Using capillary pressure curves when searching for analog objects

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Abstract. In this work, the capillary pressure curves were approximated using fractions of various types for the conditions of individual oil deposits of the West Siberian oil and gas province. A mathematical model of capillary curves in the coordinate axes of dimensionless time from the normalized water saturation has been created. The obtained models make it possible to search for analog objects and effectively solve the problems of increasing the efficiency of developing low-profitable deposits with hard-to-recover reserves based on comparing the regression equations of generalized models with models of the required deposits.

1. Introduction

It is known that capillary and gravity forces control the primary distribution of fluids in the reservoir. Capillary survey data allow determining the proportion of mobile and stationary fluids in the reservoir void space. Capillary forces are also taken into account when describing the waterflooding process in complex heterogeneous formations.

In addition, using the data of capillary studies, the following tasks are solved:
- determination of the density of distribution of pore channels of reservoir layers by size, as well as the proportion of participation of pore channels of different sizes in the filtration process;
- description of the vertical distribution of fluids in the transition zone;
- Construction of relative permeabilities curves for oil, water, and gas [1–4].

The capillary pressure curves contain information about the reservoir properties. Our research shows that it is possible to obtain analytical relationships between the reservoir parameters of the reservoir using capillarimetry data.

The generalized model is built by statistical processing of capillary data, which unambiguously characterizes this object as a productive layer.

2. Materials and methods

The use of generalized models makes it possible to assign a new object to any known analog objects in development at the stage of field withdrawal from exploration. This process makes it possible to use the experience of long-term developed fields to develop new objects [5–10].
Consider the mathematical models used for approximating capillary pressure curves. The Leverett J-function and the Brooks-Corey model [11–14] are the most widely used. 

The Leverett J-function is as follows:

$$J(K_p) = \frac{p}{\sigma \cos \theta} \sqrt{\frac{K_{prp}}{K_p}}, \quad (1)$$

where $p$ – capillary pressure; $\sigma$ – surface tension; $\theta$ – contact angle; $K_p$ – water saturation coefficient; $K_{pr}$ – absolute permeability; $K_p$ – the open porosity.

The dependence of the J-function on water saturation, as a rule, has a power-law character:

$$aJ = AK_p^{-n}, \quad (2)$$

where $A$ and $n$ are constant coefficients for a given reservoir.

In some cases, the Leverett function gives satisfactory results. These results are observed in clean or slightly clayey sandstones, in which residual water is found only in subcapillaries.

Clay reservoirs in Western Siberia contain a large amount of residual water adsorbed by clay minerals. Therefore, in the conditions of reservoirs in Western Siberia, the Brooks-Corey model is most often used:

$$K_p^* = \left(\frac{p_0}{p}\right)^{\frac{1}{n}}, \quad (3)$$

where $K_p^*$ = $\frac{K_p - K_{po}}{1 - K_{po}}$ – normalized water saturation; $K_{po}$ – residual water saturation; $p_0$ – initial (inlet) capillary pressures; $n$ – a parameter characterizing the curvature of the capillary curves.

Let us compare the Leverett model with the Brooks-Corey approximation.

Following formulas (1) and (2), the approximation of the capillary curves of the Leverett functions is given by the following expression:

$$p = AK_p^{-n} \cdot \frac{\sigma \cos \theta}{\sqrt{K_{prp} / K_p}}.$$

If the water saturation $K_p$ tends to unity, then the pressure approaches the initial (inlet) pressure:

$$p \to \frac{A \sigma \cos \theta}{\sqrt{K_{prp} / K_p}} = p_0.$$

Then for the Leverett model we get a simple formula:

$$p = p_0 K_p^{-n} \text{ or } K_p = \left(\frac{p_0}{p}\right)^{\frac{1}{n}}.$$

Comparison of the last formula with formula (3) shows that the Leverett model automatically turns into the Brooks-Corey model when using the reduced volume of space.

In other words, the Brooks-Corey model considers the immobility of residual water in the process of fluid filtration. As a consequence, this model is more reasonable and preferable.

However, the correlating functions proposed by Leverett and Brooks-Corey are quite different from the behavior of real capillary pressure curves.

Indeed, if we take the logarithm of expression (3), we get:

$$\ln(K_p^*) = \alpha \ln \left(\frac{p_0}{p}\right), \quad (4)$$

where $\alpha = \frac{1}{n}$.

Thus, in a logarithmic coordinate system, the capillary curve should have a straight-line character. However, this is not observed in real reservoirs. Moreover, the linear nature of the real curves of
The capillary pressure is observed only in the initial section, when the capillary pressure differs little from the initial (input) value.

In the area of medium and shallow water saturation values, the Brooks-Corey function gives distorted capillary pressure values.

Distortion of capillary pressure at medium and large values is equivalent to distortion of the distribution density curve of pore channels in the region of medium and small sizes.

We use the Laplace formula, and in formula (3), we pass from pressure to the corresponding radii:

$$K_p^* = \left( \frac{r}{r_m} \right)^\alpha,$$

where $\alpha = \frac{1}{n}$; $r_m$ – maximum radius of steam channels.

