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Design, construction and operation of lab scale cylindrical steam assisted gravity drainage model for heavy oil recovery

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Abstract−Based on a theoretical background [1,2], a lab scale cylindrical SAGD (steam assisted gravity drainage) model was designed, constructed and operated. There are six different parts in the apparatus: (1) water supplier, (2) steam generator, (3) SAGD cylindrical model, (4) cooling system, (5) constant pressure maintaining system and (6) production system. Temperature, pressure and steam injection rate were controlled by computer, and product (mixture of oil and water) was collected/separated manually. Extra heavy oil (<10 cp at 200 °C) and glass bead (diameter 1.5 mm) were mixed homogeneously for making porosity of 0.3 and applied for simulating oil sand. For obtaining optimum operation conditions of SAGD apparatus, several attempts were made. When the steam at high temperature (160-180 °C), high pressure (8-9 atm) was injected with 20-25 cc/min, cSOR (cumulative steam to oil ratio) of about 5 was obtained with oil recovery of 78.8%.

Key words: Oil Sand, Bitumen, SAGD Model, Scaling Factor, SOR (Steam to Oil Ratio)

INTRODUCTION

Oil sands, also known as tar sands, or extra heavy oil, are a type of bitumen deposit, and are naturally occurring mixtures of sand or clay, water and a highly dense and viscous form of oil called bitumen. Oil sands deposits have recently been considered to be a part of the world's oil reserves, as higher oil prices and new technology enable them to be profitably extracted and upgraded to usable chemical products [3,4].

For recovering bitumen from oil sand, the SAGD process, which was developed by Butler [5], has been successfully applied to oil sand fields. The main idea was to overcome the problems associated with the highly viscous bitumen by gravity drainages in steam chambers generated by displacement of heavy oil [6]. Chung and Butler reported experimental results for the SAGD process with scaled and visual reservoir model [7]. H. Shin et al. have shown that an automated process control system is capable of controlling and optimizing steam injection process like the SAGD process [1,2]. The basic concept of SAGD is illustrated in Fig. 1. Steam is introduced near the bottom of the reservoir and tends to rise, and the heavier condensate and heated oil tend to fall to the bottom. By injecting steam, a steam chamber forms directly above the production well. At the steam chamber boundary, steam is condensed to water as heat is transferred to the oil. Condensed water and hot oil flow along the steam chamber to the production chamber [8]. In this report, a lab scale SAGD model was designed, constructed and operated. It was possible to simulate a lab scale SAGD process at high pressure and high temperature, and any variables such as steam quality, injection rate, temperature and pressure had to be controlled all at once and in real time.

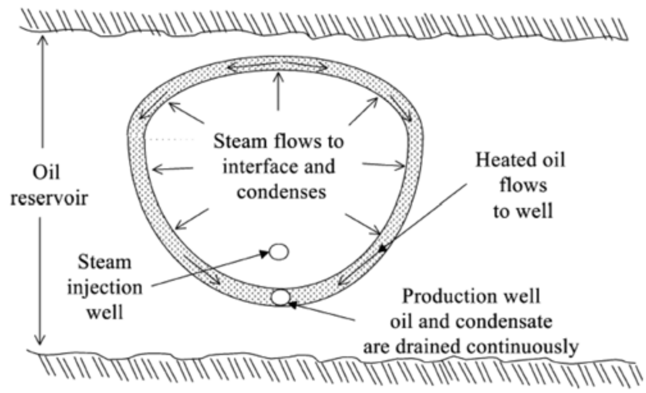

Fig. 1. The formation of the steam chamber in SAGD [7].

EXPERIMENTAL

1. Definition and Determination of Scaling Factors

Design parameters of SAGD model were calculated based on geological field data, where the scaling ratio is about 150 : 1 [1,9]. Typical parameters were calculated with following equations from (1) to (5). Detailed parameters were compared in Table 1.

