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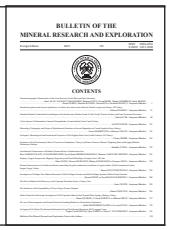

The role of enhanced oil recovery in the upstream petroleum sector, a case study from Turkey

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Research Article

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ABSTRACT

The upstream petroleum sector issues still keep its popularity worldwide. Enhanced Oil Recovery (EOR) is an essential unconventional method of improving production in the petroleum sector. The EOR is gaining more importance in the sector. 2% of the global crude oil production is performed by EOR operations currently. The crude oil production of Turkey which is now in a decreasing trend is performed from old and mature oil fields. Sharp declines are expected for the oil production in the near future if new discoveries do not take place or enhanced oil production techniques are not performed. The average recovery rate for the crude oil fields in Turkey is about at 20%. An increase in this ratio can provide significant amount of crude oil to Turkish production. The ratio of crude oil production by EOR methods is about 15% currently in Turkey. In this study, the historical background of EOR projects is explained and potential EOR methods have been discussed for Turkish crude oil fields. The aim of the research is to evaluate the crude oil production potential from existing oil fields of Turkey based on EOR methods matching with the characteristics of oil fields with statistical information on world EOR outlook.

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1. Introduction

The energy consumption in the world is increasing every year. The crude oil consists 32% of the world primary energy consumption taking the first place among all fuel types (IEA, 2017). On the other hand, the crude oil reserves and the new crude oil field discoveries are decreasing. The utilization of existing reserves may yield significant amounts of crude oil equivalent production to overcome the need for new oil field discoveries. Crude oil production is separated into three phases: primary, secondary and tertiary which is also known as Enhanced Oil Recovery (EOR). The active usage of EOR projects worldwide started after first oil crisis in 1973 and then showed wavy behavior due to instable crude oil prices. The number of EOR projects increase with increasing price of crude oil. Although EOR operations are said to bring significant economic and technical challenges, the private companies tackle 80% of the EOR operations globally (Koottungal, 2014). This is a fact showing the positive feasibility of the projects.

1.1. Enhanced Oil Recovery (EOR)

The first stage of crude oil production is called primary production which is performed by natural flow or artificial lift (pump). The second stage, called the secondary production is performed by either water or gas injection (by the gas produced from the reservoir). The importance of EOR increases with the decrease of API gravity of oil since the share of crude oil that can be produced by EOR increases as the API gravity of crude oil decreases. In case of heavy crude oil reservoir conditions the EOR ratio can even become some 90% (Sheng, 2013).

The average recovery rate for the crude oil fields is 1/3 of the reservoir volume worldwide presently. The carbonate reservoirs have lower recovery rates

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compared to sandstone reservoirs due to their fractured structure, heterogeneity, oil-wet tendency, lower permeability and porosity (Sheng, 2013). Nearly all crude oil fields of Turkey include carbonate type reservoirs with the average recovery rate 20% (GDPA, 2017). The low recovery rate for oil fields in Turkey is also a result of viscous and low gravity crude oils and poor reservoir pressure support mechanisms.

2. EOR Methods

Three major categories of EOR have been found to be commercially successful in varying degrees: Thermal Methods, Chemical Methods, Gas Injection Methods (Sheng, 2013). The thermal EOR includes the hot water flooding, in-situ combustion, and steam injection. The purpose of thermal EOR is to heat the heavy oil and mobilize it by decreasing the viscosity. The most feasible method is steam injection among thermal EOR methods due to its heat efficiency and better control. The chemical EOR includes surfactant, alkaline, and polymer flooding. The purpose in chemical EOR is to decrease the interfacial tension between crude oil, water, and rock. The viscosity arrangement to prevent viscous fingering effect is also used in polymer flooding. The gas injection EOR methods mostly include CO_2, CH_4, and N_2 injection. They aim to decrease the viscosity of crude oil and mobilize the crude oil by mainly the swelling effect. The choice of the method depends on the reservoir parameters and availability of gas source. Apart from the known EOR methods the microbial flooding and smart water injection are the new EOR methods in the upstream petroleum sector still in the trial stage which may have positive, negative, or no effects on crude oil production. The studies on these methods are mostly focused on laboratory tests and the reported results show no consensus on the usage of these methods. Thermal and chemical methods are suitable in sandstone reservoirs due to technical reasons; however gas injection and other EOR methods can be applied in both carbonate and sandstone reservoirs.

