Steam injection in porous media: Case study Wadi-Rajil, Jordan

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Hot fluid injection, the preferred method used in the recovery of heavy oil and in various mechanisms such as steam drive, cyclic steam injection, steam stimulation, has become the industrial method for increasing recovery. These methods were used to promote heavy oil recovery by reducing the viscosity of asphalt and heavy oil and increasing the mobility of oil in reservoirs. The experimental test was carried out on a core sample obtained from the Ghareb Formation in the Wadi-Rajil area using cold water, hot water, and steam injection. The maximum recovery of oil in the sample using cold and hot water was 9.75% and 27.3 % respectively. On the other hand, the recovery of oil using steam injection was 42.5%. Thus, steam injection yielded more oil than cold and hot water injections in this experiment; the steam injection influx rate was approximately 15 mL/min. The total oil recovery of the sample using these three mechanisms was around 80%. The steam injection can, thus, be considered a promising thermal recovery method for asphalt and heavy oil in the Wadi-Rajil area.

Keywords: Heavy oil; Steam injection; Steam influx rate; Sweep; efficiency; Yield oil.

Introduction

The high demand for oil and the increase in the difficulty of discovering large oil reservoirs, the reduction in reservoirs reserves, and the decrease in oil conventional reserves have led to an increased interest in heavy oil and tar sands. The amount of heavy oil and natural bitumen available worldwide is estimated to be around 69 $x10^{12}$ m^3 (434 billion barrels) and $103x10^{12}$ m^3 (651 billion barrels) respectively (Meyer and Attanasi, 2003). Jordan's heavy oil composition is about 8 $x10^{10}$ m^3 (5 billion barrels). The application of different thermal methods to reduce the oil viscosity in oil reservoirs is becoming increasingly common. One such thermal methods to increase oil recovery is steam injection. Willman *et al.* (1961) demonstrate that steam flooding produces significantly higher oil recovery than hot water flooding at the same temperature. This is mainly due to steam distillation. Closmann (1967) estimates that oil recovery with steam distillation ranges from 5–19% of the original oil in place (OOIP) for various crude oils at a steam temperature. Ali (1974) reports that 5–10% of the heavy oil recovery by steam flood may be due to steam distillation, and as much as 60% of the recovery of some light oils may be attributed to the same mechanism. Jabbour *et al.* (1996) demonstrate that high oil recovery efficiency is affected more by the thermal effects in the steam-flooding process compared to water flooding. Steam injection, as a successful process in enhanced oil recovery (EOR), is the most reliable method for recovering more heavy oil from oil reservoirs (Elliott *et al.*, 1999). According to laboratory tests, both hot-water injection and steam injection recover more oil than cold-water flooding. As described in previous studies, the main factors in steam and hot-water injection that increase oil recovery are the reduced viscosity and thermal swelling of the oil (Lashanizadegan *et al.*, 2008).

Steam injection rate is an important factor that improves the heating effect of the steam injection operation; The higher the steam injection rate, the higher the total heat energy injected (Dong *et al.*, 2020). An effective steam injection rate improves the heating effect of steam injection. An analysis of the effect of a steam chamber indicated that the cumulative steam injection-oil rate is approximately 2.7 optimum steam injection rate for 100 tons per day (Rabe *et al.*, 2020).

2. Materials and Methods

2.1 Geological settings

The widespread distribution of bitumen and asphalt bearing rocks of the Maastrichtian age in the Azraq region has been established through the drilling of four oil exploratory wells in the Wadi-Rajil area (**Figure 1**). The richest occurrences of asphalt and heavy oil are found in the Ghareb Formation of the Late Cretaceous age. **Figure 2** shows the lithostratigraphy cross-section of the Wadi-Rajil area.

