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An Experimental Study on the Feasibility of Chemical Ignition for Heavy Oil Reservoir

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ABSTRACT

Experiment investigation on the feasibility of chemical ignition method used in achieving a successful ISC process is conducted in this work, which the electrical heating method might not be a good selection due to the deep heavy oil reservoir. A longer wire connecting with the heating rod is needed and a greater electrical resistance would be generated combining with more heat release. Therefore, an accelerated thermal aging issues for the wire should be concerned. What is more, the water flooding and other enhanced oil recovery methods have been applied in this deep heavy oil reservoirs developing with edge and bottom water of Tuha oil field, and a poor performance is obtained. Hence, chemical ignition method is proposed and the composition of ignition materials are evaluated through the kinetic cell and the combustion tube experiments. The results indicate that the chemical ignition agent with a high-temperature oxidation reaction varying in the range of 120-170℃ is prone to a successful combustion tube. When the ambient temperature with an initial value of 120℃ is given, a successful ignition can be achieved with a slowly temperature rising rate, especially in its early stage. However, the temperature rise rate would be presented with a significant greater combining with an intense high temperature oxidation (HTO) process as the increasing air injection rate is performed with a higher ignition temperature value of 170 ℃. Then a successful ignition combining with a better oil recovery is obtained. Finally, the chemical ignition process was successfully verified to achieve stable expansion of the combustion chamber in three-dimensional large-scale model experiments. The results and recognition of this work can be a valuable reference for the application of chemical ignition in the development of medium to deep heavy oil reservoir.

Keywords: Middle-Deep Heavy; In-situ Combustion; Ignition with Chemical Method; Kinetic cell

1. INTRODUCTION

The in-situ combustion technology involves using electric heating or injecting chemical agent to ignite the oil reservoir. Subsequently, the continuously injected air undergoes a high-temperature oxidation reaction with the crude oil in the vicinity of the well, generating heat that causes the crude oil to evaporate. Meanwhile, in the area closer to the hot front, a portion of the crude oil undergoes cracking reactions. The light components generated by evaporation and cracking are added to the front end of the cold oil zone, causing an increase in the oil saturation and temperature in this area and the formation of a mobile oil bank. Eventually, this oil bank is pushed out of the production well by the flue gas and condensate water [1, 2]. The technology has received extensive attention in recent years due to its wide applicability, high oil recovery efficiency and low costs.

Currently, in-situ combustion technology primarily employs electrical ignition and chemical ignition methods [3]. Among them, electrical ignition has the advantages of controllable temperature and uniform preheating, and is the mainstream ignition method in shallow and medium-depth layers. At present, oil fields such as Xinjiang Oilfield, Liaohe Oilfield and Shengli Oilfield all adopt the electric ignition method [4-7]. However, due to the long heating cycle of heavy oil reservoirs, it is prone to cause cable aging and ignition device damage. Moreover, the selection basis for key parameters such as heating power and duration during the ignition process is still not very clear [8]. Similarly, excessively high temperatures at the bottom of the well also have adverse effects on the cement ring outside the wellbore and the production tubing string.

The chemical ignition process involves injecting chemical agent into the near-wellbore region of the reservoir, allowing them to undergo varying degrees of oxidation with air at formation temperature. The released heat rapidly elevates the igniter to its ignition point, initiating combustion. Subsequently, the

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substantial amount of heat generated promotes high-temperature oxidation of the crude oil within the formation [9]. For chemical ignition, finding a combustible agent with high safety and good combustion stability is the key to improving the success rate of chemical ignition [10]. In recent years, the chemical ignition process has been implemented in the heavy oil reservoirs of D66 Block and G3618 Block, and has achieved success [11].

Chemical ignition agent encompasses a variety of types. Although different chemical ignition agents exhibit considerable variations in effectiveness [13-16], they all function by releasing substantial heat through intense reactions. With the successful application of chemical ignition in diverse reservoirs, research in this area is increasingly gaining attention. Based on their composition, chemical ignition agent can be categorized into three groups: metal - based, grease-based, and self-propagating combustion composites [17]. Currently, composite chemical ignition systems have been successfully applied in the field due to their high ignition efficiency. These systems typically consist of two functional components: a catalyst and a combustion aid. The combustion aid, which has a relatively low ignition temperature, rapidly burns upon reaching that temperature and transfers heat to the surrounding crude oil. Meanwhile, the catalyst reduces the activation energy required for the oxidation reaction of the crude oil, thereby accelerating exothermic oxidation. The synergistic action of the combustion aid and the catalyst raise the reservoir temperature, achieving successful ignition [12, 18]. However, reaction kinetics of chemical ignition agent within reservoir formations have not been reported, resulting in a lack of theoretical and experimental basis for the screening of optimized formulation systems.