3. EOR Operations Worldwide

There are currently about 280 EOR operations worldwide providing 1.4 million barrel of crude oil per day forming 2% of the global crude oil production (Koottungal, 2014; IEA, 2017). The list of EOR operations by country and method is presented in table 1. The table excludes China, because the data series for China are incomplete; China is estimated to produce about 170 kb/d; 150 kb/d from steam technologies and 20 kb/d with polymer injection (IEA, 2013). 55% of EOR projects are active in Unites States, 15% in Canada and 15% in Venezuela. The rest are operated in other countries. In terms of production amounts, 31% of EOR comes from US based production, 27% from Venezuela, 24% from Canada and the rest from other countries. The role of EOR is becoming more important for the countries possessing heavy oil deposits. To give example to this case, the rate of EOR in crude oil production is 5% for USA, 10% for Canada, and 15% for Venezuela, which is above the world average. The role of thermal EOR is the highest worldwide. Gas injection methods follow the thermal methods. The world EOR production by methods is presented in figure 1

Table 1- EOR Applications by country and method (Koottungal, 2014)

Country	EOR Method	Number of Field
USA	Miscible CO_2 Injection	127
USA	Immiscible CO_2 Injection	9
USA	Miscible Hydrocarbon Gas Injection	12
USA	Immiscible Hydrocarbon Gas Injection	2
USA	Immiscible N_2 Injection	3
USA	Chemical Injection	3
Germany	Steam Injection	8
Brazil	Immiscible CO_2 Injection	1
Brazil	Miscible CO_2 Injection	2
Brazil	Microbial Injection	1
Brazil	Steam Injection	5
Indonesia	Steam Injection	2
Netherlands	Steam Injection	1
Canada	Miscible CO_2 Injection	7
Canada	Miscible Hydrocarbon Gas Injection	20
Canada	Steam Injection	10
Canada	Immiscible N_2 Injection	1
Canada	Polymer Injection	2
Egypt	Steam Injection	1
Trinidad	Steam Injection	9
Trinidad	Immiscible CO_2 Injection	5
Trinidad	Hot Water Injection	2
Turkey	Immiscible CO_2 Injection	1
Venezuela	Steam Injection	43
Venezuela	Combustion Flooding	1
Venezuela	Chemical Injection	1
Venezuela	Miscible Hydrocarbon Gas Injection	4

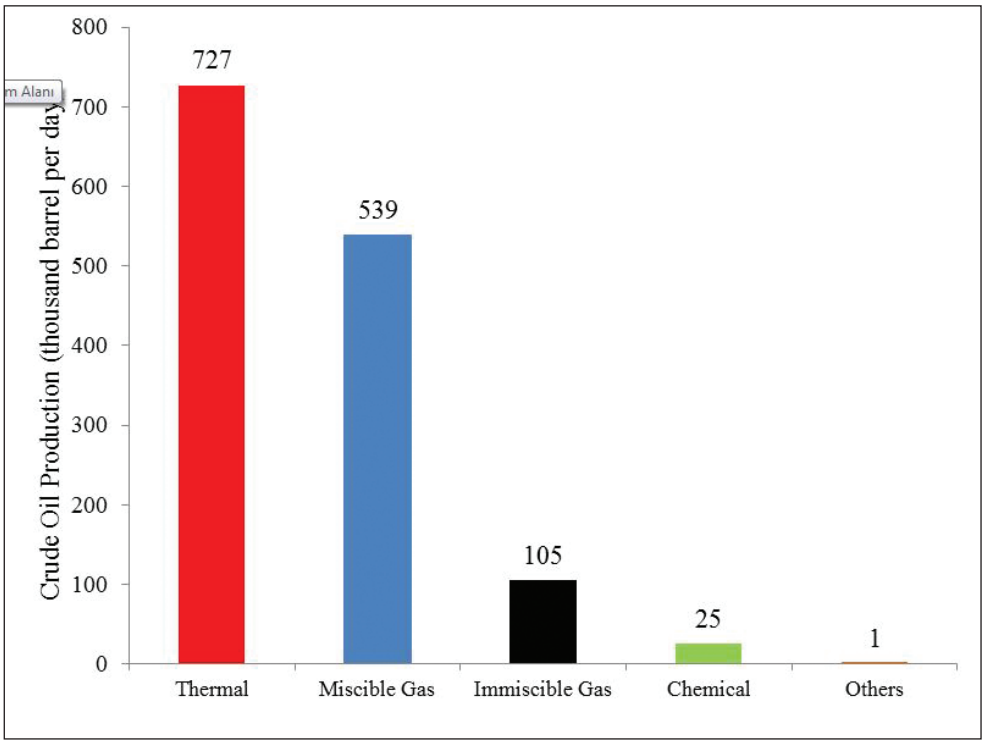

Figure 1- World EOR Productions by Methods (Koottungal, 2014)

