THE H&B BOUNDARY CONDITION IN CENTRIFUGE PC EXPERIMENTS.
(*OR WHY THERE IS NO EXPERIMENTAL EVIDENCE THAT THE PRESSURE FIELD MODEL EVER FAILED*)

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Abstract
Since Hassler and Brunner developed the measurement of Capillary Pressures by centrifuging, it has been exposed to critical concerns. Several authors proposed "experimental" evidences for its failure either by showing desaturation at the core bottom face during centrifuging, or by showing that the current procedure provides results different that those related to "improved" processes.
Herein, one revisits assumptions on the pressure field in centrifuge experiments. It is shown that desaturations reported in the literature are consistent with these assumptions. One explains why some authors reported desaturation to occur at normal centrifugal speeds, while others expected it only at unusual speeds, based on thermodynamics or physics at the pore scale. Differences observed when various ways are used for determining the capillary pressure curve are explained too.
The so-called "*evidences for the failure of the current centrifuge technique*" are the results of interpretation problems. No clear evidence of a failure has been found.

Introduction
The centrifuge technique has been widely used for determining capillary pressure curves, Pc(S), since 1945 (Hassler and Brunner, 1945, Slobod et al., 1951). It is based on fluid production measurements at different rotation speeds, ω, on assumptions regarding the physics of fluid displacement and on the inversion of an integral equation between the curve Pc(S) and the experimental data (Table 1).

Table 1 *: Principle of the centrifuge technique for capillary pressure determination*

Measurements		Assumptions			Results
Rotation speed, ω Production volume	➔	Operator controlled - wettability - stress, overburden pressure - equilibrium time - pressure model - inversion process	Un-controlled - boundary pressure condition - continuity of fluid pathways	➔	S(Pc)

During the last decades, operators produced advances in many aspects of the data inversion processes (Hoffman, 1963, van Domselaar, 1984, Rajan, 1986, Ayappa et al., 1989, Christiansen, 1992, Forbes, 1994, Forbes et al., 1994, Chen and Ruth, 1993, Forbes, 1997a). Recently, a Society of Core Analysts survey (SCA, Forbes 1997b,c) presented the state of the art for inversion processes, leading to the conclusion that the best processes are now accurate enough. Any operators can therefore decide on the choice of a reliable process ensuring consistent interpretations.

There are however still a number of factors able to affect centrifuge measurements, such as wettabillity (for oil/brine systems), stress and overburden pressure, or equilibrium time (Omoregie, 1986, Hirasaki and Rohan, 1993). These factors also relate to operators. They are known and can be controlled. Uncontrolled assumptions are actually the zero-capillary pressure at the outflow of the core, the so-called Hassler and Brunner condition, and the continuity of fluid pathway allowing to define the capillary pressure field while centrifuging. These assumptions have been investigated but so far no definitive conclusion has been drawn mainly because contradictory comments have been reported (Wunderlich 1985, Baardsen et al., 1991, O'Meara et al., 1992, Forbes et al., 1992, Chen, 1999).
The present paper revisits observations previously reported under the frame of recent progress in the interpretation processes. It will show they are valid or, at least, that there is no evidence for their failure.

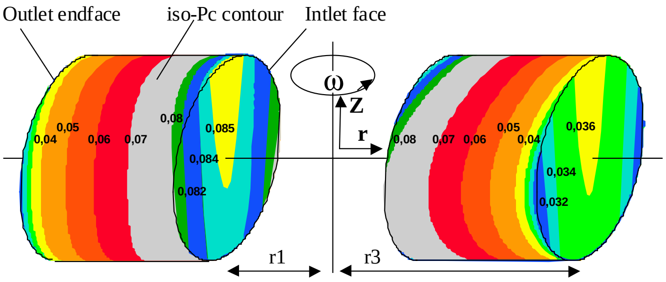

***Figure 1** : The centrifuge geometry. The pressure field distribution (including gravity) is drawn for a 2"x2"core with air-brine system rotating at 100RPM at r3= 8.6cm; iso Pc contour are indicated in psi (Forbes, 1997a).*

Recent improvements.

Centrifuge technique is based on the work by Hassler and Brunner in 1945 and further improvements (see Forbes, 1997b, for extended references). The method consists in measuring average fluid saturation in a core (Figure 1) at equilibrium during rotation at various angular velocities, ω. The sample is filled with a wetting fluid and spun within a second non wetting fluid. Due to the rotation, the inner fluid is forced out and the quantity expelled is measured to determine the average fluid saturation within the sample. The set of average saturation data allows the drainage capillary pressure curve to be determined if the pressure field within the sample is known. The way the pressure field is modeled and the related assumptions (such as the boundary condition) are therefore of paramount importance.
When rotating, the core fluids are submitted to the centrifugal field, $1/2\rho\omega^2 r^2$, and to the gravity field, $-\rho gZ$, (Figure 1). Where ρ is the fluid density, g the gravitational constant and (r, Z) refer to the cylindrical coordinates. Assuming hydrostatic equilibrium and connected fluid pathways, the pressure is given as : $P=1/2\rho\omega^2 r^2-\rho gZ+\text{const.}$ (Chen and Ruth, 1994, Forbes 1997a), leading to capillary pressure as : $Pc(r,Z,\omega)=\mathit{Const.}-1/2\ \Delta\rho\omega^2 r^2+\Delta\rho gZ$ ….(1)
In the most usual conditions the effect of gravity is negligible (Forbes 1997a) and the value of the constant *Const.* is obtained from the boundary condition assumption.
The boundary condition was initially given by Hassler & Brunner, H&B, (1945) as : "*the saturation must be 100 per cent and the capillary pressure zero at the outflow face*". Within the rough approximation of the H&B interpretation model, taking r as the coordinate along the sample length and not as the distance to the centrifuge axis, the capillary pressure was written as $Pc(r, \omega) = 1/2\ \Delta\rho\ \omega^2\ (r_3^2 - r^2)$ ……………………….(2)
The whole sample bottom face, being with $r = r_3$ and Pc=0, should therefore be fully saturated by the wetting fluid (for a first drainage). The idea that the core bottom face has to be fully saturated during a centrifuge drainage was largely accepted as a consequence of

