Impact of Volume Production Stabilization Uncertainties on Experimental Acquisitions of Capillary Pressure Curves

Quentin Danielczick[1], and Benjamin Nicot[1]

[1]TotalEnergies OneTech, 64000 Pau Cedex, France

Abstract. Capillary pressure (Pc) curves obtained from centrifuge or porous plate measurements are widely used in SCAL programs to determine irreducible saturations and characterize transition zones. The accuracy of the methods depends on two factors: the stabilization of expelled volume at a given capillary pressure step and the uncertainty associated with acquisition systems. In addition, centrifuge acquisitions must be interpreted to obtain the final and usable Pc curve in the models. Very often this is done thanks to the Forbes correction. This work presents a numerical study that quantifies how imperfect stabilization and measurement noise impact the reconstructed Pc(Sw) curves for both centrifuge and porous plate experiments. Five representative rock types are generated using Brooks–Corey laws, realistic φ–k distributions, and associated Pc curves. Cydar software is then used to simulate the "perfect experiment" scenario: Conventional 8 Pc steps, the full stabilization of production at each step and no measurement uncertainty. Deviations from this scenario, such as noisy data or imperfect stabilization, are investigated for both experiments and their impact on the reconstructed Pc For the centrifuge experiment, the impact is propagated through the Forbes correction. Results demonstrate that stabilization is the dominant source of error, particularly for porous plate experiments, while measurement noise generally has a secondary impact under typical acquisition conditions. In centrifuge measurements, stabilization effects are less critical, but the final accuracy strongly depends on data interpretation and experimental design. The Forbes correction tends to propagate and, in some cases, amplify existing uncertainties. Based on these findings, recommendations are proposed to optimize stabilization strategies and define practical trade-offs between experimental duration and data reliability in SCAL workflows.

1 Introduction

Primary drainage experiments are a cornerstone of special core analysis, as they aim to reproduce the initial invasion of hydrocarbons into a fully water-saturated porous medium and to derive key petrophysical properties such as capillary pressure, resistivity index, and initial water saturation. These measurements are commonly performed using quasi-static laboratory techniques such as porous plate or centrifuge methods, where a sequence of imposed capillary pressure steps is applied and equilibrium is assumed once production and saturation are considered stable. [1,2]

However, despite being routinely treated as equilibrium data, primary drainage experiments are inherently transient processes whose outcomes are strongly dependent on the time allowed for stabilization at each pressure step. From a physical standpoint, primary drainage corresponds to a redistribution of fluids driven by capillary forces and resisted by viscous dissipation, as described in classical capillarity theory. Several analytical and numerical studies (as proposed by Andersen et al. for example) [3] have shown that the approach to equilibrium is governed by capillary diffusion processes, characterized by an exponential relaxation toward equilibrium states rather than an instantaneous response to imposed pressure changes.

The stabilization time required to reach quasi-equilibrium during a primary drainage pressure step is controlled by a complex interplay between rock properties, fluid properties, wettability, pore structure, and experimental boundary conditions. Absolute permeability and pore-size distribution strongly influence the effective mobility of the displaced phase being expelled, consistent with pore-scale interpretations derived from capillary pressure and relative permeability relationships.

The imposed capillary pressure level itself also plays a critical role. Low capillary pressure steps, which correspond to the initial invasion of large pore throats, are associated with long stabilization times. At these conditions, drainage pathways are only partially established, and connectivity effects dominate, a behavior consistent with classical percolation and pore-network interpretations of drainage processes (Hunt et al., 2014) [4].

* Corresponding author: quentin.danielczick@totalenergies.com

Fluid properties and wettability add another layer of complexity. While primary drainage capillary pressure curves are often interpreted assuming capillary equilibrium, the dynamics of drainage and the rate at which equilibrium is reached are inherently time-dependent and governed by interfacial phenomena.

As a result, the definition of equilibrium in primary drainage experiments remains operational rather than physical. Stability criteria based on the absence of measurable production or on limited changes in saturation over arbitrarily defined time windows are widely used in industrial practice [1] yet they do not guarantee that true capillary equilibrium has been achieved. If stabilization times are underestimated, systematic biases may be introduced into capillary pressure curves and derived quantities.

1.1 Impact of uncertainties on porous plate experiments

Beyond intrinsic rock–fluid interactions, the experimental device itself can significantly control the observed stabilization time. In porous plate and membrane-based techniques, the hydraulic resistance of the plate, its flux capacity, and the associated boundary conditions can limit the discharge of the wetting phase. This effect is consistent with the fundamental principle that flow in porous media depends not only on intrinsic rock properties but also on external flow constraints. [5]

Experimental studies have explicitly demonstrated that increasing the flux capacity of porous plates can reduce stabilization times without altering the measured equilibrium capillary pressure curve. Consequently, the equilibration time observed in porous plate experiments may be controlled by apparatus limitations rather than by intrinsic drainage physics.

In this context, the choice of stabilization criterion becomes critical. Conservative criteria may lead to extremely long experimental durations, while relaxed criteria may result in incomplete drainage and biased Pc–Sw relationships. Because production rates are inherently low and progressively decrease over time, distinguishing between true stabilization and slow transient behavior remains particularly challenging.

In addition to stability, water saturation during porous plate experiments is derived from volumetric measurements of brine produced at each imposed capillary pressure step. As a result, saturation uncertainty is directly controlled by the accuracy of the volumetric measurement and by the pore volume of the tested sample. The paper investigates the impact of noisy data and stabilization on porous plate reconstructed Pc-Sw curves.

1.2 Impact of uncertainties on Centrifuge experiments

In centrifuge experiments, the transient production behavior following a speed increase has been analytically described as a function of the distance to equilibrium and effective mobility, providing a clear demonstration that saturation profiles evolve gradually over time even under constant imposed capillary pressure conditions.

The question of stabilization at each centrifuge pressure step has been extensively discussed in the literature. Fleury et al. [6] demonstrated that capillary equilibrium during centrifuge experiments is intrinsically difficult to define using simple production rates or time-based criteria. Using high-resolution measurements of saturation versus time, they showed that transient production curves cannot be described by a single characteristic time but instead exhibit two distinct time scales associated with viscous-dominated and capillary-dominated flow regimes.

To account for this behavior, they proposed a bi-exponential model to fit production or saturation data as a function of time and to extrapolate the equilibrium saturation without waiting for full experimental stabilization. The stability of the extrapolated equilibrium saturation was used as a rigorous criterion for changing the centrifuge speed. Their work demonstrated that experimental duration could be reduced by approximately a factor of two while maintaining negligible loss of accuracy.

