THE ROLE OF LABORATORY TESTS IN ENHANCED RECOVERY OF CONVENTIONAL AND NON-CONVENTIONAL HYDROCARBON RESOURCES

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Introduction

During both the increase of the recovery factor of known oil fields and the development of producing technologies of the so-called non-conventional oil fields, several laboratory tests were performed in the past years in the Research Institute of Applied Earth Sciences of the University of Miskolc. These studies pointed out that special petrophysical laboratory measurements (pore size distribution, capillary pressure, relative permeability) and the laboratory displacement test modelling of enhanced oil recovery technologies are essential to understand the processes in the underground porous / permeable structure.

In this paper, based on the laboratory tests of the past years, methods and technologies are introduced by showing measurement results as examples of special laboratory measurements (pore size distribution, displacement tests, wettability properties). Using these methods can contribute considerably to the evaluation of non-conventional hydrocarbon resources, and also to increase the recovery factor of the known hydrocarbon resources.

1. Relative permeability and relative permeability ratio functions for linearly transient flow (for displacement and phase change processes)

The initial displaced fluid saturation of a linear, cylindrical rock sample of length L, cross section A, pore volume V_p is (either oil or water) S_{ki}, and for the displacing fluid, it is S_{di}, and $S_{ki}+S_{di}=1$. The displacement of fluid **k** can occur by fluid **d** when Δp or q_i is constant, when q_i, or Δp changes during the **displacement process** (with time t). The displacement process can be described by the following equations, which can be used for several purposes, including:

- analytical description of the displacement process,
- determining relative permeability and permeability ratios that determine the fluid exchange,
- testing the efficiency of oil displacement by water or by fluid which is not miscible with oil (like water soluble chemicals),

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- reservoir engineering examination of the well draining area of oil field produced by water flooding using relationships that were written for a plane-radial flow system.

Both when ***Δp*=constant**, and ***q_i*=constant** at time intervals exceeding the moment of the breakthrough $t \geq t_a$, the linear displacement equation is valid which determines an analytical relationship between the cumulative volumes of the injected and produced volumes and can be written by the following:

$$V_i(t)/V_k = a + b\left(V_i(t)/V_p\right) \quad , \qquad (1)$$

where $a=f_{kf}=1-f_{df}$, and $b=1/(S_{dmax}-S_{di})$,

f_{kf}, f_{df} – the ratio of the displaced and the displacing fluid at the moment of the breakthrough,

S_{dmax} - maximal displacing fluid saturation, reached at infinite long displacement,

S_{di} - the initial displacing fluid saturation of the rock at the beginning of the displacement.

In case of displacement when ***Δp*=constant,** the change of the cumulative volume of the displacing fluid with respect to time can be written with the following relationship:

$$V_i(t) = a_2 t^{b_2} \quad . \qquad (2)$$

The sum mobility of the displacing and the displaced fluids can be determined by the following relationship:

$$Y(S_{d2}) = \left(L a_2 b_2^2 \left(\frac{V_p}{a_2} \right)^{\left(1-\frac{1}{b_2}\right)} \right) \Big/ \left(\Delta p k A(2b_2 - 1)\right) \cdot \left(\frac{V_i(t)}{V_p} \right)^{\left(1-\frac{1}{b_2}\right)} \quad , \qquad (3)$$

When q_i=constant during the displacement, the change of the depression with respect to time for $t \geq t_a$ time intervals can be written:

$$\Delta p(t) = a_1 \left(V_i(t)/V_p\right)^{b_1} \quad , \qquad (4)$$

The relationship for the sum mobility of the displacing and the displaced fluids can be written in this case with the following equation:

$$Y(S_{d2}) = \frac{q_i L}{kA(1-b_1)} \cdot 1 \Big/ \left[a_1 \left(\frac{V_i(t)}{V_p} \right)^{b_1} \right] \quad . \qquad (5)$$

The determination of the relative permeability functions, in case of constant ***Δp***, when μ_d and μ_k fluid viscosity values of the displaced and the displacing fluids are known, can be performed by the following procedure:

- the f_k / f_d fluid ratio can be determined from **Eq.(1**) by the following:

$$f_k = q_k/q_i = a \Big/ \left[a + b\left(V_i(t)/V_p\right)\right]^2 \quad \text{and} \quad f_d = 1 - f_k, \qquad (6)$$

