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Enhanced oil recovery (EOR) by ionic liquid assisted with low salinity water: Experimental study in carbonate rock

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Abstract

There is a growing imperative to extract oil not only through primary and secondary means but also via tertiary recovery methods to meet the escalating global energy demands. Consequently, Enhanced Oil Recovery (EOR) is slated to increase significance in the oil industry in the coming years. The amalgamation of low salinity water (LSW) with chemicals to augment oil recovery has gained substantial traction in recent years owing to its demonstrated effectiveness. In this study, a systematic investigation utilizing contact angle measurements to elucidate the underlying mechanisms was undertaken. The results reveal that the contact angle (CA) demonstrated the effectiveness of the combined fluid in altering the wettability from oil-wet to water-wet. The stability of the ionic liquid C_{12}PYCL under reservoir conditions was indicated by thermogravimetric analysis (TGA) and UV-visible spectroscopy. Following the injection of LSW for secondary recovery, core flooding tests were conducted for two different concentrations of the ionic liquid. This resulted in additional oil recoveries of 17% and 19.7% OOIP respectively, at a flow rate of 0.667 cm^3/min. At the higher concentration of the ionic liquid, core flooding tests were conducted across a range of flow rates (0.334, 1, and 1.375) cm^3/min, resulting in additional recoveries of 5%, 10.5%, and 8.2% OOIP. This study stands as one of the pioneering investigations in the southern oil fields of Iraq, exploring the potential of enhanced oil recovery across varying flow rates using a hybrid solution comprising LSW and ionic liquid.

Keywords: Wettability alteration; Enhanced oil recovery (EOR); Low salinity water (LSW); Dodecyl pyridinium chloride; Ionic liquid.

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1- Introduction

Carbonate reservoirs are estimated to hold more than 50% of the world's oil reserves [1]. Due to their intricate wettability, formation heterogeneities, and rock/fluid interactions [2, 3], carbonate reservoirs often yield limited recovery. With daily increments in oil consumption [4], astute management of carbonate reservoirs to maximize oil extraction is becoming increasingly crucial. Given the inefficacy of current oil recovery techniques, there is an urgent need for innovative solutions to enhance oil recovery. This has prompted the petroleum industry to pursue cutting-edge recovery methods for tapping into untapped unconventional sources.

Compared to traditional water flooding, injection at lower salinity can boost oil recovery [4, 5]. Low salinity water flooding (LSWF) refers to a specific water injection method that has received a great deal of attention from the academic and business communities for its low cost, low environmental impact, and high potential for improving oil recovery [6, 7]. In the context of EOR, whether in sandstone or carbonate formations, the focus has been on chemical-enhanced oil recovery (CEOR) techniques. CEOR is a promising technology that, when combined with secondary water flooding [8, 9], has the potential to significantly increase oil recovery by releasing oil contained in the porous media's small pores. Surfactants, polymers, acids, gases, salts, and traditional solvents facilitate oil extraction from depleted reservoirs. With present-day CEOR technology, around 30% of reservoir oil might be recovered. Research into using surfactants as chemicals to boost oil recovery dates back to the 1970s [10, 11].

Oil recovery can be greatly improved by using surfactant flooding by decreasing the oil/water IFT and changing the wettability of reservoir rocks, decreasing the capillary forces, and making oil mobilization easier [11]. Ionic liquids, molten salt, have attracted much attention for uses in EOR because of their eco-friendliness, which is especially appealing given the high expense and environmental difficulties connected with using conventional chemical EOR [12]. Ionic liquids are categorized according to whether or not they include inorganic anions and whether or not they contain organic cations, a total of [13]. They have favorable solubility, high ionic conductivity, reusability, and thermal stability [14]. Ionic liquids' characteristics and efficacy are sensitive to the specific composition of their anions, cations, and alkyl groups. For instance, the length of the

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alkyl group affects the ionic liquid's incremental viscosity factor when used as an injection. In addition to their surface-active nature and micelle production property [15], ionic liquids can modify wettability and decrease IFT. Lab experiments demonstrate that ionic liquids are superior to surfactants in lowering IFT in high-salinity and high-temperature settings, and these findings are supported by the literature [16, 17].

It is important to note that wettability is a major process that affects fluid flow in the reservoirs [18, 19]. More research needs to be done to show how ionic liquids change wettability. Bin-Dahbag et al. [18] used different quantities of ionic liquids in a series of flooding experiments conducted on Berea sandstone samples to determine the impact on wettability. As a result of the interplay between the oil, rock, and IL [20], it was found that ILs have the potential to convert oil-wet to water-wet ones. Mohammed and Babadagli [19] investigated the effects of several imidazolium ionic liquids on the wettability of oil-wet limestone and sandstone. To modify the wettability of oil-wet limestone and sandstone, ionic liquids are superior to other chemicals such as surfactants. High-temperature-stable, active ionic liquids are required for this method of thermal oil recovery. In particular, investigation by Bin-Dahbag et al. [18] on core samples found that injecting a mixture of Ammonium-based IL and brine into the core for tertiary recovery increased the RF for medium crude oil (API 28.77) by approximately 4.5% OOIP. Imidazolium-based IL mixed with brine and injected into a core sample as a tertiary recovery mode could extract 13% OOIP more than ammonium-based IL and brine mixes. Brine with a higher concentration of ILs has increased oil recovery from sandstone and carbonate reservoirs [19, 20].

However, Alarbah et al. discovered that when the concentration of IL [EMIM][Ac] was higher than the optimum value, increasing the RF could have been more cost-effective [21]. This research used flooding experiments to study the ability of a combination of low salinity and ionic liquid at room temperature, various IL concentrations, and a range of flow rates to enhance oil recovery in carbonate reservoirs. Moreover, the impact of IL on wettability alteration was investigated at a range of concentrations.

