African Journal of Advanced Pure and Applied Sciences (AJAPAS)

Online ISSN: 2957-644X

Volume 2, Issue 3, July-September 2023, Page No: 434-449

Website: *https://aaasjournals.com/index.php/ajapas/index*

||Arab Impact factor 2022: 0.87|| SJIFactor 2023: 5.689|| ISI 2022-2023: 0.557

Modified Soaking Procedure Based Experimental Investigation of Cyclic Gas Recovery: Effect of Gas-Phase Miscibility

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Received: August 05, 2023	Accepted: September 16, 2023	Published: September 23, 2023

Abstract:

The current and latest technology to produce unconventional oil reservoirs is the cyclic gas injection method. Over the last decade, extensive experiments have been conducted to produce tight reservoirs, and a wide variety of parameters have been considered. However, the influence of key factors such as gas-phase miscibility and miscibility mode on oil recovery remains unclear. Additionally, previous studies have focused mostly on conventional procedures that fail to satisfactorily represent depleted oil field conditions. These assumptions may be the justification for the disappointing outcomes of some pilot tests, in spite of the outstanding demonstration of competence of the lab scale. This study attempts to explore the sensitivity of CO_2 phase miscibility and CO_2 miscibility mode in enhancing the bypassed oil recovery. Prior to the cyclic gas process, oil is bypassed in tight sandstone cores using the immiscible soaking step. The findings indicate that increasing CO_2 injection pressure may not be the only factor contributing to extracting residual oil; the CO_2 phase properties may also play a significant role in producing remaining oil. The use of supercritical CO_2 resulted in the highest bypassed oil recovery rate of up to 30.40%. However, the compressed liquid CO_2 phase recovered slightly more initial oil, particularly at pressures less than or equal to the minimum miscibility pressure (MMP). Increasing the CO_2 soaking time plays a major role in extracting the bypassed oil. However, 50% of the oil can be extracted within the first cycle. Therefore, a long soaking period is not recommended in the subsequent cycles.

Keywords: Cyclic gas method, Bypassed oil recovery, CO_2 phase, Miscibility mode.

Cite this article as: M. Milad, R. Omran, A. Milad, A. Alsharif, "Modified Soaking Procedure Based Experimental Investigation of Cyclic Gas Recovery: Effect of Gas-Phase Miscibility," *African Journal of Advanced Pure and Applied Sciences (AJAPAS)*, vol. 2, no. 3, pp. 434–449, July-September 2023.

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طريقة النقع المعدل القائم على التجارب المعملية في معرفة كمية النفط المستخرج بحقن الغاز بشكل دوري: تأثير امتزاجية وطور الغاز المحقون

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الملخص

إن التقنية الحالية والأحدث لإنتاج النفط الصخري من المكامن الغير تقليدية هي طريقة حقن الغاز على شكل دورات متتالية. على مدى العقد الماضي، تم إجراء تجارب مكثفة لإنتاج الخزانات الغير تقليدية، وتم أخذ مجموعة كبيرة من العوامل في عين الاعتبار، إلا أن تأثير بعض العوامل المهمة مثل طور الغاز المحقون ودرجة امتزاجه على استخلاص النفط لا يزال غير واضح. بالإضافة إلى ذلك، ركزت الدراسات السابقة في الغالب على التجارب المعملية التقليدية والتي بدورها لا تمثل الظروف الحقيقية لحقول النفط المنتجة بشكل دقيق. قد تكون هذه الافتراضات مبررًا للنتائج المخيبة للآمال لبعض الاختبارات الحقلية في السابق، على الرغم من كمية النتائج الإيجابية المتحصل عليها من التجارب المعملية. تحاول هذه الدراسة استكشاف دور طور ثاني أكسيد الكربون المحقون ونسبة امتزاجه في تعزيز عملية استخلاص النفط الصخري المتبقي. قبل عملية حقن الغاز على هيئة دورات، يتم تجاوز الزيت في العينات اللبية باستخدام طريقة الغاز الغير قابل للامتزاج. تشير النتائج إلى أن زيادة ضغط حقن ثاني أكسيد الكربون قد لا يكون العامل الوحيد الذي يساهم في استخلاص الزيت الصخري المتبقي؛ قد تلعب خصائص أو طور ثاني أكسيد الكربون المحقون أيضًا دورًا مهمًا في إنتاج النفط. أدى استخدام ثاني أكسيد الكربون فوق الحرج إلى أعلى معدل لاستخلاص النفط والذي يصل إلى 30.40%. ومع ذلك، استعاد طور ثاني أكسيد الكربون السائل المضغوط كمية أكبر قليلاً من الزيت عند دورات النقع الأولي، خاصة عند ضغوط أقل من أو تساوي الحد الأدنى لضغط الامتزاج(MMP) . تلعب زيادة وقت نقع دورًا رئيسيًا في استخلاص الزيت المتجاوز. ومع ذلك، يمكن استخراج 50% من النفط تقريبا خلال الدورة الأولى. ولذلك، لا ينصح بفترة نقع طويلة بين الغاز المحقون والزيت المتبقي في الدورات اللاحقة.

الكلمات المفتاحية: طريقة حقن الغاز على شكل دورات متتالية، النفط المتبقي، طور غاز ثاني أكسيد الكربون، الحالة الإمتزاجية لغاز ثاني أكسيد الكربون.

Introduction

Global consumption of hydrocarbons has been gradually increasing in the 21st century. To secure the world's accelerating energy demand, a considerable amount of effort has been directed towards the development of unconventional reservoirs [1]. The vast estimated oil reserve of unlocked resources has attracted great interest. Nevertheless, tight resources have been discovered and persisted on the sidelines for many decades [1]. Unconventional oil could be oilsands, shale oil, heavy oil, and tight oil [2]. Although horizontal wells with massive fracture technology have enabled countries like the United States to be among the top worldwide tight oil producers [3], only a limited amount of oil can be extracted using existing technologies, after which advanced enhanced oil recovery (EOR) procedures become essential [4]. Due to the low permeability, oil is restricted from being easily retrieved and, thus, most tight fields reveal a quick decline in their initial production rate, less than 20% within one year [5]. Hence, unconventional reservoirs have been considered as short-term production layers; their low primary recovery remains a major problem. Although Hamdi et al. [6] reported that hydraulic fracturing technology improves the matrix permeability by up to 10 times, fractures performance may defy under extremely tight formation conditions. Infill drilling is another proposed approach to producing unconventional oil and promotes a temporary increment in oil production, yet the cost of drilling new wells with long lateral lengths is extremely high. More importantly, infill wells need to be re-fracked regularly due to their limited drainage radius, which may contribute to higher environmental concerns [7]. Alfarge et al. [8] stated that more than 20 improved oil recovery (IOR) approaches have been experienced in conventional formations. Unfortunately, the feasibility of these practices was underwhelming in shale reservoirs due to their poor sweep performance.

