https://doi.org/10.33261/jaaru.2020.27.2.007 *Association of Arab Universities Journal of Engineering Sciences (2020)27(2):60–66*

Association of Arab Universities Journal of Engineering Sciences
مجلة اتحاد الجامعات العربية للدراسات والبحوث الهندسية

Immiscible CO_2-Assisted Gravity Drainage Process for Enhancing Oil Recovery in Bottom Water Drive reservoir

Dahlia A. Al-Obaidi [1*] **,** ***Mohammed S. Al-Jawad*** [2]

[1] *Petroleum Department, College of engineering, University of Baghdad, Baghdad, Iraq,_dahliaalobedi@coeng.uobaghdad.edu.iq*

[2] *Petroleum Department, College of engineering, University of Baghdad, Baghdad, Iraq, mohaljawad@yahoo.com*

** Corresponding author : Dahlia A. Al-Obaidi,_dahliaalobedi@coeng.uobaghdad.edu.iq*

Published online: 30 June 2020

Abstract— The CO2-Assisted Gravity Drainage process (GAGD) has been introduced to become one of the most influential process to enhance oil recovery (EOR) methods in both secondary and tertiary recovery through immiscible and miscible mode. Its advantages came from the ability of this process to provide gravity-stable oil displacement for enhancing oil recovery. Vertical injectors for CO2 gas have been placed at the crest of the pay zone to form a gas cap which drain the oil towards the horizontal producing oil wells located above the oil-water-contact. The advantage of horizontal well is to provide big drainage area and small pressure drawdown due to the long penetration. Many simulation and physical models of CO2-AGD process have been implemented at reservoir and ambient conditions to study the effect of this method to improve oil recovery and to examine the most parameters that control the CO2-AGD process. The CO2-AGD process has been developed and tested to increase oil recovery in reservoirs with bottom water drive and strong water coning tendencies. In this study, a scaled prototype 3D simulation model with bottom water drive was used for CO2-assisted gravity drainage. The CO2-AGD process performance was studied. Also the effects of bottom water drive on the performance of immiscible CO2 assisted gravity drainage (enhanced oil recovery and water cut) was investigated. Four different statements scenarios through CO2-AGD process were implemented. Results revealed that: ultimate oil recovery factor increases considerably when implemented CO2-AGD process (from 13.5% to 84.3%). Recovery factor rises with increasing the activity of bottom water drive (from 77.5% to 84.3%). Also, GAGD process provides better reservoir pressure maintenance to keep water cut near 0% limit until gas flood front reaches the production well if the aquifer is active, and stays near 0% limit at all prediction period for limited water drive.

Keywords— CO_2-AGD, Gravity Drainage, EOR.

1. Introduction

Hydrocarbon exploration in reservoir with bottom water drive gives positive and negative benefits. The major advantage of present this water bearing body is that it maintain pressure and displacing oil towards the production well which increases the recovery of reservoir. On the other hand, this water drive becomes disadvantageous at the last stage of hydrocarbon production due to the water production alongside oil [2,7]. The concept of gas injection especially CO_2 gas into reservoirs has been investigated widely to improve oil recovery. The effectiveness came from its ability to lower the interfacial tension to increase microscopic displacement efficiency which lead to minimize the trapping of oil in the rock pores [14]. Also CO_2 assures delaying the breakthrough to the oil production well due to its high volumetric sweep efficiency which leads to maintain the injection pressure and increase the gas injectivity [13]. Gravity drainage is the gas/oil displacement process in which gravity forces act as a main driving force and where the gas replaces voidage volume [5,12]. To take the advantage of the in situ segregation of fluids in oil reservoirs, gas injects in the top of the reservoir to create pressure maintenance and drain oil downward the reservoir to get higher value of oil recovery [1,8]. GAGD process technology is one of the application of the gravity stable gas injection concept in different types of reservoirs which was introduced by D.N. Rao [9] to improve oil recovery in secondary and tertiary modes for both immiscible and miscible processes, a large oil recoveries around 85-95% of OOIP in field tests and nearly 100% in laboratory floods have been reported from core floods and field studies [10,13].

