Characterization of Combustion Zones in the Process of Heavy Oil Fireflooding

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Abstract

The self-designed combustion tube and the scaled physical mode were used to carry out the experiments to study the profiles of temperature, temperature and oil saturation in the process of combustion front propagation in Liaohe heavy oil reservoir. The burnt zone, combustion zone, coked zone and oil zone were observed in the combustion tube. In the coked zone of the combustion tube 5%～15% oil was deposited on the sands. The major pressure drop took place in the zones with high oil saturation as the consequence of the low gas permeability. In the scaled model runs the steam plateau zone and hot water zone were identified ahead of the combustion front. The oil sands in the main combustion zone was swept completely. After combustion in the high temperature zones the unburnt oil formed condensed coke-like materials on the rock.

Keywords

In situ combustion; heavy oil; Laboratory; Combustion zones; High temperature.

1. Introduction

In situ combustion (ISC) involves the injection of air, enriched air or oxygen to enable combustion of oil within the reservoir formation, creating chemical reactions and the release of gases. Heat ahead of the combustion front reduces oil viscosity and some in situ distillation or upgrading occurs, thus oil recovery is enhanced and the quality of the produced oil is improved[1]. Numerous combustion projects were undertaken in the US, Russia and Venezuela[2-4]. A good many of these projects were economically successful, while others failed for various reasons including unfavorable reservoir and fluid characteristics, poor engineering and operational problem. In general, most failed pilots were small experimental projects implemented in poor prospects by unknowledgeable operators that compounded odds against success.

In China the pilot in situ combustion projects are being undertaken in Liaohe Oilfield. There are many problems to be managed due to lack of the accurate and intuitive understanding of the combustion process, such as how to evaluate the combustion status and control the combustion front, etc.[5-7] In this paper the self-designed combustion tube and the scaled physical mode were used to carry out the experiments to study the profiles of temperature, temperature and oil saturation in the process of combustion front propagation in Liaohe heavy oil reservoir. The combustion zones were identified in order for better understanding the in-situ combustion process[8].

2. Experimental Section

2.1 Equipment.

A combustion tube and a scaled physical model were used to conduct the laboratory studies[9]. The combustion tube (in a horizontal position) was designed with the necessary heating devices, center and thermocouples, adiabatic control system, air flow rate control system, data acquisition system and gas-sampling and analysis equipment. The dimension of the tube is 42 cm long × 9 cm wide × 3.6 cm high, with 39 thermocouples (3 × 13) to measure the temperature variation and 5 pressure sensors to record the pressure change. Each thermocouple was 3.2cm away from any adjacent one. The first pressure sensor was located at 14cm from the starting point and the rest were evenly distributed with space of 7cm from each other until at end. The schematic diagram of the combustion tube apparatus is shown in Figure 1.

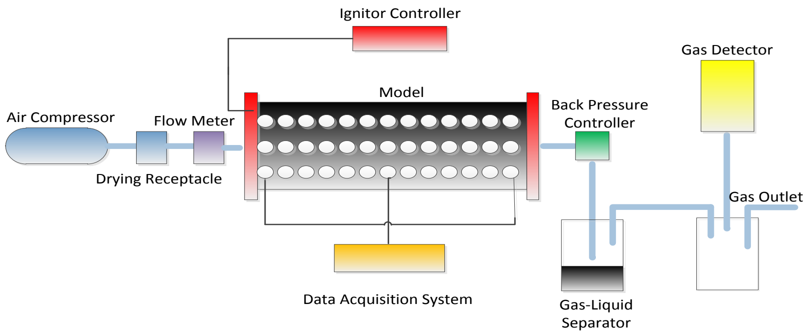

Figure 1. Schematic flow diagram of the combustion tube system

The scaled physical model used for the experiments were rectangular boxes packed with oil sands with the flexibility of adjusting the thickness of cap rock (cement) and changing the layout of thermocouples. Data acquisition system was set up to record temperature, pressure, analyze oil/gas sample composition pre/post ISC, and monitor the combustion state during ISC. The experimental system is shown in Figure 2.