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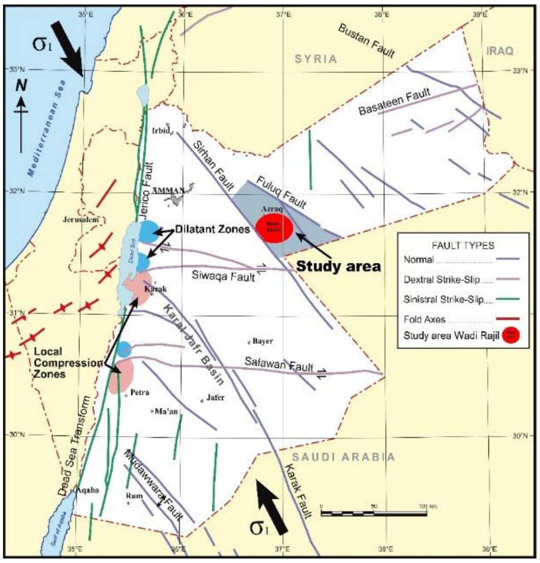

Fig.1 Location of Wadi-Rajil, Jordan. (Naylor *et al.*, 2013)

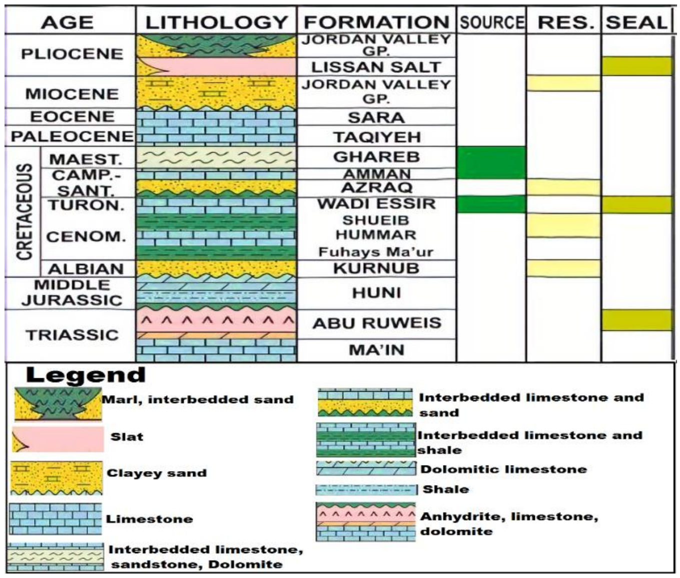

Fig. 2 Lithostratigraphy cross-section of the Wadi-Rajil area (Qteishat and Mahasneh, 2018)

The average thickness of Ghareb Formation was estimated to be about 30 m, and it consisted of dolomite and limestone. The examined core sample mainly consisted of limestone and dolomite. It can be described as light grey color, with fine medium-hard crystalline, layers of slightly porous dolomitic sandstone, and a patch of asphalt. Its porosity can be described as vuggy to cavernous, with fractures filled with asphalt and heavy oil as shown in **Figure 3**.

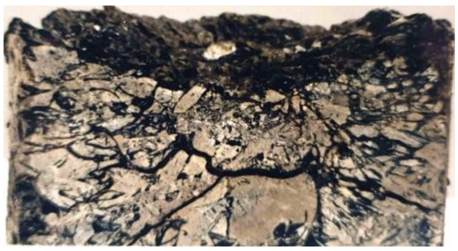

Fig. 3 Core sample from Ghareb Formation of Wadi Rajil of Jordan

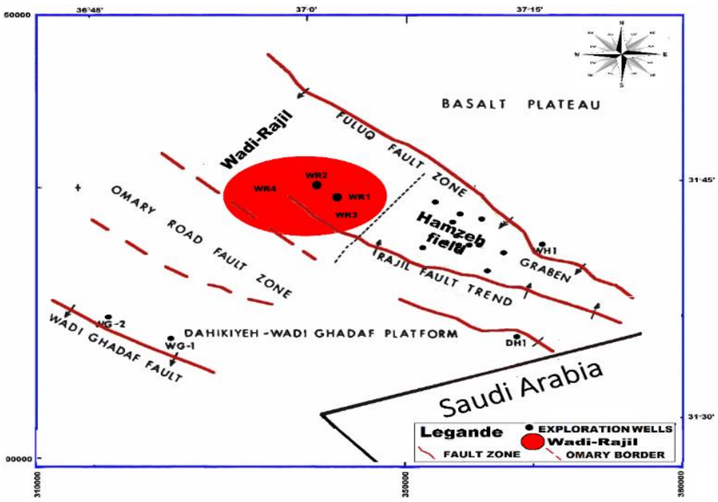

Fig. 4 Structure map of Wadi-Rajil in Azraq Basin (Qteishat and Mahasneh, 2018)

