Hindawi
Geofluids
Volume 2021, Article ID 8153583, 12 pages
https://doi.org/10.1155/2021/8153583

Research Article

In-situ Combustion Simulation from Laboratory to Field Scale

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Received 28 April 2021; Accepted 11 August 2021; Published 14 December 2021

Academic Editor: Qiqing Wang

In-situ combustion simulation from laboratory to field scale has always been challenging, due to difficulties in deciding the reaction model and Arrhenius kinetics parameters, together with erroneous results observed in simulations when using large-sized grid blocks. We present a workflow of successful simulation of heavy oil in-situ combustion process from laboratory to field scale. We choose the ongoing PetroChina Liaohe D block in-situ combustion project as a case of study. First, we conduct kinetic cell (ramped temperature oxidation) experiments, establish a suitable kinetic reaction model, and perform corresponding history match to obtain Arrhenius kinetics parameters. Second, combustion tube experiments are conducted and history matched to further determine other simulation parameters and to determine the fuel amount per unit reservoir volume. Third, we upscale the Arrhenius kinetics to the upscaled reaction model for field-scale simulations. The upscaled reaction model shows consistent results with different grid sizes. Finally, field-scale simulation forecast is conducted for the D block in-situ combustion process using computationally affordable grid sizes. In conclusion, this work demonstrates the practical workflow for predictive simulation of in-situ combustion from laboratory to field scale for a major project in China.

1. Introduction

In-situ combustion (ISC) is an enhanced oil recovery (EOR) method in which air is injected into a reservoir to burn small amount of the crude oil to generate heat, thus, driving the remaining oil towards the producers [1–3]. ISC is a thermal EOR method which involves many complex chemical reactions in the thin reaction zone usually several inches thick. The industry still demands a comprehensive workflow from laboratory history match of experiments all the way to field-scale simulation for the ISC process [4]. Major challenges include the determination of crude oil combustion reaction model and the corresponding kinetics parameters, as well as minimizing the numerical error of grid size effect when using large grid blocks in field-scale simulation.

Crude oil, as a complex multi-component mixture, exhibits complicated combustion reactions during the ISC process coupled with phase behavior and multiphase flow. Kinetic cell (Ramped Temperature Oxidation (RTO)) and combustion tube laboratory experiments are usually conducted to test crude oil reaction kinetics and displacement behavior, respectively [1–3]. This leads to the necessity of proposing "pseudo" reaction model for the crude oil and corresponding reaction kinetic parameters that determine the crude oil combustion behavior. Various reaction models have been developed with different levels of complexity to represent the low temperature and high-temperature oxidation reactions [5–7]. In recent years, the isoconversional method has been applied for the analysis of crude oil kinetic parameters [8]. The value of the apparent activation energy apparent Ea can be obtained under the premise of not introducing the specific reaction model. After building the kinetic reaction model, thermal reservoir simulation may be used to match the kinetic cell (RTO) and combustion tube experiments [7].

The simulation of the ISC process at field scale brings additional challenges, because the reaction front is narrow and centimeter-sized grid block is needed to accurately capture the kinetics. Serious grid size effect and numerical error are observed, mainly because the mass and energy conservation equations in commercial thermal reservoir simulator are solved with the Arrhenius kinetic reaction terms calculated using the average grid block properties that result in poor spatial and temporal resolution of the reaction front. This often leads to an excessive amount of fuel consumed, reaction zone temperature being too high and slower movement of the reaction front, when large-sized grid blocks are used in field-scale simulations. Different empirical approaches have been used to mitigate this problem in the past, for example, having the activation energy and the grid block temperature values adjusted in the kinetics calculations [9, 10]. The numerical method of dynamic gridding (adaptive mesh refinement) has been implemented to improve the simulation problem of the narrow reaction zone in ISC processes with a certain degree of success [11–13]. The simulations, however, still experience difficulty in coarsening up the grid blocks all the way from centimeter scale to meter scale. The time step sizes are still very much limited, even with perfect dynamic gridding implementation, since the chemical reactions take place in a very fast speed. The use of dynamic gridding still has not fully solved the demanding grid size problem in field-scale ISC simulations. In recent years, a novel reaction upscaling method has been proposed in order to minimize the grid size effect in field-scale ISC simulations [14, 15]. Both the temporal and spatial scales of kinetics and advection are very different in the ISC process. The important dimensionless parameter that characterizes this difference is the Damkohler number (Da), which represents the ratio of characteristic time and length scale of the fluid flow to those of the kinetic reactions. In field-scale ISC, Da number is usually about 10^7, which makes ISC truly a multiscale process. To alleviate this scaling problem, a grid-insensitive upscaled reaction model is implemented. The concept is based on calibrating the equivalent fuel amount consumed when the combustion front sweeps a unit reservoir volume. In this way, field-scale simulations can be conducted with reasonable computational costs. The speed and temperature of the combustion front are tracked accurately in the upscaled reaction model. In the current implementation of the upscaled reaction model, a constant fuel amount is assumed, which is exactly the theoretical foundation for the classical Gates and Ramey analytical solution for the ISC process [1, 16]. This assumption may be relaxed, i.e., making the value different in different parts of the reservoir according to its local conditions (rock types or oil properties for example). A reservoir history match study for the Suplacu ISC project in Romania was conducted based on this reaction upscaling methodology [17].

Currently, two major commercial heavy oil ISC projects are operated in China, Hongqian block in PetroChina's Xinjiang Oilfield and D block in PetroChina's Liaohe Oilfield [18–21]. In this study, we choose D block as the case of study to show the simulation of the ISC process from laboratory to field scale. Based on the methodology proposed in our previous work [4, 14, 15], we present a comprehensive case study on the simulation of heavy oil in-situ combustion from laboratory experiment to field-scale simulation. It includes kinetic cell (RTO) and combustion tube laboratory experiments, establishing kinetic reaction model, history match of experiments, and finally field-scale simulation using the proposed upscaled reaction model. We have demonstrated the proper choosing of reaction model to fully capture the low/high-temperature oxidation reactions and the effectiveness of the upscaled reaction model in field-scale simulations. This work provides a practical guideline for the predictive numerical simulation and process design for ISC.

2. D Block In-situ Combustion Field Description

The D block in Liaohe Oilfield is a multilayered heavy oil reservoir which has been developed since 1986 [20]. The reservoir shows monocline geologic structure, dipping from northwest to south east with a dip angle of 5^o~10^o. The depositional environment is fan deltaic. The area of the reservoir is 8.4 km^2, with original oil in place (OOIP) being more than 5000×10^4 ton. The depth of the reservoir ranges from 800 m to 1300 m. The lithology of the reservoir is poorly consolidated sandstone, together with conglomerates. The porosity of the reservoir is more than 0.25, with average permeability being 800 mD. The average net pay is 50 m. The reservoir typically has more than 10 layers with interbedded shales, which makes the typical per layer pay thickness being around 5 m. The density of the crude is about 0.93 g/cm^3. The dead oil viscosity is 300~2000 cp at 50°C temperature.