the H&B condition. Desaturation has been therefore used to argue for the failure of the method.
More recently, the complete pressure field description has been introduced in interpretation processes on the form (1) above. If the boundary condition if still considered, i.e. that the minimum Pc value is Pc=0, where the inner fluid is flowing out, the capillary pressure is :

$$Pc(r,Z,\omega)=1_{/2}\Delta\rho\omega^2(r_3^2-r^2)+\Delta\rho gZ+1_{/2}\Delta\rho\omega^2(n+1)R^2 \text{..........................(3)},$$

with $n=2(g/\omega^2)/R-1$, if $g/\omega^2>R$ or $n=(g/\omega^2)^2/R^2$, if $g/\omega^2<R$. (R: radius of the core), for cylindrical core sample in drainage experiment, (Forbes, 1997a). Pc=0 and the outflow are located on the border of the circular bottom face of the core for Z=-R, if $g/\omega^2>R$ or, for $Z=-g/\omega^2$, if $g/\omega^2<R$.
The capillary pressure iso-curves are cylindrical around the centrifuge axis, slightly deeping due to gravity (Figure 1). The capillary pressure is therefore varying along the flatness of the core bottom face and there is no reason to expect Pc =0 or S=1 along the whole face.
Basically this pressure field description will allow to explain the observations reported in the literature, without considering the failure of the pressure boundary condition.

Observations usually linked to the boundary condition.
O'Meara et al., 1988, evaluated the effect of using several end pieces, rubber, teflon and foot-bath, when centrifuging identical ceramic plugs (Figures 2, 3). The different capillary pressure curves fit quite well, except when rubber is used. However the curves can be adjusted if the zero capillary pressure is displaced below the core by the thickness of the rubber end piece (1 mm, Figure 3).

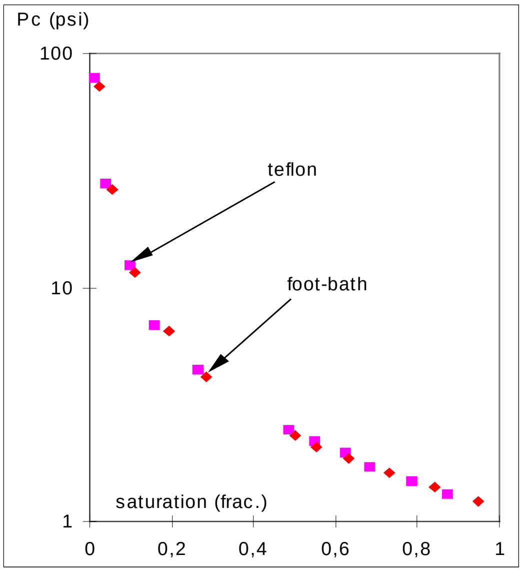

Figure 2 : *Capillary pressure curves obtained with a teflon end piece or a footbath (O'Meara et al., 98)*

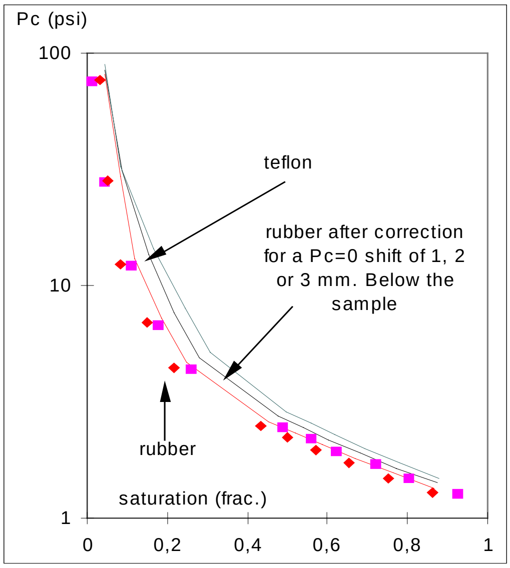

Figure 3 : *Capillary pressure curves obtained with a teflon or rubber end pieces (O'Meara et al., 98). Lines present corrections of the « rubber » case for displacement of Pc=0 1, 2 or 3 mm. below core bottom.*

Authors concluded that with a proper choice of end piece (not water-wet) the failure of the boundary was not detected at the macroscopic scale. Even when a rubber (water-wet) end piece is used, the fact that experimental results can be explained by displacing the Pc=0 location to the end piece bottom is a validation of the hypothesis used for Pc field determination. The boundary condition is displaced but still valid.

O'Meara et al., 1988, also provided data for a 330 md Berea core drained by an air/ iodohexadecane system. Freezing the iodohexadecane at 11 speeds allowed the saturation profiles to be determined by gamma attenuation scanning. The related capillary pressure curves and the centrifuge curves assuming the boundary condition superimposed well (Figure 4). Baardsen et al., 1991, did the same on Berea samples using a gas/wax system and X-ray tomography. The different profiles superimpose again (Figure 5).

