



# Numerical Simulation of Deformed Medium on In Situ Upgrading of Oil Shale via Steam Injection

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**Abstract.** Injection of high-temperature steam is an effective and environment-friendly method for in situ upgrading of oil shale. In order to determine the variation rules of porosity and permeability of oil shale during the in situ upgrading process via steam injection, a numerical simulation model was established considering the deformed medium theory. This paper analyzed the influence of steam injection rate on medium deformation and oil production from several aspects, including the temperature distribution and kerogen decomposition. The results show that, under the action of kerogen decomposition and its products, the porosity and permeability of matrix increase gradually with the temperature. There is a rapid increase stage of cumulative oil production corresponding to the changes in average porosity and permeability of reservoir. The average porosity and permeability of reservoir increase faster with the steam injection rate; moreover, the rate of oil production is accelerated and the period of it becomes shorter. The research provides theoretical basis for the application and promotion of in situ upgrading of oil shale via steam injection.

**Keywords:** Oil shale · Steam injection · Changes in porosity and permeability · Numerical simulation

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## 1 Introduction

Oil shale is a solid sedimentary rock that contains significant amounts of kerogen, and the kerogen can decompose through a series of chemical reactions into recoverable hydrocarbon products when it is heated to 300–600 °C [1]. As a kind of unconventional oil resources, a conservative estimate suggests that the total worldwide oil shale resources are approximately equivalent to  $3 \times 10^{12}$  bbl of oil [2], and China has abundant oil shale resources that are equivalent to about  $3.5 \times 10^{11}$  bbl of oil [3].

In order to avoid high pollution and low efficiency problems in the process of ground retorting [4], many researchers have begun to investigate the in situ upgrading technologies of oil shale from the 1980s [5], including the overheat steam injection technology [6]. The way it works is injecting overheat steam through injection wells with the method of huff-puff or steam driving to heat oil shale reservoirs; then, the liquid and gas products during kerogen pyrolysis are produced by production wells [7]. Compared with the ground retorting technology, the overheat steam injection technology is environment-friendly and cost-effective [8]. Numerical simulation is an important research method for oil and gas field development, and some problems about in situ upgrading of oil shale have been solved by this way [9]. Due to the pyrolysis of kerogen, both porosity and permeability of oil shale increase gradually [10]. But the important characteristics are not considered in most numerical simulation studies, and they always be replaced by the average values' definition of porosity and permeability in these models [11]. CMG is an effective reservoir simulator, and the results conducted by it can closely simulate the process of in situ upgrading of oil shale [12–15].

Therefore, in this paper, CMG was employed to establish a numerical simulation model considering the deformed medium theory. Then, the characteristics of medium deformation were revealed in the process of in situ upgrading of oil shale via steam injection, through analyzing the temperature distribution and kerogen decomposition comprehensively.

## 2 Reservoir Simulation

Shell has actively implemented a pilot project named in situ conversion process (ICP). The current version of the Shell ICP consists of a hexagonal pattern of six electric heaters surrounding one production well, but only a part of the well group with confined boundary was simulated due to the symmetry, as shown in Fig. 1. In this simulation, the electric heaters were changed into the steam injection wells, which were spaced 7 m apart, and the thickness of the simulated reservoir was 30 m.

Kerogen is a complex material, and the resulting pyrolysis products are also quite complex. Various conversion mechanisms of oil shale conversion to products have been proposed by previous researchers. Shell conducted experiments with samples obtained from the Green River Formation in the USA, and showed that kerogen pyrolysis of in situ upgrading can be simplified into several kinetic reactions.

The kinetic reactions of kerogen pyrolysis including the main components are listed in Table 1. Kerogen pyrolysis was simulated using properties of lumped representative components. Thus, the pseudo-species IC<sub>37</sub>, IC<sub>13</sub>, and IC<sub>2</sub> were used to represent the heavy oil, light oil, and hydrocarbon gas.

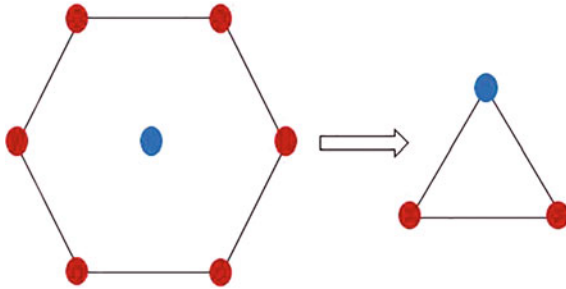


Fig. 1. Only a part of the hexagonal pattern applied for the simulation

Table 1. Kinetic reactions of kerogen pyrolysis

Number	Reactions
1	Kerogen → 0.007131IC <sub>2</sub> + 0.009722IC <sub>13</sub> + 0.010699IC <sub>37</sub> + 0.641083 Prechar
2	IC <sub>37</sub> → 1.503765IC <sub>2</sub> + 0.661282IC <sub>13</sub> + 13.4175 Prechar
3	IC <sub>13</sub> → 3.237828IC <sub>2</sub> + 5.182242 Prechar
4	Prechar → 0.017177IC <sub>2</sub> + 0.99021 Char

