Experimental Investigation and Comparison of Thermal Processes: SAGD, ES-SAGD and SAS

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Abstract − *Thermal processes such as cyclic steam stimulation (CSS), steam-assisted gravity drainage (SAGD), in-situ combustion and toe-to-heel air injection (THAI) are being applied widely to recover heavy oil and bitumen, deposited in different formations located worldwide, especially in Canada, Venezuela and United States. Among these processes, SAGD is known as the most prosperous and promising method applicable in Alberta sandstone heavy oil and bitumen reservoirs. However, existence of technical and environmental problems forced researchers to find solutions in order to mitigate deficiencies of SAGD process. Some of the main disadvantages of SAGD are: high consumption of water, waste water management and facility, high expenditures of fuel to generate steam and green-house-gas (GHG) emission. Also, it is not applicable in thin reservoirs because of heat and energy loss.*

Recently, hybrid processes were introduced to overcome the mentioned problems. Hybrid processes utilize the advantage of steam injection and solvent injection together or alternatively to reduce the viscosity of in-situ oil as much as possible. Some of these processes are: expanding-solvent SAGD (ES-SAGD), steam alternating solvent (SAS), liquid addition to steam enhanced recovery (LASER), solvent-assisted SAGD (SA-SAGD) and solvent-aided process (SAP). The salient advantages of hybrid processes over SAGD are namely; lower consumption of water and energy, higher ultimate recovery factor, faster oil drainage rate and lower CO_2 (GHG) emissions.SAGD, ES-SAGD and SAS processes were implemented in this work using cylindrical stainless steel core holder filled with glass beads and saturated with slightly upgraded Athabasca bitumen. First, performance of the mentioned processes was evaluated in terms of cumulative steam-oil ratio (CSOR), oil drainage rate, cumulative oil productionand ultimate recovery factor. SAS and ES-SAGD represented better results than SAGD process at the same conditions based on the aforementioned efficiency indicators. Thereupon, effect of steam injection rate on SAGD process and the impact of solvent injection rate and type on ES-SAGD process were investigated. Results of the experiments elucidated that higher steam injection rate yields higher oil drainage rate and recovery factor while increases the CSOR of the SAGD process. Three types of solvent namely; n-pentane, n-hexane and n-heptane were used to investigate the effect of solvent type on ES-SAGD performance. Among them n-pentane showed better outcomes, however, higher injection rate of n-hexane improved the process both in terms of CSOR and recovery factor.

Keywords − *SAGD, ES-SAGD, heavy oil and bitumen,SAS, thermal methods, glass beads*

I. INTRODUCTION

During the past two decades, due to the decline in production from conventional oil reservoirs, tendency to recover from heavy oil and bitumen reservoirs has increased. When butler et al. [1] introduced the SAGD method, it turned out to become the most promising and applicable technique to recover bitumen. In this method a pair of horizontal wells is drilled a few meters above the bottom of the reservoir with vertical spacing of around 5 meters in such a way that the bottom one acts as a producer and the upper one is considered an injector. Steam is injected from upper horizontal well and the heated mobile oil is produced at the horizontal producer. However, SAGD has some drawbacks besides its beneficial recovery factor and production rate. These impediments obliged the petroleum engineers and researchers to discover solutions to overcome the

problems. Various experimental and numerical simulation studies were fulfilled in order to find the best alternative for SAGD process. Hybrid processes were developed to try to surmount the SAGD's deficiencies. These methods utilize co-injection or alternating injection of light hydrocarbons as solvent together with steam. Hereby, some of the laboratory efforts are addressed:

Chung and Butler [2] performed a 2-D laboratory experiment on the in-situ heavy oil recovery to investigate the performance of steam-assisted gravity drainage (SAGD) process. They ran experiments with different types of porous media such as 0.85 mm Ottawa sand packs and 2-mm glass bead packs with different permeabilities. The model was saturated with Cold Lake bitumen and steam was injected at pressure of 153 kPa (7.5 psig) and actual steam temperature of 109 °C. They also tried the steam injection from top of the formation instead of conventional SAGD to evaluate the effect of water/oil emulsions. The results of laboratory experiments showed that there is higher emulsified water/oil ratio in produced fluid when steam is injected from bottom to the top of the formation because there is a counter-current flow of steam and heated heavy oil during the period that steam chamber is growing upward. When the steam is injected from top of the reservoir there is lower amount of emulsified water/oil ratio in the produced fluid as the steam goes to the sideways of the formation and the heated heavy oil drops down, below and along the interface. Also the rate of production is higher when the steam is injected from top of the formation. The effect of permeability is negligible on the water content in the water/oil emulsion. Moreover, this water/oil emulsion increases the viscosity of the produced fluid.

Another experimental/numerical analysis was carried out by Nasr et al. [3]. They used a 2-D scaled model representing the heavy/extra heavy oil reservoirs to calibrate the thermal reservoir simulator STARS. The model was visual and they investigated the effect of different parameters such as pressure difference between the wells, capillary pressure, heat losses and grid size. They concluded that enthalpy control is an urgent feature for the SAGD process as the higher

recovery and improved SOR were obtained compared to the constant injection strategy.

Nasr et al. [4] conducted laboratory studies on a two-dimensional visual cell which was scaled using Pujol and Boberg's criteria [5] to investigate the critical parameters controlling the SAGD process. The results demonstrated that oil production was reduced and higher SOR was obtained for low permeable reservoirs and the effect of permeability on the gravity drainage was non-linear. They compared the performance of SAGD process for two different initial oil mobility (Athabasca bitumen and Lloydminster heavy oil) cases. They found that the SOR was improved for lighter in situ oil (Lloydminster heavy oil). They also performed several sets of experiments to evaluate the various operating strategies for SAGD process [6]. They concluded that the choice of an effective strategy depends on reservoir characteristics. Laboratory studies illustrated that using another vertical well in a combination with paired horizontal wells improves SAGD performance. Also the performance of the process was better in the case of longer producer for a fixed length of injection well. Moreover, addition ofnaphtha to the steam improved the SOR and accelerated the process.

An experimental study on single well SAGD (SW-SAGD) was fulfilled by Akin and Bagci to optimize the startup procedure of the single well SAGD process [7]. They considered three different well configurations of single well, vertical injector-horizontal producer and horizontal injector-horizontal producer. In addition, three different production strategies of conventional, cyclic steam injection and extreme pressure were considered for SW-SAGD. Results displayed that cyclic steam injection showed better performance than the other configurations of SW-SAGD while the area of steam chamber formed in SW-SAGD was several times less than other SAGD configurations at early times of production. Horizontalinjector-horizontal producer configurationsresulted in highest efficiency.

Sasaki et al. [8]performed many experiments in scaled two-dimensional visual models using glass bead pack as porous media and special motor oil (COSMO#1000) with density of 998 kg/m^3, viscosity

of 93000 cp at initial temperature of 20 °C and 120 cp at steam temperature of 106 °C as heavy oil. They investigated the expansion rate of the steam chamber by gravity drainage, the effect of steam injection pressure and the effect of vertical spacing between wells. Results revealed that higher injection pressure (at constant production pressure) resulted in higher expansion rate of steam chamber and shorter breakthrough time because of larger driving force in this condition. Moreover, larger well spacing in the rising steam chamber case of conventional SAGD led to faster generation of the steam chamber, longer breakthrough time and higher oil production.

Experimental study on recovery from Morichal heavy oil reservoir in Venezuela was carried out by Goite et al. [9] using combined steam and propane injection method. Steam and propane were co-injected with various mass ratios from 100:0 (steam only) to 100:5. They reported that steam-propane injection with 100:5 mass ratio showed increase in peak of oil rate and production compared with steam alone. Nasr et al. [10]introduced novel Expanding Solvent-SAGD (ES-SAGD) process for combining the advantages of steam and solvents in the recovery of heavy oil and bitumen. They used cylindrical stainless steel model to investigate the performance of this method. They evacuated the model for 2-3 hrs and then pressurized it with water to 2.1 MPa. Henceforth, the model was saturated with live Burnt Lake oil. After initializing the model, slightly superheat steam and desired solvent were co-injected at a rate of 2.5 kg/hr and 39 cc/hr respectively. They injected non-condensable hydrocarbons such as methane and ethane with steam and observed no improvement in oil drainage rate as compared to conventional SAGD for live oil situation. To investigate ES-SAGD, they used light hydrocarbons from C_3 to C_8 and diluent (mainly C_4-C_{10}) as solvent in their studies. Results of the experiments specified increase in oil production rate from lighter to heavier hydrocarbons and as the vaporization temperature of the hydrocarbon additive became closer to the injected steam temperature. The peak of oil production rate was observed for hexane co-injection case as it has the closest saturation condition to the steam. They reported considerable oil drainage rate for diluent co-injection case which was comparable with hexane co-injection and three times higher than conventional SAGD.