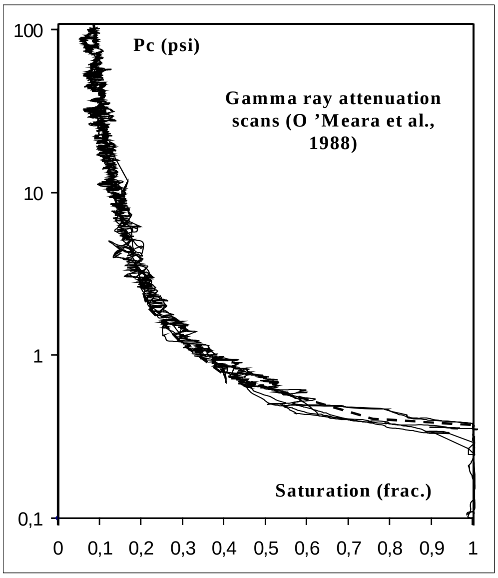

__Figure 4 :__ Capillary pressure curves from gamma ray attenuation profiles (O'Meara et al., 98).

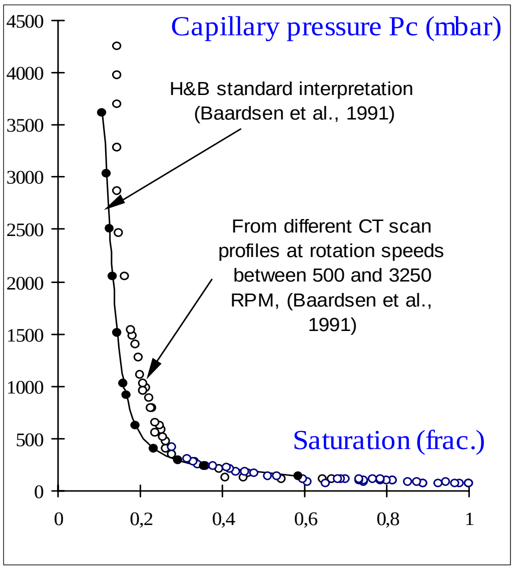

__Figure 5 :__ Capillary pressure curves from CT scan tomography profiles (Baardsen et al., 1991).

Forbes et al., 1992, also presented measurement allowing to deduce saturation values in part of samples investigated by 3 couples of ultrasonic transducers while centrifuging. These values were plotted against capillary pressure evaluated at the same locations by equation (2). Usually the 3 curves superimposed well and were comparable to the one obtained by usual interpretation of centrifuge average saturation (Figure 6). Basically these observations indicate that there is no change within the pressure field boundary condition between the different profiles obtained after running the centrifuge between 500 an 3500 RPM. More precisely, Figure 3 shows the effect on displacing the H&B condition by 1, 2 or 3 mm. below the sample bottom. It is quite large, especially if the log scale is considered, and could not be missed experimentally.

On the other hand, Baardsen et al., 1991 compared CT scan Pc curves to the standard centrifuge H&B interpretation (Figure 5). It doesn't fit, suggesting that measured average saturation was lower than expected.

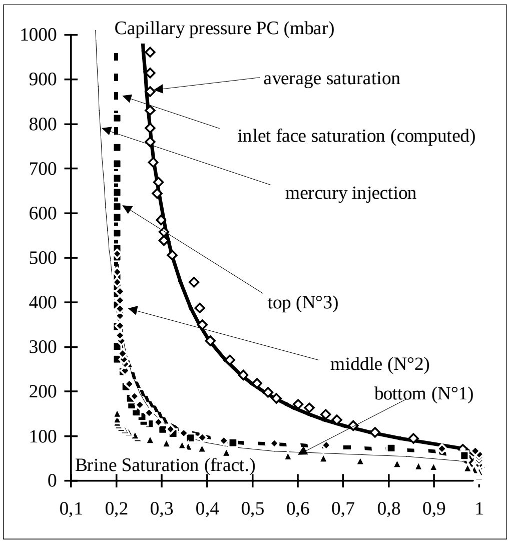

***Figure 6** : Capillary pressure curves from ultrasonic measurements (Forbes et al., 1992).*

Baardsen et al., 1991, also investigated the end face desaturation, for gas/brine or light refined oil/ brine systems. Typical results show saturation profile within central slice of core samples (Figure 7). Beside a certain rotation speed value, the outer face of the samples was showing desaturation to occur. One typical example is the gas/water drainage performed on the Berea sandstone B1. Figure 8 shows the saturation profiles recorded for different rotation speeds. All the profiles show decreasing saturation close to the sample bottom, partly due to the fluid redistribution between the stop of the centrifuge and the CT scan (2-3 minutes). Water/gas system redistribution is also reported to be faster than for water/oil system. Beside that redistribution, Figure 8 clearly shows that for rotation speed above 1000 RPM the initial bottom face saturation was lower than 100%. Authors reported these observations support the failure of the boundary condition by 1000/1250 RPM

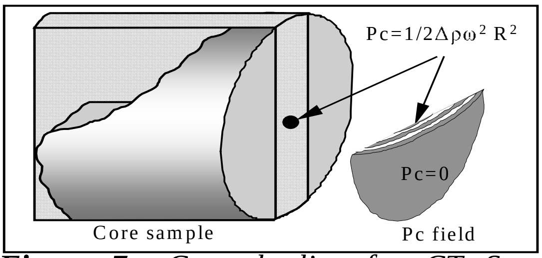

***Figure 7** : Central slice for CT Scan profiles (Baardsen et al., 1991).*

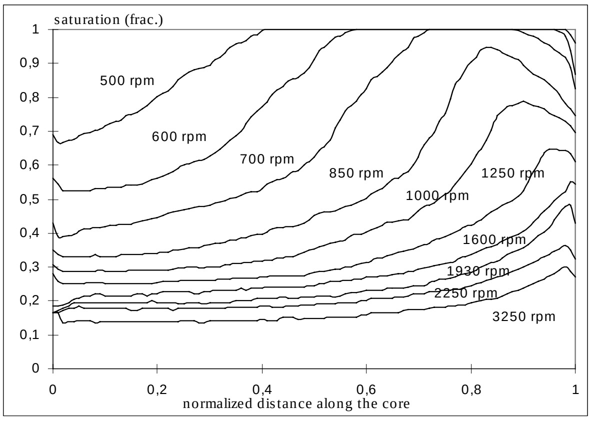

***Figure 8** : Saturation profiles from CT Scan tomography, (Baardsen et al., 1991).*

As said above, Forbes et al., 1992 presented consistent saturation measurements while centrifuging using ultrasonic devices for oil/water drainage on Vosges or Berea sandstone samples. However, ultrasonic signals allowed to evidences anomalous behaviour to occur within the samples by 1800-2200 RPM, corresponding to inlet face capillary pressure by 650-1000 mbar (Figure 9). Also, the Figure 6 shows one case where the capillary pressure curve obtained from transducers located at the core bottom did not fit the other. Forbes et al., 1992 used that departure and the change in ultrasonic records by 1800-2000 RPM, to argue on the failure of the H&B boundary condition.