2- Experimental work

2.1. Material

2.1.1. Formation water

The core plugs were saturated with a brine solution from formation water to determine their pore volume, porosity, and permeability. Chemical analysis of the brine is listed in Table 1.

2.1.2. Injection water (Low Salinity)

After the treatment system, the injection water was supplied from the third river, which lies in southern Iraq. Table 2 details the composition and properties of the injection water (low salinity) utilized in these experiments.

2.1.3. Surfactant

The ionic liquid dodecyl pyridinium chloride was purchased from Macklin Company, China. Its general properties are listed in Table 3. Fig. 1 illustrates the chemical structure of the surfactant.

Table 1. Chemical analysis of Dammam formation

Element	Concentration, (ppm)
	Brine
Chloride	127498.655-96205
Sulphate	777.139-650
Bromide	863.741
Total Carbonate	72.928 -97.6
Hydroxide	0
Butyrate	< 5
Cl :Br	168.646
Lithium	3.988
Barium	< 2
Strontium	379.453
Calcium	14119.5 – 22500
Magnesium	4257.172-33000
Sodium	57076.4155 – 30920
Potassium	1366.26 – 320
Sulphur	249.55
Total Iron	48.998
TDS	206480.8185

Table 2. The compositions and the properties of the injection water

Element	Concentration, (ppm)
	Brine
CL^{-1}	1952.5
$SO4^{-2}$	2012.12
Na^{+1}	1529
Ca^{+2}	1225
Mg^{+2}	1180
TDS	7898.62

Table 3. The properties of ionic liquid surfactant

Surfactant name	Dodecyl pyridinium chloride
Chemical formula	C17H30CIN Or (C12Py)(Cl)
Melting point, (C^0)	>80
TGA, (C^0)	250
Appearance	White or faint red-yellow solid
purity	>98%
Molecular weight(g/mol)	283.88

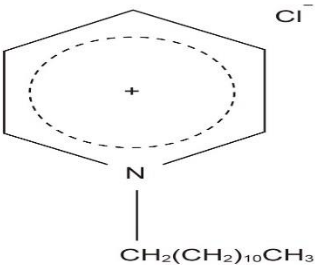

Fig. 1. Structure of 1-dodecylpyridinium chloride chemically

2.1.4. Crude oil

The crude oil utilized in these tests came from the Nasiriyah Oil Field and was obtained from Thi-qar Oil Company. The crude oil sample was centrifuged at 5000 rpm and then filtered until no precipitation of any asphaltenes was detected during storage to avoid any solids blocking or emulsion difficulties.

In the range of (24-25) cp, crude oil's dynamic viscosity is found at 21.10 ºC. Gas oil (75% by volume) was added to the crude oil to increase the dilution ratio and create a more favorable displacement situation in wettability measurements and flow experiments due to the low mobility ratio of crude oil compared to the viscosity of (1-1.5) cp for formation water and injection water. The general properties of the diluted crude oil are listed in Table 4.

Table 4. General properties of the diluted crude oil at 21.10 °C

The properties	The value
Density, g/cm^3	0.836
Specific g. (Sp.g)	0.8377
API	36.77
Dynamic viscosity, cp	3.9
	4.62 at T = 21.10 ^{O}C
Kinematic viscosity, Cst	3.18 at T = 37.8 ^{O}C
	2.52 at T = 48.7 ^{O}C
	2.16 at T = 60 ^{O}C

2.1.5. Porous media

The rock used in this study was collected from the Mishrif formation of the carbonate reservoir at Nassiriyah Oil Field. Fig. 2 shows the flowchart of the practical work steps.

2.2. Experimental steps

2.2.1. Contact angle (CA) measurements

In order to study the contact angle, thin sections of carbonate rocks were sliced. Polishing the final products was the final step. At 25°C, the carbonate rock samples were immersed in ionic liquid solutions of varying concentrations (50, 100, 150, and 250 ppm) for ten, twenty, and thirty minutes, respectively, to determine the influence of ionic liquid concentration on wettability [10].

The Theta Lite, an optical tensiometer, was used for the tests on contact angles. One drop of distilled water dripped from the tip of a needle and the bottom of a cell. Through the use of a user-defined baseline, the software on the device can generate tangent lines on either side of the drop, identifying the interface between the rock surface and the operation and providing the magnitude of the contact angles on either side of the drop in addition to the average. Instructions for using an optical tensiometer to determine contact angles are depicted in Fig. 3.

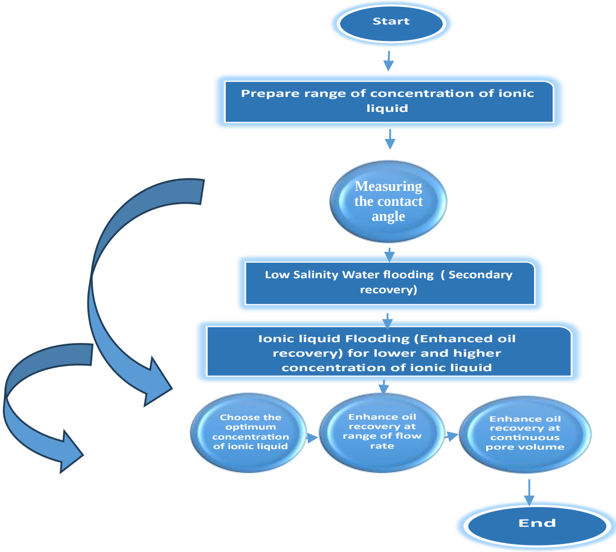

Fig. 2. Flowchart of the procedure

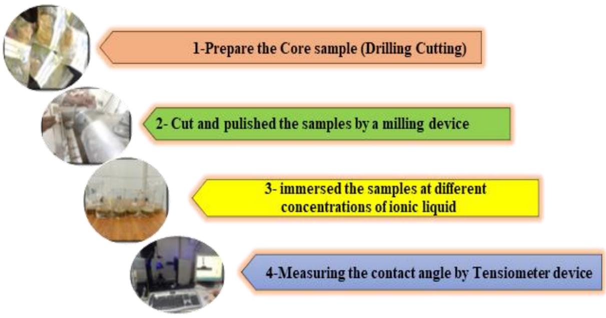

Fig. 3. Shows the steps for measuring the contact angles

2.2.2. Thermo gravimetric analysis (TGA)

During a controlled temperature program, a sample of dodecyl pyridinium chloride is exposed to thermogravimetric analysis, or TGA, which measures a material's mass (or weight) as a function of temperature or time.However, this method does have some limitations, so it cannot be relied upon completely. A (biolab.linseis) was employed in this study.

