

Article

Huff-n-Puff Experimental Studies of CO₂ with Heavy Oil

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Abstract: This work is devoted to CO₂ Huff-n-Puff studies on heavy oil. Oil recovery for heavy oil reservoirs is sufficiently small in comparison with conventional reservoirs, and, due to the physical limitation of oil flow through porous media, a strong need for better understanding of tertiary recovery mechanisms of heavy oil exists. Notwithstanding that the idea of Huff-n-Puff gas injection technology for enhanced oil recovery has existed for dozens of years, there is still no any precise methodology for evaluating the applicability and efficiency of this technology in heavy oil reservoirs. Oil recovery factor is a question of vital importance for heavy oil reservoirs. In this work, we repeated Huff-n-Puff tests more than three times at five distinct pressure points to evaluate the applicability and efficiency of CO₂ Huff-n-Puff injection to the heavy oil reservoirs. Additionally, the most critical factor that affects oil recovery in gas injection operation is the condition of miscibility. Experimental data allowed to distinguish the mixing zone of the light fractions of studied heavy oil samples. The experimental results showed that the pressure increase in the Huff-n-Puff injection process does not affect the oil recovery when the injection pressure stays between miscibility pressure of light components of oil and minimum miscibility pressure. It was detected that permeability decreases after Huff-n-Puff CO₂ tests.

Keywords: enhanced oil recovery; CO₂ injection; heavy oil; Huff-n-Puff; miscibility evaluation; permeability reduction

1. Introduction

The continuous increase in energy consumption [1] enhances the total demand for every type of hydrocarbon resource [2,3]. Despite the very challenging production of oil from heavy oil reservoirs, heavy oil is becoming a very prospective and valuable source of energy these days. Combined with the facts that (1) oil production from conventional reservoirs is decreasing [4], (2) tremendous heavy reserves are more than 3 times bigger than conventional oil reserves [5], and (3) tertiary oil recovery techniques are advancing each year [6,7], we predict that more and more studies about heavy oil will be published in the upcoming years.

This work is devoted to the experimental studies of CO₂ applicability, efficiency, and miscibility with heavy oil by Huff-n-Puff tests. Oil recovery in heavy oil reservoirs is sufficiently small in comparison with oil recovery from conventional reservoirs due to the physical limitation of the oil flow through the porous media. As heavy oil reservoirs do not effectively respond to secondary recovery

methods, the tertiary enhanced oil recovery techniques are the only practical and possible options. Therefore, a need for better understanding of tertiary recovery mechanisms for heavy oil reservoirs exists nowadays. Notwithstanding that the idea of gas injection technology for enhanced oil recovery operations, either in flooding or the Huff-n-Puff regime, was developed long time ago [8], and the first experimental studies of CO₂ applicability in heavy oil reservoirs were conducted in the 1980s and 1990s [9,10], there is no precise methodology for the evaluation of applicability and efficiency of Huff-n-Puff gas injection technology in heavy oil reservoirs [11].

Huff-n-puff CO₂ injection is an enhanced oil recovery technique that is widely used for conventional oil reservoirs [12] and is known as cyclic injection of CO₂. The Huff-n-Puff injection is presented by three divided stages: (1) the injection stage, (2) the soaking stage, and (3) the production stage [9]; all three stages will be experimentally modeled. Oil recovery factor is a question of vital importance that petroleum companies have about hard to recover resources. The most critical factor that affects oil recovery in any gas injection operation is the condition of miscibility [13]. The injected gas can be either in the miscible or immiscible regime. Commonly, gas injection over minimum miscibility pressure (MMP) is considered as the most favorable regime with the highest possible oil recovery [14]. Miscibility depends on the number of parameters like oil composition, swelling coefficient, diffusion, solubility, and mainly on pressure, which is above MMP [15]. MMP is an indication of pressure, temperature, or gas composition when gas and oil are completely miscible in any proportions [16].

Regarding the light oil of conventional reservoirs, the determination of MMP is not very challenging: MMP of CO₂ and oil can be predicted by empirical correlations, numerical simulations, and rapid experimental techniques. Most of the empirical correlations were made with the help of experimental data obtained from experiments performed with light oil. Therefore, they are hardly applicable to heavy oil [17]. For the proper numerical simulation, the composition of the oil is needed. However, the composition of heavy oil is very hard to precisely determine, and it is sufficiently different in its behavior from field to field. Due to the high compositional differences of heavy oil, it tends to have two distinct miscibility pressures at which we can reach miscibility, with light components of oil first, and only then with heavy components of oil. In the most cases related to heavy oil reservoirs, researches assume that heavy oil is not miscible because MMP in heavy oil reservoir is usually much higher than the reservoir pressure [18–20]. However, it also coincides with another problem—MMP determination for heavy oil is very challenging. Traditionally, MMP for the light oil can be determined by such conventional methods as the slim tube, Vanishing Interfacial Tension (VIT), and Rising Bubble Apparatus (RBA) tests. However, these techniques fail when dealing with high viscosity oil. The industrially accepted method, the slim tube test, is not physically affordable for high viscosity oil [21].

To evaluate heavy oil recovery by Huff-n-Puff CO₂ injection and evaluate the miscibility conditions of CO₂ and heavy oil, we implement the Huff-n-Puff gas injection tests. The studied pressure range was restricted to the field injection limitations. Obtaining oil recovery factors after five Huff-n-Puff cycles of five different pressure points expanded our knowledge on the Huff-n-Puff process and its efficiency for heavy oil reserves. Forty Huff-n-Puff gas injection tests were conducted in total. Experiments coincide with other studies where heavy oil is mainly extracted by the first three cycles of CO₂ Huff-n-Puff injection [11,22]. Then, the received data allowed to distinguish the mixing zone for the light fractions of studied oil samples with CO₂, proving that it is applicable for possible miscibility evaluation. Experiments shown no difference for oil recovery when injection pressure is between miscibility pressure of light components and MMP. Additionally, the change of oil composition after Huff-n-Puff tests was analyzed. Permeability reduction was observed by running core flood experiments with different solvents.

2. Materials

In this study, wellhead oil samples from heavy oilfields #1 and #2 were provided by LUKOIL-Engineering; the oil samples were free from gas. Reservoir properties are presented in Table 1.

