"EXPERIMENTAL DESIGN" APPROACH FOR SENSITIVITY STUDY OF CAPILLARY PRESSURE MEASUREMENTS - COMPARISON BETWEEN POROUS PLATE AND CENTRIFUGATION METHODS

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Toronto, Canada, 21-25 August 2005

ABSTRACT

When dealing with capillary pressure, we often face problems like mismatch between logs and laboratory data, differences between various laboratory techniques (Dean Stark, "Porous plate", Centrifuge, Mercury injection), difficulties to find correlations with other petrophysical parameters…

To appraise the validity of the experimental results, an "experimental design" approach has been applied to the "Porous plate" method and to the Centrifuge method. The objective is to study the sensitivity of capillary pressure measurements in the laboratory to various parameters playing a role during the drainage phase by selecting a few sets of parameters. Some of these parameters are physical characteristics of the core sample (absolute permeability, relative permeability to brine or hydrocarbons, shape of the capillary pressure curve). Other parameters are related to the experimental process (duration of capillary pressure step until stabilization of water production, permeability of the semi-permeable porous plate used). For each selected set of parameters, the fluid production is calculated via a two phase-flow lab experiment simulator taking into account gravity and capillary forces. The water saturation value derived from this simulation, which is supposed to represent the experimental data, is then compared to the theoretical curve input in the model, which is supposed to represent the physical data. The variation of the differences is then analyzed in the parameter space.

This approach allows a comparison between "Porous plate" and Centrifugation techniques for different kinds of core samples and with various experimental configurations. The conclusion is that the Centrifugation technique provides the most reliable capillary pressure curve in some critical configurations.

INTRODUCTION

One of the most important tasks in the oil industry is to quantify the oil or gas resource-in-place. For that purpose, logging data, which are sub-continuous and require interpretation, have to be compared with laboratory data. Two kinds of the latter are mainly available: either pinpoint measurements of extracted fluid ("Dean Stark" extraction of the water content with a hot solvent) on core samples, supposed to be kept in a “fresh state” since plugging at the well site, or capillary pressure curves from laboratory acquisition. Capillary pressure curves, which are continuous, are often used by reservoir engineers to quantify the vertical water saturation distribution and the corresponding hydrocarbon distribution. “Porous plate” ([1], also called “Restored States” method or Capillary pressure and Resistivity Index measurements (abbreviated to PCIR)), Centrifugation ([2]) and Mercury injection ([3], abbreviated to MICP) are the laboratory techniques currently used to obtain these curves. The drainage phase of these curves is supposed to represent the hydrocarbon migration into the reservoir.

However, when dealing with capillary pressure, reservoir engineers may face problems like mismatch between logs and laboratory data, differences between results from various laboratory techniques and difficulties of correlation with other petrophysical parameters. This paper aims at appraising the validity of the “Porous plate” and Centrifugation methods, by studying the sensitivity of the laboratory capillary pressure measurements to various parameters likely to play a role during the drainage phase, related either to the experimental process or to the physical characteristics of the core sample. The range of investigated values for the absolute permeability of core samples includes unconsolidated materials as well as rocks. Only oil/water drainage is studied in the present paper.

The study is based on an original approach combining modeling and “experimental design” applied to the “Porous plate” method and to the Centrifuge method.

PROCEDURES

Principles Of The Study

Principle Of “Experimental Design” Approach

Exhaustively studying the sensitivity of an industrial process to n parameters, each of them subject to m possible values, would require m^n experiments. This would be expensive and time consuming, if not impossible, especially for real laboratory measurements, but even for modeling data. The main objective of an “Experimental design” approach is to save time, by determining the minimum number of experiments to run in order to highlight and classify the parameters likely to play a role in the industrial process. The corresponding combinations of the involved parameters are identified. The other objective is to be predictive. These experiments are explained by an adjusted modeled surface-solution of response (y) through the full hyper-space of parameters (x_i) according to a least-squares regression. To estimate an accurate solution, the surface – solution is expressed with an order 2 polynomial (1):

$$y = a_0 + \Sigma_i (a_i * x_i) + \Sigma\Sigma_{i\neq j} (a_{ij} * x_i * x_j) + \Sigma_i (a_{ii} * x_i^2) \qquad (1)$$

where a_i are the main coefficients, a_{ij} the interaction terms and a_{ii}, the squared terms of Pareto. The main effects are not mixed with the interaction terms, which are not supposed to be negligible. The advantage is that the solution is a continuous response. For example: for a three parameters space (n=3), with each parameter able to be a minimum, a medium, or a maximum value (m=3), figure 1a shows the 15 experiments that have to be run in order to represent the full 3-dimensions space, instead of the 27 ones (3^3), when choosing a "Cubic with Centered Faces representation – full design" (called "CCF3C"). Figure 1b draws a surface solution, explaining the experiments. This uses a TOTAL in-house statistical tool, "PHASER-EST".