The D block is initially developed using vertical well cyclic steam stimulation (CSS). The recovery performance is poor before 2005, with quick pressure decline, low oil production rate, and high steam oil ratio (SOR). The expected recovery factor for CSS is about 27%. Over the years, the average reservoir pressure has dropped from the original value of 11.0 MPa down to the current value of 1.5 MPa. In-situ combustion has been chosen as the follow-up process for increasing recovery and improving project economics for this multilayered heavy oil reservoir. As a result, in-situ combustion pilot has been started through conversion to inverted nine-spot well patterns. More than 90 inverted nine-spot ISC well patterns have been formed for air injection, with the remaining well patterns still under CSS production. Figure 1 shows the in-situ combustion well patterns of D block in Liaohe Oilfield.

3. Characterization of Reaction Kinetics

3.1. Kinetic Cell (RTO) Experiment. Laboratory measurements of the parameters for crude oil reaction kinetics are the base of the overall effort. The kinetic cell mainly examines the combustion reaction kinetics of the crude. The principles and specific details of the device are fully explained in other references [1, 8]. In this study, the inner diameter of the kinetic cell is 2 cm and the length is 10 cm. We use crushed virgin state core as test samples to making the kinetic cell experiment as close to the actual reaction kinetics

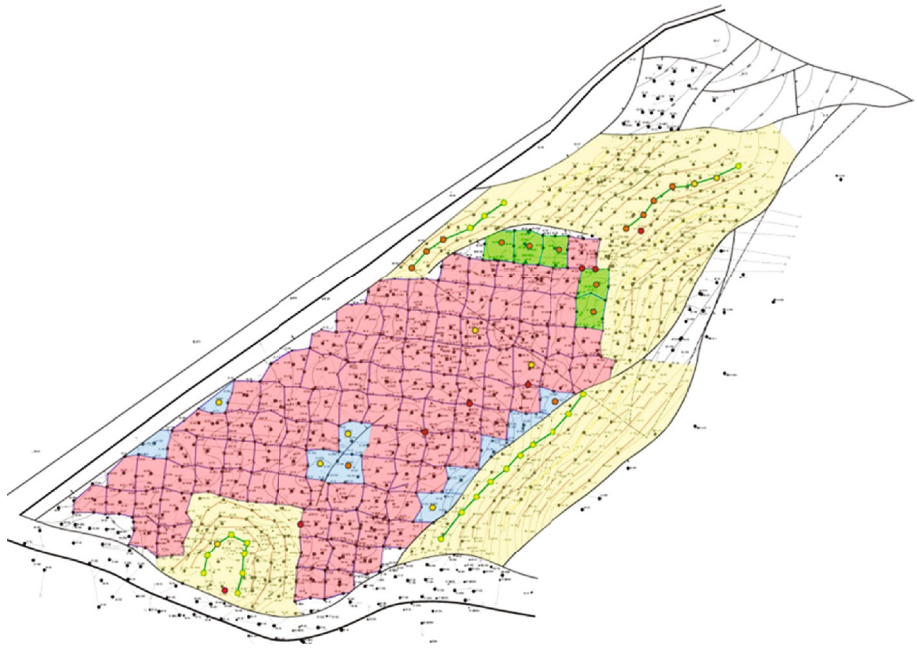

Figure 1: Inverted nine-spot well patterns of D block in Liaohe Oilfield, with red colour showing the area for ISC implementation and yellow colour showing the area for CSS implementation.

in the reservoir condition as possible. The kinetic cell is programmed for linear heating over time, with temperature recorded continuously. During the experiment, the back pressure is maintained at 2 MPa through the back pressure valve, and gas injection rate controlled at 2 L/min. The composition of the effluent gas generated is continuously monitored and recorded by a gas analyzer. In order to obtain consistent and reliable results, five sets of kinetic cell tests with different heating rates are conducted for Liaohe D block oil, while keeping all the other conditions the same. The experimental results are shown in Figures 2 and 3.

Under high-temperature oxidation (HTO) conditions, fuel and oxygen combust to generate H_2O and carbon oxides. The stoichiometric equation for the generic HTO reaction can be described as follows [1]:

$$CH_n + \left(\frac{m+2}{2m+2} + \frac{n}{2}\right)O_2 \longrightarrow \left(\frac{m}{m+1}\right)CO + \left(\frac{1}{m+1}\right)CO_2 + \frac{n}{2}H_2O, \quad (1)$$

where n represents the hydrogen to carbon (H/C) atom ratio, m represents the CO to CO_2 ratio. The values of m and n can be calculated using the component concentrations in the effluent gas, together with the oxygen concentration in the injected gas.

Equation (1) is an expression for high-temperature combustion process. The low-temperature oxidation (LTO) of crude oil is partial oxidation process or incomplete combustion. The reaction equation can be modified as follows:

$$C_{1+x}H_{n+y} + \left(\frac{m+2}{2m+2} + \frac{n}{2}\right)O_2 \longrightarrow \left(\frac{m}{m+1}\right)CO + \left(\frac{1}{m+1}\right)CO_2 + \frac{n}{2}H_2O + C_xH_y. \quad (2)$$

In general, for the HTO combustion reaction, the hydrogen to carbon atom ratio n is about 0.5 to 2. Otherwise, if high H/C ratio is interpreted, it indicates that LTO reaction dominates. All five kinetic cell (RTO) experiments for Liaohe D block heavy oil were analyzed using this approach to calculate the H/C ratio (n) and CO/CO_2 ratio (m) values during the LTO and HTO reaction stages, as shown in Table 1. The analysis of D block oil shows typical heavy oil reaction kinetics.

