

# Relative Permeability Hysteresis in Hydrophilic Collectors with Different Saturation types

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## Abstract

Multiphase flow is a subject of study in many knowledge areas. Cyclic changes of pore space saturation causes the appearance of relative permeability hysteresis. Correct account of this phenomenon is needed to avoid errors and inaccuracies in flow simulation of technological and natural processes. Role of relative permeability hysteresis and impact of this phenomenon on oil recovery process is insufficiently studied: Researches usually observe one cycle of saturation change. Goal of the present work is to identify consistent patterns of hysteresis processes in porous hydrophilic systems with different types of fluid saturation. The article presents results of relative permeability experimental studies at cyclical saturation changes in water-gas, water-oil-gas, water-oil (kerosene) systems. Hysteresis phenomenon was found in all systems explored. Qualitative and quantitative description of the observed effects is presented with interpretation in terms of the surface energy at fluid's interface. For water-oil (kerosene) system permeability hysteresis and qualitative differences in drainage/imbibition stages are mechanism of coverage ratio increase in cyclic flooding EOR.

**Keywords:** Hydrophilic Collector, Oil Recovery Process, Relative Permeability Hysteresis, Water-Gas System, Water-Oil-Gas System, Water-Oil System

## 1. Introduction

Multiphase flow is an integral part of many natural and man-made processes and is a subject of study in underground hydromechanics. Flow of liquids and gases in porous media is described by means of relative permeability curves, which is one of the hydrodynamic simulation pillars. Relative permeability curves can be obtained via the direct measurement in a filtration system unit or indirectly by means of mathematical flow models. Mathematical models should reflect the diversity of pore-scale processes and only in this case one can speak about their reliability.

Indicators of multiphase flow are determined by the pore space structure, fluid rheological properties and sur-

face effects at fluid's interfaces. One of the multiphase flow effects is a relative permeability hysteresis in systems with cycle varying saturation. Hysteresis appears in changes of the permeability curve's shape and values of residual fluid saturation. Hysteresis is usually associated with contact angle change of the drop moving forward and backward or non-wetting phase physical jamming (trapping). One should understand that in different reservoir processes both mechanisms may occur in varying degrees. Gas is a non-wetting phase, so probable hysteresis reason is trapping. For water and oil hysteresis mechanism is determined by the mineral surface properties and its wetting property to one of the fluids. Hysteresis mechanisms can be strongly separated only in numeral experiments, unlike physical experiments.

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## 2. Materials and Methods

Hysteresis occurs in cyclic changes of saturation during all immiscible fluids filtration. This phenomenon is commonly discussed in context of WAG EOR, i.e. joint or sequential injection of water and gas into a producing oil-saturated formation to enhance oil recovery. Water-gas system is also of interest in area of underground gas storage in aquifers and depleted hydrocarbon-saturated reservoirs. Storage exploitation causes seasonally cycled water saturation change, which suggests the hysteresis influence on water and gas mobility and in-situ gas losses.

Hysteresis in water-oil systems is rarely discussed, though oil infiltration in water flooded areas can happen during reservoir processes. As an example, this happens when fluid flow changes its direction in cyclic EOR methods. Increase in pore pressure results in building of a pressure drop between high- and low-permeability sub-layers, thereby water moves into the zones with low reservoir properties. Because of subsequent reduction in pore pressure the fluid flow changes its direction and water moves backwards together with oil.

In the open literature sources, one can find permeability hysteresis numerical studies and relatively small number of experimental works<sup>1-21</sup>. Calculations usually describe WAG EOR and clearly indicate the need to consider hysteresis phenomena in flow simulation<sup>1,4,5,16</sup>. Due to the low coverage of experimental research, the question of hysteresis degree in different reservoir systems and the fundamental need for its accounting in flow simulation is still actual. This paper presents results of relative permeability hysteresis experimental studies in hydrophilic plastic reservoirs for water-gas, water-gas-residual oil, water-oil (kerosene) systems. Simulated processes are different: Cycling water saturation change in water-gas system for underground gas storage facility; cyclical flow of water and gas to reduce residual oil saturation in WAG EOR; unsteady water flooding in oil-saturated reservoir. The goal is to identify patterns of hysteresis processes to assess the need of considering them in various technological conditions. Wide coverage of research objects underlines prevalence of hysteresis phenomena and need for its further consideration and incorporation of new results in hydrodynamic simulation modules.

