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A CRITICAL ANALYSIS OF CRUDE OIL FLOW THROUGH POROUS ENVIRONMENTS IN TERTIARY MIGRATION

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ABSTRACT

In the process of tertiary migration of crude oil, the phase that occurs after the cessation of primary exploitation of petroleum fluid deposits, the deposit is characterized by a state of maximum discontinuity of microscale phases and their abnormal gravitational positioning. This is precisely why it is necessary to discuss the blocking/unblocking mechanisms of wetting phase and non-wetting phase plugs in/out of capillary microtraps. The article presents for the first time a microfluidic behavior of crude oil through cores, with the analysis of polymer flow through rock pores and their filling with petroleum fluids.

Keywords: tertiary migration, oil and gas, microfluidics

INTRODUCTION

The process of tertiary migration of crude oil occurs after the cessation of primary exploitation, the oil and gas reservoirs being characterized at this time by a state of maximum microscale phase discontinuity. Anomalous gravitational positioning of these phases is also observed, the fluid movement through the rock pores being present as a homogeneous flow, interface flow, plug flow and finally as an annular flow.

The factors that influence the flow of fluids through rock pores depend mainly on internal fluid friction, (viscosity) and fluid-rock friction, Δp_{fr} (which opposes flow). Also, both the gravitational component of the fluid, Δp_g (the denser phase descends and the less dense phase ascends) and if the movement takes place in the gravitational plane as well as its gravitational component, Δp_g influence the movement through the pores of the reservoir rocks.

In practice, it has been taken as a calculation convention, the negative sign of the gravity component of the flow of petroleum fluids, when it occurs from top to bottom (that is, it helps the flow) and the positive sign when the gas phase is above and the movement is from top to bottom with a energy consumption.

Another factor influencing the flow of fluids through the pores is the capillary gradient, Δpc, which by convention has a negative sign for spontaneous imbibition and a positive sign for drainage.

The Jamin effect [1, 2] is confirmed by core analysis by the fact that in the case of plugs it always has a positive sign, because any moving plug opposes the movement, the flow being affected when the number of plugs is increasing.

Tertiary flow analysis requires the definition of flow types, the mode of transfer of petroleum fluids through trap channels, pore networks, and microtraps, as well as the macro-scale analysis of flow types.

MATERIALS AND METHODS

The Microfluids research method was used to analyze the types of flow and especially the transfer of petroleum fluids between the constituent elements of the reservoir rocks.

Microfluidics technology involves carrying out experiments on glass-silicon-glass models that imitate the image of the deposit rock.

Usually, to reproduce the structure of the pore space we used in this experiment a microtomography made on a thin section obtained from a core [3,4].

We used the transparent models, together with the experimental arrangement, to generate high-resolution images of the fluid displacement process (Figure 1).

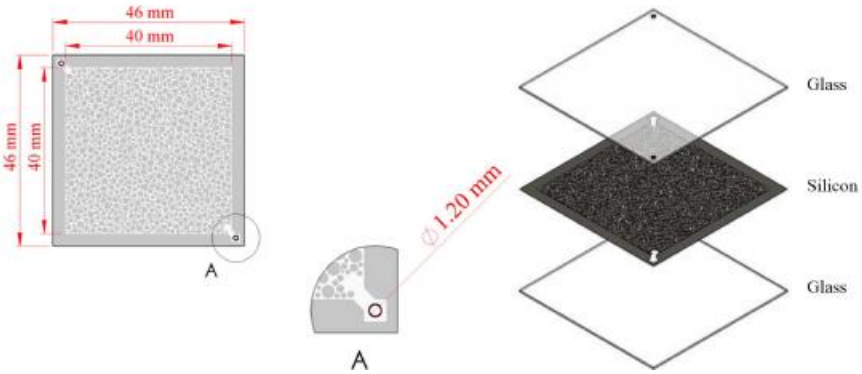

***Figure 1**. Micromodel standard-Rock on a chip devices*

By analyzing the images, the recovery factor, dislocation efficiency, front stability, tortuosity, penetration times, residual saturation and flow type could be determined [5,6].

This technology allowed us to study dislocation processes in complex pore structures by matching the actual grain morphology and pore size distribution to rock porosity.