In practice, centrifuge experiments typically reach a quasi-steady state in a matter of hours to a day at each rotational speed, particularly for moderate to high capillary pressures, due to the strong driving forces imposed by centrifugal acceleration. This is consistent with the fundamental principle that centrifugal methods accelerate capillary redistribution by increasing the effective body force applied to the fluids.

As a result, stabilization effects are often of secondary importance compared to uncertainties introduced during data interpretation. It is widely recognized that the main source of variability in centrifuge-derived capillary pressure curves lies in the inversion and interpretation procedures rather than in the acquisition stage itself.

1.3 Outline of the study

The methodology developed to analyze the respective effects of measurement noise and imperfect stabilization is first presented in the following section.

The results are then discussed separately for porous plate and centrifuge experiments. For porous plate measurements, the impact of aggressive stabilization criteria on the reconstructed Pc–Sw curves is analyzed, highlighting the strong sensitivity of this technique to stabilization uncertainties. For centrifuge experiments, results obtained under typical experimental conditions are first analyzed and compared to an optimized acquisition strategy based on bi-exponential stabilization criteria, as proposed by Fleury et al. [6]. This comparison allows assessing the practical impact of stabilization assumptions on centrifuge-derived Pc–Sw relationships.

Finally, before concluding, the influence of relative permeability behavior on transient production during primary drainage is discussed, providing additional insight into the physical origin of stabilization effects and their impact on experimental observations.

2 Methodology

2.1 Petrophysical Framework

A synthetic numerical workflow was developed to investigate the impact of stabilization and measurement uncertainties on production-derived capillary pressure reconstruction during primary drainage.

Five representative rock types, presented in Table 1, were defined to span a wide range of reservoir qualities, with absolute permeabilities ranging from 0.1 mD to 1000 mD. Porosity varied consistently with permeability to ensure realistic petrophysical trends across the dataset. These rock types do not correspond to specific core samples but instead define controlled petrophysical families suitable for parametric analysis.

Table 1. Simulated Rock Type properties

Name	Pore Volume (cc)	Permeability (mD)	Porosity (frac)	Entry pressure - Pce (bar)
RT1	4.54	0.1	0.08	1.5
RT2	6.80	1	0.12	0.7
RT3	10.21	10	0.18	0.25
RT4	13.61	100	0.24	0.1
RT5	17.01	1000	0.3	0.05

For each rock type, capillary pressure and relative permeability functions were generated using the Brooks–Corey model coupled with the Burdine pore-scale closure [7] to ensure full physical coherence between Pc and Kr. Water effective saturation was defined as:

$$S_w^* = \frac{S_w - S_w i}{1 - S_{wi}} \quad (1)$$

Where Swi is the irreducible water saturation imposed identically for all simulations. Drainage capillary pressure curves were expressed as:

$$P_c(S_w) = P_{ce} * {S_w^*}^{-1/\lambda} \quad (2)$$

Where Pce is the entry pressure and λ is the pore size distribution index. The value λ=2 was used as the reference case for all five rock types.

Relative permeabilities were derived analytically from the same Brooks–Corey capillary pressure formulation using the Burdine [7] model, ensuring that both Pc and Kr are governed by a common pore-scale description. Water relative permeability was defined as:

$$K_{rw} = {S_w^*}^{(2+3\lambda)/\lambda} \quad (3)$$

and non-wetting phase (oil or gas) relative permeability as

$$K_{rnw} = (1 - S_w^*)^2[1 - {S_w^*}^{(2+\lambda)/\lambda}] \quad (4)$$

The Brooks–Corey model coupled with the Burdine closure was selected because it ensures intrinsic coherence between capillary pressure and relative permeability through a shared pore size distribution description. This framework is particularly well suited for synthetic studies aimed at assessing stabilization and reconstruction effects, as it avoids artificial inconsistencies between Pc and Kr and allows the influence of a single physically meaningful parameter to be isolated and interpreted. This study is limited to:

- primary drainage
- water-wet conditions
- homogeneous samples

2.2 Synthetic production simulation and reference definition

For each rock type, synthetic drainage production curves were simulated using CYDAR software in terms of cumulative produced volume and time-dependent saturation evolution. These simulations yielded production data in saturation as a function of time at successive capillary pressure steps. Stabilization was evaluated using the temporal evolution of ΔSw/Δt.

A fully stabilized reference scenario, denoted STAB, was defined where saturation changes reach a negligible level at each pressure step (i.e., perfect stabilization). This dataset is used as the reference acquisition condition.

Using these production data, capillary pressure curves were reconstructed from production-derived average saturation values using the same workflow as for experimental interpretation.

It is important to distinguish between:

- REF dataset: the input Pc–Sw relationship used to generate the synthetic production data
- STAB dataset: the Pc–Sw curve reconstructed from fully stabilized production data

Differences between REF and STAB arise from the reconstruction workflow and probably from minor relative permeability effects. This point is tackled in part 3.1.

2.2 Stabilization and Noise scenarios

Two types of deviations from ideal acquisition conditions were introduced: imperfect stabilization and measurement noise.

UNSTAB scenario

An imperfect stabilization scenario (UNSTAB) was defined using a stopping criterion based on the variation of average saturation. The experiment proceeds to the next pressure step when the variation of water saturation over a 24-hour period is lower than 1 saturation unit (1 s.u.).

From a physical standpoint, this criterion remains relatively aggressive, as transient capillary diffusion processes can persist over significantly longer timescales, particularly at low capillary pressures and near the displacement threshold. This criterion was used, for example by Shafer et al. [8] to shorten the duration of a porous plate experiment while compensating the stabilization by a numerical fitting and extrapolation.

From a practical standpoint, stabilization is assessed from production trends or visual inspection of saturation evolution over predefined time windows. In practice, visual inspection generally leads to more conservative stabilization criteria than a threshold of 1 s.u. over 24 hours.

For porous plate, an additional UNSTAB scenario based on 0.5 s.u over 24 hours has also been tested to investigate the tradeoff between stability and accuracy.

NOISE scenario

Measurement noise was introduced through a Monte Carlo uncertainty propagation scheme applied to incremental volume measurements at each pressure step (8 points per curve). A volumetric uncertainty of ±0.05 ml per measurement was assumed for porous plate experiments.

This value represents a conservative upper-bound estimate compared to class-A burettes (±0.03 ml), treated as a type-B uncertainty with uniform distribution according to the GUM framework [9]. The GUM framework provides a standardized methodology to quantify and report measurement uncertainty in a consistent and rigorous way. The selected uncertainty ensures that instrumental noise is not underestimated.