## 3. Results

### 3.1 Relative Permeability Hysteresis for Water-Gas System

Hysteresis phenomena research in water-gas system is actual for underground gas storage facilities design. Such facility exploitation inevitably leads to the gas loss during its evacuation. In-situ losses include: Forming a transition reservoir zone, gas dissolution in water, gas adsorption, gas penetration in low permeability zones and trapping of gas bubbles. Practice of underground gas storage has few decades; however, experimental studies of cycling water saturation changes are quite few. As a rule, subject of these studies is only the first cycle of drainage-imbibition (decrease/increase of water saturation), which determines storage capacity and initially trapped gas volume.

If reservoir is selected for gas storage and its subsequent evacuation, the priority is given to rock collector characterized by little gas trapping effect. Lobanova underlines<sup>12</sup>, that trapping gas loss is only a fraction of a percentage of the total losses in the real working storage of hydrocarbon gases. In contrast, significant gas trapping is a positive factor in ensuring safe storage of waste products such as carbon dioxide in case of irrevocable gas utilization<sup>18</sup>.

Faizrakhmanov underlines<sup>6</sup> the importance of microscopic gas trapping processes study in several cycles of water saturation change. Results of experimental studies on the vertical reservoir model indicate directional change of residual water and gas saturations, gas permeability in few (nine) drainage/imbibition cycles.

As part of this work, research of natural clastic hydrophilic core samples of Tevlino-Russkinskoe field (Western Siberia) was carried out. Goal of the study was to determine amount of trapped gas, saturation dynamics, relative permeability hysteresis for three full drainage/imbibition cycles in water-gas system. One should note that term "trapped gas" implies not only physical trapping of gas bubbles, but also gas adsorption and its dissolution in water, because these effects cannot be fully excluded in experiment conditions.

Research object is hydrophilic sandstone (absolute permeability –  $33 \cdot 10^{-3} \mu\text{m}$ , open porosity -21%). Gas used

is technical nitrogen  $N_2$ , which has quite low formation water (20 g/l NaCl) solubility at experimental conditions (pore pressure – 70 atm, temperature – 30°C). Low gas solubility is necessary to avoid gas dissolution in water and to make focus on physical gas trapping effect.

Experiment was carried out on the Coretest CFS-830 filtration system. Water was pumped through the core column by bi-plunger chromatographic Quizix pump. Gas was delivered from the piston accumulator by water pumping. Column saturation was monitored by the material balance method, using acoustic separator in the column exit filled with water and gas at reservoir conditions. Gas and water flow rates were constant at all experiment stages.

Figure 1 presents water saturation and pressure drop dynamic for hydrophilic sandstone core column during water and gas alternating cycles.

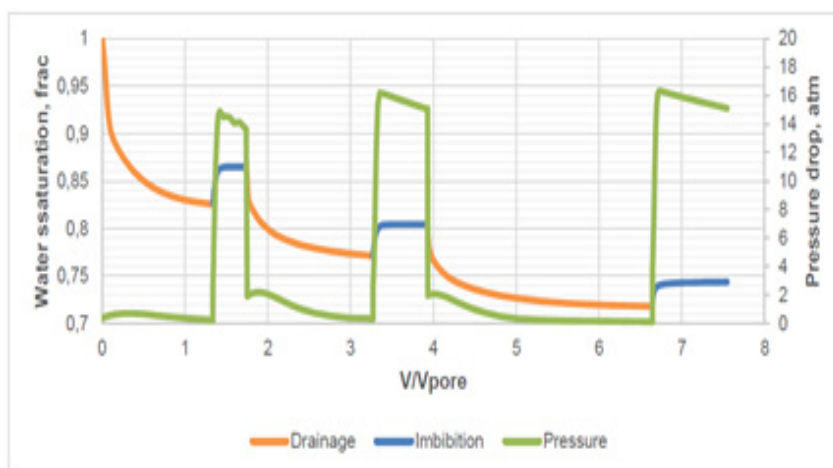
It should be noted that second and third drainage stages are characterized by higher pressure drop at gas breakthrough than the first drainage, but at the moment of water saturation stabilization all pressure drops (and gas permeability) have little difference.

Table 1 presents quantity of trapped gas and saturation change in three cycles of drainage/imbibition for water-gas system.

Data presented shows that displacement ratios and the difference between initial and final values of water saturation in drainage and imbibition stages decrease for each successive cycle.

