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Calculation Method for Ignition Temperature and Stable Combustion Temperature of the In-Situ Combustion Process

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Abstract
By theoretical derivation and applying Arrhenius prescription and Semenov's definition of ignition, the equations for calculating ignition temperature and stable combustion temperature are obtained. By previous experimental data, the empirical parameter in the equations is determined by calculation, so that the specific equations are obtained. Research shows, basically the values of ignition temperature and stable combustion temperature are only dependent on the properties of crude oil. The ignition temperature equation provides a new method for implementing in-situ combustion process design, and the stable combustion temperature equation offers a new criterion to estimating the combustion behavior of subsurface crude oil.

Key words: In-situ combustion; Ignition temperature; Stable combustion temperature; Arrhenius; Semenov; Calculation method

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INTRODUCTION

In-situ combustion is a thermal recovery technology which used in the recover the heavy oil. There are many successful examples and experiences on the field at last 30 years. Ignition is the key technology of in-situ combustion, commonly, shallow oil reservoir adopt electric heater or burner ignition, deep reservoir adopt spontaneous ignition. According to the experience of the field, the application of spontaneous ignition is suitable for the forward isc process. It's important to clear the factors which influence spontaneous. In this paper, we study the forward isc mechanism which caused by oil spontaneous because of inject air, analyze the factors of crude oil high combustion (oxidation) in porous media, based on the activation energy data of different API heavy oil by the other paper. We establish the calculation method between ignition temperature of crude oil in reservoir and stable combustion temperature.

1. THE IGNITION TEMPERATURE CALCULATION METHOD

The assumptions of high temperature oxidation (combustion) reaction of crude oil in reservoir porous media are similar to the previous[1-2], expound as follows: The high temperature oxidation(combustion) reaction of crude oil in reservoir porous media is not a complicated reaction. The reaction only relies on the reactants and is not dependent on the products. The reaction is first order reaction for oxygen concentration, and it is zero order reaction for other fuels in the reservoir. So according to the Arrhenius theory , the reaction rate expression is:

$$R'(C,T) = skC\exp\left(-\frac{E}{RT}\right). \tag{1}$$

where $R'(C,T)$ is the effective rate of the reaction, mol/(l·s); s is specific surface area of rock pore which filling the air, dimensionless; k is specific reaction rate constant, dimensionless; C is oxygen concentration,%; E is activation energy, J/mol; R is universal gas constant, J/(mol·K); T is absolute system temperature, K.

According to previous study, consider the actual, rewrite Equation (1) as:

$$R'(C,T)=A'T^n\exp\left(-\frac{E}{RT}\right), \tag{2}$$

where $A' = skC$ and is independent of temperature up to the time of ignition, dimensionless; n is value -0.5~1.

Assume that reaction heat is proportional to reaction rate, according to Equation (1) and Equation (2), the heat of high temperature oxidation(combustion) reaction of crude oil in reservoir porous media is defined as

$$Q_1=A(T-T_0)^n\exp\left(-\frac{E}{RT}\right), \tag{3}$$

where Q_1 is heat generated of high temperature oxidation(combustion) reaction, J; T_0 is temperature when combustion reaction occurs, ignition temperature, K; A is a experience constant independent of temperature, dimensionless.

At the high temperature oxidation (combustion) of crude oil in the reservoir porous media duration, the heat removed from within the porous medium is termed Q_2, Q_2 includes sensible heat removed in the air and a surface transfer or radiation boundary condition. According to heat transfer theory, Q_2 is represented by

$$Q_2 = B(T - T_0)^m, \tag{4}$$

where Q_2 is heat loss, J; B is heat loss coefficient, the value is independent of temperature, dimensionless; m is a experience constant, $m \geq 1$, dimensionless.

According to the research of the Semenov[3] shows that ignition temperature of high temperature oxidation (combustion) of crude oil in reservoir porous media definition is based on:

Accumulation of heat in the reaction ΔQ = heat generated in the reaction Q_1 - heat loss in the reaction Q_2.

Quote the ignition temperature of Semenov, according the definition, the conditions of ignition temperature are

$$Q_1 = Q_2, \tag{5}$$

$$\frac{dQ_1}{dT}=\frac{dQ_2}{dT}. \tag{6}$$

According to Equations (3)~(6):

$$\frac{dQ_1}{dT}=A(T-T_0)^n\exp\left(-\frac{E}{RT}\right)\left(\frac{n}{T-T_0}+\frac{E}{RT^2}\right), \tag{7}$$

$$\frac{dQ_2}{dT}=B(T-T_0)^m\left(\frac{m}{T-T_0}\right). \tag{8}$$

Simultaneous Equations (3), (4), (7), (8), (5), (6), thus, there is a second binary equation:

$$\frac{(m-n)RT^2}{E}-T+T_0=0. \tag{9}$$

According to the ignition temperature defined by Semenov, satisfy Equations (5), (6). Describe Equations (3), (4) on a graph of the T versus Q, the two curves should be in a state of tangent, so Equation (9) have only one solution, thus:

$$\Delta=1-\frac{4(m-n)RT_0}{E}=0, \tag{10}$$

where,

$$T_0=\frac{E}{4(m-n)R}. \tag{11}$$

so,

$$T=T_1=\frac{E}{2(m-n)R}, \tag{12}$$

where T_1 is stable combustion temperature of high temperature oxidation reaction of crude oil in reservoir porous media, $T_1 \geq T_0$, K.

