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RESEARCH PAPER

Physical simulation of improving the uniformity of steam chamber growth in the steam assisted gravity drainage

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Abstract: In steam assisted gravity drainage (SAGD) process, there is an uneven distribution of steam chamber growth along the whole length of the horizontal well. In order to solve this problem, a three-dimensional high-pressure physical model of a SAGD well pair was built. Several significant reservoirs and operation parameters for SAGD were also scaled in the model size, which was based on SAGD pilot development of a typical reservoir in China. Three experiments were conducted using the above-mentioned high-temperature and high-pressure physical model. Test 1 simulated the slow steam chamber growth at the toe end and uneven distribution of steam chamber growth. Test 2 tested the regulation strategy with dual tubing strings to adjust the steam chamber based on Test 1−combining the long and short tubing strings for injection well and production well. Test 3 tested the regulation strategy with U-shape wellbore to adjust the steam chamber. The results showed that the two regulation strategies were effective for recovering steam chamber growth at the toe end and making steam chamber growth uniform along the length of SAGD wellbore. After regulating, the oil rate increased significantly.

Key words: steam assisted gravity drainage (SAGD); high-pressure and high-temperature; 3-D scaled physical simulation; steam chamber growth

Introduction

Successful applications of the steam assisted gravity drainage (SAGD) process in Canada have established SAGD as one of the promising technologies for in-situ recovery of heavy oil and extra-heavy oil resources [1–4]. A number of SAGD projects are in operation, construction, or planning stages around the world [5]. However, there are some problems that still exist during its application. For example, the non-uniform distribution of steam chamber growth along the length of the wellbore could significantly affect the oil production performance [6–7]. Ong and Butler [8] studied wellbore flow restriction at field conditions and suggested that the steam chamber slope may be caused by a wellbore pressure drop. Nasr et al. [9] also stated that a pressure drop along the horizontal wellbore caused a slope in the steam chamber along the well. Das [10] stated that over 80% of steam was injected at the heel of the injector while the other 20% was injected to the toe. Fluid on the other hand was produced either from the heel, toe or both in the producer. This can explain sloped steam chambers and the reason for the non-uniformity of steam chamber growth along the horizontal well. By analyzing temperature data from the SAGD pilot project together with reservoir geology, Wei and Gates examined a steam conformance and its impact on the SAGD process performance [11]. An analysis of the A-well pair of the SAGD pilot suggested that the distribution of steam flow in the well contributed largely to the non-uniform steam conformance along this well pair. Ibatullin et al. [12] presented a modified SAGD technology using a pair of U-shaped wells for heterogeneous reservoirs in the Republic of Tatarstan and conducted numerical simulation of the improved technology by using CMG STARS software. Based on the modeling with STARS package, various operating practices were proposed. Flow management was achieved through an adjustment of the produced fluid and injected steam volumes, as well as adjustment of steam injection and pump setting points, which was conducive to uniform steam chamber growth while avoiding steam single point breakthrough. Li et al. [13] described a kind of SAGD well completion, in which the injector and producer are both completed with dual tubing strings, a short tubing string was landed at the heel and a long tubing string was landed at the toe. Reservoir simulations with discretized well bore models were also conducted to investigate the effect of some operation parameters on SAGD performance. The re-

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sults demonstrated the flexibility for adjusting the steam chamber.

In this paper, a 3-D high pressure physical model was designed and built to simulate the SAGD process. The injector and producer were both completed with dual tubing strings in the model. Three groups of 3-D high pressure and high temperature lab experiments were conducted to test and optimize the uniformity of steam chamber growth along the horizontal wells during the SAGD process. Test 1 simulated the slow steam chamber growth at the toe end and uneven distribution of steam chamber growth. Test 2 tested the regulation strategy with dual tubing strings to adjust the steam chamber based on Test 1-- combining the long and short tubing strings for injection wells and production wells. Test 3 tested the regulation strategy with U-shape SAGD to adjust the steam chamber.