Relative permeability curves were calculated and plotted for each cycle by Welge method [Figure 2]<sup>19</sup>.

The figure shows permeability and saturation hysteresis caused by gas trapping. Gas permeability curve changes its shape in a wide range of water saturation



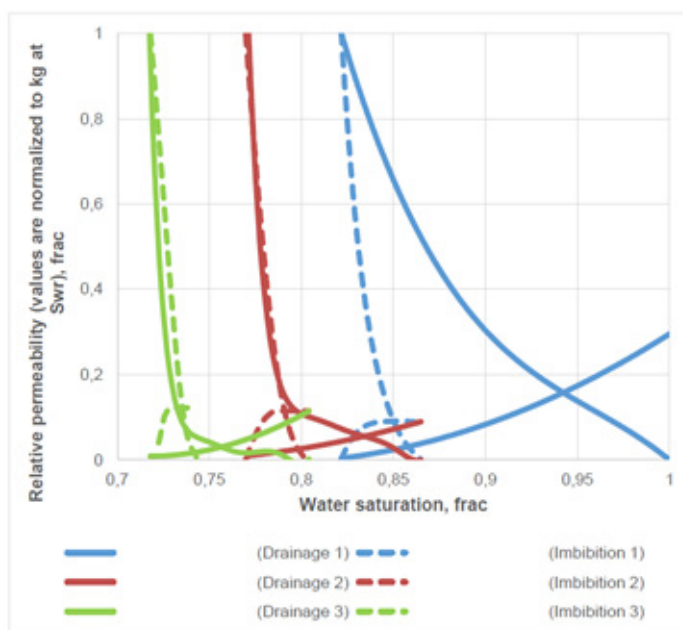
**Figure 1.** Water saturation and pressure drop dynamic for hydrophilic sandstone core column during water and gas alternating cycles.

Data presented shows that all drainage stages have non-piston displacement character, i.e. significant portion of water is displaced after gas breakthrough. At least 1.5 pore volumes of gas (in situ) is needed to be pumped through porous media to stabilize water saturation and differential pressure. Imbibition stages have piston-like displacement character, i.e. almost no gas portion is displaced after the water breakthrough. Water saturation becomes stable after very small amount of water (few tenths of pore volume) is pumped through.

for each subsequent cycle, gas mobility reduces. Such change in permeability curve shape is usually interpreted as a manifestation of surface effects. In this case, capillary forces impede gas penetration into the smaller pores for each subsequent drainage. During the first drainage, gas moves through larger channels with smaller flow resistance and becomes trapped in this channels. Gas entrapment in large channels increases their flow resistance, which appears in the increase of pressure drop

**Table 1.** Quantity of trapped gas and saturation change in three cycles of drainage/imbibition for water-gas system

Cycle	Experiment stage	Water saturation, frac		Replacement ratio, %		Part of pore space, occupied by trapped gas during cycle (Sw(init for drainage) - Sw(final for imbibition))*100%
		Initial	Final	Water moved by gas	Gas moved by water	
1	Drainage 1	1,000	0,822	17,8	-	13,5
	Imbibition 1	0,822	0,865	-	24,3	
2	Drainage 2	0,865	0,770	11,0	-	6,1
	Imbibition 2	0,770	0,804	-	14,9	
3	Drainage 3	0,804	0,718	10,7	-	6,0
	Imbibition 3	0,718	0,744	-	9,1	



**Figure 2.** Relative permeability hysteresis for water-gas system.

during imbibition stage [Figure 1]. During next drainage step gas partially passes pores drained in the previous cycle, moves and becomes entrapped in smaller pores.

Flow resistance (pressure drop) growth is indirect evidence for this explanation [Figure 1].

### 3.2 Relative Permeability Hysteresis for Water-Gas-Oil System

At the end of 20th - beginning of 21st century, there was a surge of interest in relative permeability hysteresis due to widespread of WAG (Water Alternating Gas) EOR method. This method was commercially used for North Sea oilfields, which was determined by needs of hydrocarbon gas utilization in cases where its sub-sea transportation was unprofitable<sup>7,14</sup>.

There is a series of articles in this area that examined different aspects of hysteresis assessment for WAG mathematical modeling<sup>8,9,11</sup>.

As part of this work, experimental study of WAG process in hydrophilic oil-saturated clastic core samples of Vostochno-Perevalnoe oil field (Western Siberia) was carried out. Results of the study were particularly discussed in<sup>10</sup>. Here we will present main results and conclusions of this work.