For centrifuge experiments, a volumetric uncertainty of ±0.01 ml was adopted, which is representative of the resolution of high-resolution camera systems commonly used in modern centrifuge setups. [10, 11]

For each rock type (and each experiment type), 80,000 realizations were generated, allowing a statistical characterization of the resulting uncertainty on reconstructed saturation. This noise was applied to the measured endpoints of each stabilization step, and the resulting perturbed values were treated as exact during the interpretation, without additional smoothing.

Uncertainty on initial water saturation was quantified using the 95th percentile of absolute error: p95(|ΔSwi|).

$$p95(|\Delta Swi|) = Quantile0.95(|SwiNoise - SwiSTAB|) \quad (5)$$

2.3 Porous plate simulations

For porous plate simulations, the STAB dataset is used as the reference scenario against which the UNSTAB and NOISE cases are compared.

In the UNSTAB scenario, the stabilization criterion described above is applied directly to the production curves prior to Pc–Sw reconstruction. This approach captures the cumulative nature of stabilization errors, which may either offset or accumulate along the drainage path depending on the applied pressure schedule.

In the NOISE scenario, measurement uncertainty is propagated along the full Pc–Sw sequence using Monte Carlo simulations. This allows quantification of how small incremental volume errors impact both local saturation estimates and global curve reconstruction.

Together, these scenarios enable a direct assessment of the relative contributions of stabilization versus measurement uncertainties in porous plate experiments, where equilibration times are typically long and production rates are low.

2.4 Centrifuge simulations

The present work was initially motivated by the question of whether stabilization criteria at each centrifuge pressure step could significantly affect the resulting drainage capillary pressure curve. Under the experimental conditions investigated (water wet samples λ=2), and consistently with previous centrifuge studies, stabilization effects were found to be of secondary importance. In practice, centrifuge experiments typically reach a quasi-steady state in a matter of a day at each rotational speed, particularly for moderate to high capillary pressures, such that variations in stabilization time have only a limited influence on the final Pc–Sw relationship. Our simulations confirm this general behavior in primary drainage (water wet conditions).

The question of stabilization at each centrifuge pressure step has been extensively discussed in the literature, notably by Fleury et al. [6], who demonstrated that capillary equilibrium during centrifuge experiments is intrinsically difficult to define using simple production-rate or time-based criteria. The stabilization criterion proposed by the authors was applied in this study. Their approach relies on fitting production or average saturation curves with a bi-exponential model, capturing both viscous- and capillary-dominated flow regimes, and extrapolating the equilibrium saturation S_w^∞ without waiting for full stabilization. The stability of the extrapolated equilibrium saturation, rather than the apparent cessation of production, was then used as a rigorous criterion to change the centrifuge speed. Their work demonstrated that the overall experimental duration could be reduced by approximately a factor of two while maintaining negligible loss of accuracy compared to fully stabilized experiments. In the present study, this concept was directly tested by comparing the following two scenarios:

- STAB: fully stabilized reference condition.

- D-EXP: stabilization based on the bi-exponential extrapolation method proposed by Fleury, Egerman and Goglin. The D-EXP scenario is also subject to variation criteria. Conforming to the author's recommendations, for a saturation target of 1% the fluctuations of the extrapolated saturation should be smaller than 1% during 4hours. This has been implemented in our workflow.

In the D-EXP approach, synthetic production curves are fitted with a bi-exponential model, and equilibrium saturation is estimated by extrapolation without waiting for full stabilization. The resulting Pc(entry) – ⟨Sw⟩ relationships are then reconstructed. D-EXP & Stab scenarios are compared in terms of duration and accuracy.

The impact of measurement noise is investigated through a NOISE scenario. As for porous plate, an introduction of noise through Monte Carlo simulation is done on the "acquired" Sw (from simulations).

To enable a consistent comparison with experimental workflows, reconstructed datasets are interpreted using continuous implementation of the Forbes method (Forbes + splines'), applied following the recommendations of Lenormand et al. [12]. This approach was consistently used for all Forbes-based results presented in this study.

However, this correction requires a manual inversion workflow (Cydar simulator) and cannot be applied to the full set of Monte Carlo realizations. For this reason, the impact of noise measurement was evaluated in two steps. First, 80,000 noisy realizations of Pc(entry) – ⟨Sw⟩ datasets were generated. Then, from this ensemble, the most extreme realizations (i.e., those exhibiting the largest deviation from the STAB scenario) were selected. These correspond to upper and lower envelope cases of measurement uncertainty. These extreme cases were subsequently interpreted using the Forbes correction. This approach provides a practical estimation of the maximum impact of measurement noise on centrifuge-derived Pc–Sw curves while remaining consistent with industrial data interpretation workflows.

3 Porous plate results

3.1 Impact of Non-Stabilization

Porous plate primary drainage experiments were first analyzed to quantify the impact of insufficient stabilization between imposed capillary pressure steps. The STAB experiment is presented in Fig.1 for RT3. The same profiles are generated for all RT. The duration of each pressure step was intentionally set well beyond the time required to ensure full stabilization.

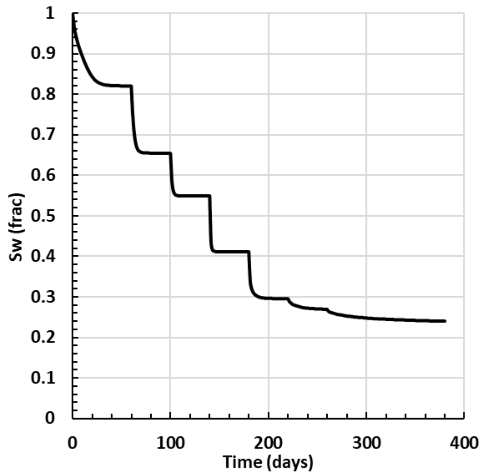

Fig. 1. Porous Plate RT3 Full stabilization (STAB) expressed in Sw

Fig.2 shows the effect of choosing the criterion of changing Pc step when the production reaches a rate lower than 0.5 s.u in 24hours.

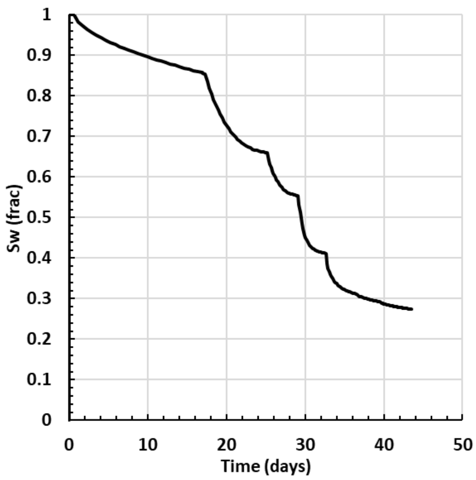

Fig. 2. Porous Plate RT3 UNSTAB production expressed in Sw (Sw evolution <= 0.5 s.u in 24 hours)

Fig.3 shows the effect of choosing the criterion of changing Pc step when the production reaches a rate lower than 1 s.u in 24hours.