Series of experimental and simulation studies were conducted by Mamora et al. [11] to evaluate the feasibility of steam-propane injection method for the Hamaca and Duri fields. Results of laboratory works demonstrated lower injection pressure and three times higher injectivity for steam-propane injection case than steam-only injection scheme. The rate of oil drainage was accelerated by use of propane but there was no evidence found for increase or decrease of oil recovery, as in situ upgrading was observed in the viscosity of produced oil.Zhao et al. [12] carried out laboratory efforts on a gas injection wind-down process following SAGD process using a high-pressure high-temperature facility. They used a 2-D rectangular stainless steel model with two horizontal wells located at the center of the cell where the producer was placed 1 cm above the bottom of the model and injector was placed 5 cm directly above the producer representing a SAGD pattern. It was filled with Ottawa sand and saturated with water first, and then dead heavy oil with a viscosity of 18000 cp at 20 °C and 4.6 cp at 220 °Cwas flooded to displace the water and initialize the system. The results of experiment divulged that 12.5% of OOIP could be produced by injection of a non-condensable gas following SAGD process. The growth of hot chamber was observed even during the gas injection processafter suspension of SAGD operation.

The Steam Alternating Solvent (SAS) process as a new method of heavy oil recovery was introduced and investigated by Zhao et al. [13]. They fulfilled experimental studies and corresponding numerical simulations using a 2-D high-pressure high-temperature model. The model was filled with Ottawa sand and saturated with water at first. The water was then displaced by Burnt Lake's dead heavy oil. The steam was injected for 10 minutes and then solvent was injected for 50 minutes in the SAS process. The mixture of methane and propane in a vapor phase was used as solvent in their experiments. The SAS process illustrated higher cumulative oil recovery, lower SOR and improved energy input compared with SAGD process. The authors remarked that the economy of this new method depends highly on the solvent retention in the reservoir. They reported that only 3% of the injected solvent left inside the reservoir in their experiment.

The ES-SAGD process was investigated experimentally at a low pressure of 1500 kPa by Ivory et al. [14] for typical Athabasca formation. They used a scaled 2-D high-pressure high-temperature stainless steel model and packed it with Ottawa sand as porous media. The Athabasca bitumen with viscosity of 3,000,000 cp at 9 °C was used to saturate the model and South Rosevear condensate was used as injected solvent. The results showed that ES-SAGD increases oil recovery, improves SOR and accelerates oil drainage rate by 15%. About 86% of the injected solvent was recovered during the experiment.Ayodele et al. [15] performed five sets of laboratory experiments to evaluate the performance of ES-SAGD at low pressure in comparison to SAGD at low and high pressure and propane-SAGD at low pressure. They used a scaled 2-D high pressure high temperature experimental model to represent Athabasca typical reservoir. They found that it is practical to apply multi-component ES-SAGD in the field at low pressures. In addition, results illustrated that multi-component ES-SAGD at low pressure is more efficient than SAGD at low/high pressure and propane-SAGD at low pressure in terms of oil recovery and energy consumption.

Another laboratory work was conducted to evaluate and compare the performance of SAGD and ES-SAGD using hexane as solvent at high pressure of 2100 kPa in Alberta Research Council [16]. They reported that ES-SAGD represents better performance than SAGD in terms of energy input per unit of recovered oil, oil production rate, ultimate oil recovery and temperature distributions. Li and Mamora[17] carried out several sets of laboratory experiments to investigate the Solvent Co-Injection (SCI) process in vapor and liquid phase to enhance SAGD performance. They constructed a 2-D cross-sectional low-pressure scaled physical model and filled it with glass beads to represent a typical SAGD process in the Athabasca reservoir. The injected solvents were C_7 and a mixture of C_7 and xylene for ES-SAGD tests. The results of experiments divulged that co-injection of solvent can improve the efficiency of SAGD process in terms of energy consumption, total oil production and CSOR.

Ardali et al. [18] investigated the effect of SCI process experimentally using two-dimensional scaled physical model. The results of laboratory tests showed that addition of hexane to steam yields higher cumulative oil production, faster oil drainage rate and lower CSOR in comparison to SAGD process at the same operational conditions.Mohebati et al. [19] examined the effect of hexane on SAGD performance at different pressures of 1500 kPa and 3500 kPausing a 3-D scaled physical model. The behavior of hexane was different at lower pressure than higher pressure; however, results showed that addition of hexane was efficient at both operating conditions. Also, checking and analyzing of sand pack after the experiment elucidated that co-injection of hexane decreased the residual oil saturation inside the formation. You et al. [20] conducted several experiments to evaluate the steam chamber growth during SAGD and ES-SAGD in thin layer heavy oil reservoirs using a scaled rectangular stainless steel model. They found that the steam chamber reached to its largest area at least 30% faster during application of ES-SAGD than SAGD. The results displayedbetter performance in oil recovery factor and CSOR for ES-SAGD process as it was more energy efficient than conventional SAGD.

The main objective of this work is to compare the three promising methods for heavy oil/bitumen recovery namely, SAGD, ES-SAGD and SAS. Several laboratory tests were performed to investigate the effect of parameters such as steam injection rate (for SAGD tests), solvent injection rate and type of injected solvent(forES-SAGD tests). Moreover, the efficiency of the mentioned processes was evaluated in terms of oilproduction rate, cumulative steam-oil ratio and oil recovery factor.

II. POROUSMEDIAPACKINGPROCEDURES

2-mm glass beads were used to represent an unconsolidated porous media. In order to pack the media a rubber sleeve with diameter of 5 cm was placed on the inlet end cap of core holder. The inlet end cap was designedto have two different ports for production and injection purposes. The Production port was divided into five holes with same diameter at the face of inlet end cap in order toevenly

distribute or recover the fluid.The injection port was elongated to 5 cm above the face of inlet cap by a welded line to allow sufficient spacing between the injection and production ports, and avoid early breakthrough of the injected fluid. To prevent movement of glass beads a metal screen finer than 2-mm sized glass beads was placed inside the sleeve at the face of inlet end cap. Afterwards, they were placed on the electric shaker and the glass beads were poured inside the sleeve to a desired height of 15 cm from the top of inlet end cap while the shaker was running.Then another metal screen was placed on top of the porous media. This procedure was repeated for all of the cases to be sure that the porous media is homogeneous and has thesamecharacteristics.

III. EXPERIMENTAL SET-UP AND PROCEDURES

Schematic of the experimental set-up used in this work is illustrated in Fig.1. A stainless steel core holder with two end-caps and a rubber sleeve were used. The packed porous media were placed inside the core holder and the area between the core holder walls and sleeve was filled by viscous paraffin oil (120 cp at room temperature) to supplythe over-burden pressure. A 650 cc cylinder with floating piston was used to containthe paraffin oil. To maintain the paraffin oil pressure around the rubber sleeve, the inlet of the cylinder was connected to a Quizix positive displacement pump. This pump has several operating options and can be set to operate at constant rate or pressure by either displacing or recovering the distilled water. So it was possible torecover extra paraffin oil due to the expansion at higher temperatures to avoidhigher confining pressures. Therefore,this pump was set to constant pressure function to supply the desired confining pressure by injection of distilled water behind the floating piston and this pressure was monitored by a pressure gauge which was placed on the paraffin line.The pump's operational range is 0.001 cc/min up to 50 cc/min. To supply steam for the experiment another Quizix pump was used to inject distilled water directly to the core holder in such a way that the water inside the pipe line was passed through a rather long slim tube, which was placed in an oven with a constant temperature of 150 °C. The temperature of oven could be increased to a

maximum of 300 °C when it was needed and in order to keep the temperature constant, it was equipped with two fans to circulate the air inside the oven. In addition, one small light source and two embedded window panels made it possible to see inside the oven clearly. The other side of the slim tube out of the oven was connected to a special line which was equipped with a heater and completely insulated. The heater could be set at any desired temperature of up to 300 °C. The mentioned line is then connected to the core holder's injection port. The production line was wrapped with heating cable to carry the effluent to the separator. The effluent was sticky at room temperature, and difficult to collect in the separator, therefore the temperature of this heating cable was set to 65 °C to warm up the line and allow easier production. The separator was filled with distilled water at initial stage and the effluent entered in from bottom. Due to the density difference between oil and water the oil was gathered at top of the column and
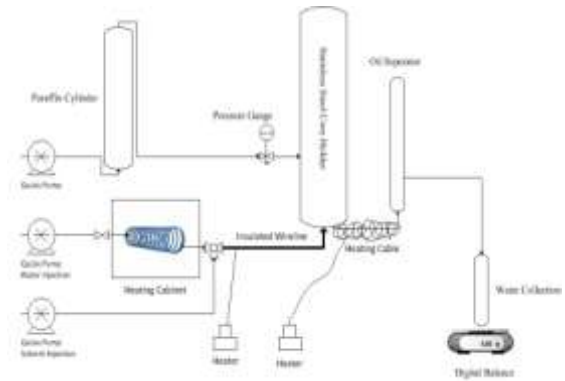