On the other hand, gas injection, such as CO_2 flooding, was found to be a more favourable technique that could improve the oil recovery of several petroleum reservoirs [9]. This system is recognized as being the most effective due to its excellent potential for displacing residual oil [10]. Theoretically, up to 90% of oil is produced using the miscible injection of CO_2 [11]. In an effort to improve oil recovery and replenish the reservoir pressure, CO_2

flooding schemes (e.g., continuous CO_2 flooding and water-alternating-CO_2 (CO_2-WAG flooding)) have been tested [12]. Those approaches were found to consume an extensive amount of gas to recover the desired oil volume. Another persistent challenge regarding the conventional gas process is the fingering phenomenon [13]. When gases are injected into tight reservoirs, they preferentially flow along those higher permeability channels and leave a sufficient amount of oil behind, called "bypassed oil." Besides reservoir heterogeneity, there are a few other causes for the bypassed region, such as gravity override phenomena [14]. Thus, using single well technology as both an injection well and a production well, Huff-n-Puff (H-n-P) has become the most practical EOR approach that can enhance residual oil recovery and prevent injected solvents from fingering [15]. However, oil can still be stocked on a macroscopic or microscopic scale, depending on the fracture's layers' length or surface area [1]. This may explain the disappointing findings of some pilot tests in spite of the outstanding demonstration of competence of the lab-scale. Therefore, extracting more oil using the soaking system has become a serious concern [16]. Field operators and laboratory researchers have mainly focused on CO_2 due to its great opportunity to boost oil production as well as reduce global warming concerns [17]. Aljamaan et al. [18] reported that when CO_2 is injected, CO_2 storage operations can also be generated, and therefore a sufficient amount of CO_2 is absorbed and stored. CO_2 gas has superior displacing ability, especially in the miscible cyclic gas process. This technique has been proven to be 9.1% more effective when used in a miscible mode than in an immiscible manner [13]. But, miscible CO_2 only flows freely through those dominant channels (either natural or hydraulic fractures), and oil is bypassed in areas that are quite a distance from the fracture, forming unwept regions [4, 11, 19]. During the last few years, enhancing the bypassed oil in tight reservoirs has become challenging for field operators, and this has aroused wide attention to the use of the CO_2 H-n-P process. Since Gamadi et al. [20] conducted the first laboratory cyclic process using cores from Eagle Ford, Barnett, and Marcos, numerous valuable investigations have been completed to access larger quantities of remaining oil. Table 1 lists common factors studied over the last decade to validate the soaking process. While several factors have been studied, the influence of CO_2 phase miscibility and CO_2 injection modes has not been considered. More importantly, the knowledge is still limited to conventional procedures. Existing laboratory procedures, for example, are designed to use a fully saturated matrix and expose all its surfaces to the injected solvent, which does not simulate depleted oil field activities. Therefore, this study aims to apply a modified methodology where an immiscible soaking process is performed ahead of the H-n-P processes to bypass the oil as required. This two-step soaking methodology can help estimate the actual recovery of the depleted tight reservoir. Furthermore, this study seeks to fill the existing gap in the body of knowledge on the influence of temperature on soaking time and soaking cycle during the CO_2 immiscible process.

Table 1 0.

Ref	Formation	Solvent	Parameters/Mechanisms
[21]	Shale	N_2	Cyclic time, injection pressure, soaking time, and number of cycles.
[22]	Tight	CO_2	Injection pressure and soaking time.
[23]	Shale	CO_2	Soaking pressure, soaking period, and number of cycles.
[24]	Tight	CO_2	Slug size, injection rate, pressure effect, and soaking time.
[25]	Shale	CH_4	Gas injection time, gas injection rate, gas production time, production rate, soaking time, and gas injection pore volume.
[26]	Shale	N_2	Soaking time and pressure depletion rate (PDR)
[27]	Shale	/	H-n-P times, number of cycles, and soaking time.
[28]	Shale	C1/CO_2	Penetration depth, diffusion, soaking time, depletion pressure, number of cycles, injection pressure, and injection gas
[13]	Shale	CO_2	Injection pressure, imbibition water, cycle number, and puff time
[29]	Shale	/	Diffusion and fracture surface area
[30]	Shale	CO_2	Gas sweep volume, injection pressure, huff time, and number of cycles

Ref	Formation	Solvent	Parameters/Mechanisms
[31]	Shale	CO_2	Injection pressure, soaking time, core permeability and fractures, and miscible condition
[17]	Shale	CO_2	Injection pressure, soaking time, gas phase, reservoir temperature, and injection cycles.

Experimental description Material
The materials used to build the experimental setups are explained.

Experimental material
The materials used to execute both saturation and CO_2 soaking are as follows:

Oil Sample. Synthetic oil (diesel) was applied to perform all tests. The oil had an API gravity of 42° and a measured density and viscosity of 0.84 gm/cm3-5.975 mm2/s, respectively.

Core Samples. Tight cores were used to simulate bypassed oil recovery. They were outcrops obtained from Sarawak, Malaysia. The cores were 2 inches in diameter and 3 inches in length.

Injected Gas. A commercially available high-pressure CO_2 cylinder was supplied with a purity of 99.99%.

High-Pressure Gauges. Gauges with a maximum pressure of 4000 psi were placed carefully in the designed setup to record the pressure for the duration of the experiments. The gauges can withstand high temperatures, making them suitable for all study objectives.

High-Pressure Valves. The valves used in the experiment were a combination of two and three-way valves. The valves placed were chosen to manage a maximum of 3000 psi; thus, the valves were securely equipped.

High-Pressure Regulator. The high-pressure regulator was mounted on the CO2 cylinder to quickly pressurize the system and inject the gas continuously when needed.

