MGPB

Toe-to-Heel Air Injection In-situ Combustion Process: Case study from the Azraq Basin, Jordan

Mehaysen Ahmed Al-Mahasneh

Jordan- Irbid (Al-Balqa Applied University- Al Huson University College, Chemical Engineering Department), m.mahasneh@bau.edu.jo, ORCID.org/0000-0003-1638-0872.

Abstract

The exploration and drilling operations for oil in the Wadi Rajil region of the Azraq Basin in northeast Jordan confirmed the existence of quantities of asphalt and heavy oil in several formations of limestone and dolomite within layers of sandstone. The estimated area was 1200 km² (120000 hectare) and possibly contained 800 million m³ (five billion barrels) of original oil. The aim of this study is to obtain in-situ combustion and to suggest the application of the drilling of two wells by an in-situ combustion process called Toe-to-Heel Air Injection In-situ Combustion in the Wadi Rajil-Hamzeh field. This approach proposes a pilot project of drilling two wells. One vertical injection well in the upper production zone and another horizontal production well at the bottom of the reservoir. Through this technique, the productivity will increase, the viscosity of the oil will decrease, and consequently the sweep efficiency will be higher. This pilot project's potential production reaches 212.94 m³/d of oil. The total time for the project to be completed is around 450 days. The efficiency of recovery in this study reached around 65 to 69%. This result can lead to the possible expansion of the approach applied in this project throughout the Wadi Rajil-Hamzeh region.

1. Introduction

The demand for oil and the increase in the difficulty of discovering large oil reservoirs, the decrease in reservoirs reserves, and the decrease in oil conventional reserves, have led to an increased interest in heavy oil and tar sands. The predominant factor limiting the economic recovery in such reserves is the high viscosity of the oil in the reservoir. Any decrease in the oil viscosity will lead to an increase in oil movement, thereby improving oil production.

This can be achieved by one of the most effective production methods, which is thermal application in the reservoir.

The fire flooding method is another way to improve oil production and is called Enhanced Oil Recovery (EOR).

The heat can be supplied to the reservoir in the form of hot water, gases, or steam. Heat might be generated in-situ by burning a portion of the oil in the reservoir known as in-situ combustion (ISC). This generated heat ignites oil in formations, leading to the spread of the propagation combustion front through the porous media that contains the oil.

Corresponding author: Mehaysen Al-Mahasneh

m.mahasneh@bau.edu.jo

The fuel needed for the continuity of combustion can be supplied from residual materials or from the coke deposited from the combustion zone in process, thermal cracking, pyrolysis, or the combustion front of the oil.

Most in-situ thermal processes use vertical wells for short distances of penetration of the formation, while in horizontal wells, large distances are penetrated. Over the past decade, great progress is achieved in drilling horizontal wells over large distances of around 1000 m.

Horizontal wells provide improved performance over conventional vertical wells, this is primarily due to the expansion of the contact area between the layers of the upper and bottom formation and the horizontal well. This is especially true for thinly stratified formations in which the reservoir is in contact with a larger area of the horizontal well than with the fully penetrated vertical well **(Giger et al., 1984).** Horizontal wells are strategically placed away from contact with liquids to reduce water/gas coning by causing a decreased displacement and consequent improvement in cumulative oil recovery **(Chaperon et al., 1986).**

Sweep efficiency during the combustion process is an important factor in the recovery process. Steam drive and cyclic steam stimulation was successfully used in the horizontal wells with the help of steam-assisted gravity drainage to produce heavy oil and oil sands from the reservoir.

A model was created and various experiments were conducted to verify the effectiveness of the group of a horizontal and a vertical well by steam flooding on the Athabasca sand field, and it was concluded that continuous steam circulation through the perforated horizontal well was effective for producing heavy oil **(Greaves et al., 2005)**.

