THE USE OF FOOTBATHS IN CENTRIFUGE CAPILLARY PRESSURE CURVE MEASUREMENTS

Klaas J. Bil
Shell Research Rijswijk, The Netherlands

Abstract Fluid production data measured in a centrifuge experiment need to be converted according to some model in order to extract a capillary-pressure curve. A widely applied procedure is the method developed by Hassler and Brunner in the 1940's. Various alternative procedures have been proposed since. All conversion procedures require the assumption introduced by Hassler and Brunner that at the bottom face of the sample the capillary pressure is zero.

This paper reports on ultracentrifuge experiments performed with and without a footbath on the same six sandstone core samples. The effect of a footbath is physically to impose the Hassler and Brunner boundary condition. Before each run the samples were fully saturated with brine, while air was used as the displacing phase. Data were processed using the Hassler and Brunner procedure, which was modified in order to account for the effect of the non-uniform gravitational field in the sample both in direction and in magnitude.

In our experiments, the wetting phase saturations corresponding to a given capillary pressure were on average about 4% V_p lower when a footbath was used. The observed effect of a footbath is explained by considering the capillary bundle model, leading to the conclusion that the Hassler and Brunner boundary condition does not hold in the case that no footbath is used (as is the conventional procedure). Consequently, centrifuge capillary-pressure curves measured with a footbath are more representative of the true capillary behaviour.

INTRODUCTION

A widely used method to determine the capillary-pressure behaviour of a rock sample involves the use of an (ultra)centrifuge. An initially liquid-saturated rock sample is spun at a series of increasing rotational speeds. As a result of gravity drainage in the centrifugal-force field, liquid is displaced from the sample until equilibrium is reached between gravitational and capillary forces. For each speed step, the equilibrium production is measured and the data are then used to calculate the capcurve, i.e. the capillary pressure, P_c, vs. the wetting-phase saturation, S_w.

Hassler and Brunner (1945), the inventors of the centrifuge capcurve measurement, developed a procedure for processing fluid production data from a centrifuge experiment in order to arrive at a capcurve. By numerical differentiation of the experimental data, the capillary pressure and saturation data at the *top* of the sample are calculated (Appendix A). Vital to the Hassler and Brunner model is the assumption that during the measurement $P_c = 0$ at the bottom face of the sample. (Hassler and Brunner further assume that $S_w = 1$ at the bottom face of the sample. They apparently deduce this second assumption from the $P_c = 0$ boundary condition, though it is unclear why, since it does not play a role in the calculation.) The $P_c = 0$ boundary condition, which is postulated by Hassler and Brunner without further discussion, is still widely relied on in the processing of centrifuge capcurve data.

Many alternative data processing methods have been proposed, which avoid numerical differentiation of experimental data (e.g. Bentsen and Anli 1974, Van Domselaar 1984, Rajan 1986, Nordtvedt and Kolltveit 1988, Ruth and Wong 1988, Ayappa *et al.*1989, Christiansen and Cerise 1989, Ruth *et al.* 1989, Glotin *et al.* 1990, Jaimes 1991). However, when the experimental data are sufficiently accurate and numerous, these data processing methods offer no advantage over the traditional Hassler and Brunner processing. Moreover, the alternative methods too invariably rely on the $P_c = 0$ boundary condition.

Some authors have cast doubt on the validity of the $P_c = 0$ boundary condition, at least in a conventional centrifuge experiment (Wunderlich 1985, Melrose 1986, O'Meara *et al.* 1988, Melrose and Mallinson 1990). Their efforts have concentrated on determining the conditions under which the Hassler and Brunner assumption is invalid, without offering a remedy. A few of these authors mention the possible use of a footbath for physically imposing the Hassler and Brunner boundary conditions. O'Meara *et al.* have reported that they observed no difference between capcurves measured with a (shallow) footbath and with a teflon support. To our knowledge, no other experiments with footbaths have been published in the open literature, presumably because footbaths are generally regarded as being cumbersome to use.

In the research described here, capcurves of six consolidated sandstone rock samples from two North Sea wells have been measured in an ultracentrifuge both with and without a footbath. This research has been performed to investigate and explain the possible influence of a footbath on the resulting capcurve.

