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Forecasting capillary pressure curves of polymineral terrigenous reservoir on the basis of well logging data

Abstract. Benefits of forecasting capillary pressure curves of a polymineral terrigenous reservoir with account for lithological heterogeneity are demonstrated. A correlation improvement between the capillary curves control parameter and the effective porosity is achieved by introducing the total water retention factor which reflects reservoir mineral composition. The significant influence of the factor is confirmed by formal statistical test. The resulting correlation trends have high determination factors providing an opportunity for reliable capillary curves forecast in heterogeneous reservoir on the basis of well logging data.

Keywords: capillary pressure, pore space structure, effective pore space, heterogeneity, polymineral reservoir, mineral composition, effective porosity, total water retention factor, Chow test.

Capillary pressure curves are one of the most important parameters of oil and gas reservoirs, defined by special petrophysical core studies. The function of capillary pressure for drainage is used to estimate saturated oil of productive formation, to build a model of transition area and unsaturated oil area. It affects on initial reserves and inflow composition in oil-water area of well (Tiab, Donaldson, 2009). Capillary pressure curve for saturation should be taken into account in the modeling of highly heterogeneous reservoir flooding, as well as in laboratory experiments on displacement and operation of wells in unsaturated areas.

Another important role of the capillary pressure curve is characterized by its relationship with pore space of the reservoir. Interpretation of the capillary curve in dependancy of capillary pressure from effective radius of pore channel allows to build their size distribution in the framework of an equivalent model of pore space. This distribution is used for qualitative parameters of the reservoir and quantitative permeability estimates, relative permeability functions (Tiab, Donaldson, 2009).

To account variations of the capillary pressure curve in heterogeneous reservoir, various models are used depending on reservoir parameters. The most widely used ones are Leverett function (J-function), various types of regulation and division into classes of reservoirs or facies (Kosetino, 2007).

Polymineral clastic reservoirs are typical for various productive objects, in particular for fields in Western Siberia. They were formed in difficult sedimentation conditions in different geological era, followed by densification of rocks and their cementation, redeposition of salts and many other phenomena occurring during the formation of oil and gas reservoirs. Therefore, the prevailing part of polymineral reservoirs is characterized by high volatility in mineral and grain composition, distribution and packaging of grains and cementing material. Lithological heterogeneity in turn causes considerable heterogeneity of productive deposits by textural and structural features, structure of pore space. This explains the significant variation of geological and physical properties of the reservoir.

In such circumstances, the existing methods to generalize core data about functions of capillary pressure give insufficiently reliable results. Basically, this is due to the lack of reliable links between parameters characterizing heterogeneity of capillary curves and interpretation of well logging data.

It is believed that structure of pore space can be described in detail by nuclear magnetic logging. However, firstly, this method is expensive and used in a small percentage of wells. Secondly, the interpretation of nuclear magnetic logging data for pore size distribution has no direct correlation with capillary measurements because of different representation of pore space.

To solve the problem of quantitative description of capillary heterogeneity and pore space of polymineral reservoir, petrophysical model of D.A. Kozhevnikov and K.V. Kovalenko is involved in this project (Kozhevnikov, Kovalenko, 2011). It is in line with ideological concept of the effective pore space (Zakirov et al., 2009). The advantage of this model and methods based on its interpretation is the possibility of direct determination by standard well logging of two highly informative parameters: effective porosity of the reservoir $K_{ef.p.}$ and parameter μ quantifying the change in mineral composition. For example, previous studies demonstrated the possibility of using $K_{ef.p.}$ and μ to significantly improve forecasting reliability in heterogeneous polymineral reservoir (Indrupskiy et al., 2013).

Modeling of capillary pressure curves

Russian and foreign publications have suggested various models of capillary pressure relation with water saturation. They are distinguished by the quality of described actual curves for high or low capillary pressures. Moreover, some models engage additional reservoir parameters, for example, permeability in Tixier model (Dakhnov, 1985), which introduces additional uncertainty in assessment by well logging.

The publication (Kozhevnikov et al., 2013) proposed a model of capillary pressure relation with water saturation, which has a number of advantages over similar models. Its testing on Jurassic core samples showed that for samples with both high and average permeability, a more accurate description of laboratory tests is provided. Furthermore, control parameter of the model has a close relation with effective porosity.

For the authors of this article the main interest is the analysis of capillary parameters relation with mineral composition of the reservoir. The above noted parameter м is used. Its value corresponds to porosity, which defines how bound water held by matrix and cement of given mineral composition fills the pore space. Publication (Indrupskiy et al., 2013) based on comparisons with X-ray diffraction showed that μ quantifies the mineral composition of rocks, with predominant influence of clay cement.

