Developing the operating principle and mathematical model of the downhole device for injecting scCO₂ in productive formations

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Abstract. Traditional technologies are not economically efficient in terms of processing heavy and extra-heavy oils. Technologies based on the use of supercritical fluids (SCF) may become one of the innovative directions in the production and processing of heavy and extra-heavy oils. Therefore, in this paper the operation principle of the downhole device for pumping scCO₂ into a productive reservoir is developed. The mathematical model is developed either. Calculations with different heat flux densities on the channel wall are carried out. The dependences of the temperature distribution along the length of the heated section are obtained. The calculation results are compared with experimental data.

1. Introduction
The increasing demand of mankind for liquid fuel forces us to produce, refine and use heavy and extra-heavy oil. Heavy and extra-heavy oil isn’t an ideal type of energy commodities, but the huge reserves allow us to link the future of the oil industry in many countries, including the Russian Federation. According to [1] 5.6 billion tons of heavy and extra-heavy oil have been explored and identified within the Russian Federation.

Traditional technologies are not economically efficient for processing extra-heavy oils [2]. Technologies based on the use of supercritical fluids (SCF) may become one of the innovative directions in the production and processing of heavy and extra-heavy oils.

Technologies for the SCF application, especially carbon dioxide, are widely used in various industries, for example, in supercritical extraction, drying, pharmaceuticals, in the production of new materials, etc. [3, 4]. SCF technologies are just at inception of introduction in the oil industry. The main scientific works are focused on SCF research for the oil refining and petrochemical industries. Many experimental laboratory studies show the effectiveness of SCF-technology for injection into the reservoir in order to increase oil recovery, especially supercritical carbon dioxide (scCO₂) [5, 6]. The scCO₂ provides effective reduction of oil viscosity in reservoir conditions.

Now carbon dioxide is pumped into the reservoir in various ways:
1. Carbonated water injection.
2. Continuous injection of CO₂.
3. Cyclic CO₂ injection process (CCIP) in an injection well.
4. CO₂-rim injection followed by water injection.
5. Displacement of oil by alternating injection of CO₂ and water.
6. Displacement of oil by injection of combined fringes of chemical reagents and CO₂.
7. Gas-cyclic injection of carbon dioxide (Huff-n-Puff process).
The injection of carbon dioxide into the reservoir can be carried out in the gas, liquid and supercritical state. Basically, the technical solutions [7, 8, 9, 10] propose to pump carbon dioxide into the reservoir in liquid or supercritical state brought to a given phase state on the well surface.

It is believed that a thermodynamic condition of formation allow the CO\textsubscript{2} to pass into the scCO\textsubscript{2} state when a critical pressure of 7.38 MPa and a critical temperature of 31.1°C are exceeded. These parameters may differ from a field and this is not always possible, especially for fields with heavy and extra-heavy oils.

It may be said that the development of the technique and technology of pumping scCO\textsubscript{2} into the reservoir and its production in field conditions is an urgent task that requires scientific study and justification.

In this scientific work it is proposed to develop a possible principle of operation of a downhole device for producing SC-CO\textsubscript{2} for injection into the reservoir and to investigate of heat transfer carbon dioxide inside the borehole device.

2. Development of operation principle of the downhole device
In scientific papers [7, 8, 9, 10], it is proposed to pump carbon dioxide into the reservoir in a liquid or supercritical state. We believe that these solutions are economically unprofitable due to the energy costs for producing supercritical carbon dioxide on the well surface. It is proposed to use thermobaric reservoir conditions (temperature, pressure) (figure 1) for the rational use of energy costs and the downhole device with heating elements and valves (figure 2). It is possible to create a technological process for the controlled injection of supercritical carbon dioxide into the reservoir by changing the temperature and pressure parameters.

**Figure 1.** Operation principle scheme of the downhole device: 1 – injection well; 2 – downhole device; 3 – productive formation.

**Figure 2.** Design scheme of the downhole device: 1 – valve; 2 – tubing string; 3 – heating element; 4 – isolator; 5 – outer pipe (casing).
It is proposed to install the downhole device at a depth where the reservoir temperature is equal to the critical temperature of carbon dioxide. If the pressure at the required depth is less, then by changing the temperature inside the downhole device the pressure may increase and supercritical carbon dioxide may be obtained. Carbon dioxide should be injected in the gas state, and the device should be mounted on bottom of the well. The condition must be met inside the downhole device:

\[
\begin{align*}
P_{cr} & \leq P_{res} \leq P_{device} \\
T_{cr} & \leq T_{res} \leq T_{device}
\end{align*}
\]

(1)

where \(P_{cr}\) is the critical pressure of carbon dioxide, MPa; \(P_{res}\) is the reservoir pressure, MPa; \(P_{device}\) is the pressure inside the downhole device, MPa; \(T_{cr}\) is the critical temperature of carbon dioxide, °C; \(T_{res}\) is the reservoir temperature, °C; and \(T_{device}\) is the temperature inside the downhole device, °C.

The downhole device may be installed in an injection well to displace oil from the productive formation.

3. Development of a mathematical model

The numerical model was based on solving the Navier-Stokes equations. The standard k-\(\varepsilon\) model was used to simulate the turbulent flow. The NIST model was used to describe the properties of a real gas. The NIST real gas models used the National Institute of Standards and Technology (NIST) Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixtures Database Version 9.1 (REFPROP v9.1) to evaluate thermodynamic and transport properties of approximately 125 fluids or a mixture of these fluids.

The problem of hydrodynamics and heat transfer of supercritical carbon dioxide in a circular channel with a constant heat flux density on the channel wall is considered as a test of the numerical model. The problem statement corresponds to the experiment of Pei-Xue Jiang et.al. [11]. The inner diameter of the channel is 0.27 mm. The length of the heated section is 90 mm. A two-dimensional axisymmetric formulation is considered. The inlet boundary conditions of the computational domain are the value of the mass flow rate of carbon dioxide and the temperature. Constant pressure from experiment [11] is set at the outlet of the computational domain. A no-slip condition is set on the inner wall, and the heat flux density constant is set on the outer wall. A computational mesh of 200,000 nodes with thickening to the channel walls is used.

Calculations with different heat flux densities on the channel wall were carried out. The dependences of the temperature distribution along the length of the heated section were obtained. The calculation results were compared with experimental data, as can be seen from the graph shown in figure 3.

![Figure 3. Temperature distribution on the wall along the length of the channel.](image-url)
There is a good agreement between the calculated and experimental data. The calculated temperature, pressure and velocity fields in the channel were obtained (figure 4).

![Pressure field](image)

![Temperature field](image)

![Velocity field](image)

**Figure 4.** The calculated pressure (a), temperature (b) and velocity (c) fields in the channel.

In the future it is planned to calculate the flow rate, temperature and pressure of carbon dioxide inside the downhole device based on the developed mathematical model.

Conclusions
In this article the operation principle of the downhole device for producing supercritical carbon dioxide has been developed. It has been proposed to install the downhole device at a depth where the reservoir temperature is equal to the critical temperature of carbon dioxide. The mathematical model has been developed either.

The mathematical model result has been compared with the experimental data. In the future the pressure, temperature and velocity values for the downhole device will be calculated.

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