As some part of the experimental procedure is meant to be conducted under atmospheric pressure, there was no need to make recombined oil samples. Berea Sandstone core plugs were used for these Huff-n-Puff tests. The main properties of dead oil samples were measured by PVT 3000-L (Chandler Engineering, Tulsa, OK, USA) and are presented in Table 2. The compositions of the oil samples were measured by gas chromatography/mass spectrometry and presented in Table 3. The initial water content of the oilfield #1 and oilfield #2 oil samples was over 20%. Therefore, the samples were dewatered by (1) thermostabilization at 90 °C for 72 h and (2) the centrifuge, PrO-ASTM BC (Centurion Scientific Ltd., Chichester, UK), at 75 °C for 80 min. Every core sample was drilled from one homogeneous block of Berea sandstone. Core diameters, lengths, and helium permeability are presented in Table 4. The volume difference of used samples does not exceed 20%, the porosity is ~20%, and permeability ranges from 154 to 175 mD. The injection gas in these Huff-n-Puff tests is CO₂ with purity greater than 99.99%.

Table 1. Reservoir properties.

Reservoir	Oilfield #1	Oilfield #2
Temperature (°C)	27.4	21.6
Pressure (MPa)	13.8	10.9

Table 2. Measured properties of dead oil samples from oilfield #1 and oilfield #2.

Dead Oil Sample	Oilfield #1	Oilfield #2
Dead oil density at 20.0 °C (kg m ³)	1006.70	931.03
Dead oil viscosity at 25.0 °C (mPa s)	1116.00	421.8
Dead oil molecular weight (g mol ⁻¹)	346.74	499.51
Dead oil compressibility (1/MPa)	4.45×10^{-4}	6.29×10^{-4}
Water content after dewatering (%)	0.78	0.33
Paraffin crystallization temperature at 0.2 MPa (°C)	30.4	33.1

Table 3. Results of compositional analysis of the dead oil samples from oilfield #1 and oilfield #2.

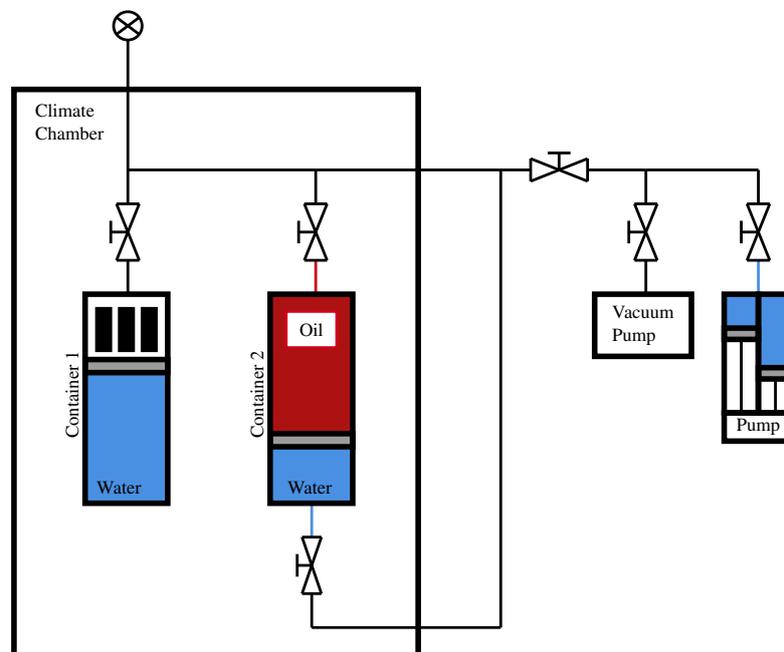
Component	Oilfield #1		Oilfield #2		Component	Oilfield #1		Oilfield #2	
	wt.%	mol.%	wt.%	mol.%		wt.%	mol.%	wt.%	mol.%
H	0	0.0003	0	0	C ₁₇	0.0784	0.1651	0.3508	0.5132
H ₂ S	0.0012	0.0170	0	0	C ₁₈	0.0993	0.1975	0.3914	0.5407
CO ₂	0.0135	0.1532	0.0005	0.0040	C ₁₉	0.0726	0.1378	0.2503	0.3299
N ₂	0.2919	5.2056	0.0188	0.2330	C ₂₀	0.0636	0.1156	0.2486	0.3134
C ₁	0.0207	0.6442	0.0139	0.2996	C ₂₁	0.0577	0.0991	0.2079	0.2477
C ₂	0.0266	0.4413	0.0460	0.5304	C ₂₂	0.0431	0.0706	0.1984	0.2256
C ₃	0.0310	0.3511	0.4608	3.6235	C ₂₃	0.0399	0.0627	0.1891	0.2062
iC ₄	0.0128	0.1104	0.0442	0.2639	C ₂₄	0.0358	0.0541	0.1687	0.1768
nC ₄	0.0349	0.2997	0.7141	4.2601	C ₂₅	0.0322	0.0466	0.1425	0.1432
iC ₅	0.0281	0.1948	0.2672	1.2843	C ₂₆	0.0314	0.0436	0.1360	0.1313
nC ₅	0.0266	0.1844	0.5736	2.7567	C ₂₇	0.0251	0.0335	0.1050	0.0973
C ₆	0.1033	0.6143	1.5685	6.4746	C ₂₈	0.0219	0.0282	0.0856	0.0765
C ₇	0.1189	0.6185	1.5188	5.4856	C ₂₉	0.0188	0.0234	0.0640	0.0552
C ₈	0.1040	0.4857	0.8171	2.6479	C ₃₀	0.0162	0.0195	0.0493	0.0411
C ₉	0.0453	0.1870	0.2532	0.7256	C ₃₁	0.0144	0.0168	0.0459	0.0370
C ₁₀	0.0465	0.1733	0.2283	0.5907	C ₃₂	0.0138	0.0156	0.0352	0.0275
C ₁₁	0.0484	0.1644	0.2064	0.4869	C ₃₃	0.0122	0.0134	0.0147	0.0111
C ₁₂	0.0495	0.1535	0.2478	0.5336	C ₃₄	0.0087	0.0092	0.0108	0.0079
C ₁₃	0.0467	0.1333	0.2829	0.5606	C ₃₅	0.0066	0.0068	0.0081	0.0058
C ₁₄	0.0666	0.1751	0.2864	0.5227	C ₃₆₊	98.0613	88.229	89.2027	64.6417
C ₁₅	0.0661	0.1603	0.2775	0.4671	Total	100	100	100	100
C ₁₆	0.0643	0.1447	0.2689	0.4201					

Table 4. Summary of physical properties of the cores applied in this study.

