EFFECT OF FLUID PROPERTIES ON OIL SHALE IN-SITU CONVERSION PERFORMANCE WITH FRACTURING

by

Bin WANG[a,b], Rui WANG[c], Yiwei WANG[b], Jianzheng SU[b], Xu ZHANG[c], Haizhu WANG[c*], and Kang CHEN[c]

[a] State Key Laboratory of Shale Oil and Gas Enrichment Mechanisms and Effective Development, China University of Petroleum – Beijing Branch, Beijing, China
[b] State Center for Research and Development of Oil Shale Exploitation, Beijing, China
[c] State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing, China

Original scientific paper
https://doi.org/10.2298/TSCI2404493W

This study studies the effect of flow and thermal transfer properties of fluids with varying densities, viscosities, and thermal conductivities on the performance of oil shale in-situ conversion process based on multi-physics coupling simulation. Results indicate that thermal convection primarily governs the heat transfer process in oil shale. Consequently, to enhance the pyrolytic effects, fluids possessing high density, low viscosity and superior thermal conductivity are recommended. This research thus provides a foundational understanding for the selection of fluid properties in the in-situ extraction of oil shale.

Key words: *oil shale, in-situ conversion, heat transfer, fluid properties*

Introduction

China boasts a wealth of oil shale resources, both in terms of abundance and geographic dispersion. The estimated total resources are approximately $7200 \cdot 10^8$ tonne, with the converted shale oil resources amounting to $473 \cdot 10^8$ tonne, thereby placing China as the world's second-largest holder of such resources. Notably, over 53% of these resources contain an oil content exceeding 5%, highlighting their high developmental value and broad application prospects [1].

Oil shale extraction methodologies primarily bifurcate into surface retorting technology and underground in-situ conversion technology. The former, despite its established use, is increasingly viewed as untenable due to its high transportation costs, waste disposal challenges, and environmental contamination, thereby rendering the effective development of oil shale resources difficult and pushing it towards obsolescence [2]. Conversely, in-situ conversion technology, with its superior energy efficiency and minimal surface pollution, has gained increasing attention [3]. In general, given the current constraints of in-situ conversion technology, economic considerations, environmental impact, and the global shift towards a diversified *new energy era*, there is an urgent need to explore novel, green, and efficient methods for oil shale development.

* Corresponding author, e-mail: whz0001@126.com

Hence, the selection of an appropriate heat-carrying fluid emerges as a critical aspect of the pyrolysis process, with the fluid distinctions primarily embodied in their inherent properties. This study conducts simulations of heat transfer during in-situ oil shale extraction under varying fluid densities, viscosities, thermal conductivities, and heat capacities, thereby facilitating the selection of an optimal fluid medium.

Model and methods

Mathematical model

Case A: Fluid-flow in porous media. In this paper, COMSOL Multiphysics software was used for numerical simulation. The fluid-flow equation is shown [4]:

$$\frac{(\partial \rho \phi_0 X_f)}{\partial t} + \nabla\left(-\rho \frac{k}{\mu} \nabla p\right) = Q_m \tag{1}$$

where ϕ_0 is the porosity, ρ_0 – the fluid density, k – the permeability of matrix, X_f – the compressibility of the fluid (here, we take $4\cdot10^{-1}$), and μ – the viscosity of the fluid.

Case B: Heat transfer in porous media. It is assumed that the fluid and the local rock mass reach an instantaneous heat balance, regardless of convection heat transfer, and the heat transfer control equation is suggested [4, 5]:

$$\rho_s c_p \frac{\partial T}{\partial t} + \rho_s c_p u \nabla T + \nabla q = Q \tag{2}$$

where ρ_s is the density of the fluid, c_p – the specific heat, and Q – the model heat source, mainly including heating heat source and chemical reaction heat source.

According to the experimental data of [6-9], and the fitting relationship of porosity with temperature, the change of porosity, φ, is given:

$$\varphi = 39.022 - \frac{37.093}{1} + \frac{T}{370.871^{6.577}} \tag{3}$$

where T is the temperature.

Permeability is obtained based on low field NMR experiments with the fitting equation:

$$K = -2\cdot10^{-9}T^4 + 2\cdot10^{-6}T^3 + 6\cdot10^{-4}T^2 + 6\cdot10^{-2}T - 0.8598 \tag{4}$$

Physical model

The horizontal section of the heating well and the horizontal section of the production well are simplified into two straight lines with three longitudinal cracks in the middle, fig. 1. It is assumed that the horizontal length of each well is 120 m. The horizontal spacing between the two wells is 50 m. The fracture length between the two wells is 90 m and the fracture width is 6 mm.Under the initial conditions, the average temperature of the reservoir model is 90 °C and the pressure is 5 MPa. For the temperature field, the heating well temperature is 620 °C. For the seepage field, the injection pressure is 10 MPa in the injection well and 5 MPa in the production well.