2.2.3. UV-visible spectroscopy

The optimum solution prepared from low salinity water and 250 ppm of ionic liquid is analyzed using UV-visible spectroscopy before injection in a core plug. This analysis can be used to know the stability of the optimum concentration of ionic liquid at a range of temperatures. The wavelength used was from 200 nm to 300 nm. For this analysis, a (UV-1900i – Shimadzu) was used in this study.

2.2.4. Core-flooding procedure

The system diagram for a core flood is shown in Fig. 4 [10,23]. The core holder features pressure gauges that can track changes in confining pressure and pressure over the core plug. The system is coupled once the accumulator for ionic liquids and brine (supplied by the ISCO pump) is full. The data collection approach was used to test the core-flooding procedure. Vacuum-assisted the initial saturation of the core, which was followed by the flooding of the core with formation water of varying pore volumes to finish the process. The injection of formation water continued continuously until the injection pressure was stable [23].

To prevent further brine formation, diluted crude oil was poured into the water-filled core of the deposit. After this was finished and the water and oil output numbers were recorded. To understand how LSW has affected carbonate rocks, researchers performed secondary recovery using low salinity water flooding on carbonate core samples [24]. The LSW was injected to boost oil production. To evaluate the samples [eness of the injection procedure, the utilization of the ionic liquid known as Dodecyl pyridinium chloride was employed for territorial recovery. This was carried out at two different concentrations, along with various flow rates (0.334, 1, and 1.375 cm^3/min), until two pore volumes (2PVs) were completed within the core plug.

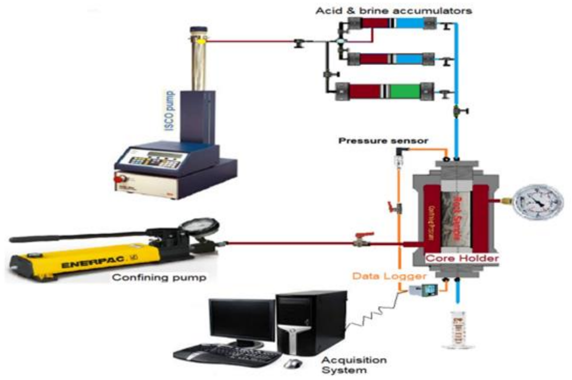

Fig. 4. Schematic of the core flooding apparatus

3- Results and discussion

3.1. Contact angle for ionic liquid

The movement, placement, and distribution of fluids in a reservoir are controlled by the rock's wettability, defined as the rock's tendency for wetting rather than the fluid in direct contact with the rock. The surface-active properties of ionic liquids allow them to affect the wettability of a reservoir. The contact angle decreased with increasing concentration in difficulties with ionic liquids, indicating a transition from a somewhat oil-wet condition to a more water-wet state.

A decrease in contact angle from (98 degrees) to (40 degrees), (101 degrees) to (38 degrees), (103 degrees) to (32 degrees), and (98 degrees) to (28 degrees) in the presence of ionic liquids is indicative of their utility in oil recovery. When a material's wettability shifts, it undergoes a phase change from an oil-wet to a water-wet state. Typically, reactions involving oil, rock, and ionic liquid significantly impact the procedure of changing wettability.

The findings in Fig. 5 show that ionic liquids convert oily rocks to water-wet ones by decreasing the contact angle. This is because the varied charges of the ionic liquids have a different effect on the rock surfaces. Cation-rich ionic liquids are more suitable for carbonate reservoirs, while anion-rich ionic liquids are better suited for sandstone reservoirs. The contact angles between water droplets and rock surfaces were evaluated and reported as a qualitative assessment of rock wettability in solutions of varying ionic liquid concentrations. Fig. 5 shows that after being submerged in brine for (40) minutes, the contact angle of water droplets on the smooth surface of rock samples increased to 45°. For different ionic liquid concentrations in brine, this value dropped over time (Fig. 5). Greater wettability changes were observed when the ionic liquid concentration was increased from 50 ppm to 250 ppm. The wettability of the material is little affected by raising the concentration of the ionic liquid from 50 to 150 ppm under the same conditions and after the same period. The contact angle measurements suggested ionic liquid solutions could convert oil-wet conditions to neutral-wet and water-wet ones.

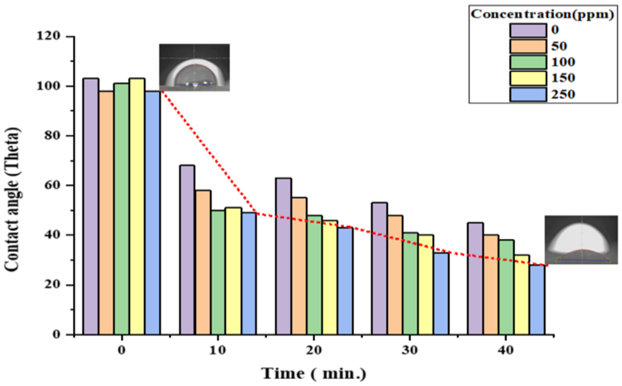

Fig. 5. Variation in contact angle with time and concentration

3.2. Thermo gravimetric analysis (TGA) for ionic liquid

Thermo Gravimetric Analysis (TGA) was employed to ascertain the thermal stability of the sample. Specifically, 12.08 mg of dodecyl pyridinium chloride was subjected to calculations in a Biolab Linseis analyzer under a pure nitrogen atmosphere. Typically, ionic liquid surfactants exhibit stability at elevated temperatures.

