Advances in Geo-Energy Research

Vol. 6, No. 6, p. 492-501, 2022

Original article

Wormholes effect in carbonate acid enhanced oil recovery methods

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Keywords:
Enhanced oil recovery
carbonate acidizing
chelating agents
wormholes

Cited as:
Alarji, H., Clark, S., Regenauer-Lieb, K. Wormholes effect in carbonate acid enhanced oil recovery methods. Advances in Geo-Energy Research, 2022, 6(6): 492-501.
https://doi.org/10.46690/ager.2022.06.06

Abstract:
Acid enhanced oil recovery has been a focus of interest in the oil industry due to its significant results on improved recovery, especially in carbonate reservoirs. However, in carbonate reservoirs, highly conductive pathways called "wormholes" are created when acidic fluids are injected into carbonate rocks. Wormholes could jeopardize the enhanced oil recovery outcome and sweep efficiency leaving a substantial volume of oil in the reservoir unswept. This phenomenon has not been investigated yet. The main objective of this study is to identify the impact of these wormholes on the overall oil recovery during enhanced oil recovery practices. This was achieved by injecting acidic fluid into Indiana limestone at various injection rates to control the creation of wormholes. The injection rates were selected based on a proposed dimensionless phase space that predicts the wormholes development and dissolution phase. Our results show that wormholes have a significant impact on the enhanced oil recovery performance resulting in a decrease in the overall oil recovery by 9.6% for portions of the reservoir that experience wormholing. In real field applications, it is recommended to avoid creating wormholes over large portions of the reservoir affected by acid injection as it may jeopardize the field development outcome leaving an unspecified amount of oil in virgin regions in the reservoir which results in additional operational complications. Wormholes are only beneficial near the wellbore for wellbore cleanup and matrix treatment purposes thus providing easier access to the reservoir. However, care needs to be taken to constrain wormhole formation to skin factor reduction and avoid far-reaching wormholes in the reservoir.

1. Introduction

The demand for energy continues to grow rapidly and globally. Various institutions analyze and predict the consumption of global energy and produce annual detailed reports (Thomas, 2008; Editors, 2021). One of the leading institutes that forecast energy consumption is the US Energy Information Administration which issues an annual outlook detailing every sector of global energy (Editors, 2021). They show the 2021 global primary energy consumption by the source where petroleum and natural gas remain the largest energy source that ensures meeting the world's need for energy.

Carbonate reservoirs represent more than half of the world's discovered oil reserves, the majority of which are recognized for their heterogeneity and randomly distributed multiscale microstructure (Masalmeh et al., 2014). About half of the proven oil reserves are in the Middle East, where most of which are in carbonate reservoirs (Pal et al., 2017). The complexity pertaining to carbonate reservoirs is recognized by highly conductive natural fractures and low permeable matrix (Lu et al., 2020). The intricate multiscale geometry of pore space results in this wide range of permeability that makes the field development even more challenging, especially in the enhanced oil recovery (EOR) process (Pal et al., 2017). This, as a result, encouraged researchers to study the nanoparticles transport in porous media using machine learning techniques to understand the complexity and hence increase the overall oil recovery (Alwated and El-Emin, 2021). In the following section, the most favorable EOR methods in the industry

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Received May 30, 2022; revised July 1, 2022; accepted July 17, 2022; available online July 20, 2022.

will be discussed: low salinity waterflooding, surfactant and polymers, carbon dioxide CO_2, and acidic fluids EOR.

1.1 Low salinity waterflooding

A popular method is low salinity waterflooding which consists of manipulating the parameters of the injected water to change rock wettability to more water-wet conditions and hence promote more oil to be produced (Kozaki, 2012). Several studies reported that oil recovery can be significantly impacted by the water composition (Yildiz et al., 1999; Ligthelm et al., 2009; Austad et al., 2010; Nasralla and Nasr-El-Din, 2011; Yousef et al., 2011). Using laboratory evidence, it was found that low salinity brine was successful to change the rock surface wettability to more water-wet and hence promote more oil to be produced (Lager et al., 2007; Mahmoud et al., 2017). However, due to the complexity of fluid interaction with reservoir rocks, the chemical/physical mechanisms of how the low salinity was able to increase the oil recovery is still a matter of discussion (Mahmoud et al., 2017). Low salinity water is usually obtained from seawater, which must go through desalination and treatment processes to overcome sulfate precipitation which can be costly and unfavorable.

1.2 Surfactants and polymers

Surfactants and polymers were found to be one of the robust and high-performance approaches of EOR methods. In the past decades, they were widely studied as they were successful in changing the wettability of carbonate rocks to more water-wet and reducing the interfacial tension (IFT) which results in producing more of the trapped oil and consequently increase oil recovery (Yang and Wadleigh, 2000; Webb et al., 2005; Azad et al., 2014). Hiwa et al. (2018) tested the sequential polymer injection instead of single polymer injection and found it to be more effective specially in heterogenous reservoirs. Recently, Azad et al. (2014) introduced a stable viscoelastic surfactant to enhance the oil recovery in carbonate reservoirs at high-salinity high-temperature conditions. However, the effectiveness of surfactant flooding is hindered by surfactant retention and adsorption to the reservoir rock (Lake, 2014).

