Laboratory approaches to estimating and localizing restrained hydrocarbon reserves in depletion-mode formations

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Abstract. A significant part of hydrocarbon reserves during development remains in the reservoir in the restrained volumes of the pore space. In depletion-mode formations, bypassed zones of hydrocarbons not affected by displacement can also form. The paper describes laboratory methods that can be used to estimate the amount of remaining restrained hydrocarbons and their distribution in the reservoir.

1. Introduction
Gas production at gas-condensate and oil-gas-condensate fields, as a rule, is carried out using natural reservoir energy - in depletion mode. Reservoir pressure drop during the development triggers the in-situ mechanisms striving to restore the disturbed thermodynamic equilibrium, including the processes of watering due to direct-flow capillary imbibition and the advancement of the bottom or edge waters into the reservoir.

The process of capillary flooding of gas-saturated sediments is accompanied by the formation of restrained volumes of free gas in the pores, removed from the filtration processes in the reservoir pressure drop mode, that reduces the gas-condensate recovery factor.

So, for the Vuktylskoye gas condensate field the recovery factors for dry gas – 0.795, stable condensate – 0.308 [1], for the Orenburgskoe oil-gas-condensate field – 0.71 [2], condensate recovery factor for Astrakhanskoe gas-condensate field – 0.57 [3], the average gas recovery factor is 0.85, and for fields with significant reservoir heterogeneity 0.7-0.8 [4].

In view of this, producing companies, with the aim of a more rational approach to hydrocarbon resources, are striving to increase the recovery factor by using additional methods of increasing recovery, such as hydraulic fracturing, chemical, thermal and other methods. However, we have previously shown that the values of residual (non-recoverable) gas reserves and their distribution in the volume of the reservoir largely depend on the pore space structure (PSS) of the reservoir rock [5].

2. Materials and methods
This paper provides a brief description of two laboratory methods that supplement the standard petrophysical complex of studies with very valuable data. These are direct-flow capillary imbibition (DCI) and aspiration thermomassometry (ATMM) methods. In the experiments, core samples of cylindrical or cubic shape are investigated with the possibility of multiple repetition.
3. Results

The first important point highlighted in this work, which should be considered when designing the development and additional development of the deposit, is the need to build a geological model of the restrained volumes in the pores, as well as the typification of rocks according to the PSS. So, in a large-pore reservoir in large pores, we have a large restrained volume that is not involved in the filtration process, and in a porous subcapillary-pore reservoir, the restrained volume will be small with a high value of the porosity coefficient. In order to extract additional volumes of hydrocarbons, specialists need to carefully select the zones of the reservoir according to the amount of hydrocarbons in the restrained pore volumes and the probability of involving these volumes in development by one or another stimulation method. It should be noted that for an oil reservoir, the amount of restrained oil will correspond to the geometric restrained pore volume, and for a gas reservoir, the amount of gas should be considered based on the equilibrium reservoir pressure at the time of development, since as the pressure drops, part of the gas in the central restrained part of the pores passes into the filter volumes and is displaced. The dynamic volume for an oil reservoir, calculated as the difference between the effective and restrained volumes, determines the maximum recoverable volume of oil in the reservoir without the use of stimulation methods.

The values of the restrained volumes $K_r$ are provided by the laboratory method of DCI. The research process consists of the following stages:

- 100% saturation of the rock sample with water;
- Centrifugation of samples, after which there is residual water in the rock (film tightly bound water and water of pore angles). The rest of the pore space is usually called effective; in the productive formation it is occupied by hydrocarbons;
- Direct-flow capillary imbibition with water, by bringing one face of the sample into contact with water. As water is imbibing, gas (air) from the pore space comes out through the open surface of the sample, forming a restrained and dynamic volume in the pores (figure 1). Continuous registration of changes in sample weight over time.

![Figure 1. Scheme of the formation of restrained volumes in pores during direct-flow capillary imbibition of hydrophilic rock with water: 1 – restrained pore volume; 2 – dynamic pore volume; 3 – water of pore angles; 4 – film water; 5 – rock sample; 6 – water surface.](image)

Then, in the process of building petrophysical relationships, the values of the restrained volumes are correlated with other parameters, such as open ($K_p$) or effective ($K_p\ ef$) porosity. For a good correlation, the studied collection of samples must be large and representative. Having a geological model, using the obtained relationships, it is easy to construct a three-dimensional distribution of the
restrained gas-saturated porosity $WKr$ and give recommendations on the most promising zones (figure 2).

