An Investigation of Noncondensable Gas - Steam Injection for Heavy Oil Recovery

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ABSTRACT

Performance of steamflooding process can be improved by the use of non-condensable gases such as CO₂ or methane. Improving steam injectivity, increasing the size of the heated areas and providing additional drive energy are several beneficial effects of the combined use of steam and gases.

A comprehensive laboratory study was conducted for the recovery of heavy oil from a linear (1-D) and a three dimensional (3-D) physical models, packed with 12 °API gravity heavy oil, water and crushed limestone. A total of 25 experiments were conducted using two different laboratory models. A linear model having 6.6 cm diameter and 100 cm length was used for the first group of experiments. In the second group, 3-D model with 35cm x 35 cm x 7.5 cm dimensions was

used to obtain the process parameters. Temperature distributions in both models, steam and gas injection pressures and fluid productions were recorded during the experiments.

Base runs involving steam injection alone facilitated the interpretation of the steam-gas injection results, and showed that on the whole steam methane and steam-CO₂ injection is a far more promising technique. Results indicated that the presence of a non-condensable gas improved steam injectivity. Lower residual oil saturations were achieved in steam-CO₂ and steam-methane injection runs, compared to the values obtained with steam alone. Among the variables studied, steam-CO₂ and steam-methane injection ratios appeared to be a significant factors in determining heavy oil recovery.

1. INTRODUCTION

Steam injection by steam stimulation and/or steam drive is the most widely used process for enhanced oil recovery. In Turkey, 80 % of the oil reservoirs are heavy oil reservoirs¹. These heavy oils are usually mobile at reservoir conditions and most can be produced with primary production but recovery is very low. In heavy oil reservoirs, a combination of steam and non-condensable gas can be used to increase heavy oil production.

Pursley² conducted experiments on a cylindrical model to investigate the effect of injecting air, methane, or CO₂ on steam stimulation. He showed a dramatic improvement in the oil/steam ratio as a result of injecting methane or air.

Redford³ reported that recovery can be improved by using CO₂ or ethane with steam. He attributed the effect of CO₂ to a solution gas drive which produces the fluid from the cooler portion of the reservoir.

Harding et al⁴ presented results of a physical model study of steamflooding with nitrogen and CO₂ additives. The tests were conducted in a linear porous medium saturated with a moderately viscous refined oil and water. It was found that the simultaneous injection of the gases with steam resulted in a significant

improvement in the ultimate recovery of the crude oil.

Stone and Malcolm⁵ carried out high pressure steam/CO₂ coinjection experiments in a 1-D physical model with Athabasca tar sand. The results from the physical model were compared with results from a numerical model study. Both models indicated that coinjection of CO₂ and steam increases ultimate recovery.

Stone and Nasr⁶ analyzed the use of steam-CO₂ and steam-N₂ mixtures in a set of continuous injection experiments in a test bed which employed a high permeability communications path between the injection and production wells. The addition of CO₂ to steam resulted in a significant change in displacement mechanism. As well as bitumen viscosity reduction due to dissolved CO₂ and an increased pressure gradient between the injection and production wells, an enhanced bitumen stripping and the formation of a gas zone around the injection well resulted in increased conformance in the test bed and increased bitumen production.

Stone and Ivory⁷ carried out steam-CO₂ experiments in a large pressure vessel which was capable of holding approximately four tons of oil sands. CO₂ presoak followed by steam injection, steam-CO₂ coinjection and steam, CO₂ and solvent coinjection

experiments were employed to understand the mechanisms behind recovery processes. In all cases investigated, the addition of CO₂ to steam resulted in improved utilization of injected energy and improved the oil recovery over that from steam alone.

Gümrah and Okandan⁸ conducted steam-CO₂ experiments in 1-D and 3-D unscaled laboratory models to evaluate the benefits of CO₂ addition to steam on the recovery of 24 °API, 12 °API and 10.6 °API gravity oils. The linear tests indicated that the oil recovery increased with increasing CO₂/steam ratios until an optimum value was reached. The light oil recovery was relatively less improved by the addition of CO₂ to the injected steam however, the oil production rate was increased considerably for all oils. The production of lighter oil fractions increased with increasing CO₂ concentration and API gravity. They concluded that the main recovery mechanism was steam drive, and the secondary forces were steam distillation, stripping effect of CO₂, viscosity reduction and gas drive effect.

The objective of the present study is to evaluate steam injection with non-condensable gases such as CO₂ and methane to produce 12 °API gravity heavy oil.

2. EXPERIMENTAL EQUIPMENT

A schematical representation of a linear (1-D) and a three-dimensional (3-D) models used during the experiments has been illustrated in Figures 1 and 2. The experimental apparatus are comprised of four main parts: steam and gas injection system, physical models, fluid production system and measuring and control system. Steam and gas injection system is consisted of a steam generator and methane or CO₂ injection unit. The 1-D model was a horizontal cylindrical steel tube 6.6 cm in diameter, 110 cm length, with flanges at both ends constructed of steel. 15 thermocouples were used to measure center temperatures. The rectangular box shaped 3-D model was a 30 cm square with a thickness of 7.5 cm. To perceive 3-D temperature distribution inside the model, 25 thermocouples have been installed. To compensate the heat dissipation, the models are wound with band heaters. Fluid production system consists of a separator and a condenser, a back pressure regulator and a wet test meter. Temperature data are gathered by a datalogger in the measuring and control system. Injection and production pressures throughout the experiments are recorded with the help of pressure gauges at the injection and production ends.