- the parameters of the $Y(S_{d2})$ function when ***Δp*** is constant can be determined from **Eqs (1),(2),(3)**, while when q_i is constant, it can be calculated from **Eqs (1),(4),(5)**.
- the saturation of the displacing fluid at the so-called inlet section, by using **Eq. (1)**,can be determined from the following relationship in both cases:

$$S_{d2} = S_{di} + b\left(\overline{S_d} - S_{di}\right)^2 = S_{di} + b \cdot \left\{ \left[\left(V_i(t)/V_p\right) \right] \Big/ \left[\left(a + b\left(V_i(t)/V_p\right)\right) \right] \right\}^2 \qquad (7)$$

- thus, the relative permeability ratio can be calculated by combining the $Y(S_{d2})$ function with **Eq. (7)**:

$$k_{rd}/k_{rk}=\mu_d/\mu_k\cdot\left[a\Big/\left(1-\sqrt{b(S_{d2}-S_{di})}\right)^2-1\right]\quad,\qquad(8)$$

- while the relative permeability of the displaced fluid by using the respective form of **Equations (1-8)** can be written by the following:

in case of constant Δp

$$k_{rk}=\frac{\mu_k L a_2 b_2^2\left(\frac{V_p}{a_2}\right)^{\left(1-\frac{1}{b_2}\right)}}{a\Delta pkA(2b_2-1)}\left[1-\sqrt{b(S_{d2}-S_{di})}\right]^{\left(1+\frac{1}{b_2}\right)}\cdot\left[\frac{a}{b^2}\sqrt{b(S_{d2}-S_{di})}\right]^{\left(1-\frac{1}{b_2}\right)}\quad,\qquad(9),$$

in case of constant q_i

$$k_{rk}=\frac{\mu_k q_i L}{a^{(1+b_1)}kAa_1(1-b_1)}\left\{\left[\left[1-\sqrt{b(S_{d2}-S_{di})}\right]^{(2+b_1)}\right]\Big/\left[\sqrt{\frac{(S_{d2}-S_{di})}{b}}\right]^{b_1}\right\}\qquad(10),$$

respectively, and in both cases:

$$k_{rd}=(k_{rd}/k_{rk})\cdot k_{rk}\quad.\qquad(11)$$

Accordingly, the **a** and **b** parameters of **Eq. (1)** – which is the so-called displacement equation – were determined by displacement tests, and it was completed with the parameters of **Eqs. (2)** and **(4)** –the so-called flow equations – and by knowing the basic parameters of the rock sample, by using **Eqs. (8), (9)** and (**10)**, the relative permeability of the two fluids **Eq. (10)** and their ratio **Eq. (11)** can be analytically determined.

1.1 Determination of relative permeability and relative permeability ratio functions. In **Fig. 1** a rock sample can be seen whose parameters are: L=5.67 cm, A=11.95 cm^2, V_p=12.79 cm^3. A displacement test was performed on it. The water permeability of the sample was k=0.0226 D, while its initial water saturation was S_{w0}=1. The water with $\mu_k=\mu_w$=1.04 mPa.s viscosity was displaced from the sample with $\mu_d=\mu_o$ =2.215 mPa.s viscosity oil with constant Δp=3.5 bar depression.

The parameters of the displacement equation are: **a**=0.552069, **b**=1.493923, while $\mathbf{a_2}$=0.0263300, $\mathbf{b_2}$=1.036056 are the parameters of the equation which describes the change of the cumulative volume of the displacing fluid with respect to time.

Since $S_{di}=S_{oi}$=0, thus, (S_{df}-S_{di})=(S_{of}-S_{oi})=((1-a)^2/b=0.1343 and (S_{dmax}-S_{di})= (S_{omax}-S_{oi})=1/b=0.6694; therefore, the relative permeability ratio and relative permeability function can be determined in the interval between these two saturation values.