According to Equations (11) and (12),when crude oil in reservoir porous media occur high temperature oxidation reaction, basically the ignition temperature and stable combustion temperature only related to the property of crude oil, neglecting the effect of other reservoir factors. So, determined the activation energy E and parameter m and n values by experiment, we can calculate the ignition temperature and stable combustion temperature.

2. VERIFY THEORETICAL FORMULA BY EXPERIMENT

From combustion mechanism, generating scheme of carbon oxide is critical to the success of in-situ combustion. Generally, the oxidation reaction is mainly divided into two categories: Low temperature oxidation reaction within the scope of 150~350 ℃, product are carbon monoxide, nitrogen and product by oxygen; high temperature oxidation reaction above 400 ℃. Combustion experiments of every kinds crude oil shows that, 343 ℃ (343.15 K) can be thought of effective combustion temperature, the ignition temperature.

Let $m - n = \xi$, so Equation (11) can be written as the following form:

$$T_0=\frac{E}{4\xi R}. \tag{13}$$

The known conditions are: T_0 = 616.15K, R = 8.314 J/(mol·K), thus:

$$\xi=\frac{E}{4T_0R}=\frac{E}{4\times 8.314\times 616.15}=\frac{E}{20490.6844}. \tag{14}$$

Table 1 shows the activation energy E of different API heavy crude oil and values of ξ.

Table 1
Crude Oil High Temperature Oxidation Kinetics Parameters

Crude oil (°API)	E/ (Btu·(1b·mol)$^{-1}$)	E/ (J·mol)$^{-1}$	ξ	Reference
No record	31,600	73,501.60	3.59	4
No record	30,800	71,640.80	3.50	4
No record	31,600	73,501.60	3.59	4
No record	36,600	85,131.60	4.15	4
No record	30,900	71,873.40	3.51	4
No record	33,800	78,618.80	3.84	4
27	30,800	71,640.80	3.50	5
18	36,400	84,666.40	4.13	6
22	30,400	70,710.40	3.45	6
19.9	30,300	70,477.80	3.44	7
27.1	31,350	72,920.10	3.56	7
27.1	31,360	72,943.36	3.56	7

From Table 1, the average of ξ: $\bar{\xi}$ = 3.65, so $m - n = 3.65$. Equations (11) and (12) can be written as the following form:

$$T_0 = \frac{E}{4 \times 3.65 \times R} = \frac{E}{14.6R}, \quad (15)$$

$$T_1 = \frac{E}{2 \times 3.65 \times R} = \frac{E}{7.3R}. \quad (16)$$

According to Equations (15) and (16), describe the relation curve between ignition temperature and activation energy of crude oil and the relation curve between stable combustion temperature and activation energy of crude oil, respectively, as shown in Figure 1. Figure 1 shows that, with the increase of activation energy E of crude oil, ignition temperature and stable combustion temperature are linearly increasing. $T_1 > T_0$ and $T_1 = 2T_0$. It's because the reaction activation energy increased, the absorb energy needed form ordinary molecules transformed into activation molecules also increase, so we need higher ignition temperature, then stable combustion temperature increase.

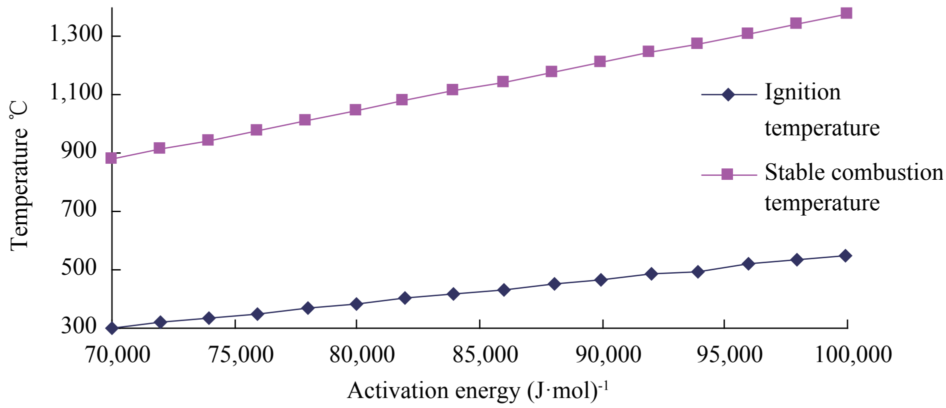

Figure 1
The Relationship Between Activation Energy of Crude Oil and Ignition Temperature, Stable Combustion Temperature

It should be pointed out that, the application of the forecasts formulas forecast the ignition temperature and stable combustion temperature on the basis of the known activation energy of crude oil. According to the comparison between the predicted values and measured values, estimate the ignition situation and combustion situation of underground crude oil. Establishment of formula is on the basic of ignition temperature is 616.5 K. If the condition meet Equation (14), the underground crude oil was ignited. So the average parameter value of 3.65 is general, can be used to predict.

CONCLUSION

(a) On the basis of activation energy data of different API heavy crude oil, we derived the ignition temperature computational formula and stable combustion temperature computational formula. it has a certain guiding significance to the production. From the formulas, basically the ignition temperature and stable combustion temperature only related to the property of crude oil, neglecting the effect of other reservoir factors

(b) According to the previous data, we ensure the experience parameters, ξ = 3.65, thus, in the case of known oil activation energy, we use the Equations (15) and (16) to predict the ignition temperature and stable combustion temperature. It provides a new method to determine underground oil ignition and combustion situation.

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