Microfluidics technology is intended for EOR processes and helps to overcome situations where there are restrictions in running core experiments, either due to the lack of cores or due to economic considerations.

Through the possibility of visualizing the phases in the dislocation process in the porous medium, we achieved a quick sorting of the chemicals with the desired effect in the EOR processes.

The decision time was reduced from several months (in the case of core experiments) to several weeks.

We also used the technology to test the efficiency of displacing petroleum fluids with salt water, fresh water, polymers, surfactants, alkaline solutions, gas or foam. By coating the surfaces using nanotechnology, the wettability of the model could be controlled, ensuring any contact angle, and implicitly any type of wettability.

Micromodels for the study of flow through porous media are considered to have moderately preferential wettability for water. This is precisely why the silicon was covered with a thin layer of oxide (SiO_2) with Si-OH termination. These Si-OH moieties are polar and can be readily deprotonated to Si-O$^-$ upon contact with water.

Likewise, water can easily form dipole-dipole, ion-dipole and hydrogen bonds with Si-OH, while crude oil, being non-polar, forms relatively weak - Van-der-Waals - bonds with the oxide.

The contact with water is thus more favorable from an energetic point of view and the wettability of the surfaces can thus be controlled [7].

MODELING OF FLUID FLOW THROUGH THE PORES OF COLLECTOR ROCKS

The pressure difference relationship that generates flow through porous media is generally defined as follows

$$\Delta p = +\Delta p_{fr} \pm \Delta p_g \pm \Delta p_c \quad (1)$$

We customized equation (1) depending on what forces are involved and the type of flow through the rock pores.

For homogeneous flow (figures 2):

$$\Delta p = +\Delta p_{fr} \pm \Delta p_g \pm 0 \quad (2)$$

In the case of flow at the interface with the meniscus on the right side (figure 3) equation (1) becomes:

$$\Delta p = +\Delta p_{fr} \pm \Delta p_g + \Delta p_c \quad (3)$$

In the case of flow at the interface with the meniscus on the right side (figure 4), equation (1) can be written as follows:

$$\Delta p = +\Delta p_{fr} \pm \Delta p_g - \Delta p_c \quad (4)$$

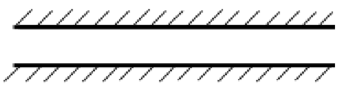

Figure 2. *Homogeneous flow*

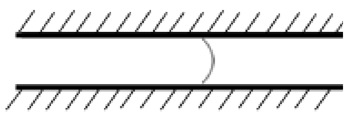

Figure 3. *Flow with interface to the right*

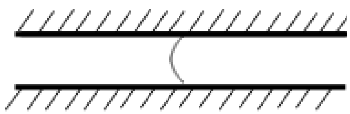

Figure 4. *Flow with interface to the left*

For the study of plug flow (figure 5) equation (1) becomes:

$$\Delta p = +\Delta p_{fr} \pm \Delta p_g + \Delta p_c \tag{5}$$

In the case of annular flow (figure 6) equation (1) can be written in the form:

$$\Delta p = +\Delta p_{fr} \pm \Delta p_g + 0 \tag{6}$$

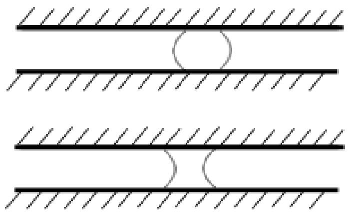

Figure 5. *Leaking oil plugs*

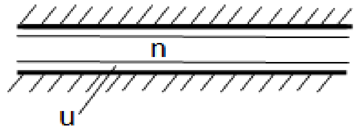

Figure 6. *Annular flow through the pores of reservoir rocks*

The annular flow regime is unstable, with a high surface energy, so it redistributes in the form of plugs. The loss of stability of interfaces and q-plugs has a significant impact in tertiary migration, especially in the initial phase.

In order to provide the clearest possible picture of this factor with a major impact in the restoration of the saturation state in abandoned deposits, in the following we have presented and graphically sketched the blocking/unblocking mechanisms of the wetting phase and non-wetting phase plugs in/from capillary microtraps.