Research objects were four core columns (absolute permeability -  $10-50 \mu\text{m}^2 \cdot 10^{-3}$ , open porosity -  $18 \pm 0.5\%$ ). Experiments were run on the Coretest CFS-830 filtration system at reservoir conditions. Main goal of the study was to determine oil, gas and water saturation changes, as well as relative permeability curves during water flooding of oil-saturated reservoir and four consecutive WAG cycles (technical nitrogen and formation water).

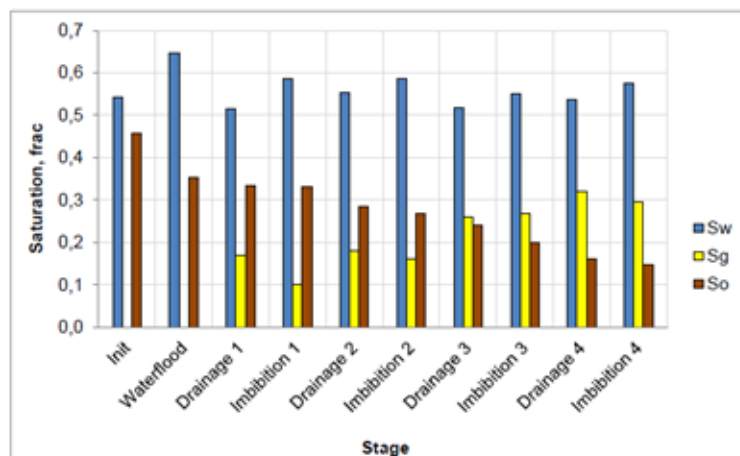
Results obtained for all columns have similar qualitative patterns of pore space saturation change [Figure 3].

During drainage/imbibition stages, oil saturation reduction happens due to the gas saturation increase and water saturation change is insignificant. Thus, there is no regularity in water saturation changes during all WAG cycles.

Rock matrix is hydrophilic, contains clay. This is evidenced by several times reduced water permeability at 100% water saturation as compared with absolute permeability as well as relatively high value of residual water saturation. Additional oil displacement occurs both at drainage and imbibition stages. Total oil and gas saturation for all cycles is approximately the same. These facts suggest a mechanism of additional oil displacement: After waterflooding the residual oil as a nonwetting phase is trapped in narrow channels of the pore space, gas displaces oil to larger channels that are subsequently washed with water.

The above results for water-gas system showed that drainage steps have non-piston displacement character and imbibition steps are piston-like. In presence of residual oil the drainage and imbibition displacement character becomes significantly different. The first drainage/imbibition cycle becomes non-piston, all subsequent cycles - only piston-like, i.e. after displacement agent breakthrough the displaced agent movement actually stops. In presence of residual oil, maximum water saturation change occurs at the first drainage/imbibition cycle.

According to experimental data, relative permeability curves for water and gas in presence of oil phase were



