Reservoir simulation of air injection assisted in situ upgrading process via subsurface electrical heating based on the horizontal well

Shufeng Pei¹,², Qiaobo Wang¹,², Panfeng Zhang¹,², Lijuan Huang¹,², Liang Zhang¹,² and Shaoran Ren¹,²,*

¹Key Laboratory of Unconventional Oil & Gas Development (China University of Petroleum (East China)), Ministry of Education, Qingdao 266580, P. R. China
²School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, P. R. China

*Corresponding author e-mail: rensr@upc.edu.cn

Abstract. Heat transfer rate is slow during the in-situ upgrading process (ISU) via underground electrical heating, which is suitable for developing super heavy oil and oil shale reservoir. Considering the advantages of air injection process and horizontal well technology, an air injection assisted in situ upgrading process (AAISU) based on the horizontal well have been proposed and simulated. Reservoir simulation results show that air injection can improve heat transfer rate, enhance oil recovery by 11.4% and improve the energy efficiency from 4.54 GJ/GJ to 8.15 GJ/GJ comparing to the ISU process without air injection. Heating temperature and air injection rate are important for the AAISU process. When the heating temperature increase, the heat transfer rate and oil recovery increase, however, the energy efficiency are reduced steady. As for the effect of air injection rate, when the air injection rate increase from 500-4000 m³/day, the oil recovery and energy efficiency are rise first and then dropped, and the oil recovery and energy efficiency are the greatest when the air injection rate is 1000 m³/day.

1. Introduction
In-situ upgrading process (ISU) via underground electrical heating and cracking is a new creative technology, which is suitable for super heavy oil, oil shale and low maturity shale oil reservoir [1, 2]. Through underground heating, the kerogen or super heavy oil is thermally cracked into light oil, coke, methane, carbon dioxide and other gases, so as to realize its in-situ upgrading propose to greatly improve the quality of crude oil, reduce water resource consumption and greenhouse gases emissions, reduce the blending and viscosity reduction process during the surface pipeline transportation. The ISU technology based on wellbore electric heating mode has been conducted in oil shale reservoir and super heavy oil reservoir, and has achieved certain results. In Viking oilfield of Canada, the field pilot test results show that the recovery factor of this technology is much higher than that of conventional steam stimulation technology, and has high energy conversion rate and has broad application prospects [3]. However, the heat transfer mode is mainly heat conduction, which is slow and require a small well distance with a long heating time. Therefore, it is urgent to improve the feasibility and economy of the in-situ cracking process.
Previous, we have proposed an efficiency gas injection assisted ISU technology, nitrogen and air have been considered and simulated during the ISU process, the results indicated gas injection can improve heat transfer rate, enhance oil recovery and heighten energy conversion efficiency [4, 5]. The role of air played during the heat transfer process is more significant than nitrogen due to the exothermic oxidation reaction. Horizontal wells can greatly increase the contact area with the formation, increase the area of oil drainage area, improve production and recovery, save drilling costs and improve oilfield development effect; at the same time, it can also solve the problems of low production and high water cut caused by directional well production, sand control and frequent operations [6].

Therefore, we propose the air injection assisted ISU technology based on the horizontal well, and combine the advantages of air injection with the advantages of horizontal wells to improve the production performance of conventional ISU propose. Reservoir simulations have been conducted to investigate the effect of air injection on the performance of ISU performance based on the horizontal wells. And the influence of engineering parameters including well pattern, heating temperature and air injection gas have also simulated. The research results will have important guiding significance for the field test and industrial development of air injection assisted electric heating in-situ pyrolysis upgrading technology.

2. Thermal cracking for ultra-heavy oil

Thermal cracking reaction is an essential chemical reaction during the ISU process, via which ultra heavy oil components are pyrolyzed into light oils, hydrocarbon gases and coke to realize the upgrading propose of crude oil. Thermal cracking experiments and kinetic modelling process of ultra heavy oils have been conducted in nitrogen and air to simulate the ISU environment [4, 5]. The kinetic modelling refers to the process where thermal cracking model (Equation 1) were utilized to fit the weight of each component after different reaction temperature and time to achieve the goal of minimum fitting error between the experiment values and fitting values. Arrhenius Equation and first-order reaction were used to modelled the chemical reaction rate,

\[
HO \xrightarrow{K} a \times LO + b \times HC GAS + (1 - a - b) \times Coke
\]  

(1)

where HO, LO, HC GAS and Coke refers to the mass content of heavy oil components, light oil components, hydrocarbon gas components and coke, wt%; K is the rate constant of the thermal cracking, 1/day, a and b refer to the ratio of the unit mass of the heavy oil converted into light oil and hydrocarbon gas during the thermal cracking reaction.

The specific experiment and kinetic modelling processes were in the reference [5], and the fitting results are displayed in Figure 1, which indicated that the fitting degree is good and the chemical model can reflect the mass fraction of each component after different reaction temperature and time. The thermal cracking reaction model and relevant parameters is showed in Table 1.