Table 1 Physical and chemical properties of asphalt and heavy oil of reservoir

Depth	800 (m)
Gravity of asphalt	9–10 (°API)
The gravity of heavy oil	17 (°API)
Density of asphalt	1 (g/cm^3)
The density of heavy oil	0.95 (g/cm^3)
Porosity	17 (%)
Permeability	76.97 (μm²)
Average thickness	30 (m)
Viscosity	400–2000 (mPa.s)
Oil saturation	70 (%)
Reservoir temperature	40 (°C)
Types of hydrocarbons	
Saturates	4.5 (wt%)
Aromatics	25.2 (wt%)
Sulphur	4.5–9.9 (wt%)
Melting point of Asphalt	79 (°C)
Metals	
Nickel	80 (ppm)
Vanadium	155 (ppm)

The physical and chemical properties of asphalt and heavy oil of the reservoir in the study area are listed in **Table 1**. Heavy oils differ from light oils by viscosity at the reservoir temperature, density, low API gravity, and contents such as oxygen, nitrogen, and Sulphur compounds and heavy metals such as contaminants of nickel and vanadium. The Azraq Basin is located in the northeast of the

Hashemite Kingdom of Jordan, which includes the region of the Wadi-Rajil wells that are located in the south of the Hamzeh oil field in the Azraq Basin as shown in **Figure 4**.

2.2 Laboratory measurements for fluids injection in porous media

The natural core sample used for this study is from the Ghareb Formation of the Wadi-Rajil area of Jordan. These samples were ground in the laboratories of the Al-Huson University College. Subsequently, the entire sample was mixed. The schematic illustrates the equipment used in the experiment for oil extraction from the porous media of the core sample. **Figure 5** shows the apparatus used for injection in the porous media. The cell was filled with the sample. The pressure gauge was mounted on the apparatus to record the pressure during the process. The temperature controller was mounted on the apparatus to record the temperature during the process. Each run of cold water, hot water, and saturated steam required 2 hours. Following this, cold water, hot water, and steam were injected. The hot water and steam were transmitted into the cell sample with different influxes rate with the use of a pump. The hot water and steam were produced by a steam generator by making adjustments in the outlet temperature. The injection line was isolated to reduce heat loss. The produced fluids were then collected in a cylinder. After the sample was prepared, cold water, hot water, and steam produced by the steam generator were injected into the sample at different temperatures (25^{o}C, 30^{o}C, 40^{o}C, 45^{o}C, 50^{o}C, 60^{o}C, 70^{o}C, 80^{o}C, 90^{o}C, 100^{o}C, 110^{o}C, 120^{o}C, and 130^{o}C) respectively. After finishing each run, the steam generator was turned off and water injection was continued until reaching the ambient temperature.

