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RESEARCH PAPER

Field control technologies of combustion assisted gravity drainage (CAGD)

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Abstract: The targets, strategies and approaches of the field controlling processes of combustion assisted gravity drainage (CAGD) are discussed based on the research of its mechanisms, advantages and defects. By taking fully advantage of gravity, CAGD process can produce the mobilized oil near the combustion front through the underlying horizontal well, serving as a possible solution for extra-heavy oil production in Xinjiang oil field. However, unidirectional conning and breakthrough of combustion front are risky to happen during the field application of CAGD. Based on laboratory three-dimensional physical simulation experiments and the experience of former pilots, it is proposed that a gently upward sloping combustion front is beneficial for the steady drainage of mobilized oil and should be the target of CAGD control. Key production parameters like the maximum production rate and corresponding air injection rate during field application are calculated with reservoir engineering approach and material balance theory. The maximum oil production rate of the CAGD pilot in Block Fengcheng, Xinjiang oil field, is 12.9 m^3/d, and the air injection rate is 14 048 m^3/d. To maximize the oil productivity and sustain combustion front moving forward steadily, the ignition position should be located at the mid-upper parts of the formation; the air injection rate at the early stage should keep slow and increase gradually; meanwhile, the production rate of flue gas should be 90% of the air injection rate. A pilot of CAGD was initiated in the Xinjiang Fengcheng Field on the basis of those research outcomes. By the end of 2016, Well Group FH005 in the pilot has succeeded in steady production for more than 400 days. Key aspects, involving the shape of combustion chamber, oil production of single horizontal producer, air oil ratio and the degree of oil upgrading are in accordance with what the development plan predicted.

Key words: super-heavy oil reservoir; fire flooding; combustion assisted gravity drainage; physical simulation; pilot

Introduction

Fire flooding technology with vertical well has entered the stage of industrial application in steam injection developed heavy oil reservoirs in China. Generally, the viscosity of oil exploited by this method is no more than 5 000 mPa·s at reservoir condition. While this value can be expanded to 20 000 mPa·s for steam injected reservoirs with high recovery degree and small well space at the early stage[1]. The viscosity of hundreds millions of tons proved extra-heavy oil reserves in China surpasses 50 000 mPa·s at reservoir condition, so unfortunately, these reservoirs cannot be developed by fire flooding with vertical wells. Exploitation with a combustion front moving from toe to heel air injection of a horizontal well (THAI), invented by Professor Greaves et al. of the Bath University, is a possible solution for extra-heavy oil development using gravity[2–3]. This process is called combustion assisted gravity drainage by our research group[4–5]. Though reasonable in theory, it has made little progress in the pilots in recent years in China and abroad. In Canada, two pilots including six wellgroups conducted in Whitesands Field failed due to sand production etc.[6]. The pilot in Wellgroup S1-38-32 of the Liaohe Oilfield, had to be terminated less than six months after ignition due to high temperature and high viscous coke blockage in the horizontal wellbore though gravity drainage effect had been observed at the early stage.

Current studies on this process are mainly on the drainage mechanism, oil recovery, in-situ oil upgrading and well patterns, etc[8–11]. The control of combustion front, productivity evaluation and risk management have been hardly investigated. Starting from analysis of mechanisms, technical advantages and inner defects of CAGD, this study has investigated the objective, strategies and approaches of CAGD field control. The research results have been applied to the pilot in Fengcheng Block, Xinjiang oil field, and achieved remarkable success.

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1. Mechanisms, technical advantages and defects of CAGD

1.1. Mechanisms and technical advantages

There are several well patterns suitable for extra-heavy oil recovery by the CAGD process. Among these well patterns, the most typical and economic one is the pattern of a vertical ignition/air injection well and a horizontal producer: the THAI process (Fig. 1). In this well pattern, the vertical well is located a few meters above the toe of the horizontal well whose horizontal section is at the very bottom of the oil layer. After ignition in the vertical well, combustion front will propagate from the toe to the heel of the horizontal well. Light components produced by distilling and thermal cracking of the high temperature combustion front would mix with the remaining oil in oil layer along the horizontal direction. Meanwhile, high temperature steam from combustion would condense and mix with the remaining oil through the coking zone. Mixed with the light components and condensed water and heated by conduction of the combustion front, the remaining oil is much less viscous and becomes movable. With the help of gravity, it will migrate downward to the horizontal wellbore, which is the so-called gravity drainage. Similar to fire flooding with vertical well[12], the zone from injection end to production end of horizontal well can be divided into five zones during CAGD process: burnt zone, combustion front, coking zone, movable oil zone and original oil zone.