The sample was heated from 298 to 800 K at a rate of 10 °C/min with a flow rate of 1 cm^3/min, then subsequently cooled to 70 °C at a rate of 20 °C/min. The TGA curves in depicted Fig. 6 indicated that the total weight loss of approximately -99.365% for C_{12}PYCL.

The sample remained stable until 260 °C, beyond which decomposition occurred. These findings affirm that, in terms of temperature stability, dodecyl pyridinium chloride is well-suited for deployment in reservoir conditions.

3.3. UV-Vis absorption spectra at different temperature for ionic liquid

Fig. 7 presents the UV-vis absorption spectra of the optimal concentration of ionic liquid at varying temperatures. The temperature of the reservoir in the Mushrif formation at the Nasiriyah oil field is 76 °C. Consequently, the highest temperature UV-vis absorption recorded for the optimal concentration surpasses this value. The maximum absorbance of dodecyl pyridinium chloride at different temperatures was gauged by UV-visible spectroscopy within a wavelength range of 200-300 nm, as illustrated in Fig. 7.

It is observed that at a temperature of 18 °C, the absorption peak reaches its zenith compared to other temperatures. The analysis indicates that an increase in temperature from 18 °C to 90 °C marginally reduced the absorbance value due to the stability of the surfactant.

This observation is congruent with the TGA analysis of C_{12}PYCL in Fig. 6, affirming that the sample remains stable until 260 °C. Thus, the ionic liquid (dodecyl pyridinium chloride) exhibits greater stability at reservoir temperatures.

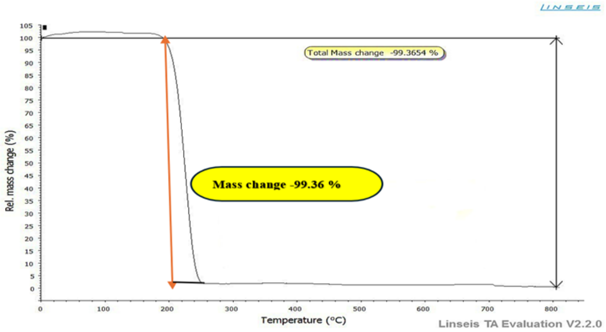

Fig. 6. TGA Thermo grams of Dodecyl pyridinium chloride

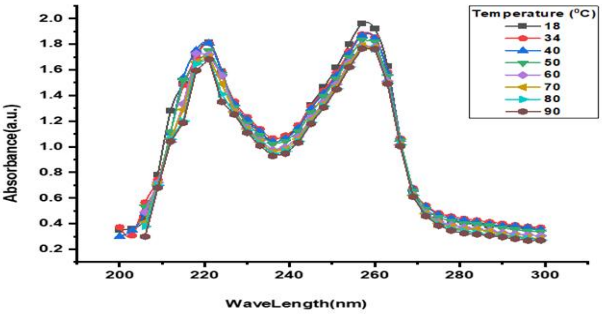

Fig. 7. Typical UV-vis spectra of hybrid optimum solution at different temperatures

3.4. Oil recovery of surfactant (ionic liquid) flooding

3.4.1. Concentration's influence on oil recovery efficiency

This study investigates the enhanced oil recovery performance of combinations of cationic surfactants (dodecyl pyridinium chloride) mixed with low salinity water through flooding and displacement studies in a lab setting, utilizing a production well in the Nasiriyah Oil Field. The use of ionic liquid has been shown to enhance oil recovery from carbonate reserves. The results indicate that one of the mechanisms responsible for the increase in oil recovery is the alteration of rock wettability towards increasingly water-wet conditions. Cationic surfactants are repelled by the positively charged carbonate surfaces, especially in the polar regions. Consequently, the nonpolar components come into contact with the rock's exterior.

This leaves the polar regions in touch with water at the rock-fluid interface, increasing the already-high humidity levels there. This explanation is consistent with the findings of Castro Dantas et al. (2014) [25]. When comparing the contact-angle-changing effects of various ionic liquid concentrations in hybrid solutions, it became evident that a concentration of 250 ppm was optimal for injection into the core plug, reducing the contact angle by 71% compared to a low concentration of 50 ppm. The pore volumes (PVs) were 21.81 cm^3 for plug 8 and 21.93 cm^3 for plug #10, with initial oil saturation of 67% and 61%, respectively. The porosity and permeability of the carbonate core plug were 26.2% and 4.17 mD for plug 8 and 26.34% and 6.84 mD for plug 10. To initiate flooding, 2 PVs of LSW (7600 ppm) were injected into the core.

Both secondary and tertiary recovery techniques were applied in this experiment. The respective recovery profiles through the carbonate rock plug are depicted in Fig. 8. This figure shows that the recovery factor of oil increased up to 0.7 PVs injected for plugs 8 and 10, yielding 48% and 63% recovery, respectively, after injecting the low-salinity brine. Oil recovery saw a slight improvement after another 1.65 PVs of brine were injected.