Sample No.	Length	Diameter	Volume	Surface Area/Volume	Porosity	Permeability
	cm	cm	cm ³	m ² /cm ³	%	mD
1	4.819	2.940	32.72	1.64	20.14	153.5
2	4.760	2.941	32.34	1.65	20.21	157.6
3	4.764	2.941	32.36	1.65	20.16	153.2
4	4.725	2.938	32.03	1.65	20.16	156.4
5	4.698	2.943	31.96	1.65	20.15	156.5
6	4.503	2.941	30.58	1.66	20.35	168.3
7	4.375	2.940	29.71	1.67	20.40	173.7
8	4.371	2.940	29.68	1.67	20.42	174.9
9	4.282	2.941	29.08	1.68	20.42	171.4
10	3.892	2.937	26.36	1.71	20.63	174.8

3. Experimental Setup

The assemblies used in saturation operations and Huff-n-Puff tests are presented in Figures 1 and 2, respectively. The assemblies are presented by two piston vessels, a climate chamber, vacuum pump, and the pump. The pump, Quizix QX (Chandler Engineering, Tulsa, OK, USA), is a piston pump with two cylinders that works in the regime of continuous delivery and receiving; it pushes the piston of the cylinder filled by oil or gas and replaces the liquid into high-pressure stainless steel container 1, which is filled by the vertically placed rock samples. The samples are placed on the piston inside the annulus of container 1, and they are free from any sleeves. The piston is adjusted on the desired level by water on the bottom side of container 1. The pump allowed to inject the gas at the pressure up to 24 MPa. The climate chamber, MK 240 (Binder GmbH, Tuttlingen, Germany), maintained the reservoir temperature with fluctuations up to 0.5 °C.

**Figure 1.** Schematic of experimental setup used for saturation.

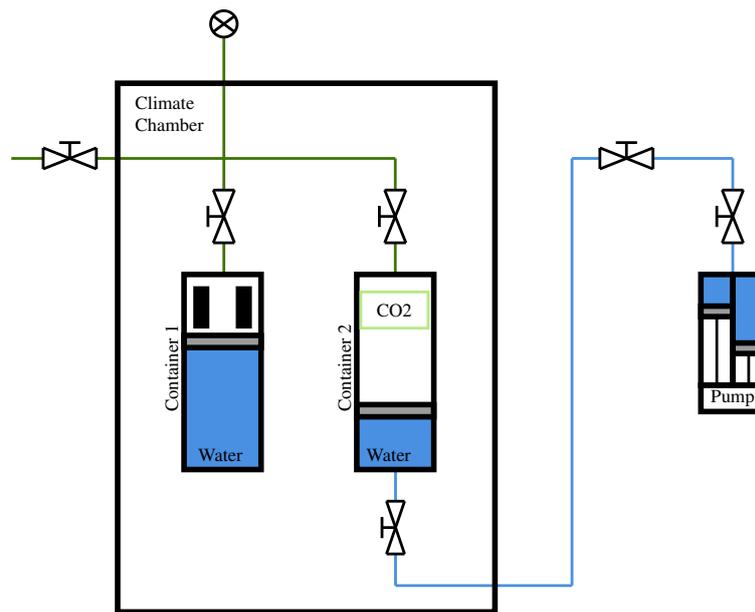


Figure 2. Schematic of experimental setup for the CO₂ Huff-n-Puff test.

4. Experimental Procedures

The experimental procedure used in this work [23] was adapted to the experiments with heavy oil. In the original procedure, the Huff-n-Puff injection of gas occurs at each pressure regime with every shale core sample. Despite the real rock samples having moderately high porosity–permeability, we decided to use highly homogeneous samples of Berea sandstone to speed up the original procedure of CO₂ Huff-n-Puff injection at different pressure regimes. The experimental procedure presented has two steps: (1) core saturation and (2) the Huff-n-Puff gas injection tests.

4.1. Saturation Step

To saturate the samples, the collection of samples was extracted by kerosene and then dried in the oven under 120 °C during 24 h. The weight (W_d) of the dried core samples was measured. Then, the samples were placed in the container 1 (Appendix A) and vacuumed in the container for 6 h. The saturation process was conducted at a temperature two times greater than the temperature of paraffin crystallization (Table 2). At the next stage, the Quizix QX pump pushed the pistons of container 2 and oil-filled container 1 with samples at a speed of 5 mL/min and restored the reservoir pressure. The pressure of container 2 was maintained for at least 24 h (Appendix B). Then, the core samples were taken out, cleaned by cleaning paper, and the weight of each sample was measured and registered as W_s . Then, the samples were stored in desiccator to keep the oil in the samples between the experiments. The core samples were saturated to 100% with oil without connate water.

4.2. Huff-n-Puff Gas Injection Procedure

Part of the Huff-n-Puff gas injection tests is presented in Figure 2 and should simulate the Huff-n-Puff injection of CO₂ in the oil field. Initially, the air in container 1 is blown off by multiple reinjections of CO₂ from the external gas cylinder under 0.25 MPa. Then, the lines between the containers are vacuumed by a vacuum pump. Then, the CO₂ is injected from container 2 to container 1 for 30 min, and then the pressure should be raised to the experimental pressure by piston pump if it is needed. The soaking time is 6 h. After the soaking period, the pressure should be released with depletion rate of 0.5 MPa/min to the atmospheric pressure. Then, the production period is 6 h. Therefore, finally, the samples are taken out from the vessel (Figure A1b) and cleaned (Figure A2). Then, the core samples are weighed (W_i). The next injection cycle starts immediately after weighing.

