Croatian Oil Fields EOR Potential

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PRELIMINARY COMMUNICATION

Every oil reservoir is determined by many characteristics, such as: reservoir pressure and temperature, reservoir rock properties, crude oil type, its composition, density and viscosity. The consequence of such a large number of variable properties is great diversity of oil reservoirs. Therefore, not all oil reservoirs are suitable for EOR and not every EOR method is applicable to a certain oil reservoir.

The process of initial oil field EOR screening involves the inventory of all significant reservoir and fluid properties and their comparison with the applicability criteria of various EOR methods. This is the first step in defining the EOR potential in a broader area, and it will quickly highlight all promising fields / reservoirs suitable for EOR implementation while removing focus from unsuitable candidates.

This initial screening was conducted on all major oil fields in Croatia. The key properties for all reservoirs containing more than 1x10^6 m^3 initial oil in place (and exceptionally, several smaller reservoirs) were listed and compared to published empirical criteria for applicability of EOR methods.

This paper presents the results of the initial EOR screening for Croatian oil fields. It further includes the total EOR potential in Croatia and applicable EOR methods.

Key words: initial EOR screening, increased recovery, Croatian EOR potential

1. Introduction

EOR (Enhanced Oil Recovery) is the process of enhancing oil recovery by injecting fluids that originally are not in the reservoir. Enhanced recovery is the result of manipulation of chemical and physical interactions within oil reservoirs in a way that enhances favorable recovery conditions.

Conventional oil production methods averagely recover around 35% of initial oil in place. This means that at the moment of production drop on a certain field, around 65% of initial oil in place remains in the reservoir. This is huge and appealing goal for EOR methods application as they have potential to change the categorization of unrecoverable oil reserves into balance reserves.

To extend the production period of depleted or unprofitable oil fields, EOR methods are often used in tertiary phase of oil reservoirs exploitation, after the production with conventional and less risky methods, like primary production and flooding, becomes unprofitable due to small well productivity and high water share in production. However it can also be used during secondary exploitation phase instead of flooding or in primary exploitation phase in heavy oil reservoirs.

All EOR methods include injecting of a certain fluid into target reservoir. Total efficiency of any of the fluid injection processes into reservoir, aimed to oil displacement, is defined by product of macroscopic and microscopic displacement efficiency.

EOR is based on three basic mechanisms:

1. Reduction of surface tension between reservoir oil and injected (displacing) fluid aimed to increase capillary number and to increase microscopic displacement efficiency.
2. Decreasing the ratio of fluid mobility to increase macroscopic efficiency of oil displacement from a reservoir. This is achieved by increasing displacement fluid viscosity, decreasing displacement fluid relative permeability and by decreasing the viscosity of oil that is displaced.
3. Reduction of oil viscosity, i.e. increasing oil mobility by bringing heat energy into the reservoir, to enable oil flow into production wells.

EOR methods are defined by fluid type that is injected in target reservoir. They can be placed in four categories:

1. Methods of gas injection in miscible conditions
   - they include methods of injecting nitrogen / smoke gases, hydrocarbon gas and CO_2
   - they lean on reduction or annulation of surface tension between reservoir oil and injected fluids
2. Chemical methods
   - they include methods of injecting polymer and micellar-polymer and alkali solutions
   - they lean on adding one or more chemical additives to injection fluid to achieve reduction or annulation of surface tension between reservoir oil and displacement fluid and/or reduction of mobility ratio among them.
3. Thermal methods
   - they include methods of cyclic and continuous steam injection and oil combustion in the reservoir.
   - they lean on heating of reservoir oil by introducing heat energy in the reservoir reducing its viscosity and easing the flow through reservoir.
4. Microbial methods
   - they lean on injection of bio-organisms into reservoir, which react with reservoir fluids by generating sufractants.

EOR projects can be highly profitable and only major oil companies, with significant investment and human potential can undertake them. Regarding EOR implementation, INA has undertaken certain activities on its oil fields. After detailed laboratory research regarding oil displacement with CO_2 in the period between 1978 and 1991, and successful pilot project of CO_2 injection on Ivanić oil field between 2003 and 2006, over the last three years, all necessary plants and facilities for EOR implementation on Ivanić and Žutica fields were constructed (at the moment this paper is written, trial CO_2 injection on Ivanić field is already being performed).

Compressor station for CO_2 was constructed on CPS Molve with three compressor units. Within Ethane plant, a compressor station for CO_2, its liquefaction system with cooling tower and heat exchanger and pump station were constructed. Membrane separator for CO_2 extraction from produced gas was constructed on Žutica field compressor station. Considerable amount was invested in surface and underground well completion for CO_2 injection into reservoirs and oil production. Also over 50 km of pipeline, power cables and optical cables were laid for carbon dioxide injection from compressor station on Ethane plant to CO_2 injection wells on Ivanić and Žutica fields. Over 500 million kuna shall be invested for complete EOR project only until 2015.