Apart from the high drainage efficiency and oil recovery rate, CAGD has some other advantages compared with traditional fire flooding with vertical well.

(1) Short distance of displacement. According to the results of 3-D physical tests and reservoir numerical simulation, the shortest distance in the formation from combustion zone to coking zone and then movable oil zone is generally between 10 cm to dozens of centimeters. The vertical height of the movable oil zone is roughly equal to the thickness of the pay zone. As the combustion front is declining, its actual length is generally greater than the pay zone thickness. Accordingly, the mobilized oil merely needs to migrate a distance a little longer than the pay zone thickness before reaching the horizontal well. This distance is much smaller than the distance between the

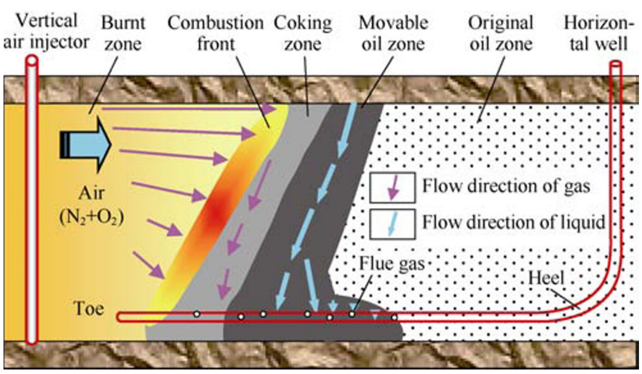

Fig. 1. Sketch showing the mechanism of CAGD.

injector and producer, which is the most important reason for CAGD to be an effective method to produce extra-heavy oil.

(2) Visbreaking effect of upgrading of oil. The oil in the movable oil zone is a mixture of initial formation oil and light components from distillation and thermal cracking. Therefore, the relative density of oil produced form the horizontal well drops by 2%, and the viscosity to 1/5-1/3[13] of its original value.

(3) High thermal efficiency. Oil in vertical-well fire flooding moves towards the vertical producer. During this process, a significant amount of heat in combustion zone and front is released to the formations above and below the pay zone, contributing little to oil recovery. While in CAGD, heated movable oil would flow vertically to the horizontal producer, losing negligible heat to the surrounding layers with short distance and time. Results from field application of these techniques indicate that the air oil ratio (AOR) of vertical-well fire flooding is about 2 000 m^3/m^3, meaning that 2000 m^3 air should be injected to produce 1 m^3 of oil. While AOR of CAGD is generally about 1 000 m^3/m^3. This is an indirect evidence supporting that the heat efficiency of CAGD is higher.

1.2. Defects of CAGD

Although with obvious merits over fire flooding with vertical well, CAGD also has some inherent defects, mainly in three aspects.

(1) Fluid production rate is difficult to control. The precise metering and controlling of produced fluid is the key to CAGD application. In a THAI process, the horizontal well is the pathway for both movable oil (liquid) and flue gas. Two-phase flow of liquid and gas within the wellbore adds complexity to the precise and stable control of production rate. It is far different from the case of SAGD (steam assisted gravity drainage) process, in which only liquid phase flows into the horizontal wellbore, making the rate control relatively easier.

(2) Directional coning is likely to appear in the plane of combustion front. In the case of vertical-well fire flooding, 4-8 producers are placed around an ignition/air-injection well[14] (the specific number of producers depends on the well patterns used). These producers act as chimneys for flue gas and guarantee production at the same time. By constraining the gas rate in a specific chimney, the propagating rate of the combustion front along this chimney can be controlled[15]. Because of the chimneys around ignition/air-injection well, the shape of the combustion front can be regulated as a circle. However, there is only one horizontal chimney for the vertical ignition/air-injection well in CAGD process, making it easy for the combustion front to cone towards the heel of the horizontal well (Fig. 2). Shown in Fig. 2a is the cross-section of the combustion chamber with gypsum molding technique