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Mechanistic simulation study of air injection assisted cyclic steam stimulation through horizontal wells for ultra heavy oil reservoirs

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ABSTRACT

Air injection assisted cyclic steam stimulation (CSS) through horizontal wells is a new technique for the exploitation of ultra heavy oil reservoirs, which has an advantage over other gas or solvent injection processes from the economic point of view. Different from in-situ combustion (ISC) process, the dominating chemical reactions occurring underground in air injection assisted CSS process are low temperature oxidation (LTO) reactions, and owing to the complicated LTO reaction mechanism, this process is still not clearly understood. Therefore, an indepth learning of this process will be of great benefit to its field application and specific project design. In this study, a comprehensive numerical simulation model was established, which accounted for the LTO reactions of different oil components in terms of SARA fractions, as well as permeability reduction induced by coke deposition. A series of simulations were then performed to explore the production performance and elucidate the impacts of various factors. The simulation results demonstrate that air injection assisted CSS using horizontal wells can enhance ultra heavy oil recovery and reduce cSOR in comparison with steam injection alone, which can be attributed to the synergistic effect of steam and air coinjection. Injection of air along with steam can have the same effect as the initial solution gas in reservoir, and the potential of air injection assisted CSS to enhance oil recovery will be more pronounced in oil layers with lean solution gas. In addition, normal air injection can be a viable choice considering the free availability of air, and injection of oxygen-reduced air can become a good option for ultra heavy oils featured with poor LTO reactivity for the sake of safe production.

1. Introduction

Heavy oil resources have the potential to serve as a bridging strategy to alleviate energy crisis during the transition from conventional hydrocarbon fuels to sustainable energy sources (Zhang et al., 2017; Ado et al., 2018). At present, the exploitation of deep heavy oil reservoirs is generally based on steam injection process, nevertheless this method is effective but not very efficient, usually faced with huge energy and water consumption for steam generation associated with considerable greenhouse gas emissions (Gates and Larter, 2014; Wang et al., 2018a, 2018b). In such context, coinjection of noncondensable gas, including nitrogen, carbon dioxide, flue gas, etc., or solvent with steam has been proposed in order to improve the field performance of steam injection and some relevant pilot testing results were very encouraging (Gates, 2010; Li et al., 2011, 2017a, 2017b; Liu et al., 2015). Air injection process (AIP), such as high pressure air injection (HPAI) for light oil reservoirs and in-situ combustion (ISC) for heavy oil reservoirs, has been applied in different kinds of oil reservoirs over the last few years (Ren et al., 2002, 2018). In consideration of the free availability and unconstraint supply of air, steam and air coinjection can prevail over other gas/solvent injection processes from an economic point of view.

In the past several decades, cyclic steam stimulation (CSS) has been extensively adopted for the exploitation of heavy oil resources, especially for ultra heavy oils, and it can be easily operated on-site in comparison with other steam injection processes (e.g., steam flooding and steam assisted gravity drainage). With the development of horizontal well technology, CSS based on horizontal wells has been gradually employed in oilfields, which has notable strengths over that by conventional vertical wells, such as larger contact area with oil bearing formation, larger steam injection capacity and greater fluid productivity (He et al., 2018). However, the oil recovery factor of CSS using horizontal wells for ultra heavy oils is still not very high, especially for oil reservoirs with thin layers. To further improve the production performance of cyclic steam injection, air injection assisted CSS through horizontal wells is proposed in this study.

Different from other steam and inert gas coinjection processes, a series of consecutive or parallel oxidation reactions will take place

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between oil components and oxygen in the injected air during steam and air coinjection process (Niu et al., 2011; Chen et al., 2013; Huang and Sheng, 2017). Since the formation temperature is generally lower than 350 °C in steam stimulation condition and there is no artificial ignition process, the prevailing oxidation reactions belong to low temperature oxidation (LTO) reactions (Wang et al., 2017, 2018c; Zhang et al., 2015b), which are distinguished from the high temperature oxidation (HTO) reactions of ISC process (Yang and Gates, 2009). A great number of products will be produced in these LTO reactions, including partially oxygenated compounds, carbon oxides, coke and water (Burger and Sahuquet, 1972; Khansari et al., 2014; Zhang et al., 2015a; Xu et al., 2016), and thus a more accurate description of the LTO process relies on multiple pseudocomponents rather than single pseudocomponent. In addition, the partially oxygenated compounds (e.g., alcohol, aldehyde, ketone, carboxylic acid and hydroperoxide) can be more viscous than their original oil components, and the coke produced arising from LTO reactions cannot be consumed effectively and hence will reduce the reservoir permeability (Luhmann et al., 2017), all of which can cause some adverse effects on oil recovery performance. In the past decades, a lot of reaction schemes have been proposed to characterize the LTO reactions on the basis of laboratory experimental results (Chen et al., 2013; Khansari et al., 2014; Zhang et al., 2015a; Yang et al., 2017), and among these models, reactions based on SARA (i.e., saturates, aromatics, resins and asphaltenes) fractions can be more appropriate to depict the LTO process of ultra heavy oils (Belgrave et al., 1993; Jia et al., 2006; Sequera et al., 2010), which enables the investigation of air injection assisted CSS process by means of numerical modeling. Furthermore, an indepth understanding of the production process of air injection assisted CSS will be of great significance to its further field-scale application as well as project design.