Polymer flooding aims at improving the mobility ratio by utilizing water-soluble polymers, mainly polyacrylamides (Mahmoud and Abdelgawad, 2015; Kamel et al., 2019). These polymers increase the viscosity of injected water to improve the sweep efficiency and the volumetric sweep (Lake, 2014). However, polymers cannot be used at high salinity conditions due to viscosity degradation as a result of the high salt concentrations. Viscoelastic surfactants (VES) can attain higher viscosity when contacting the brine, and they have very low IFT. The downside of using the VES system is its adsorption on the carbonate surface which ultimately limits the functionality of the VES. To eliminate this problem, high pH, alkaline solutions need to be added to the system (Mahmoud and Abdelgawad, 2015). However, most types of surfactants are highly affected by the oil reservoir conditions in addition to the targeted reservoir rock type, along with other challenges such as the formation of micelle at high concentration, susceptible to high salinity and temperature, microbial degradation, wellbore plugging, and the high cost (Uzoho et al., 2015; Christophe et al., 2018; Ivanova et al., 2020; Ajoma et al., 2021).

1.3 CO_2 flooding

Christophe et al. (2018) showed the number of EOR projects in operation globally from 1971 to 2017. Their numbers indicate that CO_2 injection has been growing rapidly. The CO_2 injection into hydrocarbon reservoirs was reported by many researchers to be one of the best techniques for enhanced oil recovery (Gong and Gu, 2015; Saira et al., 2020; Ajoma et al., 2021; Saira et al., 2021). The advantages of the CO_2 injection rely on its miscibility with oil which reduces oil viscosity and hence increases its mobility. However, the CO_2 flooding process frequently experiences problems such as viscous fingering and gravity override which result in a poor sweep efficiency leaving a significant amount of oil being left behind (Gong and Gu, 2015; Xu et al., 2017; Saira et al., 2020).

1.4 Acidic EOR approach

Recently, acidic EOR has been gaining momentum as an EOR method as it overcomes the CO_2 injection problems. In acidic flooding, the acid reacts with the carbonate rock and produces in-situ CO_2 which results in reducing the viscosity of the hydrocarbons and hence increases the overall oil recovery while overcoming the fingering and gravity override issues. Mahmoud and Abdelgawad (2015) injected a low pH chemical namely hydroxyethylethylenediaminetriacetic acid (HEDTA) into carbonate rock samples in an attempt to improve the oil recovery. The outcome was promising as it successfully resulted in an additional oil recovery of 20% using Indiana limestone carbonate rock.

The contact of the acidic fluid with carbonate rocks (i.e., Eq. (1) for limstone and Eq. (2) for dolomite) results in a chemical reaction that can be expressed as (Nasr-El-Din et al., 2006):

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + CO_2 + H_2O \tag{1}$$

$$CaMg\left(CO_3\right)_2 + 4HCl \rightarrow CaCl_2 + MgCl_2 + 2CO_2 + 2H_2O \tag{2}$$

The acid injection in carbonate stimulation dissolves the solid rock and creates deep conductive flow pathways called "wormholes" (Hoefner et al., 1987). These wormholes can greatly affect the EOR process as they result in creating a low resistance path and, like the above discussed fingering phenomenon, carry most of the injected fluid leaving many virgin vicinities unswept. While extremely low pH environments are the target of traditional acidizing stimulation for wellbore cleanup and near-wellbore treatment of formation damage (Fig. 1) (Crowe et al., 1992) our earlier studies (Al-Arji et al., 2022) showed that wormholes can be generated even under very low acid concentrations suggesting that they can reach far into the reservoir after sufficient pore volume sweep. In the past attempts, efforts have been made to study the effect of injecting acidic fluids into carbonate rocks to enhance oil