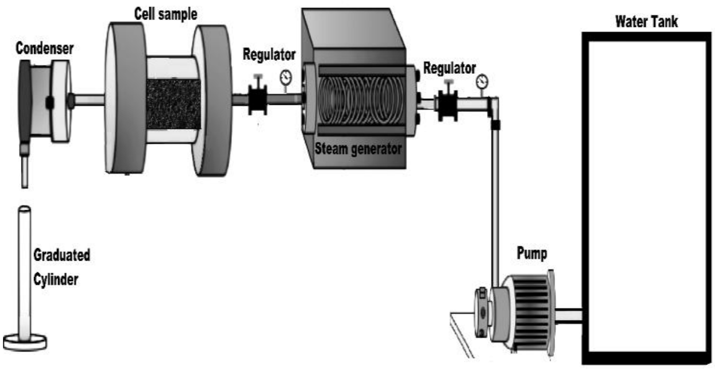

Fig. 5 Scheme of the steam injection experiment in porous media

2.3 Pilot project of steam drives

This study also includes drilling (five-spot pattern wells), with four production wells and one steam injection wells to be drilled in the middle of the pattern. The parameters required for undertaking this pilot project are available in this reservoir. These parameters include a reservoir depth of 800 m, a thickness pay zone of 30m, and an area of 5000 km^2. Additionally, a porosity of 17%, permeability of 76.97 µm², 2000 mPa.s viscosity, 70% oil saturation, and 1 g/cm3 density of asphalt are also available. The area of a five-spot pattern is 4046 m^2, with a depth of 800 m, 15 m thickness, 21.50 cm casing diameter, and 7.27 cm tubing diameter. **Figure 6** shows the pilot project of steam drives five-spot patterns wells.

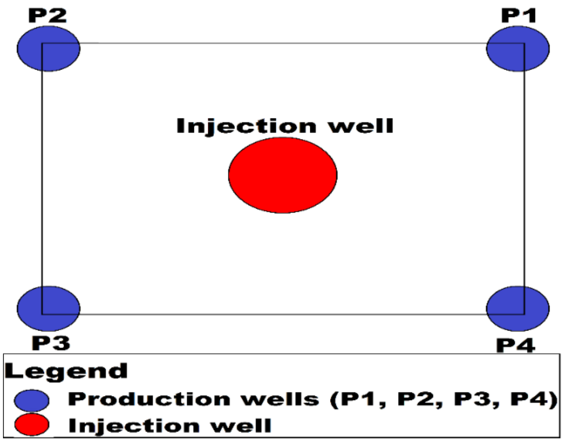

Fig. 6 Pilot project of steam drives five-spot patterns wells

The well model of steam injection requires stimulation for 10 cycles and the steam rate of the injection of the cycle is 120 m^3/day, and the duration of steam injection for 10 days. The reservoir is immersed by steam flooding for 3 days. The steam temperature increases up to 260^{o}C and the steam quality at the surface up to 80%. **Tables 3**, **4**, **5**, and **6** show the quantity of heat injected on the wellhead to be 292 x10^6 kJ. The cumulative heat loss in the well formation crossed Q_{spi}=7.95x10^6 kJ/day depending on the following parameters: radius of the well, the radius of the tubing, the diameter of the cement ring around the casing, steam temperature, surface temperature, specific coefficient of overall heat exchange, and coefficient heat transfer in the annulus. The quantity of heat run in production formation per day was Q_{spi}=281.4 x10^6 kJ. The cumulative quantity of heat run into the well for production formation after 10 days of injection was 2846 x10^6 kJ. The quality of steam run into the production formation on the first day ranged from 76.45% to 68.20%. The heat transferred into the adjacent Ghareb Formation rock depended on the enthalpy of the steam and heat capacity of the rock saturated with fluids. The heat efficiency for preheating a production formation E_i=0.97. The number of heat transfers into adjacent Ghareb Formation was 6.52 x10^{6}kJ. The quality of steam in Ghareb Formation after n days of injection

Q_{spi}=575x10^6 kJ and X_{spui}=73.45%. The radial position of heating stratum r_{ai}=3.59 to 11.378 m; r_{st} radius of steam penetrating formation ranged from 2.879 m to 9.137 m. Accumulation of heavy oil after the daily injection of steam N_i=187.26 m^3/day. Concerning the statistical data provided above, it should be noted that thermal immersion is similar to steam injection, which is suitable for the immersion of high viscosity liquids. Such immersion gives areal sweep efficiency with sufficient injection and when continued over a long period to cover a given well pattern.