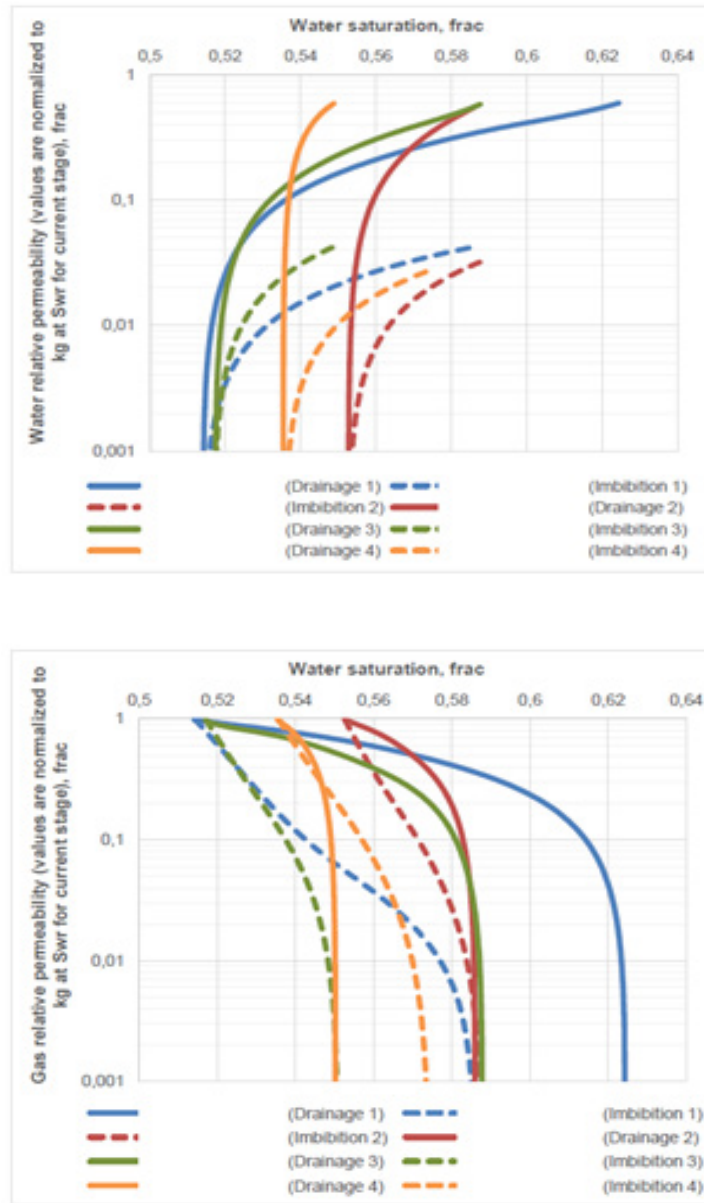
**Figure 3.** Fluid saturation change during water flooding and four WAG cycles in oil-saturated sandstone.

calculated [Figure 4]. Curves were obtained by Welge method<sup>19</sup>.

Data obtained clearly shows difference in hysteresis character for water-gas system without residual oil [Figure 2] and in its presence [Figure 4]. In the first case, there is unidirectional movement of curves and residual saturation values in the direction of decreasing water saturation. In the second case, permeability curves shift alternately to the left and right of the water saturation

axis, while residual water saturation in the first drainage step is the minimal one.

Water permeability at different drainage/imbibition stages slightly varies, due to small water saturation changes. Gas permeability at last drainage step for all four columns rose by 30.5% (average) compared with the first drainage step, which is associated with pore space gas saturation increase.



**Figure 4.** Relative permeability hysteresis for water-gas system in presence of residual oil.

### 3.1 Relative Permeability Hysteresis for Water-Oil System

Relative permeability hysteresis for water-oil system may occur when realizing hydrodynamic EOR methods: Filtration flows direction change, cyclic water injection into the reservoir. Sometimes field experience suggests low efficiency of stationary flooding, which is unable to engage poorly drained areas with relatively low permeability values into development. Reservoir engineers usually understand change of reservoir pressure by changing well modes under non-stationary flooding. Emerging pressure drops between different permeability sub-layers provide fluid flows between them and involve “dead” zones into development.

Non-stationary flooding parameters, as well as any other geological engineering event to increase oil recovery, is predicted by means of hydrodynamic simulations that usually do not take into account vertical flows and especially, the phenomenon of permeability hysteresis. The effectiveness of cyclic waterflooding is often associated only with rock mechanical deformations<sup>13</sup>. In open literature, one can meet calculated studies of permeability hysteresis for water-oil systems and a relatively small amount of experimental flow studies involving two or more cycles of drainage/imbibition<sup>20</sup>. The mechanism of hysteresis accounting in hydrodynamic simulations is also a contentious issue.

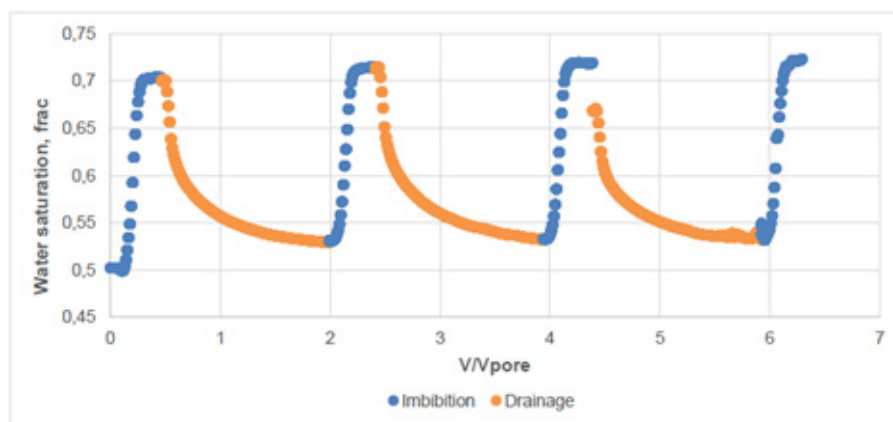
As part of this work, experimental study of permeability hysteresis for water-oil (kerosene) system in non-stationary waterflooding of oil-saturated rock was carried out. Considering case was non-stationary flooding

of a layered reservoir with cyclical rise and fall of reservoir pressure in a watered higher permeable sub-layer, which involves less permeable sub-layer into development.

