

Technology and mechanism of residual oil extraction using in-situ combustion

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Abstract. The article provides detailed information on the mechanism of residual oil extraction using the technology of intra-layer combustion. Here, the history of the emergence of this exploitation method, the stages of its development are discussed, and mainly the most widely used and the maximum achievement of annual oil production are presented. It has been theoretically proven that the speed of thermal convection is less than the speed of movement of the combustion front. In this method of development, air is used as an oxidizer, which is injected into the formation through air injection wells. An electric heater is lowered to the bottom of the well and turned on; oil vapors at the bottom of the well ignite and create a combustion group; then compressed air is injected into the formation to move it forward to the production wells. When checking the formation and progress of the combustion flame, temperatures are measured in existing wells.

The chemical formula for the combustion of petroleum residue-coke is given in two forms. The formula for calculating the volume of air required for the combustion of coke in 1m³ of the layer is given. The rate of the oxidation reaction within the layer is expressed by the Arrhenius law; based on this, the rate of oxygen entering the reaction is calculated. The combustion rate of the combustion group and its formula for any time *t* and for the radial case are given.

Keywords: in-situ combustion, residual oil, coke, extraction mechanism, technology, underground degassing, compressed air, combustion front, electric heater.

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1. Introduction. The modern oil production industry faces a key challenge: declining production from traditional fields and an increasing share of hard-to-recover oil reserves. Researchers estimate that up to 60–70% of initial geological oil reserves remain in the subsurface after primary and secondary development methods. This requires the implementation of innovative technologies aimed at increasing the ultimate oil recovery factor. Among the most promising areas, in-situ combustion (ISC) - a thermochemical method based on controlled oxidation-reduction reactions in the oil-bearing formation - occupies a special place.

Historical origins of this method are linked to D.I. Mendeleev's (1888) idea of underground coal degassing, which served as the theoretical basis for the development of thermochemical methods for influencing formations. In the 1930s, Soviet scientists A.B. Sheinman and K.K. Dubrovay first proposed using a similar principle to enhance oil recovery -initiating in-situ oxidation of oil followed by combustion. Although the first attempts to implement this method at fields in the Krasnodar Territory were unsuccessful, their research became the starting point for the development of this field.

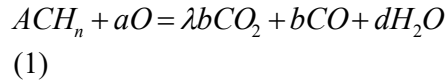
In the late 1950s and early 1960s, interest in this technology increased significantly. Laboratory and industrial tests conducted in the USSR, USA, Hungary, France, the Netherlands, and other countries confirmed that, with a properly managed combustion process, commercial-grade oil can be recovered even from low-permeability and water-saturated formations. Experiments have shown that a combustion front can propagate stably in the subsurface if a balance is maintained between the air supply rate, reaction temperature, and the composition of the oil residue (coke).

The purpose of this study is to analyze and theoretically substantiate in-situ combustion technology as one of the most effective methods for enhancing oil recovery, as well as to identify the factors influencing combustion front stability and the kinetics of oxidation reactions.

2. Materials and Methods. Accumulated global experience demonstrates that in-situ combustion is not only an effective but also a fairly versatile method applicable to various types of oil reservoirs, including heavy and highly viscous oils [1-6].

In the process of developing an oil field by the in-situ combustion method, air is mainly used as an oxidizer, which is injected into the formation from special air injection wells. Oil is taken from the producing wells, along with combustion products and water, which can also be injected into the formation; into these air injection wells or into special water injection wells. To do this, a heater assembly is lowered into the wellbore and air is injected, partially compressing the oil and water from the formation into the producing wells. Then a depth heater assembly is connected and heat is introduced into the formation. As a result, the temperature in the formation increases, the rate of oil oxidation increases, and oxidation proceeds to combustion [7-9].

The chemical formula for the combustion of oil residue - coke is written as follows:



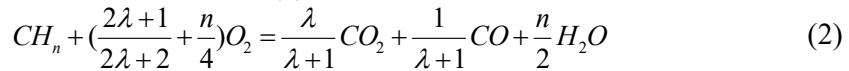
In the reaction according to formula (1), all hydrogen atoms are converted to water. Therefore, $d=n/2$. Then, by equating the hydrogen atoms on the left and right sides of formula (1), we get:

$$(\lambda + 1)b = 1; b = \frac{1}{\lambda + 1}$$

We obtain on oxygen:

$$a = \lambda b + \frac{b}{2} + \frac{d}{2} = \frac{2\lambda + 1}{2\lambda + 2} + \frac{n}{4}$$

Thus, the chemical formula for combustion (1) takes the form:



From formula (2) it can be seen that for one mole of coke to burn, $\frac{2\lambda + 1}{2\lambda + 2} + \frac{n}{4}$ mol O_2 is required.

