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Analysis of Steam Injection and *in situ* Combustion Methods of Mining Agbabu Bitumen Deposit in Ondo State, Nigeria

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Abstract: Steam injection and *in situ* combustion methods of mining Agbabu bitumen deposit were studied. Cyclic steam injection test and *in situ* combustion laboratory experiment were carried out on the bitumen deposit. The steam injection analysis was used to deduce values for key performance indicators such as: water-oil ratio; oil steam ratio; thermal ratio; heat loss to formation and energy requirements while the *in situ* combustion laboratory analysis was used to obtain information on combustion characteristics of the formation: Air requirements and fuel consumption, etc. The results of the investigation indicate high susceptibility of Agbabu bitumen formation to the two mining methods. In addition, the comparative results of the two mining methods showed that the *in situ* combustion method was more efficient and economical than the steam injection method in the mining of the Agbabu bitumen deposit.

Key words: Steam injection, *in situ* combustion, Agbabu bitumen Nigeria

INTRODUCTION

The Agbabu bitumen deposit consists of an inorganic sandstone matrix impregnated with heavy, viscous oil, which cannot be produced at commercial rates using the conventional primary recovery methods (Burger, 1979). According to Akande and Akinbinu (2005) bitumen as one of the mineral resources is a general term for group of mineral composed of mixture of hydrocarbon that are soluble in carbon disulphide

Bitumen exploration within the belt started when the defunct Nigerian Bitumen Corporation drilled 15 wells in the bituminous sand zone between 1907 and 1914. A more detailed investigation was again carried out by the Geological Consultancy Unit of Obafemi Awolowo University, Ile-Ife between 1979 and 1980. 40 boreholes including borehole number 25 were drilled within the belt and the core samples obtained were studies to facilitate the exploitation of the deposit.

The Agbabu bitumen mobility is extremely low at reservoir conditions. It has an API gravity of 9.4^0, specific gravity of 0.968 and viscosity of 300 Ns m^{-2} (Table 1). Two options for the recovery of bitumen from tar sands are-mining of the tar sands followed by-ground bitumen extraction and upgrading; and *in situ* extraction followed by above ground processing and upgrading. However, the ratio of overburden to tar sand zone thickness is greater than one and the tar sand deposit is generally unconsolidated and not structurally competent and conventional underground mining methods are precluded in its recovery. These limitations and the low bitumen mobility call for the development of *in situ* recovery methods such as steam injection and *in situ* combustion. Hence cyclic steam injection test and *in situ* combustion laboratory experiment are carried out on the bitumen deposit and the results compared to determine the more preferred method for the mining of Agbabu bitumen.

Table 1: Agbabu reservoir and fluid properties

Formation	Upper bituminous horizon	Lower bituminous horizon
Range of pay thickness (m)	9-22	3-26
Average pay thickness (m)	15	12
Range of top pay depth (m)	3-54.5	20-83
Porosity (%)	35	35
Permeability (μm^2)	1	1
Bitumen API gravity	9.4^0	9.4^0
Bitumen specific gravity	0.968	0.968
Viscosity at 38°C (Ns m^{-2})	300	300
Average bitumen saturation (wt%)	12	12
Calorific value (KJ kg^{-1})	43000	43000
Oil bearing area (m^2)	247.5×10^6	247.5×10^6
Oil in Place (OIP) (Mt)	0.998×10^9	0.798×10^9
Bulk density (g cm^{-3})	2.24	2.24

Source: Adegoke (1980), Nigerian Bitumen Implementation Committee Gazette (BPIC)

MATERIALS AND METHODS

Cyclic steam injection test was carried out in Agbabu borehole number 25 (Fig. 1). A casing of 84 m length and 0.14 m diameter was installed in the well. Two perforations

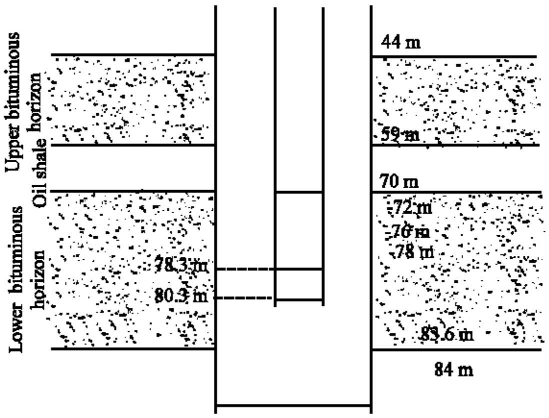

Fig. 1: Schematic diagram of the bitumen borehole

of 2m each were made in the producing horizon at depth 70-72 and 76-78 m. The steam for the injection test was supplied by an 80% air quality movable steam generator with maximum capacity of 8 ton h^{-1}. Steam flow measurement was obtained by measuring the quantity of water fed to the steam generator. A high pressure saturated steam was injected into the bitumen formation for period of 15h during which the steam spread into the formation and heat up the tar sands and built up pressure. The steam was then shut off and the well was sealed in for a period of 10 to allow the heat generated to penetrate a sufficiently broad zone around the well. The well was later opened and a mixture of water and bitumen, which has been rendered mobile, flow into the well through the 2 perforations and was withdrawn to the surface by pumping. Production was stopped well shut in and plugged 16h later. Figure 2 shows the scheme of injection and production equipment. The produced mixture of bitumen and produced water was separated. During a period of 15 h, approximately 0.639 tons of steam was injected at well head flowing pressure of 40 bars. The total production of this test was about 0.0755 m^3 of bitumen and 0.271 m^3 of produced water.