Modeling

Modeling was chosen to simulate the laboratory experiment, both for time and cost saving, and to produce results free of experimental errors and incertitude. It should be noted that a drainage acquisition by "Porous plate" usually lasts around 6 months. A TOTAL in-house two phase-flow lab experiment simulator taking into account gravity and capillary forces, "Z2C", calculates the brine production of the sample when a capillary step is imposed, and that for each selected set of parameters.

Parameters Of The Study

Variable Parameters for "Porous plate" and Centrifugation

Tables 1 and 2 summarize the parameters and their range of values with min-medium-max values that were investigated by the "experimental design" approach, both for the "Porous plate" and the Centrifugation measurements.

Some parameters describe the core sample. It is described using its absolute permeability, Kplu; a first experimental design examines the range 10-1000 mD that illustrates the unconsolidated material, a second experimental design examines the range 0.1-10 mD that is supposed to represent consolidated materials. In each case, the physical capillary pressure of the core sample is described by a theoretical and numerical relationship (2):

$$Pc = Pd.(Sw^*)^{-n} \tag{2}$$

where Pd is analogous to a displacement pressure and n to the curvature. Sw* is the reduced or normalized water saturation defined as follows (3)

$$Sw^* = (Sw - Sw_i)/(1-Sw_i) \tag{3}$$

with Sw_i, the minimum water saturation, in fraction, reached at the maximum capillary pressure. Pd and Sw_i at Pc max are fixed, n is the variable parameter. The brine and oil relative permeability formula are expressed with the Corey exponent n_w and n_o ([4], [5]) as given by (4) and (5):

$$Kr_w = (Sw^*)^{n}{}_{w} \tag{4}$$

$$Kr_o = (1-Sw^*)^{n}{}_{o} \tag{5}$$

The relative permeability is also numerically expressed. The ranges of values investigated for Kplu, n, n_w and n_o are the same for "Porous plate" and Centrifugation.

The experiments depend on other parameters. The duration of capillary pressure steps, called TePa, is investigated. This parameter is different for each kind of experiment and is given in tables 2. The medium case is supposed to be a realistic duration for each kind of experiment, around 6 months for "Porous plate" measurements and around 10 days for Centrifugation measurements. Finally, "Porous plate" measurements during drainage phase require a specific material, the water wet porous plate. The porous plate permeability, Kmem, is also investigated with the experimental design approach.

Other Parameters: Fixed Values

Table 3 gives the other values necessary to characterize the full experimental conditions: they are fixed values throughout the study. For instance, Pd and Swi in formula (2) and (3) are respectively fixed to 50 mbars and 0.10 (at Pc max=8 bars) in experimental design 1 (Kplu varying from 10 to 1000 mD): the entry capillary pressure curves are defined exactly the same way both for Centrifuge and "Porous plate". The Pc max is fixed to 20 bars for the experimental design 2 in order to draw more realistic capillary pressure curves for a set of less permeable samples (Kplu from 0.1 to 10 mD). The geometry of the core samples and their position in the machine, especially for the Centrifuge, were chosen to be realistic and to correspond to configurations recommended by Forbes (N and B parameter criterions [6]). The maximum capillary pressure step reached during experiments (table 2) also agrees with our material limitation: 3500 r/min for our centrifuge used for sands, 16000 r/min for rocks' centrifuge, 8 bars for our porous plate.

Flow Chart

For each set of parameters values, the water saturation value derived from the "Z2C" simulation, supposed to represent the experimental data, is compared to the theoretical curve input in the model, supposed to represent the physical data. The variation of the differences is then analyzed in the parameter space. Figure 2a illustrates the sequence of process and figure 2b shows the differences that are studied in the experimental design approach for the "Porous plate" experiments.

