

## DIRECT AND INDIRECT CONNATE WATER SATURATION DETERMINATION METHODS IN THE PRACTICE OF RIAES

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### Introduction

The recent increase in world energy demand makes it important to increase the recovery factor of the known hydrocarbon resources, and to improve the technologies making non-conventional hydrocarbons exploitable. In order to consider the economic aspects of the production of the conventional and non-conventional hydrocarbons, it is definitely required to determine amount of the in situ producible hydrocarbon (original oil/gas in place). The magnitude of the original oil/gas in place influences the economic assessment of the production methods available or being developed. It also affects investment decisions about available or newly applied technologies to a large extent.

When hydrocarbon resources are explored and developed, in order to estimate the original oil in place the so-called volumetric method is used, which, apart from the geometric extension of the resource (rock volume, pore volume), makes it necessary to determine the fluids filling the pore space. The original oil in place of the saturated oil field can be determined by the following relationship:

$$N = \frac{V\phi(1-S_{wi})}{B_o} , \quad (1)$$

where  $N$  - original oil in place,  $\text{sm}^3$ ;

$V$  - effective rock volume (net pay volume),  $\text{m}^3$ ;

$\phi$  - average porosity of reservoir rock, dimensionless;

$S_{wi}$  - initial or connate water saturation, dimensionless;

$B_o$  - oil formation volume factor,  $\text{m}^3/\text{sm}^3$ .

For conventional hydrocarbons, the minimum value of the initial water saturation is called the irreducible or connate water saturation. Connate water saturation is the amount of the water which adsorbs on the surface of the grains of the rock or on the walls of the porous pore channels (immobile with the traditional displacement methods) divided by the pore volume. For conventional hydrocarbon reservoirs, the initial water saturation is higher than or equal to the connate water saturation of the rock, so the following inequality can be written:  $S_{wi} \geq S_{wc}$ . It depends on the evolution circumstances whether the water saturation of the saturated oil field in our example is higher than the connate water saturation or not. For non-conventional hydrocarbon resources, the initial water saturation can be even lower than the connate water saturation.

On the basis of this, it is obvious that for the conventional hydrocarbon fields, the maximal value of the original oil in place occurs at the connate water saturation, while for non-conventional hydrocarbon fields, the connate water saturation means a good estimation of the amount of the hydrocarbon. Thus, it can be said that in order to determine the initial

water saturation and the connate water saturation, it is necessary to estimate the original oil in place.

Several methods are known from the literature to determine the saturation and the water saturation of the reservoir rocks at laboratory conditions. (i.e. the retort method, Dean-Stark distillation method, Soxhlet extraction method). All these methods assume that the tested rock sample has representative fluid saturation. However, with the traditional sampling method it is practically impossible to get a sample with representative fluid saturation. Although special sampling methods do exist (Sponge Core Barrel, Pressure core barrel), they are very expensive, and thus they are only rarely applied in industrial practice.

Considering that in most of the cases, there is no representative rock sample available, there are three methods used in the Research Institute of Applied Earth Sciences at the University of Miskolc in order to determine the connate water saturation of the rock samples. They are the following:

- Determination of connate water saturation with a rock centrifuge;
- Measuring the connate water saturation by the displacement method;
- Calculation of connate water saturation by recalculating the mercury-air capillary pressure curve for a water-air system.

The latter two methods were developed in the Research Institute of Applied Earth Sciences (RIAES), primarily for tight, non-conventional hydrocarbon reservoir rocks.

If we have samples with representative fluid saturation, the Soxhlet extraction method is used. Here the determination methods are introduced for the connate water saturation of rock samples with non-representative water saturation.

Before the tests, the plugs are prepared for laboratory measurements by drilling, cutting cleaning and drying of the reservoir rocks. The samples are then cleaned, i.e. the drilling mud and hydrocarbon impurities are removed from them. Then they are dried in a vacuum oven until they reach a constant weight. The determination of the connate water saturation is performed on rock samples prepared in this way.