As an example, we reviewed a pack of productive formations in the Jurassic sediments of N field in Western Siberia. The studied formations are represented by uneven interlayering of sandstones, siltstones and mudstones, with interlayers and lenses of carbonate rocks. Cement is characterized by prevailing content of kaolinite with small patches of mixed formations, hydromica, chlorite and carbonate impurities.

Analysis of standard and special research of samples has determined parameters of petrophysical model: porosity and water-holding capacity of matrix, variation range of water-holding capacity of cement. It also allowed us to calculate the value of parameter μ for each sample (Fig. 1). Based on comparison with particle size analysis and X-ray diffraction, applicability of the model and relation of μ and cement mineral composition are confirmed.

To approximate data of capillary measurement three models are considered.

1) Brooks-Corey Model (Brooks & Corey, 1964):

$$K_w = K_{rw} + (1 - K_{rw}) * \left(\frac{P_{dis}}{P_c} \right)^{1/\lambda}, \quad (1)$$

where K_w – current value of water saturation factor; K_{rw} – residual (irreducible) water saturation factor; P_{dis} – displacement pressure; P_c – current capillary pressure; λ – curvature parameter. The main control parameter of the model that requires adjustment for each capillary curve is λ.

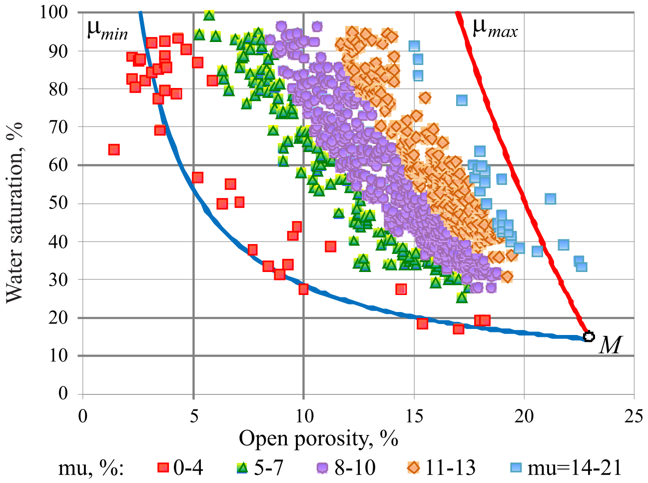

Fig. 1. Dependencies range K_p-K_{rw} for different values of total water-holding capacity of reservoir μ.

2) Tixier Model (Dakhnov, 1985):

$$K_w = \left[\sqrt{1 + \left(\sqrt{K_{per}} / b \right) * P_c} \right]^{-1}, \quad (2)$$

with a control parameter *b*. The disadvantage of this model is in the use of absolute permeability value K_{per}, which is estimated by relations with other reservoir parameters.

3) Model of D.A. Kozhevnikov, K.V. Kovalenko et al. (Kozhevnikov, Kovalenko, 2011; Kozhevnikov et al., 2013):

$$P_c = P_{dis} + \frac{P_{max} * (1 - k)}{K_o^{-1} - k}, \quad (3)$$

where P_{max} – capillary pressure, at which oil saturation reaches the limit $1 - K_{rw}$. Oil saturation K_o is expressed in fractions of effective pore volume. In conversion to conventional valuation (for open porosity) it is expressed by:

$$K_o = 1 - (K_w - K_{rw}) / (1 - K_{rw}).$$

The model is controlled by one main parameter k, closely related to reservoir properties.

As an example, Figure 1 shows best approximation results for each model (1) - (3) of experimental capillary pressure curves (for drainage) for two samples of N field. Brooks-Corey model reproduces good enough shape curves for average values of permeability (Fig. 2a, absolute permeability K_{per} = 23.5 mD), and for low permeable reservoir (K_{per} = 0.19 mD, Fig. 2b) with correctly set displacement pressure P_{dis}. Model (3) also provides qualitative approximation of laboratory curves for both samples. Tixier Model in both cases is unsatisfactory. These conclusions are generally confirmed for all core collection of the object.

We noted the following feature on the example of Figure 2. Brooks-Corey curves are similar in shape to the laboratory ones. However, values of water saturation for low and medium capillary pressure do not accurately reproduce the measured ones. The difference is 10-15 %. This is important when calculating water saturation in the transition zone or evaluating pore size distribution. Namely, both relevant procedures involve determination of pore volume part corresponding to a particular value P_c.