In the case of the *in situ* combustion laboratory experiment, pack materials consisting of 7.58 kg formation sand, 1.10 kg bitumen and 0.41 kg water obtained from borehole number 25 were thoroughly mixed in a container. The mixed materials were analyzed in the laboratory for porosity, bitumen saturation, water saturation and gas saturation as shown in Table 2. The pack materials were enclosed in the combustion tube. The combustion tube used consists of a thin walled inner jacket that contained the pack materials. This wall was surrounded with a heavy-walled jacket to allow use of high pressures. The combustion tube inside diameter was 0.064 m and the pack length was 1.5 m. Air was supplied by an air compressor with designed capacity of 85 sm^3 at 13.8 bar. Dual-column type gas chromatograph was used for analysis of gases

Table 2: Laboratory pack conditions existing at the beginning of the combustion tube study

Parameters	Values
Porosity (%)	37.5
Bitumen saturation (%)	61.8
Water saturation (%)	19.2
Gas saturation (%)	19.0
Pack materials (kg)	
Sand	7.58
Bitumen	1.10
Water	0.41

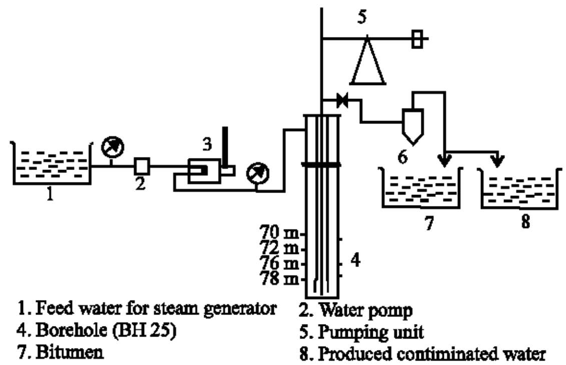

Fig. 2: Flow diagram of steam injection test

produced from the combustion tube discharge. Temperature at various positions in the sand pack was monitored using iron-constantan type thermocouple with metal-sheath insulation.

Packed materials in the combustion tube were ignited at the top by an electric heater set at 482°C. The direction of burning was vertically down and temperature observations were made at various positions in the sand pack. The advance of the burning front was also determined from the temperature observations. After ignition, air was injected into the tube. When the burning front reached 0.53 m of the tube pack length, water was injected along with air simultaneously at the ratio of 0.0017 m^3 sm^{-3} for 3 h. The water injection rate was then increased while air injection was stopped at 6 h into the tube run. Water injection continued and was stopped 30 min later. The combustion gases produced were analyzed periodically when pressure, gas rate and temperature were nearly stable. When the tube run was completed, the produced bitumen and water were separated.

RESULTS AND DISCUSSION

The results from the cyclic steam injection test are presented in Fig. 3. There is an initial resistance of the bitumen formation to steam injection. The rapid increase in steam injection from origin to 0.049 ton h^{-1} implies that the bitumen formation exhibits good permeability. The dependency of bitumen recovery on temperature observed, also, well head temperature reduces as hot

Table 3: Parameters derived from cyclic steam injection analysis

Parameters	Values
Water oil ratio	3.6
Oil-steam ratio (m^3 ton^{-1})	0.12
Thermal ratio	2.3
Fraction of calorific value of oil burned	0.43
Recoverable crude fraction	0.38
Net production	0.57
Bitumen recovery (%)	22
Heat loss to formation (J s^{-1})	27.6

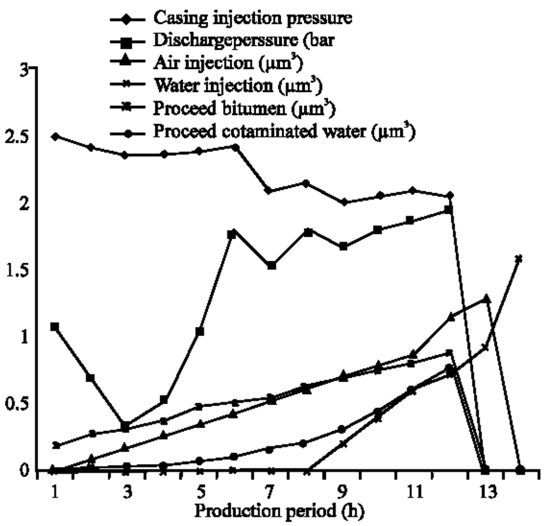

Fig. 3: Production parameters of steam injection mining method

fluids are withdrawn from the well. There is high bitumen production in the first four hours followed by higher production of water from the well. The parameters derived from the cyclic steam injection analysis are presented in Table 3.