Gas Flowmeter. A CO2 gas flowmeter was also involved in injecting the CO2 at a constant flow rate. Saturation Vessel. Two different saturation vessels were implemented. The high-pressure vessel used for the saturation process could stand up to 4000 psi. There were two valves attached to this chamber: inlet and outlet, along with a pressure gauge at one end to monitor the pressure during the saturation stage.

Vacuum Pump. The RV3 Edwards pump and VRL 200-7 were implemented to clean up the system and keep it under vacuum (Figure 1). They were also utilized to initially saturate core samples.

Oven. Two different types of ovens were included in this lab work. The first one was a conventional lab oven to dry the core plugs at 248 °F and remove any remaining fluids inside the cores. The second type was specifically designed for laboratory use, with a maximum temperature of 212 °F.

Accumulator. An accumulator incorporating a piston was used to push fluids into the saturation vessel and core holder, mostly used for boosting the CO2 injection pressure.

500D Syringe Pump. A continuous syringe pump was used as a pressure boost to further increase the injected pressure of oil and CO_2 in the accumulator. It was mainly applied to increase the CO_2 pressure inside the core holder to the designed value.

Core Holder. Two different core holders were used in this study. They were intentionally implemented to meet various objectives. The initial category is a convention core holder that works with a confining pressure system, while the second style is a high-pressure stainless vessel (free path system).

Cooling Box. The cooling box used in the experiment was made from polystyrene to maintain low gas temperature.

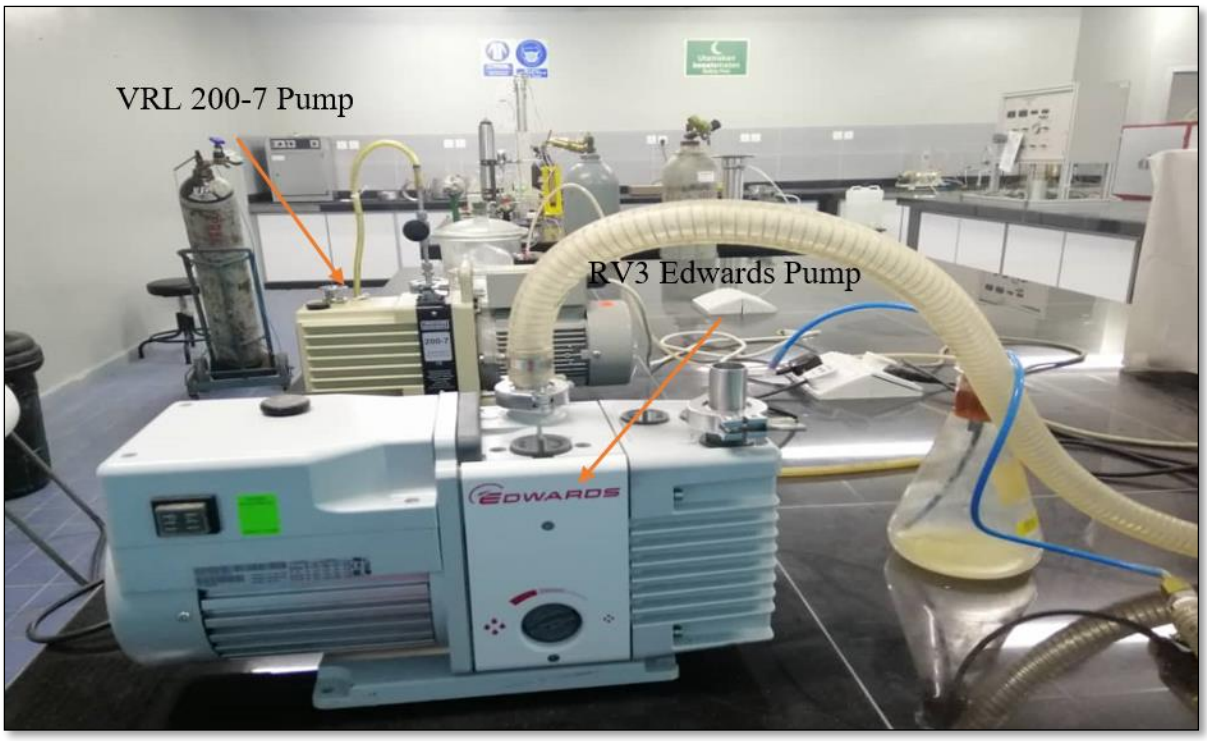

Figure 1 Photograph of the core vacuum and saturation pumps setup.

Experimental setups

In this section, three different experimental setups will be described. First, the system was developed to perform the core oil saturation process Figure. 2. Following this, the setup was assembled to carry the immiscible CO_2 soaking Figure 3. The third schematic design was to conduct the second CO_2 soaking method Figure. 4. These experimental systems were designed and modified based on past laboratory research [32-40]. Below is the detailed experimental setup.

Core saturation system

When conducting a core flooding study, it is essential to measure the exact original oil saturation of the core sample so that accurate oil recovery results can be recorded subsequently. The selection of procedures for measuring the oil saturation relies on whether the core is from an oil-producing field or an outcrop and apparatus available for investigation. Because the cores in this study were cut from an outcrop, they were saturated with oil prior to each EOR test. Special procedures were followed to achieve the maximum oil saturation. The reservoir temperature was controlled during the saturation scheme. However, the saturation operations are repeated numerous times to match the temperature of the subsequent IOR test. The system used to vacuum and saturate cores in Figure 2 was designed to have two different stages. The first stage (A) is applied to ensure the system is free of air, and also, to initially saturate the cores with oil. The apparatus used for this stage consists of a vacuum pump, liquid trapper, and saturation vessel. The second stage (B) is performed to confirm the fully saturated degree. This stage contains (1), a syringe pump to inject fluids continuously at high pressure (2), an accumulator with a piston collaborating with the syringe pump to push the oil (3), a pressure gauge to monitor the inside pressure (4), an air path oven to control the experiment temperature (5), a high-pressure saturation container. The accumulator was situated between the saturation container and the syringe pump to boost the injection pressure.