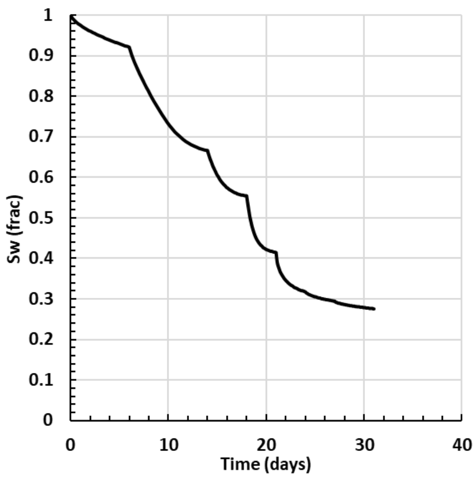

Fig. 3. Porous Plate RT3 UNSTAB production expressed in Sw (Sw evolution <= 1s.u in 24 hours)

A systematic comparison between stabilized (STAB) and non-stabilized (UNSTAB) Pc–Sw curves highlight a consistent upward bias in water saturation when stabilization is not fully reached. This bias is most pronounced at low capillary pressures, i.e. during the early stages of drainage. Across the five rock types investigated (RT1–RT5), the difference in initial water saturation due to non-stabilization, ranges from 2.2 to 6.9 saturation units between UNSTAB 1s.u/24h and STAB scenarios. Table 2 summarizes the differences between each scenario for each rock type.

Table 2. Swi values obtained by scenario

Rock-Type	Swi_ref (frac)	Swi_stab (frac)	Swi_Unstab 0.5 s.u/ 24h (frac)	Swi_Unstab 1 s.u/ 24h (frac)
RT1	0.360	0.390	0.449	0.459
RT2	0.290	0.313	0.353	0.362
RT3	0.220	0.240	0.266	0.278
RT4	0.160	0.172	0.201	0.205
RT5	0.090	0.103	0.122	0.125

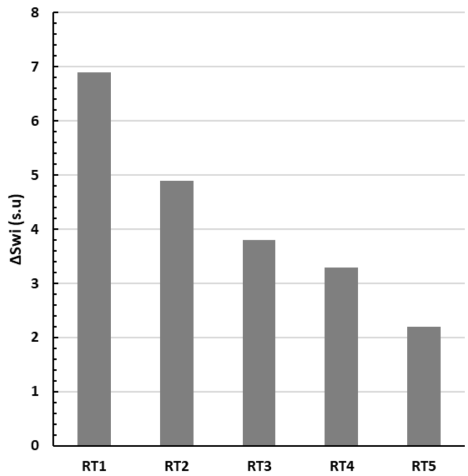

Fig. 4. ΔSwi between UNSTAB (1s.u/24h) and STAB scenarios in Porous Plate

The trend in Fig.4 shows a clear dependence on rock type. Although the stabilization criterion is defined in terms of saturation and independent of porosity, the resulting deviations are controlled by equilibration kinetics. Applying the same stabilization time to all samples leads low permeability rocks, (with slower pressure diffusion) to remain further from equilibrium and exhibit larger errors, while higher-permeability samples reach near-equilibrium conditions and show limited deviations.

As shown by the Fig.5, lowering the criterion to 0.5 s.u/24h does not appear to be an efficient way of maximizing data quality as the ΔSwi is in average only 0.7 s.u "better" than the 1.su/24h scenario.

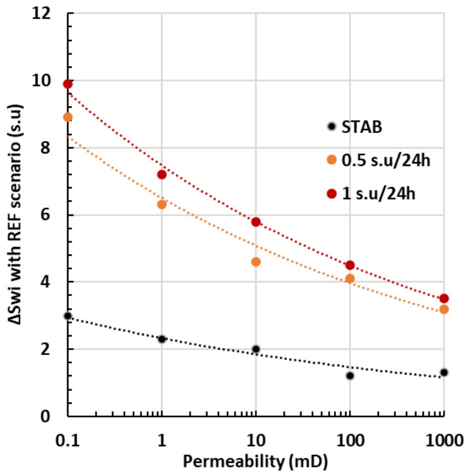

Fig. 5. ΔSwi for each RT between all scenarios and REF in Porous Plate

In addition to the clear differences observed between stabilized and non-stabilized Pc–Sw curves, a smaller but systematic discrepancy is also observed between stabilized experimental data (STAB) and the reference curves (REF) derived from numerical simulation or interpretation. In the present dataset, this difference in initial water saturation remains limited, typically in the order of 1 to 3 saturation.

Two non-exclusive mechanisms may explain the residual STAB–REF mismatch. First, a numerical effect related to saturation discretization, convergence, or update schemes may arise, especially at low water saturations where the Pc–Sw relationship is highly sensitive. Second, a physical effect linked to relative permeability may contribute. At low saturation, the associated phase mobility becomes extremely small, leading to extremely long equilibration times that are difficult to achieve experimentally. As a result, while a true equilibrium theoretically exists, it may not be fully reached within realistic timescales, leading to an apparent non-ideal equilibrium.

3.2 Impact of Measurement Noise on Saturation evaluation

As expected, measurement-induced saturation uncertainty decreases with increasing pore volume. For low-porosity samples, small absolute volume errors translate into saturation uncertainties approaching 1–2 saturation units, whereas for higher-porosity rocks the same volumetric error leads to sub-unit saturation uncertainty:
RT1 ($\phi = 0.08$): p95(|ΔSwi|) ≈ 1.8 s.u.
RT2 ($\phi = 0.12$): p95(|ΔSwi|) ≈ 1.2 s.u.
RT3 ($\phi = 0.18$): p95(|ΔSwi|) ≈ 0.8 s.u.
RT4 ($\phi = 0.24$): p95(|ΔSwi|) ≈ 0.6 s.u.
RT5 ($\phi = 0.30$): p95(|ΔSwi|) ≈ 0.5 s.u.

These results show that, even under conservative assumptions on volumetric accuracy, measurement noise alone typically contributes at most 2 saturation units to the uncertainty on Swi. This level of uncertainty remains significantly lower than the bias introduced by insufficient stabilization, as discussed in the following section. It is worth noting that the impact of such measurement noise can be significantly reduced using straightforward smoothing techniques, which were not applied here in order to assess a conservative worst-case scenario.