3.2. Building Kinetic Reaction Model. Based on the kinetics characteristics of D block crude, we propose our own four reaction kinetics model, which is an updated modification of the previous three reaction model [7]. The four reactions are oxygen addition reaction (Eq. (3a)), low temperature oxidation (Eq. (3b)), medium temperature oxidation (Eq. (3c)), and high temperature oxidation (Eq. (3d)). Compared with the original three reaction model, it considers additional oxidation reaction in the medium temperature range, which is a better characterization for the D block oil. As temperature rises and the crude combusts with oxygen, these four reactions take place in sequence. The crude oil is represented by a nonvolatile pseudocomponent, which is a good approximation for D block oil after the average reservoir pressure declined down to 1.5 MPa. The reaction model generates three intermediate reaction products (solids) for the reactions involved, namely, Coke1 ($C_{2.77}H_4O_{1.53}$) as reactant for low-temperature oxidation, Coke2 ($C_{1.27}HO_{0.83}$) as reactant for high-temperature oxidation, and Coke3 ($C_{0.5}$) as reactant for medium temperature oxidation. Overall, the process of building the reaction kinetics model is carried out mainly according to the following steps:

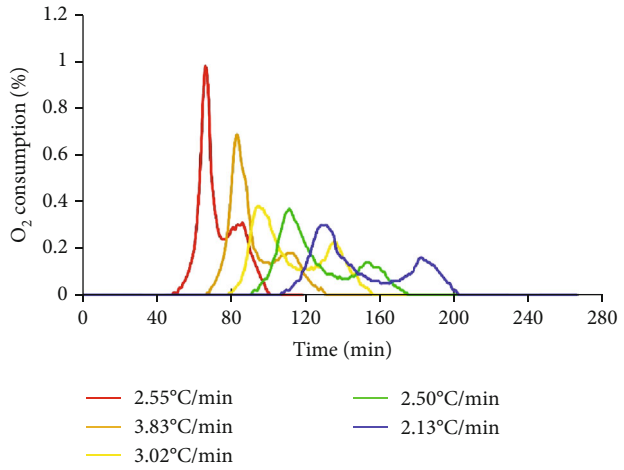

Figure 2: Oxygen consumption for kinetic cell (RTO) experiments with different heating rates.

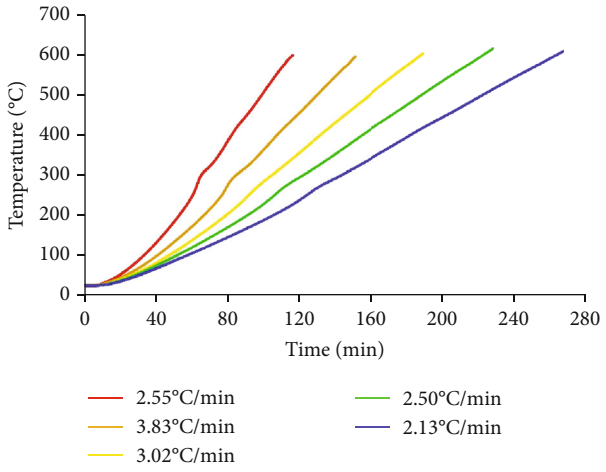

Figure 3: Temperature history for kinetic cell (RTO) experiments with different heating rates.

Table 1: H/C ratio (n) and CO/CO_2 ratio (m) values for the five kinetic cell (RTO) experiments.

	Temperature range [°C]	H/C ratio	CO/CO_2 ratio
Low-temperature oxidation	195–350	3.0–5.3	0.50–1.21
High-temperature oxidation	350–500	0.5–2.0	0.15–0.34

(1) According to the kinetic cell (RTO) effluent gas data, the reaction coefficients for the high-temperature oxidation and medium temperature oxidation reactions are established by Eqs. (1) and (2)

(2) Based on the effluent gas composition of the kinetic cell, the same procedure is applied to the low-temperature oxidation reaction by using the partial oxidation reaction Eq. (2)

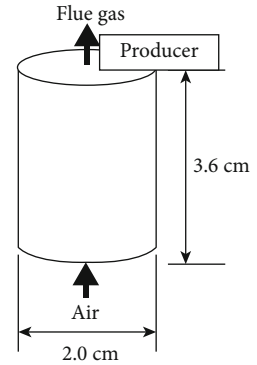

Figure 4: The numerical simulation model for kinetic cell (RTO) experiment.

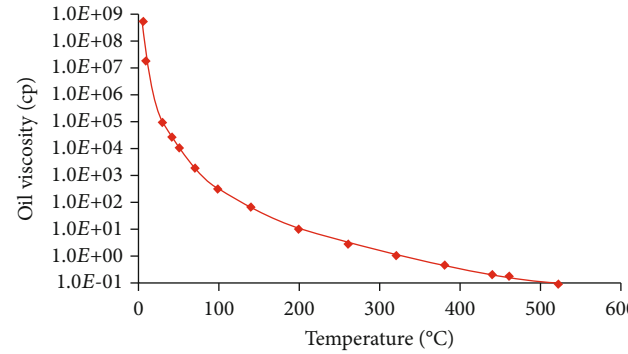

Figure 5: Oil viscosity versus temperature for numerical simulation in this study.

(3) The reaction for oxygen addition is established based on the conservation of mass

Finally, the following reaction model is proposed for D block crude oil, based on kinetic cell (RTO) effluent gas analysis.

$$\text{Oil} + 0.5O_2 \longrightarrow 6\text{Coke1} + 4\text{Coke3} + 7.2H_2O, \quad (3a)$$

$$\text{Coke1} + 1.6O_2 \longrightarrow 0.6CO + 0.9CO_2 + 1.5H_2O + \text{Coke2}, \quad (3b)$$

$$\text{Coke3} + 0.45O_2 \longrightarrow 0.1CO + 0.4CO_2, \quad (3c)$$

$$\text{Coke2} + 1.06O_2 \longrightarrow 0.09CO + 1.18CO_2 + 0.5H_2O. \quad (3d)$$

3.3. Simulation History Match of Kinetic Cell (RTO) Experiment. Numerical simulation models of our kinetic cell (RTO) experiments are established using commercial thermal reservoir simulator CMG STARS, for the purpose of history matching the experimental data. Figure 4 is a schematic diagram of the simulation model based on the actual size of the kinetic cell apparatus. Crude oil is a typical heavy oil with an API gravity of 18, with a density of 945 kg/m^3 of at the standard condition. The heavy oil viscosity versus temperature, relative permeability in our numerical simulation

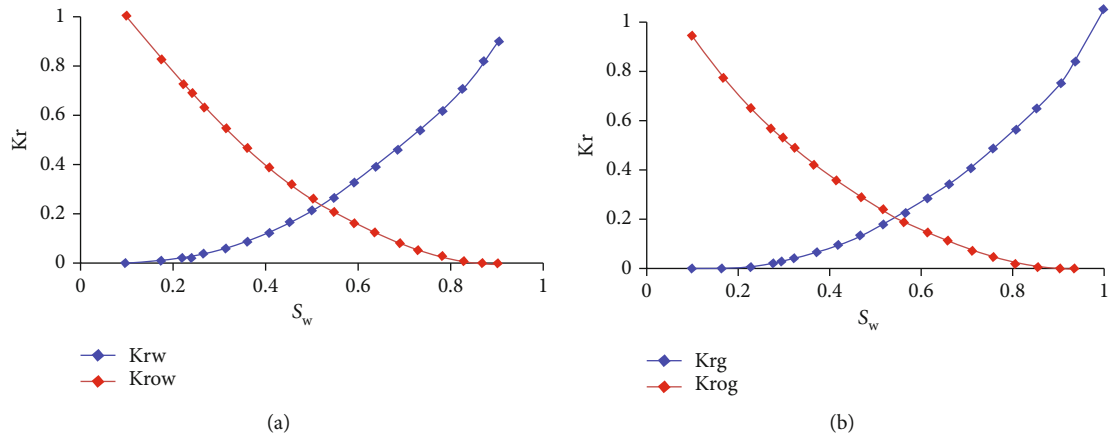

Figure 6: Relative permeability curves used in the simulation study: (a) two-phase water (K_{rw}) and oil (K_{row}) and (b) two-phase gas (K_{rg}) and oil (K_{rog}). Three-phase relative permeability is computed using the Stone 2 relationship.