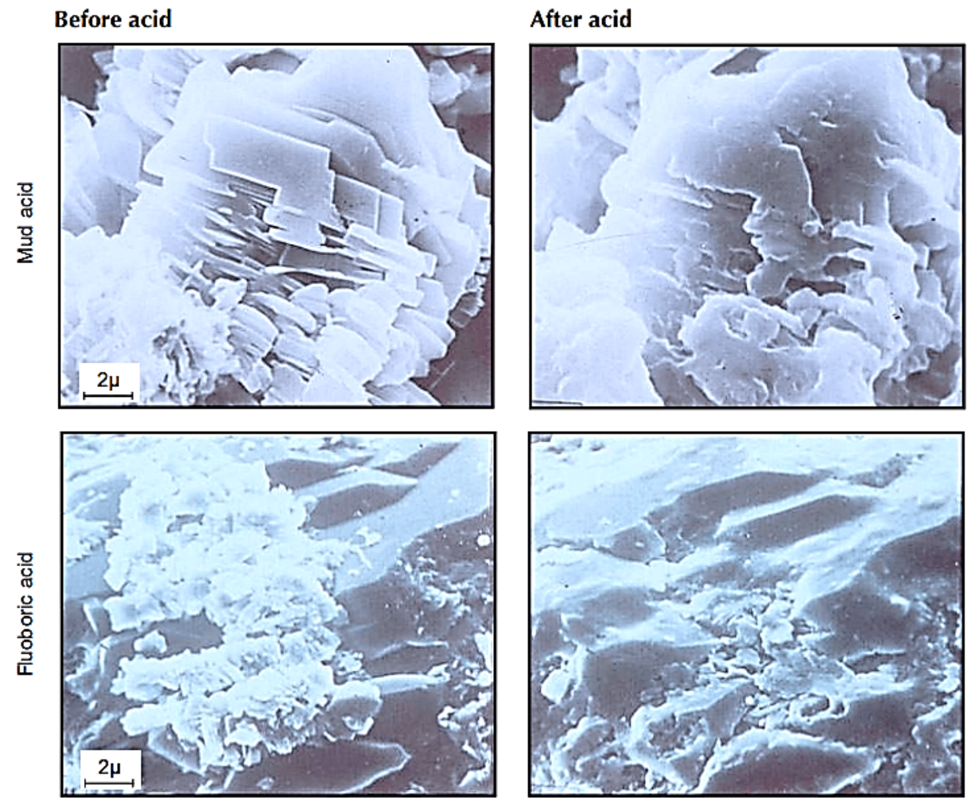

Fig. 1. Scanning electron micrographs showing the effect of injecting mud and fluoboric acids into carbonate rocks (Crowe et al., 1992).

recovery without analysing the effect of the created wormholes on the overall recovery. As per the authors' knowledge, this is the first study that analyses the effect of wormholes in the acidic carbonate EOR method. This study aims to unfold the ultimate potential of the acidic EOR method in carbonate rocks through controlling wormholes development by optimizing the injection conditions using utilizing the dimensionless phase space of Peclet and Damkohler numbers domain diagram. Damkohler number is a function of dissolution rate and the acid injection rate, and Peclet number is a function of the convection and the diffusion rate. Combining both dimensionless numbers provides a complete physical description of wormholes and hence identify the wormhole formation region in the dissolution phase space. The model was validated experimentally (Al-Arji et al., 2021) through acid injection using various HCl-concentration at different injection rates. Peclet number can be expressed as (Frick et al., 1994; Mahmoud et al., 2017):

$$\mathrm{Pe} = \frac{q\sqrt{k}}{AD_e} \tag{3}$$

where Pe is Peclet number, q is the injection flow rate, k is the permeability, and A is the sample cross-section area, and D_e is the effective diffusion coefficient. The Damkohler number can be expressed as (Fredd and Fogler, 1999; Lund et al., 1975):

$$\mathrm{Da} = \frac{\pi d L \kappa}{q} \tag{4}$$

where Da is Damkohler number, d is the core sample diameter, L is the length of the core sample, and κ is the reaction rate. The dimensionless phase space was introduced by Szymczak and Ladd (2009) who studied the dissolution of artificial fractures numerically to examine the effect of flow rate described through Damkohler and Peclet numbers. The diagram was then validated experimentally by Al-Arji et al. (2021) through coreflooding by injecting acid into carbonate rocks. Their study concluded that the critical point for dissolution pattern formation including the wormholes phenomenon can be fully captured by a domain diagram of inverse Damkohler versus Peclet number as predicted by the numerical model.

In this study, the findings will provide a robust basis for future EOR simulations that can be used to optimize fluid's acidity and flow rates for acidic EOR applications. An optimum is expected that achieves the best radius of wormhole formation near wellbore for the purpose of wellbore cleanup and no wormholes for the (spent) acid EOR in the far field.

2. Materials and methods

2.1 Rock samples

In this study, Indiana limestone rock samples (2.5 cm × 5 cm diameter and length) were used. The rationale for using this carbonate rock is attributed to the wide usage of this specific type of rock in the literature and hence it is well characterized. In addition, Indiana limestone exhibits relatively homogenous

Table 1. The rock composition and oil properties at experimental conditions.

Properties	Unit	Value
Density[a]	g/cc	0.83
Viscosity[a]	cp	2.79
API[a]	–	38.2
Saturates[a]	wt%	73.8
Aromatics[a]	wt%	18.3
Resins[a]	wt%	7.7
Asphaltenes[a]	wt%	0.06
Total acid number[a]	mg KOH/g	0.2
Total base number[a]	mg KOH/g	0.3
Mineral composition (Indiana limestone)	98.3%, Calcite ($CaCO_3$) 1.7%, Montmorillonite $(Na, Ca)_{0.33}(Al, Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$	

[a] Measurement is provided by Petrolab.
[b] Measurement is provided by ALS Global.

