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Physical modeling of oil displacement by steam in laboratory conditions

Kazan – 2020

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Bolotov A.V., Minkhanov I.F., Varfolomeev M.A. Physical modeling of oil displacement by steam in laboratory conditions. Teaching aid. Kazan Federal University. - Kazan, 2020. - 19 p.

The educational-methodical manual for undergraduate students and masters in full-time education in the areas of 03.21.01 and 04.21.01 Oil and gas business in the profile "Development of oil and gas fields". The training of specialists in vocational education institutions must meet the requirements of employers. An important component is gaining experience in conducting laboratory studies of thermal methods for increasing the number of trainees and study students intended for these studies, their components, and characteristic features.

In the training manual, a methodology for conducting experiments with processing results is given, the process of preparing the model for testing is described, and a setup diagram with control and measuring devices is presented.

Considered competencies in the course of work:

Able to solve production and (or) research tasks based on fundamental knowledge in the oil and gas field.

Able to find and process information required for decision-making in scientific research and practical technical activities.

Able to develop and implement innovative solutions in the field of enhanced oil recovery.

List of titles

Terms and definition

Formation fluid – Any fluid that occurs in the pores of a rock. Strata containing different fluids, such as various saturations of oil, gas, and water, maybe encountered in the process of drilling an oil or gas well. Fluids found in the target reservoir formation are referred to as reservoir fluids.

Reservoir - A subsurface body of rock having sufficient porosity and permeability to store and transmit fluids. Sedimentary rocks are the most common reservoir rocks because they have more porosity than most igneous and metamorphic rocks and form under temperature conditions at which hydrocarbons can be preserved. A reservoir is a critical component of a complete petroleum system.

Isoviscous model – model of oil obtained by diluting the oil with solvent to an appropriate viscosity

Displacement factor (K_{dis}) – the ratio of the volume of oil obtained during its displacement by a working displacing agent (in laboratory conditions) from core samples to reservoir conditions, to the initial volume of oil. Determined by OST 39-195-86.

Physical model of the reservoir - scaled view of the reservoir. As a model of the formation, core samples are often used, sawn from borehole samples, or a bulk model.

Introduction

The largest number of projects in the world to develop fields and increase oil recovery from deposits of viscous oils and bitumen is associated with the use of thermal methods [1]. Following the concept of M. Prats, enhanced oil recovery due to thermal effects on the formation is a family of tertiary methods, which are defined as "any process in which heat is intentionally used to influence underground hydrocarbons to extract fossil fuel through wells" [2]. The most common heat injection mechanism is saturated steam.

The oil displacement factor is the most important reservoir characteristic. The value of the displacement factor is included in the basic formula for calculating recoverable oil reserves and affects the choice of the optimal method for developing a field to achieve maximum economic efficiency.

1. Purpose and application area

This methodology is designed to determine the dynamics of changes in the oil displacement coefficient K_{dis}, temperature profile, pressures at the inlet and outlet of the reservoir model during steam at thermal exposure. At the same time, the conditions of oil displacement are as close as possible to the reservoir due to the use of reservoir or model fluids with the obligatory creation and maintenance of reservoir temperature and pressure.

The purpose of the method is to filter the fluid through the oil-saturated rock with an injection agent (hot water, steam) in equipment for physicochemical modeling of the process of steam-assisted gravity drainage (Fig. 1.1) [3].

Fig. 1.1 - Picture of the equipment for physico-chemical modeling of the process of steam-assisted gravity drainage

2. Laboratory equipment for determination of the oil displacement coefficient during thermal exposure

The equipment consists of a steam injection system, high-pressure chamber, fluid collection system, system for measuring and monitoring pressure and temperature (Fig. 2.1).