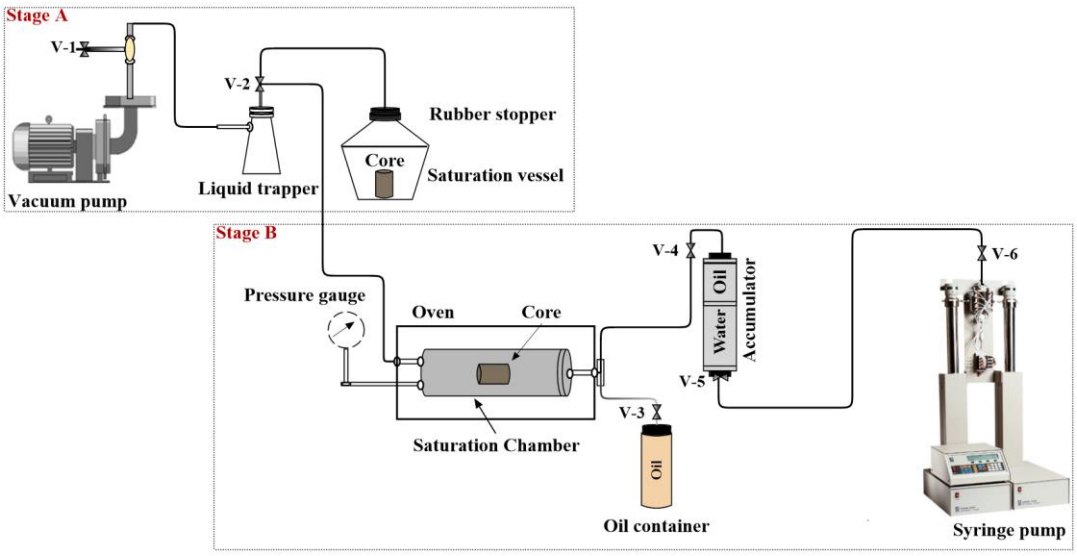

Figure 2 Core vacuuming and oil saturation setup.

Immiscible experimental setup (designed to conduct the first soaking step)

Figure 3 demonstrates the experimental setup established to conduct the first immiscible CO_2 soaking approach. The apparatus was carefully assembled to simulate unfractured cores, however, an intended space (of width 5 mm) was set in the lower end of the core holder, between the core and the injection inlet, to emulate a fracture. Such a fracture model has already been managed to bypass oil by other investigators like [11, 40-42]. In our designed system, a confining pressure was applied to prevent high-pressure CO_2 from flowing around the perimeter of the saturated cores, thus gas is enforced to only pass through the plug if possible. Once the CO_2 is injected and forced to mainly flow along the adjacent space, the saturated oil in the core is bypassed (as required). The CO_2 was injected directly from the cylinder throughout the entire soaking process. A high-pressure regulator was installed to monitor the pressure system. Gas flow meter was also installed to inject the CO_2 continuously at a constant flow rate. The setup was also composed of two backpressure regulators (BPR), and three high-pressure gauges that were properly sited. An N2 cylinder was sourced for the backpressure controller. To provide confining pressure to the core holder, a manual pump was employed (maintained at 500 psi above the pressure inside). In total, five valves were cautiously assigned and differently operated to ensure the success of the experimental work and further guarantee efficiently controlled procedures. An air bath oven was used to heat the core holder to the temperature required.

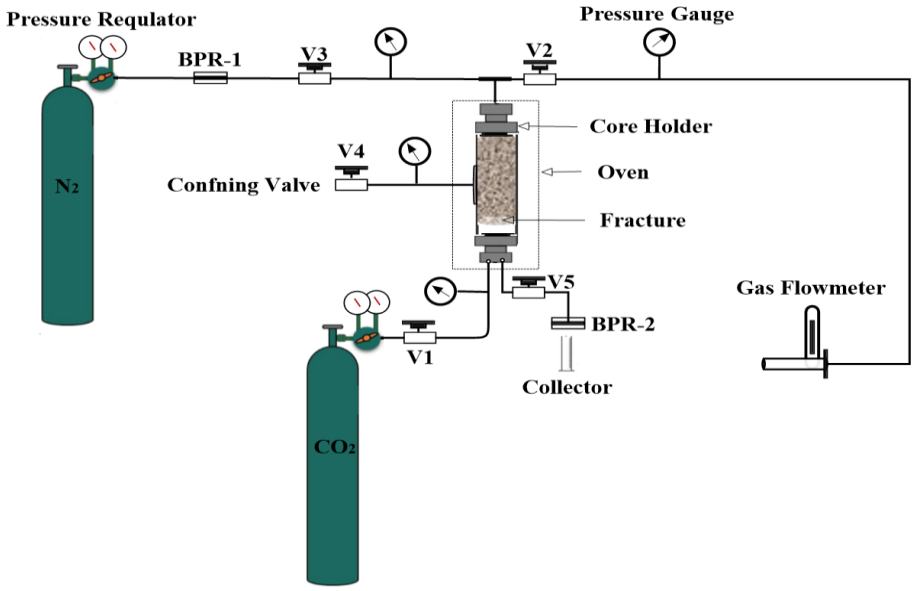

Figure 3 Schematic diagram of the modified experimental system (first IM soaking tests).

Miscible experimental setup (for second *soaking* step)

After the first soaking mentioned above, the CO_2 cyclic experiments were conducted to produce the bypassed oil. Figure. 4 illustrates the laboratory setup for the CO_2 H-n-P experiment. The setup is composed of a core holder, an accumulator to store the gas, and a syringe pump to pressurize the CO_2. The core holder employed in this method differs from the aforementioned one. No confining pressure is applied; thus, injected CO_2 travels effortlessly around the saturated plug instead of being forced to enter the core (in contrast to a conventional core holder test). The accumulator was assigned to store the gas, mostly at the maximum pressure of the operated CO_2 cylinder. The syringe pump contributes to pushing the CO_2 into the core holder at the desired pressure. A total of four valves were designated to control the experiment, including two and three-way valves. The temperature during the investigation was kept under control by using the oven. In this method, the core sample was placed horizontally on a pedestal to ensure that no produced fluid was infused into the core sample. In addition, a core pedestal was used to avoid resaturating the core sample with the oil produced. All experimental pressures were measured using three pressure gauges connected to the system, see Figure. 4.