3.3 Stabilization bias and measurement noise: practical implications

The combined analysis of stabilization effects and measurement noise enables a direct comparison between methodological bias and instrument-related uncertainty in porous plate experiments. Non-stabilization, defined here as a water saturation variation exceeding 1 saturation unit over 24 h, was shown to induce a systematic upward bias on water saturation. For the investigated rock types, the resulting difference in initial water saturation between non-stabilized and stabilized conditions ranges from 2.2 to 6.9 saturation units, with the largest effects observed for low-porosity-permeability samples.

By contrast, Monte Carlo simulations performed using a conservative volumetric uncertainty of ±0.05 ml per measurement step indicate that measurement noise alone contributes a smaller uncertainty. The 95th percentile of the absolute error on Swi ranges from ~0.5 to ~1.8 saturation units. This error depends only on sample porosity but even for the tightest sample investigated (RT1, $\phi = 0.08$), measurement-induced uncertainty remains significantly lower than the saturation bias caused by insufficient stabilization. The relative magnitudes of these effects are compared in Fig.6 below

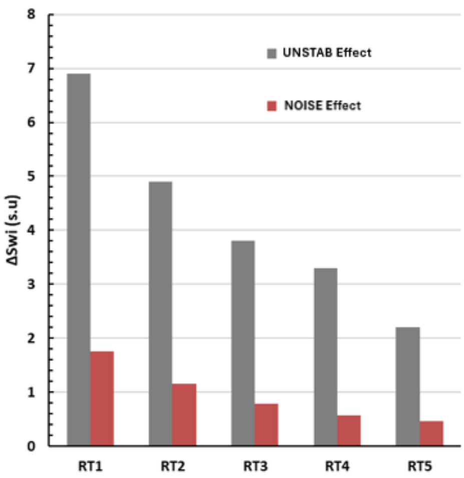

Fig. 6. ΔSwi for each RT due to UNSTAB and NOISE in Porous Plate

From a practical point of view, the results demonstrate that stabilization criteria represent a first-order control on data quality, whereas improvements in measurement resolution alone cannot compensate for insufficient equilibration. For low-porosity and tight samples, strict stabilization criteria are required to avoid saturation biases. For example, Fig.7 and 8 show the results between STAB simulation and UNSTAB 1s.u/24h simulation for RT1. While the experimental time is decreased by a factor of almost 11, the reconstructed Pc provides an Swi estimate of 6.7 s.u higher than the STAB scenario. Comparatively, the error bars (1.8 s.u) are of secondary importance. But in the worst-case scenario, adding 1.8 s.u uncertainty on such low pore volume sample would lead to committing an error of 8.5 s.u compared to the STAB Scenario.

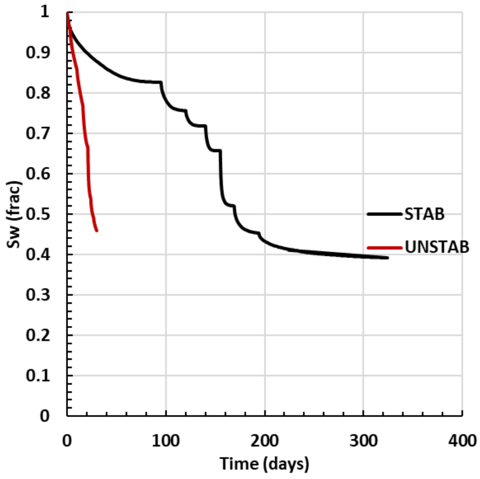

Fig. 7. Sw evolution for RT1 during time for STAB and UNSTAB in Porous Plate

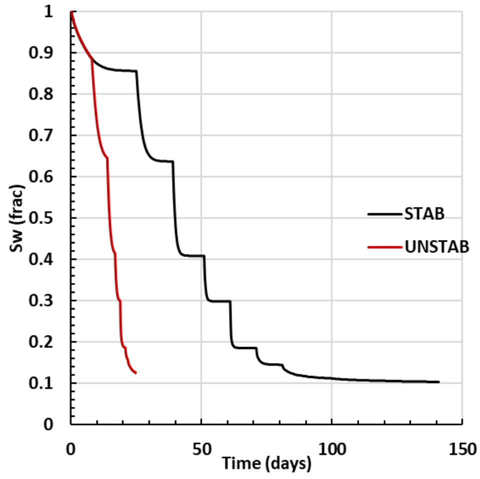

Fig. 9. Sw evolution for RT5 for both scenarios in Porous Plate

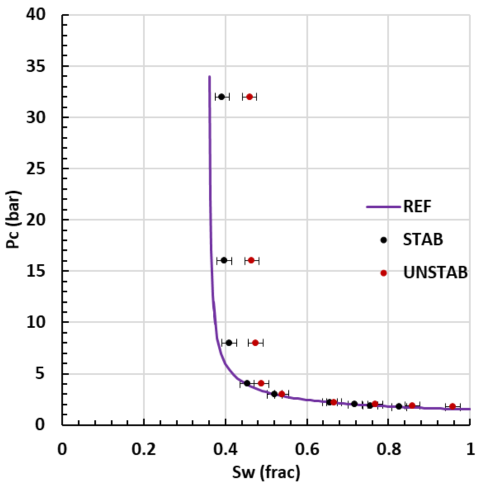

Fig. 8. Resulting interpreted Pc curves for RT1 depending on the Scenario

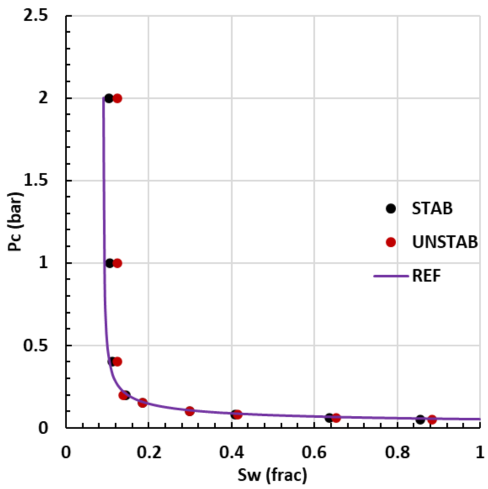

Fig. 10. Resulting interpreted Pc curves for RT5 depending on the Scenario

On the contrary, for RT5 the results presented Fig.9 and 10 shows that the experimental time has been divided by a factor of 5 while the final Swi is provided with a ΔSwi = +2.5 s.u and a +- 0.5 s.u uncertainty leading to a [+2 ; +3] s.u error interval between STAB and UNSTAB scenario. On Fig.10, error bars are so small that they are not visible. They fit approximately the size of the datapoints.

