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Influence of temperature field on rock and heavy components variation during in-situ combustion process

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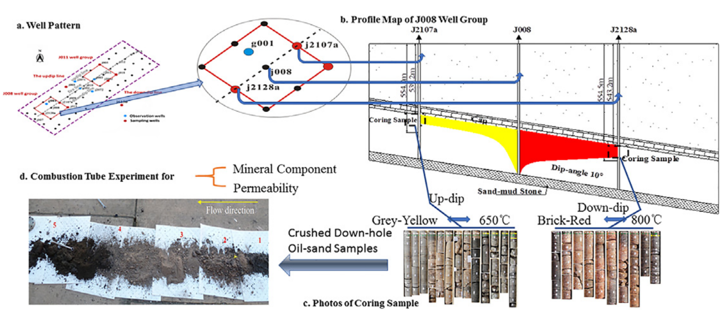
GRAPHICAL ABSTRACT



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ABSTRACT

The temperature field generated during an in-situ combustion (ISC) process sees dramatic variation from 50 °C to over 700 °C. The division of the reservoir into different temperature regions during an ISC process induces different phase state transition and chemical reactions, resulting in serious heterogeneity in oil compositions and reaction products. Combustion tube experiments were conducted to investigate the propagation behavior of combustion front, combined with outlook color observation of down-hole rock samples, permeability measurements (N_2) and organic residual analysis. Fourier transform infrared spectroscopy (FTIR) and gas chromatography–mass spectrometry (GC–MS) were used to characterize the organic materials extracted from the combustion zones. X-ray diffraction (XRD) was employed to investigate the variation of mineral components before and after the ISC process. The results indicated that most of calcite component in the down-hole rock sample was decomposed in combustion front regions within the highest temperature range of 550–650 °C. The color transfer from light grey to brick-red in the outlook color observation demonstrated that an even higher temperature can be achieved. Permeability measurement had shown that secondary diagenetic reaction involving clay triggered a significant permeability reduction during the ISC process. This study demonstrated that variation of oil compositions from different locations of formation can serve as a direct indicator to the occurrence of fire chamber enlargement.

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1. Introduction

In-situ combustion (ISC) is considered as a method with great potential in the development of heavy oil reservoirs especially in the period when steam injection becomes no longer cost-effective. With proper engineering, more field application of ISC projects have been conducted and proven to be successful in recent years, such as Xinjiang and Liaohe oil fields in China. Safety and corrosions problems are also becoming more severe due to high temperature-related chemical reactions near the wellbore, which can be a hindrance to large scale field application of ISC [1]. Hence, the prediction of temperature field distribution is the key issue for operation safety and risk control. For those above consideration factors, a great deal of extra real-time monitoring and testing are necessary during the production process.

As we all know, heavy oils are very complex feedstocks with high viscosity, low API gravity, high asphaltenes, high heteroatom content, and heavy metals content [2,34]. This means that their fractions are even more complex. The oxidation and pyrolysis reactions occurred during in-situ combustion can lead to upgrading of heavy oil, which is beneficial to the downstream refining.

Many researchers believe that the temperature distribution has a close relationship with the variation of rock mineralogy and structure. Lore et al. [2] investigated the influence of temperature on the variation of reservoir characteristics, and the results showed that mud components of rock changes their property with the generation of oxidized haloes when the temperature reached up to 300 °C. The mudstone experiences the transition from cooked mud stone to sintering oxidation when temperature rises from 350 °C to 900 °C. Fractures that can be helpful to the flow of heavy oil then appears when temperature approaches 800 °C. Eichhubl et al. [3] indicated that the phase transformation under high temperature contributed significantly to the formation of large scale fractures during the combustion process. They concluded that the reduction in surface free energy results in the tendency of the porous media to shrink, or to form opening-mode contraction fractures, if constrained by the surrounding formation. Based on the variation of color, bulk density, and hardness, alteration of the reservoir can be classified as unaltered siliceous mudstone, coked mudstone, oxidized and bleached oxidized mudstone, sintered oxidized mudstone, and clinker. Lore et al. [2] also estimated the peak alteration temperature based on the occurrence or disappearance of minerals. They demonstrated that different colors of cores are normally caused by the different mineralogy variations. Unaltered mudstone that is away from combustion zone usually appears in medium to dark grey on fresh surfaces. Oxidized mudstone is formed with a uniform yellowish-orange to orange color due to the pervasive occurrence of hematite. Sintered oxidized mudstone is of uniform reddish-orange color associated with a harder rock texture. Clinker is similar to fired clay brick, formed with the color of dark red to purple and reddish-brown. It is characterized by the instability of illite at the critical temperature of around 870 °C [4].