R=(prototype reservoir thickness / model reservoir thickness)

$$=H_p/M_m \quad (1)$$
$$=34\ \mathrm{m}/22.7\ \mathrm{cm}$$
$$=150$$

Permeability in model will be increased by "R":

$$K_m=R * K_p \quad (2)$$
$$=150 * 5=750\ \mathrm{Darcy}$$

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Table 1. Calculated scaling factors based on geological field data

	Field data		Apparatus design	
Geological Para.[a]	Depth/cm	36000	R[b]	150
	Net pay/cm	1500	Thick/cm	10
	Well slice length/cm	750	Well slice length/cm	5
	Well length/cm	75000	Well length/cm	500
	Width/cm	13000	Width/cm	86.66
	I/P[c] spacing/cm	500	I/P[c] spacing/cm	3.33
	Horizon perm.[d]/darcy	5	Horizon perm.[d]/darcy	750
	Production well distance from bottom/cm	100	Production well distance from bottom/cm	0.66
			Total volume/L	4.33
Properties	Perm.[d] ratio (KV/KH)	0.5	Average particle diameter/cm	0.14
	Porosity	0.3	Porosity	0.3
			I/P[c] pipe size	0.63
			Initial gas satu.[e]	0
			Initial oil satu.[e]	0.81
			Initial water satu.[e]	0.19
	Oil API[f]	8.5	Oil API[f]	8.5
Operational condition	Max. steam injection pressure/kPa	3000-5000	Steam injection pressure/kPa	1500
	Steam injection temp.[g]/°C	260-300	Steam injection temp.[g]/°C	150
	Maximum steam injection/cm^3/hr	390000	Maximum steam injection/cm^3/min	23.14
			1 year equivalent/hr	0.38

[a]Geological parameter
[b]Prototype reservoir thickness/Model reservoir thickness
[c]Injection well/Production well
[d]Permeability
[e]Saturation
[f]American Petroleum Institute
[g]Temperature

Table 2. Compositions of bitumen and extra heavy oil

	Component (wt%)					Component (ppm)		
	C	H	N	S	O	V	Ni	Fe
Bitumen	82.85	10.41	1.64	4.78	1.81	174	68.5	16.8
Extra heavy oil	84.58	12.73	0.35	0.0	0.90	ND[a]	61.1	10.6

[a]Not detected

Time in the model will be decreased by "R^2"; therefore 1 yr in the prototype will be:

$$T_m=(1/R^2) * T_p \quad (3)$$
$$=(1/150^2) * 365 * 24 \text{ yr}$$
$$=0.38 \text{ hr in the model}$$

The injection rate will be decreased by "R"; therefore 560 m^3/d in the prototype will be:

$$q_m=(1/R) * Q_p \quad (4)$$
$$=(1/150) * 560 \text{ m}^3\text{/d}=23 \text{ cm}^3\text{/min}$$

Glass bead size calculation of the Kozeny-Carmen equation:

$$D=\sqrt{\frac{36*c*(1-\Phi)\text{^}2*K}{\Phi\text{^}3}} \quad (5)$$

C=kozeny constant=4.16

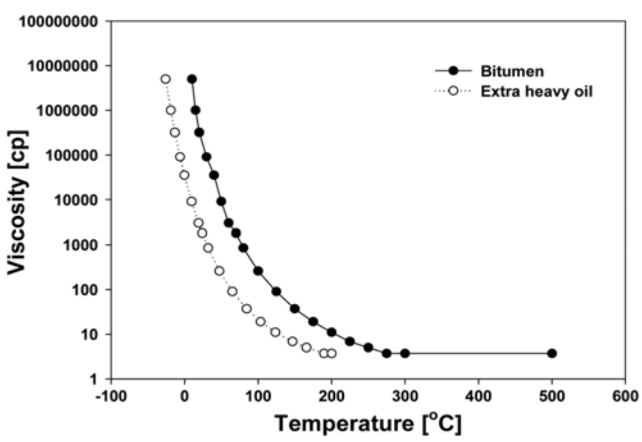

Fig. 2. Viscosity change as a function of time for bitumen and extra heavy oil.

