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COMPARISON OF THE OIL RECOVERY BETWEEN WATERFLOODING AND CO₂-EOR METHOD FOR THE JST OIL RESERVOIR**

1. INTRODUCTION

Oil exploitation from the reservoir initially is conducted by primary method that use natural energy of reservoir. Primary method allow for partial recovery of geological resources (30%). Further oil recovery requires the implementation of appropriate methods to support production, secondary methods, involving mainly the physical displacement of oil and third methods, in which additional types of energy aid the process of exploitation [13].

In the case of natural gas reservoirs the use of supportive methods is not as important as the degree of exploitation of the initial geological resources by the primary methods reaches 90%. The use of enhanced recovery methods in the case of oil reservoirs can allow even its two times to increase. This is particularly important because the enhanced oil recovery in this case can be achieved through the use of existing deep and surface infrastructure, which has a significant impact on the final economic indicators [9].

In areas where the reservoirs are well recognized, and the oil exploitation is carried out for a long time, EOR methods increase resources faster than the search for new deposits. In such cases, an increase of recoverable reserves in exploited reservoirs is more important for the industry than the discovery of new reservoirs [11].

The current used tertiary oil recovery methods can be divided into four groups: thermal (steam stimulation, cyclic injection of steam or hot water, in-situ combustion), chemical (injection of polymers, surfactants), injection of gas (miscible solvents, air, nitrogen and CO₂), other methods (microbiological, mechanical and electrical) [14].

Carbon dioxide injection (CO₂-EOR) is one of the methods that can run residual oil, chemically and physically interact with rocks and oil contained in them, creating favorable conditions for increasing oil production [18]. This method has been used from the 1970's, originating in the USA, and then implemented in other countries: Turkey, Canada, Brazil, Hungary, Trinidad [2, 5, 17].

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2. GENERAL CHARACTERISTICS OF THE EOR-METHODS

Enhanced Oil Recovery (EOR) methods allow to increase production from existing oil reservoirs. One way to increase oil recovery is the waterflooding method. Waterflooding is a secondary recovery method widely used in the oil industry implemented with the purpose of increasing additional oil recovery from oil reservoirs. Traditionally the waterflooding projects are implemented by means of injecting water through water injection wells in order to maintain or improve the reservoir pressure and to sweep the oil towards the producer wells (Fig. 1) [10]. The water displaces oil from the pore spaces, but the efficiency of such displacement depends on many factors (e.g. oil viscosity and rock characteristics) [13].

Some of the reasons for the general acceptance of water flooding are as follows [1]:

- water is an efficient agent for displacing oil of light to medium gravity,
- water is relatively easy to inject into oil-bearing formations,
- water is generally available and inexpensive,
- water flooding involves relatively lower capital investment and operating costs that leads to favorable economics.

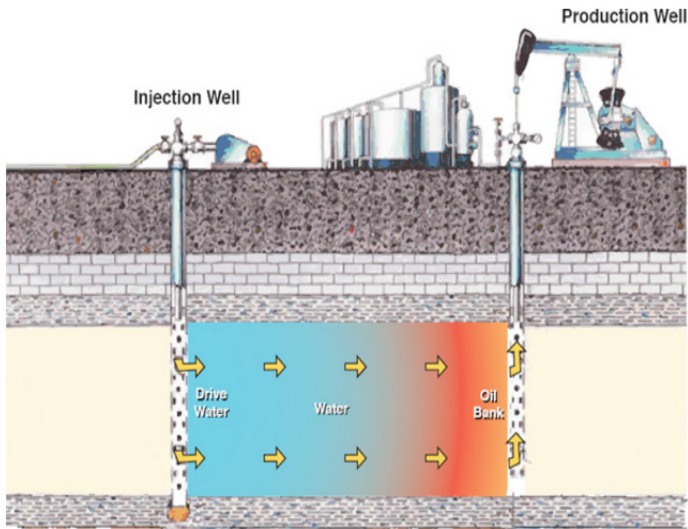


Fig. 1. Diagram illustrating waterflooding method of secondary recovery [7]

Concurrently, the scientific reasons behind waterflooding's success were identified (i.e., that water has viscosity, density, and wetting properties, compared to oil, that affect how efficiently it will displace various oils from reservoir rock). The level of effectiveness of a waterflood depends on the mobility ratio between the oil and water, and the geology of the oil reservoir. Waterflooding is effective because almost all reservoir rocks are either water-wet or mixed-wet. The depositional and diagenetic characteristics of a reservoir control major aspects of the water/oil displacement process. These characteristics can either enhance waterflood performance or have detrimental effects on the WOR as a function of time [13].