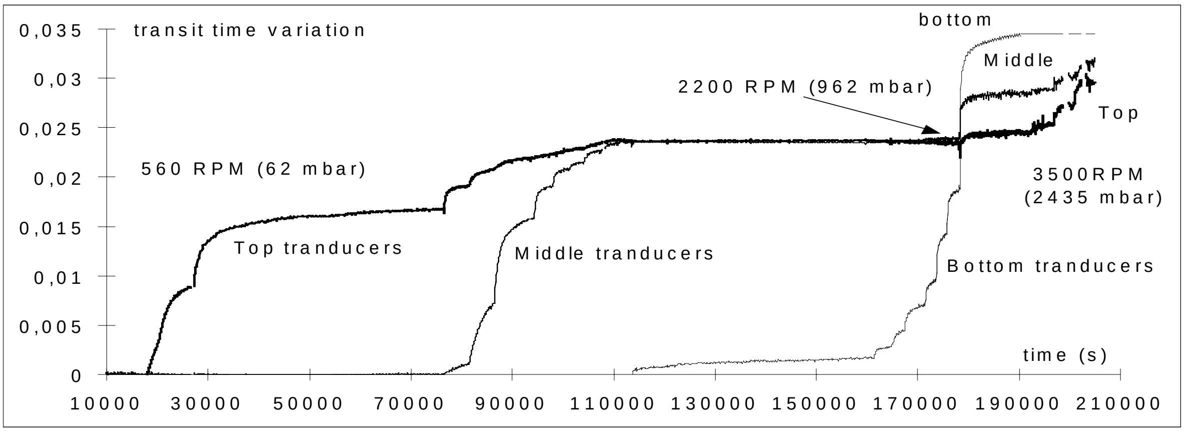

Figure 9 : Recordings of transit time variation (Δt/to) versus time for 3 locations along a Vosges sandstone core sample during centrifuging. The sample was initially fully saturated with brine progressively replaced by oil during the experiment (Forbes et al., 1992).

Ajufo et al., 1993 within a study on the effect of overburden pressure using the centrifuge, reported some comparison between porous plate and centrifuge measurements. They concluded that both exhibit equivalency. That could be considered as supporting the method, however curves are not actually equivalent (Figure 10). As they show differences up to 4-5 saturation units, they can as well support an excess of desaturation when the centrifuge method is used. At least that difference has to be explained.

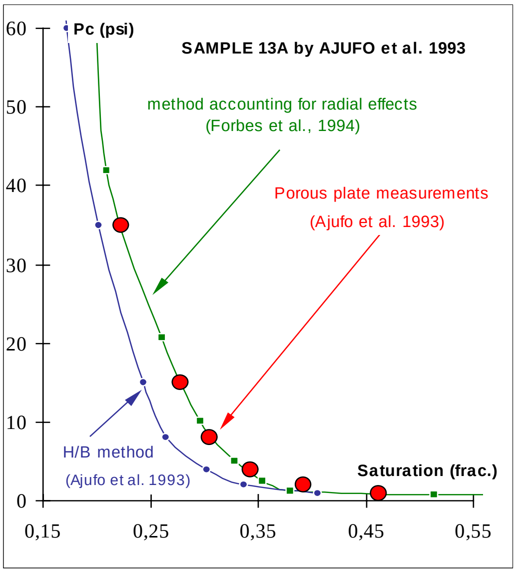

Figure 10: Comparison of capillary pressure curves, porous plate-centrifuge, Ajufo et al., 1993.

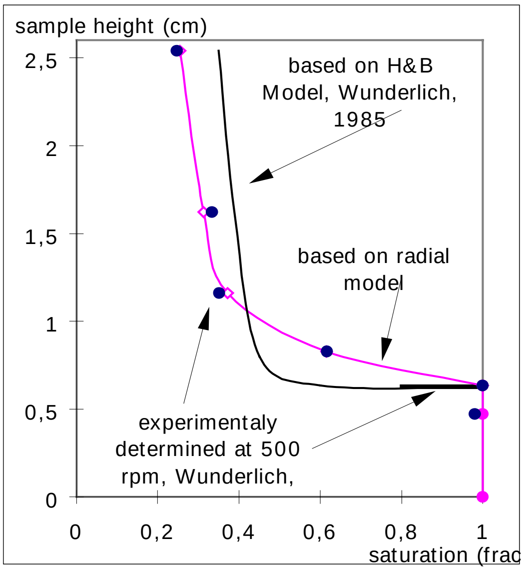

Figure 11 : Saturation profile at 500 RPM from epoxy casting imaging, (Wunderlich, 1985).

Wunderlich, 1985 imaged desaturation to occur at the end face by using an epoxy casting technique for a air/epoxy drainage system. After epoxy has been solidified, thin sections of the core were prepared to image phase distribution. The Figure 11 presents the wetting phase saturation profiles from bottom to top of the sample determined from five thin sections at 500 RPM or calculated using the initial H&B interpretation method. The profiles do not fit. The author also reported that beyond 2500 RPM the 100% saturation at the sample bottom was not valid. Quite correctly, it was concluded that one of the assumptions used to analyse the centrifuge data was failing (not necessary the boundary condition). However, number of readers related the observation to the failure of the boundary condition only.