Fig.1Schematic representation of the experimental set-up

the same volume of water was produced and collected on a digital scale. The volume of produced oil could be read by visual inspection through graduated glass tube of the separator. This set-up was used for steam-assisted gravity drainage (SAGD) experiments while for solvent co-injection (SCI) processes another pump was used to inject the desired solvent into the porous media. The small container of solvent was placed on a digital scale in order to know the amount of injected solvent. The solvent injection line was connected to the insulated line to inject steam and solvent either simultaneously or alternatively. During the experiments the outlet end cap of the core holder was dead and both injection

and production were carried out from the bottom of the core holder same as the SAGD process.

To initialize the experiment, the packed glass beads inside the rubber sleeve was placed into the core holder and the space between the sidewall of core holder and rubber sleeve was then filled by paraffin oil providing the constant pressure of 30 bars as an overburden pressure to make sure the porous media was homogeneous and compact.Afterwards, the reservoir was saturated with distilled water using vacuum pump and the porosity of the model was assessed based on the material balance calculations on the amount of water which was injected and the amount which was left behind knowing the exact value of the dead volume of connected lines. Thereupon, the core holder was placed inside the oven horizontally as there was not enough space to be placed vertically and the temperature of the oven was set to 80 °C. Because of the high viscosity of Athabasca bitumen it was not possible to inject oil inside the porous media at room temperature, so it was done inside the oven at elevated temperature to have mobile oil. Another pressure vessel was used as an oil container and placed inside the oven to warm the oil up to 80 °C. After waiting for some hours in order to have mobile oil, flooding phase was started by injecting oil at constant rate of 30 cc/hr which was less than 1 PV/hr as recommended by Polikar et al. [21].The effluent were collected out of the oven into a graduated cylinder and then the amount of oil inside the porous media calculated based on the difference in volume of water injected by pump behind the piston and volume of the produced water knowing the exact value of the dead volume of the two end caps and connected lines.

A. SAGD and SCI processes

B. Oil sample preparation and viscosity measurement

The type of oil used in this study was a blending of Athabasca bitumen and n-dodecane. The bitumen sample used was obtained from an oil sand reservoir in Athabasca region, produced using SAGD method. The sample has not been exposed to any solvent and the condensed water produced together with the bitumen has been removed at high temperature. The viscosity, density, molecular weight and some other

Since the packed porous media was initialized and the amount of original oil in place (OOIP) was determined the core holder and connected pressure vessels were taken out of oven. Thereupon, the temperature of oven and the heating cable were set to 150 °C to be able to generate steam. The experiment was carried out at atmospheric pressure but to avoid heat loss and be sure of 100 percent steam quality the temperature was set to 150 °C. Steam generator line was then connected to the injection port of the core holder and separator was connected to the production line to start the SAGD experiment. In case of SCI the solvent injection line was connected to the insulated line through a double function valve. Moreover, in ES-SAGD process, desired solvent was co-injected with steam at specified rate only for 8 hrs from start of the experiment and afterwards, solvent injection was stopped while steam-only injection was continued until the end of the experiment. However, in SAS process, steam and solvent were injected alternatively in such a way that steam was injected at a rate of 64 cc/hr for 105 minutes and then it was stopped to start solvent injection. The desired solvent was then injected at a rate of 32 cc/hr for 15 minutes and thereafter, steam injection was stared again. This cycle was repeated for first 8 hours of the experiment and then steam-only injection was continued until the end of the experiment. At the end of the experiment, the separator was disconnected andtheproducedoilwaspouredinto the beaker to remove the water from oil. Then the net weight of produced oil was recorded while in the case of SCI experiment the beaker was placed inside the oven at temperatures below the boiling point of the injected solvent in order to find out how much solvent was produced by weighing the beaker contents after 3-4 days. This way, it was possible to know how much solvent was produced during the experiment.

PVT properties of Athabasca bitumen were measured
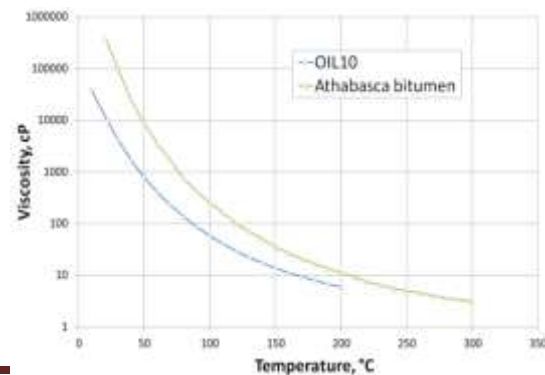
as highlighted in Ashrafi et al.[22]. Bitumen was added to n-dodecane in known amounts, and the mixture was stirred on a magnetic stirrer. The oil sample was prepared by mixing bitumen with 10% n-C_{12} added on a mass basis. This oil is referred to as OIL10. The properties of bitumen and the mixed oil sample are shown in Table I.The viscosity of this oil samplewas also measured using a digital rotational viscometer as done for Athabasca bitumen [22]. The viscosity measurements were done in 10 °C intervals, allowing sufficient time at each temperature step to have a reasonable viscosity reading. For pure Athabasca bitumen the measurements were done from room temperature up to 300 °C.

TABLE I - OIL PROPERTIES

Component	Molecular Weight (g/gmole)	Density (g/cc)
Athabasca bitumen	534	1.0129
n-dodecane (n-C_{12})	170.34	0.748
OIL10	440.1	0.9783

While for OIL10, the measurements were done up to 70 °C and extrapolated for higher temperature values. This was due to the possibility of n-dodecane evaporation at higher temperatures. The extrapolation was done using an empirical equation for the viscosity of gas free Athabasca bitumen presented by Khan et al. [23]. This equation is as follows:

$$\ln\ln\ \mu\ = c_1 \ln T + c_2 \qquad (1)$$

In this equation μ is dynamic viscosity of heavy oil sample in "mPa.s" or "cp", at atmospheric pressure and temperature of T (K). The constants c_1 and c_2 are empirical and can be found for each sample using experimental data. They can be determined using the least square parameter estimation technique. The applicability of this equation to our bitumen sample was tested and compared with the data provided by Khan et al. [23], [22]. The values of empirical constants c_1 and c_2 for the bitumen and OIL10 are presented in Table II. The viscosity versus temperature curve is also shown in Fig. 2.

TABLE II

EMPIRICAL CONSTANTS of VISCOSITY CORRELATION (1) for ATHABASCA BITUMEN and OIL10

Component	c_1	c_2
Athabasca bitumen	-3.5912	22.976
OIL10	-3.4563	21.872

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Several sets of experiments were performed to evaluate and compare the performance of different bitumen recovery approaches namely; SAGD, ES-SAGD and SAS. Also the effects of steam injection rate, type of injected solvent and solvent injection rate were studied in this work. Table III summarizes core properties and experimental parameters.

TABLE III

CORE PROPERTIES and EXPERIMENTAL PARAMETERS

Core properties	
Length (Glass beads (GBs) pack	15 cm
Diameter	5 cm
Porosity	

Fig.2 Illustration of viscosity of Athabasca bitumen and OIL10 versus temperature

Initialization Conditions	
Overburden pressure	30 bars
Oil injection rate	0.5 cc/min
Water injection rate	0.5 cc/min
Temperature	80 °C

The specifications and characteristics of each set of performed experiment in this work are listed in Table IV.

