Effectiveness of recovering heavy oil by thermal and chemical processes from inside a petroleum reservoir

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ABSTRACT

Sand pack technique indicates the recovery factor of heavy oil through hot water and CTAB flooding. Hot water flooding at 90 ˚C of 1.5 pore volumes gave 11.69 % compared to other temperatures of hot water. CTAB flooding of 1.5 pore volumes represent the optimized conditions for the better heavy oil recovery of 13.08 %. The hot water flooding followed by CTAB flooding has a recovery factor of 14.10 % than the individual hot water flooding and CTAB flooding respectively. From the sand pack column, it is concluded that the recovery of heavy oil was 4.10 % over the industrial recovery practices in middle east. CTAB surfactant used in the research work proved to be better when compared to other surfactants in 139 terms of developing emulsion with smallest possible concentration, salinity stability, temperature stability and heavy oil recovery. The recovery of heavy oil was investigated in core flooding operation using hot water and CTAB flooding. Recovery of heavy oil using hot water followed by CTAB flooding was 11.17 % higher than the individual hot water flooding of 7.89 % and individual CTAB flooding of 9.63 %. Hot water followed by CTAB flooding recovered higher quantity of heavy oil in sank pack column as well as core flooding operations. Core flooding operation implemented sandstone core sample which has low permeability and porosity than unconsolidated sand which made the recovery of heavy oil is lower in the core flooding technique. Techno-economic analyses for heavy oil recovery in different situations were calculated and found to be viable. The research work was carried out with heavy oil and reservoir sample in the laboratory scale proved to be extremely effective and the techniques have to be further tested in the heavy oil fields.

Keywords: Petroleum,reservoir,chemical,thermal,oil,heavy

1. INTRODUCTION

There are several categories of petroleum basins prepared by the U.S. Geological Survey (USGS) (2007) as shown in the Figure 1. Klemme basin type IICa is the appropriate sketch for heavy oil deposits that comprises 15 basins which accounts 1,160 billion barrels of heavy oil in place. Enormous quantities of heavy oil were contributed by Orinoco Oil Belt of eastern Venezuela and the western hemisphere. Small quantities of heavy oil were found in the Interior Craton, Deltas and Fore-Arc basins (Penney, 2010).

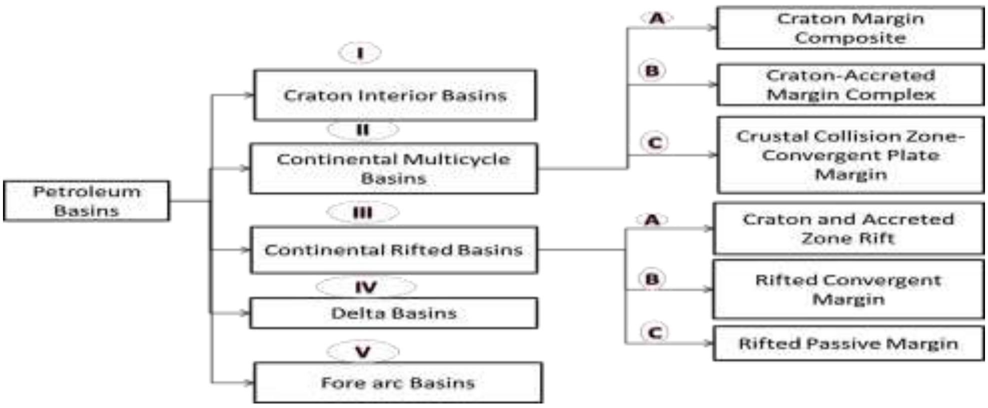

Figure 1: Classification of Petroleum Basins

Santhal field is located in the Southern part of the heavy belt of North Cambay basin. The field was explored and put on production in the year 1971 and 1974. Balol field was discovered in the year 1985. The pilot study on heavy oil recovery in the Santhal and Balol fields was successful in 1990 and the commercial scale production was started in 1997.

In Santhal field, the reservoir thickness is 150 m in the depth of 900 m along with the 28 % of average porosity and 8 to 15 Darcy of permeability. The average reservoir temperature and pressure are 70 ˚C and 100 kg/cm^2 at a depth of 990 m below MSL (Doraiah et al., 2007; Panchanan et al., 2006; Chattopadhyay et al., 2004). A typical characteristic of Santhal field and Balol field is shown in the table 2.9.