Bil, 1993, presented measurements performed with or without footbath on the same six sandstone samples for a brine/air drainage system. He determined different capillary pressure curves when obtained with or without foot-bath. The wetting phase saturation was recorded to be 1 to 6 % pore volume higher for non-foot-bath curves. Stating that the use of footbath insured appropriate boundary condition, he concluded that the condition was not effective for non foot-bath experiments (Figure 12). That conclusion is however opposite to the one presented by O'Meara et al. from their own foot-bath experiment.

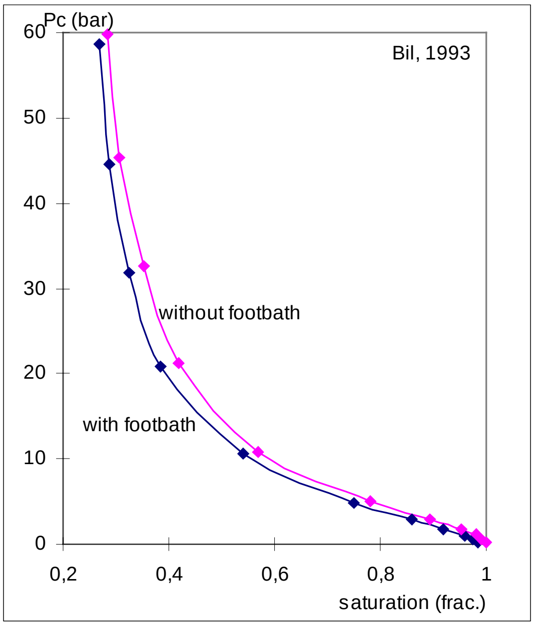

***Figure 12**: Capillary pressure curves with or without footbath, (Bil, 1993).*

Beside these macroscopic observations, microscopic mechanisms possibly affecting fluid stability were analysed too.

Mechanisms for the failure of the boundary condition or fluid instability.

Displacement towards thermodynamic equilibrium.

Wunderlich (1985) recalled that the Pc=0 can not be at the sample bottom if thermodymanic equilibrium is achieved, and therefore that centrifuge systems should be far from equilibrium. However, for the long times, the system could move towards equilibrium and the reference Pc=0 could be displaced to the fluid/fluid interface out of the core. If that happens, excess of desaturation should be observed. As noticed by O'Meara et al., 1988, and illustrated on Figure 3, if the effect were to occur it would greatly change saturation profiles and should have been sorted out from experimental data. No related observations have been reported yet.

Centrifugal instability.

Another source of failure could be centrifugal instability. Wunderlich reformulated the equation of Maxwell leading to the critical radius of capillary tube beyond which a wetting film becomes unstable : $r^*=36.6\,(\sigma/\Delta\rho\, r_3)^{1/2}\ 1/\omega$. (where σ is the interfacial tension). For usual gas-brine systems (pores size < 100 µm, σ= 72 mN/m, $\Delta\rho$=1 g/cc) it yields to instability above 10000 RPM (and to higher value for oil-brine systems). Potential effects are therefore unlikely to be observed usually.

Melrose,1988, assumed that wetting fluid breakthrough will occur when the displacement pressure is reached at about one-half of a mineral grain diameter above the core bottom. Considering high permeability sample (1000md), i.e. with large pores, the capillary pressure at the entry face should exceed 80psi to lead to the fluid breakthrough. That is that a rotation speed of about 4000 RPM has to be reached. For 100 mD sample that value moves above maximum centrifuge speed. Melrose concluded that the failure of the boundary condition is not likely to occur in normal centrifuge measurements.

This has been too analysed by O'Meara et al. 1988, reporting critical values of Bond number for different models ($N_B=\omega^2 r_3^2\, r_p^2 \Delta\rho/\sigma$). Values are in the range of 0.5 (except the first one reported by Wunderlich which is even greater). That is in the range of the one corresponding to the analysis by Melrose, mainly because all the models referred to the pore scale for assessing the level of instability. Authors concluded, as Melrose did, that the instability is going to occur in rare circumstances and that the related error is likely to be small, shifting the pressure profile by one pore diameter.

From these microscopic scale analysis it should be concluded that instability will not occur. The doubt arises because stability and boundary condition were linked to the full saturation of the end face while desaturation has been observed.

A simple way used to solve the contradiction (and support the failure) is to change analysis in order to have instability expected in usual conditions. Chen (1999) assumed that in practice heterogeneity will cause de-saturation to occur at the core bottom when the length of the fully saturated zone is shorter than 20 times pore dimensions, that is 40 times larger than the one considered by Melrose. Because the critical rotation speed and the critical thickness of the S=100% zone are inversely related, Chen found much lower critical speed, actually within the range of usual centrifuge measurement. For a typical Berea sandstone, Chen 1999 estimated that instability should occur by 2000 RPM - to be compared to the values of 1000-1250 or 2000-2500 RPM reported by Baardsen et al., (1991) and Wunderlich (1985) for desaturation of the bottom face (Table 2).

Pendant drop effect. O'Meara et al. also investigate the effect of pendant drops at the outflow. The capillary pressure at the face could be different from zero because of drop curvature and pressure shift across the interface. Authors presented an evaluation of the distance that the apparent Pc=0 condition is displaced above or below the outflow face (depending on the contact angle). They evaluated the maximum error on average saturation to be between 0.034 and -0.017 for an inflow Pc=0.5psi (air/brine systems), decreasing while centrifuging to 0.0034 and -0.0017 for an inflow Pc=50psi. Basically they obtained :

$$\delta S < z(\theta)\,(\sigma/LPc_1)^{1/2} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

L is the sample length, Pc_1 the entry face capillary pressure, θ the contact angle, $z(\theta)$ the dimensionless distance given on their figure 9 by O'Meara et al., 1988 ($-0.6<z(\theta)<1.2$).

They concluded that pendant drops change the Pc=0 condition but that the departure from zero is always small. Also one should note that pendant drop effect may exist all along the measurement, decreasing with rotation speed while instability may occur and increase above a critical speed.