For the centrifugation data, one more step is necessary: the raw medium volume computed at the exit face by "Z2C" has to be corrected because of the heterogeneous water saturation distribution in the core sample from the entry face near the centrifuge axis at maximum capillary pressure (Pc) to the exit face far from this axis (at Pc assumed equal to zero). The best version (n° 2) of Forbes' corrections [6], based on the model that properly takes into account the centrifuge forces distribution along the core sample axis and perpendicularly to this axis, is used: the tool is called "CentriForbes". Gravity forces are also taken into account. Figure 3a illustrates the sequence of process and figure 3b shows the differences that are studied in the experimental design approach for the Centrifugation experiments.

RESULTS

Results For "Porous Plate" Data: Experimental design 1: Kplu=10-1000 mD

"PHASER-EST" computed the optimized number of unit experiments necessary to well explain the Kplu-n-n_w-n_o-TePa-Kmem parameters when choosing an experimental design of kind "Cubic with Centered Faces for 6 parameters – full design" (CCF6C): 77

experiments were run with “Z2C”, combining differently the 3 possible values (min-medium-max) for each of the 6 parameters, and the corresponding differences between the modeled Pc=f(Sw) curves and the physical Pc=f(Sw) curves were calculated. “PHASER-EST” computed the optimized solution as a hyper-plan that best explained these individual differences (in fact, a surface of response for each value of Pc).

The impact of parameters was analyzed. Figure 4a shows the main Pareto coefficients. The interaction terms between the parameters as well as the square terms were also computed but are not shown. Away from the transition zone, the water relative permeability (with n_w) appears as the most important parameter, followed by the curvature of the capillary pressure curve (n), the permeability of the semi-permeable porous plate (Kmem) or of the core sample (Kplu), and the duration of the capillary pressure steps (TePa). The oil relative permeability (n_o) has no impact. An n_w increase, unfavorable to water flow, leads to an increase of the difference (modeled Sw – physical Sw) (y positive on the graph). In contrast, an increase of Kplu or Kmem, or an increase of the stabilization steps duration, favorable to the water flow, leads to a decrease of this difference (y negative on the graph). In the same way, an increase of the n curvature of the physical Pc curve, corresponding to a higher water saturation (at the same capillary pressure value), leads to a decrease of the difference.

“PHASER-EST” provides surfaces of response of whom extrema are shown in table 4.

Results For Centrifugation Data: Experimental design 1: Kplu=10-1000 mD

An experimental design of kind “Cubic with Centered Faces for 5 parameters – full design” (CCF5C) was chosen. 43 unit experiments were necessary to well explain the Kplu-n-n_w-n_o-TePa parameters according to “PHASER-EST” optimization. Therefore, the “experimental” curves modeled with “Z2C” were interpreted according to the Forbes’ solution. The corresponding differences between the solution Pc=f(Sw) curves and the physical Pc=f(Sw) curves were calculated. The optimized hyper-plan solution was then computed for each value of Pc.

Figure 4b of the main coefficients shows that, away from the transition zone, the water relative permeability (n_w) stays the dominant parameter, but its impact is less important than it is in “Porous plate” simulation. The curvature of the capillary pressure curve (n) and the permeability of the core sample (Kplu) are then more important than the duration of the capillary pressure steps (TePa), whom influence seems reduced when compared to the “Porous plate”. The impact of oil relative permeability is negligible. The impact trends (positive or negative) are the same for Centrifugation and “Porous plate” data.

The extrema values of the surfaces of responses (as differences) are shown in table 4.

Other Results: Experimental design 2: Kplu=0.1-10 mD

The same work was done both for the “Porous plate” and for the Centrifugation methods for consolidated materials in the range of plug permeability 0.1 – 10 mD. Tables 1, 2 and

3 give the parameter values, studied or fixed. The results are given in table 5 at the maximum capillary pressure reached according to the experimental technique.

DISCUSSION

Caution

For this kind of "experimental design" approach, the pertinence of the proposed solution must be verified: squared multiple regression coefficients must be high (adjusted and predicted R^2 ideally equal to 1) to guarantee the good adjustment of the solution to the experimental data and the good quality of prediction of the proposed model. This is the case in our study since all the R^2 values are more than 0.8, and very often more than 0.9.