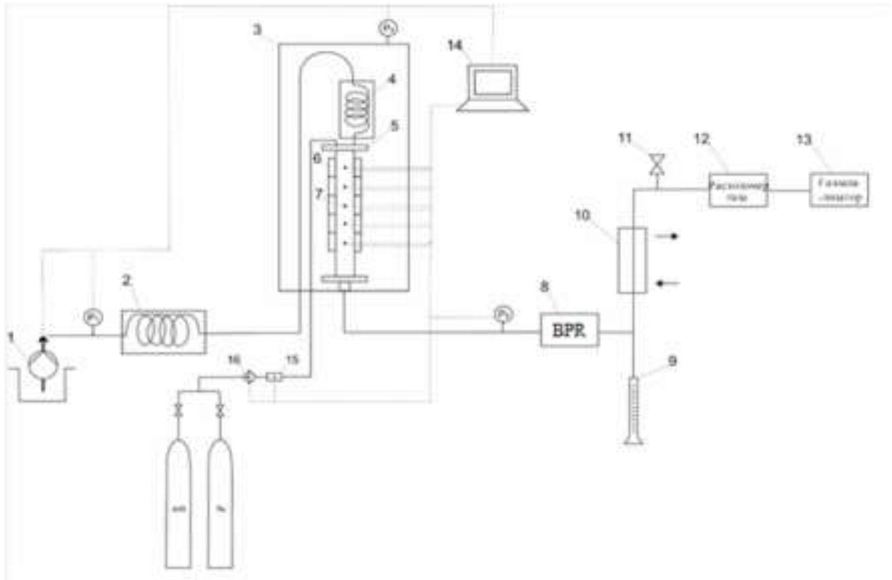

Fig. 2.1 – Equipment scheme for the study of thermal enhanced oil recovery methods

The injection agent (steam) system consists of a precision high-pressure plunger pump of the *LN-400* brand (accuracy of maintaining the flow rate of 0.5% of the current value) (1), dosing water at a constant speed to the input of an external steam generator (2), systems of tubes connecting the external (2) and internal steam generators (4), core holder (5). The high-pressure chamber (3) includes an internal steam generator (4), core holder (5) with core samples, ceramic electric heaters (6) and thermocouples (7).

The possible vertical and horizontal arrangement of the model. The fluid collection system consists of a back pressure regulator *EQUILIBAR* (8), which ensures the reservoir pressure maintained in the model and the inflow of fluid into the separation burette *Heidolf* (*GOST 2925-9.20C 2 cells, 25 ml*) (9), where separation occurs under standard conditions for liquid and gas. Gas, depending on the model of oil and the gas factor, goes through into gas meter, then into the gas analyzer (13) to determine its composition. Optionally, a gas composition by chromatography is possible to analyze in front of a gas flow meter (11).

Precision pressure sensors *KORUND-DI-001M-553* with a permissible reduced basic error of ± 0.1% are installed at the inlet and outlet of the reservoir model and reflect the pressure change in real-time. The thermocouples (7) are mounted on the core holder every 5 cm in the reservoir model and record the movement of the heat front in real-time. Ceramic annular heaters for the maintenance of adiabatic regime are installed along the core holder (5) to prevent heat loss during the experiment. The heater control system (6) is configured to turn on the heaters when the temperature inside the core model rises and the heater turns off when the temperature inside the ring heater rises by 5 °C from the core model temperature. Each heater corresponds to a thermocouple installed in this heater (7).

3. Preparation of sample and liquids for testing

For the experiment, it is possible to use formation water or prepared synthetic brine according to the known component composition. Formation water is mixed thoroughly in the storage vessel and before the application should be filtered through a "filter paper".

Depending on the task stable degassed or isoviscous sample oil can be used.

To determine the oil displacement factor, one can use a composite core model mounted from individual cylindrical samples, or a bulk core model, crushed to a fraction of 0.1-1 mm. When preparing a reservoir model, it is allowed to apply two approaches to take into account the wettability of the rock during laboratory core studies: 1) the method of preservation of wettability (studies on unextracted core); 2) a method for restoring the wettability of a rock (extraction, oil saturation, and “core aging”) [4].