2. Empiric Criteria for EOR Methods Application

EOR methods have been applied since 1959. Until today, over 600 projects were applied and many laboratory researches were performed for the purpose of better understanding of EOR mechanism. Due to high quantity of acquired theoretical knowledge and practical experience, EOR can be considered a mature technology. Considerable number of published papers in oil industry is about criteria of EOR applicability. One of the most quoted criteria groups were established by Martin Taber (Taber et.al., 1996). Taber's criteria are completely empirical, based on real projects that were implemented in the world and that represent summary of reservoir and fluid characteristics of successful EOR projects. They can be understood as suitable reservoir and reservoir fluids characteristic for certain EOR methods.

For analysis purposes in this paper, Taber criteria set has been modified and supplied by additional reservoir and fluid characteristics. The adopted criteria consist of 11 EOR methods, presented in tables with 13 reservoir and reservoir fluid characteristics.

The mentioned reservoir and fluid characteristics are the following:

- oil density in surface conditions
- current oil viscosity in reservoir
- oil content (dominant set of hydrocarbon fractions)
- current oil saturation in reservoir
- reservoir lithology (sandstone, sand, carbonate, breccia/conglomerate)
- effective reservoir thickness
- average absolute reservoir permeability
- average reservoir porosity
- reservoir depth
- reservoir temperature
- reservoir dip (more or less than 15°)
- existence and type of reservoir heterogeneity (homogenous, marl intercalations, secondary porosity)
- formation water salinity

View showing reservoir and fluid characteristics with EOR methods is given in Table 1.

Generally speaking of favorable reservoir conditions for certain EOR methods, the process of injecting miscible gases requires light oil with low viscosity. Such oils usually contain high share of light and medium hydrocarbons that are necessary for achieving miscible conditions for injected and reservoir fluid through multiple contacts (dynamic miscibility). More suitable are thinner reservoirs and/or reservoirs with higher dip, due to lower possibility of gravitational segregation of injected gas and reservoir oil, which adversely affects macroscopic efficiency of displacement. At the same time, reservoir has to be deep enough that minimal miscible pressure can be achieved.

Chemical methods require lower reservoir temperatures, to avoid thermal polymer degradation. They require sandstone reservoir, to reduce surfactant adsorption and adsorption of other expensive chemicals on the rock and the permeability should be high enough to enable sufficient injection capacity. Chemical methods function also with moderately heavy oils and with oils with higher viscosity. However it is still necessary to avoid unfavorable mobility ratio between displacement and displacing fluid.

When thermal methods are applied, the most important is to have high reservoir oil saturation, especially with steam injection method, where a considerable amount of produced oil on surface is used as fuel for steam production. At the same time, the reservoir should be shallower, as heat energy is lost within injection wells bores. When the method of oil combustion in reservoir is used, it is important that the reservoir is thicker to reduce heat loss in neighboring formations. All thermal methods are applied only in reservoirs with high viscose oils, as at original reservoir temperature they have difficulties passing through the reservoir and are slowly flowing into well preventing efficient production without introducing additional heat energy into the reservoir aimed to reduce oil viscosity.

Expressed heterogeneity and naturally cracked reservoirs are not good for all types of EOR methods and for some methods they represent elimination criterion.

Criteria from Table 1 are only directives for selection of optimal EOR method and not strict rules. They are very useful for quick and cheap quality exam of great number of reservoirs - candidates for EOR, before a decision is made on preparation of expensive reservoir studies and numerical models.

3. Technical selection of EOR methods for application on Croatian oil fields

This screening includes all significant oil accumulations in Croatia except the previously mentioned Ivanić and Žutica oil fields. All hydrodynamic units (HDU) with oil in place higher than $1x10^6$ m^3 are included (only exceptionally several smaller reservoirs are included). For all mentioned HDU, 13 key reservoir and reservoir fluids