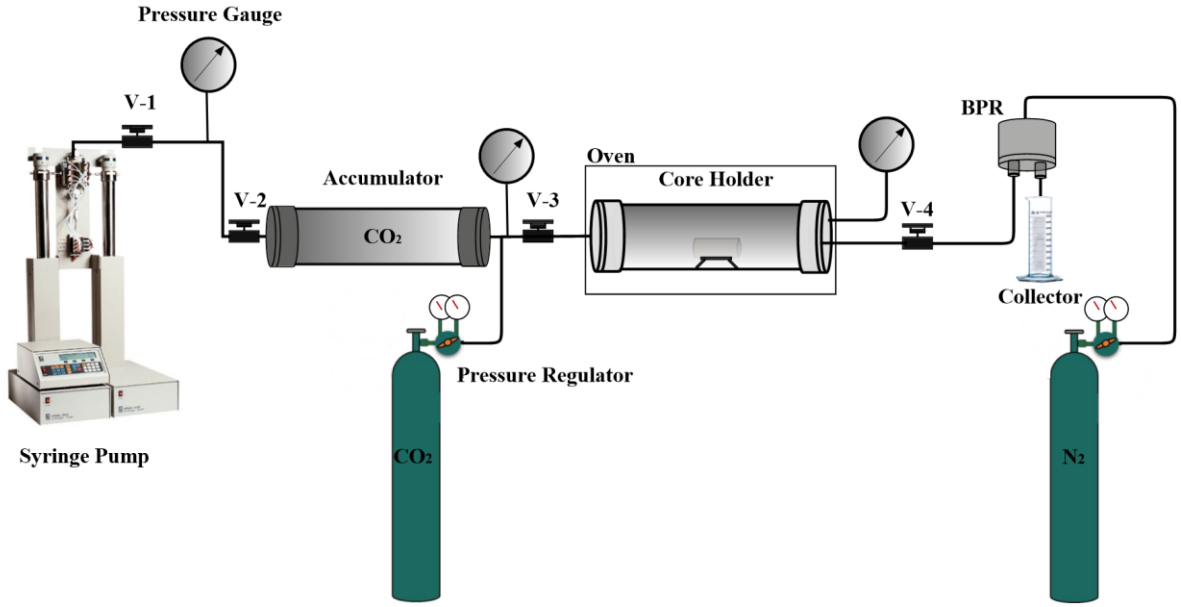

Figure 4 CO_2 H-n-P injection setup.

Experimental procedures

The procedures to perform the first and second CO_2 soaking techniques are described in detail in this section. Both experiments were carried out under a predesigned soaking cycle protocol; however, a modified step was included to accomplish individual objectives. The designed strategy was espoused and adapted based on an efficient approach applied to displace non-bypassed oil [10, 43]. However, its feasibility as a means of extracting bypassed oil and the variables concerning its performance (e.g., gas-phase miscibility) are still ill-explained in recognition of the limited number of studies on such a topic, especially at various reservoir temperatures [44]. Many attempts have been made in this research using the procedures above to validate the two-step soaking system and hence better estimate the possible recoverable bypassed oil from real unconventional reservoirs. To be able to evaluate the efficacy of the two-step system, both immiscible and miscible soaking approaches were performed consecutively using the same core samples and reservoir temperatures.

Core saturation

After the cores were dried at 248 °F and weighed as W_{dry}, key properties such as porosity and gas permeability were measured. Subsequently, cores were put in the saturation vessel in stage A and vacuumed for two days. Afterward, the pump was turned off, and the vessel was filled with oil. The pump resumed working for a few days until no gas bubbles arose in the vessel. Such a process is conducted to initially saturate the plugs. As soon as this first saturation activity was completed, the cores were transported to the stainless-steel high-pressure chamber in stage B. This time, the chamber was mounted inside an oven to saturate the cores at reservoir conditions. As the temperature effect on oil recovery is the focus of this research, cores were saturated at elevated temperatures. The temperature was adjusted based on the objective of the study. After placing the cores in the oven, valve 2 was opened toward the chamber together with the vacuum pump. Immediately, valve 3 was slowly opened to suck the

oil from the tank. As soon as the oil was delivered to the liquid trapper, which means the vessel was fully saturated, the pump was turned off, and valves 1, 2, and 3 were closed. After that, valves 4, 5, and 6 were opened, and the syringe pump was operated. The oil was pushed into the chamber that houses the core sample by the force transient from the displaced water at a constant pressure of 2100 psi. The moment the desired saturation pressure was achieved, the syringe pump along with the valves were closed. The pressure was checked daily and boosted to the original in case it decreased. This process was repeated until no pressure decrease was detected. To assure that pressure inside and outside the samples ideally reaches equilibrium, attains the maximum saturation degree, and follows an actual field procedure for saturation, the oven temperature was maintained, and the pressure was bled very slowly to avoid oil production mode or any damage to the saturated plugs caused by the pressure difference. Once the atmospheric pressure was reached, the cores were kept inside the vessel for a few hours. The weight of saturated samples was then measured and recorded as W_{sat}. At this point, samples were considered fully saturated and ready for the next gas injection test. The above procedures were repeated many times on each plug as the flooding tests were carried out under different operating conditions. Each plug's degree of oil saturation was calculated to verify that the core had achieved its maximum saturation point.

Immiscible CO_2 soaking (bypassed oil procedures)

Before starting the lab test, we first tested the whole designed system by injecting N2 at a pressure of 10% higher than the predesigned pressure. Such a step was applied to confirm that there will be no leakage once the investigation begins, which may alter the results. The procedure of the method is illustrated as follows:

1. To begin the test, a saturated core was placed in the core holder that is shown in Figure 3. The core selected was saturated at a similar temperature as the following soaking test. The core holder was then mounted vertically so additional gravity force was incorporated to properly bypass the oil as required.
2. Before commencing with the gas injection procedure, both confining pressure and backpressure were adjusted. The confining pressure was dynamically maintained at about 500 psi higher than the injected pressure. The BPR was set to keep the core pressure constant throughout the gas injection procedure.
3. CO_2 was injected into the core holder and left to soak for a certain period of time. The purpose of this soaking step is to provide an appropriate time for oil and CO_2 to establish contact and enable molecular diffusion processes to achieve a maturity level. The injected CO_2 mainly passed through the designed fracture because of the high-permeability contrast between fracture and matrix.
4. After the soaking period was completed, the holder was depressurized very slowly and CO_2 was injected through valve 2 for improved oil production, but this time at a constant flow rate of 25 ml/min. Such a modified process was applied to sweep leftover oil through valve 5. In addition, to accumulate the unproduced oil that came out to the surface during the soaking period. Hence, the following miscible process can be proficiently elucidated.
5. This method was continued until no more oil was extracted and no mass change was observed. After one cycle was completed (i), the core was weighed (usually at a wait time of 3-hours) and the weight was recorded as W_i. Then, the oil recovery factor (R_i) was calculated using Eq. (1). A series of such modified cycles were conducted using various reservoir conditions. The purpose of using a wide range of pressure, temperature, soaking time, and pressure depletion time (PDT) was to have a much more intuitive description of the bypassed oil volumes reached and to synchronously validate the role of the aforementioned factors at different reservoir conditions.

$$\text{Oil Recovery in IM Soaking Cycle i } Ri = \frac{w_{sat} - w_i}{w_{sat} - w_{dry}} \times 100 \quad (1)$$

w_{sat} is the weight of the core sample fully saturated with oil, w_i is the weight of the core sample after each soaking cycle, w_{dry} is the weight of the dry core sample.