For more porous and permeable rocks (e.g RT 3 – 4 – 5), even the UNSTAB 1s.u scenario has shown a moderate overestimate in Swi varying from 3.8 s.u for RT3 to 2.3 s.u for RT5. It exhibits logical behavior: the higher the permeability the shorter the stabilization time. It led to lower errors even with the same stabilization criterion. The practical information to take away here is that reducing experimental time even with aggressive Pc step change criteria can still lead to an acceptable result for the best rock type as their stabilization time is globally lower. This is clearly not the case for RT1 – 2 – 3. The lower the permeability the higher the attention should be kept on stabilization criteria.

4 Centrifuge discussion & results

4.1 Forbes interpretation

As highlighted by Forbes (1997) [13], different interpretation approaches applied to the same centrifuge dataset can produce discrepancies in Pc curves larger than inter-laboratory variability. These differences are most pronounced at low capillary pressure, i.e. during early drainage, where uncertainty is inherently higher. The Forbes method amplifies uncertainties due to its differential formulation and is therefore highly sensitive to the definition of the initial Pc region (Chen and Ruth, 1993 [14]). In particular, the entry pressure Pce is poorly constrained: the first measurable production does not necessarily represent true capillary entry but reflects detection limits and transient effects. Small uncertainties on the first Pc point can significantly impact the entire inversion, as shown by Forbes (1997), and Chen and Ruth (1993) emphasized that the quality of low-Pc data strongly controls the accuracy of the derived curve. Consequently, improving centrifuge Pc results should focus on the treatment of the low-Pc domain rather than stricter stabilization criteria.

From a practical standpoint, particular care must be given to the definition of Pce. When not directly captured, Pc extrapolation toward Sw = 1 is required. The extrapolated value depends strongly on the mathematical space used: linear extrapolation (Pc vs Sw) tends to underestimate Pce (Fig.11), whereas semi-log extrapolation (log Pc vs Sw) yields higher values (Fig.12). This reflects different assumptions on the Pc–Sw curvature near full wetting saturation. A robust approach is therefore to bound Pce using these two extrapolations as lower and upper limits. This interval provides a physically meaningful estimate of uncertainty and allows assessing the sensitivity of the Forbes interpretation to the choice of entry pressure.

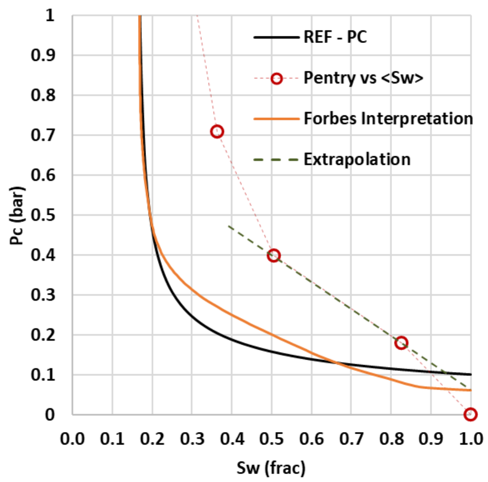

Fig. 11. RT4 Linear extrapolation for Pce determination. Pce=0.059 bar

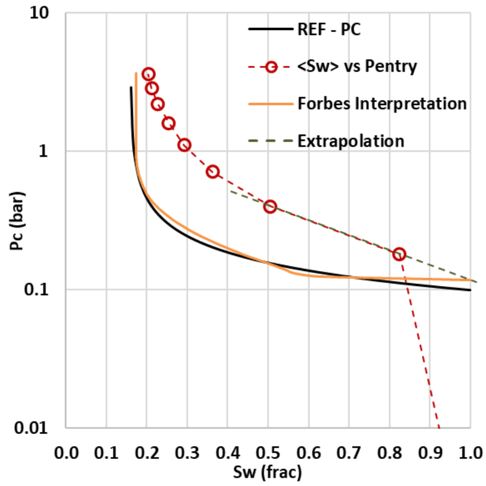

Fig. 12. RT4 Semi-Log extrapolation for Pce determination. Pce=0.116 bar

Fig.13 shows the differences that can be obtained by the Pe choice with the two mentioned approaches. While, in this case, the semi-log extrapolation would lead to a pretty good match with REF, the linear one has a non-negligible effect on the curvature and the transition zone.

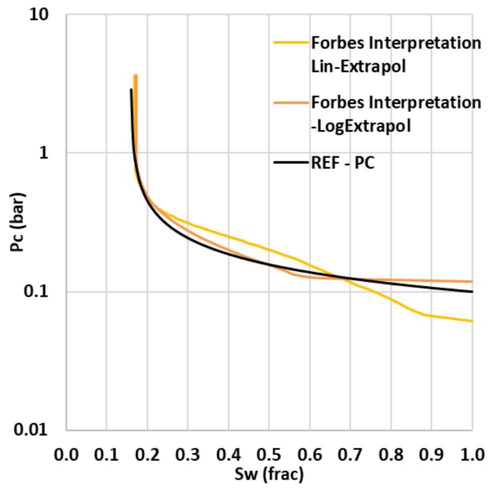

Fig. 13 RT4 Differences on Forbes interpretation depending on the Pce chosen

An alternative and equally robust approach is to constrain Pce from a continuous Pc (Sw) model fitted to the experimental data, such as Brooks–Corey or Leverett-type formulations, and to extrapolate Pce from the fitted model rather than directly from discrete data points. Such model-based extrapolation implicitly enforces the expected curvature of the Pc curve at low capillary pressures and avoids relying on the first measurable production point, which is not necessarily representative of true capillary entry. These simple practices allow the uncertainty on Pce to be explicitly acknowledged and controlled, thereby significantly improving the robustness of centrifuge Pc interpretations.

4.2 Stabilization results

Under the simulated conditions, centrifuge experiments typically reach quasi steady state within hours to a few days per pressure step. This reflects faster drainage dynamics compared to porous plate experiments, mainly due to the absence of the low-permeability porous plate that can significantly slow down equilibration.

Stabilization effects were found to be secondary compared to interpretation uncertainties, with centrifuge-derived Pc–Sw curves showing limited sensitivity to stabilization criteria once a reasonable equilibration level is reached. Since aggressive criteria such as UNSTAB (1 s.u./24h) bring limited practical value, the D-Exp scenario was compared to the STAB scenario (Fig. 14, RT3).