4. EOR Background and Assessment in Turkish Upstream Petroleum Sector

There have been six enhanced oil recovery operations at four crude oil fields in Turkey until now (Şahin et al., 2014). The general overview of the EOR projects is presented in table 2. There is only one on-going EOR project since 1986 which is an immiscible CO_2 injection, in Batı Raman oil field in Turkey presently. The first EOR project started in Turkey is the steam injection performed in Batı Raman oil field. The steam injection and immiscible CO_2 injection have been performed at İkiztepe oil field. The immiscible CO_2 injection has also been performed in Çamurlu and Batı Kozluca oil fields. The results are promising for CO_2 injection projects. However, EOR project on Batı Kozluca was stopped until the construction of recycling unit at the field to prevent the depletion of CO_2 reserve. The CO_2 projects on Çamurlu and İkiztepe oil fields have been stopped because of technical and economical reasons (Şahin et al., 2012). Apart from on-going immiscible CO_2 project in Batı Raman field, the other EOR operations were rather research projects in Turkey.

Table 2- The list of EOR performed crude oil fields in Turkey (GDPA, 2017).

City	Field	EOR Method	Operator	Years
Batman	Batı Raman	Immiscible CO_2 Steam	TPAO	1986-cont. (CO_2) 1967-1969 (steam) 2012-2013 (steam)
Şırnak	Batı Kozluca	Immiscible CO_2	TPAO	2003-2007
Mardin	Çamurlu	Immiscible CO_2	TPAO	1984-1986
Mardin	İkiztepe	Immiscible CO_2 Steam	TPAO-JNOC	1993-1995

(JNOC: Japan National Oil Company, TPAO: Turkish National Oil Company)

Based on the Hubbert curve approach for the Turkish crude oil production life, the production will likely come to the end between the years 2040 - 2045 (Özgür, 2016). The recoverable reserve amount can be increased and the life of the production can be extended if EOR projects are performed on the noticeable oil fields of Turkey.

CO_2 injection operation in Batı Raman field is currently underway. The implementation of this method in other fields can significantly increase the oil production in Turkey. There are 10 remarkable crude oil fields with recoverable reserves over 25 million barrels based on Ivanhoe and Leckie's technique (Ivanhoe and Leckie, 1993) located at southeastern part in Turkey which are candidates for enhanced oil recovery in terms of technical and economical aspects. The optimum enhanced oil recovery methods are selected for the fields considering reservoir characteristics and enhanced oil recovery criteria.

The methods which are steam injection, in-situ combustion, hot water flooding, alkaline flooding, polymer flooding, surfactant flooding, microbial flooding, miscible/immiscible gas flooding, smart-water injection and other methods are also investigated.

Because of the suitable characteristics of oil fields and carbon source potential of thermal power plants, steel factories, cement factories, refineries, sugar factories in the region, the CO_2 injection method is the optimum enhanced oil recovery method for Turkey. Construction of a pipeline network between the sources and the fields can extend the scope of CO_2 injection, and as a result, lead to environmental, economical, and strategic benefits. It is expected that the additional produced crude oil may be equal to the amount of almost two large oil field discoveries.

4.1. Evaluation and Predictions on EOR in Turkey

The crude oil fields in Turkey are carbonate types. It is a fact that the EOR operations have limited application in carbonate reservoirs. 80% of the EOR crude oil production comes from sandstone reservoirs worldwide (Koottungal, 2014). However, the good carbonate field examples are also present. The reservoir properties of remarkable crude oil fields in Turkey are given in table 3. The evaluations are based on the reservoir parameters of the fields.

The chemical EOR methods are feasible in sandstone formations. Therefore the chemical EOR are not considered for Turkey as an option due to the carbonate type reservoirs. The thermal methods are also more practical for sandstones however they may be applied in also carbonates at certain circumstances. Although the thermal methods are not advised for Turkey in this study, steam injection is also evaluated in case of a test operation. 1,500 meter depth is accepted as economic limit for steam injection in the literature. In deeper reservoirs, the heat loss problem would affect the operation economically and technically in negative manner (Sheng, 2013). Raman, Batı Raman and Garzan fields fit the criteria of the feasible steam injection operation.