The configurations shown are considered the most stable, with the wetting phase plugs being stable in the region of the constrictions and the non-wetting phase plugs between the constrictions.

a. Plug flow through channels with representation of wetting phase plug blockage in constrictions (Figure 7).

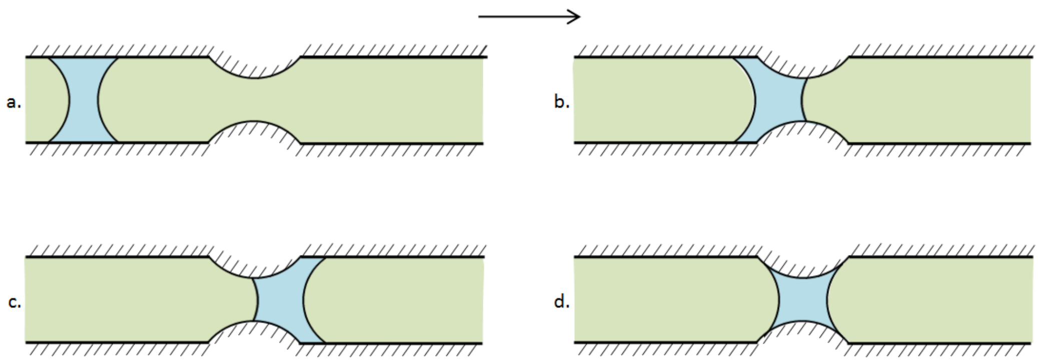

Figure 7. *Locking of wetting phase plugs in constrictions*

With the blue color we represented the wetting phase, and with green the non-wetting phase. The sequence of moving plug positions shows how to block the wetting phase plug. When advancing (fig. 7.a,b), near the constriction, it acquires an accelerated movement.

Figure 7.c. illustrates the situation where the capillary pressure difference is maximum and has the opposite direction to the initial flow direction. Figure 7.d. shows the scenario where there is no external force to force the plug past the constriction.

Increasing the curvature of the interface increases the capillary pressure difference, resulting in rebound and fixation of the plug in the constriction. It blocks and becomes a capillary trap with a major flow blocking effect, also blocking the non-wetting phase until the next constriction.

b. Where the non-wetting phase leads to the blocking of the plugs in the constrictions (figure 8), the blocking mechanism being controlled by the difference between the interface curves and the wetting hysteresis. In this case the non-wetting phase enters a capillary only by force and the pressure must be increased to continue the dislocation. The penetration of the non-wetting phase will also trigger the discontinuity of the dislocated phase.

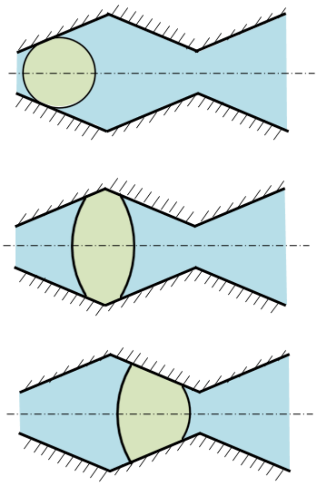

Figure 8. *Blockage of non-wetting phase plugs between constrictions*

c. The flow of plugs through pore networks has a greater complexity than the flow through individual pores, given by the phenomena that occur when the interface reaches the nodes of the network [6] (figure 9).

Analysis of wetting phase displacement (drainage) results from the fact that the non-wetting phase enters a capillary only if the driving pressure exceeds the capillary difference introduced by the interface (figure 9, section 1).

If input, two interfaces are created (figure 9, section 2), the lower one (figure 9, section 3) advancing more slowly has a stronger tendency to stabilize. If the capillary pressure difference is not overcome and for the smaller radius capillary, a plug is formed the length of the capillary. The difference in advance speed between the upper and lower capillary is due to the different radii and the increased friction in the smaller radius capillary (figure 9, section 4).

In conclusion, when a non-wetting phase penetrates a pore doublet, a discontinuity is created in the dislocated phase by the formation of a plug (figure 9 section 5). Moving this plug is practically impossible due to the Jamin effect (figure 9, section 6).