## 1. Determination of connate water saturation with a rock centrifuge

In the hydrocarbon industry, a frequently applied method of connate water saturation determination is obtaining the capillary pressure curve by a rock centrifuge measurement.

The theoretical background of this is the following. If the water is displaced from the 100-percent-water-saturated water wet sample with a non-wetting fluid (air, gas or oil) (drainage), and then, from the rock sample treated in this way, the oil/gas is displaced with a wetting fluid (water) (imbibition), and the displacement pressures are plotted against the water saturation of the sample, we can get capillary pressure curves like those shown in **Fig. 1**. To displace the fluid from a pore channel with a radius  $r$ , it must exceed the capillary pressure in the pore channel. Thus, the pressure values measured during the displacement are equal to the capillary pressure of the rock-fluid system.

In **Fig. 1** it can be seen that the drainage capillary curve asymptotically approximates the connate water saturation (dashed line). This means that the further increase of the applied displacement pressure does not result in the decrease of the saturation of the wetting fluid; thus, the irreducible or connate water saturation is reached.

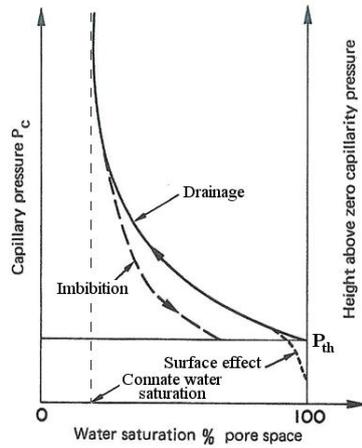


Fig. 1. Capillary pressure hysteresis of porous rock

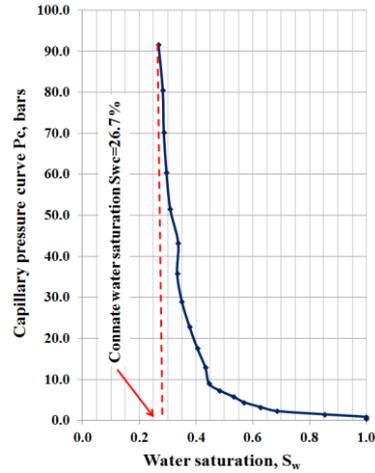


Fig. 2. Capillary pressure curve (drainage) of Sample 1

Therefore, it is obvious that if the drainage capillary pressure of a tested sample is determined by a rock centrifuge, the asymptote/tangent line dragged to the curve gives the connate water saturation of the sample.

In RIAES, a CoreTest URC-628 rock centrifuge is used to determine the capillary pressure curve and the connate water saturation. The maximum rotational speed of the centrifuge is 16,500 rpm. The geometric parameters of the centrifuge ensure a maximal  $P_c=100$  bar reachable capillary pressure for the water-gas system. Three buckets can be placed into the rotor of the URC-628 centrifuge. Into each bucket a sample can be placed of a maximum diameter  $d=1.5$  inches and length  $l=1-2$  inches. After the samples are saturated with water and placed in the buckets, the measurement can be started. The control program of the centrifuge keeps the rotational speed at a constant value during a previously set time interval before making the step to the next rotational speed value, until the maximum rotational speed. During the measurement, the fluid that leaves the sample is collected in collecting tubes at different rotational speed values (capillary pressure values), where the liquid level changes with this. The movement of the liquid level can be traced on a computer screen by the movement of the peaks of curves. The movement data is sent to the computer by a special camera installed on the centrifuge. By using a correctly calculated millilitre/pixel ratio (obtained from a previously performed calibration), the amount of the remaining fluid at a capillary pressure interval can be determined. Thus, the fluid saturation of the sample can also be determined.