The exciting data on the heavy oil production in Mehsana are shown in the table 2.10. The total heavy oil production was 533,465 bbl/d obtained from 3,686 oil wells in the year 2003. The production data of heavy oil implies that the heavy oil recovered from the shallow depth reservoir and many wells was drilled for the production.

Highly viscous heavy oil well has shown less production. ˚API and viscosity of heavy oil produced in the previous years was less viscous compared to the heavy oil in the current condition. The prolongation of time will alter the nature of heavy oil namely increases in viscosity, molecular weight, boiling point and pour point due to the degradation of lighter hydrocarbons.

Table 2: Typical characteristics of Santhal field and Balol field in middle east

Reservoir Characteristics	**Santhal field**	**Balol field**
Formation	Sand Formation	Sandstone
Depth (m)	1,000	1,000
Reservoir temperature (˚C)	70	70
Gross pay/Net pay (m)	3-29/3-15	5-60/3-15
Porosity (%)	28	28
Connate water saturation (%)	30	30
Oil saturation at start (%)	70	70
Permeability (mD)	3,000-8,000	3,000-5,000
Oil viscosity (mPa.s)	100-450	50-200
˚API	16˚	18˚
Sulphur content (%)	0.14 %	0.14 %
Reservoir pressure (psi)	1,450	1,450
OOIP (MMbbl)	128	300
Injection pressure (psi)	1,300-1,600	1,200-1,500
No. of injection wells	30	30
No. of production wells	75	105

Table 3: Heavy oil production data (Pennwell, 2005)

Heavy oil Fields	**Year of discovery**	**Depth (m)**	**˚API**	**Oil wells**	**Production (bbl/d)**
Balol	1970	1,000-1,097	16˚	82	3,575
Bechraji	1987	871	16˚	110	2,100
Lanwa	1972	1,401-3,301	15˚	74	775
Santhal	1974	1,000-1,097	17˚	120	7,200

Oil and Natural Gas Corporation (ONGC) plays a vital role in the exploration and production of heavy oil in the Mehsana. Many heavy oil wells were explored and drilled, but the production of heavy oil found to be challenging due to high viscosity and lack of technology suitable for heavy oil recovery.

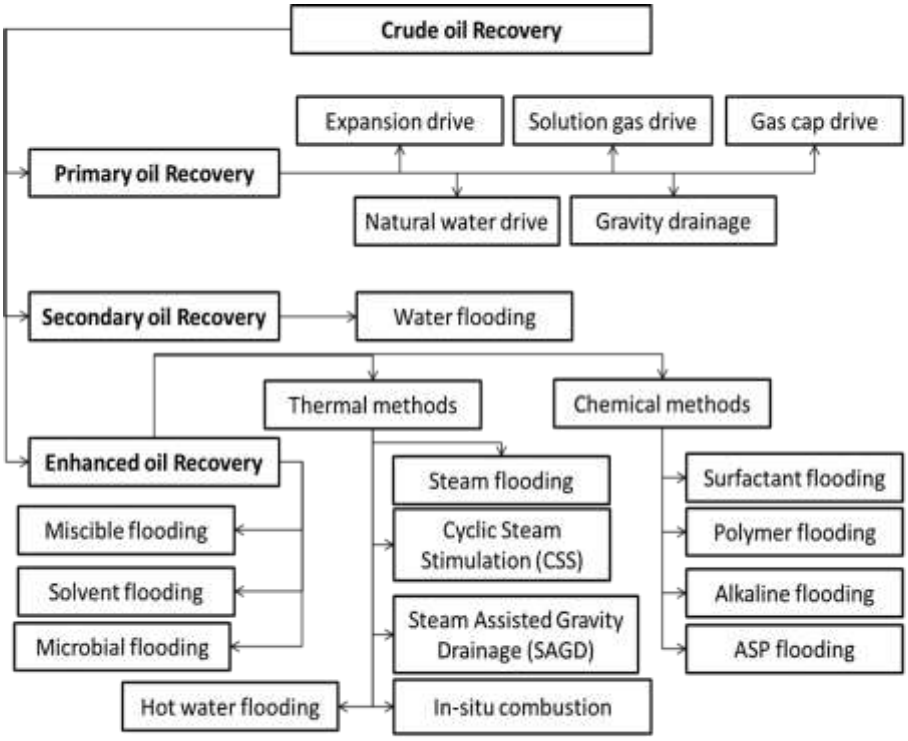

Figure 2: Crude oil recovery methods

2. CHARACTERIZATION OF HEAVY OIL

The heavy oil characterization is one of the main steps in heavy oil production. The comprehensive information of heavy oil such as nature, distillate products, physical and chemical properties is helpful in selecting the suitable method for the recovery of heavy oil.