It should be noted that the shape of the analysis curves (figures 4) and the conclusions concerning the relative impact of the parameters depend on the models that are used ($Pc=f(n)$, $Kr_w=f(n_w)$, $Kr_o=f(n_o)$) and on the range of values that are investigated for each of them. In the Pc formula (2) and (3), Swi and Pd were chosen independent of plug permeability. That is generally not observed in real data ([7]). Our pessimistic results may be exaggerated as a consequence of this simplifying choice. Moreover, work is based on simulation. Some artifacts may exist, depending on simulation quality. "Z2C" is a two phase flow tool that just uses Darcy laws, gravity equation and capillary pressure formula, but nothing related to porous network and wettability. This study put in evidence the impact, positive or negative, of some parameters. For instance, the higher the relative permeability of water, moving fluid, the easier the brine desaturation of core sample will be. In other words, the lower the value of n_w according to the Corey expression (4), the lower the difference between real or physical capillary curve and experimental or modeled curve will be. This result is quite intuitive in the case of a water-wet core sample, where brine is the continuous moving fluid. But is it so obvious when considering an oil-wet reservoir where water is not so continuous, at some degree of desaturation? This study cannot answer this question. A more sophisticated model would be required.

Comparing "Porous Plate" and Centrifugation, Experimental Designs 1 and 2

According to table 4, for several combinations of parameters configurations, "Porous plate" as well as Centrifugation, provide satisfactory results for unconsolidated materials if taking into account the following criterion on the difference: (modeled Sw - physical Sw) less or equal to 5 saturation units corresponds to good measurements. In other cases, neither the "Porous plate" method nor the Centrifugation techniques provide acceptable results. But, in some critical configurations, Centrifugation appears to be the only reliable technique, and in nearly all the cases shown, it provides better results than the porous plate. These conclusions are confirmed on consolidated core samples, as indicated on table 5, with the experimental design 2. "Porous plate" rarely provides satisfactory results compared to centrifuge method in the 0.1-10 mD range of plug permeability.

Some differences can be noted between experimental designs 1 and 2 on “Porous plate”. One can see from figure 4c that the effect of n_w is slightly increased for the less permeable samples (design 2: 0.1–10 mD). Kplu becomes a more critical parameter than it was in the high permeability range (design 1: 10-1000 mD). The effect of n is also augmented, perhaps because of the capillary pressure definition ($Sw_i = 0.10$ at 20 bars instead of 8 bars). It is difficult to say anything really pertinent about TePa because duration steps were adapted according to experimental design 1 or 2. Kmem impact seems to decrease significantly from design 1 to 2: the water flow is relatively less penalized with the worst porous plates for the less permeable core samples than it is for the most permeable core samples probably because of the set up “core sample - porous plate” in series where the less permeable element controls the global flow.

CONCLUSION

In summary, the benefits of the “experimental design” approach are the ability to estimate the main effects for each factor, qualitatively (positive or negative effect) and quantitatively. Thus, we can quickly identify which factors are important and most likely to yield improvements in the process under study if we are able to act on it and if the suggested solution is realistic.

From the experimental design 1 (Kplu = 10-1000 mD), it appears that the water relative permeability through Corey exponent, n_w, is the most important parameter playing a role during the drainage phase on unconsolidated materials for “Porous plate” (among the studied Kplu-n-n_w-n_o-TePa-Kmem parameters). Though it is the most important parameter that affects the centrifuge results, water Corey exponent n_w has lower impact on centrifuge compared to “Porous plate” (among the studied Kplu-n-n_w-n_o-TePa parameters). These tendencies were confirmed and increased for consolidated materials, using the experimental design 2 (Kplu = 0.1-10 mD). From this study, the higher the relative permeability of the water moving fluid (or the lower value of $n_{w)}$, the easier the brine desaturation of the core sample (or the lower the difference between real or physical capillary pressure curve and experimental or modeled curve). Better porous plate permeability is favorable to water flow; this parameter is less important for poorly permeable materials.

This “experimental design” approach allows a comparison between “Porous plate” and Centrifugation techniques for different kinds of core samples and with various experimental configurations. It concludes that the Centrifugation technique is able to provide reliable capillary pressure curves in some critical configurations, like poorly permeable consolidated materials and/or the cases where n_w is unfavorable. The problem is that the relative permeability to water (as well as the core sample permeability and the Pc curvature) is an intrinsic property of the core sample, so we can not act on it. Moreover, we usually don’t know it *a priori*. Complementary studies would have to be performed in order to try to restrain the range of effective n_w values (as well as n) for a Kplu value, so that the realistic space of (modeled Pc – physical Pc) should be a limited portion of the hyper-surface solution.

