Investigation of residual oil saturation in the process of filtration of viscous multicomponent flow with a wide range of pressures and temperatures

Radaev A.V. 1, Wisam Essmat Abdul-lateef 2, Ali Kamil Sebur 2, Hussain Abdulaziz Abraham 2, Mukhamadiev A.A. 1, Sabirzhanov A.N. 1, Karibullina F.R. 1, Vaseneva N.A. 1.

1 Kazan state power engineering university, Center for energy-saving equipment and technological innovation, Kazan, Russia, radaev_neftianik@mail.ru
2 University of Technology – Department of Electromechanical Engineering, Iraq, 50110@uotechnology.edu.iq, 50278@uotechnology.edu.iq, 50008@uotechnology.edu.iq

Abstract. An experimental setup was created to study the process of oil displacement by supercritical CO2 and fringes of supercritical CO2 and water from the model of homogeneous and inhomogeneous formation of different degrees of water saturation. The process of multicomponent filtration of oil-water-supercritical CO2 systems at 333 K isotherm in the pressure range of up to 14 MPa was studied at the experimental plant. The new data, the oil displacement efficiency of supercritical CO2 from a homogeneous porous medium with water content of 65% and rims supercritical CO2, and water from homogeneous porous medium with a water cut of 25%. The results showed that the use of supercritical CO2 in the filtration processes of multicomponent reservoir systems allows further displacement of oil from the watered porous medium.

Keywords: Supercritical fluid, multicomponent filtration, watered porous medium, fringing of supercritical CO2 and water, oil displacement coefficient, residual water, and oil saturation.

1. Introduction

The main share of oil currently, usually (more than 50%) and sometimes (about 85%), belongs to the category of hard to recover [1]. These include high-viscosity oils, oils confined to high-water reservoirs, and low-permeability reservoirs. The development of this kind of oil using secondary methods to increase oil recovery is difficult due to the presence of threshold restrictions. To overcome the threshold limits of reservoir oil viscosity, permeability, and degree of water-flooding, it is proposed that oil reservoirs use supercritical fluids extraction (SFE) SC-CO2. Its use meets the new licensing requirements coefficient of oil displacement, which should be more than 25%, and disposes large industrial carbon emissions.
2-Theoretical equations used

The thermo-physical properties of “oil-water-SC CO2” systems (heat capacity and thermal conductivity) are determined in accordance with the methods given in [10–16]. In accordance with [16], we assume that the thermos-physical properties of such systems obey the Neumann–Kopp additively rule. The heat capacity of the system is determined by the following equation [16]:

\[ C_p^e = \sum_{i=1}^{n} C_{pi} \left( \frac{m_i}{m_1 + m_n} \right) \]  

(1)

\( C_1 \ldots C_n \) is heat capacity of dry rock, oil, respectively, \( n \) CO2;

\( m_1 \ldots m_n \) is oil, water, and CO2, respectively, determined at a known porosity value of the rock.

Since the heat capacity of the rock at pressures up to 100 MPa practically does not depend on the pressure, we consider it constant.

The heat capacity of oil is determined by the equation [10]. For paraffin hydrocarbons,

\[ C_p (P, T) = 1,268 + 1,3358 - \frac{\pi}{10} (1,256 \cdot \tau - 0,087) \]  

(2)

\( \tau = \frac{T}{T_{sp}} \), \( \pi = \frac{P}{P_{sp}} \) - Critical temperature and pressure

For aromatic hydrocarbons,

\[ C(P, T) = \frac{A}{\rho(P, T)} \]  

(3)

Where:

\[ A = 1,7 - B \cdot n_e \]  

(4)

\( n_e \) is the number of carbon atoms;

\( B \) is the constant value, \( B = 2,2 \cdot 10^{-3} \) for aromatic hydrocarbons;

\( \rho(P, T) \) is the oil density at appropriate pressure and temperature.