Miscible CO_2 soaking (H-n-P procedures)

Following the procedure above, CO_2 cyclic experiments were carried out with the expectation of producing the residual oil in the matrix. The CO_2 tests were conducted with the apparatus shown in Figure. 4. The pressure of the second soaking step (cyclic gas practice) was adjusted to be just below, at, slightly above, and significantly above the measured minimum miscibility pressure (MMP), respectively, in order to form near-miscible, MMP, multi-contact miscibility (MCM), and first contact miscibility (FCM) conditions. More importantly, the test pressure and temperature are precisely adjusted to generate CO_2 compressed liquid and CO_2 supercritical phases. The purpose of the second CO_2 soaking step is to investigate the influence of CO_2-phase miscibility on the bypassed oil extraction. On the basis of these aspirations, the method was operated at the same temperature as the first immiscible soaking method. The principle of using the same condition is to relatively track the potential of the cyclic CO_2 system in producing depleted oil fields. Due to the time factor and to achieve trustworthy results,

a 1-hour soaking period was cautiously selected to be the judging criteria of the gas phase miscibility effect. The methodology applied is explained using the following procedures:

1. After the immiscible investigation, depleted core samples were transferred to the core holder shown in Figure 4. The CO_2 was then injected at 1200, 1300, 1500, and 1750 psi to pressurize the system for the duration of the huff process. Because CO_2 typically exists in four different forms: solid phase, gas phase, liquid phase, and supercritical phase, the pressure-temperature phase diagram proposed by Passarella [45] was followed to track the CO_2 phase behaviour and liquid-vapour critical points. The injected CO_2 moved freely inside the vessel and was in contact with all the core surfaces during the process.

2. The CO_2 was then allowed to soak for a continual 1-hour while the pressure was monitored through the gauge that was set at the right-hand end of the pressure vessel.

3. After soaking, pressure depletion was initiated, so the production mode was resumed. Such pressurizing–soaking–depressurizing steps constitute a complete H-n-P cycle. After finishing one cycle, the sample was weighed and recorded as W_{ii}. More cycles were repeated until no additional oil was extracted. The oil recovery factor of each cycle R_{ii} was then calculated using Eq. (2).

4. Using the above-mentioned saturation and soaking methods would achieve the major objectives, which are: (1) evaluating the two-step soaking process in estimating unconventional oil recovery; (2) further investigating the potential of cyclic CO_2 EOR in extracting bypassed oil reservoirs; (3) validating the performance of the main H-n-P processes under various reservoir conditions; and (4) determining the effect of CO_2 phase miscibility in producing tight oil reservoirs using H-n-P methodology.

$$\text{Oil Recovery in H-n-P Cycle i } Rii = \frac{w_{sat} - w_i}{w_{sat} - w_{dry}} \times 100 \quad (2)$$

w_{sat} is the weight of the core after being exposed to the first soaking process, and thus oil saturation changed from initial to bypassed.

Results and analysis

MMP measurements

This section discusses the results of the first and second CO_2 soaking steps in detail. The influence of each implemented parameter will be addressed and evaluated. Before the two-step soaking tests were performed, the miscible pressure of the synthetic oil and CO_2 system was first measured at different temperatures of 73, 122, and 158 °F to ensure the reliability of the research findings (see Figures. 5, 6, and 7). Therefore, the impact of reservoir temperature has received more attention. The details of the investigational setups and procedures have already been described [46-48]; thus, they will not be discussed in detail here. The findings demonstrate that oil recovery is strongly correlated with the temperature at low pressures, implying that miscibility has not yet been achieved. However, it is only marginally correlated at high pressures, suggesting that miscibility is reached. In general, MMP levels increase linearly with temperature, see Figures. 5, 6, and 7. All figures show that the MMP obtained at 73 °F is only 23 psi and lower than that obtained at 122 and 158 °F, respectively. The injection pressures were cautiously selected based on the obtained MMPs and the pressure-temperature phase diagram. Two factors, incremental oil recovery factor (IRF) and cumulative oil recovery factor (CRF), were measured to evaluate the soaking processes.

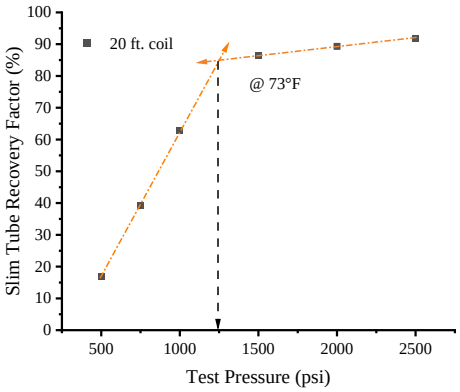

Figure 5 MMP of oil used plot using a 20 ft slim-tube coil at 73 °F.

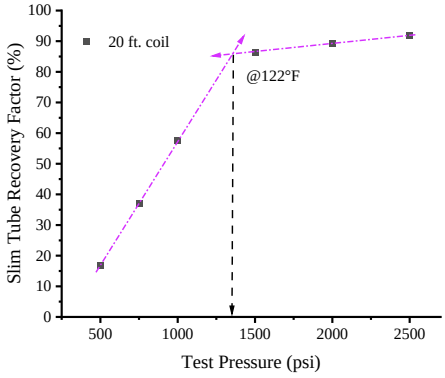

Figure 6 MMP of oil used plot using a 20 ft slim-tube coil at 122 °F.