Φ=porosity=0.3
K=permeability=750 Darcy
D=average particle diameter=1.427 mm

2. Selection of Extra Heavy Oil

Composition of bitumen and extra heavy oil used in this work is summarized in Table 2, which was observed by elemental analyzer (Quantax 200, Bruker) and ICP-MS(X-series, Thermo Elemental).

Viscosities of bitumen from the oil sand and the extra heavy oil used in this work were measured with SV-10 model of A&D Co. (Japan) and result was plotted in Fig. 2, where both samples show about 10 cp at 200 °C.

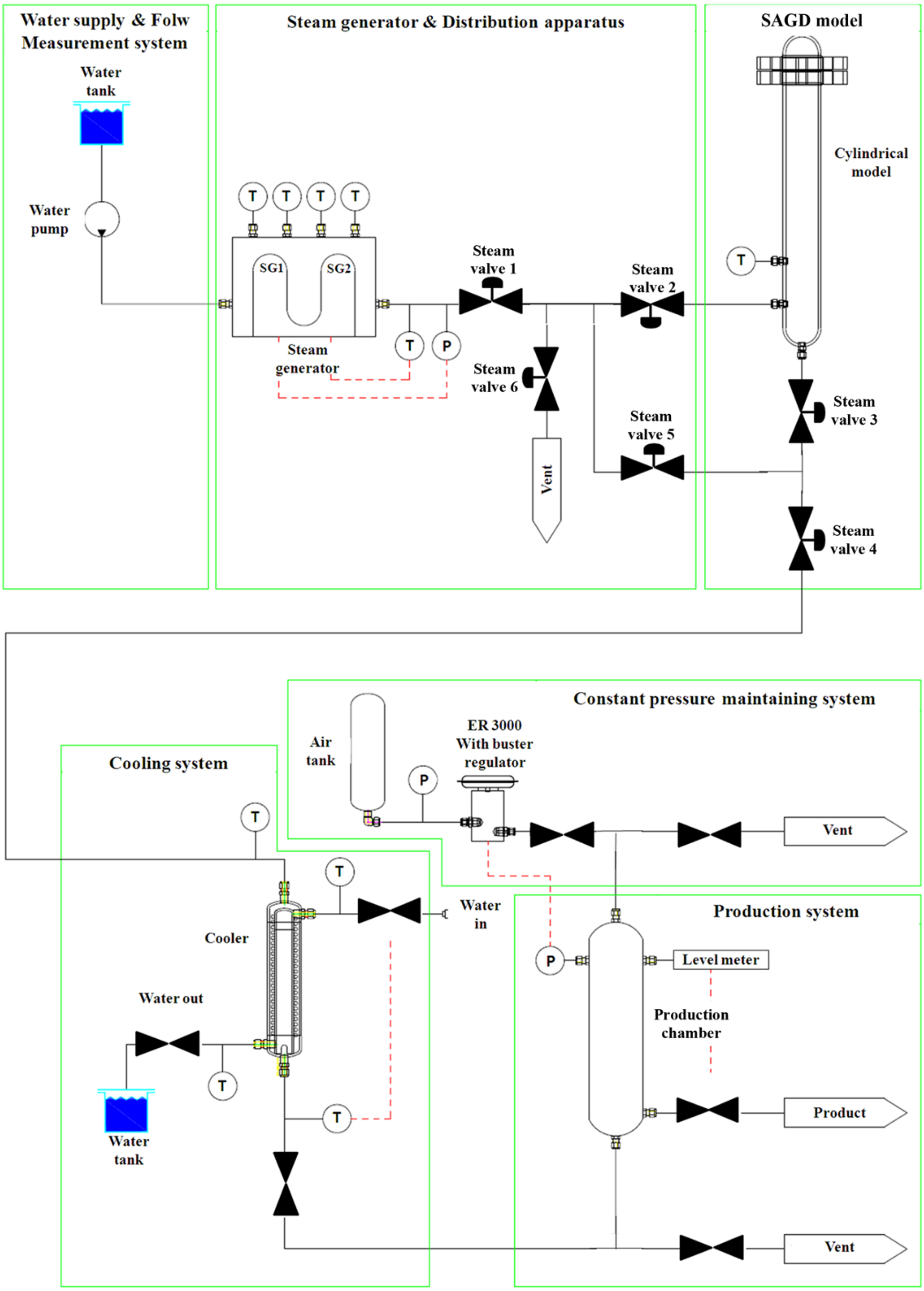

Fig. 3. A schematic diagram of lab scale SAGD model.

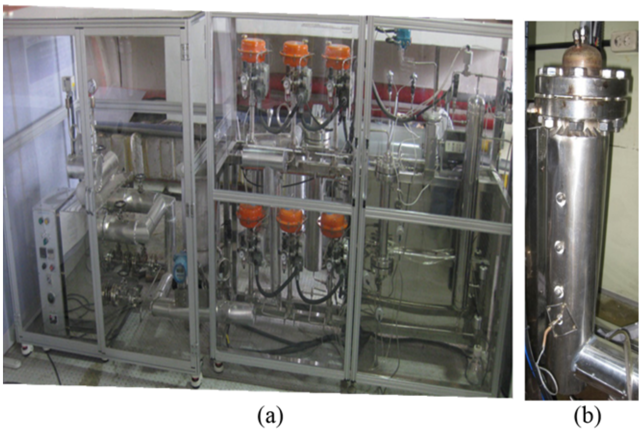

Fig. 4. A photo of (a) lab scale SAGD apparatus and (b) cylindrical model.

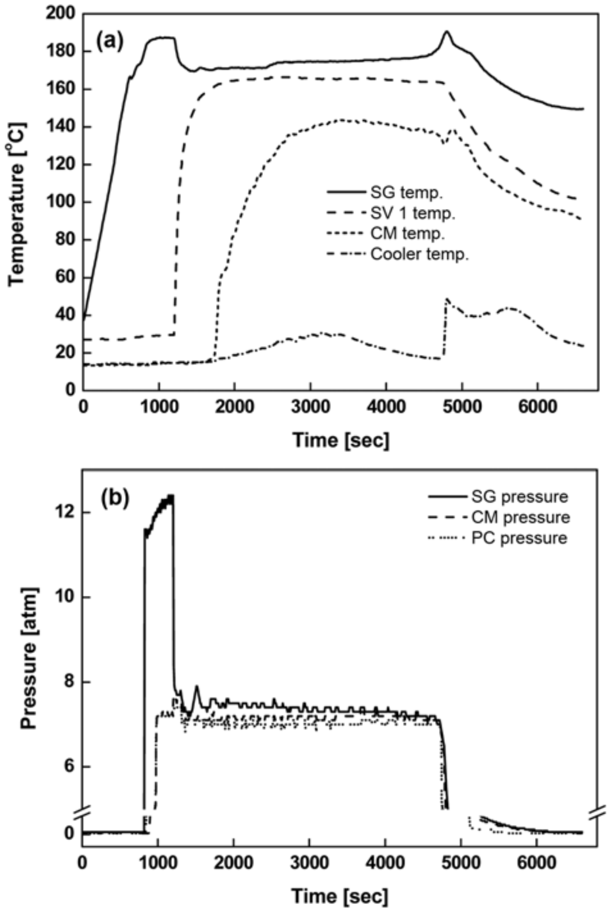

Fig. 5. Variation of (a) temperature and (b) pressure as a function of time during SAGD operation in the absence of extra heavy oil.