After completing 2 PVs of LSW, tertiary recovery was initiated by injecting 2 PVs of the hybrid solutions as chemical flooding. Oil production commenced after injecting 0.8 PVs of the chemical solution, resulting in an increase in recovery from 61% to 64.5% OOIP for plug #8 and from 63% to 73.2% OOIP for plug 10. Completing 2 PVs from the solution prepared by combining 50 ppm of ionic liquid with LSW allowed for an additional extraction of 17.1% OOIP, while the optimum concentration prepared by combining 250 ppm of ionic liquid and LSW enabled an additional extraction of 19.7% OOIP [12]. A detailed summary of the core flooding parameters is shown in Table 5.

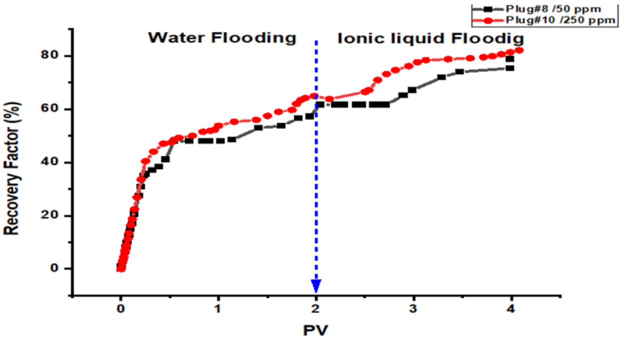

Fig. 8. Oil recovery from the core for solutions at a range of concentrations

Table 5. Summary of core flooding experiments

Plug nu.	φ (%)	K (MD)	S_{WI} (%)	Secondary recovery (%)	Ionic-liquid concentration (ppm)	Flow rate (cm^3/min)	Pore volume injection (PV)	Tertiary recovery (%)	Final recovery (%)
8	26.2	4.17	33	61	50	0.667	2	17	78
10	26.34	6.84	39	63	250	0.667		19.7	82.7
3	20.96	18.24	35	66.7	250	0.333		5	71.7
5	25.93	9.58	33	65.7	250	1.375		8.2	73.9
9	13.79	13.46	20	50.4	250	1		10.5	60.9
4	18.42	19.62	46	63	250	0.667	7.75	28.7	85.9

3.4.2. Flow rate's influence on the oil recovery efficiency

At an external temperature of 23 °C and using core samples with permeability values ranging from 4 to 20 md, the viscosity of diluted crude oil was measured 3.9 cp. Carbonate rocks, which are typically oil-wet and heterogeneous, exhibit only marginal increases in the recovery factor with slight flow rate increments (achieved by increasing the injected pore volume). Fig. 9 and Table 5 illustrate that even at the highest flow rate of 1.375 cm^3/min, oil recovery remained poor due to the anticipated particle migration. Fines migration is a common contributor to reservoir formation degradation. Natural reservoir fines migrate when oil or gas is produced with LSW, during high production or injection rates, LSW flooding into a reservoir, or when EOR is combined with any of these methods. Fines migration, especially for particles like kaolinite, illite, or non-clay fines, occurs when the flow rate surpasses the critical velocity, particularly at elevated flow rates. Fines migration can significantly compromise the formation's permeability, making it an issue that must always be addressed. As can be seen in Fig. 9, for the optimum concentration, oil recovery improves with increasing injection rates below 0.833 cm^3/min. The oil recovery rates were approximately 5%, 19.7%, 10.5%, and 8.2% at flow rates of 0.333, 0.667, 1, and 1.375 cm^3/min, respectively. As illustrated in Fig. 9, the optimal flow rate for carbonate core plugs is Q = 0.667 cm^3/min, resulting in the highest oil recovery when compared to other flow rates while utilizing the same volume of surfactant input.

After 51 minutes of surfactant injection, operating at the optimal solution and a flow rate of 0.667 cm^3/min, the oil recovery rate is close to 82%. Fig. 9 shows that the oil recovery reduces with increasing injection rate when a constant surfactant solution is injected.

At the optimum flow rate, and with an injection volume of 1 PV, the time for the optimum concentration flooding is approximately 27 minutes, resulting in an oil recovery of about 77.2%. This is due to the small size of the matrix, allowing most of the injected fluid to be generated immediately with nominal oil recovery. Fig. 9 shows that the ultimate oil recovery increases more slowly below an injection rate of 0.667 cm^3/min for a given solution injection, following a power function relation with the injection rate. Therefore, the ideal injection rate of 0.667 cm^3/min is based on surfactant flooding time, injection volume, and oil recovery.

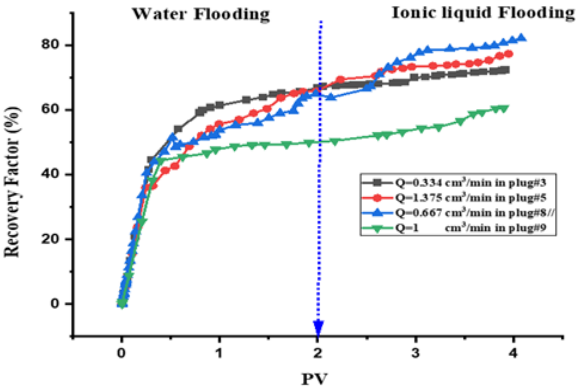

Fig. 9. Oil recovery from the core for optimum concentration of ionic liquid at the range of flow rates

3.4.3 Continuous and batch injection for ionic liquid

The flooding process theoretically continues until oil production quits, with effluents collected in graded tubes in an immediately arranged fraction collector. This assumes the injection of the optimum concentration of ionic liquid at the optimum flow rate into core plug 4. After the injection of 7.75 ionic liquid C12PYCL, the recovery factor had increased to 28.7% OOIP.

Unfortunately, the significant economic cost associated with chemical injections means that this approach is far from reflecting the actual state of affairs in the reservoir. Fig. 10 shows the recovery factor for plugs 4 and 10 for continuous and batch injections (2 PVs).