TABLE IV

PERFORMED LABORATORY EXPERIMENTS DURING THIS STUDY

Process	Steam injection rate cc/hr	Solvent type	Solvent injection rate cc/hr	Porosity %	OOIP gram	S_{oi} %
SAGD_60cc/hr	60	--------------	0	34	94.89	89.52
SAGD_100cc/hr	100	--------------	0	31.8	89.02	89.33
ES-SAGD_C6_4cc/hr	56	n-hexane	4(first 8 hrs) - 0	32.5	91.96	90.60
ES-SAGD_C6_8cc/hr	52	n-hexane	8(first 8 hrs) - 0	33.3	94.89	91.34
ES-SAGD_C5_4cc/hr	56	n-pentane	4(first 8 hrs) - 0	32.5	89.02	87.46
ES-SAGD_C7_4cc/hr	56	n-heptane	4(first 8 hrs) - 0	32.2	88.38	89.02
SAS_C6	64 (fisrt 8 hrs) - 56	n-hexane	32(first 8 hrs)- 0	32.2	88.38	89.02

To evaluate and compare the different processes, various efficiency indicators were applied. Definitions of these indicators are as follows:

Oil recovery factor (R.F.): percentage of the ratio of total oil phase production minus the total amount of liquid solvent produced to the initial amount of oil in place at standard conditions.

Cumulative steam-oil ratio (CSOR): the ratio of total amount of steam injected to the total amount of oil produced at standard conditions.

Solvent recovery factor: percentage of the ratio of total amount of produced solvent to the total amount of solvent injected.

Cumulative oil production rate: cumulative rate of oil production at experimental conditions.

Cumulative oil production: the net amount of produced oil after removing the solvent.

A.   Evaluation of processes based on cumulative oil production and recovery factor

Fig.3 represents the cumulative oil production and oil recovery factor for different processes at their specified operating conditions. Although SAS and n-C5 co-injection with steam (ES-SAGD_nC5) showed better performance than the other processes, to evaluatemore precisely based on the amount of produced oil, it is best to look at recovery factor. This parameter represents the performance of each process at the same scale. For example, in this study SAGD process at steam injection rate of 60 cc/hr (SAGD_60cc/hr) demonstrated better performance based on cumulative oil production than the case of n-heptane co-injection with steam (ES-SAGD_nC7), while looking at the recovery factor itwas clear that ES-SAGD_nC7 showed higher recovery factors than SAGD_60cc/hr experiment. The reason is that the OOIP in case of SAGD_60cc/hr was slightly higher than ES-SAGD_nC7; hence, the recovery factor is more reliable than the cumulative oil production indicator.
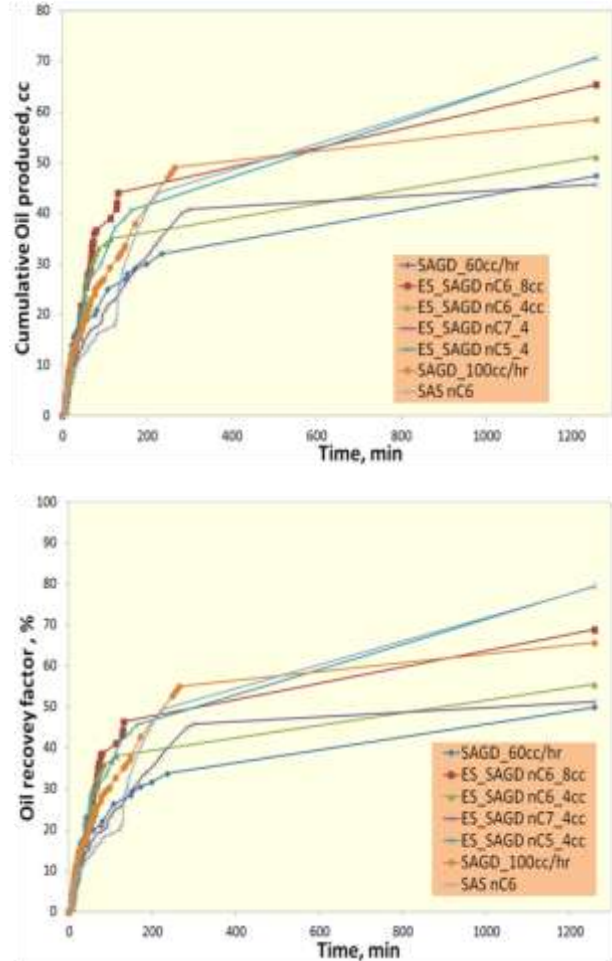

Fig.3Comparison of cumulative oil production and oil recovery factor of different processes

Fig.4 illustrates the early stage of oil recovery factor for different sets of experiments. After about 60 minutes of oil production period, ES-SAGD experiments except ES-SAGD_nC7 showed the best performance among the other processes, which indicated that this method was faster than the other approaches in terms of oil recovery. The weakness of ES-SAGD_nC7 case could be the saturation conditions of nC7 as it is heavier than nC6 and nC5 and it may become liquid when it comes in contact to the cold oil inside the porous media easier and earlier than the other solvents. Also it should be noted that there was no insulation around the core holder and it was exposed to the room temperature during experimental runs. The SAS process was not promising at earlier stages as simulation studies showed that it needs more time to become mature and efficient. However, after 180 minutes SAS became

efficient and represented considerably significant performance while at this time the SAGD_60cc/hr case had the worst performance among the others. Here, the effect of steam injection rate is absolutely evident as the recovery factor is about 45 and 30 percent in case of SAGD_100cc/hr and SAGD_60cc/hr respectively. It can be concluded that SCI processes displays better performance than SAGD process even at higher steam injection rates based on the recovery factor index.
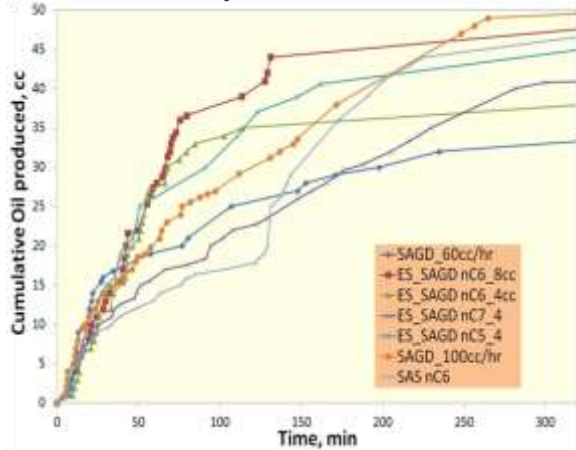
B.   Evaluation of processes based on cumulative steam-oil ratio (CSOR)