Table 2: Optimized kinetic parameters through kinetic cell simulation.

	Oxygen addition reaction Eq. (3a)	Low-temperature oxidation Eq. (3b)	Medium-temperature oxidation Eq. (3c)	High-temperature oxidation Eq. (3d)
Activation energy (kJ/mole)	78.0	86.0	120.0	96.0
Preexponential factor (1/kPa-min)	1.06×10^4	7.5×10^5	2×10^7	1×10^4
Enthalpy of reaction (J/kg)	0	3.7×10^7	2.9×10^7	3.9×10^7

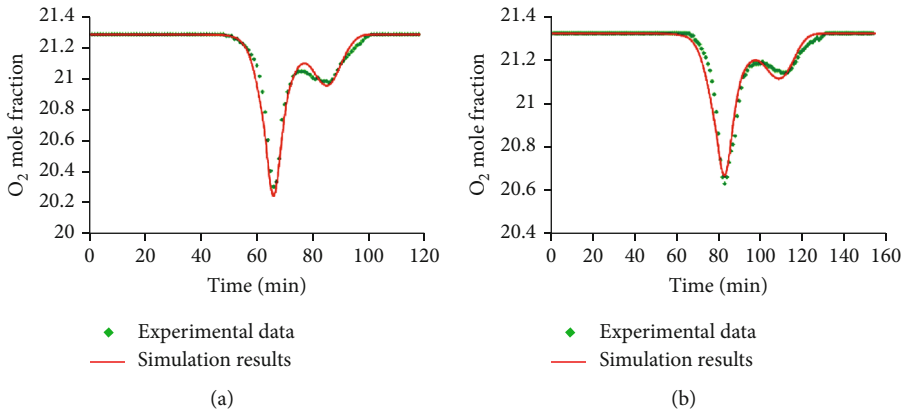

Figure 7: (a) O_2 consumption history match for the kinetic cell (RTO) experiments with heating rates of 5.22°C/min; (b) O_2 consumption history match for the kinetic cell (RTO) experiments with heating rates of 3.22°C/min.

is listed in Figures 5 and 6. Homogeneous permeability (k) of 10 D and porosity (ϕ) of 0.36 is implemented. Typical sandstone rock thermal and compression properties are used. The "Oil" component in Eq. (3a) is a dead oil component, with K-value of zero. The nitrogen, oxygen, carbon dioxide, and carbon dioxide components are treated as noncondensable gas in the simulation. By adjusting the kinetic parameters (mainly activation energies and preexponential factors), we match the effluent gas compositions from the kinetic cell tests. Table 2 shows the finally matched reaction kinetics parameters. Figures 7–9 show the O_2 consumption, CO_2 production, and CO production history match for the kinetic cell (RTO) experiment with heating rates of 5.22°C/min and 3.22°C/min. Overall, the degree of history match is pleasant with relative error being within 5%, which proves the predictability of our reaction kinetics model.

Table 2: Matched results for reaction kinetics parameters.

4. Simulation of 1D In-situ Combustion Displacement Process

4.1. Combustion Tube Experiment. The combustion tube experiment is designed to study one-dimensional (1D) ISC displacement process [1]. Due to limited amount of core samples, synthetic reservoir matrix is made by mixing crude oil, quartz sand, and clay (kaolinite in particular) in

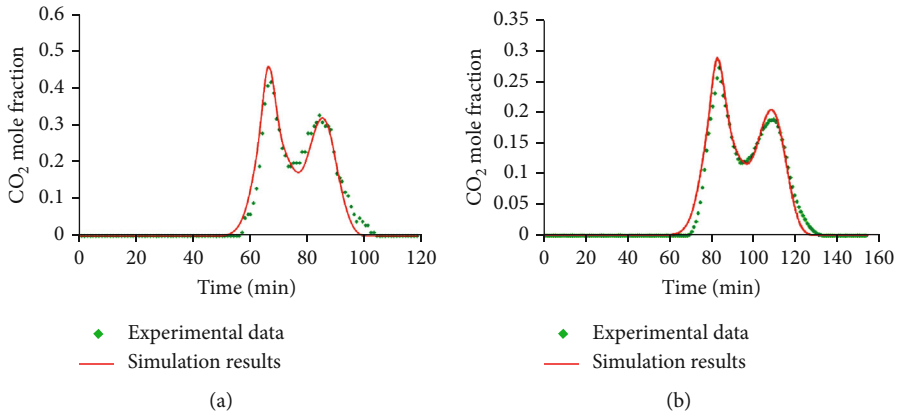

Figure 8: (a) CO_2 production history match for the kinetic cell (RTO) experiments with heating rates of 5.22°C/min; (b) CO_2 production history match for the kinetic cell (RTO) experiments with heating rates of 3.22°C/min.

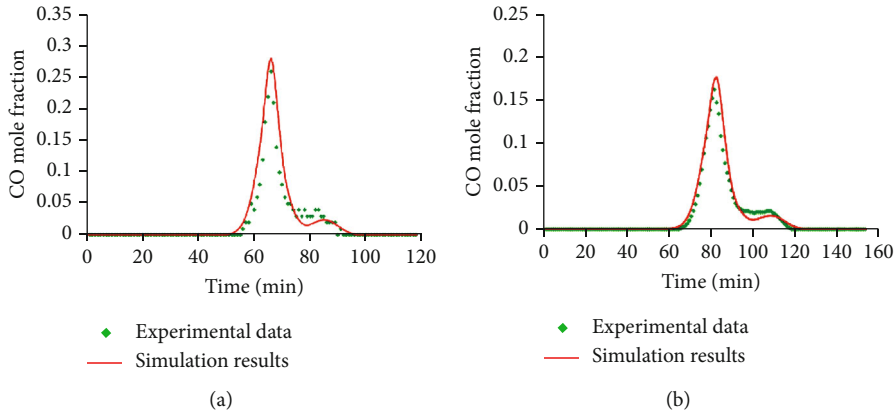

Figure 9: (a) CO production history match for the kinetic cell (RTO) experiments with heating rates of 5.22°C/min; (b) CO production history match for the kinetic cell (RTO) experiments with heating rates of 3.22°C/min.