Table 1. Criteria on EOR methods application

Favorable reservoir properties and reservoir characteristics	EOR methods: Nitrogen and flue gas miscible flooding	Hydrocarbon miscible flooding	CO_2 miscible flooding	Immiscible gas injection	Micellar polymer, Alkaline-surfactant-polymer and alkaline flooding	Polymer flooding	In situ combustion	Cyclic steam stimulation (huff and puff)	Steam flooding	SAGD (steam assisted gravity drainage)	MEOR (microbial enhanced oil recovery)
Stock tank oil density (kg/m^3)	< 850; average 790	< 916; average 820	< 922; average 845	< 986; average 918	< 934; average 850	< 966; average 896	< 1 000; average 959	< 1014; average 968	< 1014; average 968	< 1014; average 968	< 950; average 875
Current oil viscosity In situ (mPa*s)	< 0,4; average 0,2	< 3; average 0,5	< 10; average 1,5	< 600; average 65	< 35; average 13	< 150; >10	< 5 000; average 1 200	< 200 000; average 4 700	< 200 000; average 4 700	< 200 000; average 4 700	< 50
Oil composition	High percent of C_1-C_7	High percent of C_2-C_7	High percent of C_5-C_{12}	Not critical	Some organic acids	Not critical	High percent of C_{10}+; some asphaltic components	Not critical	Not critical	Not critical	Not critical
Current oil saturation (% pore volume)	> 40; average 78	> 30; average 71	> 30; average 46	> 45; average 70	> 35; average 53	> 50; average 64	> 50; average 67	> 40; average 66	> 40; average 66	> 40; average 66	> 50; average 60
Formation type	Sandstone or carbonate	Sandstone or carbonate	Sandstone or carbonate	Not critical	Sandstone	Sandstone	Sandstone, sand or carbonate	Sandstone or sand	Sandstone or sand	Sandstone or sand	Sandstone
Net pay (m)	< 3, unless dipping reservoir	< 3, unless dipping reservoir	Wide range	Not critical	Not critical	Not critical	> 3	> 6	> 6	> 6	Not critical
Average absolute permeability (mD)	Not critical	Not critical	Not critical	Not critical	> 10; average 450	> 10; average 800	> 50	> 100; average 2 700	> 100; average 2 700	> 100; average 2 700	> 75; average 190
Average porosity (%)	> 11; average 18	> 11; average 18	> 11; average 18	> 11; average 20	> 15; average 20	> 15; average 20	> 15	> 20	> 20	> 20	> 12; average 19
Reservoir depth (m)	> 1830	> 1220	> 760	> 550	< 2750; average 1000	< 2750	< 3500; average 1070	< 1220; average 460	< 1220; average 460	< 1220; average 460	< 1055; average 750
Reservoir temperature (°C)	Not critical	< 121	< 121	Not critical	< 93; average 52	< 93; average 60	> 38; average 57	Not critical	Not critical	Not critical	< 75
Dipping reservoir > 15 °	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Not critical	Not critical	Not critical	Not critical	Not critical
Reservoir heterogeneity	Fractures are unfavorable	Fractures are unfavorable	Fractures are unfavorable	Fractures are drastically unfavorable	Fractures are drastically unfavorable	Fractures are drastically unfavorable	Fractures are drastically unfavorable	Fractures are unfavorable	Fractures are drastically unfavorable	Clays are drastically unfavorable	Fractures are unfavorable
Water salinity (g/l NaCl)	Not critical	Not critical	Not critical	Not critical	< 100	< 100	Not critical	Not critical	Not critical	Not critical	< 100

Table 2. Comparison of oil reservoir A_1 characteristics in tectonic block 3 on Stružec field with EOR methods criteria

Stock tank oil density	831	kg/m^3
Oil viscosity	0,904	mPa*s
Oil saturation	38,1	%
Oil composition	High % C_5-C_{12}	
Special components	No	

Formation type	Sandstone	
Reservoir depth	820	m
Reservoir temperature	60,2	°C
Permeability	50	mD
Porosity	28,6	%

Net pay	16,2	m
Dipping reservoir > 15 °	Yes	
Reservoir heterogeneity	No	
Water salinity	8,13	g/l NaCl

Favorable reservoir properties and reservoir characteristics	EOR methods: Nitrogen and flue gas miscible flooding	Hydrocarbon miscible flooding	CO_2 miscible flooding	Immiscible gas injection	Micellar polymer, Alkaline-surfactant-polymer and alkaline flooding	Polymer flooding	In situ combustion	Cyclic steam stimulation (huff and puff)	Steam flooding	SAGD (steam assisted gravity drainage)	MEOR (microbial enhanced oil recovery)
Stock tank oil density (kg/m^3)	< 850; average 790	< 916; average 820	< 922; average 845	< 986; average 918	< 934; average 850	< 966; average 896	< 1 000; average 959	< 1014; average 968	< 1014; average 968	< 1014; average 968	< 950; average 875
Current oil viscosity In situ (mPa*s)	< 0,4; average 0,2	< 3; average 0,5	< 10; average 1,5	< 600; average 65	< 35; average 13	< 150; >10	< 5 000; average 1 200	< 200 000; average 4 700		< 200 000; average 4 700	< 50
Oil composition	High percent of C_1-C_7	High percent of C_2-C_7	High percent of C_5-C_{12}	Not critical	Some organic acids	Not critical	High percent of C_{10}+; some asphaltic components	Not critical	Not critical	Not critical	Not critical
Current oil saturation (% pore volume)	> 40; average 78	> 30; average 71	> 30; average 46	> 45; average 70	> 35; average 53	> 50; average 64	> 50; average 67	> 40; average 66	> 40; average 66	> 40; average 66	> 50; average 60
Formation type	Sandstone or carbonate	Sandstone or carbonate	Sandstone or carbonate	Not critical	Sandstone	Sandstone	Sandstone, sand or carbonate	Sandstone or sand	Sandstone or sand	Sandstone or sand	Sandstone
Net pay (m)	< 3, unless dipping reservoir	< 3, unless dipping reservoir	Wide range	Not critical	Not critical	Not critical	> 3	> 6	> 6	> 6	Not critical
Average absolute permeability (mD)	Not critical	Not critical	Not critical	Not critical	> 10; average 450	> 10; average 800	> 50	> 100; average 2 700	> 100; average 2 700	> 100; average 2 700	> 75; average 190
Average porosity (%)	> 11; average 18	> 11; average 18	> 11; average 18	> 11; average 20	> 15; average 20	> 15; average 20	> 15	> 20	> 20	> 20	> 12; average 19
Reservoir depth (m)	> 1830	> 1220	> 760	> 550	< 2750; average 1000	< 2750	< 3500; average 1070	< 1220; average 460	< 1220; average 460	< 1220; average 460	< 1055; average 750
Reservoir temperature (°C)	Not critical	< 121	< 121	Not critical	< 93; average 52	< 93; average 60	> 38; average 57	Not critical	Not critical	Not critical	< 75
Dipping reservoir > 15 °	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Favorable to maximize gravity drainage	Not critical	Not critical	Not critical	Not critical	Not critical
Reservoir heterogeneity	Fractures are unfavorable	Fractures are unfavorable	Fractures are unfavorable	Fractures are drastically unfavorable	Fractures are drastically unfavorable	Fractures are drastically unfavorable	Fractures are drastically unfavorable	Fractures are unfavorable	Fractures are drastically unfavorable	Clays are drastically unfavorable	Fractures are unfavorable
Water salinity (g/l NaCl)	Not critical	Not critical	Not critical	Not critical	< 100	< 100	Not critical	Not critical	Not critical	Not critical	< 100