From these analysis at microscopic scale, there is no evidence that fluid instability or departure from the condition Pc=0 should be significant, except if drastic instability conditions are considered (Chen, 1999). However an apparent contradiction occurs because one has :
-on one hand, macroscopic evidences of unexpected desaturations or of inconsistent interpreted capillary pressure curves suggested to be due to the failure of the technique and
-on the other hand, microscopic analysis which most of the time concluded that the failure should not occur.
To reconciliate both aspects, we defend herein that observed desaturations are just normal within the frame of the boundary condition and that inconsistencies are due to non appropriate pressure model or data analysis in use.

Discussion

The centrifugal instability as suggested by Chen, 1999, to be supported by the critical rotation speeds for end-face desaturation (Baardsen at al., 1991 at 1000-1250 RPM and Wunderlich, 1985, at 2000-2500 RPM) is questionnable. Chen used, for defining a Berea sandstone, part of data reported by Baardsen et al. (geometry, pressure thresholds) and part reported by Wunderlich (pore size), (Table 2).

Table 2 *: Evaluation of the critical rotation speed for fluid destabilisation when the S=100% zone starts to be thinner than 20 pores dimension, gas-brine system within a Berea sandstone.*

	Baardsen et al., 1991		Chen, 1999		Wunderlich, 1985
r1 (cm)	4.46				17.76
r3 (cm)	9.38	→	9.38		20.3
$\Delta\rho$ (g/cm^3)	1.0785	→	1.0785		1.068
δP_d-δP_2 (kPa)	9	→	9		4.3 (1)
σ (mN/m)	70.6				42.7
Pore size (μm)	< 16 to 31 (2)		100	←	100
	⇕		⇕		⇕
$\omega_{instability}$ (RPM) expected	> 3700 to 5000		2000		950
$\omega_{desaturation}$ (RPM) observed	1000 to 1250				2000 to 2500

(1) : calculated from Figure 5 by Wunderlich, 1985. (2) : calculated from Young-Laplace equation $\delta P_d = 2\cos(\theta)\,\sigma/r$ (r: pore throat radius) and δP_d-$\delta P_2 < \delta P_d$, for oil/water and gas/water data, Baardsen et al., 1991.

Even if the hypothesis of destabilisation for a 100% zone thinner than 20 pores dimension is still considered, one can apply the Chen calculation consistently for each kind of samples separately (Table 2). One obtains instability to occur by 4000 RPM for experiment reported by Baardsen et al. and 950 RPM for the one by Wunderlich. Both do not compare at all with the desaturation observed experimentally. Additionnaly if the last 2 mm of core sample could desaturate by instability, the desaturation will affect up to 8% of 1”x1” core. This can not be missed by experimentalists. In other words there is no evidence for supporting the single destabilisation process reported to explain significant desaturation. Observed desaturation is due to something else.

Concerning observation by Bil, 1993, one should note that it is the only one reporting missing desaturation when the standard method is used (no foot-bath). As reported above the failure of the boundary condition may produced excess of desaturation. The only way the have missing desaturation is to consider a shift of Pc=0 position above the sample bottom by pendant drop effect. In that case the saturation shift decreases with increasing pressure (O’Meara et al. 1988). The maximum shift can even be evaluated applying the equation (4). It is by $\delta S< 0.0009$ for Pc_1=55bar. That is 60 times smaller than value reported by Bil. The author also reported that no production is observed for rotation speed by 750 RPM, that is for Pc_1=0.15bar leading to $\delta S< 0.016$. Therefore, for the experiments reported by Bil, no shift higher than 1.6 saturation unit can be related to pendant drop effect. Additionally that is going to occur only for low speed and for high contact angle (>60°) what is unlikely to occur. Moreover there is not enough information on the inversion processes used, to decide if the presented Pc curves are reliable or not. That point will be addressed below to explain the observations. In practice Bil’s observation can not be related to change in the pressure regime during centrifuging.

Concerning the observations by Forbes et al., 1992, the departure of the curve for the bottom transducers (Figure 6) appears to exist all along the saturation range, that is from low to high rotation speed. It is therefore not due to a change in the pressure regime when increasing rotation speed. Also the simultaneous measurements from the other 2 couples of transducers are consistent and departure does not exist for measurements on other samples (Forbes et al., 1992). It seems therefore related to the sample rather than to the way to model the pressure or to the boundary condition. Core heterogeneity could be considered as an explanation. The change in ultrasonic behaviour above 1800-2200 RPM (Figure 9), is unlikely to be due to fluid instability because by 2200 RPM the 100% water zone at the sample bottom is still more than 3 to 4 mm. thick. This can be calculated from the pressure threshold value (by 60 mbar) or from the remaining water volume (0.6cc) to be produced before residual saturation to be reached. We have no explanation for that behaviour.

All these observations cannot be related to the boundary condition failure when the rotation speed is increased. However, actual observations remain and have to be accounted for. Most of them will be the result of the radial shape of the pressure field and related interpretation processes within the frame of the boundary condition. As said in introduction, accounting for the complete pressure field will lead to the capillary pressure given by equation (3). The capillary pressure and saturation are expected to vary within the core bottom face (Figure 1). It will allow endface desaturation keeping the fluids connectivity and Pc=0 at the outflow.

Forbes et al., 1994 and Forbes, 1997a, presented interpretation processes accounting for actual pressure distribution. Using that full scheme, data by Baardsen et al., 1991, (their table III for sample B1), can be re interpreted. The Figure 13 presents the results by comparison of capillary pressure directly obtained from CT Tomography. As shown there are no more discrepencies between the centrifuge and CT Scan results. Note that the CT Scan saturations were measured within a central longitudinal slice 8 mm thick. For the CT scan results too, the Pc values have to be shifted by $+1/2\Delta\rho\omega^2 R^2$, the value at the slice bottom (neglecting gravity effect, Figure 7). That correction also improves the profiles superposition mentioned previously. The difference between CT scan results and the H&B interpreted curve is due to the approximation of the H&B interpretation process.