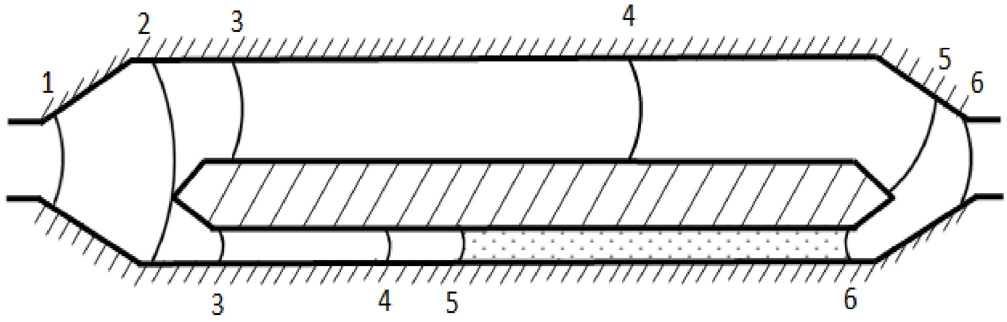

Figure 9. *Evolution of wetting phase dislocation in a pore doublet*

If the dislocation of the non-wetting phase (wetting) occurs in a pore doublet (figure 10, section 1), due to the manifestation of the phenomenon of free soaking, in this case a driving pressure is not necessarily required (figure 10, section 2).

In contrast to the previous case, the interface moves at a higher speed in the smaller radius capillary, with the interface force significantly exceeding the frictional forces (figure 10, section 3).

Fragmentation of the dislocated phase occurs and the formation of a plug, this time, of non-wetting phase, in the capillary with a larger radius (figure 10, section 4).

The two processes described above are the explanation for the existence of irreducible saturations for both the wetting phase and the non-wetting phase (figure 10, section 5).

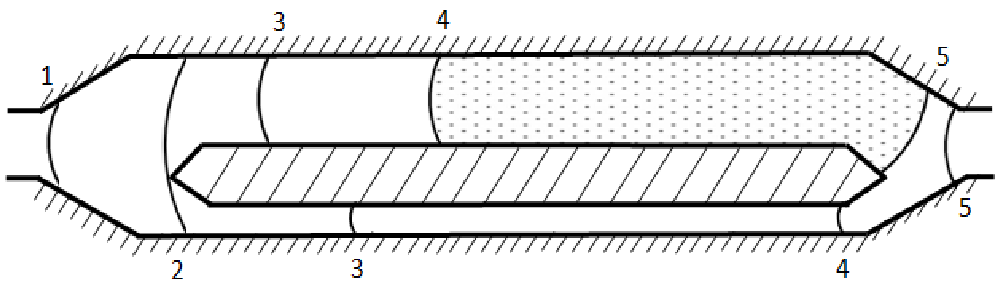

Figure 10. *Evolution of the dislocation of the non-wetting phase in a pore doublet*

d. The analysis of flow through non-wetting phase capillary microtraps in the case of gas fields showed us that the main factors influencing the formation of capillary microtraps are capillary force, hydrodynamic force, the Jamin effect (the additional resistance given by the plug when crossing narrow sections) and constriction connectivity pores.

Gas microtraps (non-wetting phase) can be cutoff or in "bottom of the bag" pores or in "plugs".

- Gas microtraps formed by the cutoff (discontinuity) phenomenon (figure 11) occurs due to the Jamin effect. These bubbles or droplets in the case of liquids stretch and change shape to flow through constrictions.

However, deformation will consume some of the energy, thus limiting the flow of bubbles or granules, adding even more resistance.

It should be noted that this resistance is an effect of the capillary force, the blocked gas may be due to the increase in the displacement pressure necessary to supplement the energy of the bubble trapped by hydrodynamic force or as an effect of the reduction of the deposit pressure, thus favoring the expansion of the gas and its entrainment (partly also due to expansion energy).

In figure 11.a. the additional energy overcomes the resistance, the plug passing the constriction whole or fragmented, and in figure 11. b. the plug expands and other gas bubbles can be aggregated.

- Gas microtraps formed in the "bottom of the bag" pores or in "plugs" make the gas present in these types of reservoir rock channels difficult to dislodge, especially if the water flow pressure in the channel is higher greater than the trapped gas pressure.