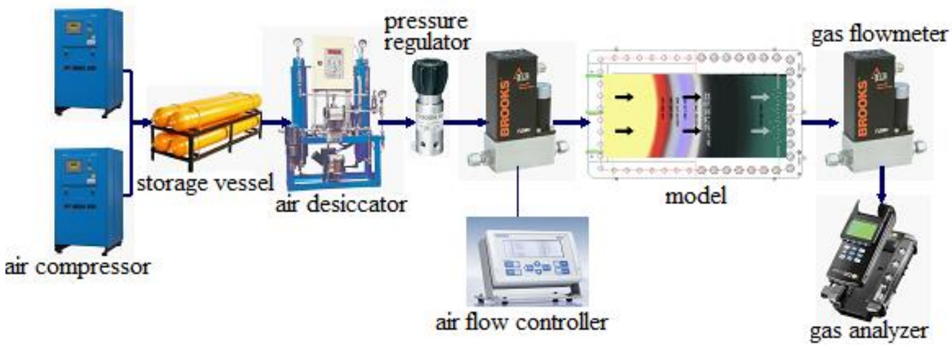

Figure 2. The scaled physical experimental system of ISC

The scaled physical model dimension is 50cm×50cm×4cm, as is shown in Figure 3. One air injector and three oil producers were located in the model to simulate the 1/4 of nine inverted nine-spot injection pattern which is the most common well pattern within Liaohe Oilfield. 2 pressure sensors (PMP) and 169 thermocouples(TMP) were located in the model for monitoring pressure and temperature during ISC. The temperature profile of the model at any given time in the combustion process can be determined through interpolation and inversion. Based on the temperature profile the combustion front propagation can be visualized.

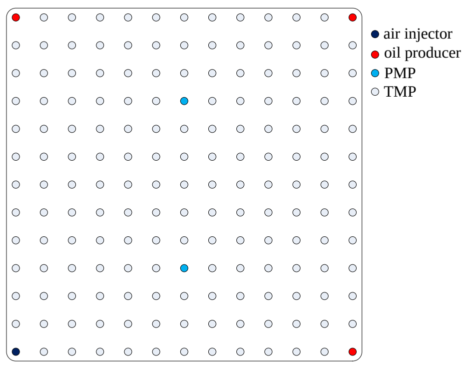

Figure 3. The layout of injector, producers, PMPs and TMPs in the physical model

2.2 Procedure.

The crude oil samples were obtained from Liaohe Oilfield. The oil S.G(20℃) is 0.983 and the viscosity(50℃) is 8670 mPa·s. The combustion tube and scaled model were packed with the quartz, which can represent the characteristics of the reservoir in Liaohe Oilfield. The heavy crude oils from the candidate wells were mixed with quartz to get oil sands with same oil saturation.

In order for the gases to be produced without blockage, nitrogen gas was injected prior to ignition to establish the connectivity to the producer. During nitrogen gas injection, the temperature was elevated to the specific initial temperature to simulate the reservoir condition. The combustion process is composed of air injection, ignition, combustion front propagation, shut-down of wells with fire breakthrough, shut-down of air injection and continuous data acquisition.

3. Results and Discussion

3.1 Characterization of combustion tube.

In order to illustrate the pressure drop at different pressure sensors during the combustion process, the pressure drop ratio is defined as

$$\gamma_i = \left(\Delta P_i / \sum_{i=1}^{n} \Delta P_i \right) \times 100\%$$

Where ΔP_i is the actual pressure drop at pressure sensor i, and n=5.

A total of two runs of combustion tube were conducted. The first run had a complete combustion till fire breakthrough. Figure 4 gives the temperature distribution and the pressure drop ratio along the axial direction of the tube when the combustion front propagated. In Figure 4 the starting point is where the air was injected and the end is where the oil was produced. The temperature peak approximately represents the area where the combustion front is propagating.