![Figure 1](image)

Figure 1. Fitting results for the oil components evolved during the thermal cracking experiments of ultra heavy oil in the present of nitrogen and air.
3. Reservoir simulation models

A geological model was constructed based on a series of petrophysical properties obtained from a typical ultra heavy oil reservoir in Liaohe oilfield (Northeast China). The dimension of the model was 10 m in width (x direction), 30 m in length (y direction) and 10 m in height (z direction), a regular Cartesian grid was adopted with the grid block size of 0.667 m × 2 m ×1 m in x, y, z directions. The burial depth is 875 m, and initial pressure and temperature are 8.5 MPa and 3 ℃, respectively. The porosity and permeability of the ultra heavy oil are 0.3 and 1000 mda, respectively. The production history matching has been conducted before to require the oil-water and gas-liquid relative permeability curves [7, 8].

The injection well and production are located the 2 m above the reservoir bottom (Figure 2), which were constrained by constant heating temperature, constant air injection rate and constant production pressure. There were eight components (i.e. water, hydrocarbon gas, nitrogen, carbon dioxide, light oil, heavy oil, oxygen and coke) and four phases (i.e., gaseous, aqueous, oleic and solid phase) in the PVT model, and some key properties of each component have been concluded in Table 3. The numerical simulation was conducted by software CMG [9]. During the AAISU process, air injection is considered to accelerate the heat transfer rate of the ISU process due to the exothermic oxidation reaction between ultra heavy oil and air. The LTO reaction can be simplified into a reaction scheme including oxidation and decarbocylation reactions, which can be obtained from the results of Wang et al [7, 8].

![Injection well and Production well](image)

**Figure 2.** Well location in the model.

### Table 1. Thermal cracking model used in this study.

| Reactions                           | Stoichiometry                      | Frequency factor (1/day) | Activation energy (kJ/mol) |
|-------------------------------------|------------------------------------|--------------------------|---------------------------|
| Thermal cracking during the ISU    | HO→0.1807 HC GAS + 0.5738 LO + 0.2455 Coke | 3.6×10¹⁸                 | 233.132                   |
| Thermal cracking during the AAISU  | HO→0.1721 HC GAS + 0.5608 LO + 0.2671 Coke | 4.8×10¹⁹                 | 248.447                   |

### Table 2. The physical properties and correlation coefficients for different components.

| Properties            | Water | Hydrocarbon Gas | Nitrogen | Carbon Dioxide | Light Oil | Heavy Oil | Oxygen | Coke |
|-----------------------|-------|-----------------|----------|----------------|-----------|-----------|--------|------|
| Molecular weight (kg/mol) | 0.018 | 0.0311          | 0.028    | 0.044          | 0.1758    | 0.888     | 0.032  | 0.012 |
| Critical pressure (kPa) | 22048 | 4615.31         | 3394.39  | 7376.46        | 2364.36   | 600.24    | 5042.95| -     |
| Critical temperature (℃) | 374.15| 16.81           | -146.95  | 31.05          | 371.70    | 926.94    | -118.57| -     |
Table 3. LTO reaction model used in this study.

| Reactions               | Stoichiometry                  | Frequency factor (1/day) | Activation energy (kJ/mol) | △H (kJ/mol) |
|-------------------------|--------------------------------|--------------------------|----------------------------|-------------|
| LTO reaction of heavy oil | HO + 1.5 O2→0.9892 HO + 0.9 CO2 + H2O | 3.9×10^4                | 28.72                      | 406         |

4. Results and discussion

4.1. The effect of air injection

Taking the cases of pure ISU and AAISU processes with the heating temperature of 350 °C and air injection rate of 1000 sm^3/day as an example, the profiles of the average formation temperature of two processes are shown in Figure 4. It can be observed that air injection can improve heat transfer rate obviously. After 10 years, the average temperature of the AAISU process can be up to 240 °C, while it is only 195 °C for the ISU process. The improved heat transfer can be attributed to thermal effect of the LTO reaction. Air injection can also improve the oil recovery and oil rate. The oil recovery is 71.4% for the AAISU process, which is enhanced by 11.4% due to the additional air injection comparing to the conventional ISU process. The oil rate is increased as shown in Figure 3.

Energy efficiency was another judging criterion for the ISU process, which is defined as the ratio of total output energy to the total input energy. The output energy refers to the chemical energy possessed by produced oils and hydrocarbon gases (40 GJ/m^3 and 36MJ/m^3 were assumed to be the energy content for oils and hydrocarbon gases [10, 11]). The input energy mainly includes the energy provided by heater and the energy required by compressed gas, and other energy required in the oil production activity is not considered. Therefore, the energy efficiency results show that energy efficiency was improved by air injection from 4.54 GJ/GJ to 8.15 GJ/GJ, this is because that improved oil recovery and thermal effect of the LTO reaction.