characteristics are listed that were afterwards compared to applicability criteria for each EOR method. If a certain reservoir or fluid characteristic was within the value range of a certain EOR method, then the cell at the crossing of characteristics and method was colored red. When a certain reservoir or fluid characteristic was at the margin of criteria value range defined by EOR method, then the cell at crossing was colored yellow. In case the characteristic was out of criteria value range, then the cell at crossing was colored red. For this initial screening, a Visual Basic program in Excel was made that strongly automatized the whole process. The example of comparing A_1 oil res-

Table 3. Summary result of EOR methods applicability technical inspection on oil fields in West Croatia production regions

EOR object (oil field, reservoir)	EOR methods							Original oil in place, 10^6 m^3	Current oil recovery, %
	Hydrocarbon Miscible Flooding	CO_2 Miscible Flooding	Immiscible Gas Injection	Micellar Polymer, Alkaline-Surfactant-Polymer and Alkaline Flooding	Polymer Flooding	Cyclic Steam Stimulation (huff and puff)	Steam Flooding		
Bunjani oil field, reservoirs I+II, III, IV, V	**reservoir depth** (oil properties, net pay, reservoir porosity)	reservoir porosity, reservoir depth	oil saturation, reservoir porosity	**reservoir permeability and porosity**	**reservoir permeability and porosity**	**reservoir permeability and porosity** (oil properties)	**reservoir permeability and porosity** (oil properties)	4,8	13,0
Dugo Selo oil field, reservoir D	**reservoir depth** (oil properties, oil saturation)	optimal	**oil saturation**	oil saturation, reservoir permeability	**oil saturationm** (reservoir permeability)	**reservoir permeability** (oil properties, oil saturation, reservoir depth)	**reservoir permeability** (oil properties, oil saturation, reservoir depth)	2,9	36,5
Dugo Selo oil field, reservoir E	**reservoir depth** (oil properties, oil saturation)	optimal	**oil saturation**	oil saturation, reservoir permeability, reservoir temperature	**oil saturationm** (reservoir permeability, reservoir temperature)	**oil saturation, reservoir permeability** (oil properties, reservoir depth)	**oil saturation, reservoir permeability** (oil properties, reservoir depth)	1,9	36,5
Kloštar oil field, I sand series, HDJ X	**reservoir depth** (oil properties, oil saturation)	optimal	**oil saturation**	**reservoir permeability** (oil saturation)	**oil saturation, reservoir permeability**	**oil saturation, reservoir permeability** (oil properties, reservoir depth)	**oil saturation, reservoir permeability** (oil properties, reservoir depth)	2,8	43,6
Kloštar oil field, reservoirs α, β, HDJ XXI	oil properties, oil saturation	optimal	oil saturation	reservoir permeability , reservoir temperature	oil viscosity, oil saturation, reservoir permeability, reservoir temperature	**reservoir permeability, reservoir depth** (oil properties, oil saturation)	**reservoir permeability, reservoir depth** (oil properties, oil saturation)	2,9	26,0
Kloštar oil field, reservoirs Pn, Ms, Tg, HDJ XXIV	oil properties, oil saturation	optimal	**oil saturation**	oil saturation, reservoir permeability , reservoir temperature	oil viscosity, oil saturation, reservoir permeability, reservoir temperature	**reservoir permeability, reservoir depth** (oil properties, oil saturation)	**reservoir permeability, reservoir depth** (oil properties, oil saturation)	5,5	24,6
Kloštar oil field, reservoirs Pn, Ms, Tg, HDJ XXVI	oil properties, oil saturation	optimal	oil saturation	oil saturation, reservoir permeability , reservoir temperature	oil viscosity, oil saturation, reservoir permeability, reservoir temperature	**reservoir permeability, reservoir depth** (oil properties, oil saturation)	**reservoir permeability, reservoir depth** (oil properties, oil saturation)	1,4	11,1
Šumećani oil field	**oil properties, net pay, reservoir depth** (oil saturation)	**oil properties, reservoir depth**	**reservoir depth** (oil properties, oil saturation)	**oil properties** (reservoir permeability)	**oil properties, oil saturation** (reservoir permeability)	oil saturation, reservoir permeability	oil saturation, reservoir permeability	4,4	25,4