The relative permeability ratio can be determined from the $k_{rd}/k_{rk}=k_{ro}/k_{rw}$=2.215/1.04·(0.552069/(1-(1.493923·(S_o-S_{oi}))$^{0.5}$)^2-1) equation (**Fig. 1**), while $k_{rk}=k_{rw}$=0.3744875·(1-(1.493923·(S_o-S_{oi}))$^{0.5}$)$^{1.9652}$·(0.247364·(1.493923·(S_o-S_{oi}))$^{0.5}$)$^{0.0348}$ equation for relative permeability for water and the $k_{rd}=k_{ro}=(k_{ro}/k_{rw})k_{rw}$ the relationships for calculating the relative permeability of water and oil were used, respectively (**Fig. 2**).

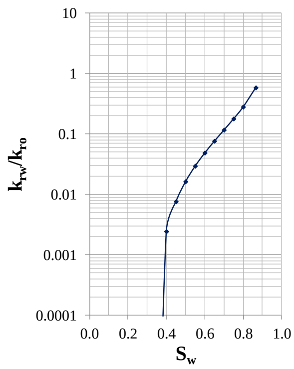

Fig. 1

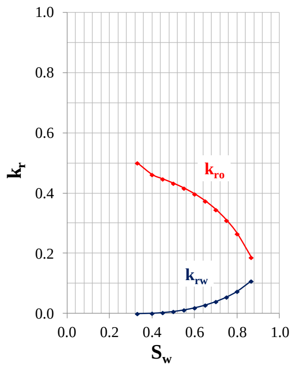

Fig. 2

1.2 Displacement of oil with water and other fluids which are not miscible with oil (e.g. water soluble chemicals); evaluation of the efficiency of the displacement. In **Fig. 3**, the displacement function of the slug type surfactant-polymer oil displacement (2 $\boldsymbol{V_p}$) is shown with the preceding 1 $\boldsymbol{V_p}$ water displacement and the 1 $\boldsymbol{V_p}$ following water injection, while in **Fig. 4** the respective excess displacement efficiency (related to the water displacement) function is plotted (the final result is ΔE_D=0.2243 on the tested sample). In **Fig. 5** the relative permeability curves for water-oil and tenside+polimer-oil systems can be seen too.

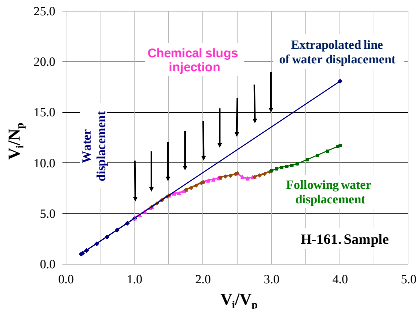

Fig. 3

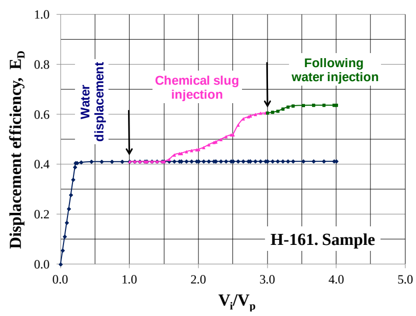

Fig. 4

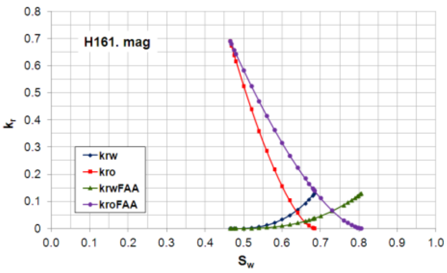

Fig. 5

1.3 Passing through capillary pressure with excess oil recovery. The efficiency of the surfactant-polymer type oil displacement (a very special EOR technology) depends on whether the hydraulic pressure gradient of the displacement is high enough to exceed the capillary pressure gradient at the pore throat or not, when a decreased interfacial tension of reservoir condition water/oil phases occurs at a certain pore distribution in the reservoir rock. The successful study of the problem is shown here with the data of a laboratory surfactant-polymer slug type displacement test.

From the basic **Eq. (12)**, the capillary pressure gradient can be calculated by knowing the water/oil interfacial tension at the pore throat exit:

$$\frac{dP_{cow}}{dl} = -\frac{2\sigma_{ow}\cos\theta}{r^2}\frac{dr}{dl} \quad , \qquad (12)$$

where $\boldsymbol{r}$ is the radius of the pore throat, $\boldsymbol{dr/dl}$ is the change of radius along the length at the pore throat exit, $\boldsymbol{\sigma_{ow}}$ is oil / water interfacial tension, and $\boldsymbol{\theta}$ is the contact angle.