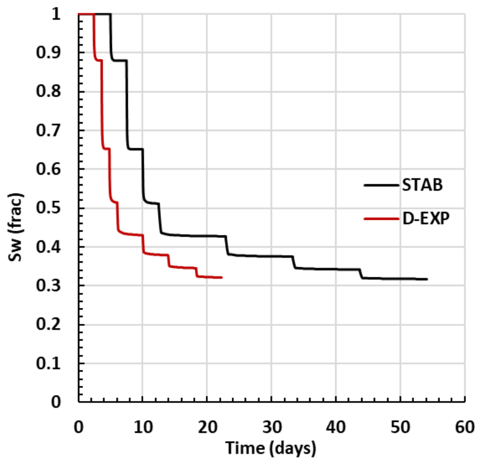

Fig. 14 RT3 duration time comparison between D-EXP and STAB scenarios in centrifuge

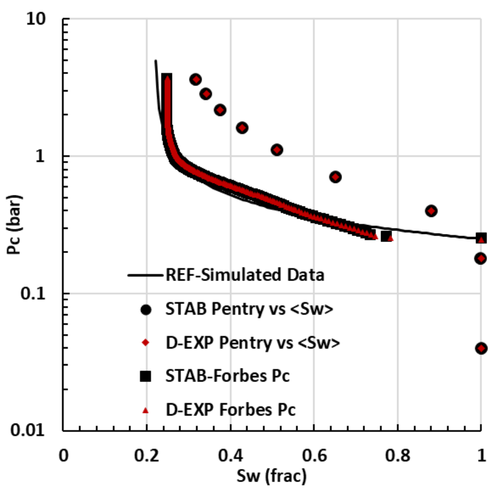

Fig. 15 RT3 resulting Pc curves (before and after Forbes interpretation)

If the experimental conditions are adequate to determine the full Pc curve and an adequate method is used to assume a Pe, then the D-EXP method can provide for all RT the same results (before and after Forbes interpretation) as the STAB scenario. For RT1 and RT2 no centrifuges available would provide sufficient Capillary pressure (in the simulated conditions) to well describe the Pce vs <Sw> and then no Forbes interpretation would be correct. For these low-permeability rock types, the selected λ leads to capillary pressures exceeding the operational limits of centrifuge methods, particularly in oil–water systems where the density contrast is low, preventing a proper characterization of the Pc– relationship. As shown in Fig.15 For RT3 the final differences between the STAB and D-EXP were lower than 0.3 s.u in the Swirr on the Forbes interpretation while the time reduction (Fig.14) as expressed by Fleury et al. is by a factor of 2 to 3. This observation is also valid for RT4 and 5 with no to very few differences with RT3.

4.3 Noise results

Measurement noise in centrifuge experiments is minimal due to high-resolution camera acquisition (±0.01 cc on volume), ensuring negligible propagation of uncertainty on saturation. For RT1 (Porosity = 0.08 – PV = 4.54 cc) the uncertainty represents 0.2% of PV for each measurement step. The result of the Monte Carlo analysis is provided as the P95 |ΔSwi| and summarized in the Fig.16 below.

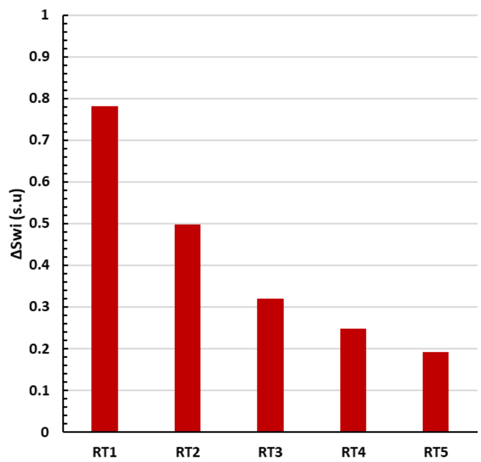

Fig. 16 P95 |ΔSwi| due to centrifuge camera equipment in centrifuge

Such low effect of noise on the average saturations acquired shows that, even in the worst-case scenario where errors are cumulative all along the Pc / Sw investigated, the global error on the Swi remains below 1s.u. The Forbes interpretation performed on NOISY scenarios (P05 and P95 Envelopes) for all the RT shows approximately the same range of errors. Under these experimental conditions the uncertainty is not exacerbated by the Forbes interpretation as shown for the RT3 in Fig.17 below where the Pc curves are superimposed.

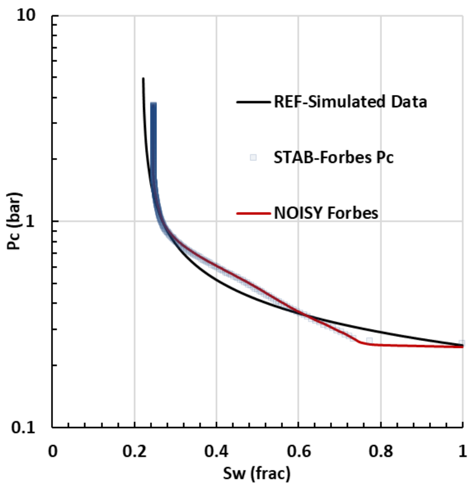

Fig. 17 Pc curves, forbes interpretation on STAB and NOISY scenarios

5 Conclusion of main findings

The present study highlights the contrasted roles of stabilization and measurement uncertainty in porous plate and centrifuge capillary pressure experiments.

For porous plate measurements, stabilization is identified as a major source of uncertainty due to poorly defined criteria. When applied in a permissive manner (based on saturation variation over time), these criteria introduce significant biases in reconstructed Pc–Sw relationships, exceeding the impact of measurement noise. Although visually robust, stabilization leads to increased experimental durations and remains poorly defined quantitatively.

In contrast, centrifuge experiments show limited sensitivity to stabilization criteria once quasi steady state is reached. The accuracy of centrifuge-derived Pc–Sw curves is primarily governed by interpretation methodology and experimental design, particularly at low capillary pressures, while measurement noise remains secondary.

Finally, the applicability of bi-exponential stabilization strategies (Fleury and Egermann) was briefly explored beyond centrifuge experiments. While offering a physically grounded alternative to full stabilization in centrifuge, it can provide a strong baseline for porous plate experiments. This point is tackled in the next “discussion” section.

Stabilization remains a recurrent challenge in core analysis experiments. In this paper the workflow has been kept to primary drainage, under “good conditions” (water-wetness and homogeneous samples). The influence of relative permeability and wettability on transient behavior is slightly expressed also in the next section.

6 Discussion

While centrifuge experiments generally exhibit rapid stabilization, this behavior is not uniform across all conditions. As shown by Fernø et al. (2007), equilibration times can extend from a few days to several weeks depending on wettability and rock properties, reflecting the strong influence of intrinsic fluid mobility and displacement dynamics. This effect could be further investigated through additional simulations (e.g., by varying the λ coefficient in Eqs. 2–4). In contrast to centrifuge experiments (that exhibit fast stabilization), porous plate acquisition still represents a time challenge. From an experimental perspective, the key is therefore to identify an optimal balance between stabilization accuracy and acquisition duration.