The density of oil at high state parameters is determined as follows [11]:

\[ \rho_n (P, T) = \rho_n + \Delta \rho_n \]  

(5)

Where:

\[ \rho_n = \rho_f \cdot e^{F(1,84410^{-3})} \]
\[ \rho_T = \rho_{293} - (1.83 - 0.0013 \cdot \rho_{293}) \cdot (T - 293) \] is the correction of oil density value for temperature;

\[ \rho_n^{293} = \frac{\rho_n + 1.83 \cdot (T - 293)}{1 + 0.00132 \cdot (T - 293)} \]

\[ \Delta \rho_n = [1.87 \cdot [1 + 1.543 \cdot (P_{nuc} - 0.1)] - 1.54 \cdot 10^{-3} \cdot \rho_n^{293}] \cdot (P - P_{nuc}) \] is the correction of oil density value for pressure. The heat capacity of carbon dioxide is determined in accordance with [12].

The thermal conductivity of the “rock-oil-SC CO2” system is also determined by the Neumann–Kopp rule in accordance with [13]. Therefore, the equation takes the following form:

\[ \lambda_p = \sum_{i=1}^{n} \lambda_{p_i} \left( \frac{m_i}{m_1 + m_n} \right) \] (6)

The thermal conductivity of Sandstone is determined by the equation [14]:

\[ \lambda_{sh}(P,T) = C(P) \cdot T^{n(P)} \] (7)

Where

\( C(P) \) and \( T^{n(P)} \) is the values determined from the table in accordance with pressure and temperature.

The thermal conductivity of oils is determined by the equation [15]:

\[ \lambda_{p,T} = [0.148 + 7 \cdot 10^{-4} \cdot (P - P_0)] \cdot \frac{0.689}{\sqrt{T}} \] (8)

The thermal conductivity of carbon dioxide at high state parameters is determined in accordance with [12]. The thermal conductivity and heat capacity of water is determined by known methods [17,18].

3-Experimental system description

The existing experimental stands used for the study of the processes of oil displacement by various displacing agents does not fully meet the requirements [2] for studies of oil displacement by supercritical fluid systems of the moist layer, rims of supercritical CO2 and water, as well as studies of the process of displacement of oil from heterogeneous reservoirs [2], and existing experimental setup [3,4] has been upgraded. The scheme of the modernized experimental installation is shown in Fig. 1.

![Fig.1. Scheme of the experimental stand for the study of the process of oil displacement using supercritical fluid systems.](image-url)
1: reservoir model; 2: feed tank with water; 3: feed tank with oil; 4: collection of oil and emulsions; 5: receiving capacity of gases; 6: receiving capacity of oil; 7: Bunsen flask; 8: gas cylinder; 9: high pressure pump for pumping water or oil; 10: high pressure pump for pumping liquid carbon dioxide; 11: vacuum pump; 12: water flowmeter; 13: oil flowmeter; 14, 15: CO2 flowmeters 16–19: pressure gauges; 20: separator; 21: filter; 22: cryotherapy thermostat; 23: thermostat heating; 24–30, 32: shut-off valves, 31: mixer (high-pressure vessel); 32: back pressure regulator (BPR). Systems and units: I - reservoir model, II - water injection unit, III - CO2 injection unit, IV - oil and water saturation system, V - supercritical carbon dioxide and water fringe unit, VI - pressure gradient measurement unit, VII - back pressure and sampling unit.

The experimental stand consists of the following systems and units: reservoir models; reservoir model watering systems under reservoir conditions; supercritical fluid systems injection systems; sampling and analysis systems. The watering process is carried out by means of system II, consisting of a system of high-pressure pumps, feed vessels with oil and water and a thermostatic system, which provides the watering of the reservoir model at reservoir temperatures and pressures with a temperature measurement error of 0.5 °C, pressure up to 0.5 ATM.

The installation allows to carry out studies of the process of displacement of oil, CO2 and water from models of homogeneous and heterogeneous formation with a degree of water cut of more than 90% by supercritical fluid systems in the range of pressures up to 20 MPa and temperatures up to 100 °C.