Another important parameter to evaluate the thermal processes economically is CSOR. This indicator is also important from environmental point of view as vast amount of water is used during thermal processes such as SAGD which leads to waste water management issues. Both SAGD_60cc/hr and SAGD_100cc/hr experiments demonstrated very high values of CSOR while the SCI processes showed prosperous performance. Although SAS displayed very high amount of CSOR at earlier periods of experiment but at later times this indicator was decreased to a reasonable amount of 4.5 cc/cc after 180 minutes of production time(Fig.5).
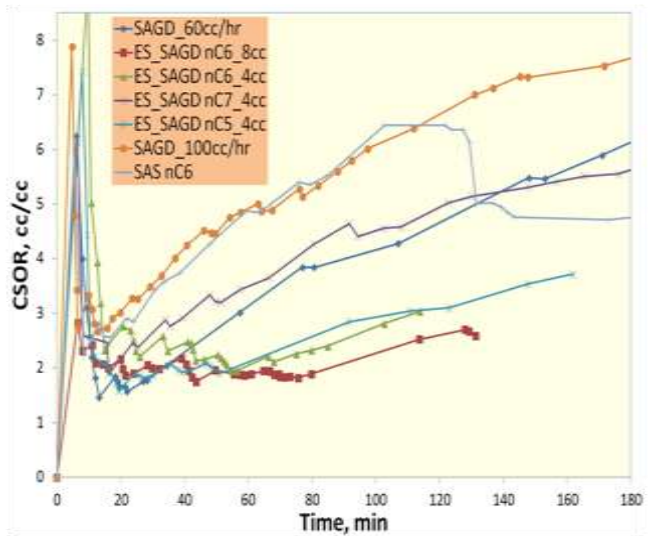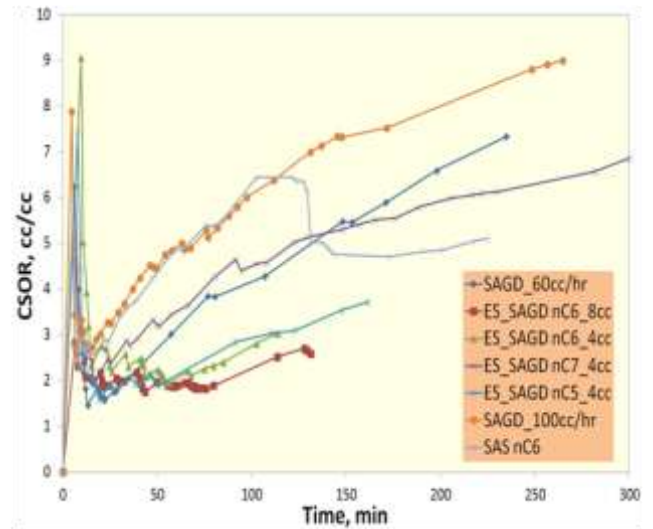
Fig.4Comparison of cumulative oil production and oil recovery factor of different processes at early stage of production
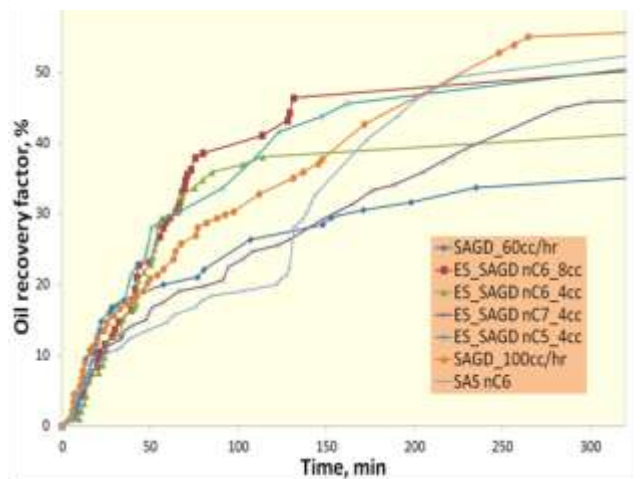

Fig.5Evaluation of different processes in terms of CSOR

Among the SCI processes ES-SAGD_nC6_8cc/hr represented the best performance as lower amount of water was injected due to the higher amount of solvent injection rate compare to the other SCI processes. Therefore, it can be found that higher injection rate of solvent can increase the rate of oil production and at the same time decrease the CSOR. One, however, should bear in mind that solvent is a light hydrocarbon which is highly valuable in the oil industry, and the amount of recovered solvent is important as it means the return of money.Therefore it is important to look at the solvent recovery for different SCI processes tested in this study.

C.   *Evaluation of processes based on oil production rate*

All of experiments demonstrated reasonable amount of oil production rate at earlier stage of experiment (Fig. 6).

However, the best performance was observed in SCI experiments excluding ES-SAGD_nC7. The rate of production declined after 80 minutes in most of the experiments. Therefore it is wise to reduce the amount of steam injection rateafter this time to avoid production of excess water and improve the CSOR. Looking to the trend of oil production rate for SAS process shows that there is a jump in the curve after 120 minutes of experiment.

This jump represents that the SAS needs more time as injection of solvent was started after 105 minutes of steam injection. Therefore, after that time the injected solvent reduced the viscosity of initial oil by diluting the oil.
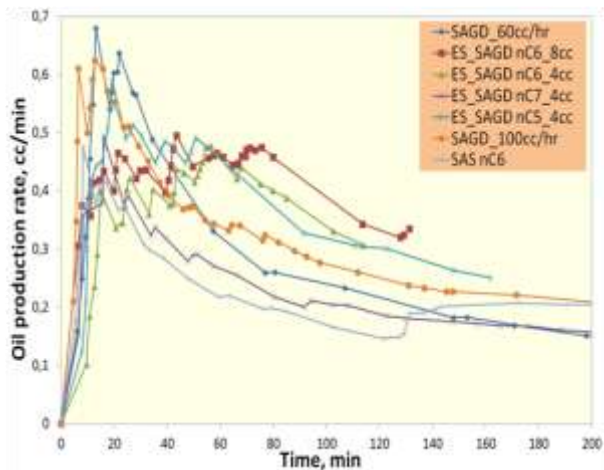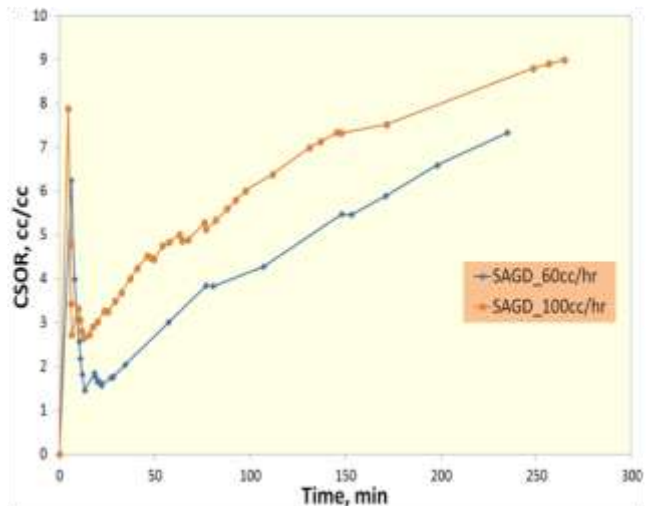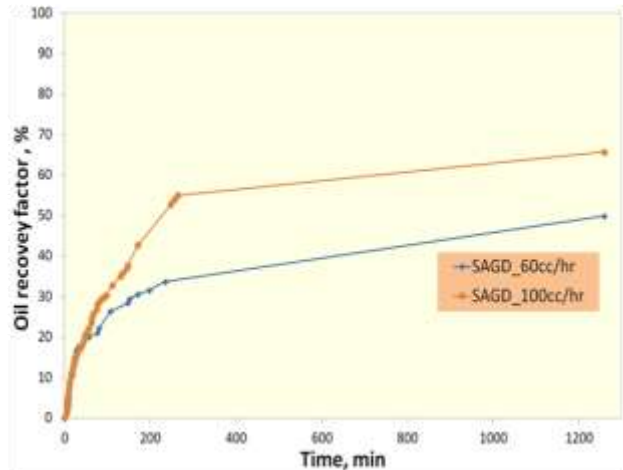
D.   *Evaluation of SAGD process based on steam injection rate*

In order to investigate the effect of steam injection rate two different sets of experiments namely SAGD_60cc/hr and SAGD_100cc/hr with injection rates of 60cc/hr and 100 cc/hr were performed. Results demonstrated that higher steam injection rate increasedoil production rate and recovery factor ofthe process, on the other hand,intensified the CSOR of the process (Fig.7). From economic point of view there should be parity between these two factors, hence, the optimum steam injection rate should be obtained according to the reservoir properties. However, it is possible to inject with higher rates at the start of process and then gradually reduce the rate of injection.
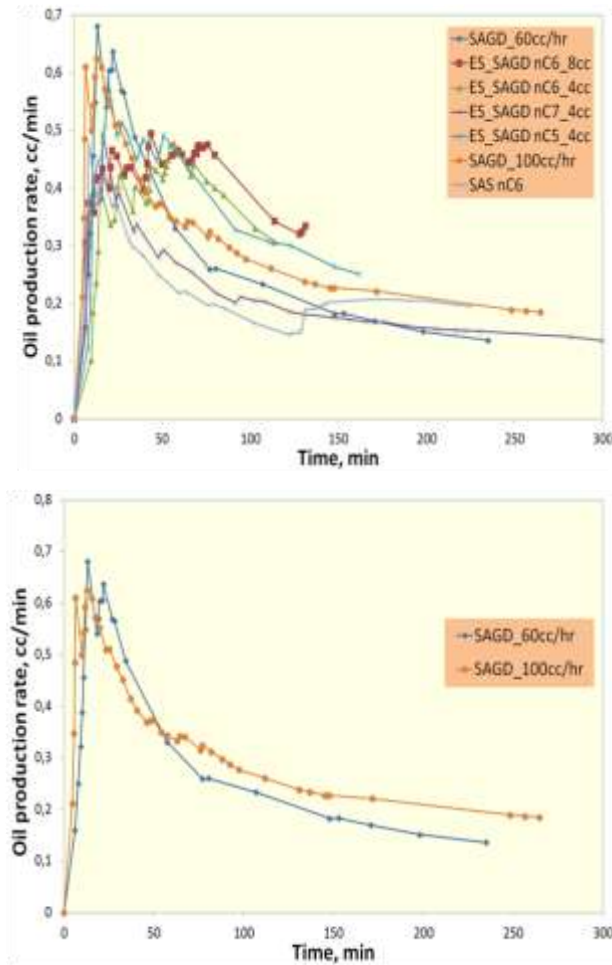