2. CO_2- Assisted Gravity Drainage Process

CO_2- Assisted Gravity Drainage is an EOR process in which CO_2 is injected in a gravity stable manner. This process takes place either in immiscible or miscible mode through vertical wells from the top of the formation while oil has been produced by placing a horizontal wells at the bottom of the oil zone above the oil water contact. The injected gas accumulates at the top of the formation to form a gas cap providing oil displacement drains towards the horizontal producer in gravity stable mode. The gravity segregation is resulted from the distinct fluid densities at reservoir condition and lead to better sweep efficiency and higher oil recovery [16]. Figure 1 shows the schematic drawing of CO_2- AGD process [4]. Due to horizontal wells, productivity increased because reservoir contact area has been increased and the cresting in the reservoir with bottom water drive and gas cap drive has been diminished due to the low pressure drawdown around well sand- face [6]. Gravity forces playing a major role at every stage of the producing life of the reservoir [7]. Oil production rate must be controlled to keep the reservoir system in a gravity dominated mode such that the oil production volumes plus minor dissolved volumes are replaced with the equivalent gas injection volumes implying constant pressure behind CO_2 flood front. The gas oil interface (GOC) moved downward slowly from high pressure zone to low pressure oil production horizontal wells located at the lower part of the pay zone under the effect of gravity drainage [15]. Many studies was introduced to test the feasibility of GAGD process to enhance oil recovery on limited real oil fields. The GAGD process was applied for immiscible and miscible modes and the results showed that the oil recovery in miscible mode is much better than the immiscible GAGD [4,11]. Also the CO_2-assisted gravity drainage process has been applied in North Louisiana field to find the optimal field prediction performance through an economic analysis [22]. Furthermore, the GAGD process has been suggested for improving oil recovery in the main pay of South Rumaila Oil Field which located in south Iraq through compositional reservoir simulation study [17]. More recovery factor was obtained using CO_2-assisted gravity drainage mechanism nearly 10% higher than Continues Gas Injection (CGI) and Water Alternating Gas (WAG) methods [18-20]. On the other hand, new studies presented and integrated Downhole water sink with GAGD process to improve oil recovery in the reservoir with high water cut and coning tendency[3,21]. In this study, CO2-assisted gravity drainage mechanism implemented on non-dipping horizontal type reservoir using scaled numerical simulation model to investigate the feasibility of CO2-assisted gravity drainage process on reservoir with bottom water drive. The effects of bottom water drive on this mechanism also studied.

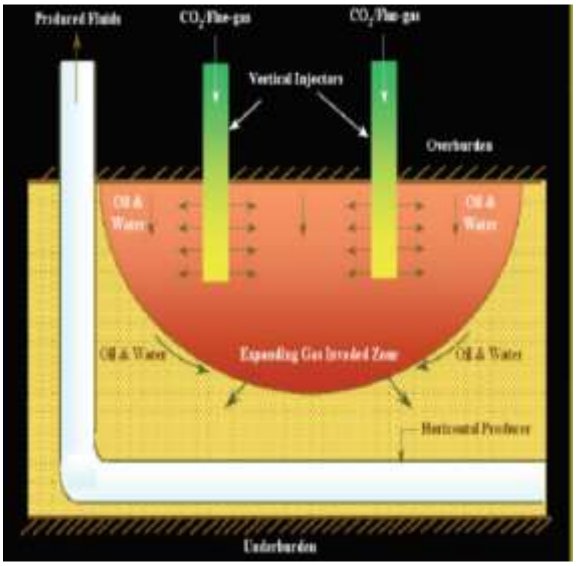

Figure 1: Schematic drawing of GAGD process [4].