![Figure 3. The effect of air injection on the performance of the AAISU process.](image)

4.2. The effect of heating temperature and air injection rate

The heating temperature and air injection rate are important for the performance of the AAISU process, because they can influence the oxidation rate between the oil and oxygen in the air. Four heating temperature including 250 °C, 300 °C, 350 °C and 400 °C have been simulated. The results have been shown in Figure 4 as following, the heat transfer rate, oil recovery, cumulative light oil and oil rate are increased with the increasing of the heating temperature, however, the energy efficiency 13 GJ/GJ, 10.5 GJ/GJ, 9.2 GJ/GJ and 8.7 GJ/GJ respectively, which is decreased stead, and this is because that the energy required to heating the formation is increased a lot and the more produced oils cannot afford the consumed energy.
To investigate the effect of air injection rate on the performance of the AAISU process, a series of simulations of four air injection rate such as 500 m³/day, 1000 m³/day, 2000 m³/day and 4000 m³/day have been conducted, and the downward air injection direction and 300 ℃ have been used during the simulation, the results shown in the Figure 5 indicated that heat transfer, cumulative light oil and oil rate are increased with the increasing of air injection rate. However, the oil recovery and energy efficiency are 9.7 GJ/GJ, 10.4 GJ/GJ, 9.8 GJ/GJ and 8.0 GJ/GJ respectively when the air injection rate is 500 m³/day-4000 m³/day, and the energy efficiency is improved when the air injection rate is 500-1000 m³/day, while, they are decreased when the air injection rate is over 1000 m³/day. Therefore, 1000 m³/day is the optimal air injection rate with the highest oil recovery and energy efficiency.

Figure 4. The effect of heating temperature on the performance of the AAISU process.

Figure 5. The effect of air injection rate on the performance of the AAISU process.

5. Conclusion
An air injection assisted in situ upgrading process (AAISU) via subsurface electrical heating based on the horizontal well have been proposed and simulated. Thermal cracking and TG experiments of ultra heavy oil have been done to get the chemical models and kinetic parameters during the ISU process. The simulation results show that air injection can improve heat transfer rate, enhance oil recovery by 11.4% and improve the energy efficiency. As the temperature is increased from 250 ℃ to 400 ℃ with air injection rate of 1000 m³/day, the heat transfer rate, oil recovery, cumulative light oil and oil rate are improved, while the energy efficiency decreased. As for the effect of the air injection rate on the performance of the AAISU process, the heat transfer, cumulative light oil and oil rate are increased with the increasing of air injection rate. However, the oil recovery and energy efficiency are improved when the air injection rate is 500-1000 m³/day, while, they are decreased when the air injection rate is over 1000 m³/day. Therefore, 1000 m³/day is the optical air injection rate with the highest oil recovery and energy efficiency.
References

[1] Youtsos M.S.K., Mastorakos E., Cant R.S.. Numerical simulation of thermal and reaction fronts for oil shale upgrading. Chem. Eng. Sci. 94(2013):200-213.

[2] Lee K.J., Moridis G.J., Ehlig-Economides C.A. A Comprehensive Simulation Model of Kerogen Pyrolysis for the In-situ Upgrading of Oil Shales. SPE J. (2016).

[3] Fowler T.D., Vinegar H.J. Oil Shale ICP - Colorado Field Pilots, 2009.

[4] Pei S.F., Wang Y.Y., Zhang L., et al. An innovative nitrogen injection assisted in-situ conversion process for oil shale recovery: Mechanism and reservoir simulation study. J. Pet. Sci. Eng. 171(2018), 507-515.

[5] Pei S.F., Cui G.D., Wang Y.Y., et al. Air assisted in situ upgrading via underground heating for ultra heavy oil: Experimental and numerical simulation study. Fuel. 279 (2020).

[6] Wang Y.Y., Ren S.R., Zhang L. Mechanistic simulation study of air injection assisted cyclic steam stimulation through horizontal wells for ultra heavy oil reservoirs. J. Pet. Sci. Eng. 172(2018):209-216.

[7] Wang Y.Y., Zhang L., Deng J.Y., et al. An innovative air assisted cyclic steam stimulation technique for enhanced heavy oil recovery. J. Pet. Sci. Eng. 151(2017):254-263.

[8] Wang Y.Y., Ren S.R., Zhang L., et al. Numerical study of air assisted cyclic steam stimulation process for heavy oil reservoirs: Recovery performance and energy efficiency analysis. Fuel. 211(2017):471-483.

[9] Computer Modelling Group (CMG) Ltd. CMG STARS user's guide-version 2012. Calgary, Alberta, Canada, 2012.

[10] McKinney, Michael L., Robert M.S. Environmental science: Systems and solutions. Jones & Bartlett Learning, 2003.

[11] Wilcock W. Energy in natural processes and human consumption-some numbers. Course material for ENVIR215: Earth, Air, Water: The Human Context, Spring, 2005.