Table 4. Summary result of EOR methods applicability technical inspection on oil fields in North Croatia production regions

EOR object (oil field, reservoir)	EOR methods					Original oil in place, 10^6 m^3	Current oil recovery, %
	CO_2 Miscible Flooding	Immiscible Gas Injection	Micellar Polymer, Alkaline-Surfactant-Polymer and Alkaline Flooding	Polymer Flooding	MEOR (Microbial enhanced oil recovery)		
Bilogora oil field reservoir F, block 1	optimal	**oil saturation**	oil saturation, reservoir permeability	**oil saturation** (oil viscosity, reservoir permeability)	**oil saturation, reservoir permeability** (reservoir depth)	3,0	34,1
Bilogora oil field reservoir F_1, block 1	optimal	**oil saturation**	oil saturation, reservoir permeability	**oil saturation** (oil viscosity, reservoir permeability)	**oil saturation, reservoir permeability** (reservoir depth)	1,3	37,4
Jagnjedovac oil field, reservoir α, block IV	**reservoir depth**	**oil saturation**	oil saturation, reservoir permeability	**oil saturation** (oil viscosity, reservoir permeability)	**oil saturation, reservoir permeability**	1,1	18,0
Jagnjedovac oil field, reservoir B, block II	**reservoir depth** (oil properties)	oil saturation	reservoir permeability	oil viscosity, oil saturation, reservoir permeability	oil saturation, reservoir permeability	1,5	11,0
Šandrovac oil field, reservoir E, block 6.6a, HDJ 4	oil saturation	**oil saturation**	oil saturation, reservoir permeability	**oil saturation** (reservoir permeability)	**oil saturation, reservoir permeability**	10,7	40,4
Šandrovac oil field, reservoir E, block 42, HDJ 6	optimal	oil saturation	optimal	**oil saturation** (reservoir permeability)	oil saturation, reservoir permeability	3,4	33,5
Šandrovac oil field, reservoir F, block 42, HDJ 2	optimal	**oil saturation**	oil saturation, reservoir permeability	**oil saturation** (reservoir permeability)	**oil saturation** (reservoir depth)	1,0	29,9

Table 5. Summary result of EOR methods applicability technical inspection on oil fields in Central Croatia production regions

EOR object (oil field, reservoir)	EOR methods						Original oil in place, 10^6 m^3	Current oil recovery, %
	Hydrocarbon Miscible Flooding	CO_2 Miscible Flooding	Immiscible Gas Injection	Micellar Polymer, Alkaline-Surfactant-Polymer and Alkaline Flooding	Polymer Flooding	MEOR (Microbial enhanced oil recovery)		
Stružec oil field, reservior P_1, block 3	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	1,8	47,0
Stružec oil field, reservior P_2, block 3	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	4,2	47,0
Stružec oil field, reservior A_1, block 3	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	6,9	47,0
Stružec oil field, reservior A_2, block 3	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	2,5	47,0
Stružec oil field, reservior A_3, block 3	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	2,9	47,0
Stružec oil field, reservior A_4, block 3	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	1,2	47,0
Stružec oil field, reservior A_1, block 4	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	2,0	47,0
Stružec oil field, reservior A_3, block 4	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	1,4	47,0
Stružec oil field, reservior A_1, block 9	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	1,1	47,0
Stružec oil field, reservior A_1, block 11	reservoir depth (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability	1,0	47,0
Jamarica oil field, reservoir L_1, block 29	net pay (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability and temperature)	oil saturation, reservoir depth and temperature	0,8	27,6
Jamarica oil field, reservoir L_1, block 38	net pay (oil properties, oil saturation)	optimal	oil saturation	reservoir permeability (oil saturation, reservoir temperature)	oil saturation, reservoir permeability (oil viscosity, reservoir temperature)	oil saturation, reservoir permeability, depth and temperature	0,7	37,1
Polje Lipovljani, ležište Kozarica I, blok 24	net pay (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation, reservoir permeability (oil viscosity)	oil saturation, reservoir permeability (reservoir depth)	1,0	33,7
Lipovljani oil field, reservoir Lipovljani 1, block 34	oil properties, oil saturation	oil saturation	oil saturation	oil saturation, reservoir permeability and temperaure	oil viscosity, oil saturation, reservoir permeability and temperaure	reservoir permeability, depth and temperature (oil saturation)	0,6	35,0
Lipovljani oil field, reservoir Bujavica, block 34	net pay (oil properties, oil saturation)	optimal	oil saturation	oil saturation, reservoir permeability	oil saturation (oil viscosity, reservoir permeability)	oil saturation, reservoir permeability (reservoir depth)	1,0	30,4
Kozarica oil field, reservoir Kozarica I	oil properties, net pay, reservoir depth	oil properties	oil saturation	oil properties	optimal	reservoir permeability	5,0	10,0

ervoir characteristics in tectonic block 3 on Stružec field with criteria of certain EOR methods is presented in Table 2.