3. CO_2-assisted gravity drainage simulation model

The simulation model is a black oil model with 3D Cartesian grid system which was scaled down from a real reservoir geometry with bottom water drive and developed using the CMG Implicit Explicit (IMEX) simulator. A total of 36 Cartesian grids were used (3 grids in the i-direction, 1 grid in the j-direction and 12 grids in the k-direction represent 12 layers as shown in figure 2. The depth to Water Oil Contact (WOC) equal 35 cm and primary gas oil contact (GOC) set to zero. In this study, a water-wet system was considered with connate water saturation Swc = 0.125 and residual oil saturation Sorw = 0.13 for oil-water system. For gas- oil system, the critical gas saturation Sgc was 0.02 and residual oil saturation Sorg was 0.2. To construct the relative permeability curves for gas-oil system, Corey correlation with exponent equal 2 was constructed, while the relative permeability curves for oil-water system were scaled down from the real reservoir data. The three phase relative permeability curve was obtained using stones'Π model and the capillary pressure effects for gas-oil and oil-water systems were neglected. The initial pressure for the model was 130 kPa while the saturation pressure was 101.3 kPa. N-Decane with sp.gr. 0.76 was used as reservoir fluid and CO2 with sp.gr. 1.5189 as injected fluid. Table 1 summarized the model details. Carter Tracy infinite and limited acting model was selected to simulate the bottom aquifer. Porosity value was constant (homogeneous) from layer 1 to 7 with 24.5% value and for the rest layers with 30% value. Horizontal permeability in I and J direction were assumed to be 20000 md with vertical to horizontal ratio (Kv/Kh) equal to 0.1 and rock compressibility was assumed to be 5.8*10-7 1/kPa. Initialization of these data yielded oil and water in place as 651cc and 768.29cc respectively.

Table 1: Simulation model details.

Property	Simulation Model
Number of grids	Cartesian 3*1*12
Grid size	10*3*5 cm
Grid thickness	5 cm
Pay thickness	35 cm
Reservoir temperature	25°C
Connate water saturation	12.5%
Vertical Permeability	2 D
Kv/Kh	0.1
Oil specific gravity	0.76
Gas specific gravity	1.518
Initial model pressure	130 kPa
Bubble point pressure Pb	101.3 kPa
Oil formation volume factor at Pb	1.02 m3/m3
Solution gas oil ratio Rs at Pb	3.849 m3/m3

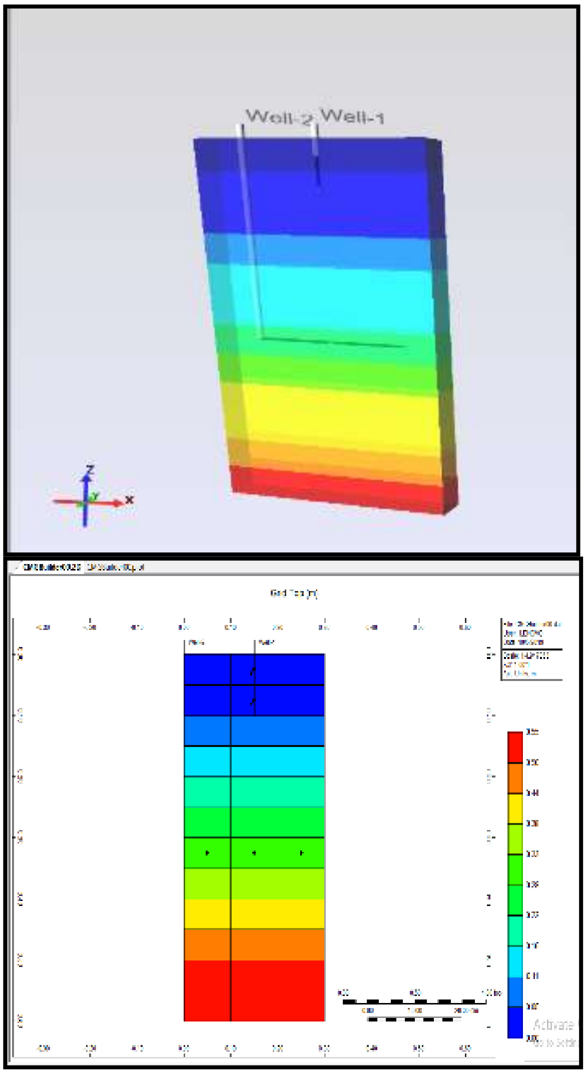

Figure 2: Simulation model developed for black oil simulation shows the grid top (m) and the position of well-1 and well-2.