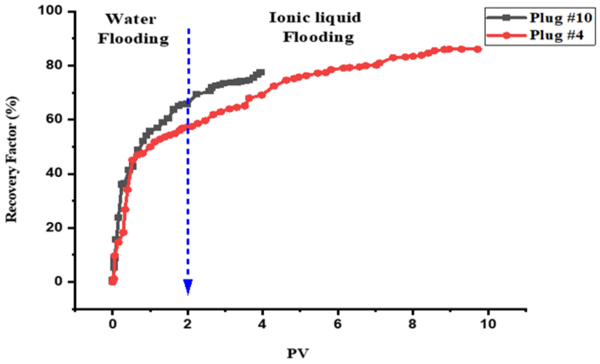

Fig. 10. Oil recovery for the optimum (concentration and flow rate) of ionic liquid after 2PVs only and 7.75PVs

3.5. Pressure drop discussion

While the injection rate stabilizes and oil is displaced by water, the pressure differential between the two ends of the core gradually increases during LSW flooding in all core samples. The elevated pressure drop may be attributed to the movement of fines. When the surfactant injection process begins, the pressure in all samples rises to a maximum of 332, 356, 397.3, 60, 151.7, and 27.5 psi for plugs 8, 10, 3, 5, 9, and 4, respectively. However, the pressure drop curve behaves differently based on the concentration of the injected fluid and the injection rate (Fig. 11). The pressure loss increases somewhat after injecting 1.5 PVs of the optimal concentration of IL, likely due to surfactant adsorption into the rock surface. Analysis of recovery and pressure drop data has shown that injecting 2 PVs of surfactant increases oil recovery without significantly damaging the formation.

3.6. Comparison analysis study

This study obtained good value for the enhanced oil recovery using the ionic liquid solution prepared by combining (low salinity water with ionic liquid) if compared with previous research. Table 6 Illustrates the comparison between the previous work on ionic liquid flooding and the present research

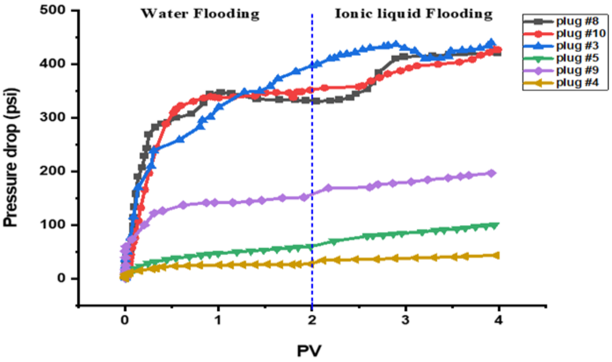

Fig. 11. The effect of pressure drops after flooding process

Table 6. Compare the previous work on ionic liquid as territory recovery with present research

	Author	Ionic Liquid	Concentration (ppm)	Brine	Secondary Extraction (% OOIP)	Flow rate (cm^3/min)	PVs injection	Additional Oil Recovery (%OOIP)
1	Hezave et al. (2013)[20]	$[C_{12}mim]Cl$	4000	Formation brine	50	0.3	/	13
2	Manshad et al. (2017)[26]	$[C_{18}mim]Cl$	170	Formation brine	38	0.5	2.7	13
3	Bin Dahbag et al. (2015)[27]	Ammoeng 102	500	20 wt%,(83%NaC,17% $CaCl_2$)	43	/		5
4	Zabihi et al. (2019) [28]	$[C_{18}mim]Cl$	3500	Formation brine	38	0.3		16.5
5	Nabipour et al. (2017)[29]	$[C_{12}mim]Cl$	500	Formation brine	54.5	0.3	0.7	3.3
6	Ouda et al. (2023) [10]	C_{12} PYCL	250	low salinity	63	0.667	2	19.7
			50		61	0.667	2	17.3
7	**The present study**	**C_{12} PYCL**	**250**	**low salinity**	**50.4**	**1**	**2**	**10.5**

4- Conclusion

The following inferences were made based on the study's experimental findings:

1) The combination of LSW and ionic liquid proved to be efficient in enhancing oil recovery. The efficiency of IL depends on the IL concentration and flow rate of injection. The results indicated that flooding at 250 ppm was more efficient than 50 ppm. Additionally, flooding at 0.667 cm^3/min proved more effective than at 0.334, 1, and 1.375 cm^3/min for the same concentration.
2) The contact angle was reduced by 71% from 98 to 28 after immersing for 40 min at 250 ppm of ionic liquid (the optimum concentration), Changing the oil-wettability to water-wettability of the surface.
3) In this study, the highest additional oil recovery factor of 85.9% OOIP was achieved after continuous injection of 7.75 PVs at the optimum concentration and flow rate. It was found that the optimum concentration of ionic liquid C_{12}PYCL is the most effective for enhancing oil recovery compared to other ILs in previous work.

References

[1] X. Deng, Z. Tariq, M. Murtaza, Sh Patil. M. Mahmoud, and M. Shahzad, "Relative contribution of wettability Alteration and interfacial tension reduction in EOR: A critical review", *Molecular Liquids*, vol. 325, pp.115175, 2021. https://doi.org/10.1016/j.molliq.2020.115175

[2] N. R. Morrow, G. V. Tang and M. X. Xie, "Prospects of improved oil recovery related to wettability and brine composition", *Petroleum Science and Engineering*, vol. 20, no. 3, pp. 267–276, 1998. https://doi.org/10.1016/S0920-4105(98)00030-8

[3] G. Tang and N. R. Morrow, "Influence of brine composition and fines migration on crude oil/brine/rock interactions and oil recovery", *Petroleum Science and Engineering, vol.* 24, pp. 99–111, 1999. https://doi.org/10.1016/S0920-4105(99)00034-0

[4] E. Alagic, K. Spildo, A. Skauge, J. Solbakken, "Effect of crude oil ageing on low salinity and low salinity surfactant flooding", *Journal of Petroleum Science and Engineering*, vol. 78, pp.220–2227, 2011. http://dx.doi.org/10.1016/j.petrol.2011.06.021