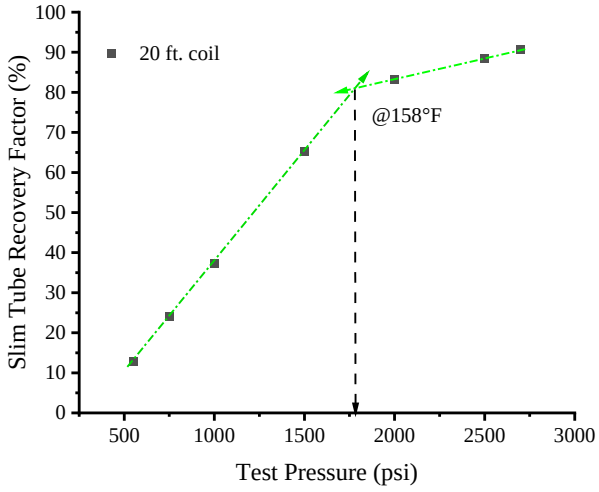

Figure 7 MMP of oil used plot using a 20 ft slim-tube coil at 158 °F.

Bypassed-oil recovery of miscible CO_2 soaking.

Although the amount of oil extracted using previous CO_2 soaking experiments was disappointing, oil was bypassed as required. The purpose of the second soaking step (cyclic CO_2 method) is to recover the remaining oil (depleted cores). A number of CO_2 experiments were carried out using CO_2 compressed liquid and CO_2 supercritical phases to know the effects of CO_2 phase miscibility and injection mode on bypassed oil recovery.

Effect of CO_2 phase miscibility

Tables 2 to 5 detail the thermodynamic state variables for CO_2. Numerous experiments were carried out with a one-hour soaking time and four modes of CO_2 miscibility: near-miscible, MMP, MCM, and FCM. The results for compressed liquid and supercritical are shown in Figures 8–11. According to the findings, altering the CO_2 phase has a significant effect on oil recovery, especially at pressures above the MMP. As illustrated in Figure 11, the use of supercritical CO_2 resulted in the highest oil recovery rate of up to 30.40%. However, the compressed liquid phase recovered slightly more initial oil, particularly when the pressure was near miscible, as shown in Figure 8. The results demonstrate that in the supercritical state, oil recovery increased gradually until it exceeded that in the compressed state, resulting in increased CRF. This proves that increasing CO_2 injection pressure alone may not be sufficient to increase oil recovery; the CO_2 phase could also play a major role. This could be due to the properties of CO_2 in its various phases. When CO_2 is compressed, it becomes denser, allowing for a greater volume of gas to be mobilized into the pores. However, a considerable volume of liquid remains trapped in the small pores, slowly reducing oil recovery.

When the CO_2 injection pressure was increased to MMP (Figure 9), the supercritical and compressed phases performed nearly identically for the first cycles before diverging. This confirms unequivocally that CO_2 miscibility is not the only significant factor influencing oil recovery; the CO_2 phase may also demonstrate a crucial

mechanism in extracting bypassed oil. Additionally, the study discovered that increasing CO_2 pressure above the MMP significantly improved oil recovery. However, as more cycles are performed, the effect of supercritical CO_2 will become dominant. For oil recovery at MCM and FCM, the performance difference between supercritical and compressed CO_2 has grown more pronounced, despite the fact that both gases are miscible. The reason could be attributed to the density of CO_2. In supercritical CO_2, the density actually becomes lower than that of the liquid, thereby allowing CO_2 to mobilize small pores by reaching deeper bypassed oil regions. Due to the fact that the pressures in the compressed and supercritical phases are identical, miscibility is believed to be unimportant. However, phase miscibility is the prevailing property. Again, increased injection pressure may not be sufficient to produce bypassed oil recovery; the CO_2 phase may also have a significant influence.

Table 2 Thermodynamic state variables of CO_2 at the near-miscible condition.

Property	Value1	Value2	Unit
Medium	CO_2	CO_2	/
state of aggregation	Compressed liquid	Supercritical	/
Miscibility	Near-miscible	Near-miscible	/
Density	0.799	0.237	gm / cm^3
Kinematic viscosity	0.091	0.089	10^{-6} m^2 / s

Table 3 Thermodynamic state variables of CO_2 at the MMP condition.

Property	Value1	Value2	Unit
Medium	CO_2	CO_2	/
state of aggregation	Compressed liquid	Supercritical	/
Miscibility	MMP	MMP	/
Density	0. 807	0. 282	gm / cm^3
Kinematic viscosity	0.092	0.081	10^{-6} m^2 / s

Table 4 Thermodynamic state variables of CO_2 at the MCM condition.

Property	Value1	Value2	Unit
Medium	CO_2	CO_2	/
state of aggregation	Compressed liquid	Supercritical	/
Miscibility	MCM	MCM	/
Density	0. 836	0. 406	gm / cm^3
Kinematic viscosity	0.095	0.074	10^{-6} m^2 / s

Table 5 Thermodynamic state variables of CO_2 at the FCM condition.

Property	Value1	Value2	Unit
Medium	CO_2	CO_2	/
state of aggregation	Compressed liquid	Supercritical	/
Miscibility	FCM	FCM	/
Density	0. 855	0. 514	gm / cm^3
Kinematic viscosity	0.098	0.077	10^{-6} m^2 / s

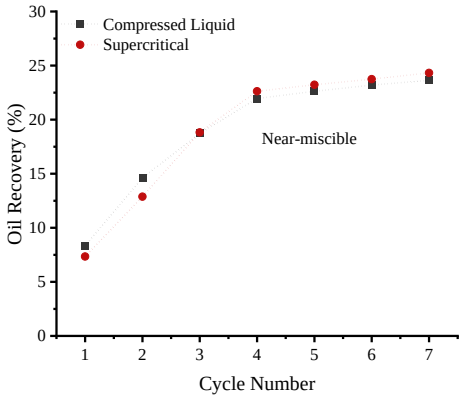

Figure 8 Effect of near-miscible CO_2 on oil recovery.

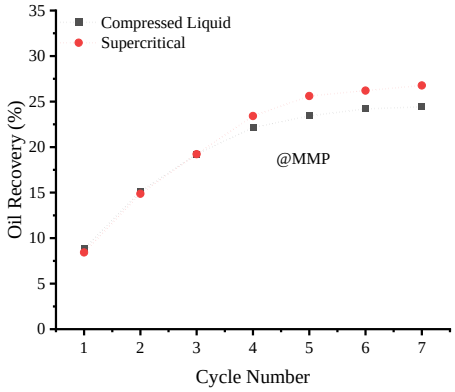

Figure 9 Effect of CO_2 MMP on oil recovery.