4. Simulation of the immiscible CO_2-AGD process

Simulation model was conducted with setting up one horizontal production well above OWC in layer 7 to produce the gravity drained oil that was displaced by CO2. The horizontal well was perforated for the entire length to reduce pressure drawdown. To formulate a gas cap and displacing oil in a gravity drainage manner, CO2 was injected in an immiscible mode through one injector which was perforated in layers 1 and 2. The last two layers represented the bottom infinite active water drive and was modeled using the Carter-Tracy acting approach. The bottom water drive aquifer was activated in the simulation model to support pressure maintenance. To represent the concept of the CO2-AGD process, secondary mode immiscible CO2 flooding was implemented to the under saturated horizontal type reservoir for number of simulation runs extended to 24 hours. The immiscible CO_2- AGD process was conducted based on some constraints in the injection and production well. Operating constraints for these wells were: 1- The oil production rate. 2- Gas injection rate. 3- The bottom hole pressure for injection and production wells. In this study, the well constraints for the GAGD process were: maximum oil production rate (MAXSTO) and minimum bottom hole pressure (MINBHP), each for oil production well. For gas injection well, maximum gas injection rate (MAXBHG) and maximum bottom hole injection pressure (MAXBHP). The immiscible CO_2- AGD process was simulated in four different scenarios. The first two cases (1 and 2) are to demonstrate the effect of bottom water drive for enhancing oil recovery using CO_2 gas. The rest two scenarios are primary active drive and primary limited dive to show the superiority of the CO_2-AGD process when compares with the first two scenarios.

Table 2 and 3 summarize these two scenarios with their constraints and aquifer properties.

Table 2: Active and limited water drive scienrios.

case	Water drive	Aquifer model	Thickness, cm	Porosity, %	Permeabili-ty, md
1, prima-ry	active	Carter-Tracy (infinite extent)	10	30	2000
2, prima-ry	limited	Carter-Tracy (limited extent)	10	30	

5. Effect of aquifer strength on CO_2 -AGD process performance.

Water from aquifer gives the dual purpose of maintaining pressure and displacing oil towards the producers. Active water drive is more efficient and provides enough energy to recover the oil towards producing well. Water cresting depends on pressure drawdown in the oil zone rather than the aquifer strength, so it may happens in both limited and active water drive. The comparison between the effect of active water drive and limited water drive on GAGD process performance (oil recovery factor and water cut) was studied. At the beginning of prediction period after implementation of the CO_2-AGD process, oil recovery factor showed the same increasing linear trend with time for the first two scenarios (1 and 2). During this period, oil production rate continuous at the maximum rate constraint with flat producing GOR profile indicates that oil production occurs at the solution GOR. After that, oil recovery factor curves change their trend from linear to near horizontal–straightening up after CO_2 breakthrough happened. Once CO_2 flood front reaches the producing well, oil production rate drops and continue to decline. After CO_2 breakthrough occurred, GOR increasing rapidly. Figures 3, 4 and 5 present the oil recovery factor, oil production rate and GOR curves with time respectively for all cases. Comparing case 1 with 2 gives the following results: 1- Breakthrough recovery increased from 55.23% for limited water drive to 80.3% for active water drive. 2- Time of gas breakthrough occurred after 9 hours for active water drive and after 6 hours for limited water drive. 3- Water cut remains near 0% for limited water drive for all 24 hours while in active bottom water drive increased dramatically after gas breakthrough time to reached uneconomical limit after 11 hours as shown in figure 6. As a results, we can see that the oil recovery factor is impacted a lot by the aquifer strength which caused by the fact that the average resservoir pressure is depleted in limited water drive faster than active water drive and, therefore, the producer does not have enough energy to continue producing as figure 7 depicts. Comparison between the first two cases (1 and 2) with the rest two cases showed that implemented GAGD process gives better pressure maintenance for the reservoir which leads to enhance oil recovery nearly 70% as shown in figure 3. On the other hand, from figure 6, we can see also that the application of CO2-AGD process on active water drive delays the time of water breakthrough a lot due to the CO2-AGD pressure maintenance.