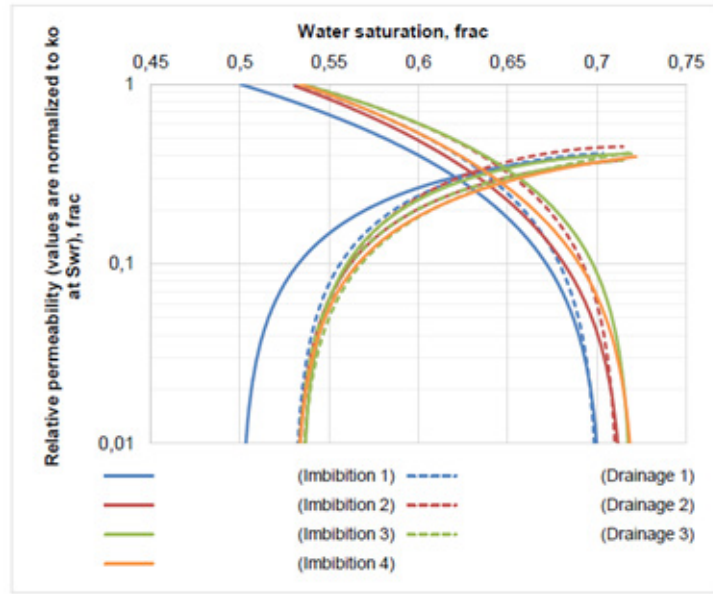
The study was performed on the Coretest RPS-817 filtration system at reservoir conditions (pore pressure - 100 atm, reservoir temperature - 35°C). The filtration system is equipped with three chromatographic bi-plunger Quizix pumps. System arrangement allows alternate or simultaneous pumping of two different fluids, filtering direction change. Saturation control was carried through using a material balance method via acoustic separator and electrical resistivity measurement (four-electrode scheme). Two electrodes were connected to the ends of the core column (length about 12 cm), two others - to the middle section of the column (3 cm apart).

Research object – clastic hydrophilic rock (open porosity - 25%, absolute permeability of  $300 \mu\text{m}^2 \cdot 10^{-3}$ , residual water - 50%). Kerosene and salt water (17.8 g/l NaCl) were used as the reservoir fluids model.

There were two experiment types. In a first type, water and kerosene were alternately pumped through the column until saturation and pressure drop stabilization. According to the results of this experiment one can calculate relative permeability curves by Welge method. The second type of experiment was closer to the real reservoir processes during cyclic flooding: Fluid flow direction change with the same volume of pumping in both directions was simulated. It is impossible to calculate relative permeability, but the overall behavior of the pore space saturation is interesting from both scientific and practical points of view.



**Figure 5.** Water saturation change during water and kerosene alternate pumping in hydrophilic rock.



**Figure 6.** Relative permeability hysteresis for water-kerosene system.

Figure 5 shows water saturation change during water and kerosene alternate pumping in hydrophilic rock.

After the first step of kerosene injection (drainage), water saturation does not reduce to the initial value of the residual water, which indicates an increase of water content in the pore space. As can be seen from the figure, all drainage steps have non-piston displacement character while imbibition steps are piston-like.

Starting with the second cycle there is a slight decrease of residual oil saturation (from 29.9% till 27.8% in the last cycle) and residual water saturation does not change, which indicates slight increase of water-filled pores fracture. This suggests that water and kerosene moved along one channel system without significant departing from its scope in second and subsequent cycles.

Relative permeability curves in water-kerosene system were calculated by Welge method [Figure 6].

