EFFECT OF RESERVOIR PROPERTIES ON THE PERFORMANCE OF OIL SHALE IN-SITU PYROLYSIS USING SUPERCRITICAL CO_2 IN FRACTURED RESERVOIR

by

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This study conducted simulations to investigate the heat transfer dynamics of supercritical CO_2 as a thermal carrier within oil shale formations. The paper aimed to elucidate the impact of formation physical properties on the pyrolysis efficiency of oil shale. The findings from the simulations indicate that porosity minimally affects the thermal sweep but is directly correlated with the heating pore area. Meanwhile, permeability significantly influences both porosity and the extent of pyrolysis sweep, suggesting the preferential selection of formations characterized by high initial porosity and permeability wherever feasible.

Key words: *supercritical CO_2, in-situ mining, heat transfer, formation physical property*

Introduction

As the economy experiences rapid growth, the demand for oil and gas continues to rise, and the increasingly serious energy crisis forces the optimization of supply channels and the transformation of the overall structure [1, 2]. The development of unconventional energy is gradually favored by countries due to the asymmetry between traditional oil and gas production capacity and needs, and has become an important means to deal with energy problems and strive for energy independence [3]. Oil shale, a sedimentary rock containing complex kerogen structures, can be converted into shale oil through thermal cracking and subsequent hydrocracking to yield refined products such as gasoline and kerosene [4]. Given China's high reliance on imported oil, oil shale holds significant utilization and research value in this context.

Surface retorting technology presents various drawbacks, including high transportation costs, challenging waste disposal, and environmental pollution, rendering effective oil shale development unattainable and placing it on the brink of obsolescence [5]. In contrast, in-situ conversion technology has garnered greater attention due to its high energy efficiency and minimal surface pollution. Academician Shen Zhonghou of China University of Petroleum (Beijing) has pioneered a novel concept advocating the use of supercritical CO_2 as a *green*

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drilling and completion fluid in China [6]. Supercritical CO_2 fluid exhibits low viscosity, high diffusion capacity, low surface tension, and numerous advantages [7, 8].

To address these issues, based on the changes of porosity and permeability characteristics at different temperatures, this paper conducts fluid-flow and heat transfer simulations of in-situ supercritical CO_2 exploitation of oil shale, elucidating the impact of formation physical properties on flow and heat transfer characteristics under multi-field coupling effects, and delineates the influence of formation physical properties on the pyrolysis efficiency of oil shale.

Model and methods

In this paper, COMSOL Multiphysics software was used for numerical simulation, which could conveniently and efficiently carry out multi-physical field coupling, so as to accurately simulate the pyrolysis process of oil shale.

Mathematical model

In this paper, COMSOL Multiphysics software was used for numerical simulation, which could conveniently and efficiently carry out multi-physical field coupling, so as to accurately simulate the pyrolysis process of oil shale. The fluid-flow in porous media can be expressed [9]:

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

where ϕ_0 is the porosity, ρ_0 – the fluid density, k – the permeability of matrix, X_f – the compressibility of the fluid, and μ – the viscosity of the fluid.

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 established [10]:

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

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.

Physical property model of supercritical CO_2 fluid

Supercritical CO_2 exhibits heightened sensitivity to temperature and pressure, with all physical parameters demonstrating pronounced non-linearity in response to variations in temperature and pressure. Consequently, the ideal gas equation of state is inadequate for depicting the correlation between CO_2 density and changes in temperature and pressure.

The physical properties of carbon dioxide are evaluated using the Span and Wagner formulations. Refprop is a physical property database from the National Institute of Standards and Technology (NIST). Its full name is Reference Fluid Thermodynamic and Transport Properties Database. In this work, an open source software CoolProp is adopted for CO_2 fluid propreties evaluation.

Physical model

Assume that hydraulic fracturing creates three interconnected fractures between two horizontal Wells, each with a horizontal length of 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 6mm. The geometric model shown in fig. 1 is established. 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 model assumes that the boundaries of the reservoir are set as adiabatic boundary conditions, the temperature is equal to the initial formation temperature, and the heating well temperature is 620 °C . For the seepage field, the boundary of the reservoir model is set as no flow boundary condition. The injection pressure is 10 MPa in the injection well and 5 MPa in the production well.

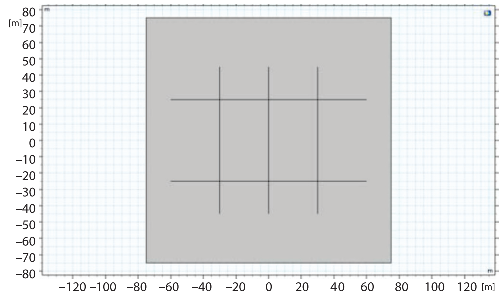

Figure 1. Schematic diagram of the physical model

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. 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 total area of all discrete units of oil shale at a temperature higher than 473.15 K is considered in this article.