Table 2 Physical criteria and constants

Diffusivity coefficient heating	0.004 m^2/h	Specific coefficient of overall heat exchange	6.2835 kJ/m^2.h.^{o}C
Formation temperature	35^{o}C	Geothermal gradient	0.03^{o}C/m
Surfers temperature	20^{o}C	Porosity	17%
Water saturation	30 %	Oil saturation	70%
Rock density	2000 kg/m^3	Water density	1000 kg/m^3
Specific heat rock	1000 J/kg.^{o}C	Specific heat water	4189 J/kg.^{o}C
Specific heat oil	2500 J/kg.^{o}C	Conductivity of rock	8.37kJ/h.m^2
Injection pressure	5066 kPa	Injection steam temperature	262^{o}C
Enthalpy of steam	3 x10^6 J/kg	Enthalpy of water	1.2x10^6 J/kg
Latent heat of steam	1.8 x10^6 J/kg	Quality of steam	80%
Steam injection rate	120 m^3 /day		

Table 3 The quantity of heat transfers in the adjacent formation and production formation and quality of steam

Day	T_{spi}x10^{-3}	I_{sa} (%)	Q_{sai}x 10^6 kJ	Q_{sai} x10^6 kJ	X_{spui} (%)	E (%)
1	0.001216	2.3	6.52	6.52	73.45	0.97
2	0.00243	3.16	8.97	15.49	72/31	0.96
3	0.00364	4.13	11.72	27.21	71.36	0.958
4	0.00486	4.60	13.02	40.23	70.95	0.954
5	0.00608	5.30	15.03	55.26	70.16	0.947
6	0.00729	5.78	16.37	71.63	69.65	0.942
7	0.00851	6.22	17.62	89.25	69.16	0.937
8	0.00972	6.63	18.79	108.04	68.69	0.933
9	0.001094	6.80	19.30	127.33	68.52	0.932
10	0.00121	7.10	20.13	147.46	68.20	0.929

Table 4 Volume of oil pores and accumulation of displaced oil

No. day	Volume of pores of the heated zone (m^3)	Volume of oil from heated zone (m^3)	Ni-cumulative quantity of oil extracted	Ratio oil /steam
1	82.26	53.47	18.71	0.1559
2	162.35	105.52	36.93	0.1538
3	241.98	157.28	55.05	0.1529
4	321.88	209.22	73.22	0.1525
5	400.45	260.29	91.10	0.1518
6	478.07	310.74	108.76	0.1510
7	555.87	361.31	126.46	0.1505
8	632.04	410.82	143.78	0.1497.
9	744.81	484.13	169.44	0.1568
10	823.16	535.05	187.26	0.156o

Table 5 The quantity of the daily values of heat and frontal radius of heat and steam

No	Q_{spui} (st+w) x10^6 (kJ/hr)	Q_{spui} st x 10^6 (kJ/hr)	t_{spi} x10^{-3}	r_{ai} (m)	r_{st} (m)
1	11.24	7.23	1.216	3.59	2.879
2	11.26	7.23	2.43	5.o53	4.050
3	11.29	7.26	3.64	6.169	4.823
4	11.32	7.28	4.86	7.115	5.698
5	11.32	7.29	6.08	7.936	6.367
6	11.33	7.30	7.29	8.671	6.959
7	11.34	7.30	8.51	9.350	7.505
8	11.34	7.31	9.72	9.97	8.008
9	11.35	7.31	10.94	10.823	8.691
10	11.35	7.32	12.1	11.378	9.137

3 Results and discussion

In the first stage, cold water with a temperature ranging from 25°C to 45°C was injected, with different influx rates on each run as recorded in **Table 7**. The experimental results of the cold-water injection are listed in Table 7. **Figure 7** presents the oil recovery variation on temperature ranging from 25°C to 45°C; the most amount of oil recovery was observed between 2.5 and 9.75%. The enthalpy content of cold water was low, and the residual oil saturation was higher.