EQUIPMENT AND PROCEDURES

Drainage air/brine capillary-pressure curves were measured with a Beckman L5-50P ultracentrifuge, equipped with a PIR-20 rotor. In this set-up, up to six rock samples can be accommodated. Before each centrifuge run, the samples were fully saturated with brine; this was used as the wetting phase, while air was used as the non-wetting phase. The samples were not jacketed. The rotational speed programme was identical in all centrifuge runs, and consisted of 12 speeds increasing from 750 rev/min up to 15 000 rev/min; the total duration of this speed programme was about two weeks. The brine produced from each sample was collected in a transparent tube extending from the sample holder, and monitored by means of a stroboscope and a CCD line scan camera (1024 pixels). The production measurement is accurate to one pixel, which is equivalent to 0.0025 ml; in a typical case this corresponds to 0.15% of the sample's pore volume. The temperature of the rotor was kept constant at 25 °C to within a few °C. Production data, along with temperature and rotational speed, were read at regular time intervals and stored in a computer memory. The execution of the speed programme and the acquisition of data are fully automated. The production data were processed according to the Hassler and Brunner theory, modified to take into account the effects of non-uniform gravity both in magnitude and in direction (see Appendix A).

Conventionally, in (ultra)centrifuge capcurve measurements the rock sample rests on a perforated rubber pad supported by a grooved disc, thereby allowing brine to flow from the bottom face of the sample. When a footbath is used, however, each sample is supported by a stainless steel disc with an upright edge of 1.4 mm, which is filled with brine (Figures 1 and 2). During the experiment, any brine produced from the sample's pore volume flows over the rim of the footbath edge, so that the bottom face of the sample is always submerged in brine.

The footbath has a dead volume (between the sample, the footbath edge and the brine surface) of only about 0.05 ml. When a sample was mounted in the sample holder, it was intentionally kept "over-wet". This excess brine filled the footbath at the first few revolutions of the centrifuge rotor, while any redundant brine was collected in the production tube. From the experimental data it appeared that at the first speed (750 rev/min) no production from the sample took place. This allowed us to take the brine level in the tube at 750 rev/min as the zero production reference level.

The brine in the footbath assumes a cylindrically curved surface (i.e. curved around the rotor axis). The volume of the sample below this surface is in fact inactive in the measurement; parameters such as pore volume and spinning radius were adjusted accordingly.

EXPERIMENTS AND RESULTS

First Set of Samples

The first ultracentrifuge run was carried out *without footbaths* on three samples (3, 111S and 114S), the basic properties of which are given in Table 1. These samples had been stored ("preserved") under NaCl brines of different salinities (146.2 - 180.9 g/l) for a period of several years. After completion of this centrifuge run the samples were solvent-cleaned in a hot extraction apparatus, oven-dried and vacuum-saturated with 180 g/l NaCl brine. Their air/brine capcurves were measured again, now *with footbaths*. A typical example of the resulting capcurves has been plotted in Figure 3.