1 Physical simulation

1.1 Scaling criteria

To study the uniformity of steam chamber growth along the length of the SAGD wellbore, it is necessary to make scale models of the reservoir and wellbore. The scaling criteria developed by Pujol and Boberg [14] were used to design the lab model reservoir. This scaling approach is suitable for a steam injection process, especially if gravitational effects are dominant. With the Navier-Stokes equation and the variable mass pipe flow model, Shi Lin et al. [15] derived the horizontal wellbore scaling criteria for the high-pressure model, which were used to make scale models of the horizontal wellbore in this paper.

Several parameters significant to oil recovery by SAGD were scaled in the model size based on an extra-heavy oil SAGD pilot reservoir. The major parameters of physical model and operating conditions are listed in Table 1 and Table 2.

1.2 Experimental setup

Lab tests were conducted using a high pressure, high temperature scale model facility at RIPED (Research Institute of Petroleum Exploration and Development), PetroChina. A schematic diagram of the experimental setup is shown in Figure 1. The setup consists of the model system, the injection system, the production system, and the data acquisition system. The injection system consists of steam generators as well as positive displacement pumps. The injection system can supply high temperature, high pressure steam at constant pressure or constant flow. The model system consists of a pressure vessel, scale model, heating/cooling device, magnetic stirrer, and auxiliary device and the scaled model is the core of the experimental setup, which simulates the reservoir prototype based on scaling criteria. In a scaled model, an intact injection-production unit or symmetry element of a unit in the prototype was scaled down by hundredfold to simulate the geometry and dimensions of the well configuration. The permeability, steam rate and time are also scaled using the same scaling criteria. The model is placed into the pressure vessel. The blanks between the model and the vessel are then filled with nitrogen gas to simulate the actual reservoir pressure condition. The data acquisition and control system consists of computers, a high accuracy data acquisition platform PXIe-1075 (developed by NI), and a graphic analysis software to log, store data and show real-time the temperature profiles and pressure field, as well as control the experiment process. The fluids which the model produces are collected and measured by the production system. For details of the experimental setup, see the reference [16].

Table 1 Reservoir parameters for prototypes and scale models

Parameters	Prototype	Model	Ratio (model/ prototype)
Reservoir height	32 m	16 cm	1/200
Reservoir width	100 m	50 cm	1/200
Well length	100 m	50 cm	1/200
Producer-injector spacing	7.2 m	36 mm	1/200
Producer-reservoir bottom Spacing	2 m	10 mm	1/200
Porosity	0.32	0.35	≈1
Permeability/μm^2	1.8	360	200
Initial oil saturation	0.75	0.88	≈1
Thermal conductivity of oil sand/($W \cdot m^{-1} \cdot K^{-1}$))	1.04	0.94	≈1
Volumetric heat capacity of oil sand/($J \cdot m^{-3} \cdot K^{-1}$)	1.54×10^6	1.22×10^6	≈1
Wellbore radius/mm	177.8	12	0.067
Perforation radius/mm	3	1.75	0.58
Perforation density/($hole \cdot m^{-1}$)	400	250	0.625

Table 2 Operation parameters for the SAGD production stage

Parameters	Prototype	Model	Ratio
Pressure/MPa	2.2	2.2	1
Steam injection rate	58 m^3/d	200 mL/min	≈1/200
Steam injection temperature/°C	217	217	1
Steam quality	>0.95	>0.95	≈1
Injection recovery time	1 a	13.14 min	1/40 000
Production-injection pressure difference	0.2 MPa	1 kPa	1/200
Production/injection ratio	1.3 – 1.4	>1.4	≈1

1.3 Physical model

According to the scaling criteria, a model with the dimension of 500 mm × 500 mm × 160 mm (length × width × height) was built (Figure 2). The model was constructed of 316 L stainless steel sheets with a wall thickness of 2 mm, which