The same procedure is repeated for all subsequent cycles after the first cycle of injection. The weight measurements are done to estimate oil recovery using Equation (1). However, Equation (1) does not estimate the density of the original oil as being similar to the remaining oils at different stages.

$$\text{Oil Recovery in cycle } i = \frac{W_i - W_d}{W_s - W_d} \times 100\% \quad (1)$$

In the original procedure developed for the shale samples, each sample should go through all of the injection pressure regimes. However, in our case, homogeneous Berea sandstone samples were used. Despite the high similarity in size, porosity, and permeability among the samples, oil recovery of each sample should be normalized according to their surface area and volume using Equation (2). The first injection cycle yielded the highest incremental oil recovery from 20.70% to 27.67% for different injection pressure regimes. The porosity has not been used in this normalizing factor as it is taken into account in the oil recovery values itself.

$$\text{Oil Recovery}_{\text{normalized}} = \frac{\text{Oil Recovery}_{\text{cycle } i}}{\frac{\text{Surface Area}}{\text{Volume}}} \times \frac{\text{Mean Surface Area}}{\text{Mean Volume}} \quad (2)$$

5. Results and Discussion

5.1. Effect of Cycle Number

Each subsequent cycle of the Huff-n-Puff CO₂ injection gives less incremental oil recovery than the previous cycle. Experiments with oil from oilfield #1 was conducted earlier than experiment with oil from oilfield #2. The biggest amount of oil from oilfield #1 is extracted during the first three cycles of injection, and then just a small volume of oil can be produced. This is why we only use three cycles of injection instead of six cycles in the experiments with oil from oilfield #2. Incremental oil recovery for each injection cycle is shown in Tables 5 and 6 for both reservoirs. The decrease of subsequent incremental oil recovery occurs because of the reduction of the contact area of CO₂ and oil inside the pore space, which caused the remaining oil to become heavier and more viscous (2) and the heavy oil deposits to be destabilized, and they caused a decrease of permeability of the core samples (3). The first two cycles can give an incremental recovery factor above 35%. After these cycles, the incremental oil recovery does not usually exceed 3% in one cycle. Raw experimental data was previously published by Maksakov and Cheremisin [24].

Table 5. Incremental oil recovery at each cycle of Huff-n-Puff CO₂ injection for experiments with oil from oilfield #1.

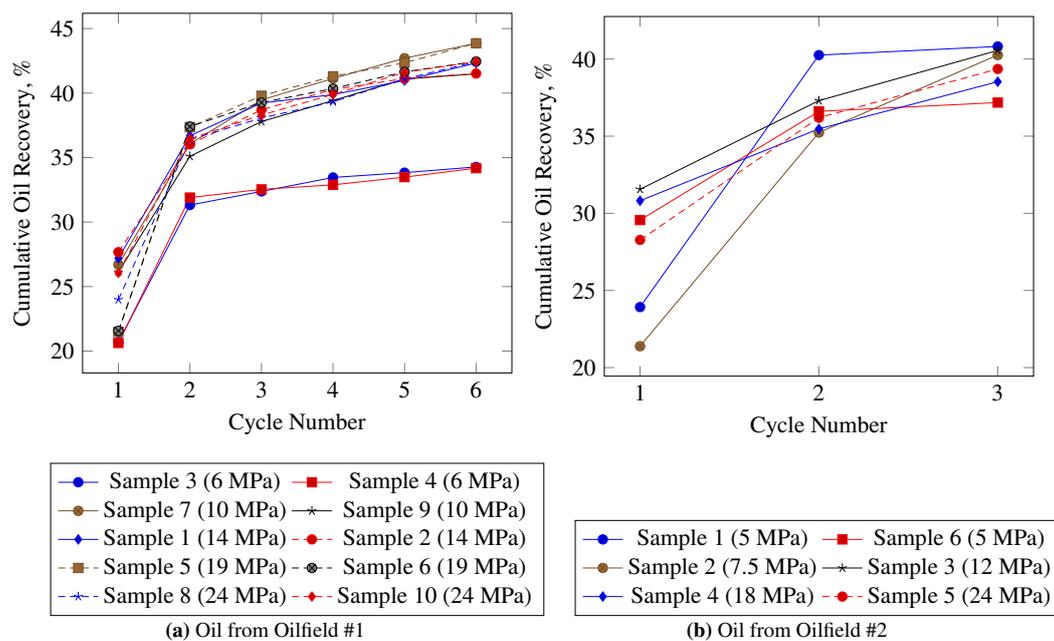
Sample No.	Pressure	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6
	MPa	%	%	%	%	%	%
3	6	20.70	10.62	1.06	1.08	0.37	0.44
4	6	20.63	11.27	0.64	0.35	0.60	0.69
7	10	26.70	9.37	3.41	1.66	1.57	1.15
9	10	26.12	8.98	2.70	1.63	1.67	0.40
2	14	27.20	9.49	2.54	0.65	1.10	1.35
1	14	27.67	8.36	2.68	1.57	0.85	0.39
5	19	21.48	15.88	2.43	1.51	1.05	1.51
6	19	21.57	15.84	1.86	1.08	1.30	0.81
8	24	23.99	12.41	1.67	1.26	1.78	1.32
10	24	26.06	10.40	1.84	1.61	1.71	0.83

Table 6. Incremental oil recovery at each cycle of Huff-n-Puff CO₂ injection for experiments with oil from oilfield #2.

Sample No.	Pressure	Cycle 1	Cycle 2	Cycle 3
	MPa	%	%	%
1	5	23.92	16.33	0.56
6	5	29.56	7.05	0.57
2	7.5	21.39	13.84	5.02
3	12	31.56	5.75	3.25
4	18	30.81	4.66	3.06
5	24	28.27	7.92	3.16

5.2. Cumulative Oil Recovery

The graphical representation of cumulative oil recovery for both oil reservoirs is presented in Figure 3. Clearly, three cycles is not high enough for the experiments with oilfield #2, as shown in Figure 3b, if the experiments continued cumulative oil recovery for different pressure regimes would be equalized. According to the company's prerequisite, the range of injection pressure of CO₂ was predetermined by the limitation of the surface injection pumps and reservoir fracture pressure. The cumulative heavy oil recovery can be over 40% after a number of Huff-n-Puff CO₂ injection cycles.