Fig.6Evaluation of different processes in terms of oil production rate

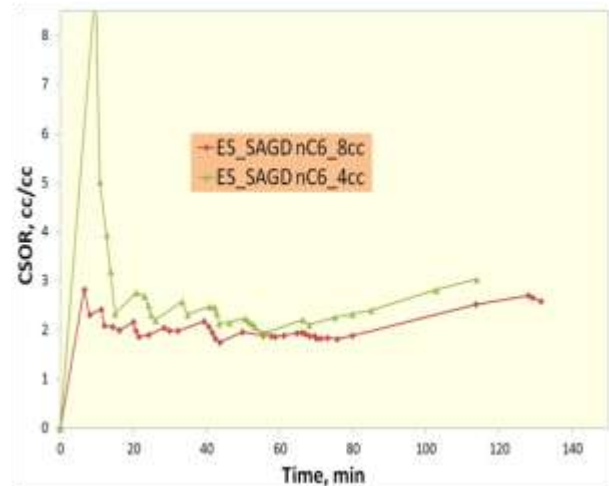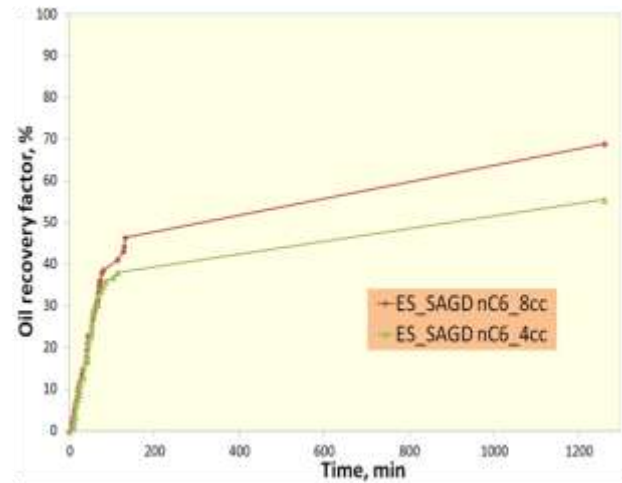Fig.7Effect of steam injection rate on SAGD process

E.   Evaluation of ES-SAGD process based on solvent injection rate

One of the important parameters of each ES-SAGD process is solvent injection rate. Adjusting this parameter helps to find the exact amount of valuable hydrocarbon for the process. In fact, higher solvent injection rate can produce more oil and modify the CSOR of the SAGD process but the amount of retained hydrocarbon inside the reservoir is vital for economy of the process. Two ES-SAGD processes were carried out in this study by co-injection of steam and n-hexane as solvent with following constraints:

ES-SAGD_nC6_8cc/hr: Steam injection rate = 52 cc/hr, Solvent injection rate = 8 cc/hr

ES-SAGD_nC6_4cc/hr: Steam injection rate = 56 cc/hr, Solvent injection rate = 4 cc/hr

Both of processes were run for 21 hrs while solvent was injected only for 8 hrs from start of the experiments. The other parameters remained constant as for the SAGD process. Fig.8shows the results of study for these two cases. Higher solvent injection rate increased the oil production rate, recovery factor and modified the CSOR of the process. In addition, the production of oil was started earlier and accelerated at higher solvent injection rate. However, as it was mentioned earlier the recovery of injected solvent is an important factor for economy of the process. Results show that the amount of solvent recovery factor was higher in case of ES-SAGD_nC6_4cc/hr (73.34%) than ES-SAGD_nC6_8cc/hr (59.73%).
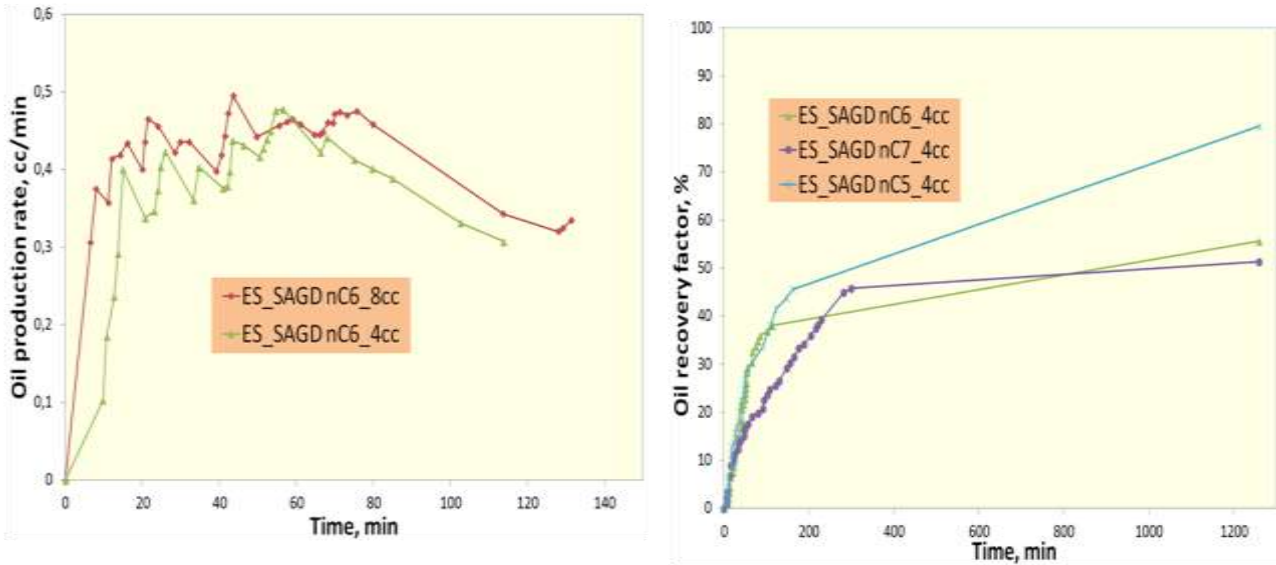
Fig.8Evaluation of ES-SAGD process in terms of solvent injection rate

F.   Evaluation of ES-SAGD process based on type of injected solvent

The other important parameter for assessment of ES-SAGD process is the type of injected solvent. In fact, the reservoir conditions such as temperature and pressure define the type of solvent for ES-SAGD process and the other SCI processes as the injected solvent should be in vapor phase near to its dew point curve at reservoir conditions. Because at this point solvent has the best efficiency and can diffuse into the cold oil and dilute it more effectively. Therefore, the type of desired solvent should be obtained by several experiments and simulation studies according to the reservoir conditions. In this study, only the impacts of different solvent types on ES-SAGD process were investigated at atmospheric pressure in the presence of dry steam. Three sets of experiments were run with following constraints:

ES-SAGD_nC5_4cc/hr: steam injection rate = 56 cc/hr, solvent type = n-pentane, solvent injection rate = 4 cc/hr

ES-SAGD_nC6_4cc/hr: steam injection rate = 56 cc/hr, solvent type = n-hexane, solvent injection rate = 4 cc/hr