Table 3: GAGD process constraints.

Case	GAGD Process Constraints			
	Injector		Producer	
	MAXBHG,(m^3/d)	MAXBHP, kPa	MAXSTO,(m^3/d)	MINBHP, kPa
1 active drive	0.00432	106.8	0.00144	101.3
2 limited drive	0.00432	106.8	0.00144	101.3
Primary active drive	Shutdown	Shutdown	0.00144	101.3
Primary limited drive	Shutdown	Shutdown	0.00144	101.3

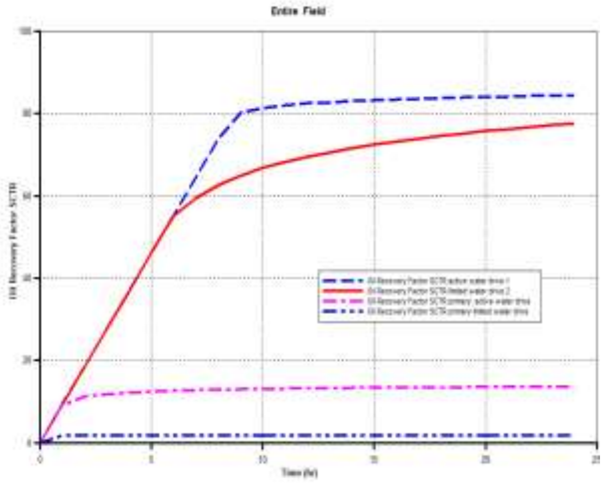

Figure 3: Oil recovery factor for active and limited water drive.

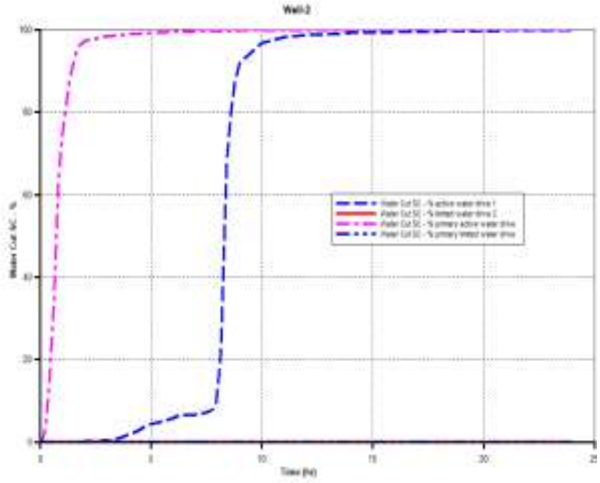

Figure 6: Water Cut for active and limited water drive.

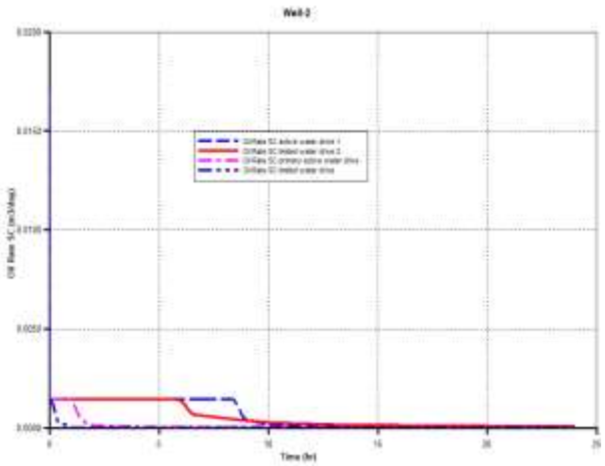

Figure 4: Oil production rate for active and limited water drive.