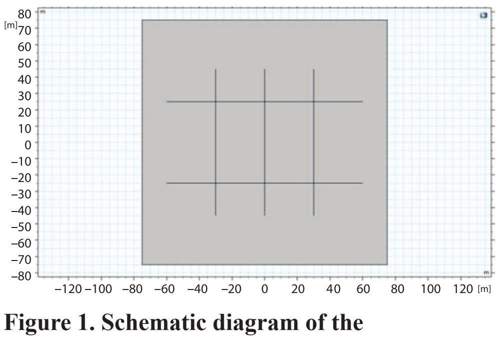

Figure 1. Schematic diagram of the physical model

Performance evaluation index

In this paper, the pyrolysis pore area and the pyrolysis swept area are defined to quantitatively describe the pyrolysis of oil shale, and the final curve is obtained and the relevant laws are analyzed:

– Pyrolysis pore area. The porosity of each discrete unit of oil shale multiplied by the reservoir area divided by the maximum porosity of oil shale multiplied by the reservoir area.

The pyrolysis pore $V_{\rm po}$ area reads:

$$V_{\rm po} = \int V_\varphi \tag{5}$$

where V is the total area of oil shale reservoir and φ – the porosity of oil shale.

– Pyrolysis swept area. We now consider the total area of all discrete units of oil shale at a temperature higher than 473.15 K. Here, we show the total area of all discrete units of oil shale, given:

$$V_n = \sum_{T=473.15}^{T_{\max}} v_T \tag{6}$$

where v_T [m^2] is the area of the discrete unit at temperature, T.

Results

In the initial conditions, the physical parameters of supercritical CO_2 fluid were selected at 10 MPa and 893.15 K, the density was set to 80 kg/m^3, the viscosity was set to $5.8 \cdot 10^{-5}$ Pa·s, the thermal conductivity was set to 0.140 W/mK.

Effect of fluid density on pyrolysis

This section simulates the effects of fluids with densities of 20 kg/m^3, 50 kg/m^3, 80 kg/m^3, 110 kg/m^3, and 140 kg/m^3 on the pyrolysis performance of oil shale when other conditions remain constant.

The figs. 2 and 3 suggest that under simulated conditions, when the fluid density is low, the heat transfer received by production wells is minimal, and most reservoirs fail to attain the ideal pyrolysis temperature. For a fluid with a density of 140 kg/m^3, the pyrolysis pore area and the pyrolysis swept area are, respectively 1627.42 m^2 and 6063.79 m^2, which are 28.33% and 24.83% higher than those of a fluid with a density of 20 kg/m^3. However, in comparison a fluid with a density of 110 kg/m^3, the pyrolysis pore area is only 1.3% larger and the pyrolysis swept area is merely 2% greater.

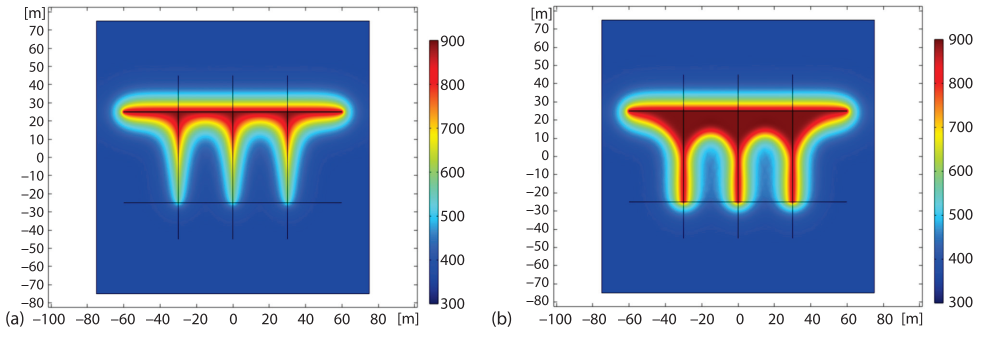

Figure 2. Temperature clouds with fluid densities of (a) 20 kg/m^3 and (b) 140 kg/m^3 at 1000 days