The D-EXP scenario, as applied both by Fleury et al. and in the present study, proved effective for centrifuge results. When applied to the porous plate simulation for RT1, which is characterized by low permeability and long stabilization times, it provided the following trade-off:

- Reduction of the experimental time by a factor of 4 (Fig.18)
- $\Delta Swi = +2.5$ s.u (Fig.19)

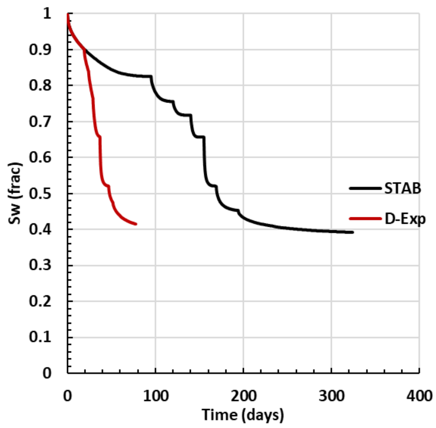

Fig. 18 RT1 Porous Plate duration D-EXP and STAB Scenario

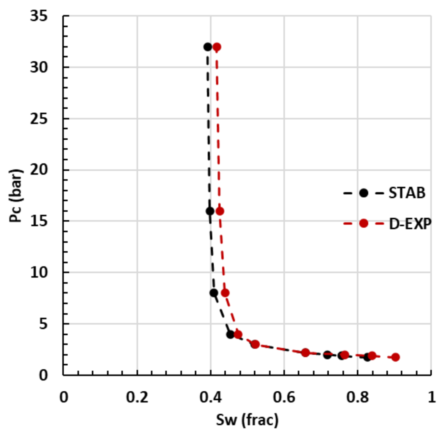

Fig. 19 RT1 resulting Pc curve interpretation

7 Recommendations

The combined analysis of porous plate and centrifuge results enables the definition of a practical framework for optimizing SCAL capillary pressure measurements. By considering the petrophysical properties of the sample (notably porosity and permeability), it becomes possible to anticipate the relative importance of experimental design, interpretation, stabilization effects and measurement uncertainties, and to define an acceptable trade-off between experimental duration and data quality.

This study shows that, by order of importance, it is recommended to:

1. Carefully design Pc steps based on preliminary simulations (like with a Brooks–Corey framework).

2. Ensure accurate determination of entry pressure and Swi (critical for centrifuge data).

3. Apply Forbes correction only on well-conditioned datasets (Lenormand guidelines).

4. Define stabilization criteria based on rock quality (permeability or rock quality driven trade-off).

5. Consider bi-exponential extrapolation (Fleury et al.) to optimize duration vs accuracy

6. Apply increased caution in case of heterogeneity or non-water-wet conditions, as uncertainties are amplified

Nomenclature

Pc: Capillary pressure (bar)
Pce: Entry pressure (bar)
Sw: Water saturation (fraction)
⟨Sw⟩: Average water saturation from production data
Pc(Sw): Capillary pressure–saturation relationship
Sw∞: Extrapolated equilibrium water saturation
Swi: Irreducible water saturation (fraction)
Sw*: Effective water saturation (-)
Krw: Water relative permeability (-)
Krnw: Non-wetting phase relative permeability (-)
φ: Porosity (fraction)
k: Absolute permeability (mD)
λ: Pore size distribution index (Brooks–Corey) (-)
PV: Pore volume (cc)
ΔSw: Variation of water saturation (fraction or saturation unit, s.u)
ΔSw/Δt: Rate of saturation change (s.u per unit time)
ΔSwi: Error on irreducible water saturation (s.u)
p95(ΔSwi): 95th percentile of irreducible water saturation error (s.u)
t: Time (hours or days)
REF: Reference dataset (input Pc–Sw relationship)
STAB: Fully stabilized dataset
UNSTAB: Non-stabilized dataset
NOISE: Dataset including measurement uncertainty
D-EXP: Bi-exponential extrapolated stabilization dataset
Quantile0.95: 95th percentile used in Monte Carlo analysis

References

1. C. McPhee, J. Reed, I. Zubizarreta, Core Analysis: A Best Practice Guide (Elsevier, Oxford, 2015)

2. Hassler, G.L., Brunner, E., Measurement of capillary pressures in small core samples, Petroleum Transactions, AIME 160, 114 (1945)

3.Andersen, P.Ø., Skjæveland, S.M., Standnes, D.C. ,An analytical model for analysis of capillary pressure measurements by centrifuge, Petrophysics 58, 366–375 (2017)

4. A.G. Hunt, R.P. Ewing, B. Ghanbarian, Percolation Theory for Flow in Porous Media, Lect. Notes Phys. 880 (Springer, 2014)

5. R.H. Brooks, A.T. Corey, Properties of Porous Media Affecting Fluid Flow, J. Irrig. Drain. Div., ASCE 92, 61–90 (1966)

6. J. Fleury, C. Egermann, D. Goglin, A model of capillary equilibrium for the centrifuge technique, SCA 2000-31 (2000)

7. N.T. Burdine, Petroleum Transactions, AIME 198, 71 (1953)

8. Shafer, J., Lasswell, P., Modeling Porous Plate Capillary Pressure Production Data: Shortening Test Duration and Quality Controlling Data, SPWLA 48th Annual Logging Symposium (2007)

9. JCGM 100:2008, Evaluation of measurement data — Guide to the expression of uncertainty in measurement

10. Fernø, M.A., Treinen, R., and Graue, A., “Measurement of Capillary Pressure and Relative Permeability during CO2 Injection in Sandstones at Reservoir Conditions,” Paper SCA2007-22, International Symposium of the Society of Core Analysts, Calgary, Canada, 2007.

11. Winter, A.S., Compan, A.L.M., De Andrade, F.B., and Moreno, R.B.Z.L., “Sensitivity Analysis for Capillary Pressure Data from Centrifuge Considering Different Rotation Speed Range, Centrifuges Models and Sample Size,” Paper SCA2025-1050, Society of Core Analysts International Symposium, Hannover, Germany, 2025.

12 Bauget, F., Gautier, S., Lenormand, R., and Samouillet, A., “Gas-Liquid Relative Permeabilities from One-Step and Multi-Step Centrifuge Experiments,” Paper SCA2012-13, International Symposium of the Society of Core Analysts, Aberdeen, Scotland, 2012.

13. Forbes, P., “Quantitative Evaluation and Correction of Gravity Effects on Centrifuge Capillary Pressure Curves,” Paper SCA1997-34, International Symposium of the Society of Core Analysts, Calgary, Canada, 1997.

14. Chen, Z.A., and Ruth, D.W.,“Centrifuge Capillary Pressure Data Reduction with a Modified Forbes Method,” Journal of Petroleum Science and Engineering, 9, 303–312, 1993.