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Influence of the pore space structure and wettability on residual gas saturation

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Abstract. A significant part of hydrocarbon deposits in Russia is in the late stage of development. The distribution of residual oil and gas reserves is determined by the properties of the holding rocks. Estimating of deposits' residual gas saturation is an important scientific task. The allocation of zones with the maximum undeveloped gas reserves will allow to select areas in long-developed fields for the intensification of production in the most efficient way. To search for such "sweet" zones, it is necessary to determine the factors that provide the value of the residual gas saturation.

The article proposes a method for estimating of residual trapped in pores gas saturation based on quantitative characteristics of the pore space structure and rock wettability.The influence of formation pressure value and behaviour on making up of residual gas saturation during field development is not accounted in this work.

The study of a wide collection of core sampled from productive deposits of the Orenburg oil and gas condensate field, the Vuktylskoe oil and gas condensate field, oil and gas field of Orenburg region, and also three areas in the East Caucasian petroleum province confirmed that the value of structure-trapped oil and gas saturation of carbonate and terrigenous rocks is directly proportional to the ratio of pore diameters and channels connecting them. Herewith the angular coefficient of the regression equation for this relationship for carbonate rocks directly depends on the quantitative characteristics of the predominant (relative) wettability.

The obtained relationships make it possible to predict the value of residual gas saturation based on knowledge about the pore space structure and the surface properties of rocks.

Keywords: residual gas saturation, trapped gas saturation, structure-trapped gas saturation, pore space structure, selective wettability, relative wettability, predominant wettability

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Introduction

Late stages of field development call for improvement of oil and gas recovery. For this purpose, it is necessary to understand the distribution of residual petroleum reserves, which is dependent on reservoir rock properties as well as technology-related factors (Mikhailov, 1992; Surguchev et al., 1984).

Two types of residual hydrocarbon reserves are distinguished. These are of macro-and micro scales. Macro-scale residual oil and gas reserves are located in by-passed zones, lenses and unswept intervals, while micro-scale residual hydrocarbons are accumulated in the flooded areas of the formation (Mikhailov, 1992).

The paper considers a scenario of the buildup of residual gas saturation at the micro scale, particularly behind the flood front under depletion-drive development.

Stronger water-wet properties of a porous gas-saturated medium provide higher residual gas saturation. This results from ever-increasing growth of gas bubbles due to increase in the curvature and concavity of the meniscus of moving water at capillary imbibition front and ever-greater advance of meniscus edges relative to the center during their closure and formation of a new meniscus upon reaching pore contraction point at the subsequent entry into the channel. The larger the pores and the thinner the pore connecting channels (i.e. the greater than unity is the ratio between average diameters of pores and

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connecting channels $d_{pore}/d_{channel}$), the larger the trapped gas bubbles and the higher the trapped gas saturation behind capillary imbibition front at observed reservoir pressures (Bolshakov et al., 2014).

Since residual gas trapping in pores is largely determined by pore structure of reservoir rocks, the resultant residual gas saturation and the corresponding pore volume can be defined as structure-trapped. The fraction of the net productive reservoir volume filled with water intruded during capillary imbibition is defined as producing or dynamic reservoir volume. The extent of this continuously bounded dynamic volume depends substantially on average diameter of pore connecting channels $d_{channel}$ and physical and chemical properties of the surface (Bolshakov et al, 2014, Skibitskaya et al., 2010).

Spot-to-spot variation of water cut in reservoir rocks of gas-condensate and oil-gas-condensate fields, developed generally under depletion drive, is dominated by capillary imbibition behavior depending on porosity and permeability, physical and chemical properties and structure-and-capacity properties of the rocks at macro- and micro scales. The stronger the water-wet state of a gas-saturated reservoir, the greater the rate of direct-flow capillary imbibition. Various studies have demonstrated that the rate of direct-flow capillary imbibition in oil-wet gas-saturated carbonate reservoirs can reach as low as zero (Skibitskaya et al., 2018). Reservoirs with heterogeneous water wetting properties will more likely tend to contain unswept regions at micro- and macro-scales.

Materials and Methods

A comprehensive study of rock samples using lithological and petrophysical, geochemical, physical and chemical methods provided a unique database for the

Fig. 1. A location map of the examined fields and areas. GOF-1 – a gas-oil field located in the Orenburg Region, A1, A2, A3 – production areas of the East Predcaucasus petroleum region.