According to the characteristics of in situ upgrading of oil shale via steam injection, double-porosity model was used in this simulation. Matrix system represented the inorganic mineral skeleton where kerogen existed. Kerogen pyrolysis led to a large number of pores in matrix and further affected the matrix porosity and permeability. The relationship between porosity and permeability of matrix was described using deformed medium theory in the following equation. Kerogen pyrolysis also resulted in the cracks, which were represented by fracture system. And other main parameters of the reservoir simulation are listed in Table 2.

$$k = k_o(\phi/\phi_o)^3[(1 - \phi_o)/(1 - \phi)]^2 \tag{1}$$

where  $\phi$  and  $\phi_o$  are the matrix effective porosity and the original porosity, respectively, fraction;  $k$  and  $k_o$  are the matrix effective permeability and the original permeability, respectively,  $10^{-3} \mu\text{m}^2$ .

**Table 2.** Main parameters of the reservoir simulation

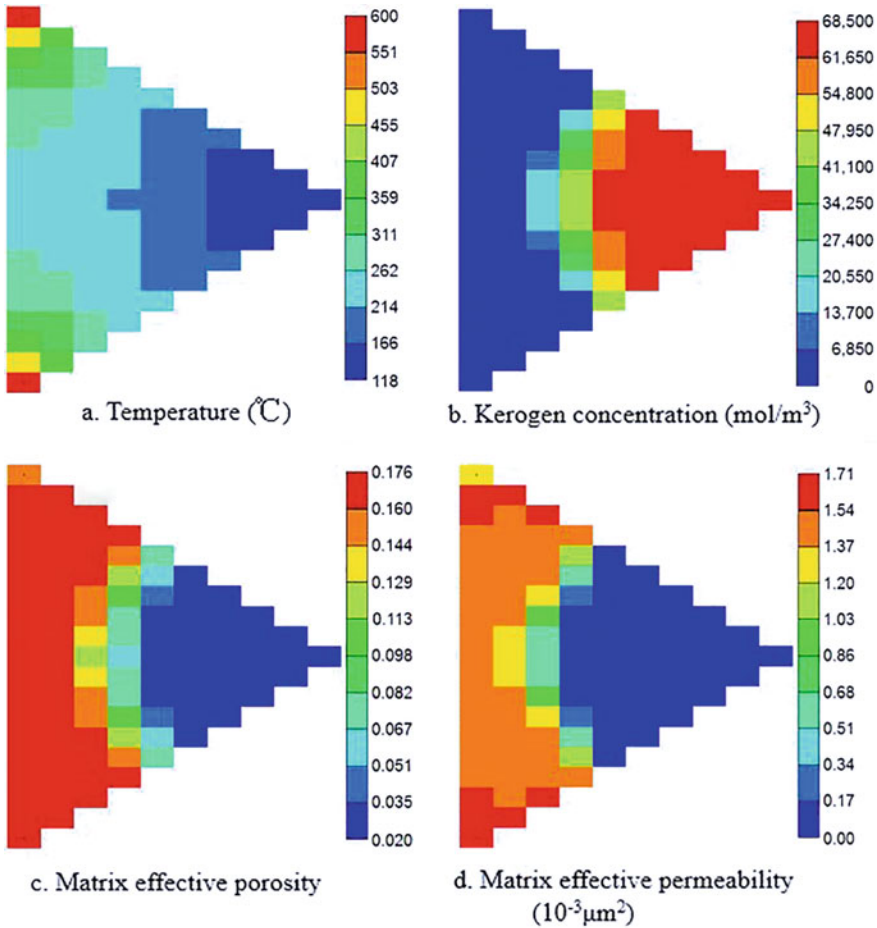
Parameter	Value
Thickness of reservoir	30 m
Injector–producer distance	7 m
Initial temperature	23 °C
Initial pressure	2 MPa
Initial kerogen	68,500 mol/m <sup>3</sup>
Original porosity of matrix	0.02
Original permeability of matrix	$0.002 \times 10^{-3} \mu\text{m}^2$
Porosity of fracture	0.05
Permeability of fracture	$100 \times 10^{-3} \mu\text{m}^2$
Rock volume heat capacity	$1.677 \times 10^6 \text{ J}/(\text{m}^3 \text{ } ^\circ\text{C})$
Thermal conductivity	93,459.7 J/(m·d °C)
Steam temperature	600 °C
Steam quality	1
Injection rate	20 t/d

### 3 Results and Discussion

Figure 2a shows the temperature distribution in formation when steam is injected for 2 years at 600 °C. In this time, most of the formations attain the pyrolysis window where kerogen decomposition takes place. Figure 2b shows the distribution of kerogen concentration in heated interval over the duration of 2 years. Figure 2c shows that the matrix effective porosity increases near the steam injection wells, and the area expands to the production well gradually due to kerogen decomposition in the heating process. The distribution of matrix effective permeability corresponds to the matrix effective porosity as expected in Fig. 2d; it tends to increase with the matrix effective porosity.