3. Operation Procedure of SAGD Model without Extra Heavy Oil

As shown in Fig. 3, six parts are assembled together for making SAGD model: (1) water supplier, (2) steam generator (SG), (3) SAGD cylindrical model (CM), (4) cooling system, (5) constant pressure maintaining system and (6) production system. For steam injection, initially water is heated at 180 °C at SG1 and subsequently it is heated again at 250 °C at SG2 for improving steam quality. This superheated steam is transferred to CM via SV2 in Fig. 3. At the cooling system, the heated extra heavy oil is cooled down to about 60 °C by cooling water, and the final product (mixture of water and extra heavy oil) is delivered to the production chamber (PC). While running the SAGD model, the system is maintained and controlled at constant pressure by buster regulator, otherwise heated extra heavy oil will not flow to the PC. All the line with stainless steel tubing of 6.35 mm diameter is heated or insulated for maintaining fluid viscosity, so that the extra heavy oil flows smoothly from CM to PC. A photo of the whole real apparatus and cylindrical model apparatus is in Fig. 4(a) and 4(b), respectively.

4. Operation Procedure of SAGD Model with Extra Heavy Oil

CM in Fig. 4(b) is made of stainless steel with dimension of height 60 cm and diameter 7.6 cm and the outer surface is insulated. For simulating oil sand, extra heavy oil and glass bead (diameter 1.5 mm) was mixed homogeneously for making porosity of 0.3 in the CM. A thermocouple is located at 10 cm above the injection port of CM for monitoring the steam temperature. The temperature and pressure of CM is maintained at about 160 °C and 7 atm, respectively, and the steam injection rate is about 20 cc/min.

RESULTS AND DISCUSSION

All thermal methods tend to reduce the flow resistance by reducing the viscosity of the heavy oil.

1. Performance of SAGD without Extra Heavy Oil

It is known that injection of steam having 100% steam quality is important in the SAGD process [2]. The steam quality was not measured in this work; however, in order to increase steam quality, initially formed steam is heated subsequently for injecting improved steam quality and this steam quality is assumed to be 100% in this work. The performance of SAGD model is checked without extra heavy oil and the variation of pressure and temperature as a function of time is observed as follows.

It was possible to control the pressure and temperature at about 7 atm and 140 °C, respectively, during SAGD demonstration without extra heavy oil.

1-1. Temperature Variation

In Fig. 5(a), the temperature change of each part such as SG, steam valve 1 (SV1), CM and cooler is monitored. When water is heated at 180 °C at SG1 and reheated subsequently at 250 °C at SG2, temperature of SG is maintained at 170 °C after about 1,500 sec and the temperature of CM remains constant at about 140 °C due to some heat loss during flow of steam from SG to CM.

1-2. Pressure Variation

The pressure change of each part such as SG, CM and PC is monitored and plotted in Fig. 5(b). Due to the initial steam pressure suddenly formed at SG, the pressure rises up to 13 atm; however, at 1,500 sec the pressure of CM is maintained at about 7 atm after opening SV1.

2. Performance of SAGD with Extra Heavy Oil by Method A

Extra heavy oil having viscosity of 10 cp at 150 °C, which is similar to that of bitumen of oil sand, as compared in Fig. 2, is used in this work. After carrying out SAGD demonstration, final product in the PC is collected in every 10 min. The pressure of PC should be lower at least 0.1 atm than that of SG by adjusting SV4. When pressure of PC is higher than that of SV1, steam does not flow, and when the pressure of PC is much lower than that of SV1, steam flows too fast and this will show unexpected irregular SOR [1].

2-1. Temperature Variation

As shown in Fig. 6(a), the temperature of CM is maintained at 160-170 °C after 5,000 sec for about 5,000 sec. Sometimes, for example, the temperature of CM drops to 80 °C at 4,500 sec, due to unexpected temporary stopping of steam flow during operation in the line.