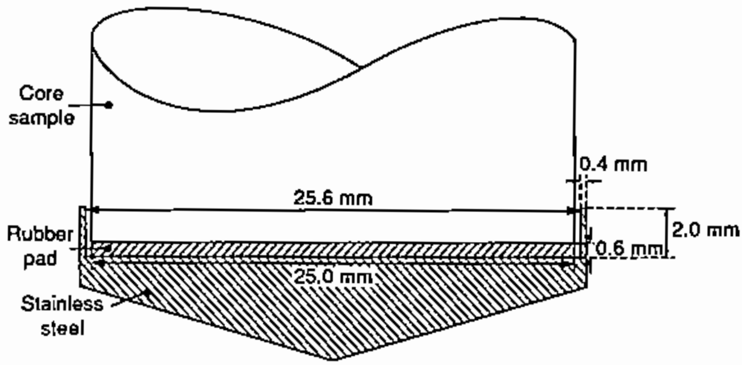

FIGURE 1 Dimensions of the footbath

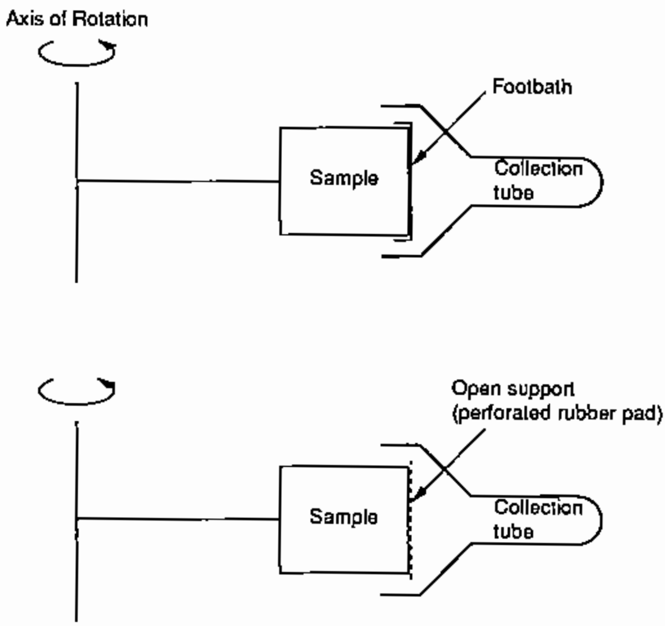

FIGURE 2 Position of footbath and conventional support

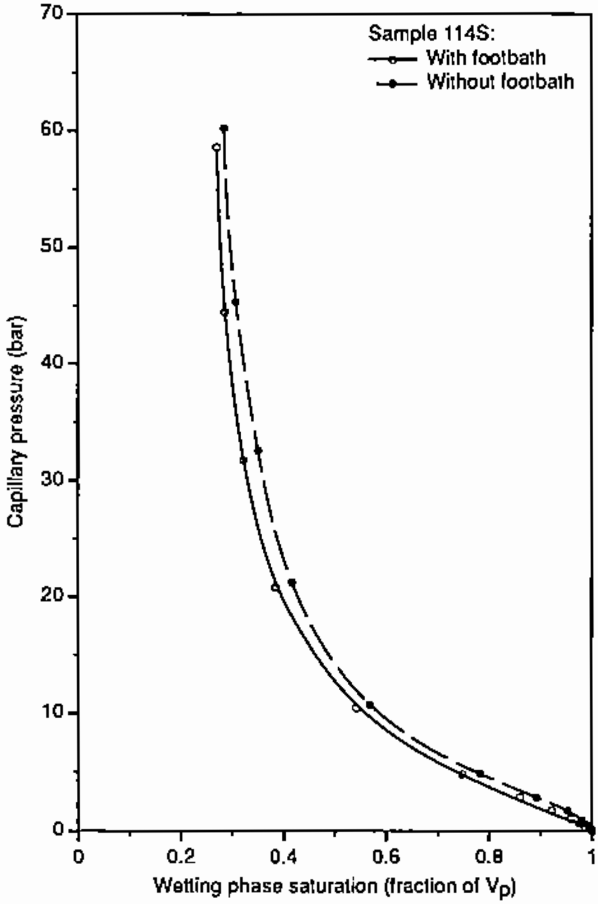

FIGURE 3 Typical example of centrifuge capillary-pressure curves with and without a footbath

TABLE 1 Basic properties of samples used

sample id.	initial condition	ϕ [% V_b]	k [mD]
3	preserved	11.8	0.21
111S	preserved	11.4	0.03
114S	preserved	16.2	0.36
2	unpreserved	12.1	0.17
5	unpreserved	7.6	0.10
13	unpreserved	7.0	0.15

Of each sample, the overall shape of the footbath and non-footbath capcurves is similar. However, the saturation values for footbath and non-footbath capcurves corresponding to a given capillary pressure are somewhat different. To facilitate comparison, the saturation values that correspond to an (arbitrary) capillary pressure of 55 bar are given in Table 2. The difference between the two saturation values is termed "missing" desaturation, since it is the amount of desaturation that has not occurred because no footbath was used. The "missing" desaturation in the non-footbath capcurves varies between some 1% and 6% of the pore volume.

TABLE 2 Results of air/brine capcurves with and without a footbath.

sample id.	S_w at P_c = 55 bar without footbath [% V_p]	with footbath [% V_p]	"missing" desaturation [% V_p]
3	33.3	27.4	5.9
111S	35.2	34.1	1.1
114S	29.0	27.6	1.4
2	28.2	18.4	9.8
5	42.0	34.3	7.7
13	35.6	38.4	-2.8

Second Set of Samples

From the above experiment one cannot yet firmly conclude that the "missing desaturation" was solely due to the absence of a footbath. Apart from the footbath, there were two more differences between the two runs:

i) prior to the first run the samples had been preserved in brine for years. When the samples were put through the second run, however, they had been saturated less than two weeks before;
ii) in the second run the samples had been subjected to one more cleaning and resaturating cycle than in the first.

To exclude the possibility of spurious results because of these additional differences, another pair of ultracentrifuge runs was carried out on three new samples (Nos. 2, 5, and 13, see Table 1 for basic properties), which had been stored in a dry condition for years ("unpreserved"). The sequence of footbath and non-footbath runs was reversed: the first run was carried out *with* footbaths, the second run *without* footbaths. By doing so, the number of samples studied would increase from three to six, provided that the cleaning and measurement sequence would appear to have no effect on the capcurve. Before both the footbath and the non-footbath run, the unpreserved samples were solvent-cleaned in a hot extraction apparatus, oven-dried and vacuum-saturated with 180 g/l NaCl brine.