i. Determination of Water Content

Heavy oil and water were separated by the ASTM D4006. Dean and Stark apparatus is used for the direct determination of water content in crude oil by distillation process. Initial amount of crude oil was taken and weighed. Equal volume of heavy oil and toluene was added in the round bottom flask. Insert a loose non-absorbing cotton plug into the top of the condenser.

Boil and reflux the content until most of the water has been collected in the trap. Minimum reflux of two drops per second was adjusted with the heating mantle to obtain complete heavy oil and water separation. Toluene and water are immiscible in which water is collected from the bottom. The water content present in the heavy oil is calculated from the formula given below. Correction factor helps to prevent deviations in the calculation due to toluene.

$$\text{Water content (\%)} = \frac{[\text{Vol. of Water Distilled}] \times 100}{[\text{Correction Factor} \times \text{Wt. of heavy oil taken}]} \qquad \text{- (1)}$$

ii. Determination of Specific Gravity by Hydrometer

Hydrometer method is a suitable method for determining the relative density of viscous oil by allowing sufficient time for the hydrometer to attain equilibrium. The procedure is followed as given in the ASTM D1298-12b. A hydrometer reading was obtained at 15 ˚C to calculate the ˚API of the heavy oil. The ˚API of crude oil is calculated by the formula given below.

$$^\circ\text{API} = \{141.5 / [\text{specific gravity of crude oil at 60 }^\circ\text{F}]\} - 131.5 \qquad \text{- (2)}$$

iii. Determination of Pour Point

The pour point of heavy oil was determined by ASTM D97. The ice was filled in the pour point apparatus, and the heavy oil was poured in the test jar until the level marked. The thermometer was filled in the rubber cork and inserted in the test jar. The test jar was placed in the jacket filled with ice.

The temperature at which the heavy oil ceases to flow was noted, and it is termed as pour point. Typically, the pour point of crude oil varies in the range from – 60 ˚C to 30 ˚C. Light crude oil with low viscosity has low pour point and heavy crude oil with high viscosity have high pour point.

iv. SARA Analysis

SARA analysis is the determination of individual constituents namely Saturates, Aromatics, Resin and Asphaltene present in the heavy oil. SARA analysis is useful in understanding the heavy oil nature, the stability and deposition problem of asphaltene in heavy oil. The overall procedure of SARA analysis is shown in the figure 3.1.

- **Asphaltene**

Heavy oil and n-heptane (1: 40) are taken in the round bottom flask. Close the lid and shake the round bottom flask completely and keep it for 2 days at room temperature. Shake the content in the flask twice a day and filter it in the Whattman filter paper No. 42. The asphaltene is retained in the filter paper and deasphalted oil is filtered. Dry the retained asphaltene in the filter paper and weigh in the balance.

$$\text{Wt. of asphaltene} = \frac{\text{Dry asphaltene}}{\text{Wt. of heavy oil taken}} \qquad -(3)$$