Table 2. Rock properties and injection conditions.

Sample #	Porosity (%)	k (mD)	HEDTA (wt%)	Rate (cc/min)	EOR		Ultimate oil recovery (%)
					Water injection	HEDTA injection	
EOR-1	14.9	121	2	1	Yes	Yes	82.5
EOR-2	15.4	135	2	0.3	Yes	Yes	92.1
EOR-3	15.1	120	5	0.3	No	Yes	88.8
EOR-4	16.0	128	5	1	No	Yes	62.1
EOR-5	16.2	136	5	3	No	Yes	45

mineralogy (> 98% calcite). Table 1 shows the mineralogy composition of the Indiana limestone samples. The porosity of the samples was calculated using the saturation method and is presented in Table 2.

2.2 Fluids

The crude oil composition was measured by a saturate, aromatic, resin and asphaltene analysis at the experimental conditions. The summary of the crude oil composition and properties is provided in Table 1.

The acidic fluid used in this study is HEDTA. This fluid was selected since it revealed promising results in the area of carbonate acid-EOR (Mahmoud and Abdelgawad, 2015). The acidic fluid is composed of chelating agents that contain various functional groups that have the tendency to form a stable complex at various temperatures (Bakken and Sohoffel, 1996). The primary mechanism behind chelating agents is the ability to sequester metal ions and avoid metal precipitation in carbonate rocks. Hence, the oil recovery enhancement of injecting these chelating agents into carbonate rocks is attributed mainly to rock dissolution, interfacial tension reduction, and wettability alteration. In addition, this fluid is ideal for the field environment as it overcomes the problem associated with regular acidic fluids (such as hydrochloric acid HCl) such as high corrosiveness which affects the tubular and production facility (Mahmoud and Abdelgawad, 2015).

2.3 Experimental setup and procedure

The experimental setup is presented in Fig. 2. Since low-pH fluids are used, all materials utilized in the experimental setup are ensured to be acid compatible. A Vindum pump (0.05% pressure accuracy) with two cylinders was used to inject the required fluids which are connected by 1/16-inch polyetheretherketone tubing that was utilized as a flowline. The confining pressure was set to 6.9 MPa to avoid any fluid outflow. Two high-precision Omega differential pressure transducers were utilized to measure the pressure drop across the core samples. The experimental protocol is as follows:

1) The core sample is cleaned using a Soxhlet distillation extraction method.
2) The core sample is dried in the oven at 50 °C for 24 hours.
3) The core sample is saturated with water using a desiccator. Then, the saturated sample is placed in a core holder.

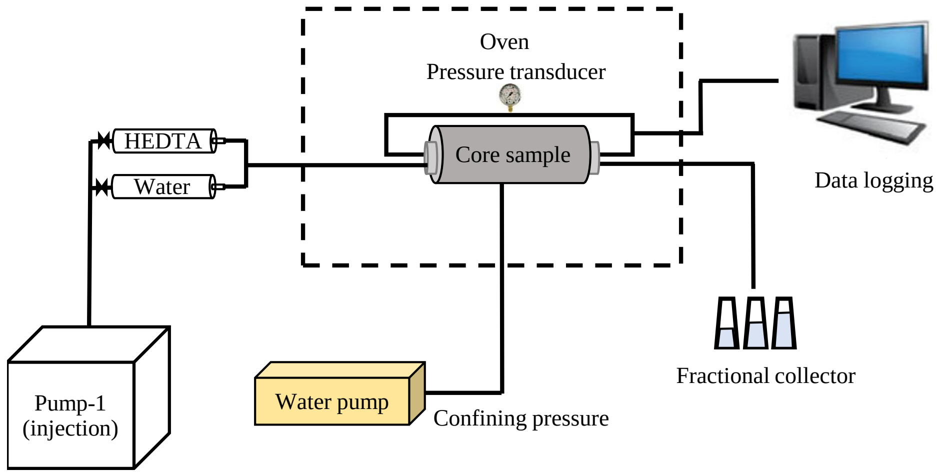

Fig. 2. Acidic flooding experimental set up.

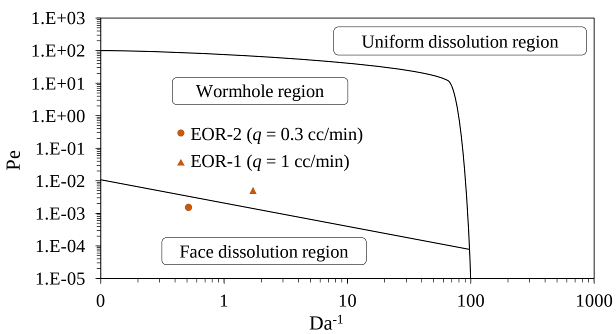

Fig. 3. Phase dissolution diagram of Indiana limestone rock samples showing the dissolution region of the selected injection rates of EOR-1 and 2.