If $K_p^*$ is differentiated by radius, then we will get the density of distribution of pore channels by size [21, 22]:

$$g(r) = \frac{\partial K_p^*}{\partial r} = \frac{\alpha}{r_m} \left( \frac{r}{r_m} \right)^{\alpha - 1},$$

where $g(r)$ is a distribution density of the pore channels along the radius.

Our research shows that, as a rule, the value of $\alpha$ is less than one.

Following this formula, as the radius of the pore channel approaches zero, the distribution density increases indefinitely.

Consequently, the Brooks-Corey function gives distorted capillary pressure values at low water saturation values. In addition, the distribution density function following formula (6) decreases monotonically with an increase in the radius of the pore channel. It does not have an extremum in the interval of existence of the size of the pore channels. However, real density curves obtained under laboratory conditions at small radii increase, reach a maximum, and then decrease and asymptotically approach zero.

3. Results and Discussion

All of the above shows that the Brooks-Corey approximation and the Leverett function are not accurate enough and need to be modified.

The figure shows the dependence of the dimensionless capillary pressure on the normalized water saturation in the logarithmic coordinate system for the AV31 reservoir of the Las-Egan field in Western Siberia.

It is easy to see that the relationship between capillary pressure and water saturation in logarithmic coordinates is parabolic and differs significantly from a straight line.

Since the actual curves of the capillary pressure in the logarithmic system have the form of a parabola, the regression line for the indicated graph is expressed by the following formula:

$$\ln(pr_0) = a + b ln K_p^* + c ln^2 K_p^*,$$

where $r_0 = \sqrt{\frac{K_{pr}}{K_p}}$ – a parameter having the dimension of a radius; $pr_0$ – dimensionless pressure; $a, b, c$ are fixed parameters determined by statistical processing of capillary data.
Let us investigate the approximation function (7). As $K_v^*$ tends to unity, the capillary pressure tends to the initial (inlet) pressure $p_0$.

Thus, $\ln(p_0 r_0) = a$.

Conclusion: parameter $a$ characterizes the initial capillary pressure.

If we substitute the value of the parameter $a$, then formula (7) is transformed to the following form:

$$\ln\left(\frac{p}{p_0}\right) = b \ln K_v^* + c \ln^2 K_v^*.$$  \hspace{1cm} (8)

If we neglect parameter $c$, we get the Brooks-Corey equation. Thus, parameter $b$ characterizes the behavior of the capillary pressure curve in the region of medium and high water saturation values.

A more detailed analysis shows that parameter $b$ characterizes the inhomogeneity of the sizes of the pore channels.

As for parameter $c$, it characterizes the behavior of the capillary curve in the region of medium and small values of the pore channel sizes.

At the fields of Western Siberia, at the stage of exploration and calculation of reserves, a laboratory study of filtration-capacity parameters (porosity, permeability, residual water saturation) is carried out, and capillarimetric studies of core samples for productive formations.

In this case, as a rule, the sample covers the entire range of changes in the reservoir properties of the object, and the sample size is sufficient for statistical analysis at a quantitative level.

Based on the data of capillarity studies of core samples of this object, it is possible to construct a graph comparing the dimensionless capillary pressure from the reduced water saturation in a logarithmic coordinate system. By statistically processing the data of the comparison graph, it is possible to obtain a parabolic approximation of the graph in the form of function (7).

Obviously, the comparison graph contains information about the entire set of data from capillary studies of core samples and the corresponding reservoir properties of these samples. That is, it is a graphical "image" of this object.

In accordance with the above, the parabolic regression equation (7) will be called the mathematical model of the capillary pressure curves, and the coefficients $a$, $b$, and $c$ are the parameters of the generalized model.

Table 1 shows the regression equations for the generalized capillary curve model for many reservoirs of some fields.
Table 1. Regression equations for some fields

| Field name           | Reservoir | Regression equation                        |
|----------------------|-----------|-------------------------------------------|
| Urievskoe            | AB_1      | $y = -0.1642x^2 - 1.7439x - 3.0532$        |
| Andreevskoe          | II        | $y = -0.4034x^2 - 1.7956x - 3.0082$        |
| Cevero-Potochnoe     | BB_8      | $y = 0.1125x^2 - 0.6824x - 2.0565$         |
| Novoortyagunskoe     | IOB_1     | $y = 0.5608x^2 - 1.753x - 2.606$          |
| Ravenskoe            | IOC_2     | $y = -0.0153x^2 - 0.805x - 0.3151$        |
| Las-Yeganskoe        | AB_2      | $y = -0.1684x^2 - 1.2836x - 2.4662$       |
| Las-Yeganskoe        | BB_8      | $y = -0.1249x^2 - 1.412x - 2.924$         |
| Kamennoe             | BK_2      | $y = -0.2046x^2 - 1.7365x - 3.6273$       |
| Lovinskoe            | IO_5      | $y = -0.1419x^2 - 1.4133x - 3.4468$       |
| Lovinskoe            | IO_6      | $y = -0.1879x^2 - 1.5115x - 2.8304$       |

4. Conclusion

Thus, the proposed generalized model makes it possible to approximate real capillary pressure curves with high accuracy, and this, in turn, will make it possible to increase the accuracy and reliability of solving geology and development problems based on the results of capillary studies.

By comparing the regression equations of the generalized model, it is possible to identify analog objects among the fields in development.

At the same time, the experience of developing an analog object can be confidently used in developing this field.

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