It has been shown experimentally that this gas can only be partially produced by reducing the dislocation pressure (figure 12).

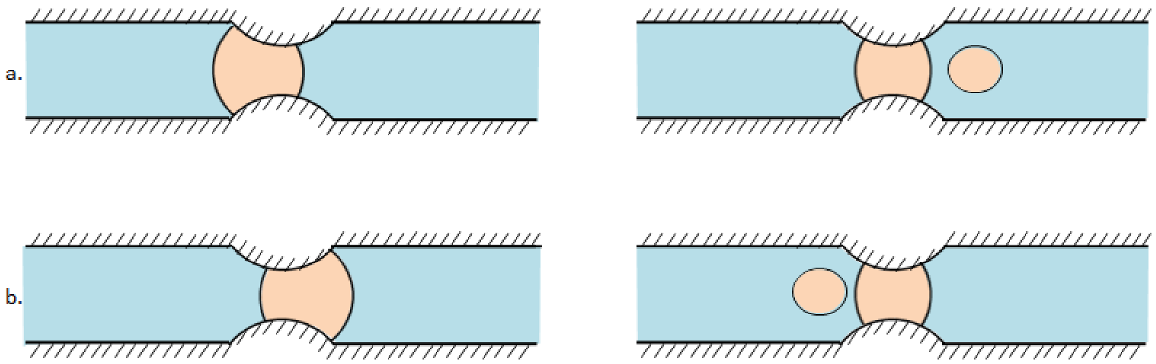

***Figure 11**. Mechanisms for obtaining blocked gas.*
a. Increase in dislocation pressure. b. Reduction of reservoir pressure.

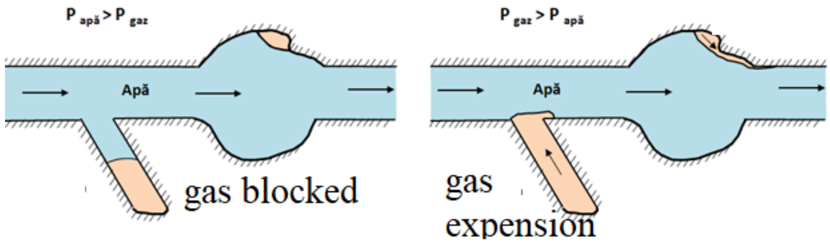

***Figure 12**. The mechanism of production of gas stuck*
in "blockages" or "bottom of the bag" pores.

- Gas microtraps formed by the circumfluence phenomenon have a flow mechanism similar to that shown in figure 8, water being the wetting phase and gas the non-wetting phase. Water enters the channel with reduced section having high flow velocity under the influence of capillary force. Due to the reduced volume of gas and the increased velocity of water in the small-section channel, the water flows quickly through it and blocks the gas that has not had time to be displaced from the larger-section channel.

However, if the hydrodynamic force becomes the main force (dislocation pressure is high) the trap formation mechanism is opposite to the capillary force case. Water preferentially enters the larger cross-section channel, flows through it, and traps gas that has not been displaced in the small cross-section channel.

e. Macro-scale flow is the combined effect of the 4 types of flow, which have different weight depending on the state of saturation (number of phases, saturation in each phase, distribution of phases in the pores), the way in which the change in saturation occurs (if saturation in a phase increases or decreases), wetting hysteresis, interfacial tension value, pore space structure (uniformity, distribution and weight of constrictions, structural difficulty index), wettability contrast and available pressure gradient [8].

As expected, permeability can cover a fairly wide range of values. For this reason, the concept of relative permeability is used, which is obtained from the ratio of the effective permeability of the rock for a certain phase to the absolute permeability of the rock [9].

When only one phase is present in the rock, homogeneous flow occurs. Two or three phases can be present in the deposits, so we are dealing with a heterogeneous flow. There is the possibility of extending Darcy's law for the mathematical definition of heterogeneous flow.

However, considering all the previously mentioned parameters that have an influence on permeability, the most realistic approach for obtaining relative permeability cubes is to carry out laboratory experiments (figure 13).