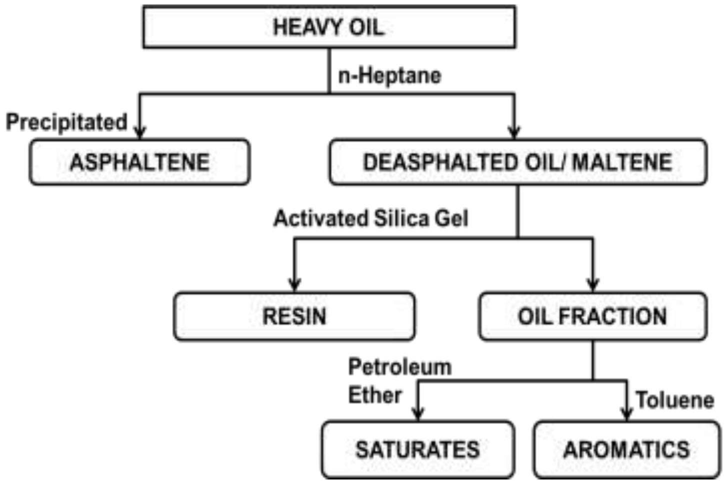

Figure 3: SARA analysis

- **Resins**

Take the deasphalted oil and add activated silica gel till the colour of the solution becomes light yellow. Resins get adsorbed in silica gel. Filter it and keep the filtrate for wax content determination. Extract the resins from the activated silica gel by soxhlation method.

Soxhlet apparatus contains toluene as reflux solvent for extracting resins from the silica gel. Extracted resins are kept in the hot air oven at 100 ˚C for solvent evaporation. Take the ultimate weight and calculate the resin percentage similar to asphaltene.

- **Wax**

Filtrate from the resins is taken and add 110 ml of acetone, then cool it to -20˚C for overnight. Pre-cooled funnel with pre-weighed filter paper along with a flask is used for the filtration process. Filter the precipitated wax slowly into the funnel and dry the wax. Weight of the wax is measured, and percentage of wax is calculated.

- **Saturates and Aromatics**

Deasphalted oil is charged on glass column packed with silica gel. Saturates are eluted with 150 ml of petroleum ether. Aromatics are eluted with 125 ml of toluene. Dry and weigh the amount of saturates and aromatics to calculate the individual percentages respectively.

- **NSO**

NSO Stands for Nitrogen, Sulphur and Oxygen. The amount of NSO is calculated by the classic formula given below.

$$NSO = 100 - [asphaltene + resins + wax + saturates + aromatics] \quad (4)$$

- **Colloidal Instability Index (CII)**

CII is calculated from SARA values. It is an approach to determine the instability of heavy oil based on the chemical composition of crude oil. If (resin/asphaltene) > 1 are less subjected to asphaltene deposition. The CII can be calculated from the formula given below (Siavash Ashoori et al., 2017). Several cases for the different values of CII are listed in the table 3.4.

$$CII = \frac{[saturates + asphaltene]}{[aromatics + resins]} \quad - (5)$$

The visual observation of heavy oil at 30 ˚C is shown in the figure 4.4. Heavy oil properties were analyzed via determination of water content, specific gravity, viscosity and fractional distillation. The water content in the heavy oil was 8 % which was measured and calculated. The calculated specific gravity and ˚API was found to be 0.995 and 10.71˚ respectively at 60 ˚F. The pour point of heavy oil was observed to be 10 ˚C.

Figure 4: Visual observation of heavy oil at 30˚C

Figure 5: Separation of asphaltene and resins

Figure 6: Separation of aromatics and saturates

The results of SARA analysis comprise of 4.05 % asphaltene, 13.72 % resins, 1.75 % wax, 36.24 % saturates, 42.04 % aromatics and 2.2 % NSO. Figure 4.5 and 4.6 shows the separated asphaltene, resins, aromatics and saturates from the heavy oil. The ratio of resin to asphaltene was 3.39 > 1, less subjected to asphaltene deposition. The heavy oil values of CII lead to moderate stability of asphaltene in crude and causes a mild asphaltene deposition problem.

Typical heavy oil from Venezuela contains about 14 % of asphaltene, 37% of resin and remaining 49 % saturates and aromatics. Heavy oil from Canada consists of 15 % asphaltene, 27 % resin and remaining 58 % saturates and aromatics. Most of the heavy oil in the World contains high asphaltene and resin content which deposits in the pipelines and restrain the heavy oil production. Meantime, the highly viscous heavy oil in the Mehsana field has minor asphaltene and resin content compared to other countries (Santos et al., 2014).

Predominantly, the carbon content in heavy oil is in the range of 83 % to 86 %. The carbon and sulphur content in heavy oil were found to be 83.8210 % and 0.098 % respectively. The tested heavy oil was found to be sweet crude which contains less than 1 % of sulphur. A small amount of sulphur in heavy oil reduces the sulphur removal unit during refining process.