The Azraq Basin (see **Figure 1)** is located in the northeast region of the Hashemite Kingdom of Jordan, which includes the region Wadi Rajil-Hamzeh and contains probable reserves of asphalt and heavy oil estimated to be around 800 million m³ (five billion barrels). **Figure 1** shows the study area.
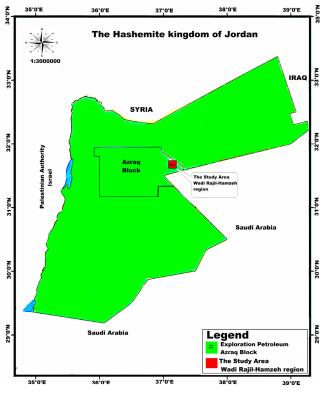

Figure 1: The Hashemite Kingdom of Jordan map, the study area

ISC is a thermal EOR method in which a small fraction of the oil (coke) in the oil layer is burned to mobilise the unburned fraction. Due to the strong exothermic oxidation reactions between hydrocarbon (coke) and oxygen, the temperature of the oil-bearing matrix in the combustion zone reaches 500 to 700°C, which is much higher than that in steam flood processes (150 to 250°C). Higher temperatures are very favourable for tar sands and heavy oil reservoirs because not only is the oil viscosity reduced by several orders of magnitude, but the heavy residue is also thermally cracked to lighter compounds **(Xia and Greaves, 2002)**.

In the conventional ISC process which uses vertical wells for injection and production, the size of the sweep is limited because of the presence of challenges in the layers and excessive work. The toe-to-heel air injection in-situ combustion (ISC) process is a new technology that uses the horizontal wells at the bottom of the reservoir, developed to recover the oil from the heavy oil reservoir, to increase the productivity as well as the sweep efficiency.

2. Geological settings

The widespread distribution of bitumen- and asphalt-bearing rocks of the Maastrichtian Age in the Azraq region has been clearly established through the drilling of 22 oil wells for exploration in the Wadi Rajil-Hamzeh area. Although bitumen, asphalt and heavy oil are sporadically present through the lithostratigraphy column as shown in **Figure 2**, the richest occurrences of heavy residual hydrocarbons are found in the Ghareb Formation of Late Cretaceous Age.
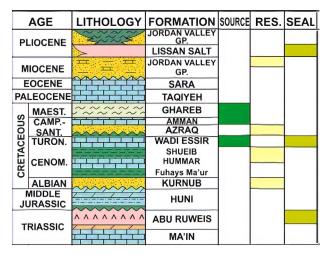

Figure 2: Lithostratigraphy cross-section of the Hamzeh-Wadi Rajil area **(Qteishat and Mahasneh, 2018)**

Using petrophysical logs, descriptions of well site cuttings and core sample analysis indicated that the Ghareb Formation contained dolomite and limestone, described as a light grey fine crystalline, medium hard, with patchy distributions of asphalt and heavy oil.

Figure 3 shows the structure map of the Wadi Rajil-Hamzeh in the Azraq Basin, **Table 1** shows the physical and chemical properties of the oil field.

The porosity was described as vuggy to cavernous with fractures and vugs filled with heavy oil. The average thickness of the centre zone of the Ghareb Formation was estimated to be about 29 m.

Accordingly, the drill stem test (DST) was conducted in the bituminous-asphaltic region in the upper zone of the Ghareb Formation. However, the analysis of the core sample taken from a depth of 962 m in Hamzeh well 4 indicated 24% water saturation and 76% residual oil saturation. Thereafter, a second (DST) was conducted in
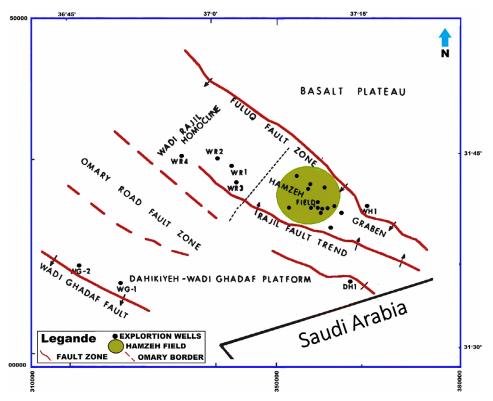
Figure 3: Structure map of Wadi Rajil- Hamzeh in Azraq Basin **(Qteishat and Mahasneh, 2018)**

the lower Ghareb Formation, which recovered 4 liters of heavy oil from the drill stem.