When assembling core samples, it should be noted that to experiment with a thermal effect, a cylindrical core should be fixed inside the core holder so that there is no possibility of an overflow of steam and hot water through the sealing material between the steel wall of the core holder and the core. Overcoming the temperature barrier T = 400°C of a core sealing material, good adhesion to core and steel, the absence of a “wall effect” for the correct determination of the oil displacement coefficient is a decisive factor. The use of fluorinated rubber (*Viton type*) for overburden pressure is usually limited to a temperature of +250°C, and epoxy resins of +300°C. Therefore, in experiments with temperatures above 300°C, a cylindrical core sample is installed inside the core holder to assemble a cylindrical core seal, a centering ring is installed on the end of the core holder, the gap between the inner cylindrical surface of the core holder and the compacted outer surface of the core is filled with thermally expanded graphite, crushed to a fraction of less than 3 mm. Next, thermally expanded graphite is compacted. The assembly procedure is described in detail in [5].

In the case of using a bulk model of the formation, the core material of a fraction of 0.1-1 mm is loaded and rammed into the core holder, if necessary, pressed using a press. The permeability of the reservoir model by nitrogen in the reservoir conditions is determined. To prevent sand grains from entering and discharging tubes, perforated metal disks with screens on them are used.

4. The methodology of the experiment

The core holder for conducting experiments on a bulk and composite core model of the reservoir is a steel pipe with two flanges welded at the ends. Thermocouples are located in the center of the core holder. When arrangement a composite model, thermocouples are located between cylindrical samples, between the end surfaces of which a layer of crushed rock with a thickness of less than 0.3 mm is used to ensure capillary contact. The scheme is presented in Figure 4.1.

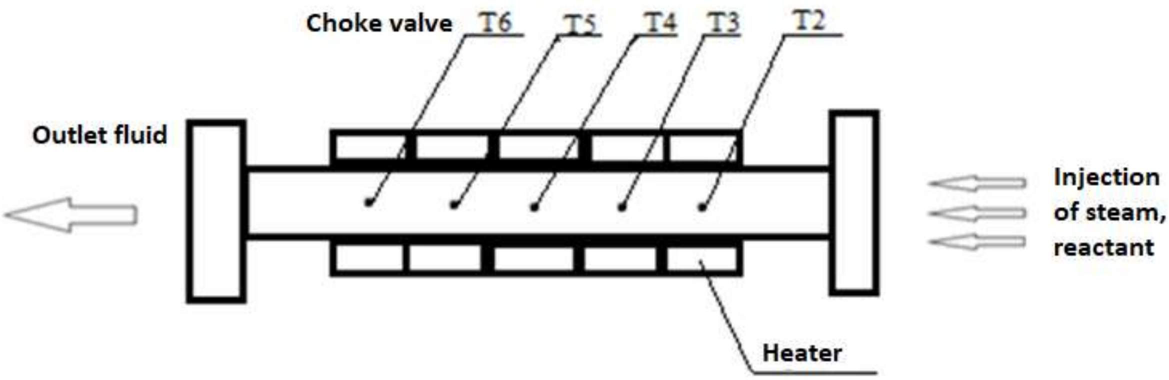

Fig. 4.1 Core holder scheme

At the beginning of the experiment, the reservoir pressure is created by injecting nitrogen into the core holder. Overburden pressure is created by nitrogen taking into account P_{ovb}= 1.2×P_r. It is heated to operating temperature by using an electric heater located at the entrance to the model. To reduce the temperature gradient between the core holder and the environment, the ceramic ring heaters located on the core holder are used to maintain the system in adiabatic conditions.