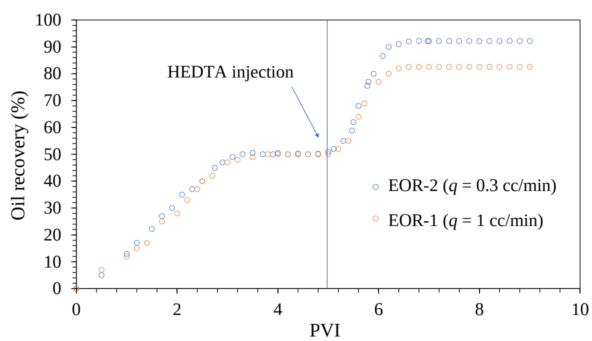

Fig. 4. The oil recovery versus pore volume injected (PVI) of rock samples EOR 1 and 2.

4) Fresh water was injected into the core sample until the pressure drop across the sample reaches a steady state. Then, the absolute permeability (summarized in Table 2) was calculated using the Darcy equation (Darcy, 1856):

$$q = \frac{kAdp}{\mu L} \tag{5}$$

where μ is fluid viscosity, and p is pressure, MPa.

5) The core sample is flushed with oil until it reaches a steady state to establish the irreducible water saturation condition. The steady-state was reached by flushing around 8 pore volumes (PVs). To ensure all the movable water is produced, samples were flushed with oil up to 12 PVs. Irreducible water saturation represents the initial condition for the acidic fluid (HEDTA) injection.
6) The injection experiments started with water flooding until no more oil is produced and the pressure across the sample is stabilized.
7) Then, the acidic fluid is injected at the designed rate at ambient condition using the dimensionless phase space proposed by Al-Arji et al. (2022).
8) The pressure drop is reordered during the experiment to identify the wormholes breakthrough time.
9) The rock outlet face was imaged by high-resolution microscopic images (up to 10 μm) post the flooding experiment to confirm the wormholes presence.

3. Result and discussion

3.1 Experimental runs

Table 2 summarizes the experimental runs. Since this is the first study that aims to characterize the wormholes in the acid carbonate EOR process, the experiments were performed at ambient conditions to provide a fundamental baseline for the wormholes' effect on the carbonate acidic flooding. In addition, to investigate the phase transitions and hydro-mechanical coupling, the CO_2 was not suppressed in the fluid. Furthermore, performing the experiments under ambient conditions enabled the accurate time determination of wormholes breakthrough by monitoring the pressure profile across the samples (Al-Arji et al., 2021).

3.1.1 The first set of experiments

The objective of this set of experiments is to test the effect of wormholes' existence on the carbonate EOR method. Hence, two experiments were conducted where the HEDTA concentration was fixed at 2 wt% and various injection rates namely, 0.3 and 1 cc/min. The acidic concentration was selected to have a feasible range for creating/avoiding the

Fig. 5. Microscopical images of the outlet face post HEDTA injection of rock samples EOR-1 and 2.

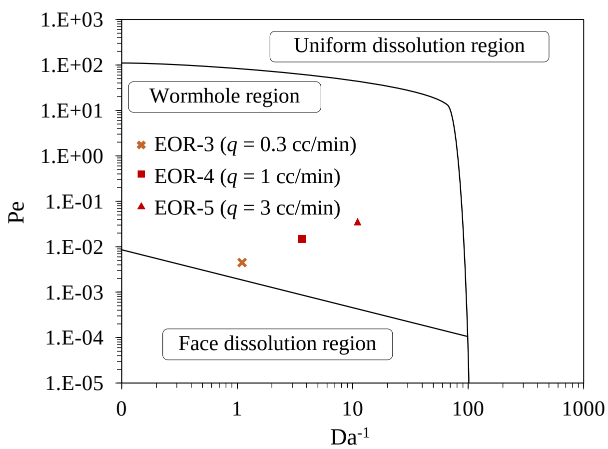

Fig. 6. Phase dissolution diagram of Indiana limestone rocks samples showing the dissolution region of the selected injection rates of EOR-3, 4 and 5.

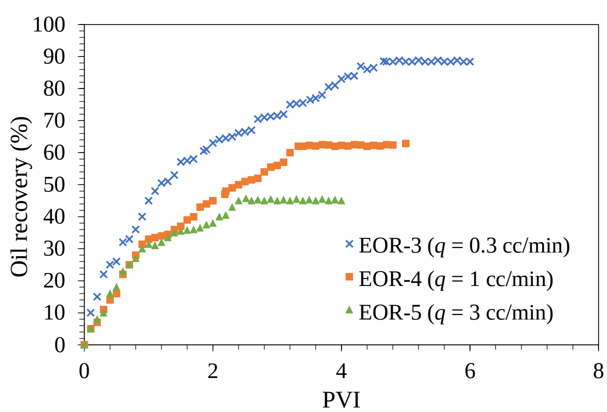

Fig. 7. The oil recovery versus PVI for rock samples EOR-3, 4 and 5 at a fixed HEDTA concentration of 5 wt%.

wormholes development. It would be impractical to test the wormholes influence at high HEDTA concentration as wormholes would quickly develop and this would defeat the purpose of analyzing the effect of the created wormholes on the EOR performance. The injection rates were selected based on the dimensionless phase space proposed by (Al-Arji et al., 2022). The first injection rate (0.3 cc/min) was selected to avoid creating wormholes during the acidic EOR flooding. The second injection rate (1 cc/min) was designed to create wormholes to properly identify the effect of wormholes on the carbonate EOR experiments.