Other EOR methods like microbial flooding and smart water injection were also analyzed from a research point of view for pilot field studies and applications. In microbial flooding, the temperature and salinity of the reservoir are important. Generally speaking, the temperature should be lower than 70 ^oC and salinity should be lower than 50,000 ppm for the increase of microorganism activities. Besides, the higher permeability is better for the distribution of microorganisms in reservoir. Raman field seems the ideal oil field for the pilot application of microbial flooding. For smart water injection, the high temperature reservoir is the good option. Karakuş and Kuzey Karakuş fields meet the criteria and they are

Table 3- Reservoir Properties of Remarkable Crude Oil Fields of Turkey (GDPA, 2017).

Field	Formation	Ø	k, md	Depth, m	Salinity (1000 ppm)	T,^oC	API	μ, cp
Raman	limestone	14	50	1360	40	60	18	60
B. Raman	limestone	18	58	1300	120	65	13	600
Kurkan	limestone	15	9	1600	20	55	31	9
B. Kayaköy	limestone	17	4	1890	5	58	35	5
Beykan	limestone	12	1	1900	25	58	33	4
Şelmo	dolomitic limestone	7	100	1890	12	77	34	3
Karakuş	dolomitic limestone	6	100	2700	30	118	30	3
Garzan	limestone	11	15	1450	45	70	24	7
Kayaköy	limestone	15	2	2100	10	60	38	3
K. Karakuş	dolomitic limestone	6	100	2590	25	110	30	3

also close to the low salinity water sources (lakes and rivers).

Among all EOR methods CO_2 gas injection method is the most suitable method for Turkish oil fields. The good example of "Batı Raman" oil fields and good reservoir parameters make the gas injection best choice for Turkey. It is expected that the miscible CO_2 gas injection will increase recovery factor by 15% and the immiscible CO_2 gas injection by 10% (Sheng, 2013; Perera et al., 2016). The API gravity of crude oil is one of the most important things to determine the type of injection whether it would be miscible or immiscible along with the reservoir temperature, reservoir pressure and injected gas composition (Meyer, 2007). After a certain lower API value, the injection process cannot be performed as immiscible regardless of the injection pressure. The oil fields with the gravity over 25 API are good candidates for miscible gas injection practically (Perera et al, 2016). Raman, Batı Raman and Garzan fields which have lower API gravities than 25 are suitable for immiscible gas injection. On the other hand Kurkan, Batı Kayaköy, Beykan, Şelmo, Karakuş, Kayaköy, and Kuzey Karakuş are suitable for miscible gas injection.

Extra 385 million barrels of crude oil can be produced from existing production fields in Turkey considering the characteristics of fields and EOR methods. The amount of necessary CO_2 to produce 385 million barrel of oils is 85,42 million tones based on the Batı Raman case in Turkey; 4.5 ton CO_2 is required for the production of one barrel oil (GDPA, 2017). The EOR project is planned for 35 year duration. The yearly necessity for CO_2 will be about 2,5 million tones. The required CO_2 amount can be provided from the cement factories through the construction of pipelines in the region. The annual CO_2 emission of cement factories is about 15 million tons and the factories in the southeastern part of Turkey can provide enough CO_2 for the EOR operations in the region (Okandan et al., 2011). The EOR analysis of Turkish oil fields is presented in table 4, table 5, and figure 2. The reserve information about the crude oil fields is provided in table 5 (GDPA, 2015).

Table 4- EOR Analysis of Remarkable Crude Oil Fields of Turkey (GDPA, 2017).

Technical Information of 10 Remarkable Crude Oil Fields	
Original Oil in Place, million barrel	4536,6
Recoverable Reserve, million barrel	841,1
Recovery Factor, %	18,5
Suggested EOR Method	**Miscible/Immiscible CO_2 Injection**
New Recovery Factor After EOR, %	27,0
Extra Crude Oil Production After EOR, million barrel	384,4
Necessary CO_2 Amount (million tons)	85,42

Table 5- Prediction on EOR Potential of Remarkable Turkish Crude Oil Fields (GDPA, 2017).

Field	**Original Oil in Place**	**Recoverable Oil Reserve**	**Recovery Factor**	**Suggested EOR Method**	**New Recovery Factor**	**Extra Oil Production**
Raman	615,3	146,9	23,9	Immiscible CO_2	33,9	61,7
Batı Raman	1841,0	192,9	10,5	Immiscible CO_2	12,0	28,0
Kurkan	287,0	67,3	23,4	Miscible CO_2	38,4	42,9
Batı Kayaköy	225,6	63,4	28,1	Miscible CO_2	43,1	33,8
Beykan	432,8	89,8	20,7	Miscible CO_2	35,7	64,7
Şelmo	539,0	99,3	18,4	Miscible CO_2	33,4	80,7
Karakuş	209,1	61,6	29,5	Miscible CO_2	44,5	31,4
Garzan	199,1	46,5	23,4	Immiscible CO_2	33,4	20,0
Kayaköy	99,9	31,2	31,2	Miscible CO_2	46,2	15,0
Kuzey Karakuş	87,8	42,2	48,1	Miscible CO_2	55,0	6,1
Total	4536,6	841,1	18,5 (avg.)	-	27,0 (avg.)	384,4