This study is based on modeling with a two phase flow tool that does not take into account porous network and wetting considerations. A more sophisticated model would be necessary to complete the study.

ACKNOWLEDGEMENTS

The author would like to gratefully acknowledge TOTAL for technical support.

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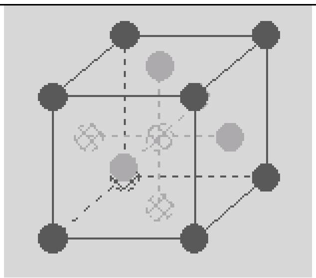
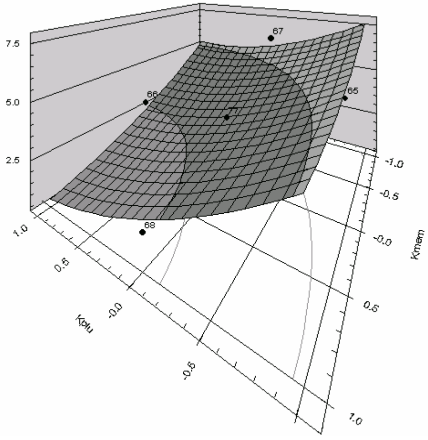
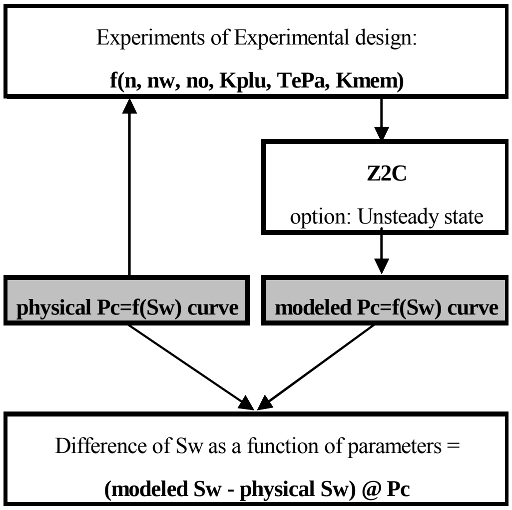
(7) Hamon G., “Field-Wide Variations of Wettability, SPE 63144 (2000) SPE ATCE, Dallas, Texas, U.S.A

 Figure 1a: “Experimental design” basis: the 15 experiments needed to well describe a 3 parameter space with (min, medium, max) values when selecting a “Cubic with Centered Faces” design with “full resolution” (CCF3C)	 Figure 1b: surface of response (horizontal: x_1, x_2 axis for parameters; vertical: y solution) and experimental points



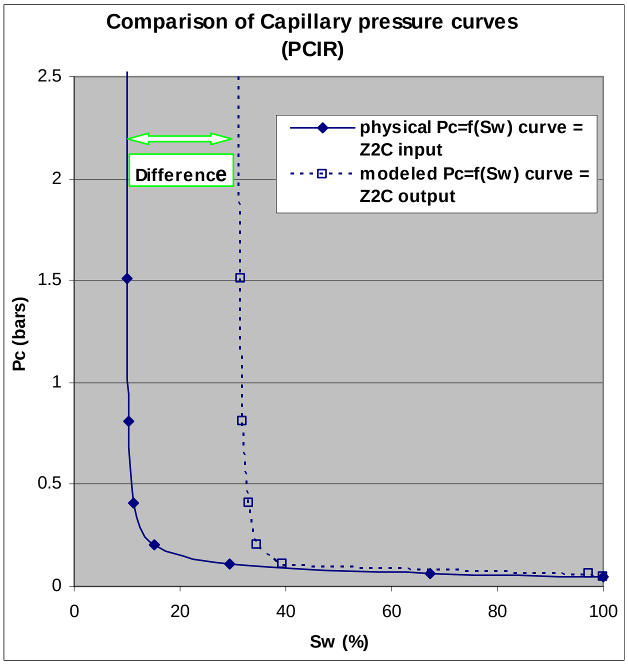
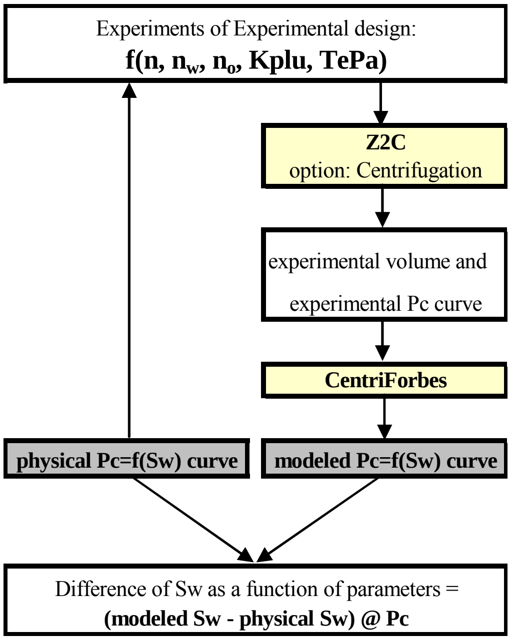