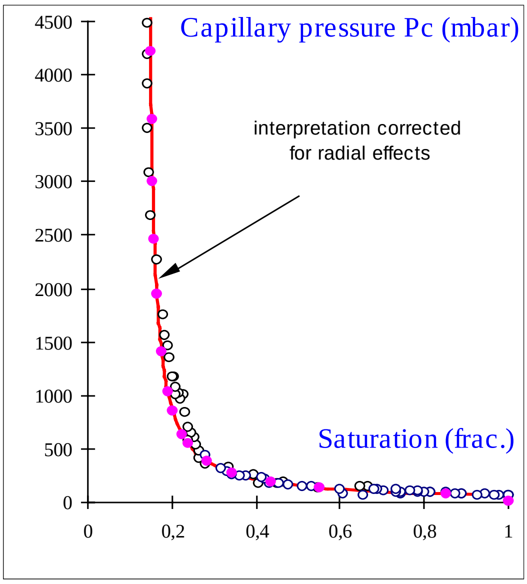

Figure 13 : *Capillary pressure curves from CT scan tomography (Baardsen et al., 1991). Comparison to interpretation accounting for radial effects.*

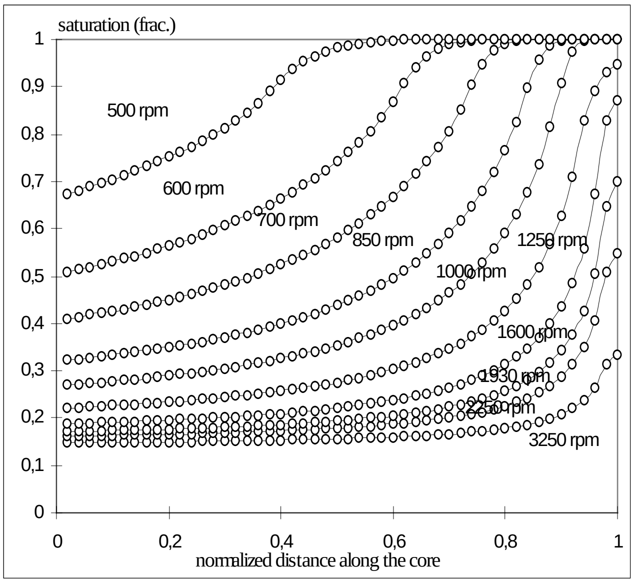

Figure 14 : *Calculated CT Scan tomography profiles, to be compared to figure 8 (core central slice as on Fig 7).*

The saturation profiles, showing desaturation to occur by 1000-1250 RPM, were also computed using the full pressure model within a 8 mm. thick central slice. Figure 14 shows desaturation expected to start between 1000 RPM and 1250 RPM as experimentally observed. Desaturation is therefore normal and consistent with the boundary condition.
To test if the results by Wunderlich are consistent too with the pressure model we operated as follows. The local capillary pressure curve is assumed to be of the form $S=1-a(Pc-\delta P_d)^b$ for $Pc>\delta P_d$ and S=1 otherwise. Using that form, the average saturation is computed for the five transverse sections and one central longitudinal section imaged by Wunderlich. The calculation is done for 500 RPM, accounting for the usual model for pressure field (including the boundary condition, radial distribution and gravity) and for sections of 50

μm thick (the author reported to have prepared section thicker than the usual 30 μm ones). Parameters a, b and δP_d are optimised to fit the data provided by the author (Figure 11) including the height of 100% saturation at 500 RPM. Figure 11 shows that the corresponding profile fit very well experimental data.
Using that S(Pc) curve one recalculated for longitudinal central section the heights of 100% saturation at 1000 and 1500 RPM. Table 3 shows that the agreement with observed value is very good too.

RPM	Wunderlich	calculated
500	0.63 cm.	0.63 cm.
1000	0.13 cm.	0.13 cm.
1500	0.04 cm.	0.035 cm.

***Table 3** : Height of 100% saturation versus rotation speeds for centrifuge design by Wunderlich, 1985.*

Using again the same curve, one calculated the average saturation for the end face, still assuming the complete pressure model for different rotation speeds. Figure 15 shows that desaturation is expected between 2000 and 2500 RPM, as observed by the author.

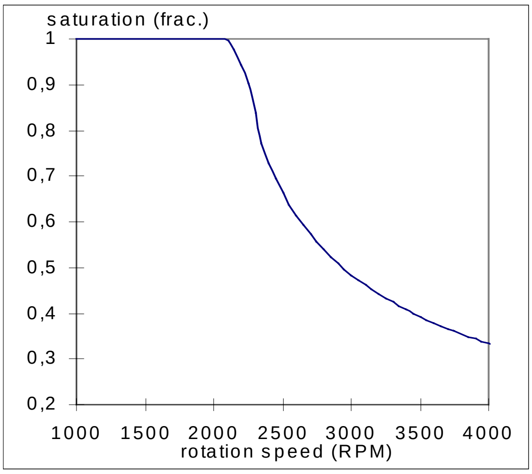

***Figure 15** : Calculated end face saturation for experimental design by Wunderlich, 1985.*

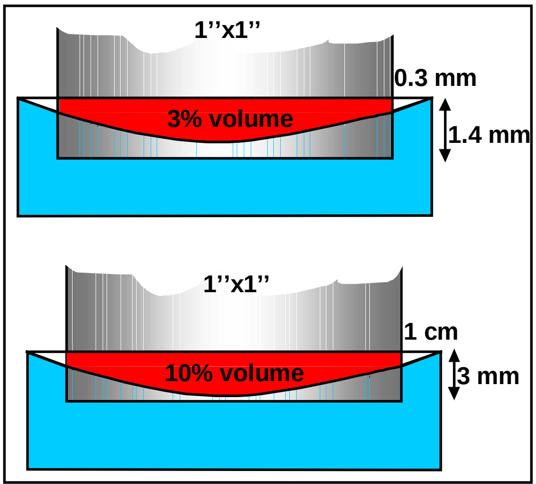

***Figure 17** : Pressure field shape in the core bottom for fixed level systems.*

The same applies for results presented by Ajufo et al., 1993. When centrifuge measurements are interpretated accounting for radial effect a much better fit is obtained with the corresponding porous plate measurements (Figure 8, Forbes et al., 1994).