(Reserves and production amounts are presented in "million barrel")

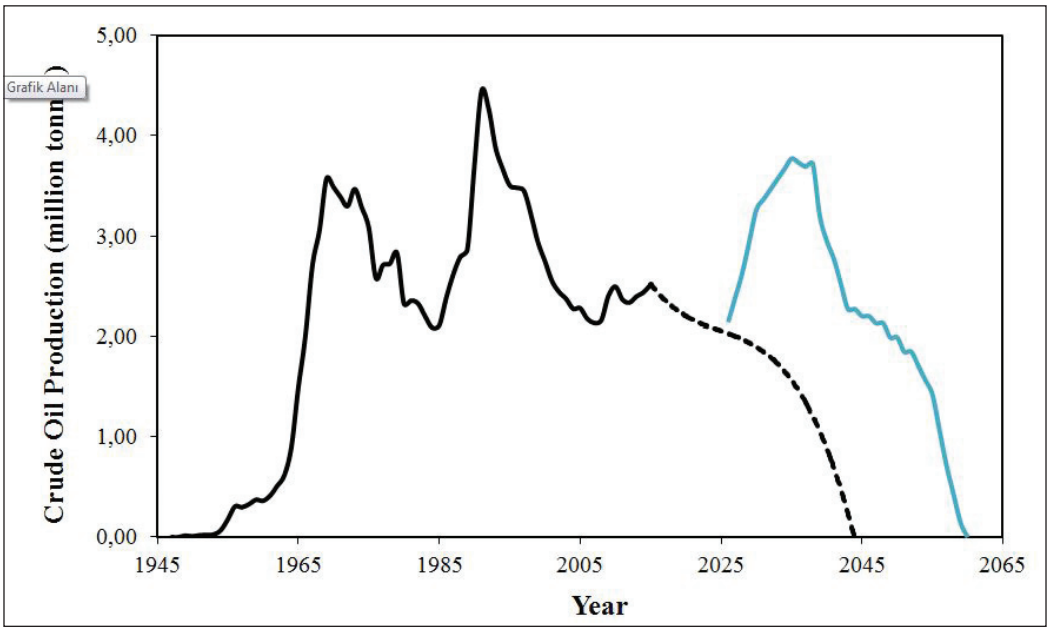

Figure 2- Turkey's Historical Crude Oil Production and Forecast (Black line: historical production, dashed line: oil production forecast, blue line: oil production forecast with EOR production)

5. Conclusions

Although EOR projects are expensive operations and require skilled staff, the existing infrastructure and pipelines in the fields provide advantage and easy access of produced oil to markets with no additional exploration costs. 20% of the EOR based crude oil production worldwide is performed by national oil companies (Koottungal, 2014). The rest is produced by private oil companies showing the positive feasibility of the EOR projects worldwide. The current ratio of crude oil production by EOR methods is about 2% (1.4 million barrel per day) of global production; however according to the International Energy Agency report (IEA, 2017) this ratio will increase to 4.25% (4.3 million barrel per day) by 2040.

There are currently 132 crude oil fields Turkey and 10 of them (Batı Raman, Raman, Kurkan, Batı Kayaköy, Beykan, Şelmo, Karakuş, Garzan, Kayaköy, and Kuzey Karakuş) are remarkable whose recoverable reserves over 25 million barrels. There is currently one active immiscible CO_2 EOR project performed for 30 years on the biggest crude oil field, Batı Raman, of Turkey forming 15% of the Turkish crude oil production. The application of immiscible / miscible CO_2 injection EOR methods on other fields together with the current one can provide about 385 million barrels of extra crude oil increasing the average recovery ratio of those 10 fields from 18.5% to 27%. This may extend the depletion of crude oil to the years 2060-2065 from the presently expected 2040-2045. One word for the pilot application of other EOR methods for research purpose: Raman oil field seems ideal for microbial flooding. Karakuş and Kuzey Karakuş fields seem ideal for smart water injection.

Some comments may also be made regarding the regulations in Turkey. The reduction in the royalty tax for the crude oil production by EOR would be a good motivation for oil companies. Considering lower crude oil prices, decreasing crude oil production trend and difficult geological conditions for petroleum exploration in Turkey, the introduction of such a regulation may lead to positive results in the long term.

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