This paper proposes a methodology for screening (or evaluating) ignition agent formulations. Based on the method, a novel chemical ignition system was identified. Its ignition performance was subsequently evaluated through one-dimensional combustion tube experiments and three-dimensional large-scale physical simulation experiments. The preliminary results demonstrate the feasibility of the proposed method. This work provides an evaluation method for screening chemical ignitors for air injection enhanced oil recovery technology in different reservoirs, and offers insights relevant to safety assessments associated with air injection processes.

2. MATERIAL AND METHODS

2.1 Material

The crude oil sample was taken from the TH oilfield. Before conducting the experiment, the crude oil was fully dehydrated using an electric dehydrator. The viscosity of the crude oil at the reservoir temperature (67°C) is 526 mPa • s (shear rate is 10 s^{-1}) and the density was 0.9381 g/cm^3 at the ambient conditions. The oil viscosity variation versus temperature is depicted in Fig. 1.

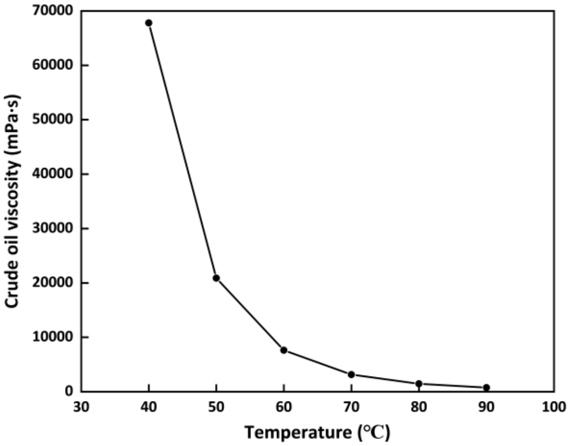

Fig. 1 The viscosity of heavy oil changes at different temperatures

2.2 Experimental apparatuses

The independently developed kinetic cell device mainly consists of a heating furnace, a reaction chamber, a gas control system and data acquisition components, and is used to study the reaction kinetics behavior of chemical ignition agent and crude oil with air in the pores. In comparison, the one-dimensional combustion tube device serves to validate the feasibility of chemical ignition and study oil displacement mechanisms. It is equipped with a 200 W heating rod at the gas injection end, while the outlet is connected to a gas-liquid separator for separating and metering produced oil and water. Finally, the real-time component analysis is conducted on the separated gas. The schematic diagram of kinetic cell and combustion tube experiments are presented in Fig. 2.

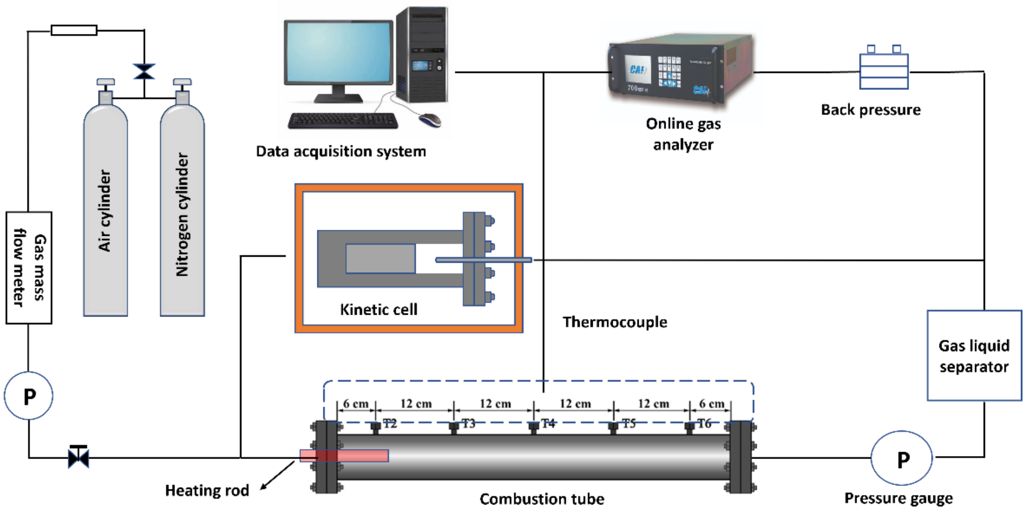

Fig. 2 The schematic diagram of kinetic cell and combustion tube experiments

Further, a set of three-dimensional large-scale model experiment was carried out to validate the effectiveness of the chemical ignition agent. The apparatus similarly consists of four main components: the model body, injection system, temperature monitoring system, and data acquisition system. The model has a diameter of 800 mm, a wall thickness of 10 mm, and a total volume of 220 L. There is a vertical gas injection well and three oil production wells inside the model. Moreover, the produced crude oil and gas from these three production wells are collected in a three-phase separator. Then, the gas is dehydrated and enters a gas analyzer for online concentration monitoring. Meanwhile, the liquid is regularly collected and weighed. The model device is shown in Figure 3.