These unpreserved samples show essentially the same behaviour as the preserved samples (see Table 2). This justifies the conclusion that the saturation differences observed in both sample sets may indeed be attributed to the presence of a footbath. The average "missing" desaturation at P_c = 55 bar for all six samples is 3.9% V_p, the standard deviation of this average value being 1.9% V_p. The spread could not be correlated with parameters such as permeability or porosity. It is therefore regarded as a measure of the repeatability of the measurement. The reproducibility of centrifuge capcurves has been investigated earlier at KSEPL on (homogeneous) outcrop material and was reported to be within 3% saturation. We have no experimental figures on the reproducibility of the measurement on reservoir rock.

DISCUSSION

The main Hassler and Brunner boundary condition that is generally assumed to prevail at the bottom face of the sample (i.e. $P_c = 0$), is certainly satisfied when the sample is placed in a footbath. If $P_c = 0$ were also satisfied during a centrifuge capcurve measurement without a footbath, then the presence of a footbath should have no influence on the resulting capcurve. Since our measurements have shown a clear footbath influence, it can be concluded that the $P_c = 0$ condition does not apply when the sample is placed on a conventional open support.

This can be illustrated by considering the "capillary bundle model" shown in Figure 4.

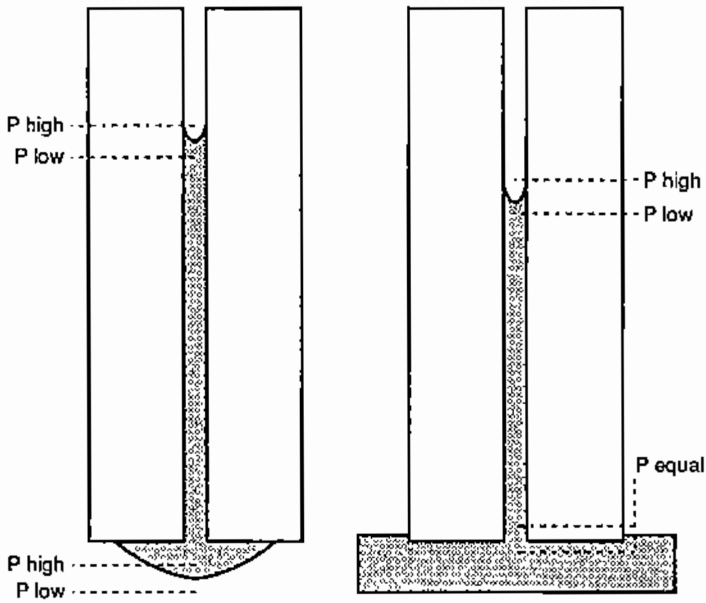

FIGURE 4 Effect of footbath on capillary rise

If a sample is spun at a low centrifuge speed and if no footbath is used, each capillary in the sample contains a certain volume of brine that is confined between two curved air/brine interfaces. Besides the upper interface, the lower interface also assists in holding up this brine against the gravitational force, hence the $P_c = 0$ assumption is invalid. (When the centrifuge speed exceeds a critical value that depends on experimental conditions, some capillaries may even drain completely. In that case the second Hassler and Brunner boundary condition, i.e. $S_w = 1$, does not hold anymore either.) However, if the capillary bundle is placed in a footbath, the lower interface is eliminated. As a consequence, $P_c = 0$ at the bottom end of the capillary. Therefore, the total force acting against gravity is reduced and the volume of brine in each capillary is decreased. In addition, the complete drainage of capillaries cannot occur at any centrifuge speed, so that $S_w = 1$ at the bottom face at all times.

It must be noted that the $P_c = 0$ plane is cylindrically curved in the footbath case, whereas Hassler and Brunner assume it to be flat (based on the non-footbath case). Therefore, the bottom face boundary conditions are not easily comparable. Though this has been accounted for by calculating an average length of the sample, it adds some uncertainty to the final conclusions.

Effect of Stress

During an ultracentrifuge experiment the samples are subjected to a rather peculiar stress regime. Not only does the (axial) stress level increase with each rotational speed step, but it also varies along the length of the sample. The non-uniform centrifugal force field (both in direction and in magnitude) complicates the stress regime even further. In the bottom face of a typical rock sample, the axial stress is equal to about 100 bar at 15 000 rev/min in the PIR-20 rotor, whereas the sample is radially unconfined.