Steam injection temperature is selected based on pressure according to table 4.1

Table 4.1 - Boiling points of water from 0 to 100 bar [6]

Saturated steam pressure	Boiling temperature	Saturated steam pressure	Boiling temperature	Saturated steam pressure	Boiling temperature
bar	°C	bar	°C	bar	°C
0.02	17.51	11	184.06	58	273.36
0.03	24.10	12	187.96	59	274.47
0.04	28.98	13	191.60	60	275.56
0.05	32.90	14	195.04	61	276.64
0.06	36.18	15	198.28	62	277.71
0.07	39.02	16	201.37	63	278.76
0.08	41.53	17	204.30	64	279.80
0.09	43.79	18	207.11	65	280.83
0.1	45.83	19	209.79	66	281.85
0.2	60.09	20	212.37	67	282.85
0.3	69.13	21	214.85	68	283.85
0.4	75.89	22	217.24	69	284.83
0.5	81.35	23	219.55	70	285.80
0.6	85.95	24	221.78	71	286.76
0.7	89.96	25	223.94	72	287.71
0.8	93.51	26	226.03	73	288.65
0.9	96.71	27	228.06	74	289.59
1	99.63	28	230.04	75	290.51
1.1	102.32	29	231.96	76	291.42
1.2	104.81	30	233.84	77	292.32
1.3	107.13	30	233.84	78	293.22
1.4	109.32	31	235.66	79	294.10
1.5	111.37	32	237.44	80	294.98
1.5	111.37	33	239.18	81	295.85
1.6	113.32	34	240.88	82	296.71
1.7	115.17	35	242.54	83	297.56
1.8	116.93	36	244.16	84	298.40
1.9	118.62	37	245.75	85	299.24
2	120.23	38	247.31	86	300.07
2.2	123.27	39	248.84	87	300.89
2.4	126.09	40	250.33	88	301.71
2.6	128.73	41	251.80	89	302.51
2.8	131.20	42	253.24	90	303.31
3	133.54	43	254.66	91	304.11
3.5	138.87	44	256.05	92	304.89
4	143.63	45	257.41	93	305.67
4.5	147.92	46	258.76	94	306.45
5	151.85	47	260.08	95	307.22
5.5	155.47	48	261.38	96	307.98
6	158.84	49	262.66	97	308.73
6.5	161.99	50	263.92	98	309.48
7	164.96	51	265.16	99	310.22
7.5	167.76	52	266.38	100	310.96
8	170.42	53	267.58		
8.5	172.94	54	268.77		
9	175.36	55	269.94		
9.5	177.67	56	271.09		
10	179.88	57	272.23		

During the experiment, readings of temperatures, pressures, steam flow by water, and the composition of the exhaust gases are recorded. The injection continues until the flow of oil to the separation burette ceases.

Laboratory tests are allowed for students who have passed safety training approved by KFU [7].

5. Processing the results

After the experiment, all the results obtained are presented in the form of the following tables 5.1 and 5.2. A graph of the filtration dynamics is being built: changes in K_{dis}, the drawdown on the model, and temperature profile.

Table 5.1. Reservoir model data

№ sample	Diameter of sample, cm	Length of sample, cm	Porosity, %	Permeability by nitrogen, 10^{-3} μm^2	Initial oil saturation, %
-	-	-	-	-	-

Table 5.2. Data for processing experimental results

Time, min	The volume of injection agent*	T_1, ^0C	T_2, ^0C	T_n, ^0C	P_{inlet}, MPa	P_{outlet}, MPa	V_{liquid}, cm^3
-	-	-	-	-	-	-	-

* The volume of the injection agent V_{inj} is determined by the formula (5.3)

The oil displacement factor K_{dis} by steam is calculated for composite samples containing residual water in an amount corresponding to reservoir conditions, according to the formula:

$$K_{dis} = \frac{Vo}{Voi}, \quad (5.1)$$

where V_o - the volume of oil displaced from the sample under test conditions (reservoir) cm^3;

V_{oi} - the volume of oil originally contained in the sample under test conditions (reservoir).