**Figure 3.** Pressure effect on CO₂ Huff-n-Puff performance.

5.3. Miscibility Studies

To evaluate the miscibility of oil samples with CO₂, vast Huff-n-Puff injection experiments were conducted at five different pressure regimes for both oil heavy samples. Each oil recovery was normalized according to the volume and surface area of the used samples, and the mean value was taken if more than one samples were used in the Huff-n-Puff injection test. Normalized oil recovery for oil samples from oilfield #1 and oilfield #2 are presented in Figures 4 and 5. For the normalized oil recovery studies (Oilfield #1) shown in Figure 4b–f, two straight lines can be drawn. As there is not a clear intersection of these lines, the miscibility pressure cannot be determined. According to the special PVT studies of oil samples from oilfield #1 and oilfield #2, these oil samples tended to form two-phase systems under reservoir conditions when the concentration of CO₂ was higher than 70% mole (Appendix C). These two-phase systems formed by the phase of CO₂ and light oil components

and by the phase of heavy oil components. Taking into account the results of special PVT studies, it is possible to define the mixing zone, when CO₂ becomes miscible with light components of oil. The mixing zone of CO₂ with light oil components of oil from oilfield #1 lies in the interval from 6 MPa to 10 MPa, as shown in Figure 4f. The mixing zone of CO₂ and light oil components of oil from oilfield #2 is below 5 MPa, as it is shown in Figure 5c. Oil samples from oilfield #1 and oilfield #2 tended to split into the two-phase mixture over 10 MPa and 5 MPa accordingly. Therefore, we made the following assumption: when the miscibility pressure of CO₂ with light components is achieved, the oil recovery remained the same until it reaches miscibility pressure with heavy components.

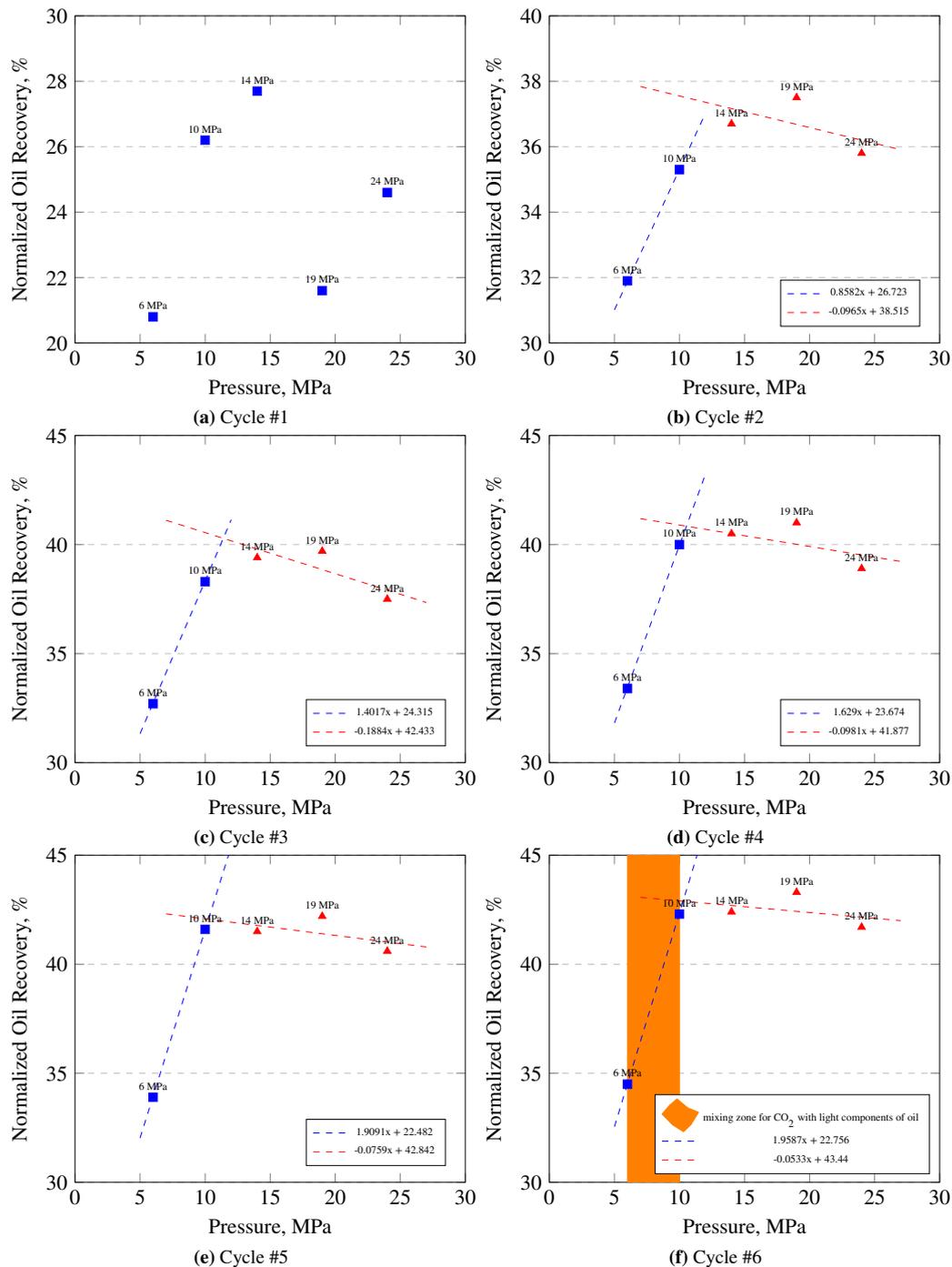


Figure 4. Effect of pressure on normalized oil recovery at different cycles of Huff-n-Puff CO₂ injection with oil from oilfield #1.