Fig. 2a & 2b: sequence of process and differences studied in the experimental design approach for “Porous plate”



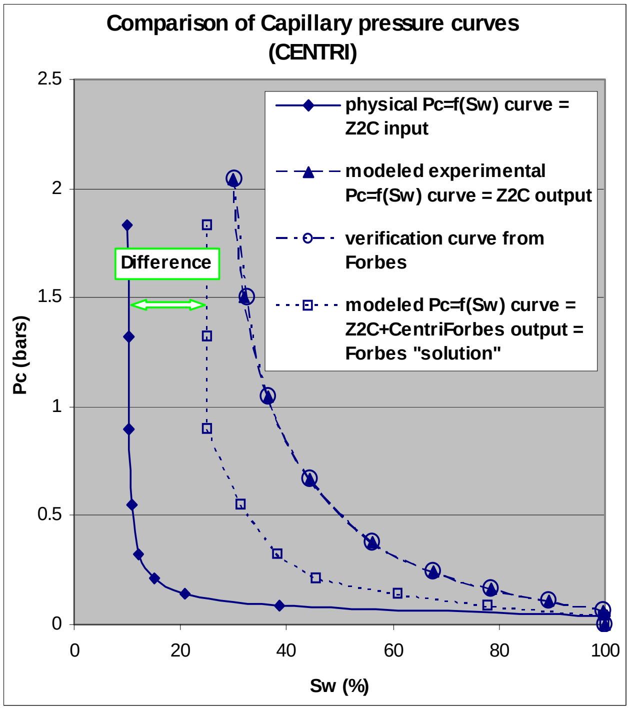


Fig. 3a & 3b: sequence of process and differences studied in the experimental design approach for Centrifugation