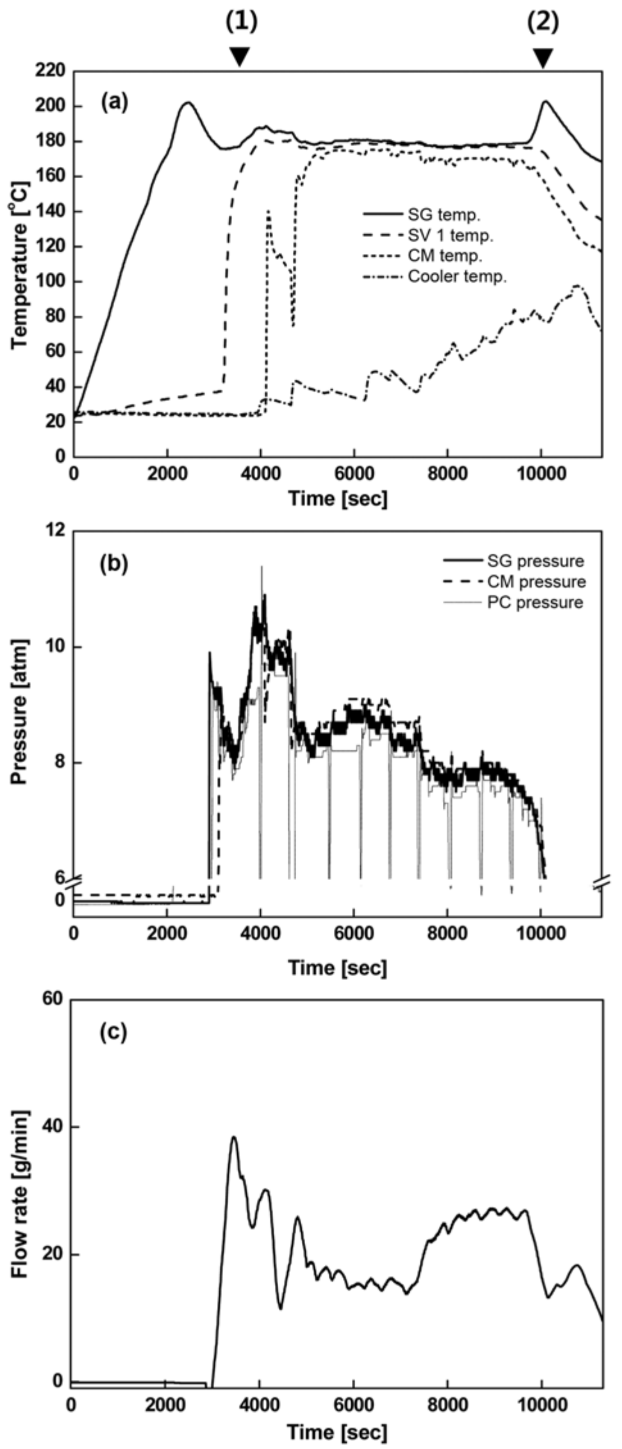

Fig. 6. Variation of (a) temperature, (b) pressure and (c) flow rate as a function of time during SAGD operation with extra heavy oil by method A. Experiment starts at (1) and finishes at (2). See Table 3 of experimental data for cSOR.