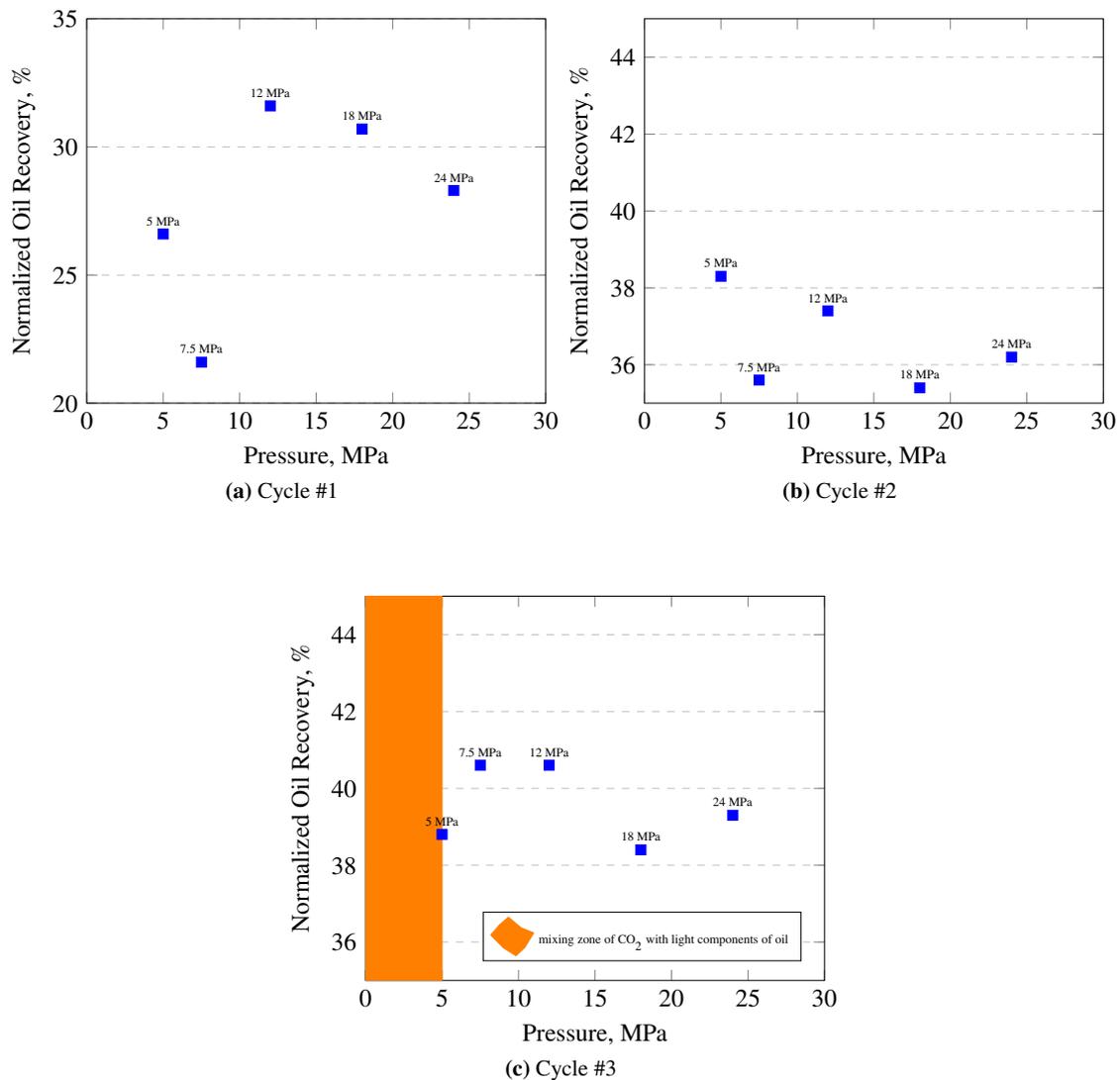


Figure 5. Effect of pressure on normalized oil recovery at different cycles of Huff-n-Puff CO₂ injection with oil from oilfield #2.

5.4. Effect of CO₂ Injection on Oil and Rock Properties

The Huff-n-Puff injection of CO₂ leads to the extraction of light components first and can accelerate heavy oil depositions. To prove the idea that light components of oil yield first, the extracted oil sample was collected after Huff-n-Puff CO₂ injection tests and analyzed using gas chromatography–mass spectrometry (GC-MS). The oil sample from oilfield #1 was collected after the 1st cycle of injection at 14 MPa, and the oil sample from oilfield #2 was collected after the 1st cycle of injection at 5 MPa. Figure 6 presents the difference of composition of the original oil, extracted oil, and the remaining oil in the samples after yield. The composition of remained oil was calculated using compositions of initial and extracted oil, and the masses of oil before and after the experiments. This investigation of the change of oil composition after Huff-n-Puff injection of CO₂ tests proved that the extracted oil from the samples is much lighter than the oil that remained in the samples. However, it represents an open question about heavy oil deposits.

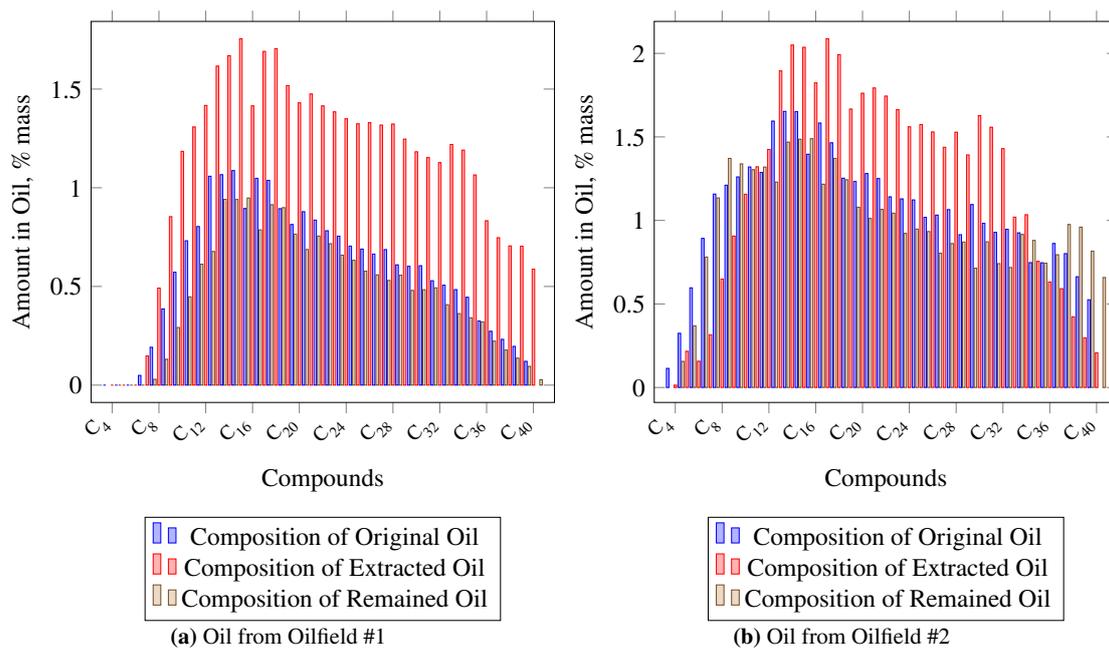


Figure 6. Difference in oil composition after CO₂ Huff-n-Puff injection.