[5] R. Jalil, H. Hussein, "Alteration wettability of carbonate rocks by Nano fluids and comparison with PEG and SDS, *Journal of Petroleum Research & Studies*, vol. 29, no. 12, 2020. http://dx.doi.org/10.52716/jprs.v10i4.367

[6] G. N. Jreou, "Increasing of Oil Field Productivity by Implementation of Re-entry Horizontal Injection Well, Case study", *Iraqi Journal of Chemical and Petroleum Engineering*, vol. 13, no. 3, pp. 17–34, 2012, https://doi.org/10.31699/IJCPE.2012.3.3

[7] M. H. Derkani , A. J. Fletcher, W . Abdallah, B. Sauerer, J. Anderson and Z. J. Zhang, "Low Salinity Waterflooding in Carbonate Reservoirs: Review of Interfacial Mechanisms", *Colloids Interfaces*, vol20, no. 2, 2018. http://dx.doi.org/10.3390/colloids2020020

[8] H. A. Baker, K. A. Alwan and S. F. Fadhil, "Enhanced Oil Recovery using Smart Water Injection", *Journal of Engineering*, vol. 24, no. 8, 2018. https://doi.org/10.31026/j.eng.2018.08.04

[9] A. H. Assi, F. H. M. Almahdawi, and Q. A. Khalti, "The Influence of Glass Fiber and Milled Glass Fiber on the Performance of Iraqi Oil Well Cement", *Journal of Petroleum Research and Studies*, vol. 11, no. 2, pp. 30-48, 2021. https://doi.org/10.52716/jprs.v11i2.496

[10] M. Mahdi, S. Al-Anssari, and Z.-U.-A. Arain, "Influence of Nanofluid Flooding on Oil Displacement in Porous Media", *Iraqi Journal of Chemical and Petroleum Engineering*, vol. 24, no. 2, pp. 19–30, 2023, https://doi.org/10.31699/IJCPE.2023.2.3

[11] B. Haq, "Green Enhanced Oil Recovery for Carbonate Reservoirs", *Polymers*, vol. 13, pp. 3269, 2021. https://doi.org/10.3390/polym13193269

[12] M. Kh. Jalil, "Q. Hussein and R. R. Jalil, "Study of the effect of ionic liquid on the wettability alteration of carbonate reservoir", *Chemical Papers*. Volume 77, pp. 3663–3669, 2023, https://doi.org/10.1007/s11696-023-02728-0

[13] A. Kokorin, Ionic Liquids: Applications and Perspectives. Intechopen, 2011. https://doi.org/10.5772/13974

[14] M. Earle, and K. Seddon, "Ionic liquids. Green solvents for the future", *Pure and Applied Chemistry*, vol.72, pp. 1391–8, 2000. http://dx.doi.org/10.1351/pac200072071391

[15] J. Brennecke, and E. Maginn, "Ionic liquids: innovative fluids for chemical processing". *The Global Home of Chemical Engineers*. vol. 47, no. 11, 2001. https://doi.org/10.1002/aic.690471102

[16] A. Rezaei, M. Riazi, M, Escrochi, and R. Elhaei, "Integrating Surfactant, Alkali and Nano-Fluid Flooding for Enhanced Oil Recovery: A Mechanistic Experimental Study of Novel Chemical Combinations", *Journal of Molecular Liquids*. Vol. 308, pp. 113106, 2020. https://doi.org/10.1016/j.molliq.2020.113106

[17] Z. He, and P. Alexandridis, "Ionic liquid and nanoparticle hybrid systems: emerging applications". *Advances in Colloid and Interface Science*, vol. 244, pp. 54–70, 2017. https://doi.org/10.1016/j.cis.2016.08.004

[18] A. Bera, H. Belhaj, "Ionic liquids as alternatives of surfactants in enhanced oil recovery—a state-of-the-art review", *Journal of Molecular Liquid*. Vol. 224, pp. 177–188, 2016. http://dx.doi.org/10.1016/j.molliq.2016.09.105

[19] A. Hezave, Z. Dorostkar, S. Ayatollahi, S. Nabipour, and B. Hemmateenejad, "Dynamic interfacial tension behavior between heavy crude oil and ionic liquid solution (1-dodecyl-3-methylimidazolium chloride ([C12mim][Cl]+ distilled or saline water/ heavy crude oil)) as a new surfactant", *Journal of Molecular Liquid, vol.* 187, pp. 83–89, 2013. https://doi.org/10.1016/j.molliq.2013.05.007

[20] M. Bin-Dahbag, A. AL.Quraishi, M. Benzagouta, M. Kinawy, J. AL Nashef, and E. AL Mushaegeh, "Experimental Study of Use of Ionic Liquids in Enhanced Oil Recovery", *Journal of Petroleum and Environmental Biotechnology, vol.* 4, no.165, 2014. http://dx.doi.org/10.4172/2157-7463.1000165

[21] M. Mohammed, and T. Babadagli, "Experimental investigation of wettability alteration in oil-wet reservoirs containing heavy oil", SPE *Reservoir Evaluation Engineering, vol. 19,* pp. 633–644, 2016. https://doi.org/10.2118/170034-PA

[22] A. Hezavea, S. Dorostkar, Sh. Ayatollahi, M. Nabipour, and B. hemmateenejad, "Investigating the effect of ionic liquid (1-dodecyl-3-methylimidazolium chloride ([C12mim] [Cl])) on the water/oil interfacial tension as a novel surfactant", *Colloids and Surfaces A: Physicochemical and Engineering Aspects, vol.* 421, pp. 63–71, 2013. https://doi.org/10.1016/j.colsurfa.2012.12.008