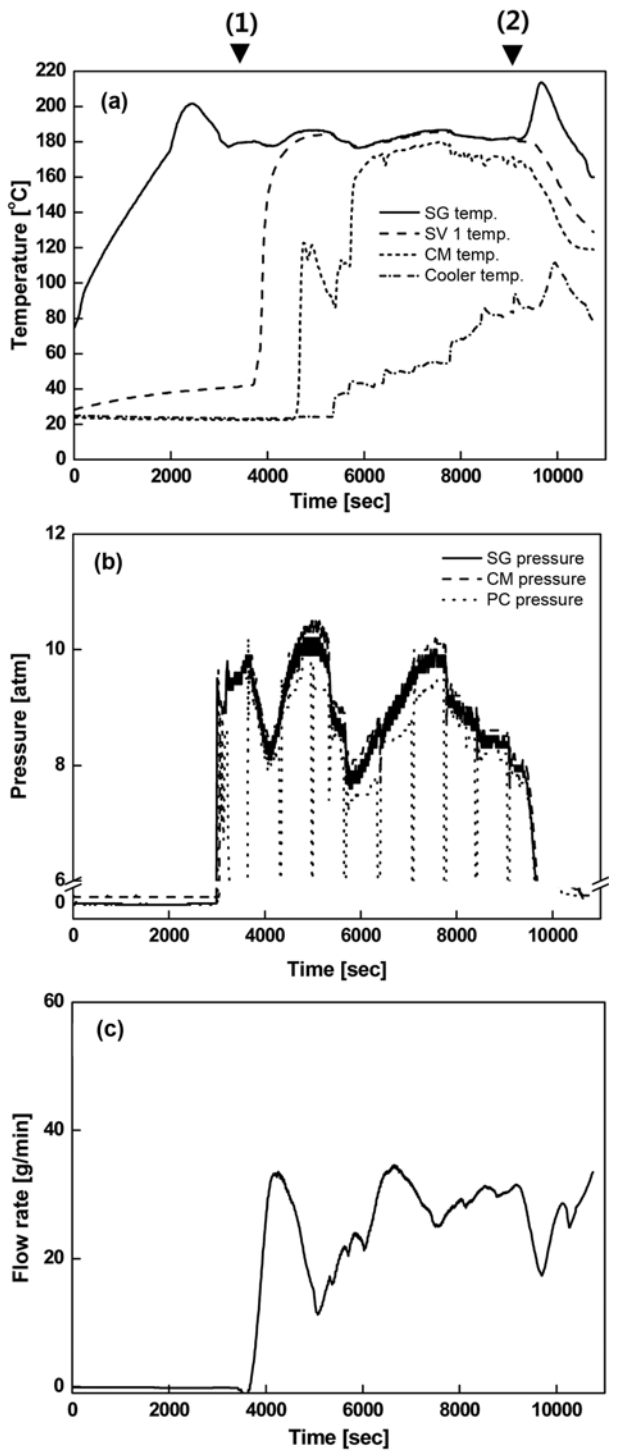

Fig. 7. Variation of (a) temperature, (b) pressure and (c) flow rate as a function of time during SAGD operation with extra heavy oil by method B. Experiment starts at (1) and finishes at (2). See Table 3 of experimental data for cSOR.

Table 3. Recovered amount of water and extra heavy oil in regular intervals and cSOR

Method A			Method B		
Time (s)[a]	Water (mL)	Extra heavy oil[c] (mL)	Time (s)[a]	Water (mL)	Extra heavy oil[c] (mL)
4000 (1)[b]	500	0	3640 (1)[b]	600	0
4620	180	10	4320	180	0
5470	390	190	4980	270	10
6140	40	10	5660	80	330
6770	320	260	6360	220	200
7380	70	30	7080	180	170
8040	240	130	7740	350	70
8700	240	80	8390	320	30
9360	300	10	9060 (2)[b]	490	30
9980	220	30	-	-	-
10650 (2)[b]	290	10	-	-	-
Total quantity (mL)	2790	760	Total quantity (mL)	2690	840
cSOR	6.61 (3.80)[d]		cSOR	4.89 (3.85)[d]	
Oil recovery (%)	57.3		Oil recovery (%)	78.8	

[a]Real time data corresponding to Fig. 6 and Fig. 7 for method A and method B, respectively
[b]Experiment starts at (1) and finishes at (2) as shown in Fig. 6 and Fig. 7
[c]Extra heavy oil contains some water; see text for net amount of extra heavy oil recovered
[d]Estimated value of cSOR

2-2. Pressure Variation

For collecting the final product, the SV4 is locked temporarily every 60 sec. As shown in Fig. 6(b), the pressure of each part is not regulated properly and the pressure of CM is higher by about 0.1-0.2 atm, resulting in extra heavy oil not flowing smoothly and continuously.

2-3. Steam Injection Rate Variation

Due to the problem of pressure control as indicated in 3-2-2, steam flow rate fluctuated highly from 20 cc/min, as shown in Fig. 6(b). As summarized in Table 3, collected product amount is irregular. Cumulative SOR (cSOR) shows about 6.61. During SAGD experiment 2,508 mL of water and 661 mL of extra heavy oil were used from which the calculated cSOR is 3.80.