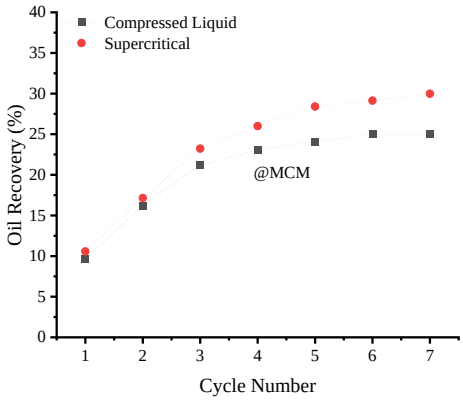

Figure 10 Effect of CO_2 MCM on oil recovery.

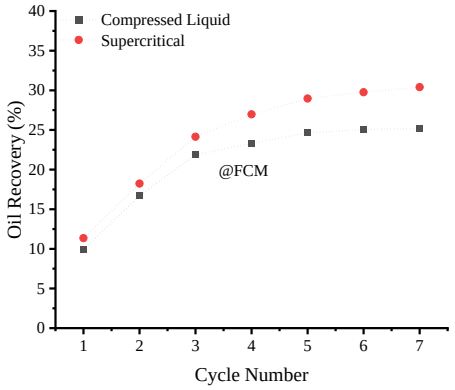

Figure 11 Effect of CO_2 FCM on oil recovery

Total oil recovery of the first soaking method and the corresponding bypassed oil achieved is presented in Table 6.

Table 6 Effect of CO_2 phase miscibility state on total oil recovery of Six sample.

Immiscible RF, %	Miscibility condition	Miscibility mode	Miscible RF, %	Total recovery, %
15.537	Near-miscible	Compressed liquid	23.632	39.169
20.312	Near-miscible	Supercritical phase	24.321	44.633
18.075	MMP	Compressed liquid	24.421	42.496
21.083	MMP	Supercritical phase	26.767	47.850
19.639	MCM	Compressed liquid	25.012	44.651
21.194	MCM	Supercritical phase	29.983	51.177

Effect of CO_2 miscibility Mode

The effect of CO_2 injection on bypassed oil was also investigated using soaking pressures of 1000, 1200.1300, 1500, 1750, and 2000 psi. Figure 12 depicts the oil recovery results for all six pressures. All findings were recorded

at 122 °F after one hour of soaking. Increased oil recovery was observed when the injection pressure of CO_2 was increased. Additionally, it was noted that increasing the pressure increased the number of productive CO_2 cycles. On the other hand, increasing the pressure from 1500 to 2000 psi resulted in a modest improvement in oil recovery. This could be due to some key variables, including the CO_2 phase that discussed in the previous section. While increased injection pressure results in increased bypassed oil production, the rate of increase is determined by the miscibility mode. Insufficient improvements are obtained by increasing the soaking pressure above the MMP, particularly in subsequent cycles. The primary reason for this is that the core's low permeability results in a considerable pressure drop between the core's surface and the central region [1]. To ensure that CO_2 and oil are miscible in the core's central region, the injection pressure must be greater than the MMP. In comparison to the MMP finding, establishing full miscibility throughout the core, particularly in the central region, is more challenging [1]. The research findings indicate that there are optimal injection pressures for cyclic CO_2 in tight reservoirs (close to the MMP). This conclusion is consistent with the previous one established by Zhu, et al. [37].

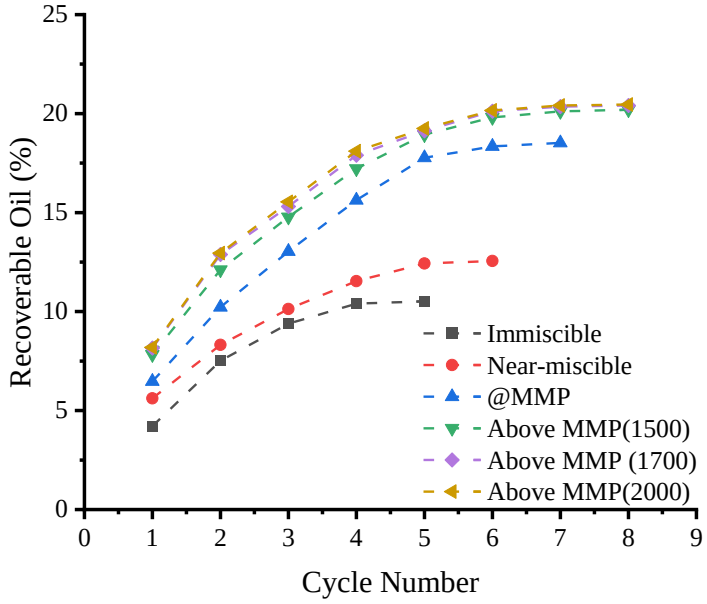

Figure 12 Effect of CO_2 miscibility pressure on residual oil recovery

Conclusion

The contribution of this work is to develop a better understanding of how bypassed oil can be extracted using soaking processes. The effect of CO_2 phase miscibility and miscibility modes on bypassed-oil recovery was subsequently considered. The following are the major findings from this study:

1. The study established that two-step modified soaking is the recommended method for validating H-n-P performance in actual oil reservoirs.
2. The research findings demonstrated that increasing the CO_2 injection pressure is not the only factor affecting bypassed oil extraction; the CO_2 phase miscibility mode may also significantly contribute to tight oil recovery.
3. While the CO_2 supercritical phase had the highest oil recovery at high injection pressures, the performance difference between supercritical and compressed CO_2 is negligible at lower pressures, despite the fact that both gases are miscible.
4. Internal mapping of the cores prior to and following soaking would enhance our contribution. Thus, additional research using CAT or acoustic scanning can provide valuable insights and help to better justify the research findings.

Acknowledgments

The first author would like to thank University of Zawia and the Ministry of Higher Education and Scientific Research –Libya for supporting this study by providing a scholarship. Additionally, the acknowledgement goes to University Teknologi Malaysia (UTM) for proving laboratory facilities. Eventually, appreciation goes to colleagues who are supporting this work directly or indirectly.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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