Location	Field	Lithology	Age	Tectonic confinedness	Number of samples examined in SEM
Volga-Ural Petroleum Province	Orenburgskoye	Carbonate rocks	P_1 - C	Sol-Iletsk Dome	51
Timan-Pechora Petroleum Province	Vuktylskoye	Carbonate rocks	P_1 - C	Northern part of Upper Pechora Depression Pre-Urals Foreland Basin	49
Volga-Ural Petroleum Province	Gas-oil field (GOF-1)	Carbonate rocks	P_1	Sol-Iletsk Dome	21
East Predcaucasus Petroleum Region	Area 1	Carbonate, terrigenous rocks	T_1	Northern edge of East-Manychsky Trough	25
	Area 2	Terrigenous rocks	K_1, J_2, T_3	Chograisky Trough of Manuchsky Troughs zone	22
	Area 3	Carbonate, terrigenous rocks	D_3	South-Western part of Pre-Caspian Depression	10
				Total:	178

Table 1. Characteristics of examined sediments

Orenburgskoye oil-gas-condensate field, Vuktylskoye oilgas-condensate field, a gas-oil field in the Orenburg Region (GOF-1), as well as three areas of the East Predcaucasus petroleum region (A1, A2, A3) (Fig. 1, Table 1) (Khisamov et al., 2014). The aggregated dataset covers the Devonian, Carboniferous, Permian, Triassic, Jurassic, and Cretaceous sediments.

The samples represent, for the most part, carbonate rocks, however terrigenous sediments have also been examined. It is important to note that extraction of the samples did not intend to preserve the native wetting state of the rock surface. Pore structure and wettability of pore surfaces are considered to be the main rock properties responsible for oil trapping effect (Mikhailov, 1992; Surguchev et al., 1984; Dullien et al., 1972).

Results of core studies of the fields listed above enable analysis of these effects. The pore structure of rock samples was examined in a scanning electronic microscope (SEM) using cathode luminescence method (Kuzmin, 1984). Obtained microscopic images of the pore space were processed in *Collector* software program. Its computation algorithm relies on understanding of the void space as a system of pores and channels (Bolshakov et al., 2007). The program allows evaluation of different structural parameters of the pore space, including the ratio between average diameter of pores and the average diameter of pore connecting channels $d_{pore}/d_{channel}$.

Residual (trapped) gas saturation factor S_{gr} was determined by means of direct-flow capillary water imbibition of unextracted rock samples in a state of residual water saturation (Skibitskaya et al., 2018). The authors believe that this method for simulation of residual gas saturation in a core sample most closely reflects residual gas saturation buildup processes during field operation.

Fractional wettability was evaluated using conventional optical measurements of contact angle based on estimated angles of the meniscus formed on sample surface in water/ hydrocarbon fluid system which were updated with state of-the-art digital instruments (Skibitskaya et al., 2016). Water contact angles of hexane-saturated samples in hexane medium $\theta_{w\text{-}h}$ and hexane contact angle of water-saturated samples in water medium $\theta_{h\text{-}w}$ were estimated.

Given that the examined rocks are characterized by complex composition and complex structure of the void space, and the fact that pore surface is unevenly covered with high-molecular oil components of different composition from mixed-wet (asphaltenes, heavy resins) to oil-wet (oils), a part of the pore surface may be water-wet while another part is oil-wet.

In this case, the term “predominant wettability” should be used to characterize the surface properties of the rock.

Predominant wettability represents the tendency of one liquid to adhere to the rock surface in presence of another fluid; particularly, oil-versus-water wetting preference. Predominant wettability was quantitatively expressed in terms of relative wettability parameter $\theta_{h\text{-}w}/\theta_{w\text{-}h}$, which is determined as the ratio between rock contact angles with hydrocarbons and with water. Should relative wettability be less than unity, the sample predominantly imbibes hydrocarbons, i.e. the rock is predominantly oil-wet. Otherwise, relative wettability $\theta_{h\text{-}w}/\theta_{w\text{-}h}$ above unity is indicative of water-wet rock.