If all 13 reservoir characteristics optimally met criteria of a certain EOR method (or some of them were irrelevant), then the method was pronounced as optimal for considered HDU unit. In case certain characteristics were in the marginal criteria range of EOR method, then the method was pronounced as conditionally applicable for the considered HDU which indicates the need for additional laboratory testing before the method is accepted/rejected. When certain characteristics did not meet EOR method criteria, then the method was pronounced as not applicable for the considered HDU.

Results of such screening were categorized according to production regions in Croatia and were presented in summary tables 3-6. Only HDU that were suitable for certain EOR method and methods that can be applied in the considered production area were presented. Data on oil in place and current recovery of analyzed HDU is presented with the table of initial screening results.

Table 6. Summary result of EOR methods applicability technical inspection on oil fields in East Croatia production regions

EOR object (oil field, reservoir)	EOR methods							Original oil in place, 10^6 m^3	Current oil recovery, %
	Hydrocarbon Miscible Flooding	CO_2 Miscible Flooding	Micellar Polymer, Alkaline-Surfactant-Polymer and Alkaline Flooding	Polymer Flooding	Cyclic Steam Stimulation (huff and puff)	Steam Flooding	MEOR (Microbial enhanced oil recovery)		
Bizovac oil field, reservoir Bizovac 2	oil properties, oil saturation, natural fractures	oil properties, natural fractures	**formation type, reservoir permeability, reservoir temperature, natural fractures**	**formation type, reservoir permeability, reservoir temperature, natural fractures**	**formation type, reservoir permeability, porosity and depth** (oil properties and satur.)	**formation type, reservoir permeability, porosity and depth** (oil properties and satur.)	**formation type, reservoir permeability, depth and temperature** (oil saturation)	**1,1**	**25,9**
Beničanci oil field, reservoir Beničanci	oil properties, oil saturation, reservoir temperature, natural fractures	oil saturation, reservoir temperature, natural fractures	**reservoir temperature, natural fractures** (oil saturation, reservoir permeability)	**oil saturation, reservoir temperature, natural fractures** (reservoir permeability)	**oil saturation, reservoir permeability, porosity and depth** (oil prop., natural fractures)	**oil saturation, reservoir permeability, porosity and depth** (oil prop., natural fractures)	**oil saturation, reservoir permeability, depth and temperature** (natural fractures)	**39,8**	**45,3**
Kučanci-Kapelna oil field, reservoir Ladislavci (E_L, F_{1a}, F_{1b})	**oil properties** (oil saturation, reservoir temperature, natural fractures)	oil properties, reservoir temperature, natural fractures	**reservoir temperature, natural fractures** (oil saturation, reservoir permeability)	**oil saturation, reservoir temperature, natural fractures** (reservoir permeability)	**oil saturation, reservoir permeability, porosity and depth** (oil prop., natural fractures)	**oil saturation, reservoir permeability, porosity and depth** (oil prop., natural fractures)	**oil saturation, reservoir permeability, depth and temperature** (natural fractures)	**1,8**	**41,6**
Obod Lacići oil field, reservoir Lacići-1	oil properties, oil saturation, reservoir temperature, natural fractures	oil saturation, reservoir temperature, natural fractures	**reservoir permeability, reservoir temperature, natural fractures** (oil saturation)	**oil saturation, reservoir permeability, reservoir temperature, natural fractures**	**oil saturation, reservoir permeability, porosity and depth** (oil prop., natural fractures)	**oil saturation, reservoir permeability, porosity and depth** (oil prop., natural fractures)	**oil saturation, reservoir permeability, depth and temperature** (natural fractures)	**2,6**	**34,9**
Obod Lacići oil field, reservoir Lacići-1a	oil properties, oil saturation, reservoir temperature, natural fractures	reservoir temperature, natural fractures	**reservoir permeability, reservoir temperature, natural fractures** (oil saturation)	**oil saturation, reservoir permeability, reservoir temperature, natural fractures**	**reservoir permeability, porosity and depth** (oil properties, saturation, natural fractures)	**reservoir permeability, porosity and depth** (oil properties, saturation, natural fractures)	**oil saturation, reservoir permeability, depth and temperature** (natural fractures)	**1,6**	**41,2**
Đeletovci oil field, reservoir c+i	**reservoir depth** (oil properties, oil saturation, natural fractures)	oil properties, oil saturation, natural fractures	**natural fractures** (oil saturation)	**oil saturation, natural fractures** (reservoir permeability)	**oil saturation, reservoir porosity** (oil prop., reservoir permeability and depth)	**oil saturation, reservoir porosity** (oil prop., reservoir permeability and depth)	**oil saturation** (reservoir depth, natural fractures)	**5,7**	**41,7**
Privlaka oil field, reservoir Privlaka	**oil properties, reservoir depth** (oil saturation, natural fractures)	oil properties, natural fractures	**natural fractures** (oil saturation)	**oil saturation, natural fractures** (reservoir permeability)	**oil saturation, reservoir porosity** (oil prop., reservoir permeability and depth)	**oil saturation, reservoir porosity** (oil prop., reservoir permeability and depth)	**oil saturation** (reservoir depth, natural fractures)	**1,9**	**43,0**
Privlaka oil field, reservoir A_4	**oil properties, reservoir depth** (oil saturation, net pay)	oil properties	oil properties, oil saturation	oil saturation	net pay, oil properties, oil saturation, reservoir permeability and depth	net pay, oil properties, oil saturation, reservoir permeability and depth	oil saturation	**0,7**	**20,7**