Another way to increase oil recovery is the injection of CO₂ into oil reservoirs (CO₂-EOR). Carbon dioxide is injected to the reservoir resulting in the displacement of oil from the pores of the rock (Fig. 2). The main physical phenomena associated with this process are related to the behavior of the mixture of oil and carbon dioxide. These include: reduction of viscosity and density of the oil, evaporation of some components of the oil, reducing the surface tension of CO₂-oil and water-oil, increase of permeability [15, 16].

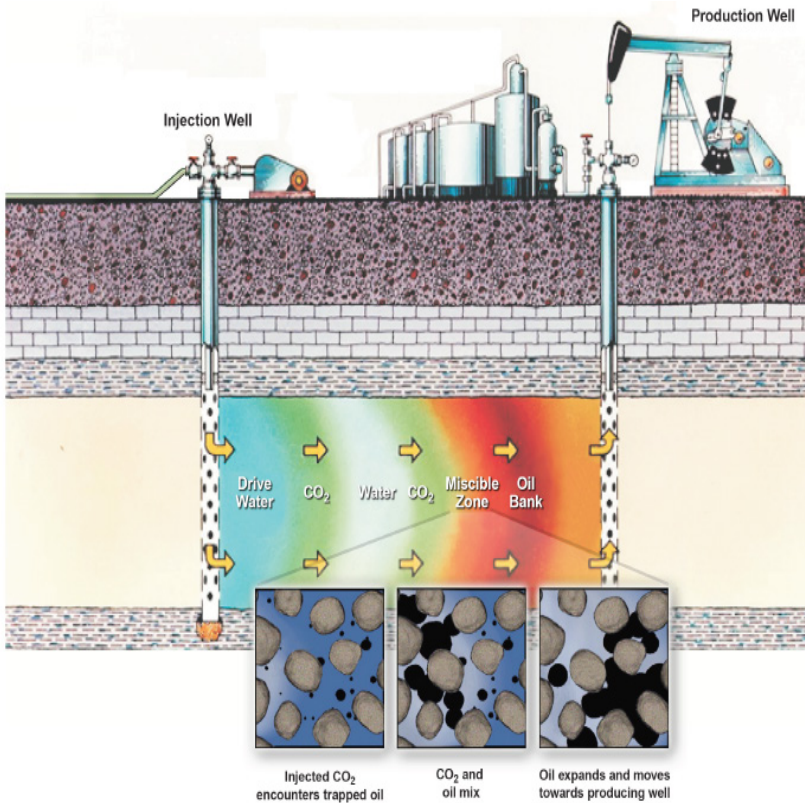


Fig. 2. Enhanced oil recovery through CO₂ injection [7]

Several CO₂ processes have been proposed or used for enhanced oil recovery in the reservoir and/or the laboratory, such as [5, 6]:

- continuous CO₂ gas injection,
- injection of water-CO₂ mixture,
- injection of CO₂ gas or liquid slug followed by continuous water injection,
- CO₂ gas or liquid slug followed by water alternating CO₂ gas injection (WAG),
- huff and puff processes.

Depending on the oil composition, the pressure and the temperature of the reservoir, the carbon dioxide can be mixed together with oil (miscible) or immiscible. Therefore, the

advanced method of exploitation CO₂-EOR is based on two mechanisms: miscible CO₂-EOR and immiscible CO₂-EOR (Tab. 1) [15].