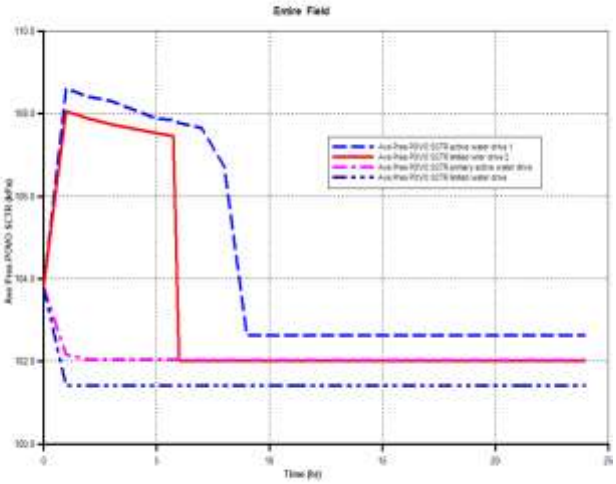

Figure 7: Average pore pressure for active and limited water drive.

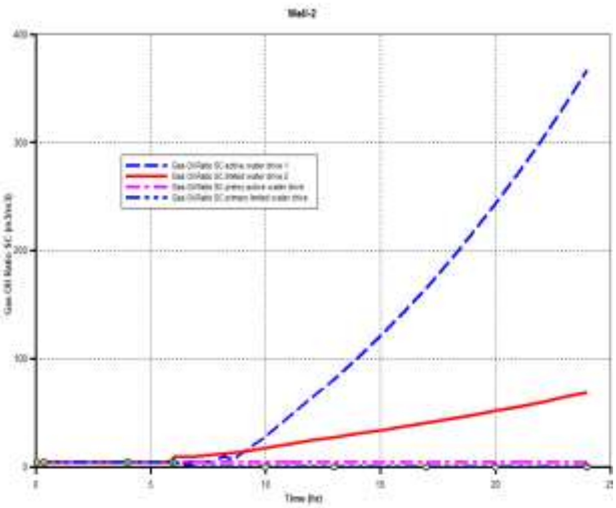

Figure 5: Gas Oil Ratio for active and limited water drive.

6. Conclusions

1- Ultimate oil recovery factor increases considerably when implemented CO_2-AGD process on the reservoir with bottom water drive about 70%.

2- Ultimate oil recovery factor impacts by the aquifer strength which increasing from 77.5% to 84.3% with increasing the activity of bottom water drive.

3- GAGD process gives better reservoir pressure maintenance to keep water cut near 0% limit until gas flood front reaches the production well if the aquifer is active, and stays near 0% limit at all prediction period for limited water drive.

4- Application of CO2-AGD process on active water drive delays the time of water breakthrough a lot.

Acknowledgments

The authers would like to thank Basra Oil Company for providing the required data to achieve this study.

References

[1] A. P. Sharma and D. N. Rao, "Scaled physical model experiments to characterize the gas-assisted gravity drainage EOR process," in Proceedings - SPE Symposium on Improved Oil Recovery, 2008, vol. 2.

[2] A. N. Okon, D. T. Olagunju, and J. U. Akpabio, "Water Coning Control : A Comparison of Downhole Water Sink and Downhole Water Loop Technologies Available online www.jsaer.com Journal of Scientific and Engineering Research , 2017 , 4 (12): 137-148 Water Coning Control : A Comparison of Downhole Water ," no. December, 2017.

[3] D. A. Al-Obaidi, W. J. Al-Mudhafar, A. K. Wojtanowicz, M. S. Al-Jawad, and D. Saini, "Evaluation of Gas and Downhole Water Sink-Assisted Gravity Drainage GDWS-AGD Process in Saturated Oil Reservoirs with Infinite-Acting Aquifer," SPE- 195332-MS, 2019.