Finally, concerning observations when using foot-baths, Bil, 1993, reported the use of an appropriate interpretation process which is not described. It may be appropriate or not for the foot-bath case or for the non foot-bath case, but certainly not for both. When a foot bath is used the bottom cylindrical part defined by the Pc=0 line (see *, Figure 16), is included within the sample and does participate to production. It is out of the sample with a open end face and therefore does not contribute to production. The same interpretation model can not be used for both.

If that occurs, a missing desaturation corresponding to the missing production of the part (*) will appear between the two cases (Figure 16). The cylindrical part (*) in the experimental conditions by Bil represents about 3 % of the core volume (Figure 17).
Accordingly, on may expect differences from 0 to 3 saturation units between the cases, increasing at higher speed when the sample bottom desaturates. The experimental reproducibility is not better than 3 saturation units according to the author. Therefore, one may expect differences from 0 to 6 saturation units between the curves, increasing with rotational speed in average, without any consideration of the boundary condition failure. That is exactly what Bil reported.

To conclude, reported observations can be accounted for within the frame of the centrifuge pressure model, including the boundary condition.

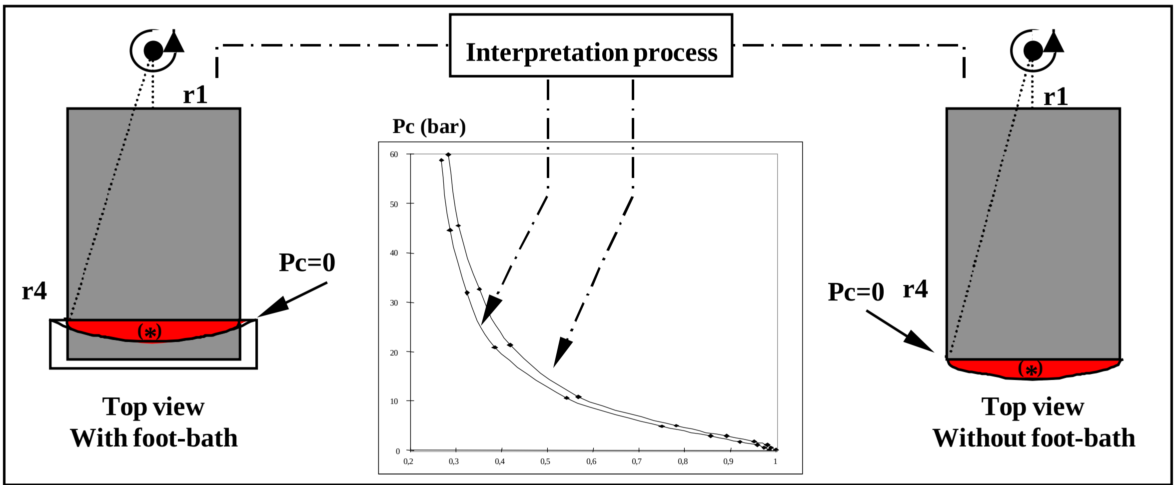

***Figure 16** : Interpretation process for Bil 1993 experiments with and without foot-bath.*
(*) denotes areas making the experiments not comparable if the same interpretation model is used.

Improved measurement methods

We emphasised here that, under controlled conditions and when using appropriate interpretation processes, one does not expect any problem to obtain reliable capillary pressure curves from usual centrifuge measurements. To increase confidence in the technique the use of foot-bath (Bil, 1993, O'Meara et al, 1988) or controlled/fixed level (Fleury et al., 1999, Firoozabadi et al., 1988) have been recommended. One also may use calibrated end pieces ensuring the boundary condition. These approaches may be a step forward to be sure to control the boundary conditions but they are still exposed to other problems. Basically they suffer that no appropriate interpretation process has been developed. In practice the use of controlled level above the core bottom generates an additional productive volume by comparison of interpretation schemes in use (Figure 17). That volume can represent 3 to 10 % of the productive volume depending on the location where the fluid level is controlled. The use of calibrated end pieces also change the pressure distribution and associated correction is going to be significant and more complex than a constant pressure shift (Figure 3).
In the future the use of foot bath or controlled level will certainly give more confidence in the technique but specific interpretation schemes are still needed to be developed.

Conclusions

After reviewing microscopic mechanisms and macroscopic observations reported for supporting the failure of the boundary condition in centrifuge capillary pressure measurements, one came to the following :

- there is no evidence supporting the failure in usual experimental conditions,
- related observations are due to inappropriate interpretation processes in use,
- the standard centrifuge technique can be recommended if correct interpretation processes are used,
- improved experimental devices could be recommended too, but correct interpretation processes are not developed for the moment.

Nomenclature

g	gravity constant
Z	vertical coordinate
L	core plug length, cm
P_c	capillary pressure
P_{c1}	capillary pressure at rl
R	the radius of core cylinder plug, cm
r	rotation radius, cm
$r*$	critical radius (Wunderlich, 1985)
r_1	the radius to the inlet endface, cm
r_3	the radius to the outlet endface, cm
r_p	the largest pore radius
S	wetting phase saturation
$z(\theta)$	dimensionless distance (O'Meara et al., 1988)
δS	average saturation error (O'Meara et al., 1988)
δP_2	pressure drop at the core exit end (Chen, 1999)
δP_d	entry/threshold pressure
$\Delta\rho$	density difference of fluid pairs
θ	contact angle
ω	angular rotation speed

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