Due to exothermic oxidation reactions between hydrocarbons and oxygen, the wide region of temperature change inside the reservoir can lead to much different fuel availability at different locations [5]. Other researchers found that oxygen reacts with the solid carbonaceous residues (coke) deposited on the reservoir rock, giving rise to temperatures of up to 700 °C [6]. Most investigations into compositional changes associated with in-situ combustion are focused on laboratory-scale experiments or examination of core samples [7–12].

For the variation of rock permeability during the ISC, however, there is little literature reports. This work conducts a series of investigations on the influence of ISC on the change of rock mineralogy, core's permeability, and the evolution of organic functional groups.

Fourier transform infrared (FTIR) spectroscopy possesses the advantages of fast scanning speed, simultaneous determination of all frequency information with high resolution, good sensitivity and high accuracy during the scanning period. Therefore it can provide reliable information of chemical composition on the aliphatic and aromatic compounds [13,22]. Fourier transform infrared (FTIR) spectroscopy is also widely used in the study of petroleum and rock mineral [13,39], for which it is especially suited for the analysis of functional groups in the complex mixtures.

Permanyer et al. [13,14] analyzed the properties of six crude oil samples which belonged to different stages of exploitation using FTIR spectroscopy. They identified oil samples from different reservoirs and made an evaluation of reservoir compartmentalization based on the FTIR results. It is worth mentioning that they regarded FTIR as a good alternative and complementation tool to the GC method but failed to combine the two technologies in their work. Aleksandrov et al. [15] characterized the differences in functional groups by SARA fractions during ISC process using FTIR spectroscopy. Furthermore, they investigated the reason for the decrease in viscosity of upgraded oil and the variation in SARA fractions. Xu Qianghui et al. [16] compared the FTIR spectra of the LTO coke with that of the pyrolysis coke, and analyzed the chemical functionality characteristics in the LTO coke. Kang Jimoon et al. [17] compared the FTIR spectra between the maltene component of raw material and that from the upgraded product in order to check the effect of the scMeOH upgrading. They found from the spectra that scMeOH had participated in the upgrading of crude oil and enhanced the formation of esters. Niu Zhiyuan et al. [18] explained the evolution of the main functional groups in coal structure during pyrolysis and also discussed the kinetic characterization of pyrolysis of bituminous coal through FTIR spectroscopy. Notably, the FTIR spectra under different temperature were compared in order to contrast any obvious distinction in the type and intensity of the functional groups.

There is still a lack of research on the comparative analysis of down-hole drilling samples from different layers using FTIR directly. Therefore, the functional groups and related substances in the formation were determined by the type of bond, while the relative contents in different layers were analyzed by the variation of absorption intensity.

GC–MS, which is especially suitable for the analysis of complex organic substances like petroleum, is an effective analysis tool that enables qualitative and fast and is able to separate and analyze samples simultaneously. There are some research concerning the property variation before and after the upgrading of crude oil using gas chromatograph-mass spectroscopy (GC–MS) [19–21]. Chen Yanling et al. [19] employed GC–MS assisted with elemental analysis to investigate the variation of saturated hydrocarbons, aromatic and non-hydrocarbons in the oil, gas and water phases before and after catalytic aquathermolysis, through which the mechanism of viscosity reduction was explained. The comparison of spectrum is an unambiguous way to display the change of crude oil. Li Chen et al. [20] studied the viscosity evolution of heavy oil by peroxide oxidation and successive thermal pyrolysis. The combination of FTIR and GC–MS was conducted to ascertain the structure of the carboxylic acids and the mechanism of the heavy oil viscosity evolution. Their research indicated that the coupling technique was an effective way to characterize the compounds structure. Ian M. Head et al. [21] analyzed the variation of saturated hydrocarbon content in crude oil extracted from different depths of core samples by the means of GC–MS so as to indicate that the biodegradation intensified with depth. The spectrum was displayed in a stacking sequence to emphasize the influence of depth. In conclusion, GC–MS is an appropriate way to investigate the upgrading of crude oil during ISC process.

In this paper, the GC–MS spectra of down-hole drilling samples at different depths were compared and the composition changes in crude oil at different depths were evaluated by the absorption intensity and peak number, which corresponded to the effect of the temperature field on the crude oil. The results of GC–MS and FTIR had a good consistency, which verified the analysis of influence of dip angle on the ISC process.

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