Compositional change of heavy oil due to injection CO₂ can lead to destabilization of asphaltenes, resin, and paraffin deposits [25]. As this process can cause the precipitation and deposition of asphaltene particles in the pore space of the samples [26], we needed to evaluate the change of permeability after Huff-n-Puff CO₂ injection. To evaluate the permeability, sample #7 from experiments with oil from oilfield #1 and sample #2 from experiments with oil from oilfield #2 were taken. Flood experiments were conducted, and permeability was measured by N-pentane with both samples. Permeability was measured in the presence of asphaltenes because N-pentane does not dissolve precipitated heavy oil deposits [27,28]. Then, the samples were dried, and permeability by helium was measured so as to compare it with the initial permeability before the Huff-n-Puff tests. Therefore, in the end, further core flood experiments were conducted using toluene. Toluene dissolves all heavy deposits, which is why true liquid permeability was measured. The injection pressure was equal to reservoir pressure. The confining pressure was 30% higher than the injection pressure. The injection speed was 0.5 mL/min in flood experiments with solvents. These permeability tests proved that the injection of CO₂ decreased the permeability of the rock sample due to the heavy oil deposits, and all the permeability values are presented in Table 7.

These tests indicated the permeability decrease after Huff-n-Puff injection tests, but the damage from heavy oil deposits depends on the specific oil composition, amount of heavy oil deposits of the specific oil, reservoir pressure and temperature, gas injection rate, and oil depletion rate. A universal strategy could not exist due to the high amount of variables.

Table 7. Permeability change due to the Huff-n-Puff CO₂ injection.

Sample No.	Reservoir	Helium Permeability before Experiments	N-Pentane Permeability after Experiments	Helium Permeability after Experiments	Toluene Permeability after Experiments
		mD	mD	mD	mD
7 (10 MPa)	Oilfield #1	173	13	159	77
2 (7.5 MPa)	Oilfield #2	147	8	144	39

6. Conclusions

In this study, CO₂ Huff-n-Puff tests with two heavy oil samples were conducted using Berea sandstone samples. The determination of oil miscibility with CO₂ by Huff-n-Puff tests was proved. From this study, some conclusions can be drawn:

1. The recovery of heavy oil obtained from CO₂ injection experiments was as high as 43%. This result shows that CO₂ Huff-n-Puff injection can be an efficient approach to enhance heavy oil recovery. However, it was not possible to differentiate the oil recovery as a result of solution gas drive (gas nucleation, gas expansion) during the pressure drop mode.
2. The major amount of oil is extracted by the first three cycles of CO₂ injection. The subsequent cycles of CO₂ injection do not cause a considerable change in oil recovery.
3. CO₂ injection in heavy oil causes heavy oil deposition and decreases permeability. Permeability measured by gas, n-pentane, and toluene showed the difference of permeability of the core plugs in the presence and the absence of heavy oil deposits.
4. Huff-n-puff tests can be applied for miscibility studies of heavy oil with gas. However, MMP for heavy oil is very high should be taken into consideration.
5. When miscibility of CO₂ with light oil components of heavy oil is achieved, the subsequent pressure increase under MMP does not affect oil recovery at the core scale experiments. However, it would be conjecture to presume that the higher injection pressure of gas leads to the higher rate of oil heavy deposits and more severe porosity and permeability damage.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript.

W_d	dry core sample weight, g
W_s	saturated core sample weight, g
W_i	core sample weight after Huff-n-Puff injection cycle, g
AS/V	surface-to-volume ratio, cm ² /cm ³

Appendix A. Example Photos

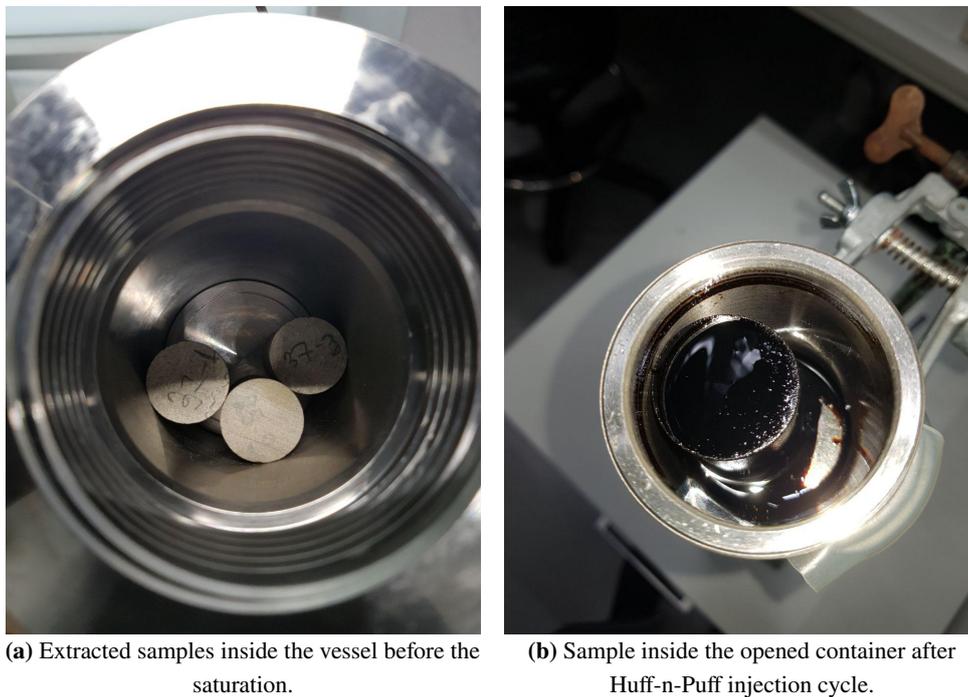


Figure A1. Example of experimental operations.