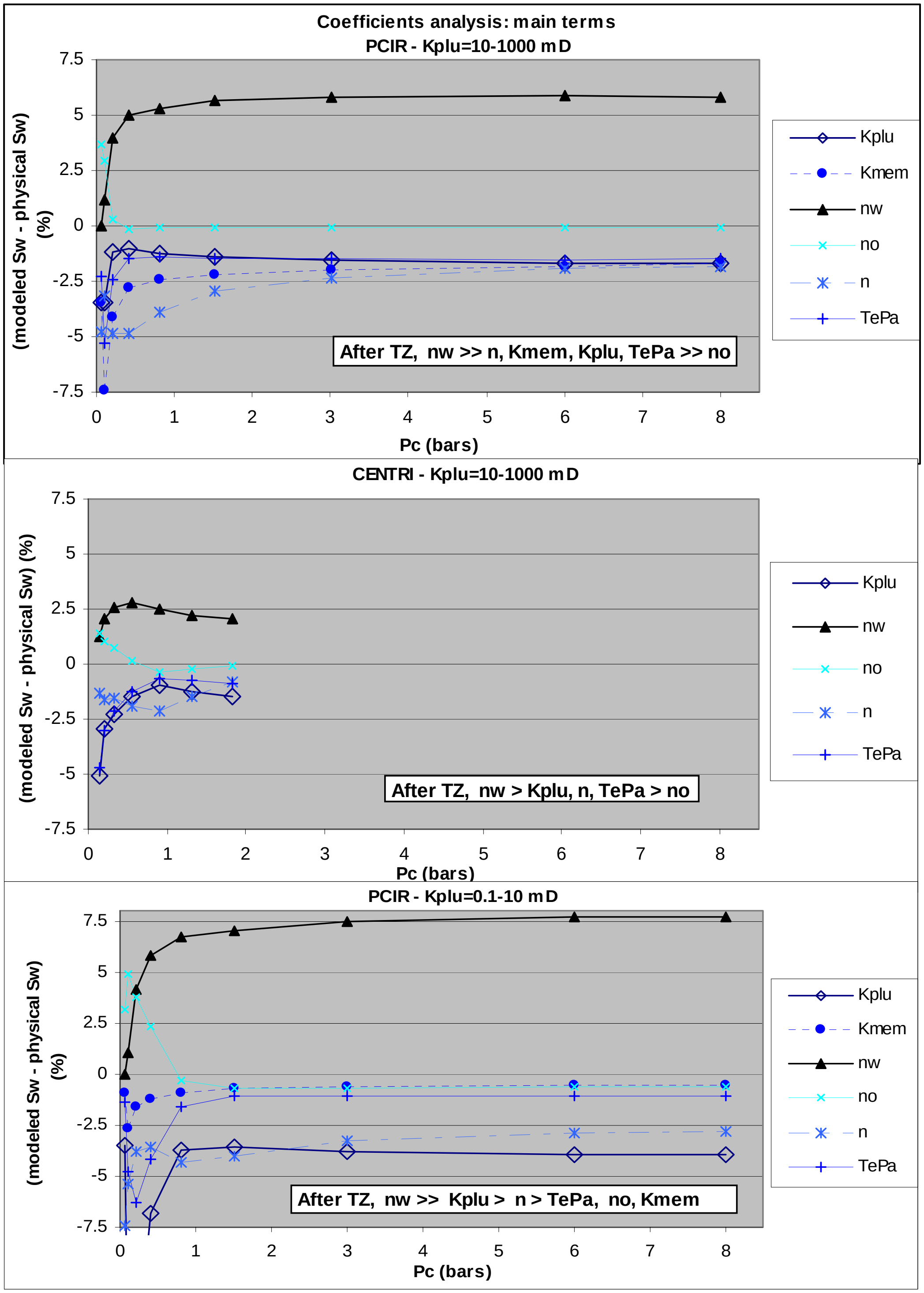


Fig. 4a-4b-4c: Analysis of the coefficients: main terms for "Porous plate" and Centrifugation - Experimental design 1 (4a-4b) and "Porous plate" - Experimental design 2 (4c)

Table 1: Main parameters, variable in experimental design approach:
"Porous plate" (PCIR) and Centrifugation (CENTRI)

Variable parameters in experimental design approach	**min**	**max**	**medium**
describing core samples	**common to PCIR & CENTRI**		
sample permeability: **Kplu** (mD) - **experimental design 1**	10	1000	100
sample permeability: **Kplu** (mD) - **experimental design 2**	0.1	10	1
Corey exponent for Kr_w: $\mathbf{n_w}$	3	6	4.5
Corey exponent for Kr_o: $\mathbf{n_o}$	2	5	3.5
Capillary pressure exponent: **n**	0.5	1.5	1
describing experiments	**specific to PCIR or CENTRI**		
stabilisation duration of Pc steps: **TePa**	Tab. 2	Tab. 2	Tab. 2
	PCIR only		
permeability of 1/2 permeable porous plate: **Kmem** (mD)	0.01	1	0.1

Tables 2: Duration of Capillary Pressure steps for each experimental design:
"Porous plate" (PCIR) and Centrifugation (CENTRI)

PCIR: experimental design 1: 10-1000 mD			
Pc (bars)	**Time medium (days)**	**Time min (days)**	**Time max (days)**
0.055	25	10	40
0.1	25	10	40
0.2	25	10	40
0.4	25	10	40
0.8	25	10	40
1.5	15	5	25
3	15	5	25
6	10	2	18
8	10	2	18
Total (days)=	**175**	**64**	**286**

CENTRI: experimental design 1: 10-1000 mD			
Speed (rpm)	**Time medium (days)**	**Time min (hours)**	**Time max (days)**
600	1	4	6
800	1	4	6
1000	1	4	6
1200	1	4	6
1500	1	4	6
2000	1	4	6
2500	1	4	6
3000	1	4	6
3500	1	4	6
Total (days)=	**9**	**1.5**	**54**

PCIR: experimental design 2: 0.1-10 mD			
Pc (bars)	**Time medium (days)**	**Time min (days)**	**Time max (days)**
0.055	30	15	60
0.1	30	15	60
0.2	30	15	60
0.4	30	15	60
0.8	30	15	60
1.5	30	15	60
3	20	10	40
6	20	10	40
8	20	10	40
Total (days)=	**240**	**120**	**480**