Cells at crossings of lines with titles of monitored HDU and columns with EOR method titles are colored depending on reservoir and EOR method compatibility. Green color defines complete compatibility with EOR method criteria, yellow defines partial (conditional) compatibility while red means that there is no compatibility. Along with that, cells also define characteristics of monitored HDU that are not compatible with criteria of certain EOR method. Characteristics that are out of criteria are presented in bold letters while characteristics that partly satisfy the criteria are presented in parenthesis.

4. Total remaining EOR potentials in Croatia and applicable EOR methods

Results of EOR methods applicability screening show that each production region has a possibility for some of those methods. When initial oil in place of all reservoirs that can be affected by any of EOR methods (HDU in green and yellow) is added up, the following results are acquired:

- West Croatia production region: 26.6 x 10^6 m^3 of oil
- North Croatia production region: 33.5 x 10^6 m^3 of oil
- Central Croatia production region: 22.2 x 10^6 m^3 of oil
- East Croatia production region: 59.7 x 10^6 m^3 of oil

Considering that all major fields in Croatia have been exploited for decades and belong to the category of depleted fields with relatively low current oil saturation, it is obvious that methods based on increased microscopic efficiency, i.e. mobilization of immobile oil, shall be the most applicable ones. The method of CO_2 injection in miscible conditions is the most promising one, as a method suitable for the widest range of reservoir conditions. Twenty four candidates that optimally meet the CO_2 injection criteria are recognized followed by 12 candidates that partially meet the criteria. Main candidates are Beničanci field and selected HDU on Stružec, Šandrovac and Kloštar fields with most significant oil in place. Some of these HDU with deeper burial depth and lighter oil, are partially suitable for hydrocarbon gases injection in miscible conditions (Beničanci and selected HDU on Kloštar, Obod Lacići and Lipovljani fields).

The second most applied EOR method in Croatia is alkali-micellar-polymer flooding, that also operates on principle of increasing microscopic displacement efficiency. However it is more demanding regarding permeability and maximal reservoir temperature. Two candidates were selected by screening (selected HDU on Kozarica and Šandrovac fields) and 26 partial candidates (selected HDU on Stružec, Šandrovac, Kloštar, Dugo Selo, Bilogora fields...). Some of those HDU, with higher current oil saturation are suitable for pure polymer flooding (selected HDU on Kozarica, Kloštar, Jagnjedovac, Privlaka and Lipovljani fields).

Microbial methods are younger and can be considered experimental, as their application worldwide has remained restrained to pilot projects. Six potential candidates that partially meet the criteria were selected: distinguished HDU on Đeletovci, Kozarica, Šandrovac, Privlaka and Jagnjedovac fields.

Thermal steam injection methods into reservoir are the ones that are applied the least because suitable reservoirs with heavy and viscous oils are very rare in Croatia. Also there are very few reservoirs with sufficient current oil saturation. Only two partial candidates were selected: Šumećani field and A_4 reservoir on Privlaka field.

It is also obvious that some of the mentioned EOR methods, according to initial screening, are not applicable in Croatia. Injection of nitrogen and smoke gases is the method with the strictest criteria for achieving miscible conditions and the screening has not discovered any satisfactory candidates. Oil combustion in reservoir is not applicable because in Croatia fields with extremely viscose oil have not been discovered. SAGD (steam-assisted gravity drainage) is also not applicable in Croatia. Although there are partial candidates for classic steam injection, they are characterized by marl intercalations in reservoir preventing key vertical fluid movement in the reservoir and which spontaneously occurs at gravity drainage.

Analysis results described in previous two chapters, i.e. distinguished oil fields and HDU, can be understood as real author's suggestions for additional consideration within EOR implementation context. If there should be interest for additional exploitation of the remaining EOR potential in the Republic of Croatia area, work from this paper can be expanded wit further analyses and studies with feasibility study through pilot project operation. The current legislation prescribes the same fee for exploitation with application of EOR methods and for fields where EOR method is not applied, as well as on all other exploitation fields which affects commercial feasibility of the project.