In Fig. 2, the centrifuge capillary pressure of a medium porosity ( $\phi=11.3\%$ ) low water permeability ( $k_w=2.6$  mD) Hungarian hydrocarbon reservoir sandstone sample can be seen. The connate water saturation ( $S_{wc}=26.7\%$ ) determined from the capillary pressure curve is also shown in the figure.

## 2. Measuring the connate water saturation by displacement method

We place the prepared, 100-percent-water-saturated rock sample into a Hassler type core holder. To secure isolation, a mantle pressure is set that is 15-20 bar higher than the measured pressure. Then, with a pressure control valve at the inlet of the rock sample the pressure of the nitrogen gas is gradually increased, while at the outlet, 1 bar pressure is held. At the outlet of the rock sample, a special electrode detects the start of the fluid flow, which is placed in a capillary glass tube, i.e. the pressure is measured when the non-wetting nitrogen gas penetrates the rock sample. This pressure value is considered the so-called threshold pressure.

After measuring the threshold pressure on the brine-saturated samples, the displacement is continued after the gas breakthrough until no more water production can be observed. At this point we assume that the sample plug has only connate water saturation and the other part of the pore volume of the plugs is occupied by Nitrogen. After finishing the displacement, the weight of the sample is measured. Since before the displacement the wet weight data of the plug samples were measured and their dry weights are also known, the connate water saturation of the plug samples can be calculated. The connate water saturation  $S_{wc}$  is calculated using the following equations.

$$V_p = \frac{m_{\text{wet sample}} - m_{\text{dry sample}}}{\rho_{\text{brine}}} \quad (2)$$

$$V_{w \text{ out}} = \frac{m_{\text{wet sample}} - m_{\text{dispsample}}}{\rho_{\text{brine}}} \quad (3)$$

$$S_{\text{wirr}} = S_{\text{wc}} = \frac{V_p - V_{w \text{ out}}}{V_p} \quad (4)$$

where  $\rho_{\text{brine}}$  - brine density, g/cm<sup>3</sup>;  
 $m_{\text{dry sample}}$  - dry weight of the sample, g;  
 $m_{\text{wet sample}}$  - wet weight of the sample ( $S_w=1$ ), g;  
 $m_{\text{disp sample}}$  - weight of the sample after displacement, g;  
 $V_{w \text{ out}}$  - water volume produced from the plug sample, cm<sup>3</sup>;  
 $V_p$  - pore volume of the plug sample, cm<sup>3</sup>.

On a low porosity ( $\phi=7.7\%$ ), tight, extremely low absolute permeability ( $k_{gabs}=0.007$  mD) sandstone sample (Sample 2) from 4,095 m depth the threshold pressure ( $P_{th}=73.6$  bars) and the connate water saturation were determined with the introduced method. The connate water saturation was found to be  $S_{wc}=67\%$ .

### 3. Calculation of connate water saturation with recalculates the mercury-air capillary pressure curve for water-air system

During the mercury injection porosity measurement of the rock samples, the so-called mercury-air capillary pressure curve can be determined. In RIAES a calculation method was developed with which not only the capillary pressure of the mercury-air capillary pressure can be recalculated to an water-air system, but water saturation can also be calculated from the mercury saturation.

Thus, from the calculated capillary pressure curve for the water-air system, with the determination of the tangent and asymptote, respectively, shown in Section 1, the connate water saturation can also be determined.

Using the mercury capillary pressure curve data (air/mercury system), first the capillary pressure to water/gas system  $P_{cw/g}$  was calculated. This can be done by the following relationship:

$$P_{c\ w/g} = \frac{\sigma_{w/g} \cos \theta_{w/g}}{\sigma_{Hg/Air} \cos \theta_{Hg/air}} \cdot P_{c\ Hg/Air} \quad (5)$$

where  $P_{c\ Hg/Air}$  - is the measured capillary pressure for mercury-air system by Pascal 140 and 440 equipment;

$\sigma_{Hg/Air}$  - is the interfacial tension between the mercury and air (480 mN/m);

$\theta_{Hg/Air}$  - is the contact angle between the mercury and air (141.3°);

$\sigma_{w/g}$  - is the interfacial tension between the water and gas at laboratory condition (70 mN/m);

$\theta_{w/g}$  - is the contact angle between the water and gas (0°) at laboratory condition.