Table 7 Results of the cold water injection

No	Weight sample (g)	Influx rate (mL/min)	Temperature (°C)	Oil content (g)	Oil recovery (%)
1	20	12	20	0.49	2.5
2	20	13	30	0.70	3.5
3	20	14	40	1.68	8.4
4	20	15	45	1.95	9.75

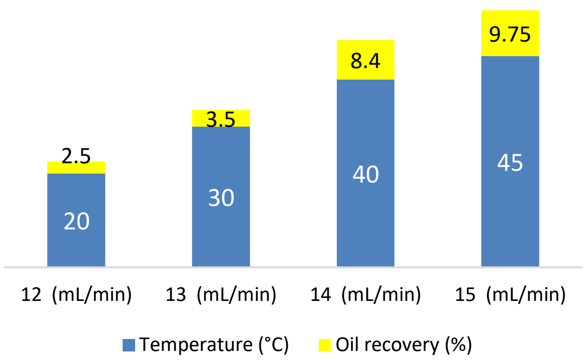

Fig. 7 The relation between the cold water injection and oil recovery

In the second stage, after the sample was prepared, hot water with temperatures ranging from 50°C to 90°C was produced by the steam generator and subsequently injected with different influx rates on each run as shown in **Table 8**. The experimental results of hot water injection are listed in Table 9. The oil recovery of each temperature (50°C, 60°C, 70°C, 80°C, and 90°C) was 12.1%, 15.9%, 19.7%, 23.5 %, and 27.3% respectively. It indicates that oil recovery increases with an increase in temperature. At increased temperature, oil viscosity decreases, and oil mobility increases significantly. The residual oil saturation remains the same as in cold water injection. The enthalpy content of hot water is higher than that of cold water.

Figure 8 shows that oil recovery increases as temperature increases and the mechanism of hot water flooding are such that the increase in temperature significantly reduces the viscosity of heavy oil. In the third stage, the sample is prepared and steam is produced by the steam generator and injected at temperatures ranging from 100°C to130°C with different influx rates on each run as shown in **Table 9**. The experimental results of the steam-water injection are listed in Table 9. The oil recovery of each temperature (100°C, 110°C, 120°C, and 130°C) is 31.1%, 34%, 38.7%, and 42.5% respectively.

Table 8 Results of hot water injection

No	Weight sample (g)	Influx rate (mL/min)	Temperature (°C)	Oil content (g)	Oil recovery (%)
1	20	12	50	2.5	12.1
2	20	13	60	3.18	15.9
3	20	14	70	3.94	19.7
4	20	15	80	4.70	23.5
5	20	16	90	5.50	27.3

Figure 9 shows that the residual oil saturation in the steam stage was considerably lower than the residual oil saturation in cold and hot waters. Higher quality of steam has a higher enthalpy content and a huge specific volume, which results in higher oil displacement. **Figure 10** and **Table 10** show the experimental summary results of the three stages of cold water, hot water, and steam injection influx. According to the results of the laboratory experiment, the steam injection method can be applied in the future to produce oil from the Wadi-Rajil area.