Table 1: Physical and chemical properties of reservoir

Properties	Unit	Value
Average depth	m	845–1112
Gravity of asphalt	API	9-10 º
Gravity heavy oil	API	17 º
Density heavy oil	gr/cm³	0.95
Density of asphalt	gr/cm³	1.0071-1
Porosity	%	18
Permeability	μm²	592.15
Average thickness	m	29–40
Viscosity	mPa-s	400–1000
Oil saturation	%	45–75
Reservoir temperature	˚C	40
C/H ratio	%	2.58
Hydrocarbons types		
Saturates	wt %	4.5
Aromatics	wt %	25.2
Sulfur	wt %	9.9–11.65
Melting point of Asphalt	˚C	79
Conradson Carbon	wt %	6.1
Metals		
Nickel	ppm	80
Vanadium	ppm	155

From the logs, the average porosity for these zones was 13 to 19%. The total thickness of the formation towards the Fuluk Fault zone was in the northeast region. However, the Ghareb Formation found in the northeast of the Wadi Rajil wells WR1, WR2, WR3 and directly to the south of the Hamzeh oil field.

3. Materials and methods of examination

3.1. Device for studying oil oxidation in porous media

The experimental device for studying oil oxidation in porous media is used to measure the reactivity of different oils in a porous medium. The sample is packed into the cell to be provided with the necessary temperature, pressure, and flow control as shown in **Figure 4**. The shape of the cell is designed so that the temperature and composition of the reactants is as uniform as possible.

3.2. Oxidation procedure

The original core sample containing asphalt and heavy oil was grinded and sieved, thereafter it was packed in the cell and heated to 500°C according to the linear program of the time function. The volume of the sample was 32 cm³, and the amount of air flow ranged between 23 and 44 cm³/m² per hour.

The device was programmed at a linear heating temperature of 80°C/hour, while the average heating temperature of the sample was around 68 to 78°C/hour. The
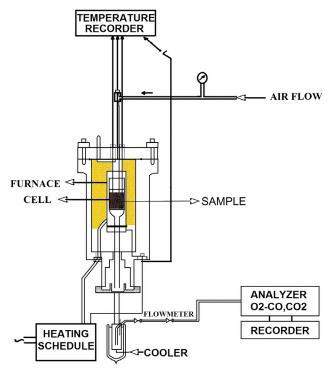
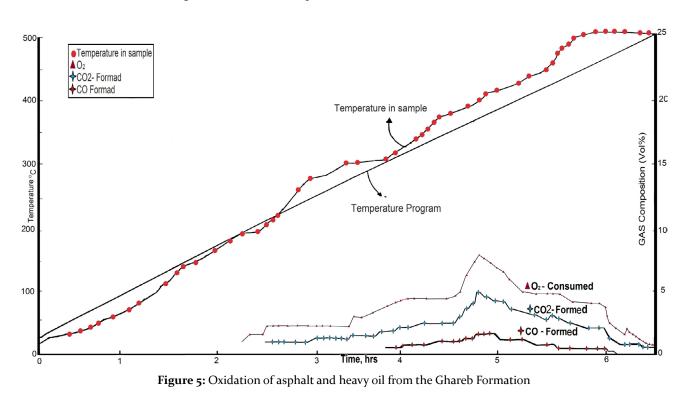**Figure 4:** Experimental device for studying oil oxidation in porous media (**Burger et al., 1985**)

tion progressed. The non-linear heating temperature of the sample was changing because of the significant interaction within hydrocarbon mixtures in the sample.