After recalculating the mercury-air capillary pressure to capillary pressure valid for water-gas system, the water saturation could be calculated applying the Purcell [1] method.

Let us consider the change in saturation,  $\Delta S$ , which occurs when the pressure is increased from ( $P_{c1}$ ) to ( $P_{c2}$ ). This change in saturation is a result of liquid either entering (non-wetting liquid) or receding from (wetting liquid) all pores having capillary pressures lying between ( $P_{c1}$ ), and ( $P_{c2}$ ). All pores in this interval may be treated as if they exhibited some intermediate average capillary pressure, ( $P_c$ )<sub>av</sub>. If a number,  $r$ , of such intervals is chosen and if  $n$  is the number of pores in the  $j^{\text{th}}$  interval, then we can derive the following equation:

$$\sum_{i=1}^{n_i} \frac{S_i}{(p_{ci})^2} \cong \left[ \frac{\Delta S}{(p_c)_{av}^2} \right]_j = \int_{s=0}^1 \frac{S_i}{(p_{ci})^2} \quad (6)$$

This integral may be determined by applying trapezoid rule, Simpson's rule or other numerical integration rules. With these averaging techniques, the mercury saturation could be recalculated to average mercury saturation  $S_{Hgav}$  corresponding to the average mercury capillary pressure  $P_{cav}$  that was used in the calculation of the gas-water capillary pressure curves. Then it was assumed that the water saturation  $S_w$  equals  $1 - S_{Hgav}$ .

Thus, the capillary pressure of water-gas system  $P_{cw/g}$  was calculated along with the corresponding average water saturation  $S_w$ . These calculated data can be seen in **Fig. 3** for Sample 2. In **Fig. 3**, apart from the measured mercury-air capillary pressure curve and the capillary pressure curve in water-air system, the connate water saturation determined by our

method is also shown. In **Fig. 3** it can be noticed that the water saturation of Sample 2, which was described in Section 2, is  $S_{wc}=65.89\%$  with this calculation method.

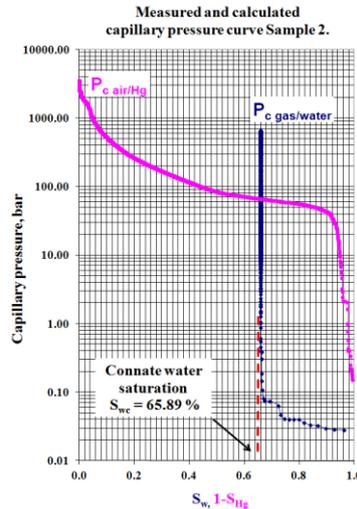


Fig. 3. Measured and calculated capillary pressure curves of Sample 2

## Conclusion

It can be concluded that in the Research Institute for Applied Earth Sciences, using the developed and applied methods for determining residual water saturation, the residual water saturation of rock samples can be determined with acceptable reliability considering petroleum engineering practical aspects.

The presented measurement results of Sample 2, and experience gained from our other numerous measurements on sandstone samples, show that both the direct (displacement method) and indirect (calculation from capillary pressure curve) methods are applicable in petroleum engineering practice for determining the connate water saturation.

It can be concluded that at RIAES there are a wide range of methods and technologies to determine the connate water saturation for the rock samples of both conventional and non-conventional hydrocarbon resources.

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## References

- [1] Purcell, W. R.: Capillary Pressures – Their Measurement Using Mercury and the Calculation of Permeability Therefrom, Petroleum Transactions, AIME, Texas, 1956