Table 1
Miscible and immiscible CO₂-EOR method [15]

Miscible CO ₂ -EOR method	Immiscible CO ₂ -EOR method
<ul style="list-style-type: none"> – mixing of the oil and CO₂ (depth below of 1200 m, the oil density greater than 870 kg /m³), at the reservoir pressure higher than the minimum miscibility pressure (MMP) – oil with CO₂ forms a single liquid phase – exploited oil mixed with CO₂ (approximately 30% of the injected gas); on the surface of the gas is separated from the oil, compressed and reinjected into the reservoir; the remaining part of the gas is immobilized in the pores of a rock or dissolved in the reservoir fluid – can use the infrastructure already used for injecting water – method is possible to use on the part of the reservoir on a small scale 	<ul style="list-style-type: none"> – there is no mixing of the oil and CO₂ (shallow reservoirs containing heavy oil or low reservoir pressure) – partial dissolution of CO₂ in oil – this method has limited uses mainly due to low economic efficiency; applying large quantities of carbon dioxide and it is necessary drilling of new wells; Additional oil production starts after long-term injection of carbon dioxide – the immiscible method is applied on whole reservoirs and has a limited use on a small scale (part of the reservoir)

Carbon dioxide gas has some key benefits as an injection gas [6]:

- Miscibility is achieved at lower pressures than with hydrocarbon gases.
- Due to its high density, CO₂ has minimum problems of gas overriding. At typical reservoir conditions, CO₂ nearly as heavy as reservoir oil.
- The use of CO₂ for injection releases hydrocarbon gas for alternative uses, e.g. sales.

The Polish oil reservoirs are exploited mostly by primary methods, secondary methods of exploitation were used mainly in the Carpathian Mountains in the years 1932–1987. The most used methods were the injection of air – 13 projects (5 positive), gas injection – 3 projects (all positive), microbiological methods – 8 projects (2 positive) and injection of gas and water – 2 projects positive [15]. Among the secondary methods used so far impact on the Polish oil reservoirs should be mentioned waterflooding in the following reservoirs: Osobnica, Kamień Pomorski and B-3 (Petrobaltic) [9].

3. GEOLOGICAL CHARACTERISTICS OF THE JST OIL RESERVOIR

JSt oil reservoir is located in Podkarpackie Province, in the commune Czarna. The area of the reservoir includes villages: Borowa, Jaźwiny, Róża and Stara Jastrząbka.

The accumulation of oil is conditioned by the anticlinal form extending in the NW-SE direction, which is north-west limited dislocation of the NW-SE direction (Fig. 3). The north-east wing of the anticline is cut off by a fault and stepped dropped by approximately 50 m [3, 8].

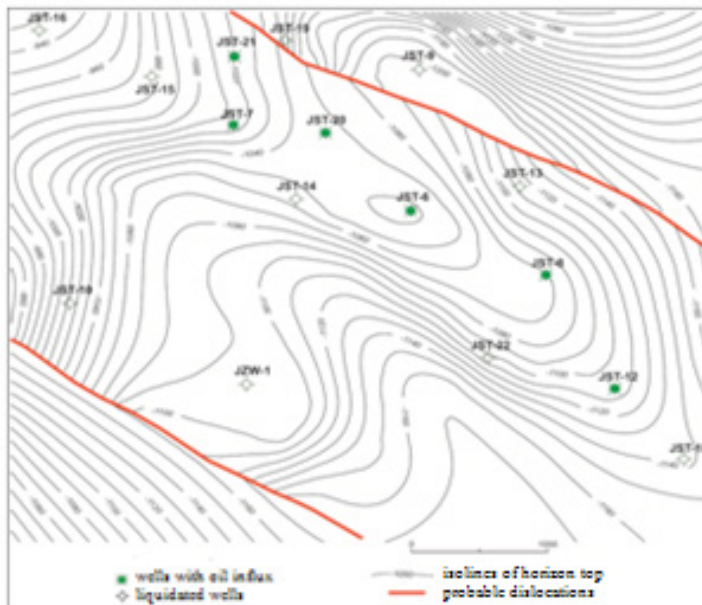


Fig. 3. Map of the top of JSt deposit [3]

Reservoir rocks of the JSt reservoir are the sandstones occurring among carbonates of Upper Cretaceous – Senonian. In the Upper Cretaceous 4 lithological complexes with different reservoir properties separated. On the bottom occur numerous limestones, towards the top there is increasing the share of marls and appear sandstone levels. The levels of sandstone have a wider lateral range, thickness of the order of 2–15 m and favorable reservoir parameters [3].