It has been observed that in some samples macroscopic cracks had developed during the measurement, probably as a result of these deviatoric stresses. Sometimes, the samples even fell apart on removing them from the sample holder. Samples in which cracks were detected were excluded from further measurement (in total, 14 samples were used in the experiments). It was argued, however, that cracks that developed during a centrifuge run did not render the data from that run useless. Vertical cracks should not influence the flow or indeed the equilibrium saturation of the sample (since the situation is equivalent to two identical but separate samples), whereas cracks with an appreciable horizontal component that develop during the experiment are kept closed by the centrifugal force.

It is quite conceivable that microcracks too have developed as a result of the stress regime. Such microcracks may influence the pore geometry, and thereby the measured capcurve. If this phenomenon has occurred in our study, footbath and non-footbath capcurves have been influenced to the same degree, so their comparison remains valid.

CONCLUSIONS

i) The application of a footbath in centrifuge capillary-pressure curve measurements guarantees that both Hassler and Brunner boundary conditions assumed at the bottom face of the sample ($P_c = 0$ and $S_w = 1$) are satisfied.

ii) When no footbath is used, the main Hassler and Brunner assumption that $P_c = 0$ at the bottom face of the sample is not satisfied.

iii) Centrifuge capcurves measured with a footbath are more representative of the true capillary behaviour. In our experiments on six low-permeability sandstone samples, S_w at a given P_c was on average 3.9% V_p lower when a footbath was used.

iv) The application of a footbath in a centrifuge capcurve experiment is technically feasible, and should be standard procedure in measurements of this kind.

NOMENCLATURE

$\Delta\rho$	density difference between wetting and non-wetting phase	kg/m^3
g	centrifugal acceleration	m/s^2
h	height within the sample	m
k	air permeability	mD
L	sample length	m
P_c	capillary pressure	Pa
$P_{c\,top}$	capillary pressure in the top of the sample	Pa
rev/min	revolutions per minute	
$\bar{S}$	average wetting phase saturation	% V_p
S_w	wetting phase saturation	% V_p
V_b	bulk volume of the sample	m^3
V_p	pore volume of the sample	m^3

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APPENDIX A THE HASSLER AND BRUNNER PROCESSING METHOD

Hassler and Brunner (1945) developed a procedure for processing fluid production data from a centrifuge experiment in order to arrive at a capcurve. With this procedure, the capillary pressure and saturation data at the *top* of the sample are calculated. Hassler and Brunner state that the average wetting phase saturation in the rock sample, $\bar{S}$, which can be directly deduced from the measurement of fluid production, is equal to the integral of the saturation over the length of the sample:

$$\bar{S} = \frac{1}{L} \int_0^L S_w \, (\Delta\rho \, . \, g \, . \, h) \, dh \qquad (1)$$

At this point Hassler and Brunner introduce their $P_c = 0$ assumption, by stating that if the capillary pressure P_c at the bottom of the sample is equal to zero, then the capillary pressure at the top of the sample, $P_{c\,top}$, is equal to the pressure gradient multiplied by the sample's length:

$$P_{c\,top} = \Delta\rho \, . \, g \, . \, L \qquad (2)$$

Let x be equal to $\Delta\rho \, . \, g \, . \, h$, then

$$P_{c\,top} \, . \, \bar{S} = \int_0^{P_{c\,top}} S_w(x) \, dx \qquad (3)$$

Thus the saturation in the top of the sample can be calculated:

$$S_w(P_{c\,top}) = \frac{d}{dP_{c\,top}} (P_{c\,top} \, . \, \bar{S}) \qquad (4)$$

Hassler and Brunner realized that the centrifugal acceleration varies along the length of the sample. They developed a procedure involving successive iterations to solve eq. (4). This iterative procedure is not very widely used, since the variation of the magnitude of the centrifugal acceleration hardly influences the capcurve, unless a small-radius rotor (such as the PIR-20) is used. Also, the directional variation of the centrifugal acceleration is important only in small-radius rotors; it is not mentioned by Hassler and Brunner. The directional variation can be accounted for by relating all distances to the rotor axis instead of to a plane through the rotor axis, and consequently defining *curved* planes of equal P_c (and hence saturation). The results reported in this paper have been calculated using such a modified Hassler and Brunner procedure, accounting for the effects of non-uniform gravity both in magnitude and in direction.