Results

Experimental studies of core samples from the central part of the Orenburgskoye oil-gas-condensate field has revealed that residual gas saturation of productive carbonate rocks is defined by the ratio between average diameters of pores and pore connecting channels $d_{pore}/d_{channel}$ (Skibitskaya et al., 2010). Direct linear relationship between S_{gr} and $d_{pore}/d_{channel}$ is characterized by large correlation coefficient and is common for

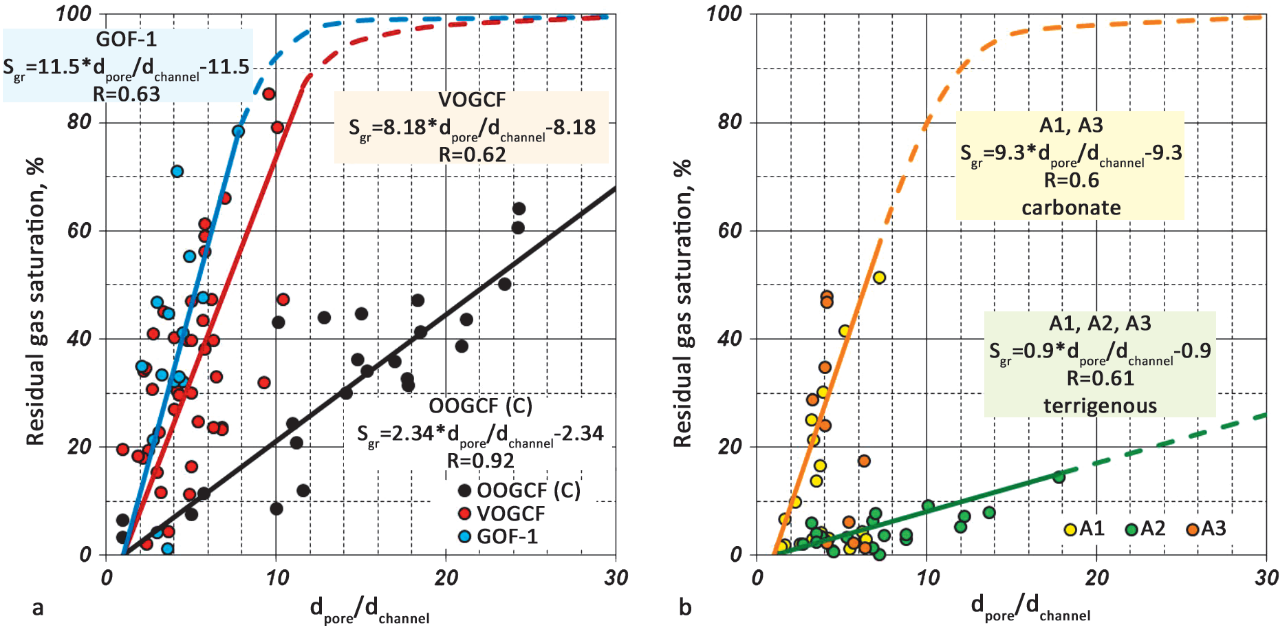

Fig. 2. Relationship between structure-trapped gas saturation factor S_{gr} and the ratio between diameters of pores and pore channel ($d_{pore}/d_{channel}$). a – for productive sediments of the central part of Orenburgkoye oil-gas-condensate field (OOGCF (C)), Vuktylskoye oil-gas condensate field (VOGCF), gas-oil field in the Orenburg Region (GOF-1); b – for productive sediments of Areas 1 (A1), 2 (A2) and 3 (A3) of East Predcaucasus petroleum region.

all stratigraphic units of the field (Fig. 2a). Since gas trapping does not occur if pores and channels have similar diameters, this relationship stems from the point where $d_{pore}/d_{channel}$ equals unity and S_{gr} equals zero. Thus, the regression equation of $S_{gr} = f(d_{pore}/d_{channel})$ takes the form of a linear non-homogeneous equation:

$$S_{gr} = m\cdot(d_{pore}/d_{channel}) - b, \quad (1)$$

where S_{gr} is structure-trapped gas saturation, %; m is slope factor of linear regression equation, %; b is an intercept of linear regression equation, numerically equal to m, %.

Studies of core samples from other fields yielded similar close relationships (Fig. 2a, b). It should be noted that examined core samples from the Orenburgskoye oil-gascondensate field exhibit maximum S_{gr} up to 65% in pores with diameters 24 times greater than channel diameters. The study of core samples from Vuktylskoye oil-gascondensate field and gas-oil field in the Orenburg Region has demonstrated that residual gas saturation reaches 80-90% even at $d_{pore}/d_{channel}$ of approximately 10. At higher pore/channel diameter ratios the function $S_{gr} = f(d_{pore}/d_{channel})$ for these fields will probably be nonlinear (Fig. 2a). However, no actual data has been obtained to confirm it for this set of samples.