The useful raw material of the JSt reservoir is crude oil and accompanying natural gas. Crude oil is a light oil with a specific gravity from 0.817 g/cm³ to 0.854 g/cm³ at 20°C. This is medium paraffin oil of low viscosity 3,91–17,0 cSt (1 cSt = 10⁻⁶ m²/s). It has a low boiling temperature of the 52–69°C and relatively high content of the gasoline fraction 23–32% vol. [4, 8]. The geological and petrophysical characteristic of the JSt reservoir are shown in Table 2.

Table 2

The basic properties of the reservoir rock [12]

Reservoir parameters	Values
Reservoir rock stratigraphy	Upper Cretaceous – sandstones with carbonate cement
Type of the main mineral	Crude oil paraffin, paraffin content 6–11%
Reservoir effective thickness [m]	Horizon I: 5–14
Porosity [%]	4–14
Permeability [mD]	Horizon I: 25
Reservoir temperature [K]	Horizon I: 363

Table 2 cont.

Reservoir parameters	Values
Primary pressure [MPa]	18.5
Actual pressure [MPa]	13.78
The primary recoverable oil reserves (thousands of tons)	92
Primary geological oil reserves (thousands of tons)	630
Summary production (thousands of tons)	38.2 (years 1988–2011)

4. SIMULATION OF ENHANCED OIL RECOVERY

The article shows studies of the simulation effectiveness of the use of waterflooding and gasflooding processes for the selected oil reservoir using CO₂ Prophet software. CO₂ Prophet- Water and CO₂ Flood Prediction Software used for modeling water and gas flooding processes for reservoir of hydrocarbons (waterflooding, miscible and immiscible CO₂ injection, CO₂ WAG injection). The simulation is carried out on a model of the reservoir, which may contain up to 10 layers, it consists of three components: solvent – gas, water and oil. The simulation can be performed based on several patterns of the distribution of injection and production wells. The program combines the features of a simulation based on the correlation of analytical and numerical equations [4].

Based on the reservoir parameters, it was established that the reservoir qualifies for the miscible CO₂-EOR method, i.e. has adequate, referred to in the literature values for the following parameters: viscosity, density, oil saturation in pores, the depth and the reservoir pressure. These parameters create adequate physico-chemical conditions for the occurrence of the phenomenon for the mixing of injected carbon dioxide with the oil, which may lead to the greater efficiency of the intensification method (Tab. 3).

Table 3

Summary parameters qualifying the JSt reservoir to use the CO₂-EOR method

Reservoir parameters	Values
Viscosity [N·s/m ²]	0.0133–0.0375
Density [kg/m ³]	843
Saturation [%]	70
Depth [m]	1060–1180
Reservoir pressure [MPa]	13.78

Based on the available reservoir data, a number of input parameters to the program describing a reservoir horizon of JSt reservoir was established. Due to the nature of the reservoir (three reservoir levels, the lack of industrial inflows in two of them) it was decided to only take into account in the simulation the resources defined by the Polish Geological Institute as a balance resources [12]. This avoids the overestimation of the effects of treatments performed on the reservoir.

Table 4

The input data for the J-St reservoir, introduced into the program CO₂-PROPHET

Reservoir parameters	Value
Dykstra-Parsons coefficient	0.7
Reservoir temperature [K]	363
Average reservoir pressure [MPa]	15.17
Minimum Miscibility Pressure (MMP) [MPa]	13.79
Oil viscosity [mPa · s]	3.875
Oil formation volume factor [m ³ /m ³]	1.2
Solution gas – oil ratio [m ³ /m ³]	109
Oil density [kg/m ³]	843
Specific gravity of a gas	0.7
Water viscosity [mPa · s]	0.38
Salinity [ppm]	100000

The author have chosen a classic pattern of distribution of injection and production wells, used on a large scale in the USA, the so-called *five spot pattern*, whose visualization is shown below (Fig. 4).