![Figure 2](image.png)

**Figure 2.** Stages of allocation of zones with maximum concentrations of residual volumes of restrained in the pores gas $WKr=Kr*Kp$.

- Results of direct-flow capillary water imbibition of rock samples in residual water saturation state (DCI experimental curves);
- Petrophysical relationships $WKr=f(Kp\;ef)$;
- 3D model of the distribution of the restrained gas-saturated porosity and the maps of linear volume values of the restrained gas saturation in the pores $WKr$ during watering of the reservoir.

Knowing the distribution of the restrained volumes is important during the development of the reservoir, until it is fully watered, however, studies of the DCI can provide valuable information for watered objects at a late stage of development.

In field practice, the phenomenon of the formation of bypassed zones - areas in the depleted part of the deposit, from which oil remains unrecovered - is widely known [6]. One of the main reasons for the appearance of bypassed zones is the uneven moving of the water-bearing contour, the formation of watering tongues due to capillary forces leading the front of the piston displacement. The formation of oil bypassed zones leads to a decrease in the overall hydrocarbon recovery factor.

The experiment on the DCI with data logging in real time gives us not only the value of the restrained and dynamic volumes, but also characterizes the dynamics of fluid movement due to capillary forces - this is the second important parameter that must be considered when planning additional development of the reservoir. As was shown in [7], the speed of the DCI depends on a number of parameters, such as wettability, porosity, permeability, and can have a different form of relationships for different objects. However, having reliable regularities, 3D models of porosity, permeability and wettability it is also possible to come to creating of a 3D mathematical DCI speed model and then a hydrodynamic model that considers DCI speed (figure 3).
Another laboratory method that can supplement the DCI method with important information is the ATMM method. The laboratory method [8] developed in the 70s of the XX century received insufficient attention, but today its applicability is undeniable. The essence of the method consists in drying a rock sample saturated with liquid (water / hydrocarbons) in an air stream of constant speed and temperature (25 °C). During the experiment, readings of changes in mass, temperature of the sample surface and air are taken.

The ATMM unit improved with the latest technical advances gives a "passport" of the fluid saturation of the rock according to the forms of energy connection with the rock - from 100% saturation to a hygroscopic state. That is, using thermomassometric curves within one experiment, it is possible to distinguish the restrained volume of liquid in the pores, the funicular (dynamic) volume, the fraction of fluid in the corners of the pores, the fraction of fluid in microcapillaries of different radii (figure 4).

4. Discussion
In oil and gas science there is already an understanding of the need to work with effective pore space, speaking of fluid filtration [9,10]. While going along the path of complication, one should also remember that the effective space includes both dynamic bound volumes and volumes that are restrained by the pore structure and the physicochemical properties of the pore surface. The laboratory methods described above provide data to estimate the amount of hydrocarbons in the restrained and free state.

Using the DCI speed in the hydrodynamic model makes it possible to obtain a more reliable picture of the reservoir coverage by waterflooding and to identify possible bypassed zones both at the moment of development and in the predicted future. On the basis of these data, it is possible to make recommendations for the development of the zones of hydrocarbon deposits not affected by flooding.
Figure 4. An example of the experimental relationship between the water saturation of the sample (Kw) with the difference in air and sample temperatures (dT).

ATMM method can be an alternative, a control method, or an additional source of information for centrifugation, semipermeable membrane, NMR, DCI methods. An additional advantage of this method is the preservation of the sample in an intact state – in case of centrifugation, a weakly consolidated core can be destroyed.

5. Conclusion
Laboratory petrophysical CDI and ATMM methods are very relevant today, since they allow:

- Estimate hydrocarbon reserves restrained in pores;
- Create a model of the DCI speeds in the reservoir and to localize the potential or existing at the time of development bypassed hydrocarbons zones, due to the capillary movement of water, ahead of the displacement front or the rise of the OWC;
- Obtain fluid-saturation passport of by the forms of the energy connection of fluid with the rock without destroying the sample.

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