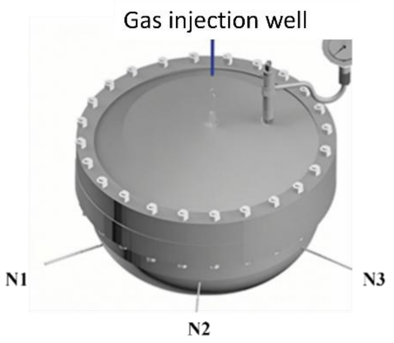

Fig. 3 Illustration of the 3D model appearance

2.3 Experimental procedures and conditions

2.3.1 Kinetic cell experiment

The Kinetic cell experiment was conducted by controlling the linear heating of the heating furnace, using thermocouples to monitor the temperature of the kinetic cell, and employing gas analyzers to monitor the output gas in real time. Firstly, prepared the oil sand samples in a certain proportion, and successively installed the sand control net, quartz sand layer, oil sand layer and ceramic cotton filter layer. Then assembled the kinetic cell and connected the pipelines for airtightness check. After that, started the heating program at a constant gas injection rate, heat to the target temperature at the set heating rate, and simultaneously record the temperature and gas concentration data. After that, the heating program was initiated at a constant gas injection rate, raising the temperature to the target value according to the predefined heating rate, with temperature and gas concentration data being recorded throughout the process. This experiment conducted a comparative study between oil sand systems with and without the chemical ignition agent to analyze their differences in combustion reaction kinetics. The effect of the chemical ignition agent was evaluated based on the temperature (or time) at which the oxidation reaction occurred, the concentration of the produced gas, and the changes in the temperature peak. The physical parameters of kinetic cell experiments are listed in Table. 1.

Table 1 Physical parameters of kinetic cell experiments

No.	Crude oil	Ignition agent	Heating rate	Back pressure	Air Injection rate
KC1	0.5g	0.0g	4.11℃/min	0.5MPa	2L/min
KC2	0.5g	0.1g			

2.3.2 Combustion tube experiment

The combustion tube experiment procedure includes oil sand packing, saturation calculation, device assembly, leak testing, insulation treatment, chemical ignition agent injection, preheating and ignition, and data acquisition. The experiment is conducted by injecting air (2.5 L/min) and controlling the back pressure (0.7 MPa), using electric heating or chemical ignition agent to ignite, and simultaneously monitoring changes in temperature, pressure and gas components. Finally, samples are taken and data are exported for analysis. In this study, two sets of combustion tube experiments were conducted to evaluate and select the chemical ignition agent system. Meanwhile, the influence law of chemical ignition on combustion stability was investigated. The experimental scheme is shown in Table 2.

Table 2 Physical parameters of combustion tube experiments

No.	Ignition agent	Oil saturation	Water saturation	Heating rod temperature
E1	0g	57.1%	42.9%	150℃
E2	30g			150℃

2.3.3 Three-dimensional D model experiment

The main procedures of the three-dimensional model experiment were as follows: First, the oil-sand sample was thoroughly mixed and packed into the large model in layers, while high-temperature cement was applied to the inner wall to prevent gas channeling. Next, a leaking test was conducted to ensure the pressure met the required standards. Thereafter, the chemical ignition agent was injected, and the model was preheated while monitoring temperature changes near the injection well. Once the temperature stabilized, ignition was achieved through multiple cycles of intermittent air injection, and the gas injection rate was gradually adjusted to sustain combustion front propagation. Finally, when the oxygen concentration at the production well exceeded 15% or the combustion front reached the designated position, nitrogen was injected to extinguish the combustion and terminate the experiment.