More water is produced than is expected from the test as a result of bottom water influx and the existence of gas or vapour-filled space in the reservoir due to rise in reservoir temperature Mainland (1984). The oil-steam ratio of 0.12m^3/ton determined by the reservoir and steam properties, according to Hertzberg *et al.* (1983), is relatively low. The thermal ratio need be greater than 3 for economic recovery of bitumen as predicted by Hicks and Probstein (1982). According to Harmsen (1971), the distribution of the injected heat reveals that the amount of heat stored in
the steam zone is small compared to the large amount transported into the formations adjacent to it. Hence the high rate of heat loss of 27.6J/s to adjacent formations is due to poor adaptation of the thin Agbabu bitumen strata. The quantity of energy expended in the steam generator to produce steam represent a significant fraction of the calorific value of the bitumen produced (Burger, 1979).

Table 4: Parameters derived from combustion tube analysis

Parameters	Values
Hydrogen-carbon atom ratio of fuel	1.2
Oxygen utilization (%)	99.4
Air required to consume 1kg of carbon (sm^3)	5.24
Air required to burn 1 kg of fuel (sm^3)	4.76
Air required to form 1 kg of water (sm^3)	5.82
Carbon consumed /m^3 of bitumen reservoir burned (kg)	34.48
Fuel consumed /m^3 of bitumen reservoir burned (L)	38.01
Air required /m^3 of bitumen reservoir burned (sm^3)	180.68
Water formed /m^3 of bitumen reservoir burned (L)	31.10
Bitumen displaced /m^3 of bitumen reservoir burned (L)	241.08
Bitumen recovery (%)	73
Water displaced by burning front (L)	117.81
Theoretical Air-oil ratio (sm^3/L)	0.75
Theoretical water-oil ratio	0.33

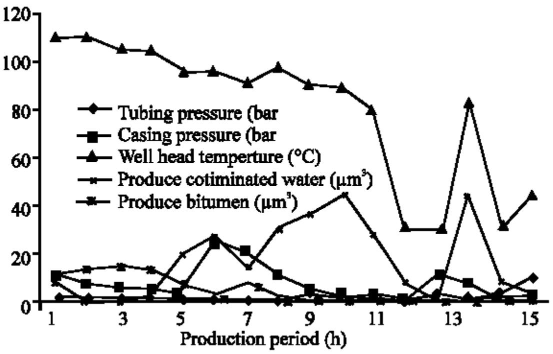

Fig. 4: Production parameters of in-situ-combustion mining method

Therefore the 0.43 value of oil burned in the steam generator is too large and it represents approximately one-half of the calorific value of the bitumen produced.

The results of the *in situ* combustion laboratory experiment are shown in Fig. 4. The air injection rate is fairly constant before the injection of water. Fluid block start to break when the burning front is at 0.36 m and gas permeability increases rapidly leading to reduction in injection pressure to 2.07 Mpa . A heat scavenging period occurs when there is a sharp rise in water injection rate and there is rapid movement of the burning front during the water injection period. There is faster movement of the burning front as simultaneous injection of air and water commences. The analysis of gases produced shows the average composition by percent volume as: Carbon dioxide 14.47, Oxygen 0.14, Nitrogen 80.79, Carbon monoxide 3.5, Argon 1.10. There is high residual temperature behind the front, high temperature at the burning front and rapid decrease in temperature ahead of the front, with average combustion temperature being 484°C. The first production from the tube is bitumen with steadily increasing production rate and only small amount of water is produced during the first 3 h . The result of the combustion gases analysis leads to derivation of parameters show in Table 4.

The use of combined air and water injection reduces the air required for heating the bitumen reservoir (White and Moss, 1983). The availability of the fuel for the process, Coke, which is deposited from the residual bitumen as it is thermally cracked, depends on oil gravity, porosity, oil saturation, oil viscosity and atomic hydrogen-carbon ratio (Hertzeberg *et al*., 1983). The fuel acts as viscous displacing fluid so that the sweep efficiency in combustion will be high. The high asphathene content of Agbabu bitumen and its good combustion characteristics results in the low fuel consumption of 38.01 L per m^3 of bitumen reservoir burned. As predicted by White and Moss (1983), high bitumen mobility due to hot gases, increase temperature from sufficient heat generated and additional water injected that condensed ahead of the burning leads to high bitumen recovery of 73% of the original bitumen in place.

CONCLUSION

The steam injection and *in situ* combustion methods have been duly analyzed using the various parameters to determine their appropriateness for the mining of Agbabu bitumen deposit. Evaluation showed that the *in situ* combustion method in the mining of Agbabu bitumen deposit is more preferred due to the following reasons.

- The bitumen recovery rate of this method during mining is high with almost the total bitumen in place.
- This method fits perfectly into the Agbabu bitumen deposit geological terrain.
- It requires less and cheap energy input with energy conservation during operation.
- It minimizes water pollution through the generation of smaller possible quantity of waste and smaller water handling problem.
- It is less prone to sand production problem and the produced bitumen is easier to process on the surface.
- It avoids subjection to inflationary trend and accrued cost of future investment of follow-up operations to recover left over bitumen in the reservoir.

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