On the other hand, irreducible water saturation (saturated oil) is determined by capillary curve asymptote. Therefore moderate errors in calculation of P_c in its high values, with a small change in saturation, are acceptable.

Thus, when choosing a model describing the dependence K_w – P_c, it is necessary to consider further purpose of its use. From this perspective, preference for the examined object should be given to the model (3).

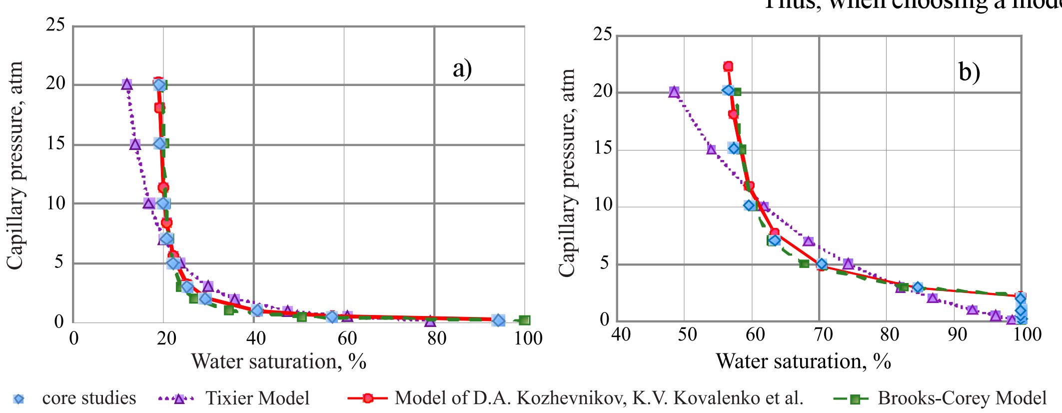

Fig. 2. The capillary pressure curves of two samples of N field according to core studies.

The relation of capillary parameters and effective porosity and mineral composition of the reservoir

To reliably forecast capillary curves in heterogeneous reservoir there must be reliable connections of control parameters with reservoir characteristics interpreted by well logging. Figure 3 shows that curvature parameters λ and b of Brooks-Corey and Tixier models respectively do not identify apparent quantitative relation with reservoir properties. Calculation of mineral composition of the reservoir also does not identify such dependancies (parameter μ).

On the contrary, in the case of model (3) Figure 4a confirms the conclusion of authors (Kozhevnikov et al., 2013) of a close connection of parameter k with effective porosity. Division of samples by parameter μ indicates on some influence of mineral composition. Separate relation can be identified for small values of μ, which corresponds to predominantly kaolinite cement composition for the given group of objects (Fig. 4b).

In general, in Figure 4a it is noticeable that parameter k increases with effective porosity of the reservoir. Separation of trends by parameter μ leads to a further increase in already high coefficient of dependency determination.

Low values of μ are characterized by a steady growth of κ with an increase of $K_{ef.p.}$. This may be due to the different structure of pore space, not fully covered in the value $K_{ef.p.}$, and due to the change of quantitative indicators of wettability of particular pore channels, depending on the mineral composition of cement.

Figure 4b shows that the displacement pressure has also close relation with effective porosity, which is usually interpreted as a reflection of radius of the largest flow pore channel. Involvement of μ parameter further differentiates and adjusts dependence $K_{ef.p.} – P_{dis}$.

Influence of mineral composition on the dependence $K_{ef.p.}$ – k is confirmed by formal statistical test using Chow criterion (Chow, 1960). This criterion is used to check the hypothesis that calculation of differences in correlating trends for two subsamples of total sampling leads to a significant reduction in the total error of forecast correlation. In this case, the total sampling is subdivided into subsamples with low (7-8 %) and higher (9-16 %) values of μ. Chow criterion statistic is expressed by

$$F_{Chow} = \frac{RSS - RSS_1 - RSS_2}{RSS_1 + RSS_2} \cdot \frac{n - k_1 - k_2}{k_1 + k_2 - k}, \qquad (4)$$

where RSS, RSS_1 and RSS_2 – residual sum of squares (sum of squared deviations of actual values from calculated by trend) for general trend of the entire sampling, trends of the first and second subsamples, respectively; k, k_1 and k_2 – number of parameters of relevant trends; n – total number of samples in the sampling.