3.1.2 The second set of experiments

This set of experiments was designed to identify the effect of injection rates on the EOR performance under the presence of wormholes. That means all the experiments in this set will be conducted at conditions that stimulate the development of wormholes to define the extent of the impact of wormholes on the EOR process. This was established by conducting three experiments where the HEDTA concentration was kept constant at 5 wt% and changing the injection rates at 0.3, 1 and 3 cc/min.

3.2 The effect of wormholes on the acidic EOR

To identify the effect of wormholes' creation on the EOR performance, two experiments were conducted: one with wormholes and the other one without wormholes. First, fresh water was injected into the rock samples EOR-1 and EOR-2 and recovered 51.1% and 50.5% of the initial oil in place, respectively. Then, the acidic fluid (HEDTA) was fixed at 2 wt%, whereas the injection rates were varied at 0.3 and 1 cc/min. The injection rates were selected based on a dimensionless phase space proposed by (Al-Arji et al., 2022). Fig. 3 depicts our selected injection rates on the dimensionless phase space. The higher injection rate (1 cc/min) lies in the wormhole region, whereas the lower injection rate (0.3 cc/min) lies in the face dissolution region. Fig. 4 shows the oil recovery of EOR-1 and 2. The first core flooding was conducted using EOR-1 by only injecting water and resulted in a recovery of 51.1%. Then, HEDTA (2 wt%) was injected at an injection rate of 1 cc/min. The additional oil recovery was found to be 31.4% and the total oil recovery was 82.5%. The second experiment (EOR-2) was conducted by injecting water and resulted in 50.5% oil recovery. Then, HEDTA was injected at the same concentration (2 wt%) and the injection rate was decreased to 0.3 cc/min to deliberately avoid creating wormholes as per the dimensionless phase diagram (Fig. 3). The additional oil recovery of EOR-2 increased by 9.6% compared to EOR-1, resulting in a total recovery of 92.1%.

It is worth mentioning that in traditional EOR applications, increasing the injection rate results in higher oil recovery. The reason is mainly that a high injection rate is carried out under viscous-gravity transition, whereas a low injection rate is under the gravity-dominant phase (Darcy, 1856; Frenier et al., 1988). However, in our experiments, an opposite phenomenon was noticed where increasing the injection rate decreases the recovered oil. This decrease in oil recovery is attributed mainly to the wormhole phenomenon as it creates a highly conductive pathway offering the least resistance for fluid to flow. Consequently, this conductive fracture-like pathway carries most of the injected fluids hindering the acidic fluid from invading virgin regions in the core sample. Consequently, a significant part of the oil is left behind which decreases the overall oil recovery. Fig. 5 shows microscopical images for the outlet face of EOR-1 and 2. Fig. 5 shows the wormhole breakthrough at the outlet face of the core samples, namely EOR-1 and 2. The core sample EOR-1 showed a wormhole breakthrough, whereas EOR-2 did not show a wormhole breakthrough. This process can greatly impact the oil recovery in real field applications and once these wormholes are created and connect the injection wells to the producers, they act as fractures that carry most of the injected fluid to the producer wells minimizing the pore accessibility which defeats the main purpose of performing EOR operations.

3.3 The impact of injection rates on carbonate EOR practices under wormholes development

To better understand the wormhole effect on the carbonate acidic flooding and the magnitude impact of these wormholes on the overall oil recovery, the performance of the EOR method was tested with wormholes development at varying injection rates. In this protocol, three experiments were conducted keeping the acidic fluid (HEDTA) concentration constant at 5 wt% and the injection rates were varied at 0.3, 1 and 3 cc/min. The injection rates were selected based on conditions that stimulate wormholes development utilizing the previously mentioned dimensionless phase space. Fig. 6 shows our selected injection rates on the dimensionless phase space. As can be seen from Fig. 6, EOR-3, 4 and 5 lie in the wormhole region. Table 2 summarizes the results of the experimental runs. EOR-3, 4, and 5 were conducted at injection rates of 0.3, 1, and 3 cc/min, respectively. Fig. 7 shows the oil recovery of the three samples versus the PVI. As can be seen from Fig. 7, the oil recovery decreases when the injection rate increases. The oil recovery for EOR-3, 4 and 5 was found to be 88.8%, 62.1% and 45%, respectively. This can be explained by how fast these wormholes breakthrough. Increasing the injection rate requires less PVI to breakthrough (Zhou et al., 1997; Al-Arji et al., 2021). As explained previously, once these wormholes breakthrough, they carry all the injected fluid through the created channel reducing the accessibility of the injected fluid to the pores which reduces the overall oil recovery. Fig. 8 shows the microscopical images of the outlet face post the HEDTA injection of EOR-3, 4 and 5 as a confirmation of wormholes breakthrough. As can be seen from Fig. 8, all samples showed wormholes breakthrough.