During the displacement tests, a hydraulic differential pressure (depression) $\boldsymbol{\Delta p}$ is applied along the whole length ($\boldsymbol{L}$) of the rock assembly to move the fluids (oil and displacing fluid), thus, the following approximation can be assumed: $\boldsymbol{\Delta p/L \sim dp/dL}$. Thus, if the condition

$$\frac{dp}{dL} \geq \frac{dP_{cow}}{dl} \qquad (13)$$

occurs, the surfactant-polymer slug type oil displacement will be efficient. On the other hand, the pore throats in sandstone-type reservoir rocks are of different radii, what means a difficulty to some extent, but their whole distribution can be given by converting measurement data for air/mercury capillary pressure to a water/oil system (see **Fig. 6**).

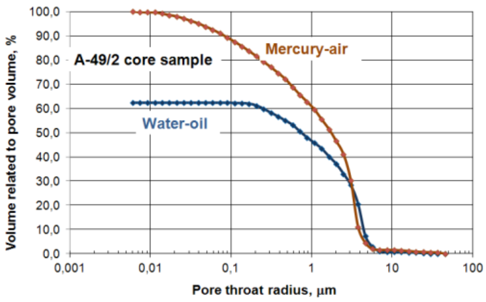

Fig. 6

It is a correct assumption that the oil can be displaced first from the largest pores, then from the smaller ones; thus, by knowing the data of the rock sample and taking the pore throat size distribution (**Fig. 6**) into account, the capillary pressure distribution and hydraulic pressure gradient distribution can be plotted in **Figs. 7-8** at $\boldsymbol{\sigma_{ow}}$=0.5 and $\boldsymbol{\sigma_{ow}}$ =0.1 mN/m and at three different values of dr/dl=0.0001-0.0005-0.0010 as the function of the water saturation.

As can be seen clearly in **Figs. 7-8**, at $\boldsymbol{\sigma_{ow}}$=0.5 mN/m interfacial tension, the hydraulic pressure gradient is not high enough to move the oil droplets at the following water injection, independently from the ***dr/dl*** parameter; therefore, no more oil can be produced during the process. On the contrary, at $\boldsymbol{\sigma_{ow}}$=0.1 mN/m oil/water interfacial tension (**Fig. 8**), the hydraulic pressure gradient remains higher than the capillary pressure gradient throughout the whole displacement; thus, excess oil can be constantly produced.

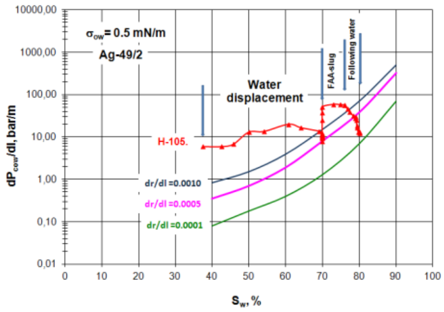

Fig. 7

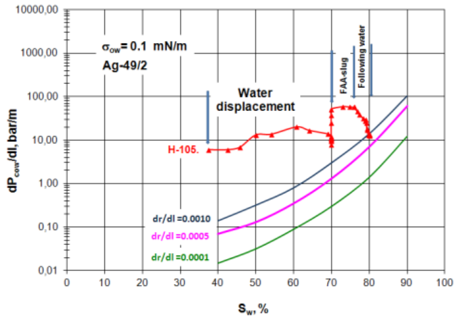

Fig. 8

On the basis of these results (**Figs. 7-8**) it can be assumed that the σ_{ow} interfacial tension is near 0.1 mN/m, since oil can be produced during the following water injection as well.

Summary

Taking the reviewed methods and described examples into account, it is obvious that the evaluation of the recovery factor of the conventional hydrocarbon fields, along with the increase of the oil production, make comprehensive laboratory tests necessary. The aim of performing these tests is to obtain detailed information regarding the relationships between the properties of the reservoir rock and the properties of the fluids, and to clarify the flow processes taking place in the reservoir.

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