Presented curves clearly show that the first stage of water injection is unique with respect to all following imbibition steps. We can say that for present system permeability hysteresis is significant only for the first cycle of drainage/imbibition. Curve movement to higher water saturation area shows aqueous phase retention in rock pores at the drainage step. In this case, it is incorrect to

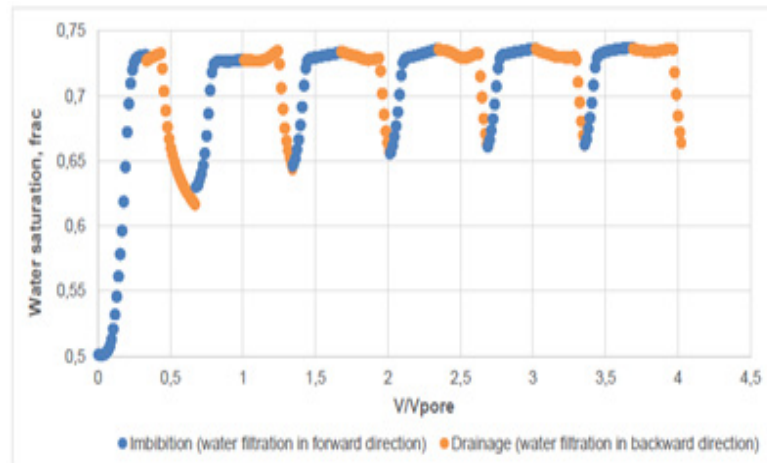
use term “trapping”, because we are talking about the wetting phase.

An experiment with periodic change of filtration direction was conducted to understand how relative permeability hysteresis, drainage/imbibition character and aqueous phase restraining affects parameters of cyclical flooding. Research object remained the same.

Water imbibition was carried out in the “forward” direction in amount of 1/3 core column pore volume, which corresponds to the process of water penetration into less permeable oil-saturated sub-layer while increasing reservoir pressure in more permeable sub-layer. During drainage step water and kerosene filtration was carried out in the “opposite” direction in amount of 1/3 core column pore volume, which corresponds to the process of product extraction from less permeable sub-layer while reducing reservoir pressure in more permeable sub-layer.

Equal pumping pore volumes in forward and backward direction were chosen for reasons of reservoir pressure equality at the beginning of each real flooding cycle and material balance. Volume leveling at 1/3 of pore volume was subjectively chosen based on the following considerations. Presented experiment should be





**Figure 7.** Water saturation during cycle flooding with filtration direction changes.

close to the real reservoir processes where drainage volume between sub-layers in a single pressure change cycle cannot be several pore volumes. Reducing the volume of one pumping cycle should increase the number of cycles needed to stabilize residual saturations.

Figure 7 shows water saturation behavior for middle section of the core column, measured by electrical resistivity for six full cycles of imbibition/drainage. Due to the electrodes proximity we can conditionally assume that collected data reflects middle column cut properties.

The figure shows that cycle change brings gradual increase of residual water saturation while residual oil saturation does not change significantly. Last two cycles have identical shape and residual values of oil and water saturations, which indicates stabilization of residual water and oil distribution in rock pores.

Following conclusions can be obtained from water-kerosene permeability hysteresis data. During the first imbibition in amount of 1/3 pore volume water moves inside the core column on its partial length. During the drainage step, water becomes restrained and drained pore volume becomes smaller. At the second imbibition step 1/3 pore volume of water is injected into the column again. As a result of the drained pore volume reduction, displacement water front moves further than at the first imbibition step. Subsequent cycles repeat this process. Relative permeability curves for water-kerosene system

are not significantly affected by hysteresis since second cycle (Figure 6), so saturation in new experiment gradually comes to “balance”. This means that stable channel system is created in pore space and it is alternately filled with water and kerosene, which is observed on the last cycle [Figure 7].

## 4. Discussion

Experimental data presented includes different ways of anthropogenic impact on natural oil and water reservoirs. Relative permeability hysteresis phenomena in cyclic saturation changes are common for all of them. However, qualitative hysteresis character for hydrophilic medium researched depends on saturation type.

For water-gas and water-oil-gas systems determinant hysteresis factor is gas bubbles trapping during imbibition stages, but relative permeability change is different.

Sohrabi describes WAG mechanism by visual observation of hydrophilic porous medium model<sup>15</sup>. Authors show that during initial flooding water moves along pore walls and surrounds oil globules in large pores. This results in immobilization of oil globules, which are not capable to overcome interporous channels because of surface tension force. Surface tension between gas and oil is lower than between gas and water. For this reason, gas preferably enters oil-filled pores instead of water-filled during

the drainage step. Gas pushes oil causing its globules to merge and oil mobility increases. Additional oil displacement ratio by gas is not so large and its value is about 6%. During subsequent imbibition stage, water penetrates gas-filled pores causing gas bubble crushing and trapping. At the next drainage step, gas penetrates larger number of pores and process repeats. After the third cycle, no significant fluids redistribution was observed.