As shown in Table 3, experimentally collected amount of extra heavy oil (760 mL) is higher than that of initially utilized amount of oil (661 mL), probably because extra heavy oil absorbs some amount of air bubbles and moisture, forming a kind of froth that cannot be separated clearly into oil and water. Since the final collected total amount of mixture is 3,550 mL and initially injected amount of water is 2,508 mL, the collected extra heavy oil contains about 380 mL water, and the collected net volume of extra heavy oil can be assumed as 379 mL, and the oil recovery can be calculated as 57.3%.

3. Performance of SAGD with Extra Heavy Oil by Method B

In order to regulate a constant steam flow rate, the experimental procedure is modified as follows. After closing SV4, reduce the pressure of PC and receiving the product, followed by opening SV4 for adjusting CM pressure lower by about 0.1-0.2 atm than SG and then increase PC pressure.

3-1. Temperature Variation

As shown in Fig. 7(a), at 6,000 sec, the temperature of CM starts to be stabilized at about 170 °C for 5,800 sec, after sudden drop of CM temperature at about 5,000 sec due to the unexpected experimental stopping of steam flow.

3-2. Pressure Variation

As shown in Fig. 7(b), in the case of method B, a similar pressure change was observed for the case of method A. For collecting the final product, the SV4 is locked temporarily every 60 sec. At 5,000 sec, there is no steam flow because of rising CM pressure by about 0.4 atm and the temperature goes down temporarily. However, after a while, the CM pressure keeps almost constant between 8 and 10 atm, and it was observed that the steam flows at least 20 g/min (see Table 3), which is better than the case of method A.

3-3. Steam Injection Rate Variation

As indicated in Fig. 7(c) and Table 3, after 5,000 sec, similar amount of product was collected every 10 min, which indicates almost constant steam flow. Cumulative SOR shows about 4.89, which is better than the case of method A, which is similar to another's result [10]. During SAGD experiment 2,550 mL of water and 661 mL of extra heavy oil were used from which theoretical cSOR is 3.85. Experiment for 7,000 sec with SAGD model is equivalent to about 5 years in the field as indicated in Table 1.

As shown in Table 3, experimentally collected amount of extra heavy oil (840 mL) is higher than that of initially injected amount of oil (661 mL), probably because extra heavy oil absorbs some amount of air bubbles and moisture, forming a kind of froth which cannot be separated into oil and water clearly. Since the finally collected total amount of mixture is 3,530 mL and initially injected amount of water is 2,550 mL, the collected extra heavy oil contains about 319 mL water, the collected net volume of extra heavy oil can be assumed as 521 mL, and the oil recovery can be calculated as 78.8%, which is better than the case of method A.

The results mentioned above indicate that effective injection by controlling optimum temperature and pressure is absolutely necessary for oil recovery. Currently, operation with a geological SAGD model is under study.

CONCLUSIONS

Since the cold oil in a reservoir is very viscous and does not flow easily, the thermal oil recovery method is recommended for recovering heavy oil. In this study steam injection is used on the laboratory models to investigate the effects of pressure and temperature rise on viscosity reduction and consequently the production rate. Lab scale SAGD model was designed and constructed with scaling factor of 150 : 1 based on a theoretical background. The SAGD model was operated as a function of pressure, temperature and steam flow rate by using extra heavy oil and glass bead instead of oil sand. In this work, steam quality was assumed 100% by using a two-stage steam heating method. The critical constant operational factors such as high pressure, high temperature and steam flow should be optimized and balanced continuously in real time. It was possible to control constant experimental conditions such as temperature, pressure and steam flow rate of 160-180 ^{o}C, 8-9 atm and 20-25 cc/min, respectively, and cSOR shows about 5 with oil recovery of 78.8% for 7,000 sec, which corresponds to about 5 years in a real field.

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