3. RESULTS

3.1 Kinetic behavior of chemical ignition agent

The variation curves of gas concentration and temperature produced by kinetic cell experiments are presented in Fig. 4. In the KC1 experiment without the participation of the chemical ignition agent, two gas concentration peaks appeared on the CO_X concentration curve, while no obvious hump was observed on the temperature curve. On the contrary, in the experimental KC2 with the addition of the ignition agent, the oil sand system reached a temperature peak of 151℃ at 3068 seconds, indicating that some of the ignition agent had reached its flash point and undergone a heat-releasing reaction. Subsequently, the gasification absorbed heat, causing the temperature to drop to 143℃ at 3393 seconds. Then, the heating rate significantly increased to 7.41℃/min, and then rose sharply after reaching 245.3℃, reaching 409.8℃ at a rate of 67.1℃/min within 147 seconds. Meanwhile, the peak concentration of CO_X rose to 13.01%. Compared with the case without ignition agent, the peak concentration of high-temperature oxidation increased by 9.75 times, and the heating rate increased by 11.2 times. It indicates that chemical ignition can significantly enhance the reaction intensity and efficiency, and greatly shorten the ignition time.

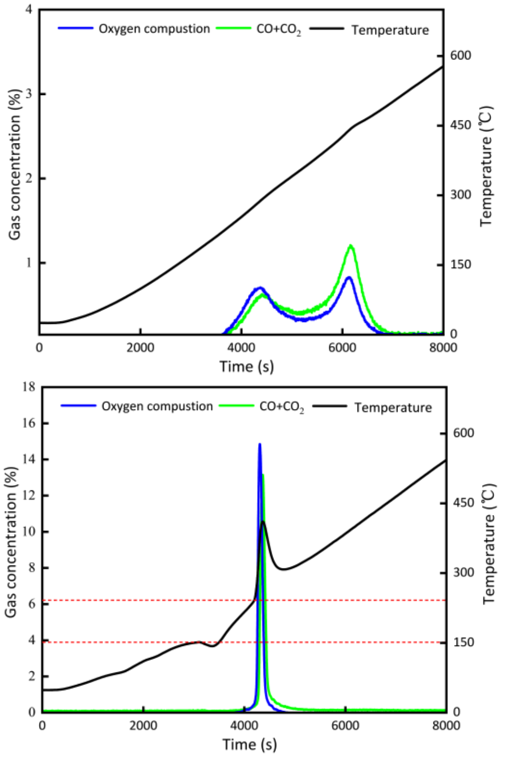

Fig. 4. The variation curves of gas concentration and temperature produced by kinetic cells

3.2 Evaluation of chemical ignition agent

In the combustion tube experiment, the temperature of heating rod T1 was set constant at 150 °C, with a backpressure of 0.7 MPa and an air injection rate of 2.5 L/min. To reduce heat loss, heating tape wrapped around the injection end of the tube was also set to 150 °C. The temperature changes at each measurement point in Experiment E1 and E2 are shown in Fig. 5. It indicates that only gas phase flow and heat transfer processes occur within the combustion tube when no ignition agent was added. Meanwhile, no chemical reactions or heat generation were detected. On the contrary, after injecting the ignition agent in Experiment E2, intermittent gas injection was adopted to prevent its movement away. Subsequently, the temperature at thermal well T3 rose rapidly within 724 seconds, indicating that the ignition agent occurred exothermic reaction with oxygen and reached the critical temperature of 186.7℃ at 1270 seconds. The T3 area had a higher concentration of chemical ignition agent, resulting in a significant increase in temperature, reaching up to 691.9℃. Especially, the heating rate was 46.4℃/min, which was 7.2 times that of electric heating. Then, the fire front successfully formed and propagated to the thermal well T6. The results demonstrate that chemical ignition significantly enhances near-wellbore temperatures and promotes stable propagation of the combustion front.