Assuming that WAG mechanism for natural of hydrophilic reservoirs is similar to the above, we can propose the following explanation for hysteresis differences in water-gas and water-oil-gas systems. In water-gas system there is one type of interface between the fluids, whereas water-oil-gas system has three interface types - between water and gas, water and oil, gas and oil. During several saturation change cycles for water-gas system, interface area and therefore surface energy becomes bigger, which appears in unidirectional movement of relative permeability curves. For water-oil-gas system redistribution of surface energy occurs, for example, growth of water-gas interface is accompanied by decrease in water-oil interface area. Redistribution of the surface energy appears in the multidirectional movement of relative permeability curves in the same area of water saturation in the different WAG cycles.

From the surface energy changes point of view water-oil (kerosene) system is close to the water-gas system. In both cases, there is one type of interface between fluids. Interface area and its energy grow for several saturation change cycles and permeability curves change is unidirectional.

We should also discuss nature of the saturation stabilization in drainage/imbibition cycles for water-oil (kerosene) system (Figure 5). Water imbibition always has piston-like displacement character, the filtration velocity of both fluids matches; saturation quickly becomes stable after the displacement front passage. Displacement has non-piston character after kerosene breakthrough at the outlet end of the core column when kerosene is pumped at a constant rate during drainage, so water flow velocity is lower than kerosene flow velocity at this moment. Presumably, a system of flow channels and pores filled with kerosene is formed during kerosene injection and rock resistance to kerosene filtration is reduced. This results in dead zones formation in pore space where water restrains because of the hydrodynamic pressure drop absence.

At the beginning of the article it was noted that the reason for hysteresis existence is the contact angles difference of the drop moving forward and backward and non-wetting phase trapping. For water-oil (kerosene) system of, use of the "trapping" term is not correct because hysteresis is associated with water and kerosene velocity difference and water retention in dead zones.

The difference of water filtration velocity for imbibition and drainage stages has significant impact in symmetric delivery/extraction cycles (Figure 7). For the same pumping pore volume, water saturation at the drainage step does not have time to stabilize, which leads to increased water retention effect. This results in dynamic pore volume reduction and water displacement front is able to promote deeper in oil-saturated reservoir. Summarizing, we can say that water retention and relative permeability hysteresis for water-oil (kerosene) system are mechanisms of coverage ratio increase in cyclic water flooding EOR.

## 5. Conclusion

- Relative permeability hysteresis phenomena was observed in all hydrophilic pore systems researched (water-gas, water-oil-gas, water-oil (kerosene)).
- For water-gas system, hysteresis effect appears in unidirectional movement of relative permeability curves in lower water saturation direction. Gas trapping in pore space happened at each imbibition stage. Fluids move in smaller pore channels in each subsequent cycle, which causes filtration resistance increase.
- For water-oil-gas system, hysteresis effect appears in multidirectional movement of relative permeability curves along water saturation axis. Curves span is very small and reduces for each subsequent cycle. Oil saturation decreased by gas trapping in WAG, while water saturation was almost constant in experimental conditions.
- For water-oil (kerosene) system, hysteresis effect appears in unidirectional movement of relative permeability curves in higher water saturation direction. Hysteresis significantly appears in the first drainage step where water retention occurs. Subsequent cycles do not bring significant changes of relative permeability curves shape and position. Residual water saturation did not significantly

change and residual oil saturation decreased from 30 to 28 % since second cycle for current research object.

- Hysteresis type (unidirectional or multidirectional movement of relative permeability curves) can be linked to surface energy change at interfaces between the fluids. If system has one type of interface (oil-water, water-gas systems), then cyclic saturation change brings unidirectional change of the interface area, surface energy and relative permeability curves. If system has three interface types (oil-water-gas system), then redistribution of interfacial area and surface energy happens during cyclic gas and water injection, which brings multidirectional shifting of relative permeability curves along water saturation axis.
- Hysteresis and water retention in a hydrophilic rock provides accelerated promotion of water displacement front during cyclical impact on the formation during reservoir pressure and filtration flows direction change.

## 6. Acknowledgements

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