Similar dependence plots were obtained for reservoir rocks of production arears 1 (A1), 2 (A2) and 3 (A3) of the East Predcaucasus petroleum region (Fig. 2b). Comparison of linear sections of $S_{gr} = f(d_{pore}/d_{channel})$ functions for different fields have shown that the slope angles of these relationships differ significantly (Fig. 2a, b).

Comprehensive analysis of petrophysical, geochemical and physical-chemical parameters of examined samples has revealed that relative (predominant) wettability $\theta_{h\text{-}w}/\theta_{w\text{-}h}$ is the main factor determining the slope angle of $S_{gr} = f(d_{pore}/d_{channel})$, and, accordingly, the growth rate of the residual structure-trapped gas saturation factor when the pore structure undergoes changes from capillary-like to large-pore structure.

This statement is fair for examined carbonate sediments: rock samples from the central part of the Orenburgskoye oil-gas-condensate field, Vuktylskoye oil-gas-condensate field, gas-oil field in the Orenburg Region, as well as for predominantly carbonate rocks of areas 1, 2, and 3 (Table 2). The $S_{gr} = f(d_{pore}/d_{channel})$ relationships for terrigenous rock samples obtained from areas 1 and 3 have substantially lower percent slope compared to carbonate rocks despite high relative wettability (Table 2).

Since the examined terrigenous rock samples are few in number, further studies of the effects of terrigenous rocks wettability on residual gas saturation are required.

Data analysis has indicated a close relationship between relative wettability and the slope "m" of equation (1) (Fig. 3). Thus, an experimental evidence of the influence of relative (predominant) wettability of rocks on trapped gas saturation of carbonate rocks has been obtained.

Conclusion

Studies have shown that the ratio of average diameter of pores to average diameter of pore connecting channels

Field	Lithology	Average wettability $\theta_{h-w}/\theta_{w-h}$	Slope m, %
Orenburgskoye (central part)	Carbonate rocks	0.83	2.34
Vuktylskoye	Carbonate rocks	0.93	8.18
Gas-oil field	Carbonate rocks	1.15	11.5
Areas 1 and 3 East Predcaucasus region	Carbonate rocks	1.1	9.3
Areas 1, 2 and 3 East Predcaucasus region	Terrigenous rocks	1.06	0.9

Table 2. Comparison of average relative wettabilities $\theta_{h-w}/\theta_{w-h}$ and slopes m of equation for $S_{gr} = f(d_{pore}/d_{channel})$ relationship for various fields

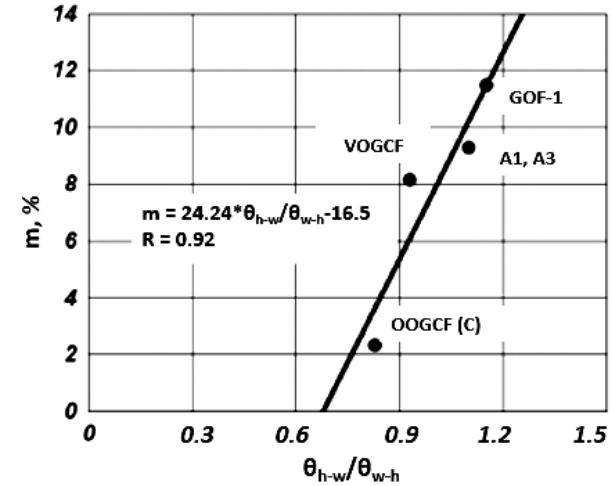

Fig. 3. Relationship between the slope m of the equation $S_{gr} = f(d_{pore}/d_{channel})$ and relative wettability $\theta_{h-w}/\theta_{w-h}$ based on the results of studies of rock samples from the central part of the Orenburgskoye oil-gas-condensate field (OOGCF (C)), Vuktylskoye field oil-gas-condensate field (VOGCF), gas-oil field in the Orenburg Region (GOF-1), areas 1 (A1) and 3 (A3) of East Predcaucasus petroleum region.

controls the volume of trapped gas in both carbonate, and terrigenous rocks. The *S*gr growth rate when carbonate rock pore structure undergoes changes from capillary-like to large-pore structure is dependent on relative (predominant) wettability of the rocks. Attained results enable prediction of residual gas saturation in gas-saturated carbonate sediments of gas-condensate and oil-gas-condensate fields from pore structure and relative (predominant) wettability of rocks. According to conducted studies, predominantly water-wet large-pore carbonate rocks will have the highest trapped gas saturation. Study results confirm the theoretical understanding of the effects of pore structure, physical-chemical rock properties and lithological characteristics on residual gas saturation.

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