The molar mass of the CH_n group of coke is $12+n$. Thus, $\frac{2\lambda + 1}{2\lambda + 2} + \frac{n}{4} / (12+n)$ kg/mol O_2 is required for 1 kg of coke.

An important parameter of the layer affected by combustion is the amount of coke in its unit volume. This quantity is denoted by z . Thus, the volume of air required for the combustion of coke

in $1m^3$ of the layer (brought to standard conditions) is:

$$V_{air} = \frac{22,4 \left(\frac{2\lambda + 1}{2\lambda + 2} + \frac{n}{4} \right)}{a_1 a_2 (12 + n)} \quad (3)$$

Here, a_1 is the amount of oxygen in the air; a_2 is the degree of oxygen utilization.

It should be noted that according to expression (2), or from 1 kg/mol of coke in the developed

combustion process in the formation, $\lambda/(\lambda+1)$ kg·mol of CO_2 and $n/2$ kg/mol of water are released.

3. Results and discussion. Let us quantitatively evaluate the formation of various substances during intensive combustion in the formation. Let us assume that $n=2$ and, according to experimental data, a significantly small amount of CO is formed as a result of combustion. In this case, $\lambda=10$. The amount of coke in the rock is $z_t=25 \text{ kg/m}^3$, $a_1=0.21$, $a_2=0.9$, and

$$V_{air} = \frac{22,4 \left(\frac{2 \cdot 10 + 1}{2 \cdot 10 + 2} + 0,5 \right)}{0,21 \cdot 0,9(12 + 2)} \approx 308 \text{ m}^3/\text{m}^3$$

Thus, for the combustion of 1 m^3 of coke from the bed, 308 m^3 of air will be required under standard conditions. For the combustion of 1 kg of coke, 21.31 m^3 of air is required under standard conditions. As it can be seen from expression (2), the following amount of CO_2 gas is formed in the reservoir for 1 kg of burnt coke:

$$\frac{44\lambda}{(\lambda + 1)(12 + n)} = 2,86 \text{ kg}.$$

And the water:

$$\frac{9n}{12 + n} = 1,286 \text{ kg}$$

An important characteristic of the combustion process within the formation is the rate of oxidation reaction w , i.e. the rate of reaction of oxygen with coke per unit volume of the formation. This rate can be multiplied by certain coefficients to obtain the rate of temperature drop in 1 m^3 of the formation.

Studies of oil oxidation in porous media show that the rate of oxidation reaction within the formation is expressed by the Arrhenius law. Thus, according to this law, the following formula exists for the reaction rate of oxygen w_{ox} :

$$w_{ox} = a_0 P_{ox}^n \cdot e^{-\frac{E}{RT}} \quad (4)$$

Here, a_0 , n are the coefficients determined experimentally for various oils and oil reservoirs; P_{ox} is the partial pressure of oxygen in the oxidizer; E - the activation energy; R - the gas constant; T - the absolute temperature, in K^0 .

To determine the constants a_0 , n and $B=E/R$, laboratory studies of the oxidation kinetics of specific oils are carried out on natural and artificial samples of mountain rocks.

It was found experimentally that the oxidation kinetics constants of oils included in formula (4) have the following order: $E/R=(8-9)103$; $n=0.5-1.0$; $a_0=(1-5)104 \text{ (kgO}_2 \cdot \text{MPa)} \cdot n/\text{kg coke} \cdot \text{s}$). The dimension $[w_{ox}]=\text{kgO}_2/(\text{kg coke} \cdot \text{s})$. Let us estimate the value of w_{ox} according to formula (4). Let us assume that $A/R=8.5 \cdot 103 \text{ K}$; $n=1.0$; $a_0=3 \cdot 104 \text{ kgO}_2/(\text{kg oil} \cdot \text{s} \cdot \text{MPa})$; $P=10 \text{ MPa}$; $P_{ox}=0.21 \cdot 10=2.1 \text{ MPa}$; $T=313.15 \text{ K (40C)}$. We get:

$$w_{ox} = 3 \cdot 10^4 \cdot 0,21 \cdot 10 e^{-\frac{8,5 \cdot 10^3}{313,15}} = 10,27 \cdot 10^{-8} \text{ kgO}_2/(\text{kg coke} \cdot \text{s}) = 8,87 \cdot 10^{-3} \text{ kgO}_2/(\text{kg coke} \cdot \text{day}).$$