3. EXPERIMENTAL PROCEDURE

In both models, the crushed limestone, crude oil and water are

Figure 1. Schematic diagram of experimental set-up (1-D model).

1. Steam generator	9. Isolation box
2. Methane supply	10. Thermocouples
3. Ball valve	11. Separators
4. Rotameter	12. Wet test meter
5. Flow control valve	13. Datalogger
6. Pressure gauge	14. Computer
7. Check valve	15. Temperature controller
8. 1-D model or 3-D model	

Figure 2. Schematic diagram of experimental set-up (3-D model).

mixed homogeneously to yield the desired fluid saturations and packed into the models. At the end of the packing operations, center thermocouples are inserted into the models. The necessary electrical and mechanical connections are made afterwards. Prior to fluid injection, the models are heated with the aid of band heaters, until the temperature inside the model reaches upto 50 °C. During steam-CO₂ and steam-methane injection experiments, the steam generator was brought to its maximum temperature and the flowmeter is set

to desired CO₂ and methane flow rate. Temperature distribution inside the model is registered at the expiry of every 5 minutes during the advance of each experiment. Steam injection pressure, CO₂ and methane injection pressure, production pressure, temperature at the inlet and outlet end, and oil and water production data are recorded during the experiments.

4. RESULTS AND DISCUSSIONS

A total of 16 experiments were carried out in 1-D model and 9

experiments were conducted in 3-D model. The experimental conditions and results are presented in Table 1 and 2, respectively.

4.1. 1-D Model Experiments

The experiments were chosen so that the comparisons could be made between steamflood performance with the addition of CO₂ and methane, and

steamflood performance without gas additives. Performance comparisons were made on the basis of overall oil recovery.

Centre-line temperature data for three experiments are presented in Figure 3 in order to illustrate the general character of the tests. The temperature profiles showed the slow

Table 1. Experimental conditions and results (1-D model).

RUN NO	BKL-1	BKL-2	BKL-3	BKL-4	BKL-5	BKL-6	BKL-14	BKL-15	BKL-16
Oil saturation, %	80.8	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
Water saturation, %	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Steam inj. rate, cc/min	52.50	16.80	24.10	-	-	-	-	-	-
Steam inj. pressure, kPa	275	315	295	-	-	-	-	-	-
Steam temp. °C	140	141	139	-	-	-	-	-	-
Methane inj. rate, cc/min	-	-	-	250	480	900	-	-	-
CO ₂ inj. rate, cc/min	-	-	-	-	-	-	250	500	1000
Methane inj. pres., kPa	-	-	-	300	295	315	-	-	-
CO ₂ inj. pres., kPa	-	-	-	-	-	-	275	260	290
Steam/oil ratio, ml/ml	3.07	3.04	2.89	-	-	-	-	-	-
Oil recovery, %OOIP	43.30	59.60	62.60	6.24	11.48	14.52	4.52	8.52	12.00

RUN NO	BKL-7	BKL-8	BKL-9	BKL-10	BKL-11	BKL-12	BKL-13
Oil saturation, %	80	80	80	80	80	80	80
Water saturation, %	20	20	20	20	20	20	20
Steam inj. rate, cc/min	25.20	29.20	88.00	28.80	56.40	46.60	48.30
Steam inj. pres. kPa	295	295	320	275	280	295	280
Steam temp. °C	140	140	145	140	140	149	140
Methane inj. rate, cc/min	180	465	755	755	-	-	-
CO ₂ inj. rate, cc/min	-	-	-	-	220	440	990
CO ₂ inj. pres., kPa	-	-	-	-	280	295	280
Methane inj. pres., kPa	295	295	320	275	-	-	-
Steam/CO ₂ ratio, cc/cc	-	-	-	-	0.256	0.106	0.049
Steam/methane ratio, cc/cc	0.142	0.106	0.117	0.038	-	-	-
Steam/oil ratio, cc/cc	3.01	3.29	4.04	2.53	2.46	1.98	2.59
Oil recovery, %OOIP	75.00	70.10	72.90	55.10	66.20	96.20	62.20

Table 2. Experimental conditions and results (3-D model).