Figs. 9(a)-9(c) show the wormhole breakthrough using the pressure drop profile for EOR-3, 4 and 5. At ambient conditions, when wormholes are created in the carbonate acidizing process, the pressure tends to increase during the experiment and once the wormholes breakthrough, the pressure decreases sharply since the wormholes create a conductive pathway that connects both ends of the core sample offering the least resistance pathway for fluid to flow (Al-Arji et al., 2022). Figs. 9(a)-9(c) show that when the injection rate increases, the pore volume to breakthrough (PVBT) decreases. The PVBT for EOR-3, 4 and 5 are 1.65, 1.51 and 1.27, respectively. Consequently, the injected acidic fluid tends to flow through the least resistant pathway leaving part of the oil behind in unswept vicinities. It was noticed that once the pressure drop reaches almost zero value, a pathway connecting the inlet to outlet is already created and the pressure drop never increases beyond this stage. Hence, when the pressure reaches almost zero value in Figs. 9(a)-9(c), the data is stopped unlike the oil recovery data which is continued until water production reaches 100%.

To better understand the physics of the wormhole phenomenon, the EOR performance prior to wormholes' breakthrough was assessed. Fig. 10 shows the oil recovery of the three rock samples (EOR-3, 4 and 5) prior to the wormholes breakthrough. It is noticed that when increasing the injection rate, the overall oil recovery decreases even before the wormhole breakthrough. This observation confirms the significant impact of the rock dissolution structure on the EOR experiment performance. When increasing the injection rate, the rock dissolution structure tends to form a dominant wormhole that carries the injected fluids toward the tip of the developing dominant wormhole which results in preventing the acidic fluid from invading virgin vicinities in the rock sample, which ultimately reduces the acidic fluid sweep efficiency. However, when decreasing the injection rate, the acidic fluids are focused on the inlet surface, resulting in forming a face dissolution structure with minimal penetration depth which allows the injected fluids to invade more unswept areas in the rock sample which results in increasing the oil recovery. Fig. 6 confirms this observation and shows that when decreasing the injection rate, the dissolution structure gets further away from the wormhole region and more into the face dissolution which results in higher overall oil recovery, as we have also seen earlier when analyzing the impact of wormholes' existence by comparing EOR-1 and EOR-2 (Fig. 3).

4. Summary and conclusion

The findings of this study provide important fundamental insights and data for future reservoir models that aim at optimizing the overall oil recovery in carbonate reservoirs under acidic enhanced oil recovery projects. This study has analyzed the influence of wormholes in acidic carbonate EOR using HEDTA to optimize the design of real field applications. The effect of acidic carbonate EOR under the presence and absence of wormholes is studied. The effect of injection rate on the EOR performance in the presence of wormholes is analyzed. The experiments were performed on Indiana limestone rock

Fig. 8. Microscopical images of the outlet face post HEDTA injection of rock samples EOR-3, 4 and 5.