4-Results and discussions

The main conclusions from the results of the work on the displacement of oil by supercritical CO2 from the model of an un-watered oil reservoir are the following: First, the increase in the viscosity of the model oil in the experiments – transformer oil from 9 to 18 MPa * s – did not lead to a decrease in displaced oil ratio (DOR) within the error of the experiment. Second, the main mechanism of increasing oil losses in experiments with transformer oil is the dissolution of supercritical CO2 in the oil, the approximation of the filtration regime to the mixing one and the increase in the mobility of gas-saturated transformer oil. Third, the simultaneous increase in temperature and pressure acts in opposite directions, which leads to immutability within the error of the DOR experiment: the decrease in solubility with increasing temperature is compensated by its increasing pressure. In addition, an important conclusion from the results is that the final DOR in these experiments did not exceed 20%. The reason for this phenomenon is micro-breaks of carbon dioxide during the entire time of the experiment, violating the mixing regime of the flow of “oil-supercritical carbon dioxide” systems, determined by a decrease in the temperature of the carbon dioxide coming out of the model reservoir.

Results of the studies on the watered reservoir are shown in Fig. 2 and 3. Oil displacement was carried out from the 65% water cut reservoir model.
Fig. 2. The results of the oil displacement process studies from the model with 65% water cut by supercritical CO2 in the pressure range of 8–14 MPa, at isotherms 333 k.

Fig. 3. The results of the oil displacement process studies from the model with 65% water cut by supercritical CO2 in the pressure range of 8–14 MPa, at isotherms 313 k.

At the same time, the values of the oil displacement coefficients significantly exceeded those obtained in [5-8], which corresponds with the modern ideas about the high efficiency of supercritical fluid systems when injected into highly watered oil formations [9], the oil displacement coefficient at pressures of 10 and 12 MPa did not differ within the experimental error. However, as in the experiments on non-watered formations, the required amount of supercritical carbon dioxide at higher pressure was less: at a pressure of 10 MPa, 1.0 pumped pore volume was injected. Supercritical CO2, at a pressure of 12 MPa, about 0.8 pumped pore volume to achieve the same DOR within the error of the experiment (as shown in Fig. 4).

Fig. 4. Value of residual oil saturation in experiments on non-watered formations within the error of the experiment.
The nature of the experimental curves is also the same, although the current values of DOR at a pressure of 12 MPa are formed at lower costs of the displacing agent, which ultimately leads to a total smaller volume of carbon dioxide expended. The mechanism of this kind of displacement processes according to modern ideas is that when supercritical CO2 is dissolved in oil, its dynamic viscosity decreases; when dissolved in water, the viscosity of water increases. Due to these processes, the viscosity of the displacing and displacing agent converges, leading to the alignment of the displacement front. It was found that throughout the studied pressure range, the increase in the oil displacement coefficient was the same within the error of the experiment, 9–10%; however, the required volume of injection of SFE SC-CO2 is different and decreases with increasing pressure. At a pressure of 10 MPa, more than 3 pumped pore volume of SFE, SC-CO2 was required to be pumped into the reservoir model; at 14 MPa, this volume decreased to about 1.5–2 pumped pore volume. The experiments also revealed a significant decrease in residual oil and water saturation during injection of supercritical CO2 and fringes of supercritical CO2 and water. The values of residual oil saturation when oil is displaced by supercritical CO2 and fringes of supercritical CO2 and water are shown in Fig.5 and 6, respectively.

![Graph showing the value of residual oil saturation of a homogeneous porous medium during injection of supercritical CO2 into a watered formation](image)

**Fig.5.** The value of residual oil saturation of a homogeneous porous medium during injection of supercritical CO2 into a watered formation
Fig 6. Value of residual oil saturation of homogeneous porous medium during injection of supercritical CO2 fringes and water.