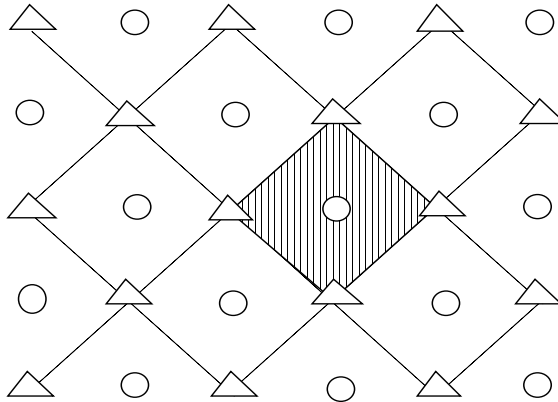


Fig. 4. Pattern of distribution of injection and production wells [4]

The simulation operates on the balance of the oil resources present in the reservoir 20 years ago – this is to compare the simulation results with actual reservoir production in recent years. These resources were estimated at 76,200 tons [12]. In order to evaluate the effect of the waterflooding and CO₂ injection methods, different prognostic variants were made:

- Variant 1: Filling the entire volume of the pore space at a rate of 28000 m³ CO₂/day.
- Variant 2: Filling the entire volume of the pore space using the technique of “Simple WAG” with rate of 28000 m³ CO₂ per day (Water / Gas Ratio = 1).

- Variant 3: Filling the entire volume of the pore space using the technique of “Continuous CO₂” (water injection by approx. ¼ of the process time, followed by injection of CO₂ with rate of 28000 m³ CO₂ per day).
- Variant 4: Filling the entire volume of the pore space using the technique of “Tapered WAG” – CO₂ injection with rate of 28000 m³ CO₂ per day (Water / Gas ratio gradually decreases from 1.25 to 0.5).
- Variant 5: Filling the entire volume of the pore space with water rate responding in variant 2 (150 m³ of water per day).

On the basis of the output data of the program, results of the individual variants of simulations were developed and they are summarized in the graphs below (Fig. 5).

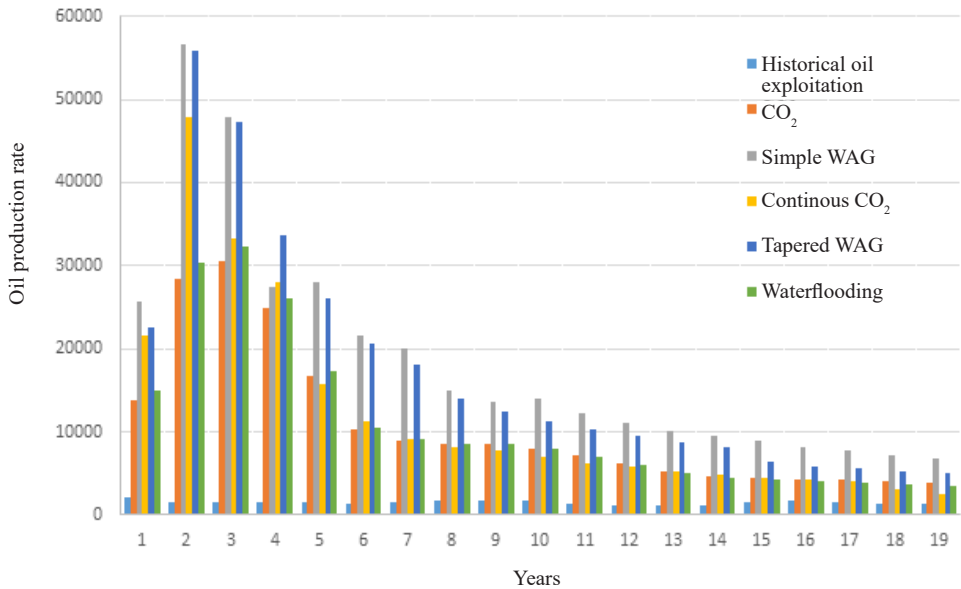


Fig. 5. Oil production from the JSt reservoir for particular variants

The below graph present the recovery factor of remaining balance resources in reservoir exploited during injection processes (Fig. 6).