The oxygen combustion temperature was between 50 and 190°C, which was suitable for the continued burning of the oxygen consumed to complete the process successfully. The plateau temperature was 190 to 220°C.

The amount of CO_2 formed after oxidation of the sample at the beginning of the test was very low due to the primary reactions before initiating the combustion which is called low-temperature oxidation (LTO). Due to the continuity reactions to complete the process of

Table 2: Results of the oxidation test.

The initial temperature of the sample	22°C
Final temperature of a sample	500°C
Average temperature/hour	68–78°C
The temperature at the beginning of the oxygen consumption	50–190°C
The temperature to form carbon monoxide	65°C
The temperature to form carbon dioxide	225°C
carbon dioxide formed	8.5 vol %
Carbon monoxide formed	4.25 vol %
Oxygen not consumed	4.1 vol %
Fuel consumption	47 kg/m³
air requirement per m³ of rock	524 Sm³/m³
Air-to-fuel ratio	11.15 m³/kg rock
Air-to-oil ratio	2428 Sm³/m³

difference between the temperature of the device and average heating temperature of the sample indicates the presence of an interaction within the sample materials with varying temperatures. This provides evidence that the heavy flow of oil under this condition is possible.

Figure 5 shows the results of the heavy oil sample oxidation in the cell and the gases formed as the opera-

Figure 5: Oxidation of asphalt and heavy oil from the Ghareb Formation

combustion, the amount of CO_2 increased, which is called high-temperature combustion (HTC).

The CO evaluation showed that the average percentage of CO was less than CO_2, which implies that the combustion process is going forward and will be completed successfully **(Mahasneh, 2012)**.

Table 2 shows the rate of fuel consumption (available fuel) through laboratory tests to be 47 kg/m³, and this rate might exceed as in the Shannon field with 49 kg/m³. Moreover, CO_2 formed at 225°C. Experimental data **Table 2** shows that the required average air is 524 Sm³/m³ for burning rocks, and the heating value of the fuel is high.

3.3. *Toe-to-heel air injection in-situ combustion process*

The benefits of this modern method are as follows **(Turta, 2018):**
- Increased control over the ISC front propagation compared to conventional ISC process; ISC front breakthrough always at the toe and progressive advancement towards the heel;
- Easier to implement when heavy oil has some mobility at reservoir conditions, otherwise initial hot communication is needed;
- Easy to implement using existing facilities and horizontal wells (HWs), especially if HWs are placed near the bottom of the oil layer.

4. Pilot project for ISC from toe-to-heel by air injection (THAI)

The pilot project includes drilling a vertical well for air injection in the upper reservoir, and a horizontal well for production at the bottom of the reservoir. The application of this technology in-situ, involves the process of combustion in the stable location of the HTC interface from the top to the bottom of the heavy reservoir.

This depends on the vertical and horizontal permeability and porosity of the reservoir for helping the propa-
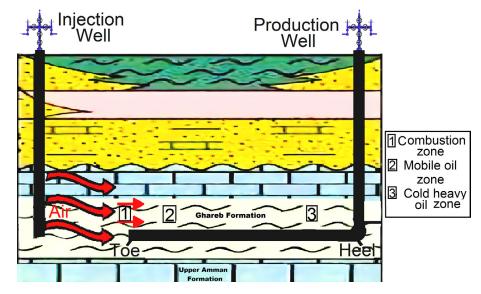