ES-SAGD_nC7_4cc/hr: steam injection rate = 56 cc/hr, solvent type = n-heptane, solvent injection rate = 4 cc/hr
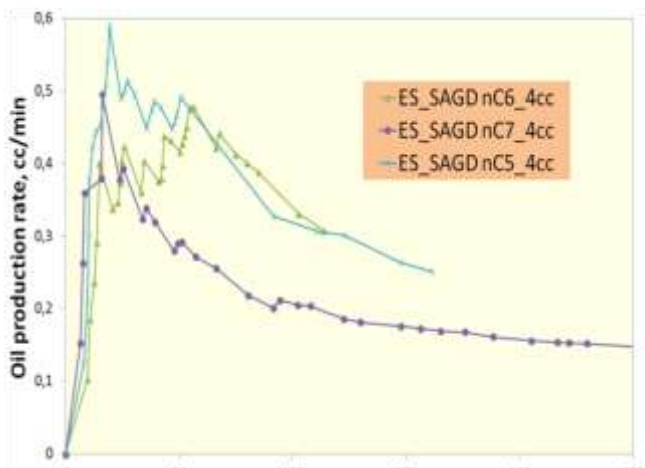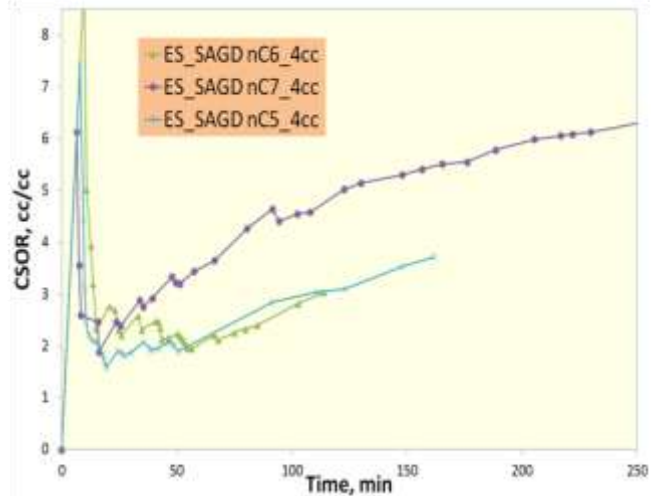

Fig.9Evaluation of ES-SAGD process in terms of solvent injection type

All sets of experiment were run for 21 hrs while solvent was injected only for 8 hrs from start of the experiments. Results of this work indicated that at the mentioned conditions n-pentane had a better performance than the other solvents, as it is lighter than the two others, and can stay in vapor phase at lower temperatures. So, even due to the heat loss to the ambient around the core holder and also into the porous media, to the rubber sleeve and confining oil, n-pentane can still diffuse and reduce the viscosity of the in-situ oil effectively compared to the other two solvents. The evidence to this was the fact that we observed very low amount of residual oil in the porous media after the experiment and the produced oil was considerably lighter than the other experiments. To be sure that the experiment was correct, it was repeated twice and the results were the same. ES-SAGD_nC5_4cc/hr illustrated higher oil production rate, lower amount of CSOR and greater ultimate oil recovery factor (Fig.9).

G.   Comparison of ES-SAGD and SAS processes

Among the different types of SCI processes, ES-SAGD and SAS were designated to compare their efficiency. For this purpose, two different sets of experiment were carried out at atmospheric pressure by co-injection of n-hexane as solvent with dry steam in ES-SAGD case and alternative injection of dry steam and n-hexane for SAS experiment. In ES-SAGD process, n-hexane with rate of4 cc/hr was injected with dry steam at a rate of 56 cc/hr. The experiment lasted for 21 hrsbut solvent co-injection was stopped after 8 hrs of the process. In SAS experiment, dry steam was injected at a rate of 64 cc/hr for 105 minutes and then steam injection stopped and n-hexane injection started for 15 minutes. Afterwards, solvent injection was halted and dry steam injection with the mentioned rate was started again and this cycle was repeated three times. Indeed, after 8 hrs of the experiment this cycle was stopped and the continuous injection of steam at a rate of 56 cc/hr commenced.Fig.10 shows the result of experiments based on the different indicators. SAS displayed better recovery factor at the expense of higher CSOR, whereas ES-SAGD showed better performance at earlier stages of production based on the recovery factor. Moreover, very low CSOR were obtained for ES-SAGD process. However, the solvent recovery factor of these two processes was almost the same (73.71% for SAS and 73.34% for ES-SAGD).
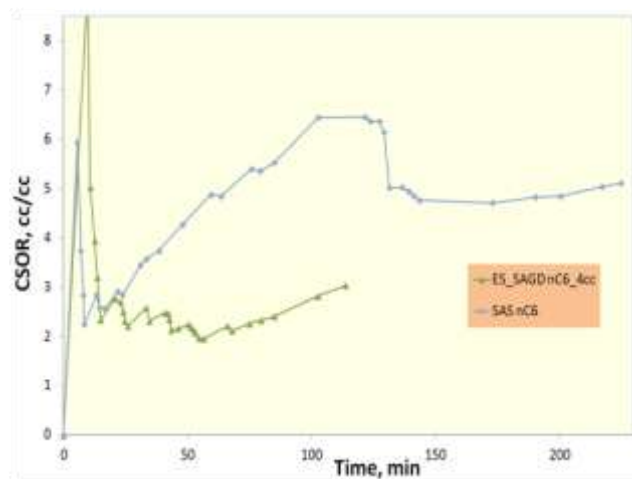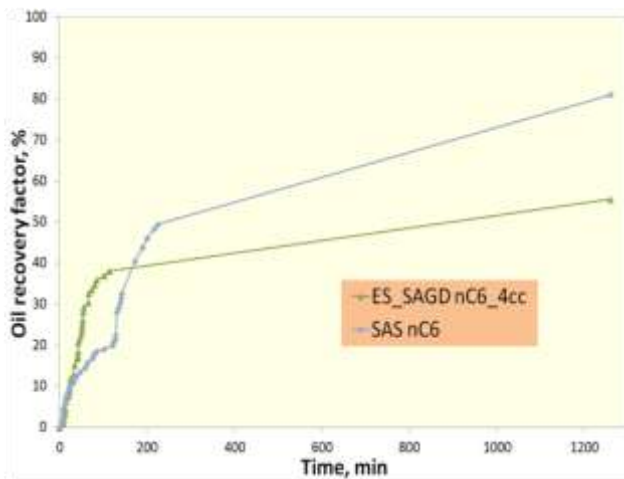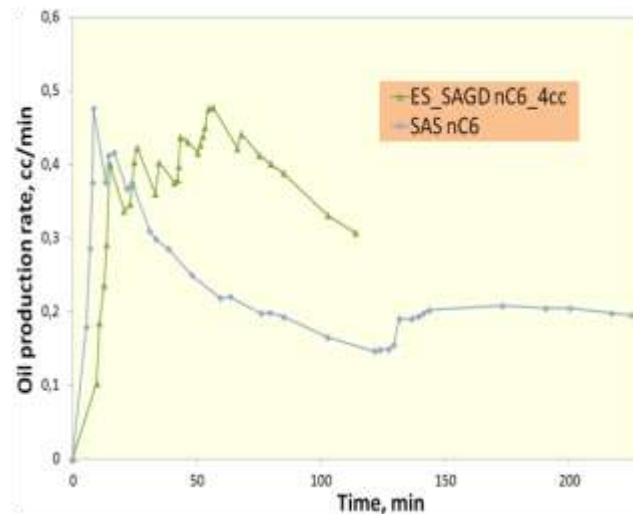
Fig.10Performance evaluation of ES-SAGD and SAS

V.   CONCLUSIONS

Several laboratory experiments were conducted to investigate the efficiency of different types of thermal processes for heavy oil recovery. This work compared SAGD, ES-SAGD and SAS processes based on various economical indicators such as oil production rate, oil recovery factor and CSOR. Among these methods, ES-SAGD_nC5 and SAS showed the best performance according to the ultimate oil recovery factor, while ES-SAGD_nC6 and ES-SAGD_nC5 illustrated highest oil production rate and lowest CSOR. Moreover, effect of steam injection rate on SAGD process was studied and the results of experiments represented that higher steam injection rate leads to a better ultimate recovery factor and oil production rates, while intensifies the CSOR. Therefore, an optimum steam injection rate should be obtained for each SAGD process according to the reservoir conditions.

In addition, injected solvent type and rate were evaluated for ES-SAGD process. Three different types of hydrocarbons namely n-pentane, n-hexane and n-heptane were usedfor this investigation. Higher oil production rate, ultimate recovery factor and lower CSOR were obtained for ES-SAGD_nC5 and ES-SAGD_nC6, while ES-SAGD_nC7 was not promising compared to the other two. Actually n-heptane, which is   heavier than the other two solvents, was not so effective at our experimental conditions, but still its performance was comparable to SAGD process. Also, investigations on the effect of solvent injection rate represented that higher rate increases the oil recovery factor and oil production rate, itaccelerates the process, while leaves higher amount of solvent behind. The amount of solvent retention inside the reservoir was higher in case of higher solvent injection rate. Comparison of ES-SAGD and SAS demonstrated that both processes were promising according to the efficiency indicators such as oil production rate, oil recovery factor and CSOR, however, SAS showed better recovery factor and ES-SAGD displayed better CSOR. The amount of solvent recovery factor was the same for both of the methods and relatively reasonable.

