al. (2005), Marie et al. (2005), Jenings et al. (2006), and Peng et al. (2019). In this case, the EVA inhibitor delays the formation of wax deposits to lower temperatures, and lowering the waxing temperature is due to the formation of tiny nucleation sites (wax crystals) that are not large enough for detection. Chen et al. (2010) and Jafari Ansaroudi et al. (2013) have also expressed a similar finding.

4. Conclusions

This study examined the effect of various concentrations of ethylene-vinyl acetate inhibitor on the wax appearance temperature and morphology of oil wax crystals of Iran's crude oil using differential scanning calorimetric and microscopic methods to solve the problems caused by the formation of a wax deposit. The results of this research are as follows:

- In the absence of an inhibitor, the size of crude oil wax crystals is small, but there are many crystals. Therefore, they can easily connect and overlap, which leads to the formation of a continuous lattice structure of the wax crystals.
- In the absence of an inhibitor, facilitating nucleation and the formation of numerous nucleation sites increase the wax appearance temperature of crude oil.

- Aliphatic and aromatic hydrocarbons crystallize as needle-shaped and amorphous crystals in the crude oil wax composition without an inhibitor.
- Increasing the residence time and further decreasing the temperature increase the crude oil wax crystals and the formation of crystal clusters and reduce the number of voids in the wax sediment structure.
- At low concentrations of the EVA inhibitor (200–100 ppm), the intense effect of EVA crystallization leads to further growth of the average size of crude oil wax crystals and the formation of spherical crystals in the early moments. Nevertheless, high concentrations of this inhibitor (800–500 ppm) form tiny spherical and needle-shaped crystals in the early moments.
- The EVA inhibitor deforms the wax crystals from spherical and needle-shaped crystals to amorphous ones.
- The EVA inhibitor has an excellent performance in reducing the wax appearance temperature of crude oil in Iranian oil fields. The decrease in the wax appearance temperature of crude oil crystals at low concentrations of the EVA inhibitor is due to the change in the structure of the wax crystals from needle-shaped to spherical. Lowering the wax appearance temperature of crude oil at high concentrations of this inhibitor is because the formation of nucleation sites (wax crystals) is so small that they do not have the required size for detection.
- Increasing the EVA inhibitor reduces the size of crude oil wax crystals and increases their number.
- Increasing the EVA inhibitor results in the weaker structures of crude oil wax crystals that cannot bond together and form a network. This result is because the EVA inhibitor slows their growth and prevents them from crystallizing and accumulating by adsorbing on the growing crystals. The lack of growth of crystals and their lack of connection to each other to form crystal lattices give rise to weaker structures.
- A concentration of 800 ppm of the EVA inhibitor is selected as the optimal concentration due to the formation of weaker structures of crude oil wax crystals and more voids and a lower wax appearance temperature.

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Nomenclature

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
DSC	Differential scanning calorimetry
EVA	Ethylene-vinyl acetate
FTIRS	Fourier transform infrared spectroscopy
WAT	Wax appearance temperature
WDT	Wax disappearance temperature

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