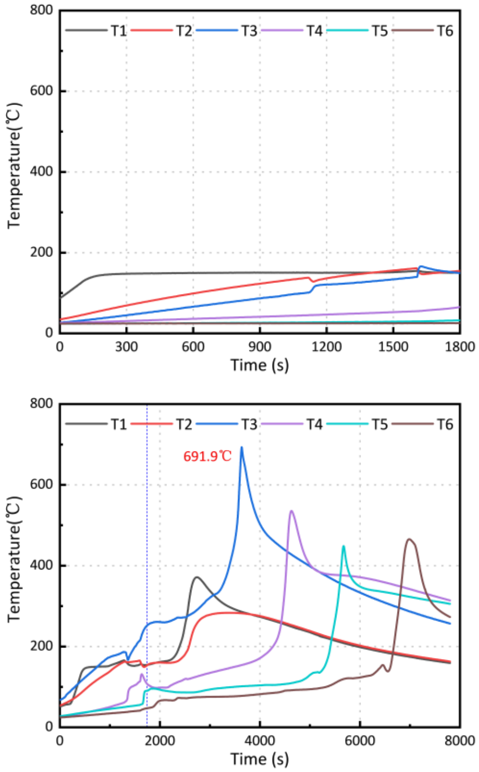

Fig. 5 Temperature variation of each temperature detection well

3.3 Verification of Chemical Ignition in 3D Model

In this experiment, the heating rod temperature was set at 170°C. Additionally, an intermittent gas injection method was employed to ensure that the ignition agent and air had sufficient contact. The temperature variation and gas flow rate curve near the gas injection well are shown in Fig.6. After 17 rounds of intermittent gas injection, the method was changed to continuous gas injection. At 280 minutes, the heating rate increased sharply to 36.6℃/min, which was 20.7 times that of electric heating, indicating the successful achievement of chemical ignition. Moreover, the expansion of the combustion chamber within the model during the experiment reconstructed based on the monitored temperature data is shown in Figure 7. The results show that the combustion chamber can expand stably within 2 to 10 hours, further verifying the feasibility of the chemical ignition agent.

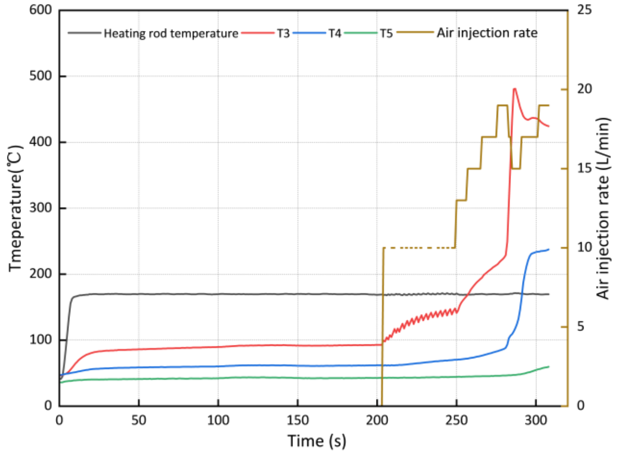

Fig. 6 Temperature variation curve near the gas injection well

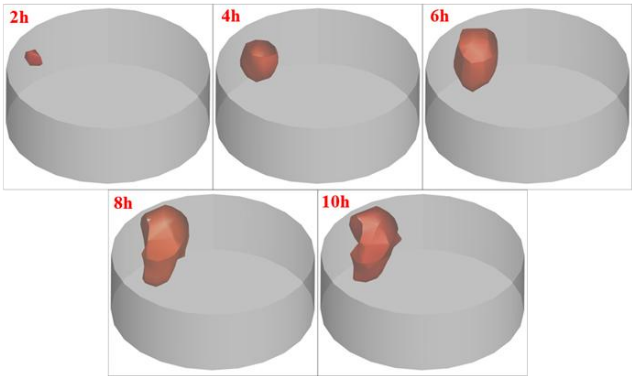

Fig. 7 Variation of combustion chamber geometry versus time.

4. DISCUSSION

This study conducted multi-scale experiments to verify that the chemical ignition agent can efficiently initiate oxidation reactions at low temperatures ranging from 120 to 170°C, resulting in significant increases in the heating rate and the temperature of the flame line, as well as promoting the stable expansion of the combustion chamber. Compared with existing studies, the focus of this research lies in verifying the feasibility of chemical ignition agent in the physical model, breaking through the traditional limitations of electric heating on temperature and time. At the same time, the intermittent gas injection method effectively alleviates the problem of ignition agent migration, and is more controllable than the continuous gas injection scheme. However, there are still certain limitations such as not considering issues like reservoir heterogeneity, the long-term stability of the ignition agent, and scale effects. In the future, it is necessary to combine numerical simulation, optimize the formula, and evaluate the adaptability to complex reservoirs, in order to further explore its synergy with various enhanced oil recovery technologies.

5. CONCLUSIONS

For the difficulty in conducting electrical ignition in deep heavy oil reservoirs, kinetic cell and combustion tubes experiments were conducted to study the reaction kinetics of heavy oil with the participation of chemical ignition agents. Finally, an evaluation method for chemical ignition agents was established. The main insights obtained include:

(1) Intense oxidation reactions can be initiated by the chemical ignition agent in a low temperature environment ranging from 120 to 170°C, facilitating a rapid transition from low to high temperature combustion.

(2) The chemical ignition heating rate can be as high as 7 to 22 times that of electric heating, and it is the key to determining the success of ignition.

(3) The effectiveness of the chemical ignition agent was verified through combustion tube and 3D model experiments. In summary, by increasing the reservoir temperature (such as injecting a certain amount of high-temperature steam), creating a temperature environment of 120-170℃ in the vicinity of the well, the ignition success rate can be significantly improved.

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