In the present study, a comprehensive reservoir simulation model of air injection assisted CSS using horizontal wells was constructed, which was coupled with a complex LTO reaction scheme in terms of SARA fractions and considered the reduction of reservoir permeability owing to coke deposition. Then, a series of numerical simulations were conducted to explore the performance of air injection assisted CSS using horizontal wells. In addition, the influences of different factors, including oil layer thickness, initial solution gas to oil ratio, operated air to steam ratio, oxygen content, were analyzed on the basis of the numerical simulation results. The results outlined in this study can deepen the understanding of air injection assisted CSS by horizontal wells for extracting oil from ultra heavy oil formations.

2. Numerical simulation study

2.1. Reservoir simulation model

A representative model for CSS process based on single horizontal well has been shown in Fig. 1, and only the right half part of this model was selected to build a 2D conceptual homogeneous reservoir model for

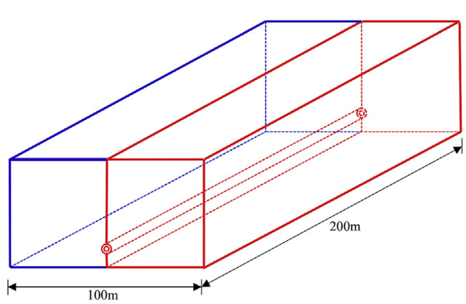

Fig. 1. A representative model for cyclic steam stimulation using single horizontal well with only half of the model (right zone in red) used for numerical simulation owing to symmetry. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Basic properties adopted in the reservoir simulation model.

Property	Value
Reference depth	873
Porosity	0.30
Horizontal permeability (mD)	2000
k_v/k_h	0.50
Oil saturation	0.65
Effective formation compressibility (1/kPa)	3.5×10^{-5}
Reference pressure (kPa)	8500
Original reservoir temperature (°C)	33
Rock volumetric heat capacity (kJ/m^3 °C)	2450
Rock thermal conductivity (kJ/m day °C)	150
Water thermal conductivity (kJ/m day °C)	53.5
Oil thermal conductivity (kJ/m day °C)	11.5
Gas thermal conductivity (kJ/m day °C)	3.2
Over/underburden rock volumetric heat capacity (kJ/m^3 °C)	2350
Over/underburden rock thermal conductivity (kJ/m day °C)	104.96
Temperature of injected steam (°C)	320
Steam quality at sandface	0.75

subsequent numerical simulation. The reservoir model has physical dimensions of 50 m in width (*x* direction), 200 m in length (*y* direction), 3 m–20 m in height (*z* direction). The horizontal well is located 1.25 m above the formation bottom. The reservoir model was discretized into a regular Cartesian grid system, with dimensions of 1 m in cross well direction, 200 m in downwell direction, and 0.5 m in vertical direction. The physical properties of the reservoir (e.g., porosity, horizontal permeability and oil/water saturations, etc.) were partly referred to the core data taken from a representative ultra heavy oil reservoir in Liaohe Oilfield, Northeast China. The original reservoir pressure and temperature are 8500 kPa and 33 °C, respectively. The basic properties for the reservoir model have been summarized in Table 1. Single reservoir rock type (i.e., sandstone reservoir) was adopted in the model, and the overburden and underburden layers were assumed to be perfect seals with respect to the movement of reservoir fluids, whereas heat loss to the overburden and underburden formations was taken into account. The numerical simulations were conducted using CMG STARS software (STARS User's Guide, Computer Modeling Group Ltd., Canada, 2012).

2.2. Fluid model

In simulation model, the reservoir fluids were composed of solution gas, water and ultra heavy oil. Four phases (i.e., aqueous, oleic, gaseous, and solid phases) and eleven components (i.e., water, saturates, aromatics, resin1, resins, asphaltenes, carbon dioxide, methane, nitrogen, oxygen, coke) were adopted in the fluid model. Water can exist in either aqueous or gaseous phase, and the original ultra heavy oil was characterized using four pseudocomponents (i.e., SARA fractions), and each component existed mainly in oleic phase besides in gaseous phase, while the oxygen was assumed to exist only in gaseous phase. The Peng-Robinson equation of state (PR EoS) available in CMG WinProp was applied to model the ultra heavy oil, and the basic pressure-volume-temperature (PVT) data for individual pseudocomponent have been given Table 2. The molecular weights and specific gravities of the SARA

Table 2
The PVT data for individual pseudocomponent (with molecular weights and specific gravities referred to Peramanu et al., 1999).

Pseudocomponent	Fraction (mol%)	Molecular weight (g/mol)	P_c (kPa)	T_c (°C)	Specific gravity
Saturates	27.35	381	928.12	591.19	0.885
Aromatics	19.71	408	1065.34	683.80	0.998
Resins	36.32	947	465.87	847.11	1.037
Asphaltenes	16.62	2005	251.13	1123.26	1.203