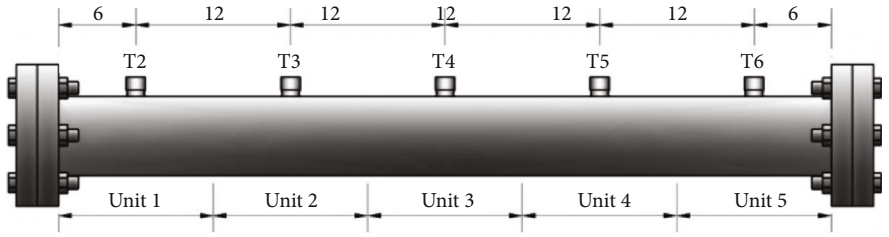

Figure 10: Schematic of the combustion tube for D block tests, with T1 to T5 being the temperature measurement points (12 cm apart).

predetermined proportions. The clay content of the reservoir core is determined using the XRD experiment. The combustion tube with a length of 60 cm and an inner diameter of 3.8 cm is horizontally placed, with air injected from one end and fluid produced from the other end. The schematic of the combustion tube used in this study is shown in Figure 10. The back pressure during the test is controlled at 2 MPa. The temperature along the tube is continuously measured by five thermocouples placed in the center of the tube. Initially, nitrogen is injected with a section of the injection end preheated by electric heater. When the first temperature measurement point reaches 300°C, air is injected at the rate of 3 L/min for ignition. To ensure successful ignition, the electric heater is only turned off when the first temperature point reaches approximately 400°C. Peak temperature indicates the approximate location of the combustion front. The fluid produced during the experiment is collected and metered. The gas analyzer is used to analyze and record the composition of the effluent gas at the outlet. After the combustion tube experiment, the combustion front propagation speed, the fuel amount, and other related parameters are interpreted.

A total of four 1D combustion tube tests were conducted. Figure 11 shows the temperature changes over time for different measurement points in one test. Figure 12 shows the flue gas compositions change over time. It also

shows the change of apparent H/C ratio over time for the flue gas generated from the combustion tube test. In the early stage of the experiment (0 ~ 65 min), the average temperature of the combustion front is low which is about 370°C. The apparent H/C atomic ratio is greater than 3.8, indicating dominance of LTO reactions. During 65~140 min, the apparent H/C atomic ratio is within the range of 1.0 ~ 2.1, showing dominance of HTO reactions. In the combustion tube test, we observe the peak temperature of the combustion tube test for HTO reactions is about 550°C. Table 3 shows some indicators of experimental analysis. During the stable combustion stage, a low air-oil ratio of 1302 kg/m^3 was observed, which means lower air requirement for unit oil production. Overall, the D block crude shows good combustion characteristics.

4.2. Simulation History Match of Combustion Tube Experiment. History match of combustion tube experiment is further conducted. Here, we only focus on the stable combustion front propagation process, because this is more relevant to the actual ISC process in the reservoir. Bypassed oxygen is taken out of consideration for the numerical simulation. History match of the stable combustion front propagation is carried out based on the previously established reaction kinetics model. The simulation model reflects the actual conditions of the combustion tube. The permeability and porosity of the matrix are 10 Darcies and 0.35. The initial oil saturation is 0.5. The 60 cm long tube is discretized into 600 grids with a grid length of 0.1 cm, to ensure the kinetic reactions within the reaction front can be precisely captured with enough accuracy. A grid size sensitivity test is conducted to ensure the convergence of the result with this grid resolution.

The combustion tube simulation results are shown in Figure 13. Figure 14 shows the simulated temperature history at the locations of experimental temperature measurement points along the tube (T1 ~ T5). Figure 15 further shows the flue gas composition history match. The simulation results show good match with the experimental results based on the kinetic model established mainly from kinetic cell (RTO) experiments.

5. Reaction Upscaling for Large-Scale In-situ Combustion Simulation

Upscaling of reaction kinetics for large-scale reservoir simulation is conducted after the successful match of kinetic cell and combustion tube experiments. A key element of this method is the realistic assumption that the fuel consumed per unit reservoir volume in the ISC process is relatively constant (the theoretical basis for classical Gates and Ramey ISC analytical solution), which yields constant speed reaction front propagation in 1D with constant air flux. This is consistent with observations in combustion tube tests. Due to the high Damkohler (Da) number in field-scale ISC process, we assume equilibrium rather than using reactions kinetics in the upscaled reaction model. Detailed derivation of the method can be found in our previous work [14, 15]. One limitation for this method is the assumption that the

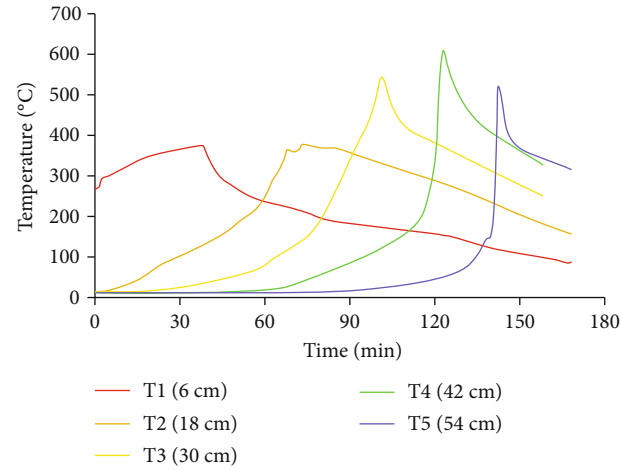

Figure 11: Temperature changes over time for different measurement points in 1D combustion tube test for D block.

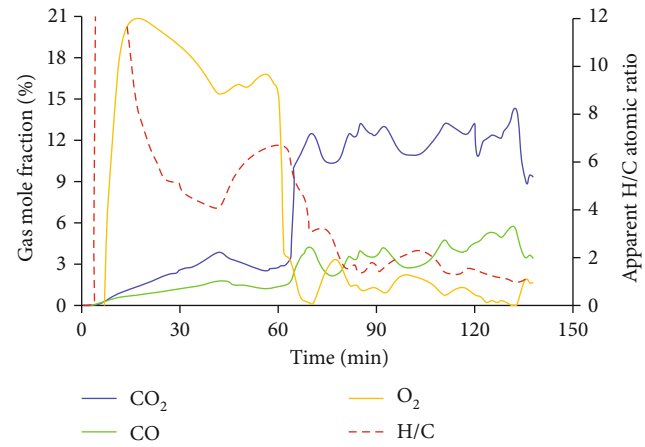

Figure 12: Flue gas composition and apparent H/C atomic ratio changes over time in combustion tube test for D block.