5. Conclusion

This review presents technical evaluation of EOR methods applicability on Croatian oil fields. The result is defining of remaining EOR potential in Croatia, i.e. list of fields and reservoirs where EOR methods can be applied and most suitable EOR methods to be used on them. This step also eliminates all reservoirs and fields that are not suitable for EOR application and that shall not be subject of further consideration.

In each Croatian production region there is a possibility of applying several EOR methods. The most applied method is CO_2 injection and it can be applied to reservoirs with the total of 130.9 x 10^6 m^3 of initial oil in place. From previous experience of applying these EOR methods worldwide, oil recovery increase can be expected by 3 - 7%, and in certain cases even more. There are significant CO_2 sources in Croatia which additionally distinguish this method as the first choice on Croatian oil fields. After that most applied are chemical methods followed by thermal methods.

Work on this paper represents the first step in the process of initiating EOR project in any area. Next step is analytical assessment of increase of recoverable reserves and oil production with application of EOR and first commercial cost effectiveness assessment. Then detailed reservoir studies shall be made that include laboratory testing of reservoir rock and fluid and preparation of numerical models with precise production forecasts. After that pilot projects implementation shall start that should confirm feasibility and positive effect of EOR and calibration of numerical modes with pilot results. During the last step, if the pilot project proves to be successful, EOR project shall be expanded to the level of the entire field.

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References

1. Abass, E., and Lin Song, C.: " Artificial Intelligence Selection with Capability of Editing New Parameter for EOR Screening Criteria", Journal of Engineering Science and Technology Vol. 6, No. 5 (2011).
2. Al Adasani, A., and Baojun, B.: "Analysis of EOR projects and updated screening criteria", Journal of Petroleum Science and Engineering 79 (2011).
3. Almeida, J.: "Practical Applications and Novel EOR Methods", Halliburton (2009).
4. Andrei, M. et al.: "Enhanced Oil Recovery with CO_2 Capture and Sequestration", ENI exploration and production division, Italy & ENI refining and marketing division, Italy
5. Awan, A.R., Teigland, R., and Kleppe, J.: "A Survey of North Sea Enhanced-Oil-Recovery Projects Initiated During the Years 1975 to 2005", SPE 99546 (February 2008).
6. Babadagli, E.: "Selection of Proper EOR Method for Efficient Matrix Recovery in Naturally Fractured Reservoirs", SPE 69564 (March 2001).
7. Berrufet, M.A.: "Class notes for PETE 609 - Module 1 - Introduction to Enhanced Oil Recovery (EOR) Methods", (2001).
8. Ferno, M.: "Enhanced Oil Recovery in Fractured Reservoirs", Department of Physics and Technology, University of Bergen, Norway.
9. Goričnik, B.: "Possible Revitalization of Mature Oilfields in Croatia - CO_2 Process Assessment from Laboratory Data, International Oil and Gas Conference, Zadar, Croatia (October, 2001).
10. Jamaloei, B.Y.: "Chemical Flooding in Naturally Fractured reservoirs: Fundamental Aspects and Field-Scale Practices", Oil & Gas Science and Technology, Vol. 66 (2011).
11. Lake, L.W., and Walsh, M.P.: "Technical Report: Enhanced Oil Recovery (EOR) Field Data Literature Search", (2008).
12. Manrique, E. et al.: "Effective EOR Decision Strategies with Limited Data: Field Cases", SPE 113269 (April 2008).
13. Novosel, D., Leonard, N.: "Utiskivanje ugljičnog dioksida u tercijarnoj fazi iskorištavanja naftnih ležišta eksploatacijskih polja Ivanić i Žutica", Plin (2013).
14. Sarma, H.K.: "Gas Processes: Principles and Field Applications, General Screening Criteria-1".
15. Sečen J., Istiskivanje nafte tekućinama podatljivim miješanju, INA, INA-Naftaplin Zagreb, 1987., str. 1-188, 124 slike, 254 bibl. Izvora.
16. Sečen J., Metode povećanja iscrpka nafte, INA-Industrija nafte d.d., Naftaplin, Zagreb, 2006., str. 1-604, 256 slike, 146 bibl. Izvora.
17. Terry, R.E.: "Enhanced Oil Recovery", Encyclopedia of Physical Science and Technology 3rd Edition, vol.18 (2001).
18. Taber, J.J., Martin, F.D., and Seright, R.S.: "EOR Screening Criteria Revisited-Part 1: Introduction to Screening Criteria and Enhanced Recovery Field Projects", SPE 35385 (June, 1997).
19. Taber, J.J., Martin, F.D., and Seright, R.S.: "EOR Screening Criteria Revisited-Part 2: Applications and Impact of Oil Prices", SPE 39234 (June, 1997).
20. Thomas, F.B. et al.: "Enhanced Oil Recovery by Gas Injection: Proposed Screening Criteria", Petroleum Society of CIM, CIM #96-119 (1996).
21. Trujillo, M. et al.: "Selection Methodology for Screening Evaluation of Enhanced-Oil-Recovery Methods", SPE 139222 (December 2010).

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