Heavy oil was subjected to fractional distillation and the values are shown in the table 4.7. The heavy oil has initial boiling point at 80 ˚C. The fractional distillation of heavy oil comprises of 4 % gasoline fraction, 11.5 % kerosene fraction, 19.5 % diesel fraction. The percentage of distillate up to 350˚C was 35 % and residue after 350 ˚C was 65 %. From CI, the nature of heavy oil is Naphthenic-Aromatic in nature.

Table 4: Fractional distillations of heavy oil

Temperature (˚C)		**Vol. of Oil Fraction collected (ml)**	**Wt. Fraction of Oil collected (g)**	**Density at Room Temperature**	**Density at 15.5 ˚C**	**Specific Gravity at 15.5 ˚C**	**CI**
From	**To**						
IBP	100	0.5	1.8542	0.7544	0.7444	0.7451	29.92
100	125	1.5	1.8900	0.7690	0.7592	0.7600	29.16
125	150	2	1.9591	0.7971	0.7873	0.7881	34.78
150	175	2	1.9635	0.7989	0.7895	0.7903	29.02
175	200	3	2.0677	0.8413	0.8317	0.8325	42.93
200	225	3.5	2.0810	0.8467	0.8373	0.8381	40.14
225	250	3	2.0872	0.8492	0.8394	0.8403	36.28
250	275	4	2.1319	0.8674	0.8577	0.8586	40.49
275	300	4.5	2.1412	0.8712	0.8613	0.8622	38.14
300	325	5	2.2081	0.8984	0.8885	0.8894	47.32
325	350	6	2.2206	0.9035	0.8957	0.8966	47.32

The rheological properties of heavy oil were investigated through the various graph plotted from the data obtained through rheometer. Figure 7 to 9 shows the behaviour of heavy oil corresponding to shear rate and shear stress. The graphs plotted using the rheometer data were compared with the standard curves of Newtonian and non-Newtonian fluids since developing a rheological model is difficult and only few models are present. Rheological studies were conducted in the atmospheric pressure with three different temperatures namely 30 ˚C, 70 ˚C and 90 ˚C. In the entire shear rate vs. shear stress figures, crude and treated heavy oil were observed to be non-Newtonian fluid and investigated further for the classification of non-Newtonian fluid.

Non-Newtonian behaviour of crude and treated heavy oil was found to be classified as yield pseudo plastic. Yield pseudo plastic fluid behaves as a pseudo plastic fluid above the yield stress level. Yield stress of crude heavy oil at 30 ˚C, 70 ˚C and 90 ˚C were 87 Pa, 7.5 Pa and 2.2 Pa as shown in the figure 10. In treated heavy oil, volatile impurities were removed during high heating process and clearly indicated the yield pseudo plastic behaviour of non- Newtonian fluids. Yield stress of treated heavy oil at 30 ˚C, 70 ˚C and 90 ˚C were 5.4 Pa, 0.01 Pa and 0.002 Pa as shown in the figure 10.

In crude and treated heavy oil, yield stress decreases with increase in temperature. The viscosity of crude and treated heavy oil decreases with increase in temperature which in turn decreases the yield stress of heavy oil drastically as shown in the figure 4.10. Pseudo plastic flow behaviour is also known as shear thinning. Shear thinning behaviour indicates that the fluid viscosity decreases with increase in shear rate as shown in the figure 11.

The oscillations in the figure 7 to figure 9 were due to the creation of air gap by the highly viscous heavy oil placed on the rheometer plate. Non- Newtonian fluid of heavy oil has the dependence of viscosity on shear rate. The increase in the temperature of crude heavy oil clearly exhibits the pseudo plastic behaviour (Hans Petter Rønningsen, 2012).

The viscosity of heavy oil over a time period was observed, and a graph was plotted which is shown in the figure 11. The graph of viscosity with time provides the nature of heavy oil as either thixotropic or rheopexy. The viscosity of fluid decreases with increasing in time is known as thixotropic fluid and increases in viscosity of fluid with increasing in time is termed as rheopectic fluid. Figure 12 shows the thixotropic fluid behaviour. The viscosity of heavy oil greatly dependent upon the time and shows the thixotropic fluid behaviour.