[4] D. N. Rao, S. C. Ayirala, M. M. Kulkarni, and A. P. Sharma, "Development of Gas Assisted Gravity Drainage (GAGD) Process for Improved Light Oil Recovery," Spe, 2004.

[5] J. Hagoort, "Oil Recovery by Gravity Drainage," Soc. Pet. Eng. J., vol. 20, no. 3, pp. 139–150, 1980.

[6] Joshi. S. D., "Horizontal Well Tecnology," PeenWell books, pp. 1–287, 1991.

[7] L. P. Dake, "The practice of reservoir engineering, Revised Edition," Elsevier, vol. 14, no. 3–4, p. 263, 1996.

[8] M. Muskat, " The flow of homogenous fluid through porous media, " McGraw Hill books ,1946 .

[9] M. M. Kulkarni and D. N. Rao, "Is gravity drainage an effective alternative to WAG?," AIChE Annu. Meet. Conf. Proc., pp. 6073–6093, 2004.

[10] M. M. Kulkarni and D. N. Rao, "Analytical modeling of the forced gravity drainage GAGD process," in AIChE Annual Meeting, Conference Proceedings, 2006.

[11] N. Kasiri and A. Bashiri, "Gas-Assisted Gravity Drainage (GAGD) process for improved oil recovery," Soc. Pet. Eng. - Int. Pet. Technol. Conf. 2009, IPTC 2009, vol. 1, no. December, pp. 582–588, 2009.

[12] O. Arslan, "Optimal operating strategy for wells with downhole water sink completions to control water production and improve performance," 2005.

[13] P. S. Jadhawar and H. K. Sarma, "Improved Production Strategy for Enhancing the Immiscible and Miscible CO2-Assisted Gravity Drainage Oil Recovery, " 2010.

[14] P. S. Jadhawar and H. K. Sarma, "Numerical simulation and sensitivity analysis of gas-oil gravity drainage process of enhanced oil recovery," vol. 49, no. 2. 2010, pp. 64–70.

[15] P. S. Jadhawar and H. K. Sarma, "Effect of well pattern and injection well type on the CO2-assisted gravity drainage enhanced oil recovery," J. Pet. Sci. Eng., 2012.

[16] T. N. Mahmoud and D. N. Rao, "Range of Operability of Gas-Assisted Gravity Drainage Process," 2008.

[17] W. J. Al-Mudhafar and D. Rao, "Lessons Learned from the Field-Scale Simulation of the Gas-Assisted Gravity Drainage GAGD Process in Heterogeneous Sandstone Oil Reservoirs," SPE West. Reg. Meet., 2017.

[18] W. J. Al-Mudhafar, D. N. Rao, and S. Srinivasan, "Robust Optimization of Cyclic CO2 flooding through the Gas-Assisted Gravity Drainage process under geological uncertainties," J. Pet. Sci. Eng., vol. 166, 2018.

[19] W. J. Al-mudhafar, B. O. Company, A. K. Al-maliki, and B. O. Company, "Field-Scale Evaluation of Re-injecting the Associated Gas to Enhance the Recovery of Oil Through the GAGD Process : A Prospective Pilot Project in A Southern Iraqi Oil Field," SPE-190355-MS, 2018.

[20] W. J. Al-Mudhafar, D. N. Rao, and S. Srinivasan, “Reservoir sensitivity analysis for heterogeneity and anisotropy effects quantification through the cyclic CO2-Assisted Gravity Drainage EOR process – A case study from South Rumaila oil field,” Fuel, vol. 221, no. October 2017, pp. 455–468, 2018.

[21] W. J. Al-Mudhafar, A. K. Wojtanowicz, and D. N. Rao, “Hybrid Process of Gas and Downhole Water Sink-Assisted Gravity Drainage (G&DWS-AGD) to Enhance Oil Recovery in Reservoirs with Water Coning,” Carbon Manag. Technol. Conf., 2017.