Results

Flow and pyrolysis characteristics of basic model

The in-situ extraction of oil shale reservoirs via the injection of supercritical CO_2 nanofluids encompasses a multitude of physical processes, including seepage and heat transfer, which interact to directly influence the pyrolysis efficiency of oil shale. Within this section, assessment indices are employed to analyze and unveil the coupling characteristics based on the pyrolysis scenario of the fundamental model.

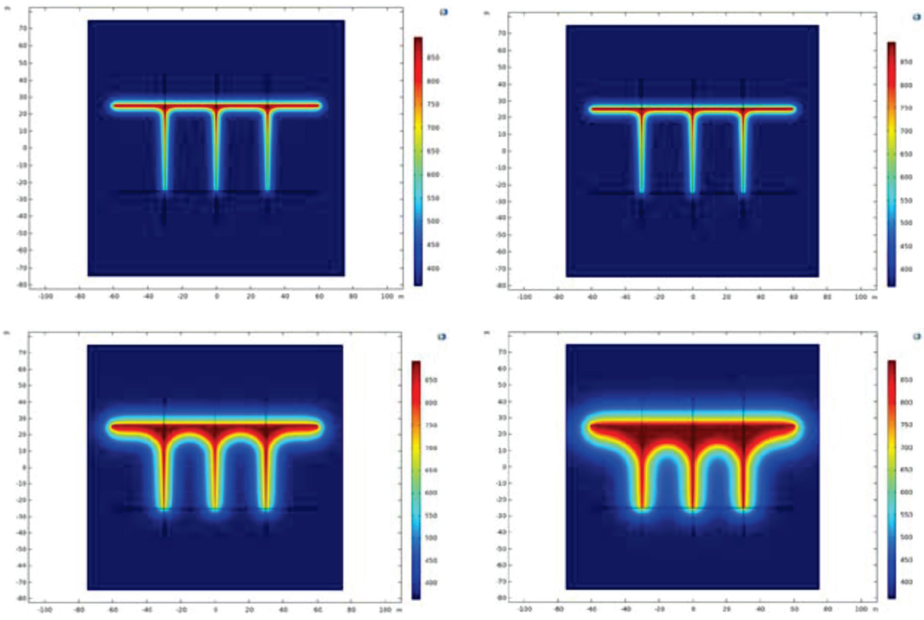

Figure 2. The 100/200/500/1000 days temperature field distribution clouds

Figure 2 illustrates that proximity to the heating well and fracture corresponds to a swifter temperature escalation and higher reservoir temperatures. Owing to the homogeneity of the formation, temperature uniformly diffuses from the vicinity of the well over time. The fracture serves as the primary seepage pathway, manifesting a discernible heat transfer effect. The predominant heat transfer and flow of supercritical CO_2 nanofluids occur through the fracture, resulting in rapid elevation of reservoir temperature in the nearby vicinity. Subsequently, this heightened temperature is swiftly transmitted to the interconnected region between the production well and the fracture. Conversely, minimal temperature fluctuation is observed in the horizontal section of the wellbore and the remote area from the fracture due to the majority of fluid percolating along the fracture. Only a fraction of the fluid permeates to deeper levels, where heat transfer to the formation leads to temperature decline, impeding its transmission distant zones with elevated temperatures, thus failing to attain the pyrolysis temperature of the oil shale.

Effect of porosity

Based on the original model, this section modifies the porosity to 0.5, 0.75, 1.25, and 1.5 times of the original for simulation and comparative analysis.

As depicted in fig. 3 it is evident that assuming the formation porosity to be half of the original value results in a pyrolysis pore area of 799.73 m^2 under the 1000-day basis model, representing a reduction of 806.75 m^2 compared to the normal state. Concurrently, the pyrolysis propagation area is 6218.96 m^2, indicating an increase of 175.07 m^2 relative to the normal state. Conversely, assuming the formation porosity to be 1.5 times the original value yields a pyrolysis pore area of 2197.71 m^2 under the 1000-day basis model, signifying an increment of 591.23 m^2 compared to the normal state. Additionally, the pyrolysis spread area is 5834.35 m^2,which is 209.54 m^2 greater than the normal state. These results signify a significant variation in the porosity of each micro-unit in the model when the porosity change amplitude and the maximum pyrolysis value are altered, while maintaining a constant pyrolysis temperature. Furthermore, based on the defined pyrolysis pore area, corresponding changes occur in accordance with the variation in porosity amplitude. Moreover, it is observed that reducing the range of porosity variation and the maximum pyrolysis value leads to a slight increase in the pyrolysis spread area.