The volume of oil displaced from the sample is determined by:

$$V_o = b * V_d \quad (5.2)$$

где V_d – the volume of degassed oil in the separation burette, cm^3;

b – formation volume factor.

In the case of using a bulk extracted model saturated obtained by mixing with formation water and stable oil breakdown, it is not allowed to take into account the coefficient of oil volume change - b. If the sample is saturated with oil under reservoir conditions, to calculate Vo, the coefficient b is determined experimentally from the change in the volume of oil in the piston-cylinder at elevated pressure under isothermal conditions.

The agent injection volume is calculated:

$$V_{inj} = \frac{t \times q}{Vp}, \quad (5.3)$$

где V_{inj} – the volume of agent injected into the model (in water equivalent)

t – agent exposure time, min

q – flow rate, cm^3/min

V_p – pore volume of the model, cm^3

Drawdown is calculated on the ΔP model by the formula:

$$\Delta P = P_{inlet} - P_{outlet}, \quad (5.4)$$

where P_{outlet} – model outlet pressure, MPa

P_{inlet} – inlet pressure, MPa

The oil-steam ratio is calculated:

$$OSR = \frac{V_{inj}}{Vo} \quad (5.5)$$

where

где OSR– oil-steam ratio, cm^3/ cm^3

V_{inj} – the volume of the injected agent (hot water, steam), cm^3

V_o – the volume of oil displaced from the model, cm^3

The calculated data are entered in a table and graphs are built (Table 5.3):

Table 5.3. Main characteristics of the experiment

The volume of the injected agent, p.v.	K_{dis}, %	ΔP_{inlet}, MPa	OSR, cm^3/cm^3
-	-	-	-

6. Practical part

The laboratory work is carried out in teams formed by the head of the laboratory, after mastering the theoretical material.

The head of the laboratory issues a technical task to each formed group with which the experiment will be performed, which will be the main stage of educational practice.

Research work is provided in the form of a report and presentation.

Technical task example

Filtration studies to evaluate the effectiveness of thermal methods of oil displacement

1. Purpose of the experiment: Definition K_{dis}

2. The sequence of the experiment;

2.1. Selection of steam injection temperature by a given reservoir pressure;

2.2. Model preparation;

2.3. Determination of the initial oil saturation of the core sample;

2.4. Assembling of the model in the core holder;

2.5. Determination permeability by nitrogen before and after injection;

2.6. Observation of volumes of oil, water and gas affluent, changes in temperature and pressure during the experiment;

2.7. Pressing out the model at the end of the experiment;

2.8. Calculation of K_{dis}, ΔP, OSR

Table 6. Parameters of the experiment

№	Experiment Stage	Parameters				
		Temperature, ^{0}C	Fluid supply cm3/min	Pressure, MPa	Duration	Note
1	Coldwater	23	-	-	-	
	Hot water	100			-	
	Steam	120			-	

3 Processing Results

3.1. Build a graph of the dynamics of fluid filtration at water and steam injection;

3.2. Create a report in Microsoft Word.

3.3. Preparing a presentation in Microsoft PowerPoint and defending it.

Test questions

1) What is a reservoir fluid?

2) What is reservoir oil?

3) What is a recombined oil sample?

4) What is the isoviscose model?

5) What is the coefficient of oil displacement?

6) What is the physical model of the formation?

7) Description of the principle of operation of the laboratory equipment of physicochemical modeling of the process of steam-assisted gravity drainage

8) What is a Core holder, and what is its purpose?

9) What is the backpressure regulator designed for?

10) What device records the gas flow?

11) What is a bulk core model?

12) What is a composite core model?

13) Features of the assembly of core holders with bulk core model?

14) Features of the assembly of the core holder with a composite core model?

15) What is the methodology of the experiment?

16) What is Overburden pressure?

17) How to control the steam flow rate?

18) Which indicators are recorded during the experiment?

19) How to determine the residual oil saturation?

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