Figure 6: Schematic diagram of the THAI process

Table 3: Design criteria for the pilot project

Volume of air injected for the first stage	6.877×10⁶ Sm³	Volume of air injected for the second stage	17.7×10⁶ Sm³	Volume of air injected for the third stage	13.74×10⁶ Sm³
Time required for the first stage	137 days	Time required for the second stage	176 days	Time required for the third stage	137 days
Air requirement per m³ of rock	524 Sm³/m³	Air flux	78.6 Sm³/m² day	Compressor horsepower requirement	3945.12 kW
Maximum air injection pressure	4091.349 kPa	Maximum air rate	100379.2 Sm³/day	Oil displaced per unburned reservoir	7560 m³
Total time for pilot project	450 days	Total air for pilot project	31.44×10⁶ m³	Oil displaced per burned	8208 m³
Air oil ratio	2428 Sm³/m³	Overall recovery efficiency	65% to 69%		

gation of the combustion front direction to the horizontal well to provide displacement of the oil from the reservoir. **Figure 6** shows a schematic diagram of the THAI process.

Based on the results obtained from the laboratory experiment as shown on **Table 2**, and the criteria that must be found in the field such as depth, viscosity, porosity, thickness, area, oil saturation, water saturation, fuel deposit, air requirements and the hydrocarbons all lead to the possibility of applying this THAI technology in the formations of the Ghareb in the Wadi Rajil-Hamzeh area in the Azraq Basin.

The amount of fuel produced from the burning zone ranged from medium to high. The amount of fuel consumed increases with the increasing viscosity of oil and saturation of rocks. Based on the results obtained in the field tests globally, the thermal methods can be used to produce heavy oil. **Table 3** shows that it is possible to stimulate the reservoir with methods of thermal recovery, such as the ISC process in the Wadi Rajil-Hamzeh area in the Azraq Basin. **Table 3** shows the parameters of the design of the THAI ISC process. Several authors have provided procedures for designing the ISC process (**Nelson and McNeil, 1961; Parrish et al., 1962; Gates and Ramey, 1980; Fassihi et al., 1981; Sarathi, 1998**).

The THAI process burns some oil in the underground sediments in such a way that the residual oil flows to the surface on its own through production wells. The oil displaced for each volume might be produced from the combustion reservoir, heavy oil reservoir, and some unguided areas of the fire front through a combination of gravity and hot gas movement (**Tverberg, 2007**). **Tverberg (2007)** indicated that it is expected that THAI will recover 70%–80% of oil originally in the pilot project.

It has been shown that the THAI process can still operate stably for a wide range of reservoir permeabilities and types and degrees of geological heterogeneity. However, the degree of heterogeneity affects the pattern of oxygen utilization, and geological heterogeneity affects fuel concentration and thereby the progression of the combustion front (**Ado et al., 2019**).

In this study it is possible that THAI will recover 65 to 69% of the oil originally in the pilot project. This finding coincides with that of (**Tverberg, 2007**).

5. Results and discussion

The experimental laboratory tests helped to obtain the primary in-situ combustion parameters such as fuel requirements, air requirements, reaction peak temperature, oxygen utilization and effluent gas analysis of combustion. These parameters provide the possibility to apply ISC from toe-to-heel air injection (THAI) in the Wadi Rajil–Hamzeh field. The concept of injection through the THAI combustion process involves the production

of heavy oil by drilling a vertical injection well at the top of the reservoir and a horizontal production well located along the bottom of the reservoir.

Air is pumped in through the vertical injection well and the combustion front zone is formed which propagates from the injection well towards the horizontal production well from the THAI. The air injection is continued in such a manner that it moves towards the combustion front. The oxygen reacts chemically with oil to provide the coke for combustion. In the beginning of this process, the temperature is low and involves LTO. It increases gradually until it reaches high-temperature oxidation (HTO) in which the combustion reaction is between oxygen and oil in a porous media. The combustion gases that are produced lead to the mobility of fluids downstream until they reach the horizontal production well. A small area of mobile oil is formed ahead of the combustion front. The heavy oil reservoir has a high viscosity of oil in the area far from the combustion front which is called the cold heavy oil zone as shown in **Figure 6**. The combustion front process continues to progress while maintaining the rate of air injection for the continuity of the process. **Table 3** shows that the required air for the project is 31.44 x 10^6 m^3, and the minimum air flow required to sustain combustion is 78.6 Sm^3/m^2 day from the front.