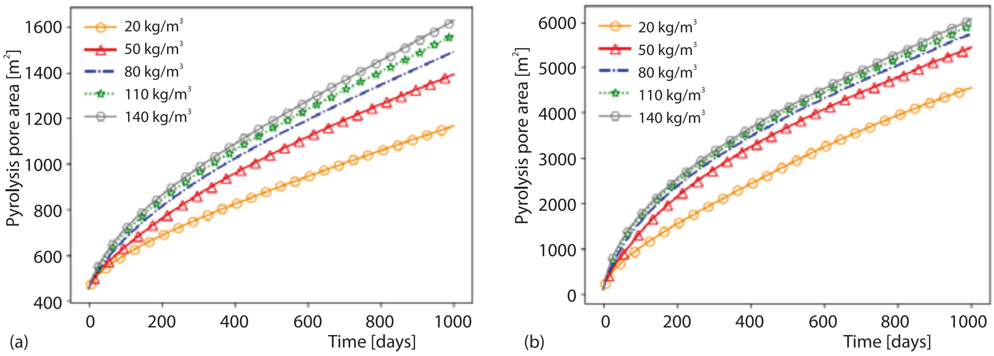

Figure 3. Effect of fluid density on pyrolysis pore area / pyrolysis swept area; (a) pyrolysis pore area and (b) pyrolysis swept area

Effect of fluid viscosity on pyrolysis

This subsection simulates the effects of fluids with viscosity of $3.8 \cdot 10^{-5}$ Pa·s, $4.8 \cdot 10^{-5}$ Pa·s, $5.8 \cdot 10^{-5}$ Pa·s, and $6.8 \cdot 10^{-5}$ Pa·s on the pyrolysis performance of oil shale, all other conditions being constant.

Figure 4 demonstrate that with a decrease in viscosity, the range of fluid pyrolysis broadens, and the reservoir temperature escalates more rapidly. This is attributable to the reduced resistance experienced by the heating medium at lower viscosities, thereby facilitating improved flow within the reservoir. As viscosity increases, each index continues to rise at an accelerating rate. According to the image and development trend, the pyrolysis effect of oil shale reservoir is more sensitive to viscosity when the viscosity is higher, and the sensitivity becomes weaker when the viscosity decreases. In general, viscosity, as an important physical property parameter of fluid, has a certain influence on pyrolysis when the range of change is low. In the case of other physical properties being the same, low viscosity fluids should be preferred to enhance the flow of fluids in the formation.

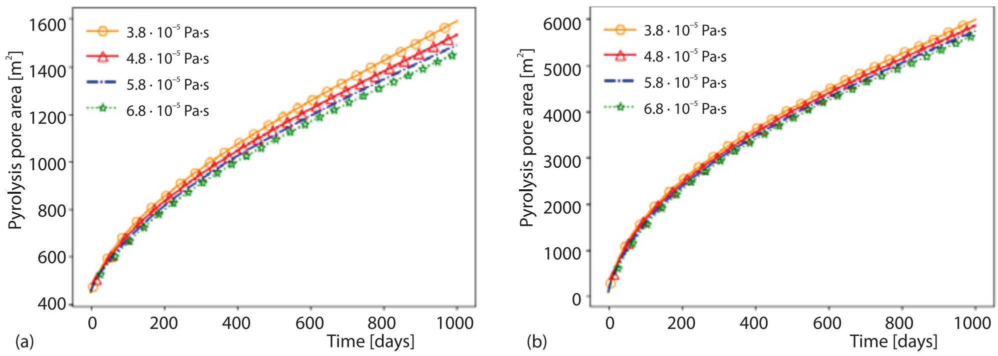

Figure 4. Effect of fluid viscosity on pyrolysis pore area / pyrolysis swept area; (a) pyrolysis pore area and (b) pyrolysis swept area

Effect of fluid thermal conductivity on pyrolysis

This section when other condition is constant, simulates the coefficient of thermal conductivity is 0.7 W/mK, 1.4 W/mK, 2.1 W/mK, and 2.8 W/mK fluid influence on the effect of oil shale pyrolysis.

The fig. 5 illustrate that higher thermal conductivity corresponds to increased fluid conductivity, resulting in greater pyrolysis pore area and pyrolysis swept area. Non-etheless, at 1000 days, the pyrolysis pore area and pyrolysis swept area for a fluid with a thermal conductivity of 2.8 W/mK were 1503.97 m^2 and 5783.90 m^2, respectively. In comparison a fluid with a thermal conductivity of 0.7 W/mK, the pyrolysis pore area and pyrolysis swept area were higher by 19.81 m^2 and 58.94 m^2. In conclusion, during the pyrolysis of oil shale, variations in fluid thermal conductivity have minimal influence on the thermal recovery process.