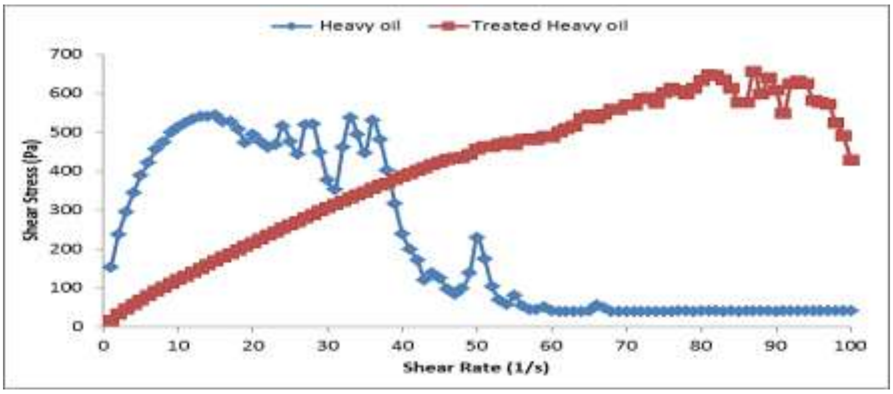

Figure 7: Rheological curves of heavy oil at 30 ˚C

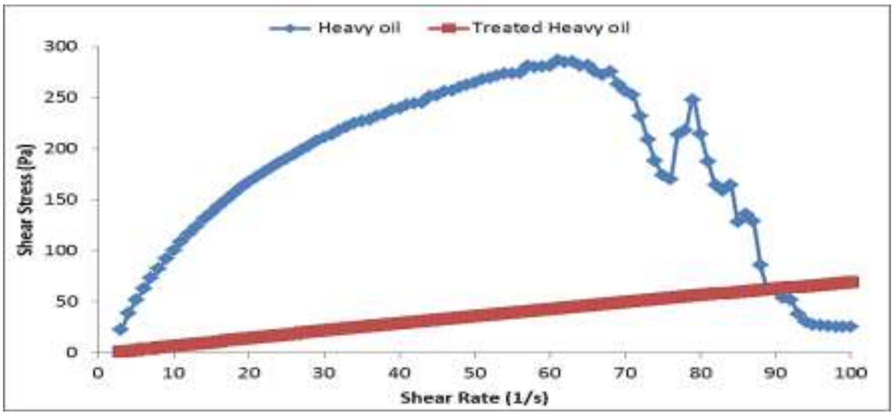

Figure 8: Rheological curves of heavy oil at 70 ˚C

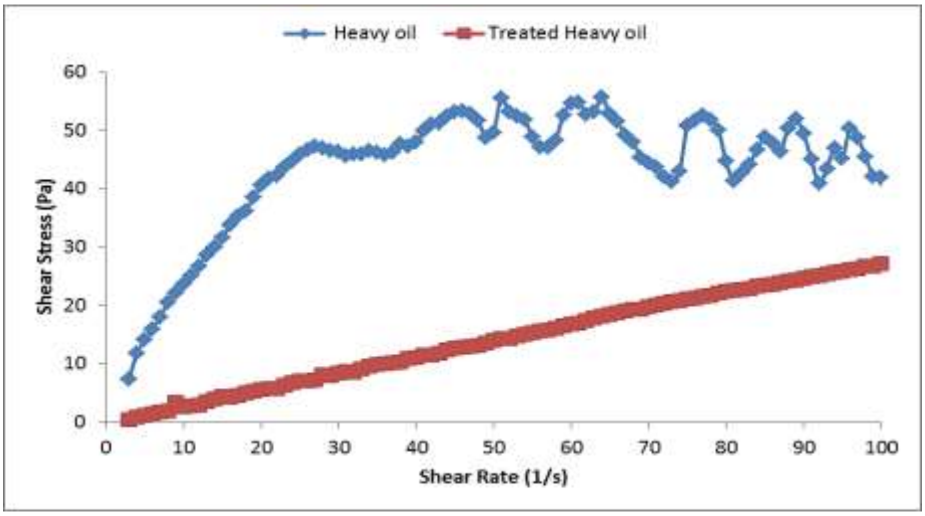

Figure 9: Rheological curves of heavy oil at 90 ˚C

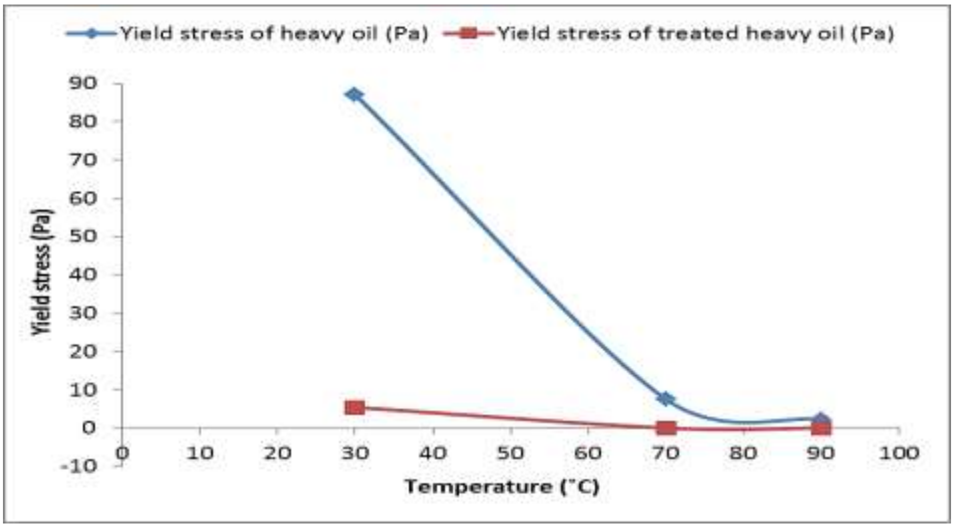

Figure 10: Effect of yield stress on three different temperatures

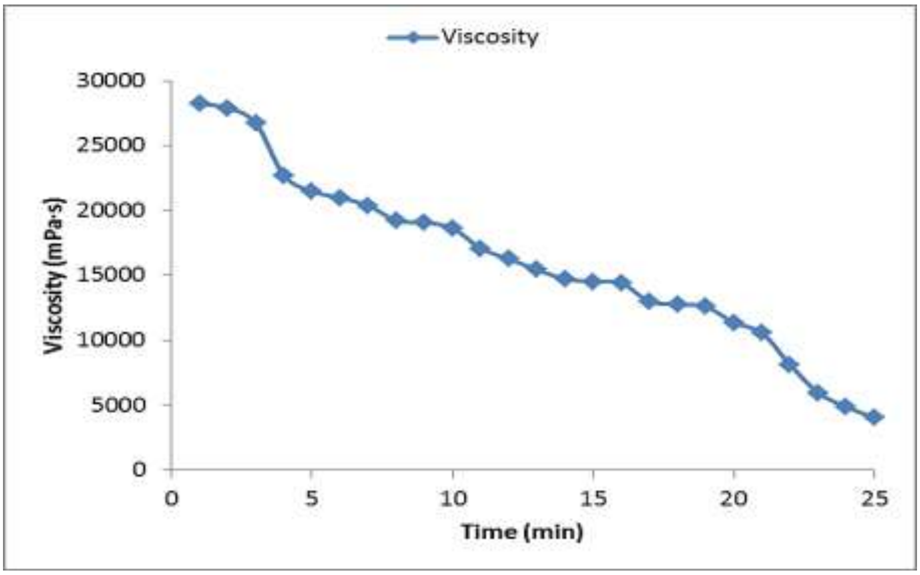

Figure 11: Viscosity-Time curve of heavy oil

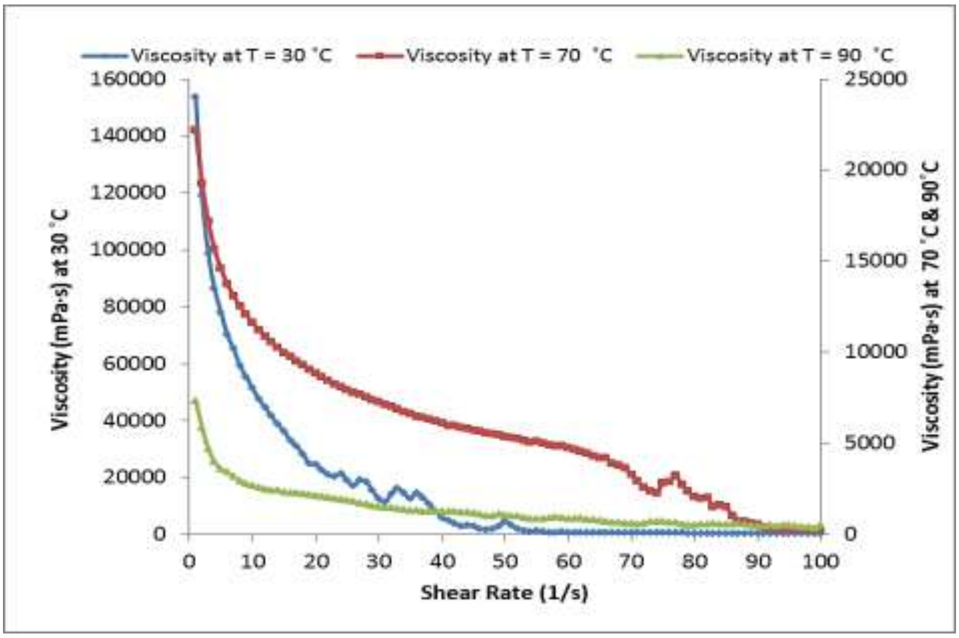

Figure 12: Effect of temperature on the viscosity of heavy oil

Heavy oil viscosity decreases with increasing shear rate and when the temperature of heavy oil was increased, the viscosity decreased which is shown in figure 12. There was a sharp decrease in the viscosity of heavy oil when the temperature of the heavy oil was increased. The shear rate vs. viscosity also indicated the pseudo plastic behaviour of non- Newtonian fluids which has shear thinning characteristics (Hans Petter Rønningsen, 2012). Dependence of viscosity on temperature plays a key role in the recovery of heavy oil. The characteristics of heavy oil are shown in thetable 5.

Table 5: Characteristics of heavy oil