Table 3: The experimental results of the combustion tube under the stable combustion stage.

Fuel amount [kg/m^3]	Air requirement [m^3/m^3]	Air-oil ratio [m^3/m^3]
17.1	205	1302

combustion reaction will maintain in HTO mode, while conversion to LTO mode or extinction do occur if the field operations is not managed properly. Further study in simulating these combustion mode conversions is our ongoing work.

The first step in upscaled reaction method is to calculate the equivalent fuel amount $S_{o,\text{fuel}}$, which is the equivalent oil saturation that is finally converted into fuel for combustion with oxygen. In this case, we calculate $S_{o,\text{fuel}} = 0.13$, based on history matched numerical simulation and material balance analysis from combustion tube experiments. Upscaled reaction model generally works for conditions when initial oil saturation S_{oi} is larger than $S_{o,\text{fuel}}$ to maintain the

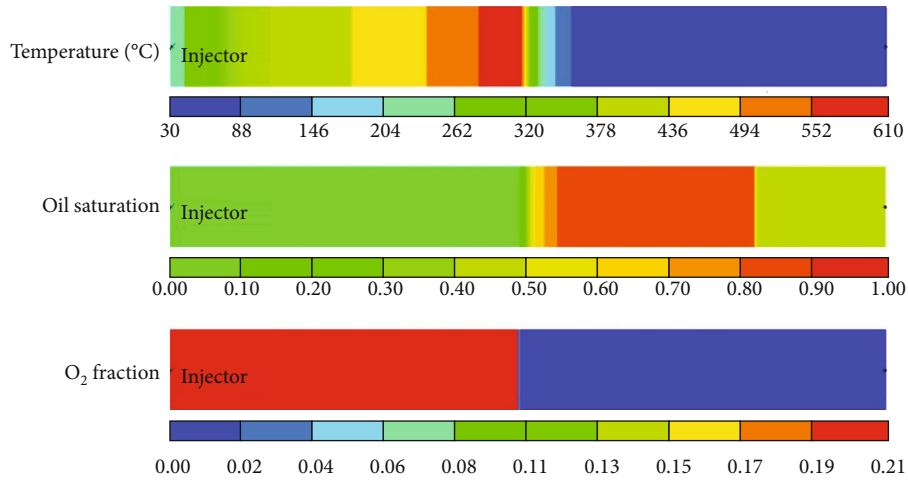

Figure 13: The temperature, oil saturation and O_2 mole fraction in gas phase at the time of 80 min for D block combustion tube numerical simulation (inject from left, produce from right).

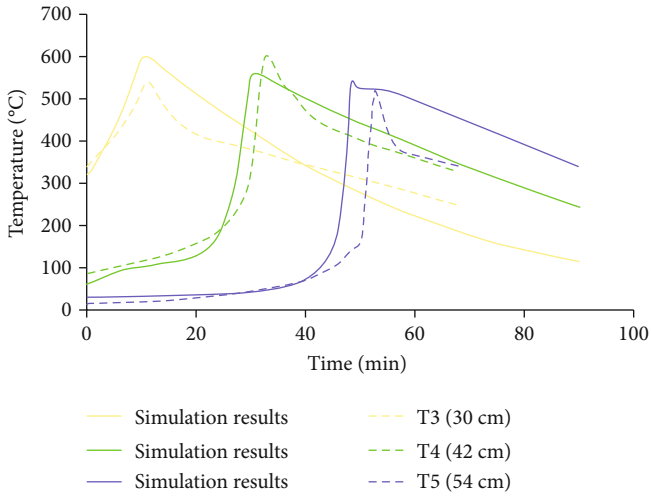

Figure 14: The temperature evolution at the locations of temperature measurement points along the tube (T3 ~ T5) in D block combustion tube numerical simulation.

propagation of the combustion front. In actual implementation, we deposit predetermined equivalent fuel amount in the beginning of simulation. Relative permeability curves need to be modified due to this reduction in oil saturation, so that the flow behavior is the same as before. Equilibrium combustion reactions take place when the injected oxygen encounter the deposited fuel. In this way, the precalibrated equivalent fuel amount is consumed gradually in the simulation. This method is attractive because it minimizes the sensitivity of reaction terms to the grid size, which significantly reduces the numerical error, i.e., the grid size effect.

An example for D block 1D simulation using upscaled reaction model is demonstrated here. The simulated 1D ISC problem is 2.0 m in length. In order to get an accurate and reliable reference solution, 2000 grids with a length of 0.1 cm are implemented in the Arrhenius kinetic-based simulation. Coarse grid simulations using both Arrhenius kinetics and upscaled reaction model with only 20 grid blocks (grid length 10 cm) are compared with the reference result. The upscaled reaction model has an equivalent fuel amount of $S_{o,\text{fuel}} = 0.13$. Figures 16 and 17 show the oil saturation and temperature profiles for 2.0 m length 1D ISC simulation with Arrhenius kinetics and 2000 grids, upscaled reaction model and 20 grids, and Arrhenius kinetics and 20 grids. Comparing the fine grid and coarse grid simulation results, it can be seen that the coarse grid solution computed with Arrhenius kinetics has significant numerical error or grid size effect [14, 15]. The front propagates slower, with excessive amount of coke generated. This also causes the peak temperature to be higher. On the other hand, the result generated using upscaled reaction model has good consistency with the fine-scale reference solution. The peak temperature and combustion front location match the ones in fine grid simulation using Arrhenius kinetics. Overall, the upscaled reaction model makes it possible of using large-sized grid blocks in field-scale ISC simulation.

6. Field-Scale Simulation of D Block In-situ Combustion Process

In order to demonstrate the capability of field scale ISC process simulation, we build a heterogeneous sector model for the D block using Petrel. The heterogeneous reservoir model has 13 layers with the grid system being $55 \times 35 \times 68$. It has a total of 23 vertical CSS wells initially. The model incorporates the corresponding fluid and rock property data for D block. Over and under burden heat loss is calculated assuming the same rock thermal properties as the reservoir. Figure 18 shows the post-CSS temperature and oil saturation distribution for the sector model. This sector model forms the basis for field-scale ISC process predictions, as air injection and ignition started in this part of the field in Oct 2018.