Oxidation reaction $T=473,15 \text{ K (200}^0\text{C)}$ temperaturda sürətini hesablayıb, alırıq:

$$w_{ox} = 3 \cdot 10^4 \cdot 0,21 \cdot 10 e^{-\frac{8,5 \cdot 10^3}{473,15}} = 9,954 \cdot 10^{-4} \text{ kgO}_2/(\text{kg coke} \cdot \text{s}) = 86 \text{ kgO}_2/(\text{kg coke} \cdot \text{day}).$$

Unit of measure $[w_T]=\text{kJoule/m}^3 \cdot \text{s}$; then we write:

$$w_T = w_{ox} \cdot H_T \cdot Z_T = 8,87 \cdot 10^3 \cdot 10,5 \cdot 10^3 \cdot 25 = 2328 \text{ kJoule/m}^3 \text{ day}$$

If we assume that the average heat capacity of the layer $C_{for}=2.5 \cdot 103 \text{ kJoule/(m}^3\text{K)}$, then at this rate the temperature will rise by $(2.238 \cdot 103)/(2.5 \cdot 103) \approx 1 \text{ K}$ during the day. We assume the temperature $T=473.15 \text{ K}$ and calculate:

$$w_T = 9,954 \cdot 10^{-4} \cdot 10,5 \cdot 10^3 \cdot 25 = 261,3 \frac{\text{kJoule}}{\text{m}^3 \text{ s}} = 225,8 \cdot 10^5 \text{ kJoule/m}^3 \text{ day}$$

If air is injected to move the combustion front in a straight layer, then the combustion speed of the front is:

$$w_f = q_{air} / R_{air} \cdot bh \quad (5)$$

Here, q_{air} is the air flow rate in the layer element; b is the width of the layer; h is the thickness of the layer covered by combustion.

At any time t , the state of the combustion front X_f is:

$$X_f = \frac{\int_0^t q_{air}(t) dt}{R_{air}bh} \quad (6)$$

In the radial case:

$$2\pi r_f dr_f h R_{air} = q_{air} dt; w_f = \frac{q_{air}}{2\pi r_f h R_{air}}$$

Then

$$\pi h R_{air} r_f^2 = \int_0^t q_{air}(t) dt \text{ yaxud}$$

$$r_f = \left[\frac{\int_0^t q_{air}(t) dt}{\pi h R_{air}} \right]^{1/2} \quad (7)$$

Let us assume that in the radial case, under standard conditions, $q_{air}=30 \cdot 10^3 \text{ m}^3/\text{day}$; $Z_t=25 \text{ kg/m}^3$;

$h=10\text{m}$; $R_{hava}=308 \text{ m}^3/\text{m}^3$. Then, after 1 year=365 days, the combustion front will advance to the following distance from the well.

$$r_f = \left[\frac{30 \cdot 10^3 \cdot 365}{3,14 \cdot 10 \cdot 308} \right]^{1/2} = 33,65 \text{ m}$$

Thus, all the main indicators of the considered method are analyzed and determined. This proposed technology and mechanism are effective in designing the field development system.

4. Conclusion. The study outlines the key mechanisms and calculation relationships that characterize in-situ combustion processes for recovering residual oil. It is shown that the combustion front is formed by injecting compressed air and initiated by an electric heater, while its movement is controlled through temperature measurements in the reservoir. The chemical equations of coke combustion, the calculation of the air volume required for its oxidation, and Arrhenius-based formulas describing the reaction kinetics and the combustion front velocity are presented. The results refine the physicochemical parameters of the process and confirm the potential of in-situ combustion as an effective enhanced oil recovery method.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research.

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