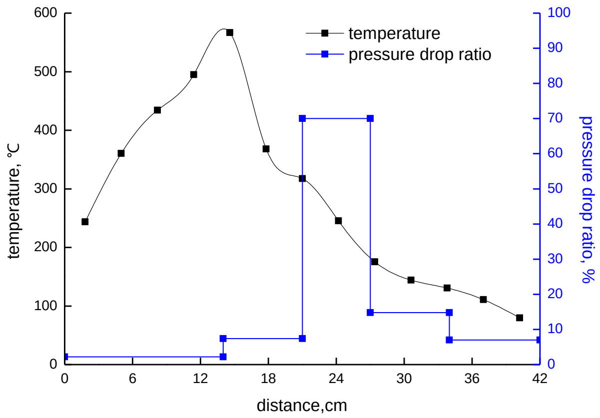

Figure 4. The temperature profile and the pressure drop ratio along the axial direction of the tube

As is shown in Figure 4, the pressure drop was negligible in the burnt region where the fluids were completely swept and burnt and the relative gas permeability was close to 1.0. There was also no pressure drop at combustion front and the nearby high temperature area ahead of it due to the low liquid saturation and high gas permeability. The pressure drop primarily occurred in the region 10-20cm ahead of the combustion zone. The primary pressure drop took place at the oil bank where high oil saturation is expected, resulting in the high gas flow resistance and low gas permeability.

During the second run the fire was distinguished by nitrogen gas in the process of combustion when the oil was ignited and propagated for 180mins. The combustion tube was broken out and the observation is given in Figure 5.

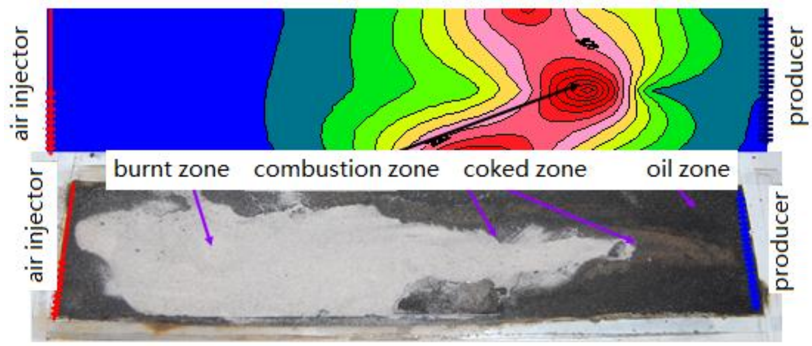

Figure 5. The combustion zones during the second combustion tube run.

In combination of Figure 4 and Figure 5, we can see that the zone adjacent to the air injector is the burnt zone where the combustion had already taken place. The color of the burnt zone is white representing that the oil saturation is close to 0. Because of the continuous influx of air, the temperature in the burnt zone increases from formation temperature near the injector to near combustion temperature in the vicinity of combustion zone. Immediately ahead of the burnt zone is the combustion zone where reaction between oxygen and fuel takes place generating heat. The combustion zone is a very narrow region where burning takes place to produce primarily water and combustion gases.

The fuel is predominantly coke, which is formed in the thermal cracking zone just ahead of the combustion zone. Figure 6 shows scanning electron microscopy(SEM) of the deposited oil sand. The coke-like materials deposited on the sands and filled the porosity resulting in reduction in permeability, which is the primary reason for the increase in pressure drop ratio. In the region around 5%～15% oil was deposited post combustion.

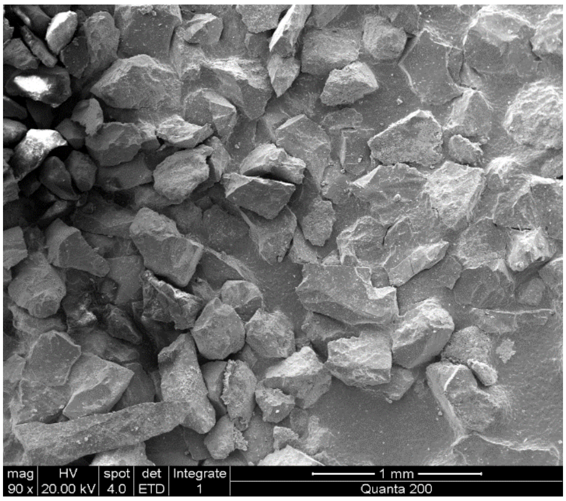

Figure 6. Deposited oil sands by SEM

Adjacent to the cracking zone is the condensation zone, downstream of which the water bank and oil bank were formed. As is concluded, the overall fluid transport mechanism in a combustion process is a highly complex sequence of gas drive (combustion gases), water drive (re-condensed formation water and water of combustion), steam drive, miscible gas and solvent drive.