The area of the sector model has been converted to air injection in Oct 2018, with four wells ignited using electrical

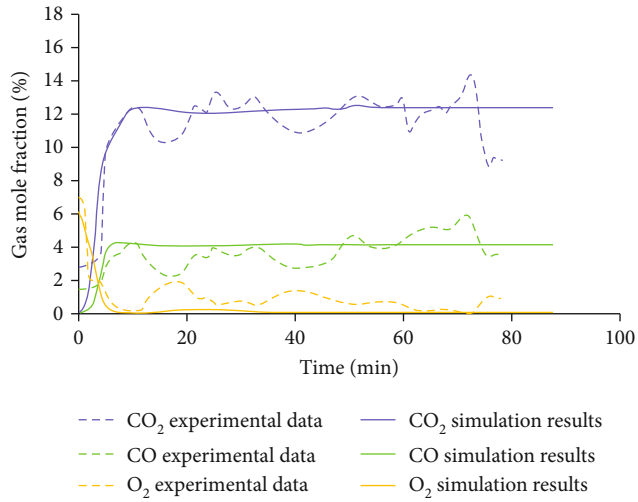

Figure 15: Flue gas composition history match for D block combustion tube numerical simulation.

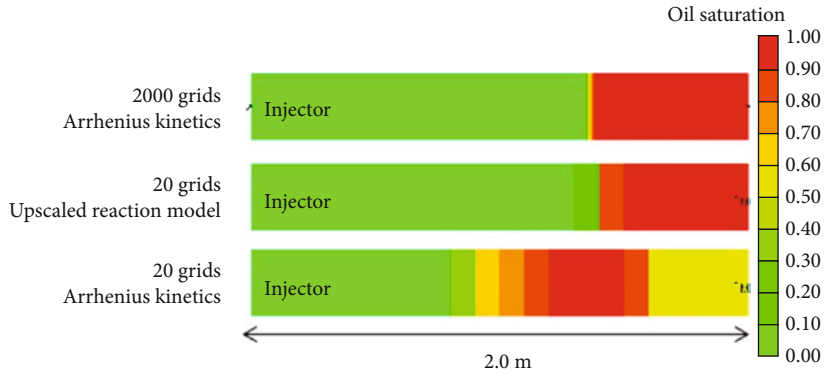

Figure 16: Oil saturation profile for 2.0 m length 1D ISC simulation with Arrhenius kinetics and 2000 grids, upscaled reaction model and 20 grids, and Arrhenius kinetics and 20 grids (inject from left, produce from right).

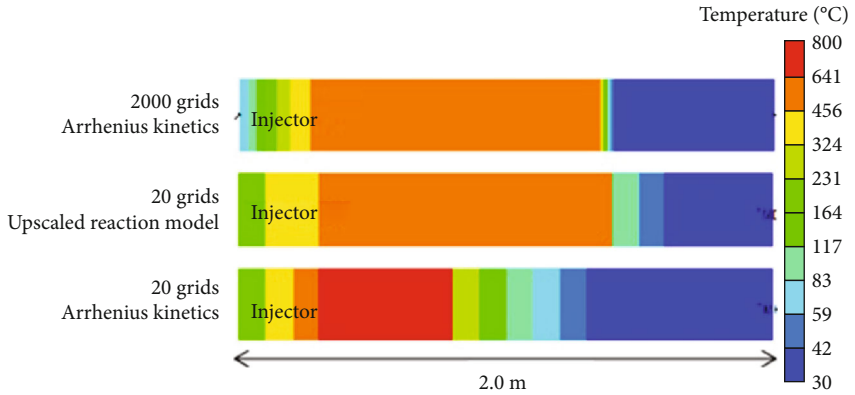

Figure 17: Temperature profile for 2.0 m length 1D ISC simulation with Arrhenius kinetics and 2000 grids, upscaled reaction model and 20 grids, and Arrhenius kinetics and 20 grids (inject from left, produce from right).

heating and converted to air injectors. This forms a line drive configuration to displace the oil towards the offset producers. We implement the upscaled reaction model for field-scale ISC simulation. The reaction model is based on previous kinetic cell test, combustion tube test, and laboratory experiment history matches. Again, the fuel amount is chosen to be the same as the calibrated value from the combustion tube experiment and its simulation. Each injector

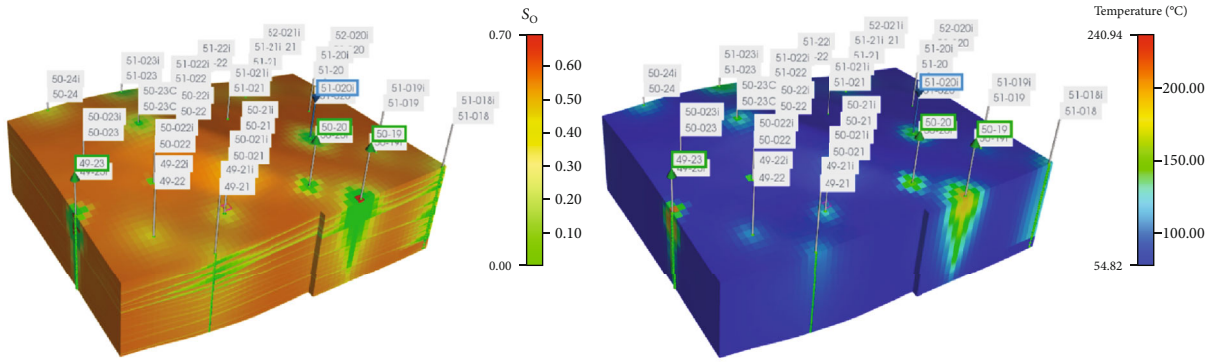

Figure 18: Post-CSS temperature and oil saturation distribution for the D block sector model (2018-10-30).

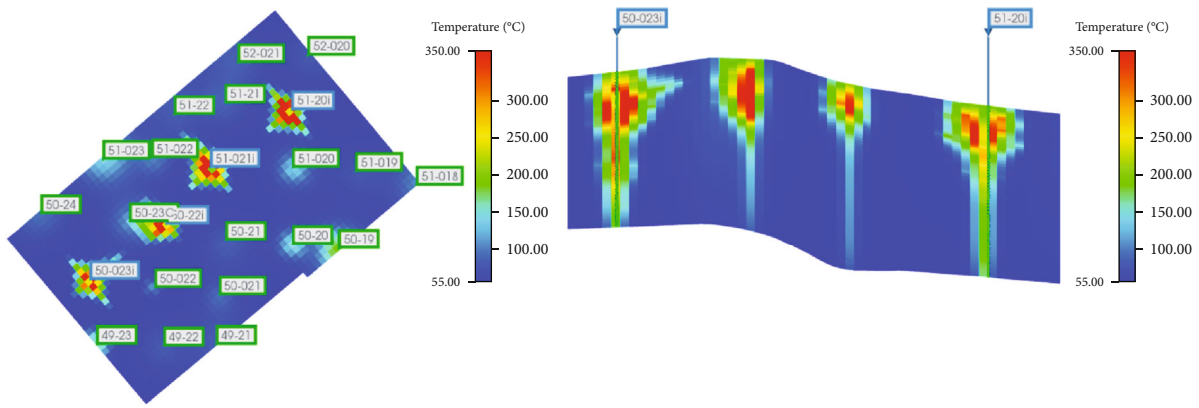

Figure 19: Prediction of ISC process temperature distribution for the D block sector model (layer 10 and reservoir cross-section, 2020-01-01).