The volume of oil removed per burning is 8208 m^3, and the amount of oil produced from the non-combusted reservoir area is 7560 m^3. Total oil extraction from the burned and non-burned area is 15768 m^3 as we know the productivity of HWs is four to five times more than vertical wells. Furthermore, the air-oil ratio is 2428 Sm^3/m^3. Considering that the productivity of HWs is between four to five times that of vertical wells, the productivity per day becomes 212.94 m^3. Based on these results of the laboratory experiment, they can lead us to apply the project in the future to produce oil from the study area.

6. Conclusion

- Through exploratory wells, the presence of heavy and asphalt oil was demonstrated in Wadi Rajil-Hamzeh-Wadi Al Ghadaf area in the formations of the Ghareb (Maastrichtian) and Upper Amman, (Campanian-Santonian) region.
- Formations of these deposits of hydrocarbons range from 680 to 1650 m in the Ghareb and from 1310 to 2040 m in Upper Amman Formation.
- Accumulation of hydrocarbons showed an uneven distribution, from small spots to cracks and cavities filled with asphalt and heavy oil and were directly connected with the porosity and cracks of the collected rocks. Reservoir rock limestone, dolomite, and sandstone interferences were found because of the repeated number of core samples extracted from different wells which showed hydrocarbons.

- The analysis of oil and asphalt showed that the asphalt contained a sulphur content in the range from 9.92% to 11.65% with a melting point of 79°C.
- The amount of the original hydrocarbons present is probably 800 million m³ (five billion barrels).
- Based on laboratory experiments with the oxidation cell device, the design criteria were obtained for a pilot project with thermal conditions THAI, which can be applied when drilling a vertical well for injection and another horizontal well for production.
- The productivity of HWs is four to five times more than in vertical wells; furthermore, the air oil ratio is 2428 Sm³/m³.
- The production rate of oil is 47.32 m³/day. Given that the productivity of HWs is between four to five times that of vertical wells, it implies that productivity per day becomes 212.94 m³.

7. References

Papers:

Ado, M.R., Greaves, M. and Rigby, S. (2019): Numerical simulation of the impact of geological heterogeneity on performance and safety of THAI heavy oil production process. Journal of Petroleum Science and Engineering, 173, 1130-1148. doi:org/10.1016/j.petrol.2018.10.087.

Chaperon, I. (1986): Theoretical Study of Coning Toward Horizontal and Vertical Wells in Anisotropic Formations: Subcritical and Critical Rates. SPE Annual Technical Conference and Exhibition, 5-8 October, New Orleans, Louisiana, Society of Petroleum Engineers. doi: org/10.2118/ 15377-MS.

Gates, C. and Ramey Jr, H. (1980): A Method for Engineering In-Situ Combustion Oil Recovery Projects. Journal of Petroleum Technology, 32(02), 285–294. doi:org/10.2118 /7149-PA.

Giger, F., Reiss, L. and Jourdan, A. (1984): The Reservoir Engineering Aspects of Horizontal Drilling. SPE Annual Technical Conference and Exhibition, 16-19 September, Houston, Texas, Society of Petroleum Engineers. doi: org/10.2118/13024-MS.

Greaves, M., Xia, T. and Ayasse, C. (2005): Underground Upgrading of Heavy OIl Using THAI- 'Toe-to-Heel Air Injection'. SPE International Thermal Operations and Heavy Oil Symposium, 1-3 November, Calgary, Alberta, Canada, Society of Petroleum Engineers. doi: org/10.2118 /97728-MS.

Mahasneh, M. (2012): Determine factors affecting fuel availability and composition by cell oxidation during laboratory test for in-situ combustion. Contemporary Engineering Sciences, 5(4), 171-188.