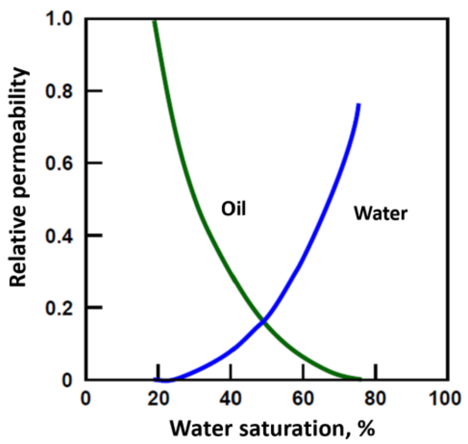

Figure 13. *Typical relative permeability curve for crude oil extracted from Meotian, Sacel, Maramures*

RESULTS AND DISCUSSIONS

The experiments investigating a potential additional mobilization of crude oil extracted from the Meotian and Dacian (Sacel, Maramures) show us that by injecting polymers after the water injection process is finished we obtain a saturation distribution after 14 injected pore volumes (green: crude oil, blue: water, black: solid).

The viscosity of the crude oil used in the experiment is 10.2 mPa s and the pressure difference measured along the micromodel was about $\Delta p \approx 12$mbar.

We observe that after the completion of water displacement in water-preferential wettability medium, the remaining crude oil exists in the form of nodular bulbs called ganglions.

The crude oil remaining after injection of 15 pore volumes is approximately 8 mm^3, of which 71.5 % (5.3 mm^3) is classified as difficult to dislodge and 30% (2.15 mm^3) is considered stuck.

It is possible that polymer solution injection will mobilize some of this difficult-to-dislodge crude under practical conditions.

Blocked crude oil can be directly mobilized only through EOR technologies that involve injection of solutions with surfactants (reduction of interfacial tension).

The average pore size calculated by image analysis from this model is 0.0265 mm^2. The average size of the nodes is 0.55 mm^2. Thus, statistically, a ganglion becomes blocked if it occupies less than about 22 pores.

Ganglions are subdivided into 2 major classes: blocked and difficult to dislodge.

At the same time, in figure 14 we have shown a micromodel with preferential wettability for water and crude oil (Dacian, Meotian, Sacel) where we notice that the colors Green represent the crude oil, Blue is the water present in the analysis and Black is the silicone.

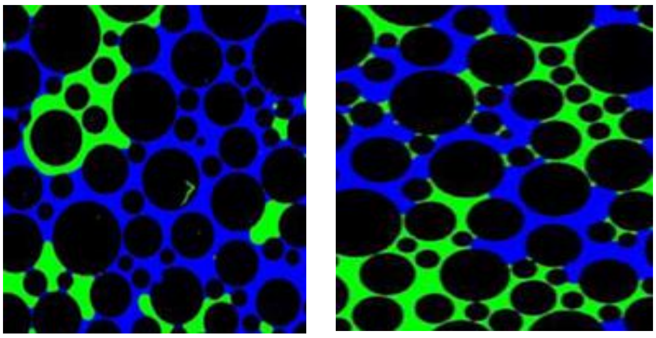

***Figure 14**. Left: micromodel with preferential wettability for water (Dacian, Sacel). Right: micromodel with preferential wettability for crude oil (Meotian, Sacel) (Green: crude oil, Blue: water, Black: silicone)*

CONCLUSIONS

The importance of understanding the formation of nonwetting phase capillary microtraps is not limited to petroleum systems.

CO_2 storage in saline formations such as aquifers may be a solution to climate change.

In this field, however, in the absence of evidence on the existence of a protective rock, the interest is to obtain a residual gas saturation as high as possible.

The material balance known from the dislocation experiments on cores is here substituted with the analysis of the images with an algorithm, with the help of which it is possible to determine:

- the saturation of the oily phase and the aqueous phase and the volumes (distribution),
- statistics on ganglia and their dynamics,
- dislocation and areal washing efficiency,
- recovery factor of crude oil vs. time or injected pore volumes,
- mixing zones during miscible dislocation.

Besides the effects on recovery factor, dislocation efficiency, front stability, tortuosity, penetration times, residual saturation, these experiments can provide new information on some essential parameters in EOR processes such as capillary microtraps and mobilization mechanisms.

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