Formal verification has shown that deviations of values calculated by trends from the values actually measured by core can be considered as subordinate to normal distribution. In this case, the statistic of Chow criterion (4) corresponds to Fisher distribution with number of degrees of freedom (k_1+k_2 – k, n – k_1 – k_2). To check the hypothesis, it must be compared with critical value – quintile of the distribution for accepted significance value α = 0.05. With regard to the reviewed samples F_{Chow} = 9,27 at F_{crit} = 3,49. Consequently, the result is not contrary to the hypothesis of significant influence of mineral composition parameter м on dependence $K_{ef.p.}$.

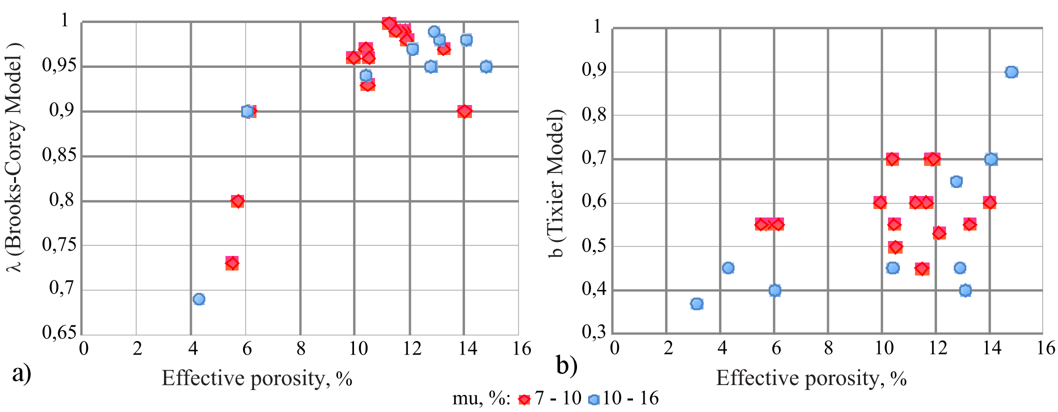

Fig. 3. Relation between parameter λ of the Brooks-Corey Model (a) and parameter b of Tixier Model (b) with effective porosity of samples.

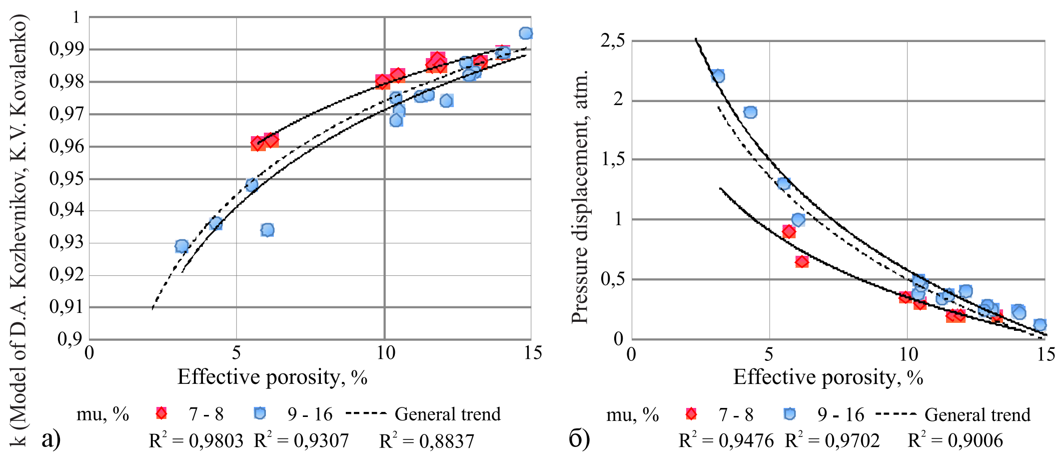

Fig. 4. Relation between parameter κ of Model (3) (a) and pressure displacement P_{dis} (b) with effective porosity and division of trends by parameter μ.

Conclusions

As a part of this project the forecast possibility of capillary curves in heterogeneous polymineral clastic reservoirs by well logging is shown on the example of productive deposits of N field in Western Siberia. High performance of the approach is confirmed using effective pore space and petrophysical model of polymineral clastic reservoir. Dependencies of capillary curves parameters from effective porosity have high coefficients of determination.

To further enhance the forecasting reliability of capillary parameters it is suggested to consider mineral composition of heterogeneous reservoir based on petrophysical model parameter м, defined in conjunction with Кп.эф according to standard well logging. The significant influence of this parameter is confirmed by formal statistical criteria.

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