Properties of Heavy Oil	**Test Method**	**Results**
Colour	Visual analysis	Dark brown
Water content (%)	ASTM D4006	8
˚API	ASTM D1298-12b	10.71˚
Pour point (˚C)	ASTM D97	10˚
Rheological Properties	ASTM D4440	Yield pseudo plastic behaviour in terms of shear rate dependence and thixotropic in terms of time-dependence
Asphaltene (%)	SARA analysis	4.05
Resins (%)		13.72
Wax content (%)		1.75
Saturates (%)		36.24
Aromatics (%)		42.04
NSO (%)		2.2
Carbon content (%)	ASTM E1019	83.8210
Sulphur content (%)		0.098
Fractional distillation	ASTM D86	Naphthenic-Aromatic Gasoline fraction = 4 % Kerosene fraction = 11.5 % Diesel fraction = 19.5 %

3. CONCLUSION

Heavy oil contains only 0.098 % of sulphur which is categorized as sweet crude oil. Heavy oil was capable of producing valuable products up to 35 % during fractional distillation. Reservoir contains both heavy oil and high salinity water. Produced water characteristics provide the conformation of crude oil presences in the reservoir. Produced water contains 10,347 ppm of sodium chloride along with other ions. Produced water was classified as meteoric water that exists in the shallow reservoirs. Due to very poor or nil recovery during primary recovery, enhancement of oil recovery plays a vital role in the heavy oil production. Crude displacement test on heavy oil at 70 ˚C indicated positive results with selected chemicals namely 138 SDS, Triton X-100, ethoxy ethanol, CTAB, ethanol, calcium chloride and disodium hydrogen phosphate. Triton X-100 and CTAB have the ability to develop emulsion with heavy oil at 70 ˚C reservoir temperature. 0.2 % of Triton X-100 formed O/W macro emulsion with heavy oil which was found to be unstable after an hour. Conversely, 0.1 % of CTAB formed O/W micro emulsion with heavy oil which was thermodynamically stable up to 72 hrs with a suitable emulsion condition for Enhanced Oil Recovery (EOR). Emulsion stability of CTAB with heavy oil was not affected by high salinity condition. High temperature of 70 ˚C and above was supportive in the emulsion development and stability of CTAB with heavy oil. CMC of CTAB increases with increasing temperature while decrease with increasing salinity. CTAB at different salinity concentration appeared to be transparent and no sign of precipitation after 24 hrs. CMC and precipitation details of CTAB help in determining the concentration of CTAB and CTAB retention for chemical flooding method.

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