In addition, various simulations were performed to assess the influence of steam injection rate on in situ upgrading of oil shale via steam injection, and three levels of it were 20, 30, and 40 t/d. Affected by the theory of double-porosity media, the results for changes in average porosity and permeability of reservoir are shown in Figs. 3 and 4. Both the curves of average porosity and permeability increase with the heating time, and there is a rapid increase stage in curves before reaching the maximum values. With the increase in steam injection rate, the faster average porosity and permeability of reservoir increase.

The results for cumulative oil production are shown in Fig. 5. Based on the analysis of Figs. 3 and 4, it can be seen that due to the large-scale improvement of physical properties of the reservoir, there is a rapid increase stage of cumulative oil production



**Fig. 2.** Changes in several parameters of the simulation after 2 years

corresponding to the changes in average porosity and permeability of reservoir. When the average porosity and permeability are close to the maximum values, the oil production rate becomes slower caused by the decrease of the remaining oil. With the increase in steam injection rate, the faster cumulative oil production increases.

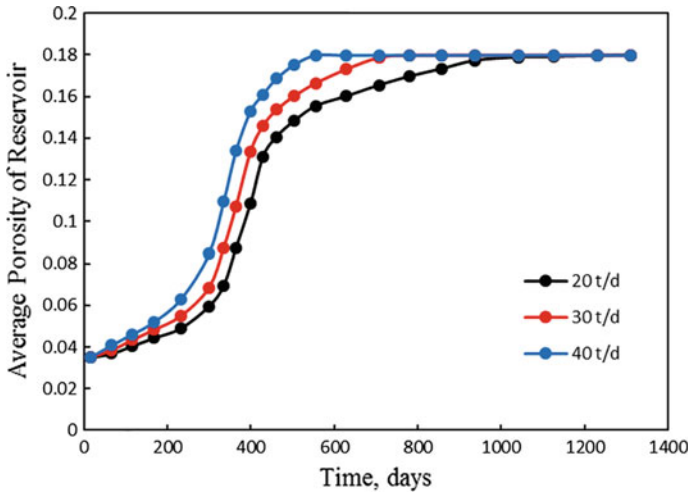


Fig. 3. Influence of steam injection rate on average porosity of reservoir

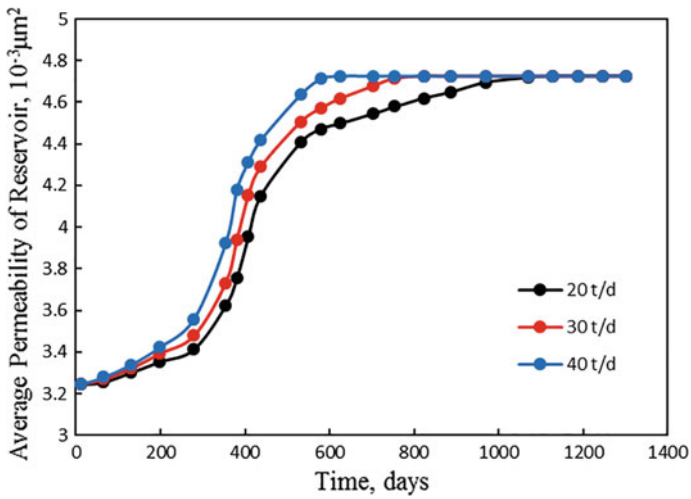


Fig. 4. Influence of steam injection rate on average permeability of reservoir

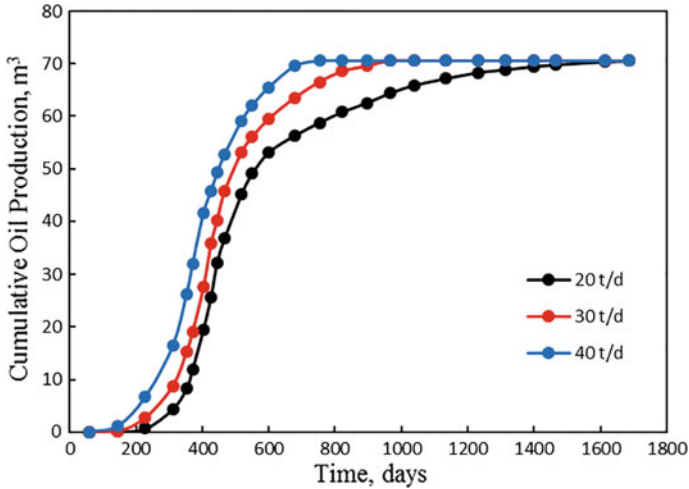


Fig. 5. Influence of steam injection rate on cumulative oil production

## 4 Conclusions

1. A numerical simulation model of in situ upgrading of oil shale via steam injection is established considering the deformed medium theory.
2. The results show that, under the action of kerogen decomposition and its products, the porosity and permeability of oil shale increase gradually with the temperature.
3. Due to the large-scale improvement of physical properties of the reservoir, there is a rapid increase stage of cumulative oil production corresponding to the changes in average porosity and permeability of reservoir.
4. The average porosity and permeability of reservoir increase faster with the steam injection rate; moreover, the rate of oil production is accelerated and the period of it becomes shorter.

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