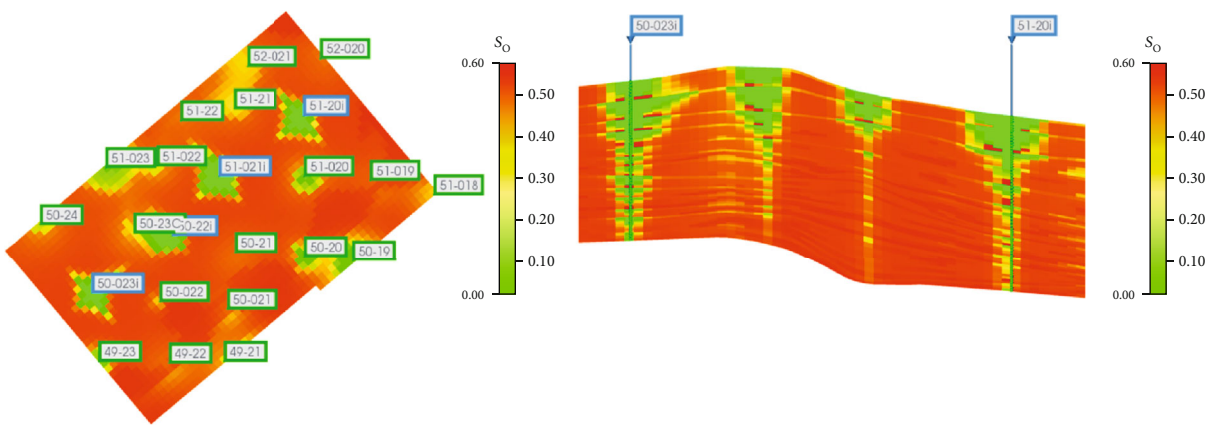

Figure 20: Prediction of ISC process oil saturation distribution for the D block sector model (layer 10 and reservoir cross-section, 2020-01-01).

has air injection rate of 5×10^4 m^3/day. This rate is typical value in field operation. Everything else is kept the same as the previous CSS simulation settings. Predictions are made, with air injection started in 2018-10-30. Figure 19 shows the prediction of ISC process temperature distribution for the D block sector model. We observe the high temperatures due to combustion reactions. The remaining heat from the previous CSS is also seen here. Figure 20 gives the prediction of ISC process oil saturation distribution for the D block sector model. The combustion front has left "no oil behind" in the burnt zone. Figure 21 gives the prediction of oxygen mole fraction in the gas phase for the D block sector model. It clearly shows the locations of the reaction front for the four injectors. Gravity override can clearly be seen from these simulation results of the reservoir cross-section.

Overall, the D block case study demonstrates the capability of using this simulation workflow to eventually make field-scale predictions for designing an ISC process.

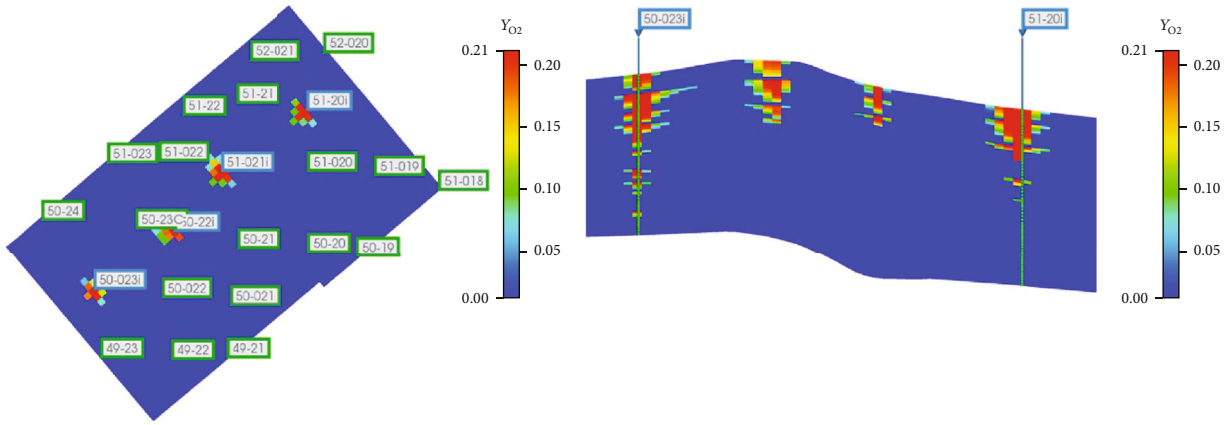

FIGURE 21: Prediction of ISC process O_2 mole fraction in gas phase for the D block sector model (layer 10 and reservoir cross-section, 2020-01-01).

7. Conclusions

In conclusion, we demonstrate the ISC simulation workflow from laboratory to field scale for D block in Liaohe Oilfield. We present the following specific conclusions:

(1) The reaction kinetics of D block crude is characterized in the kinetic cell (RTO) experiment, through ramping of temperature and measurement of flue gas compositions. A four-reaction kinetics model is successfully established in numerical simulation to accurately reflect the combustion behavior

(2) Combustion tube experiment is conducted to study the 1D ISC displacement. Based on the kinetics model, numerical simulation successfully matches the 1D ISC displacement

(3) The upscaled reaction model is implemented to minimize the numerical error caused by the grid size effect, which provides a practical way for field-scale ISC simulation. The coarse grid simulation with upscaled reaction model for D block provides consistent results as the fine-scale kinetics-based simulation

(4) Finally, a sector model for multiple well patterns in D block is built. History match is conducted for early CSS production since 1988. Production performance is predicted using the upscaled reaction method for conversion into future ISC process

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

Part of this work was previously presented as conference proceeding in the 2019 SPE Western Regional Meeting, April 23-26, 2019. The authors thank PetroChina Liaohe Oilfield for permission to publish this work. This research was funded by the National Natural Science Foundation of China, grant number 51804315.

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