[22] W. Paidin, P. Mwangi, and D. Rao, “Economic Evaluation within the Scope of the Field Development and Application of the Gas-Assisted Gravity Drainage (GAGD) Process in an Actual Northern Louisiana Field, ” SPE-129723-MS, 2010.

تعزيز انتاج النفط في مكامن الدفع المائي بطريقة تصريف الجاذبية و بمساعدة غاز ثنائي أوكسيد الكربون غيرالقابل للامتزاج

داليا عبد الهادي العبيدي[1]* ، *محمد صالح الجواد*[2]

[1] *قسم النفط ، كلية الهندسة ، جامعة بغداد ، بغداد ، العراق ،* *dahliaalobedi@coeng.uobaghdad.edu.iq*

[2] *قسم النفط ، كلية الهندسة ، جامعة بغداد ، بغداد ، العراق*

* *الباحث الممثل: داليا عبد الهادي العبيدي،* *dahliaalobedi@coeng.uobaghdad.edu.iq*

نشر في: 30 حزيران 2020

الخلاصة – اصبحت عملية تصريف الجاذبية بمساعدة الغاز (GAGD) واحدة من الطرق الرئيسية لتعزيزانتاج النفط (EOR) في كل من طرق الاستخلاص الثانوي والثالثي وذلك عن طريق حقن الغازغير القابل للامتزاج او الممتزج. جاءت مزاياه لقدرة هذه العملية على توفير إزاحة مستقرة بمساعدة الجاذبية لتعزيز استخلاص النفط مقارنةً بطرق حقن الغاز التقليدية: الحقن المستمر للغاز (CGI) وحقن الغاز والماء بالتناوب (WAG). تم وضع حاقن عمودي لغاز ثاني أوكسيد الكربون في أعلى المكمن لتكوين قبة غازية تهدف الى تصريف النفط باتجاه الآبارالأفقية المنتجة للنفط والتي تقع فوق منطقة تلامس الزيت مع الماء. ان ميزة البئرالأفقية هي توفير مساحة صرف كبيرة والحصول على فرق ضغط صغير بسبب مسافة الاختراق الطويلة للبئر الافقية. تمت دراسة العديد من النماذج الفيزيائية والمحاكاة لأداء GAGD في الظروف المحيطة والمكمنية لمعرفة تأثير هذه الطريقة لتعزيز استعادة النفط . لقد تم تطوير واختبار CO2-AGD لزيادة استخلاص النفط في المكامن ذات الدفع المائي من الاسفل. في هذه الدراسة ، تم استخدام نموذج محاكاة ثلاثي الأبعاد لمكمن محاط من الاسفل بخزان مائي وتطبيق طريقة تصريف الجاذبية بمساعدة غاز ثاني أوكسيد الكربون. تمت دراسة أداء عملية CO2-AGD. كما تم التحقق في تأثيرات دفع المياه السفلية على أداء تصريف الجاذبية بمساعدة ثاني أكسيد الكربون غير الممتزج . تم تنفيذ أربعة سيناريوهات مختلفة للبيانات من خلال عملية CO2-AGD. أظهرت النتائج أن: عامل الاستخلاص النهائي للنفط يزداد بشكل كبير عند تنفيذ عملية CO2-AGD (من 13.5 ٪ إلى 84.3 ٪). يرتفع عامل الاستخلاص مع زيادة دفع المياه السفلية (من 77.5٪ إلى 84.3٪). من ناحية أخرى ، توفر عملية GAGD ادارة أفضل لضغط المكمن للحفاظ على قطع المياه بالقرب من حد 0٪ حتى تصل واجهة الفيضان الغازي إلى بئر الإنتاج إذا كان دفع المياه السفلية نشطا ، وتبقى قريبة من الحد 0٪ في جميع فترة التنبؤ عندما يكون الدفع المائي محدودا.

الكلمات الرئيسية – تصريف الجاذبية، الدفع المائي، حقن الغاز.