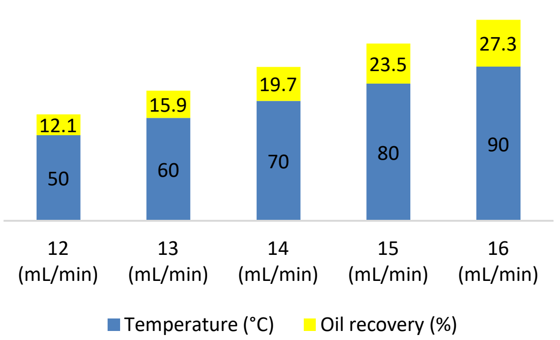

Fig. 8 The relation between hot water injection and oil recovery

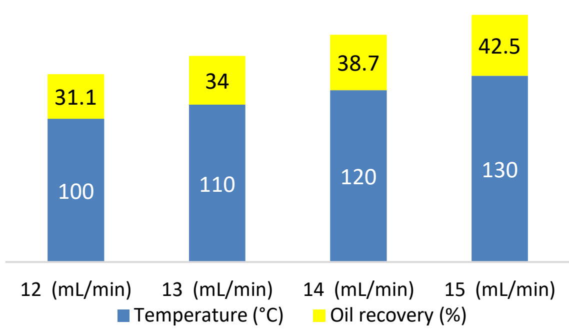

Fig. 9 The relation between the steam injection and oil recovery

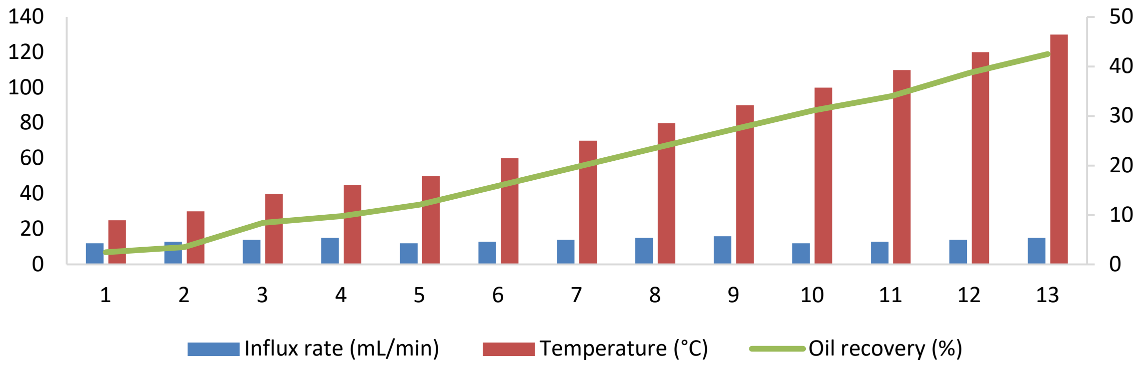

Fig. 10 Summary results of three stages: cold water, hot water, and steam

Table 9 Experimental results of steam injection

No	Weight sample (g)	Influx rate (mL/min)	Temperature (°C)	Oil content (g)	Oil recovery (%)
1	20	12	100	6.22	31.1
2	20	13	110	6.80	34
3	20	14	120	7.74	38.7
4	20	15	130	8.5	42.5

Table 10 Summary results of three stages: cold water, hot water, and steam

Influx rate (mL/min)	Temperature (°C)	Oil content (g)	Oil recovery (%)
12	25	0	2.5
13	30	0.9	3.5
14	40	0.5	8.4
15	45	0.3	9.75
12	50	2.5	12.1
13	60	3.18	15.9
14	70	3.94	19.7
15	80	4.70	23.5
16	90	5.50	27.3
12	100	6.22	31.1
13	110	6.80	34
14	120	7.74	38.7
15	130	8.5	42.5

Conclusions

The experimental results obtained here have come up with different conclusion such as: the maximum recovery of oil using cold water injection (9.75%), hot water injection (27.3%), and steam injection (42.5%). Steam injection yields more oil recovery than cold and hot water injections. Maximum oil recovery reached 42.5% when the steam injection rate was 15 mL/min. The steam injection improved heavy oil recovery due to the decrease in oil viscosity and the increase in thermal expansion of oil. The high steam quality runs generated a larger volume for each temperature than the low steam quality. The steam quality had higher enthalpy and larger specific volume, which resulted in higher oil displacement. The total oil recovery of the sample using these three mechanisms was approximately 80%. The process of steam injection can be considered a promising thermal recovery method for asphalt and heavy oil in the Wadi-Rajil area in Jordan.

Nomenclature

E	=Heat efficiency a preheating a production formation	[%]
$F(ti)$	=Function dimensionless time	[-]
I_{inj}	=Enthalpy of steam temperature injection	[kJ/kg]
Q_{fpi}	=Cumulative of heat losses in the well formation crossed	[kJ/hr]
Q_{sai}	=Heat transfer into adjacent formation	[(kJ]
Q_{spi}	=Quantity of heat run in production formation	[kJ/day]
$Q_{spui}st$	= (steam): Quantity of heat for steam	[kJ/hr]
$Q_{spui}(st+w)$	=steam, water, Quantity of heat for steam and water	[(kJ/hr]
r_{ai}	=Radial position of heating stratum	[m]
r_{st}	=Steam radius penetrate formation	[m]
t_i	=Time of injection	[hr]
T_{spi}	= Dimensionless time in producing formation	[-]

X_{spi} =Quality of steam into strata after n day of injection [%]
X_{spu} = Quality of steam into strata after n day of injection [%]

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