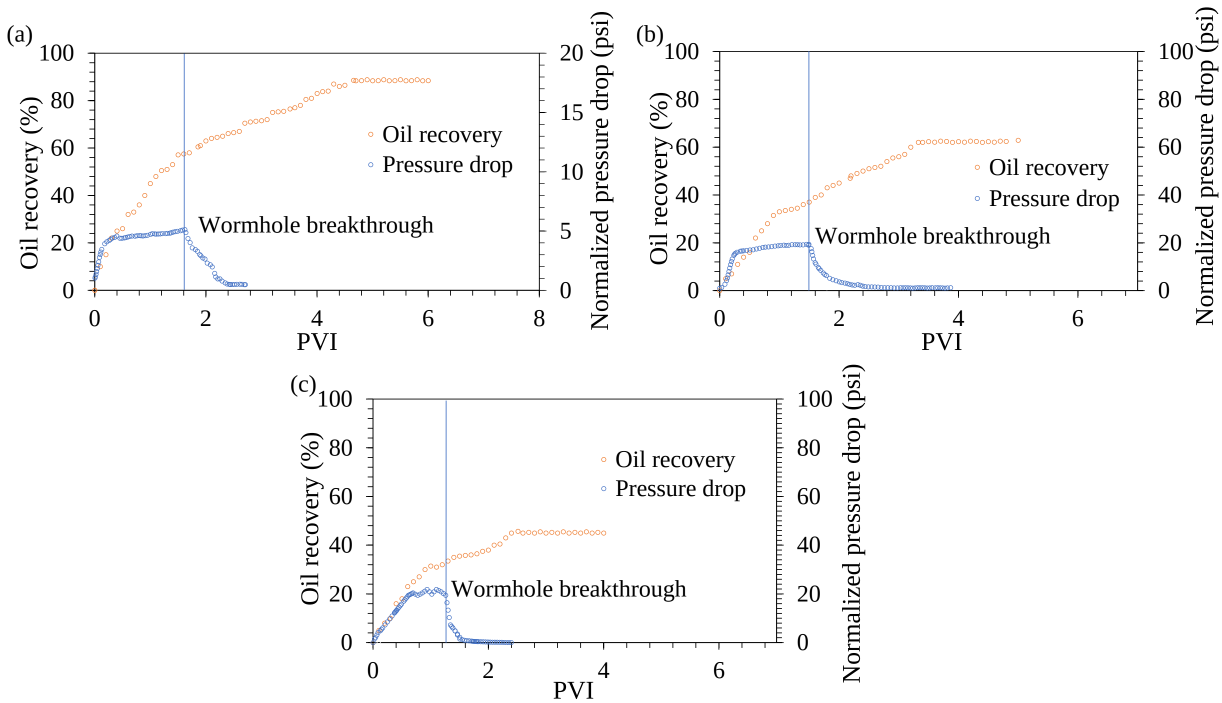

Fig. 9. (a) The oil recovery and normalized pressure drop (NPD) of rock sample EOR-3, (b) the oil recovery and NPD of rock sample EOR-4, (c) the oil recovery and NPD of rock sample EOR-5.

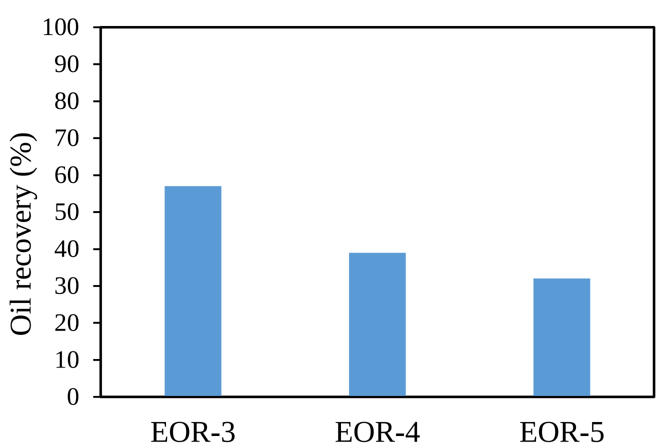

Fig. 10. The oil recovery prior wormhole breakthrough for rock samples EOR-3, 4 and 5.

samples. The following conclusions are revealed:

1) The creation of wormholes has a significant impact on the oil recovery as it decreased the oil recovery by 9.6% compared to the experiment where no wormholes were developed. This decrease is attributed mainly to the wormhole phenomenon as it creates a highly conductive pathway offering the least resistance for fluid to flow. Consequently, most of the acidic fluid flow through that conductive channel and part of the oil remains unswept in virgin vicinities which decreases the overall oil recovery.
2) Experiments under the presence of wormholes showed that oil recovery decreases when the injection rate increases. This can be explained by how fast these wormholes breakthrough. Increasing the injection rate requires less PVBT. Hence, once these wormholes breakthrough, they carry all the fluid in the created channel bypassing part of the oil areas which reduces the overall oil recovery.

3) The oil recovery prior to wormholes' breakthrough tends to increase when decreasing the injection rate at fixed acidic concentration. This is mainly attributed to the rock dissolution structure during the acidic flooding. The face dissolution region results in an additional increase in the oil recovery attributed to a wide range of pore accessibility, unlike the wormholes which significantly reduce the oil recovery.

In real field applications, it is recommended to avoid creating wormholes during the acidic carbonate EOR process as it may jeopardize the field development since creating these wormholes will result in creating highly conductive pathways mimicking fracture characteristics that carry the fluid through leaving a tremendous amount of oil unswept in virgin vicinities. Since this study is the first assessment of wormholes in EOR application and intended to be a baseline for wormholes effect in carbonate EOR applications, more work needs to be conducted to have a detailed understanding of the effect of these wormholes in different conditions such as high temperature, high pressure, formation water to mimic the reservoir conditions and to compare the results with this study to acquire a comprehensive understanding of the wormholes phenomenon in the EOR applications.

The method of determining phase dissolution diagrams provides a powerful design tool for future optimal low-pH injection EOR designs and the method presented in this paper is easily replicable for different carbonates. The detrimental effect of wormhole formation on sweep efficiency is especially strong for pure carbonates as wormholes can form for low acid concentrations. Future studies on different porosity limestones are needed to assess potential negative effects on acidic EOR.

Acknowledgement

The authors would like to thank Artur Shapoval for providing the crude oil and the hydrocarbons compositional report.

Conflict of interest

The authors declare no competing interest.

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