The graphs clearly show a significant increase of production caused by the injection of fluids into the reservoir – in the case of historical data, in the analyzed period, they exploited approx. 5% of the remaining resources in the reservoir. In the case of the use of injection fluids, there has been a recovery factor of these resources at the level of 36–64%. The best results were obtained for the cyclic injection of carbon dioxide and water (especially for the methods Simple WAG and Tapered WAG). In the case of the injection water alone and the carbon dioxide, identical results were almost reached, but noticeably less than in the case of cyclic injection. The continuous CO₂ injection method proved to be the least effective method of cyclic injection – reported an increased rate of recovery by approx. 5% compared to the continuous injection of carbon dioxide.

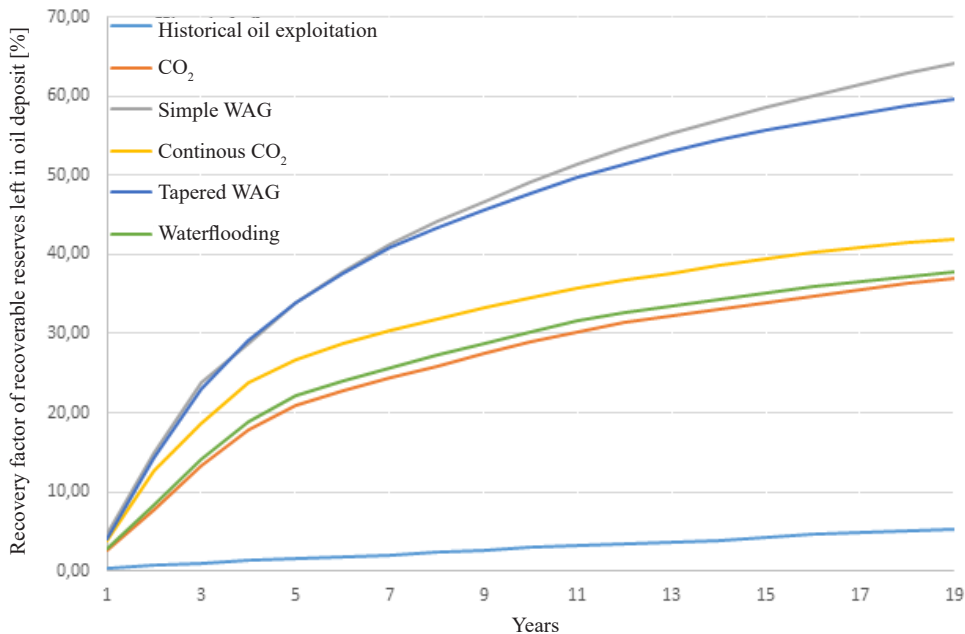


Fig. 6. Oil recovery factor of remaining balance resources left in oil reservoir during injection processes

For all variants the highest production in the first few years after the start of injection was recorded (maximum production was achieved already in the second year of the injection fluids). At the end of the period of injection, oil production approaches to historical values of the reservoir.

5. CONCLUSIONS

Enhanced Oil Recovery methods allow production to increase from existing oil reservoirs. The article presents and describes methods of increase oil recovery. Waterflooding is the most commonly used secondary oil recovery method. This is because water is inexpensive and readily available in large volumes and because water is very effective at substantially increasing oil recovery. Carbon dioxide flooding also is one of effective enhanced oil recovery processes, because injected CO₂ lowers interface tension, causes reductions of oil viscosity, changes in oil and water density and improving formation permeability.

In the paper the authors present the simulation studies of the effectiveness of the use waterflooding and gasflooding processes for the JSt oil reservoir using CO₂ Prophet software. All variants of the simulation were recorded in the highest production in the first few years after the start of injection, maximum production has already been achieved in the second year of injection fluids. At the end of the period of injection, oil production approaches to historical values of the reservoir.

The exceptionally high efficiency of injection methods may be caused by the imperfection of the program (its analytical – numerical character), which make the full representation of the construction of the reservoir impossible – the shape of the reservoir traps, occurring inhomogeneities and discontinuities. In fact, the resulting increase in oil production could be smaller.

In summary, the performed simulations confirmed that the JSt reservoir is qualified to use the secondary (waterflooding) and tertiary (CO₂-EOR) methods. Their use leads to a significant increase in hydrocarbon production. It also confirmed the ability to optimize treatments of CO₂ injection, through the use of cyclic injection, in order to maximize the oil recovery coefficient.

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