5-Conclusions

The water saturation decreased very significantly, not less than 10 percent or more, because each measurement of the volume of displaced oil was marked by an exit from the reservoir of water during the experiment. It was found that the pressure change did not lead to a significant increase or decrease in the volume of displaced water within the error of the experiment, i.e., at a pressure of 14 MPa, the final volume of displaced water was approximately the same as at 8, 10, and 12 MPa, although its current value changed.

Three points are presented as follows:

1. The use of supercritical CO2 allows to significantly reduce the value of residual oil saturation of a homogeneous watered porous medium in a wide range of changes in temperatures and pressures of carbon dioxide injection.

2. Supercritical CO2 is the optimal agent for oil displacement from highly watered porous media and supercritical CO2 and water fringes for low-watered media.

3. An increase in the CO2 injection pressure at supercritical state parameters leads to an increase in the value of the displaced oil at all studied isotherms.

6-References:

[1] Muslimov R.Kh. Fundamental problems of the Russian oil industry and ways of transition to innovative development / R.Kh. Muslimov // Horizontal wells and hydraulic fracturing in improving the efficiency of oil field development: Materials of a scientific and practical conference. - Kazan: Slovo Publishing House, 2017.-320s.

[2] Gazizov A.A. Enhanced oil recovery in heterogeneous formations at a late stage of development, 2002.- 640 s.

[3] Radaev A.V. An experimental setup for studying the process of water-gas exposure during the displacement of viscous oils / I.A. Kondratiev, N.R. Batrakov, A.V. Radaev, R.R. Galimzyanov, A.A.
Mukhamadiev, A.N. Sabirzyanov // Bulletin of Kazan Technological University, 2013.- T.6.-№ 6.- P. 199-200;

[4] Effect of Thermobaric Conditions in a Uniform Bed on the Displacement of Low Viscosity Oil by Supercritical Carbon Dioxide / A. V. Radaev *, N. R. Batrakov, A. A. Mukhamadiev, and A. N. Sabirzyanov Russian Journal of Physical Chemistry B, 2009, Vol. 3, No. 8, pp. 1134–1139

[5] Radaev A.V. The influence of thermobaric conditions in a homogeneous reservoir on the displacement of low-viscosity oil by supercritical carbon dioxide / A.V. Radaev, N.R. Batrakov, A.A. Mukhamadiev, A.N. Sabirzyanov // Supercritical fluids: theory and practice. - M: Nauka, 2009.-T.4.- No. 3.- S. 7-15;

[6] Radaev A.V. Investigation of the process of oil displacement by supercritical CO2 on a terrigenous reservoir model / N.R. Batrakov, I.D. Zakiev, R.R. Galimzyanov, A.V. Radaev, A.B. Kuzmin, A.A. Mukhamadiev, A.N. Sabirzyanov // Scientific session of KSTU, Kazan, 2014;

[7] Radaev A.V. Investigation of the displacement of hard-to-recover oils using supercritical CO2 / I.D., Zakiev A.V. Radaev, N.R. Batrakov // IX International Youth Scientific Conference "Tinchurin Readings." - Kazan, April 23-25, 2014;

[8] Radaev A.V. Investigation of the process of displacing viscous oils from carbonate reservoirs using supercritical CO2 // IX International Youth Scientific Conference “Tinchurinsky Readings.” Kazan, April 23-25, 2014;

[9] Ballint V. The use of carbon dioxide in oil production. M: Nedra, 1977.- p. 240.

[10] Mustafayev R.A. Thermophysical properties of hydrocarbons at high state parameters / R.A. Mustafaev. - M: Energoatomizdat. - 1991, 312 p .;

[11] Brot R.A. Determination of rheophysical parameters of gas-saturated oils / R.A. Brot S.E. Kutukov // Oil and Gas Business, 2005.-s. 2-12;

[12] Altunin V.V. Thermophysical properties of carbon dioxide / V.V. Altunin.- M.: Publishing house of standards, 1975.- 546 p .;