RUN NO	BK3B1	BK3B2	BK3B3	BK3B4	BK3B5	BK3B6	BK3B7	BK3B8	BK3B9
Oil saturation, %	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
Water saturation, %	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Steam inj. rate, cc/min	70.60	65.10	73.50	74.75	105.3	94.00	74.30	57.70	59.70
Steam inj. pres. kPa	260	300	290	275	295	295	275	260	275
Steam temp. °C	143	141	140	138	142	143	143	140	142
Methane inj. rate, cc/min	---	---	-	440	200	950	-	-	-
CO ₂ inj. rate, cc/min	-	-	-	-	-	-	360	500	990
CO ₂ inj. pres., kPa	-	-	-	-	-	-	280	295	280
Methane inj. pres., kPa	-	-	-	295	295	320	-	-	-
Steam/CO ₂ ratio, cc/cc	-	-	-	-	-	-	0.206	0.115	0.060
Steam/methane ratio, cc/cc	-	-	-	0.170	0.529	0.099	-	-	-
Steam/oil ratio, cc/cc	6.33	5.95	5.44	5.24	3.72	3.31	5.38	3.89	10.1
Oil recovery, %OOIP	20.70	22.40	21.20	57.4	48.9	51.4	32.1	37.1	13.7

rise to steam temperature of inlet and caused by direct contact between steam and the inlet end flanges of the 1-D model. Temperature gradients in the steam-gas injection experiments were not as steep as in the steam only case indicating a widening of the high temperature zone. Depression of the steam

temperature due to presence of non-condensable gases is evident from examination of the figures.

Figures 4 and 5 compare steam-CO₂ and steam-methane runs to that of steam only. In these figures, the steam-gas injection runs showed similar performance which is significantly

Figure 3. Temperature profiles along the 1-D model.

different from that of the steam only case. The addition of methane and CO_2 to steam supplied a higher oil recovery over steam only case.

It is evident from these results that non-condensable gas was of benefit in accelerating the rate of oil production. The flooding experiments showed that the simultaneous injection of CO_2 or methane with steam will definitely increase the

Figure 4. Oil recoveries as a function of pore volumes of injected steam.

Figure 5. Oil recoveries as a function of pore volumes of injected steam.

ultimate recovery over steam alone and that there is an optimum steam/ CO_2 and steam/methane ratios that result in the highest recovery. Figure 6 shows the oil recovery as a function of optimum steam/ CO_2 and steam/methane ratios. The results indicate that the optimum steam/ CO_2 for maximizing the recovery is 0.106 cc/cc. The optimum steam/methane ratio is found to be 0.155 cc/cc for steam-methane injection runs. These steam-gas mixtures recovered 61.4 % more crude for steam- CO_2 test and 17.6 % more crude for steam-methane test than tests with injection of steam only. The other experiments at various steam/gas ratios yielded

Figure 6. Oil recovery as a function of steam/gas ratio (1-D model).

recoveries between the results of steam alone and steam-gas at optimum conditions.

4.2. 3-D Model Experiments

Steam only, steam-CO₂ and steam-methane injection experiments were conducted in a 3-D model. Two-dimensional temperature contours were drawn along the horizontal mid-plane in the model. This was observed in areal temperature distribution at the top where higher temperatures were recorded than the bottom of the model. For steam-CO₂ tests, temperatures increased and then decreased following the average steam injection pressure behavior. However, for steam only test, the injection pressure stayed at the increased level throughout the test. Temperature profiles in Figure 7 show that breeding of temperature contours are more uniform in the model.

The oil recovery curves of the steam-CO₂ and steam-methane tests are compared with steam only run in

STEAM ONLY

STEAM-METHANE

STEAM-CO₂

Figure 7. Areal temperature contours at the end of steam only, steam-CO₂ and steam-methane runs.

Figure 8. Oil recovery was substantially improved by the addition of CO₂ and methane to steam. The use of too much CO₂ or methane can have undesirable effects. Firstly, the gas occupies volume and reduces the amount of steam injected. Secondly, if too much gas is injected

Figure 8. Comparison of oil recoveries for steam only, steam-CO₂ and steam-methane runs.

it increases the gas saturation flowing between the injection and production wells and causes channeling of the steam to the production point. This effect is noted in the experimental results presented here by the reduced recovery and lower steam injectivity at higher CO₂ and methane concentrations.

Figure 9 shows the oil recovery as a function of steam/CO₂ and steam/methane ratios. 0.115 cc/cc is obtained as optimum steam/CO₂ ratio while optimum steam/methane ratio is 0.163 cc/cc from 3-D runs. 61.0 % more crude for steam-methane test and 39.7 % more crude for steam-CO₂ test are recovered than steam only test.

5. CONCLUSIONS

For the linear and the three-dimensional laboratory models investigated, following conclusions may be drawn:

Figure 9. Oil recovery as a function of steam/gas ratio (3-D model).

1. The improvement in steamflood performance due to the addition of non-condensable gases occurred for both models. The presence of non-condensable gas (CO₂ or methane) with steam resulted in lower residual oil saturation compared to steam injection alone.

2. The results indicate that the optimum steam/gas ratio for maximizing oil recovery is about 0.110 cc/cc and 0.163 cc/cc for steam-CO₂ and steam-methane processes respectively from both 1-D and 3-D tests.

3. Carbondioxide, as a steam additive, yielded a higher incremental oil recovery than obtained with either steam only and steam-methane systems.

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