3.2 Characterization of scaled physical model.

Figure 7 shows the combustion front propagation in the scaled model at different periods of the combustion (30min, 60min, 180min and 270min). The basic temperature data were obtained from the 169 thermocouples and the temperature profile was determined by interpolation and inversion. The data at the location of the thermocouples were accurate and numerically developed data were approximately indicating the actual temperature distribution during combustion process. In the laboratory the producer was shut down when the produced fluids above 300℃ or the oxygen gas percentage more than 10%, but leaving the rest of the wells to produce until the final fire breakthroughs.

The oil around the ignitor was ignited first and temperature reached the peak of 700℃ but lasted only a few minutes, then dropped to 400℃ approximately. The temperature was recorded more than 500℃ in the center of the model with the combustion front propagation and the heat expansion. At the later stage of the combustion, a big high temperature zone (most likely the steam plateau) was formed near the combustion zone. At the leading edge of the steam plateau where the temperature is lower than the condensation temperature of steam, a hot water bank is formed driving the oil bank moving forward.

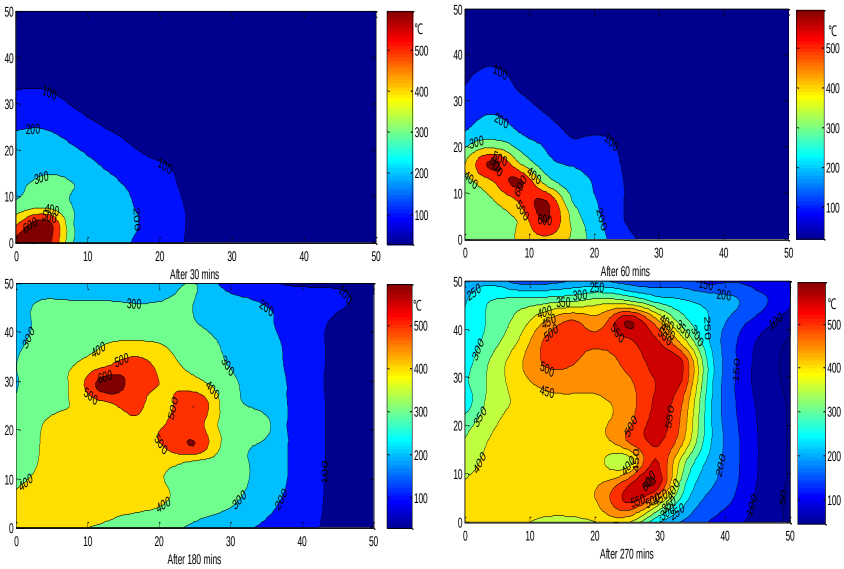

Figure 7. The combustion front propagation in the scaled model

In the process of the experiment, the significant observations were that the combustion front advanced to the production wells in relation to the air flow, and the fire could sweep any part in the model where the air could flow through. The direction of the combustion front propagation was more likely towards nearby short-distance wells rather than the farthest well at the corner. The combustion front propagation could be controlled in order for the better sweep efficiency by optimizing the operational parameters when required.

4. Conclusion

Combustion tube and scaled physical model combustion runs were conducted to characterize the combustion zones during Liaohe heavy oil fireflooding.

The burnt zone, combustion zone, coked zone and oil zone can be clearly observed in the combustion tube run. In the coked zone 5%～15% oil was deposited on the sands as the fuel to support combustion. The pressure drop was negligible in the burnt zone and combustion zone. The major pressure drop took place at the area with high oil saturation as the consequence of the low gas permeability.

In the scaled model runs the steam plateau zone and hot water zone were identified ahead of the combustion front. The oil sands in the main combustion zone was swept completely. After combustion in the high temperature zones the unburnt oil formed condensed coke-like materials on the rock.

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