Parrish, D., Rausch, R., Beaver, K. and Wood, H. (1962): Underground Combustion in the Shannon Pool, Wyoming. Journal of Petroleum Technology; Society of Petroleum Engineers, 14(02), 197–205. doi:org/10.2118/141-PA

Qteishat, A. and AL-Mahasneh, M.A. (2018): Hydrocarbons Potential in the Azraq Area. Open Journal of Geology, 8, 753-763. doi.org/10.4236/ojg.2018.88044.

Xia, T. and Greaves, M. (2002): Upgrading Athabasca Tar Sand Using Toe-to-Heel Air Injection. Journal of Canadian Petroleum Technology, 41(08), 51-57. doi: org/10.2118/02-08-02.

Books/thesis:

Burger, J., Sourieau, P. and Combarnous, M. (1985): Thermal methods of oil recovery (Vol. First). Gulf Publishing Company, Book Division, 430 p.

Fassihi, M., Gobran, B. and Ramey, H. (1981): Algorithm for computing in-situ combustion oil recovery performance. United States: Stanford Univ., CA (USA). Petroleum Research Inst, 29 p.

Nelson, T., and J.S. McNeil. (1961): How to engineer an in-situ combustion project; New York. lecture presented at University of Texas, 31 p.

Sarathi, P. (1998): In-Situ Combustion Handbook-Principles and Practices. Tulsa, United States: National Petroleum Technology Office, 423 p. doi:10.2172/3175.

Internet sources:

URL1: Turta, A. (2018). Toe-To-Heel Air Injection (THAI) Process. Retrieved from In-Situ Combustion (ISC), ALEX TURTA'S WEBSITE: https://www.insitucombustion.ca/ Advanced_THAI_Brochure.pdf (accessed October 2018).

URL2: Tverberg, G. (2007, August 28). Extracting Heavy Oil: Using Toe to Heel Air Injection (THAI). Retrieved from The Oil Drum:Canada: http://theoildrum.com/node/2907 (accessed October 2018).

SAŽETAK

Proces *Toe-to-Heel* utiskivanja zraka za *in-situ* spaljivanje nafte u ležištu: primjer iz bazena Azraq, Jordan

Tijekom istraživačkih i bušaćih aktivnosti u regiji Wadi Rajil (bazen Azraq) na sjeveroistoku Jordana utvrđeno je postojanje određenih akumulacija asfalta i teške sirove nafte u nekoliko litotipova vapnenca i dolomita unutar slojeva pješčenjaka. Potencijalne rezerve nafte iznose 800 milijuna m³ (pet milijardi barela) te zahvaćaju površinu od približno 1200 km² (120 000 hektara). Cilj ove studije bio je istražiti mogućnost primjene procesa *Toe-to-Heel* utiskivanja zraka za *in-situ* spaljivanje nafte u ležištu na polju Wadi Rajil-Hamzeh, za čije je provođenje predviđena izrada dviju novih bušotina. U sklopu pokusnoga projekta izradile bi se dvije nove bušotine, odnosno jedna okomita (utisna) bušotina kojom bi se zahvatilo područje bliže krovini ležišta te vodoravna (eksploatacijska) bušotina koja bi bila položena bliže podini ležišta. Primjenom ove tehnologije povećala bi se proizvodnost iz spomenutoga ležišta, smanjila bi se viskoznost nafte te bi se povećao koeficijent obuhvata ležišta istiskivanjem. Pokusnim projektom predviđeno je pridobivanje i do 212,94 m³ nafte na dan. Ukupno je predviđeno vrijeme za provedbu pokusnoga projekta približno 450 dana, a procijenjeno je da se njegovom primjenom može ostvariti iscrpak od 65 do 69 %. Dobiveni rezultati upućuju na mogućnost proširenja primjene iste tehnologije na cijelo područje Wadi Rajil-Hamzeh.

Ključne riječi:
Toe-to-Heel, utiskivanje zraka, teška sirova nafta, *in-situ* spaljivanje, horizontalna bušotina