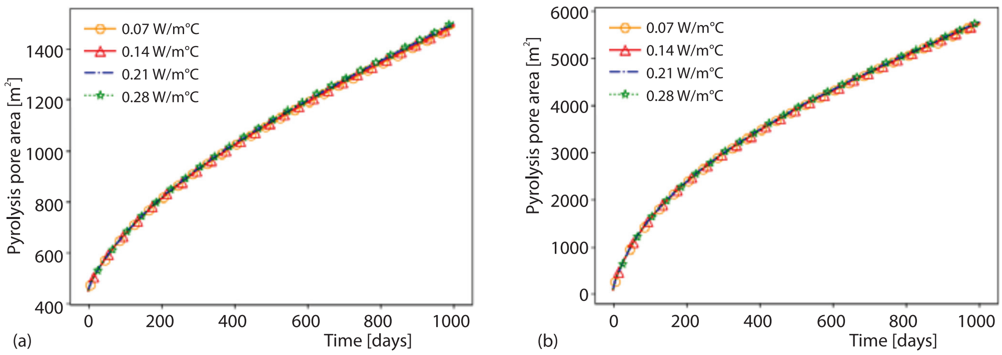

Figure 5. Effect of fluid thermal conductivity on pyrolysis pore area/pyrolysis swept area; (a) pyrolysis pore area and (b) pyrolysis swept area

Conclusion

Through the sensitivity analysis of fluid properties, it is found that the heat transfer of fluid in oil shale is dominated by thermal convection. In order to improve the pyrolysis effect, density and viscosity should be considered first, and fluids with high density and low viscosity are preferred. Although the thermal conductivity has a certain impact, the impact is relatively small in the case of suitable density viscosity, the medium with high thermal conductivity should be preferred.

Nomenclature

c_p – specific heat, [$Jkg^{-1}K^{-1}$]
k – permeability, [m^3]
T – temperature, [°C]
V_{po} – pyrolysis pore area, [m^2]

Greek symbols

μ – viscosity of the fluid, [P ·s]
ρ_0 – density, [kgm^{-3}]
ϕ_0 – porosity, [–]

Acknowledgments

This work is supported by the Open Fund of State Key Laboratory of Shale Oil and Gas Enrichment Mechanisms and Effective Development, China (No. 33550000-22-ZC0613-0239).

References

[1] Liu, R., *et al*., Study on Oil Shale Enrichment and Geological Events in China, *Acta Sedimentologica*, *39* (2021), 1, pp. 10-28
[2] Gu, J., *et al*., Pyrolysis Behavior and Pyrolysate Characteristics of Huadian Oil Shale Kerogen Catalyzed by Nickel-Modified Montmorillonite, *Advances in Geo-Energy Research*, *11* (2024), 3, pp. 168-180
[3] Sun, Y. H., *et al.*, Current Situation and Development Trend of in-Situ Transformation and Drilling and Production Technology of Oil Shale, *Drilling Engineering*, *48* (2021), 1, pp. 56-67

[4] Neuman, S. P., Theoretical Derivation of Darcy's Law, *Acta Mechanica*, *25* (1977), 3-4, pp. 153-170
[5] Xu, W., *et al*., An Integrated Model for Fracture Propagation and Production Performance of Thermal Enhanced Shale Gas Recovery, *Energy*, *263* (2023), 3, ID125682
[6] Guo, W., *et al*., Reliability Analysis of Elastic Graphite Packer in Heat Injection Well During Oil Shale In-Situ Conversion, *Advances in Geo-Energy Research*, *7* (2023), 1, pp. 28-38
[7] Yang, T., *et al*., Study on Pore-Change Characteristics of Shale after High-Temperature Exposure Using NMR, *Arabian Journal of Geosciences*, *15* (2022), 8, pp. 770-777
[8] Huang, H., *et al.*, A Coupled Thermo-Hydro-Mechanical-Chemical Model for Production Performance of Oil Shale Reservoirs during in-Situ Conversion Process, *Energy*, *268* (2023), 2, ID126700
[9] Yang, D., *et al*., Experimental Investigation of Anisotropic Thermal Deformation of Oil Shale Under High Temperature and Triaxial Stress Based on Mineral and Micro-Fracture Characteristics, *Natural Resources Research*, *29* (2020), Mar., pp. 3987-4002

Paper submitted: December 2, 2023
Paper revised: December 14, 2023
Paper accepted: January 15, 2024