ACKNOWLEDGMENT

REFERENCES

[1]   Butler, R.M., McNab, G.S. and Lo, H.Y.: Theoretical Studies on the Gravity Drainage of Heavy Oil During Steam Heating. The Canadian Journal of Chemical Engineering, Vol. 59, No. 4, pp. 455-460, August (1981)

[2]   Chung, K.H. and Butler, R.M.: Geometrical Effect of Steam Injection on the Formation of Emulsions in the Steam-Assisted Gravity Drainage Process. The Journal of Canadian Petroleum Technology, Vol. 27, No. 1, pp. 35-42, January-February (1988).doi: 10.2118/88-01-02

[3]   Nasr, T.N., Golbeck, H. and Lorimer, S.: Analysis of the Steam Assisted Gravity Drainage (SAGD) Process Using Experimental/Numerical Tools. Paper SPE 37116 presented at the SPE International Conference on Horizontal Well Technology held in Calgary, Canada (18-20 November 1996)

[4]   Nasr, T.N., Golbeck, H., Korpany, G. and Pierce, G.: Steam Assisted Gravity Drainage (SAGD) in Horizontal Wells: A Visualization Model Study. Paper SPE 37521 presented at

the SPE International Thermal Operations and Heavy Oil Symposium held in Bakersfield, California, USA (10-12 February 1997)

[5] Pujol, L. and Boberg, T.C.: Scaling Accuracy of Laboratory Steam Flooding Models. Paper SPE 4191 presented at the SPE California Regional Meeting held in Bakersfield, California, USA (8-10 November 1972). doi: 10.2118/4191-MS

[6] Nasr, T.N., Golbeck, H., Korpany, G. and Pierce, G.: Sand Operating Strategies. Paper SPE 50411 presented at the SPE International Conference on Horizontal Well Technology held in Calgary, Alberta, Canada (1-4 November 1998)

[7] Akin, S. and Bagci, S.: An Experimental Study on Single Well Steam Assisted Gravity Drainage. Paper 2000-10 presented at the Petroleum Society's Canadian International Petroleum Conference held in Calgary, Alberta, Canada (4-8 June 2000)

[8] Sasaki, k., Akibayashi, S., Yazawa, N., Doan, Q.T. and Farouq Ali, S.M.: Experimental Modeling of the SAGD Process-Enhancing SAGD Performance with Periodic Stimulation of the Horizontal Producer. SPE Journal, Vol. 6, No. 1, pp. 89-97, March (2001)

[9] Goite, J.G., Mamora, D.D. and Ferguson, M.A.: Experimental Study of Morichal Heavy Oil Recovery Using Combined Steam and Propane Injection. Paper SPE 69566 presented at the SPE Latin American and Caribbean Petroleum Engineering Conference held in Buenos Aires, Argentina (25-28 March 2001)

[10] Nasr, T.N., Beaulieu, G., Golbeck, H. and Heck, G.: Novel Expanding Solvent-SAGD Process "ES-SAGD". Paper 2002-072 presented at the Petroleum Society's Canadian International Petroleum Conference held in Calgary, Alberta, Canada (11-13 June 2002)

[11] Mamora, D.D., Rivero, J.A., Hendroyono, A. and Venturini, G.J.: Experimental and Simulation Studies of Steam-Propane Injection for the Hamaca and Duri Fields. Paper SPE 84201 presented at the SPE Annual Technical Conference and Exhibition held in Denver, Colorado, USA (5-8 October 2003)

[12] Zhao, L., Law, D.H.S., Nasr, T.N., Coates, R., Golbeck, H., Beaulieu, G. and Heck, G.: SAGD Wind-Down: Lab Test and Simulation. The Journal of Canadian Petroleum Technology, Vol. 44, No. 1, pp. 49-53, January (2005).doi:10.2118/05-01-04

[13] Zhao, L., Nasr, T.N., Huang, H., Beaulieu, G., Heck, G. and Golbeck, H.: Steam Alternating Solvent Process: Lab Test and Simulation. The Journal of Canadian Petroleum Technology, Vol. 44, No. 9, pp. 37-43, September (2005).doi:10.2118/05-09-04

[14] Ivory, J., Zheng, R., Nasr, T. N., Deng, X., Beaulieu, G. and Heck, G.: Investigation of Low Pressure ES-SAGD. Paper SPE 117759-MS presented at the SPE International Thermal Operations and Heavy Oil Symposium held in Calgary, Alberta, Canada (20-23 October 2008)

[15] Ayodele, O.R., Nasr, T.N., Beaulieu, G. and Heck, G.: Laboratory Experimental Testing and Development of an Efficient Low-Pressure ES-SAGD Process. Journal of Canadian Petroleum Technology, Vol. 48, No. 9, pp. 54-61, September (2009)

[16] Ayodele, O.R., Nasr, T.N., Ivory, J., Beaulieu, G. and Heck, G.: Testing and History Matching of ES-SAGD (Using Hexane). Paper SPE 134002-MS presented at the SPE Western Regional Meeting held in Anaheim, California, USA (27-29 May 2010)

[17] Li, W. and Mamora, D. D.: Experimental Investigation of Solvent Co-Injection in Vapor and Liquid Phase to Enhance SAGD Performance. Paper SPE 133277-MS presented at the SPE Annual Technical Conference and Exhibition held in Florence, Italy (19-22 September 2010)

[18] Ardali, M., Mamora, D.D. and Barrufet, M.: Experimental Study of Co-injection of Potential Solvents with Steam to Enhance SAGD Process. Paper SPE 144598-MS presented at the SPE Western North American Region Meeting held in Anchorage, Alaska, USA (7-11 May 2011)

[19] Mohebati, M. H., Maini, B. B. and Harding, T. G.: Experimental Investigation of the Effect of Hexane on SAGD Performance at Different Operating Pressures. Paper SPE 158498-MS presented at the SPE Heavy Oil Conference held in Calgary, Alberta, Canada (12-14 June 2012)

[20] You, N., Yoon, S. and Lee, C. W.: Steam chamber evolution during SAGD and ES-SAGD in thin layer oil sand reservoirs using a 2-D scaled model. Journal of Industrial and Engineering Chemistry, Vol. 18, pp. 2051-2058, (2012)

[21] Polikar, M., Farouq Ali, S.M., Puttagunta, V.R.: High Temperature Relative Permeabilities for Athabasca Oil Sands. SPERE.5(1), 25-32 (1990).doi: 10.2118/17424-PA

[22] Ashrafi, M., Souraki, Y., Karimaie, H., Torsaeter, O., Bjorkvik B.J.A.: Experimental PVT Property Analyses for Athabasca Bitumen. Paper CSUG/SPE 147064 presented at the Canadian Unconventional Resources Conference held in Calgary, Alberta, Canada (15-17 November 2011). doi: 10.2118/147064-MS

[23] Khan, M. A. B., Mehrotra, A. K., Svrcek, W. Y.: Viscosity Models for Gas-Free Athabasca Bitumen. J. Can. Pet. Tech., 23(3), 47-53 (1984). doi: 10.2118/84-03-05

NOMENCLATURE

CSOR	Cumulative Steam-Oil Ratio
CSS	Cyclic Steam Stimulation
ES-SAGD	Expanding-Solvent SAGD
GB	Glass Beads
GHG	Green-House-Gas
OOIP	Original Oil In Place
PV	Pore Volume
R.F.	Recovery Factor
SAGD	Steam-Assisted Gravity Drainage
SAP	Solvent Aided Process
SAS	Steam Alternating Solvent
SA-SAGD	Solvent-Assisted SAGD
SCI	Solvent Co-Injection
SOR	Steam-Oil Ratio
SW-SAGD	Single-Well SAGD
T	Absolute Temperature, K
THAI	Toe-to-Heel Air Injection
S_{oi}	Initial Oil Saturation
μ	Dynamic Viscosity, cP
LASER	Liquid Addition to Steam Enhanced Recovery