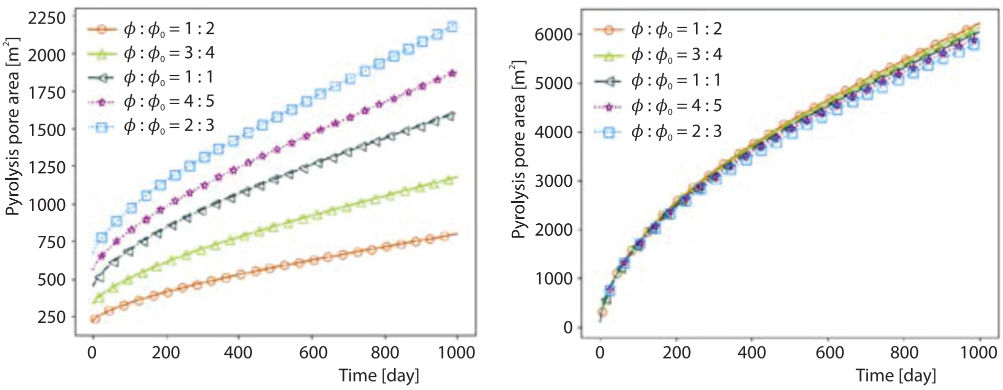

Figure 3. Comparison of pyrolysis pore area and pyrolysis spread area with different porosity

Effect of permeability

The permeability of oil shale is a crucial factor, which determines the direction and range of fluid transport. On the basis of the original model, the permeability was changed to 1/3, 1/10, 1/100, and 2 times of the original permeability for simulation and comparison.

The observations in fig. 4 suggests that following the reduction in permeability, all parameters experience significant diminution due to the deceleration of fluid-flow in the reservoir, leading to an inadequate pyrolysis effect. Furthermore, if the formation permeability is reduced to one-tenth of the normal state, the variation in each index is less than 5% compared to the one-third level. Similarly, with the formation permeability at one-hundredth of the normal state, the change in each index is less than 2% compared to the one-tenth level. These findings indicate that when the permeability is low, the range of permeability variation exerts minimal influence on the pyrolysis effect. Additionally, a comparison with the index changes when the permeability is twice the original value reveals a higher change amplitude for the altered permeability relative to the original permeability.

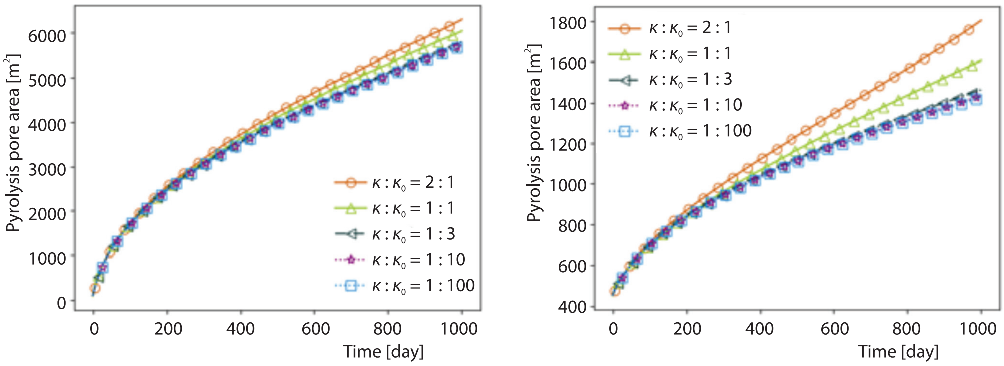

Figure 4. Comparison of pyrolysis pore area and pyrolysis spread area with different permeability

Conclusion

In this paper, the pyrolysis process of in-situ exploitation of oil shale by supercritical CO_2 fluid was studied, the influence of reservoir porosity and permeability with temperature was taken into account, a heat-fluid-solid coupling calculation model was established, and the influence of formation properties on the effect of oil shale was studied. Porosity has little influence on the pyrolysis sweep, but it is directly related to the heated pore area. Therefore, strata with higher final value of porosity change with temperature can have better pyrolysis effect. When the permeability is reduced to a certain value, the further reduction of permeability has little effect on the pyrolysis of oil shale, so the formation with high initial permeability should be chosen as far as possible for pyrolysis.

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Nomenclature

c_p – specific heat, [Jkg^{-1}K^{-1}]
k – permeability, [m^3]
X_f – compressibility, [Pa^{-1}]

Greek symbols

μ – the viscosity of the fluid
ρ_0 – represents fluid density, [kgm^{-3}]
ρ_s – represents the density of the fluid, [gcm^{-3}]
ϕ_0 – porosity, [–]

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