CENTRI: experimental design 2: 0.1-10 mD			
Speed (rpm)	**Time medium (days)**	**Time min (hours)**	**Time max (days)**
800	1.5	6	9
900	1.5	6	9
1000	1.5	6	9
1300	1.5	6	9
2000	1.5	6	9
4000	1.5	6	9
6000	1.5	6	9
8000	1.5	6	9
12000	1.5	6	9
16000	1.5	6	9
Total (days)=	**15**	**2.5**	**90**

Table 3: Other parameters, fixed in experimental design approach:
experimental conditions for “Porous plate” (PCIR) and Centrifugation (CENTRI)

Experimental design	**1 (10-1000 mD)**	**2 (0.1-10 mD)**	**1 (10-1000 mD)**	**2 (0.1-10 mD)**
Core sample geometry, position and property	**PCIR**		**CENTRI**	
Porosity of sample (frac)	0.20	0.15	0.20	0.15
Diameter of sample (cm)	4.0	4.0	3.0	3.8
Lenght of sample (cm)	6.5	6.5	4.4	5.0
Porous plate thickness (cm)	1.0	1.0	-	-
Distance to rotation axis (cm)	-	-	12.47	4.13
Fluids characteristics	**PCIR**		**CENTRI**	
brine density: RHO_w (g/cc)	1.04	1.04	1.04	1.04
oil density: RHO_o (g/cc)	0.80	0.80	0.80	0.80
brine viscosity: μ_w (cPo)	1.04	1.04	1.04	1.04
oil viscosity: μ_o (cPo)	11.5	11.5	11.5	11.5
Capillary pressure (and Kr) definition	**PCIR**		**CENTRI**	
displacement pressure: Pd (bars)	0.050	0.050	0.050	0.050
Pc max (bars)	8	20	8	20
Sw_i (frac) @ Pc max (for Kr too)	0.10	0.10	0.10	0.10

Table 4: Experimental design 1 (Kplu=10-1000 mD): “Porous plate” / Centrifugation comparison – Synthetic results of difference from surface response (values given for Kmem = 0.01-1 mD in “Porous plate” simulations).

EXPERIMENTAL DESIGN 1: Kplu = 10-1000 mD						
Configurations			**Sw Difference @ 8 bars - PCIR**		**Sw Difference @ 2 bars - CENTRI**	
n_w	**n**	**TePa**	**Comments**	**Values** s.u.	**Comments**	**Values** s.u.
medium	medium	medium	Always good except Kmem min or Kplug min	0 to 7	Always good	0 to 4
max	medium	medium	Never good	5 to 18	Good in 2/5 of cases	3 to 9
min	medium	medium	Always good	<= 2.5	Always good	<= 2.5
min	**min**	**min**	Always good even if other parameters not fair	<= 4	Always good even if other parameters not fair	<= 4
max	**min**	medium	Never good	7 to 22	Good in 1/5 of cases	3 to 12
max	**min**	*max*	Never good	7 to 18	Good in 2/5 of cases	3 to 9
max	*max*	medium	Some good configurations	3 to 14	Good in 4/5 of cases	1 to 7

Configurations: *in italic*: parameter favorable to water flow/**in bold**: unfavorable
Results: in grey: globally good / in dark grey: globally bad results
Criterion: good results: Sw difference <= 5 s.u. / bad: Sw difference > 5 s.u.

Table 5: Experimental design 2 (Kplu=0.1-10 mD): Porous plate / Centrifugation comparison

EXPERIMENTAL DESIGN 2: Kplu = 0.1-10 mD						
Configurations			**Sw Difference @ 8 bars - PCIR**		**Sw Difference @ 19 bars - CENTRI**	
n_w	**n**	**TePa**	**Comments**	**Values** s.u.	**Comments**	**Values** s.u.
medium	medium	medium	Never good	5 to 15	Good in 2/5 of cases	3 to 9
max	medium	medium	Never good	11 to 26	Never good	7 to 19
min	medium	medium	Nearly always good	0 to 6	Aways good	<= 2.0
min	**min**	**min**	Good in 1/2 of cases if other parameters not fair	3 to 8.5	Always good even if other parameters not fair	<= 2.0
max	**min**	medium	Never good	13 to 29	Never good	6 to 19
max	**min**	*max*	Never good	12 to 27	Good in 1/5 of cases	3.5 to 14
max	*max*	medium	Never good	7.5 to 22	Never good	5 to 17