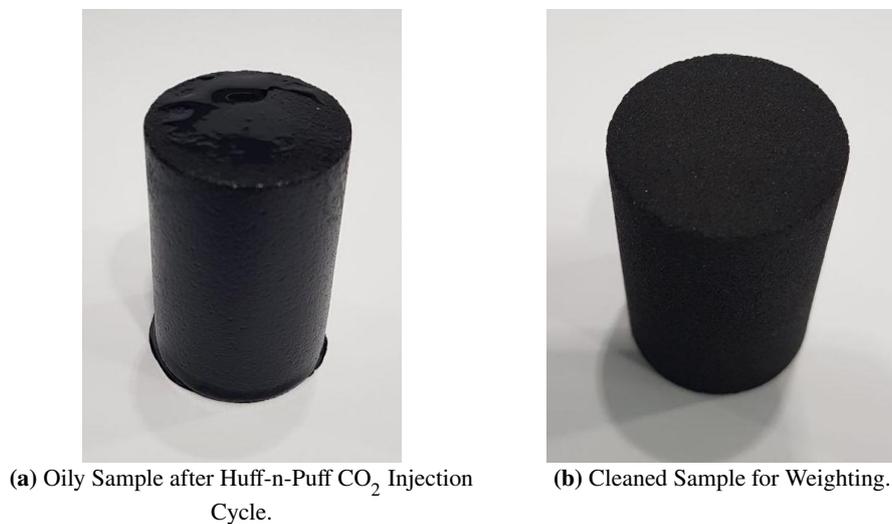


Figure A2. Photos of sample after Huff-n-Puff injection cycle.

Appendix B. Saturation Logs

As the samples were placed to the stainless steel container 1 (Figure A1a), the oil should fill the empty volume of the container first and only then the porous media of the samples. Figure A3a shows the saturation process of the samples by the oil sample from Oilfield #1; during this saturation operation, an oil leakage between the transfer vessel filled with oil and the vessel filled with samples occurred; that is why the amount of transferred oil is bigger than in the next saturation operation. Figure A3b shows the saturation process of the samples by the oil sample from Oilfield #2; after transferring of 209 mL of oil, the pressure was rapidly increased to the reservoir pressure of 10.3 MPa.

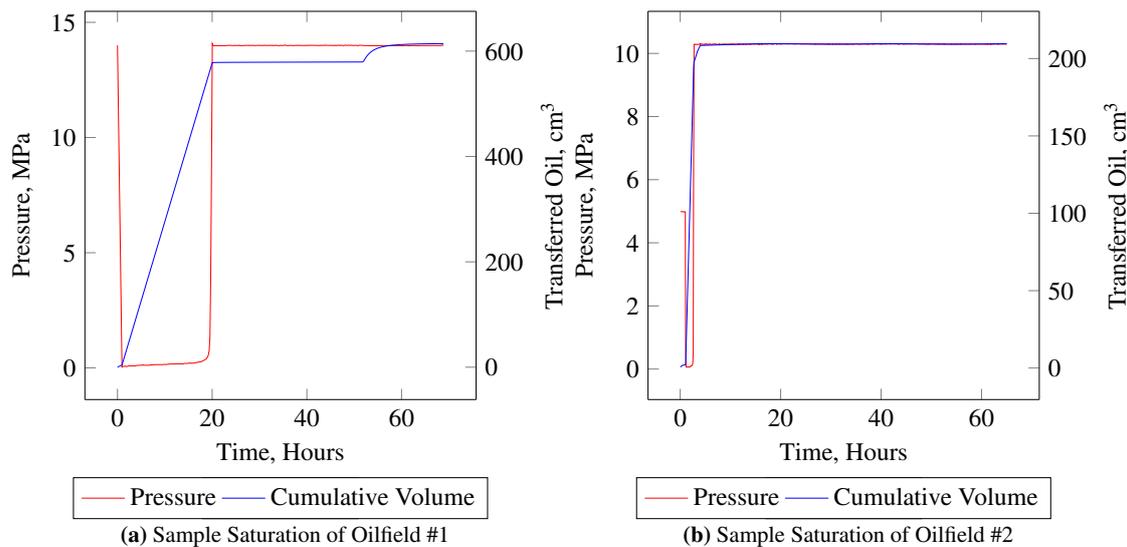


Figure A3. Saturation logs.

Appendix C. Viscosity Measurements from Special PVT Test

According to the special PVT studies, if the concentration of CO_2 is over 70%, the oils from both oilfields split to unmixed light and heavy phases; it is reflected by viscosity increase on the Figure A4. The special PVT studies were done with recombined oil samples, which are less viscous than the dead oil samples used in the Huff-n-Puff experiments. The light phase is presented mainly by CO_2 , and the heavy phase is mainly presented by oil.

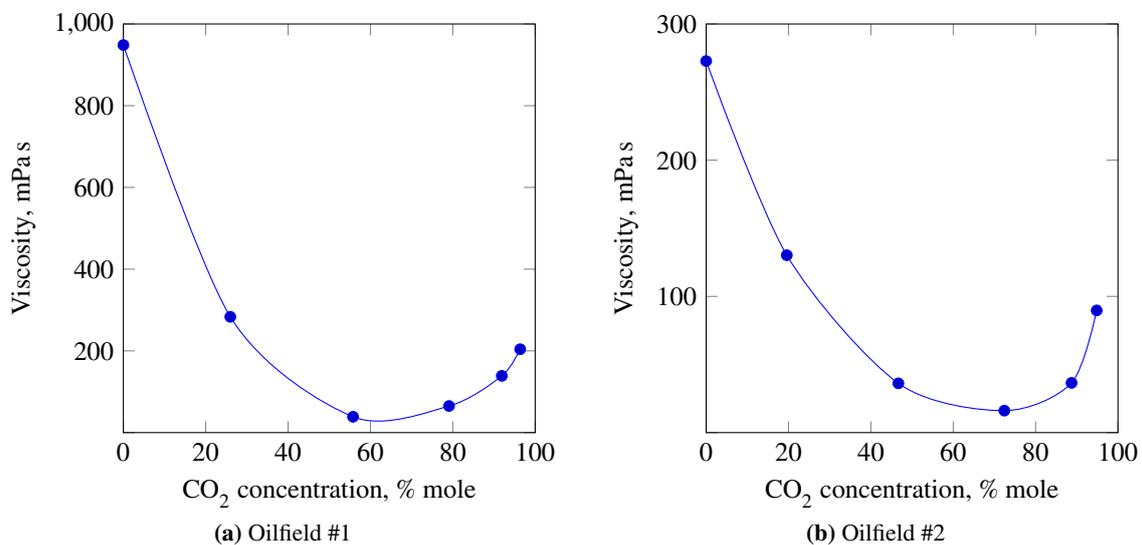


Figure A4. Viscosity of heavy phase depending on amount CO_2 mole concentration for recombined oil.

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