[23] A. Alarbah, M. Shirif , and E. Shirif , "Investigation of Different Ionic Liquids in Improving Oil Recovery Factor", *Advances in Chemical Engineering and Science*, vol. 9, pp. 87-98, 2019. https://doi.org/10.4236/aces.2019.91007

[24] P. Pillai, A. Kumar, and A. Mandal, "Mechanistic studies of enhanced oil recovery by imidazolium-based ionic liquids as novel surfactants*", Journal of Industrial and Engineering Chemistry, vol.* 63, pp. 262–274, 2018. https://doi.org/10.1016/j.jiec.2018.02.024

[25] U. Alameedy, A. Alhaleem, A. Isah, A. Al-Yaseri, A. Mahmoud, M. Salih, “Effect of acid treatment on the geomechanical properties of rocks: an experimental investigation in Ahdeb oil field”, *Journal of Petroleum Exploration Product Technol*, vol.12, pp. 3425–3441, 2022. http://dx.doi.org/10.1007/s13202-022-01533-x

[26] A. Radhi, and M. Aljwad, “Normalize and De-Normalize of Relative Permeability Data for Mishrif Formation in WQ1: An Experimental Work”, *Iraqi journal of chemical and petroleum engineering*, vol. 23, no. 4, pp. 71–80, 2022. https://doi.org/10.31699/IJCPE.2022.4.9

[27] T. Castro, P. Soares, A. Wanderley, A. Dantas, and E. Barros, “Implementing new microemulsion systems in wettability inversion and oil recovery from carbonate reservoirs”, *Energy Fuels*, *vol.* 28, pp. 6749–6759, 2014. https://doi.org/10.1021/ef501697x

[28] A. Manshad, M. Rezaei, S. Moradi, I. Nowrouzi, and A. Mohammadi, “Wettability Alteration and Interfacial Tension (IFT) Reduction in Enhanced Oil Recovery (EOR) Process with Ionic Liquid Flooding”, *Journal of Molecular Liquids, vol. 248, pp. 153-162,* 2017. https://doi.org/10.1016/j.molliq.2017.10.009

[29] M. Dahbag, A. AL.Quraishi, and M. Benzagouta, “Efficiency of ionic liquids for chemical-enhanced oil recovery, *Journal of Petroleum Exploration and Production Technology*, vol. 5, pp. 353–361, 2015. https://doi.org/10.1007/s13202-014-0147-5

[30] S. Zabihia, D. Farajia, Y. Rahnamab, A. Hezaveb, “Relative permeability measurement in carbonate rocks, the effects of conventional surfactants vs. Ionic liquid-based surfactants”, *Journal of Dispersion Science and Technology*, pp. 1797-1811, 2020. https://doi.org/10.1080/01932691.2019.1637262

[31] M. Nabipour, Sh. Ayatollahi, Sh, and P. Keshavarz, “Application of different novel and newly designed commercial ionic liquids and surfactants for more oil recovery from an Iranian oil field”, *Journal of Molecular Liquids* vol. 230, pp. 579–588, 2017. http://dx.doi.org/10.1016/j.molliq.2017.01.062

تحسين استخلاص النفط (EOR) بواسطة السائل الأيوني بمساعدة المياه المنخفضة الملوحة في أحد حقول النفط الجنوبية في العراق: دراسة تجريبية في الصخور الكربونية

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الخلاصة

هناك ضرورة متزايدة لاستخراج النفط ليس فقط من خلال الوسائل الأولية والثانوية ولكن أيضًا من خلال طرق الاستخلاص الثالث لتلبية الطلب العالمي المتزايد على الطاقة.وبالتالي، من المتوقع أن يكتسب الاستخلاص المعزز للنفط (EOR) أهمية متزايدة في صناعة النفط في السنوات القادمة.لقد اكتسب دمج المياه منخفضة الملوحة LSW مع المواد الكيميائية لزيادة استخلاص النفط جاذبية كبيرة في السنوات الأخيرة بسبب فعاليته المثبتة. في هذه الدراسة، نقوم بإجراء تحقيق منهجي باستخدام قياسات زاوية الاتصال لتوضيح الآليات الأساسية.كشفت النتائج أن زاوية التلامس (CA) أثبتت فعالية المائع المدمج في تغيير قابلية التبلل من الزيت الرطب إلى الماء الرطب .تمت الإشارة إلى ثبات السائل الأيوني C12PYCL في ظل ظروف الخزان من خلال تحليل قياس الوزن الحراري (TGA) والتحليل الطيفي للأشعة فوق البنفسجية المرئية.

بعد حقن LSW للأستخلاص الثانوي، أجريت اختبارات الفيضانات الأساسية لتركيزين مختلفين من السائل الأيوني.وأدى ذلك إلى استخلاص نفط إضافي بنسبة ١٧% و١٩,٧% OOIP على التوالي، بمعدل تدفق قدره ٠,٦٦٧ سم^{٣}/دقيقة. عند التركيز العالي للسائل الأيوني، أجريت اختبارات الفيضانات الأساسية عبر مجموعة من معدلات التدفق (٠,٣٣٤ و١ و١,٣٧٥) سم^{٣}/دقيقة، مما أدى إلى استرداد إضافي بنسبة ٥% و١٠,٥% و٨,٢% OOIP. تعتبر هذه الدراسة واحدة من الأبحاث الرائدة في حقول النفط الجنوبية في العراق، حيث تستكشف إمكانية الاستخلاص المعزز للنفط عبر معدلات تدفق مختلفة باستخدام محلول هجين يشتمل على LSW والسائل الأيوني.

الكلمات الدالة: : تغيير قابلية التبلل، الاستخلاص المعزز للنفط (EOR)، المياه منخفضة الملوحة (LSW)، كلوريد دوديسيل بيريدينيوم، السائل الأيوني.