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Imbibition capillary pressure curve modelling for two-phase flow in mixed-wet reservoirs

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Abstract

Until the early 2000s, the majority of reservoirs worldwide were considered to be either water-wet or oil-wet and capillary pressure correlations were developed subsequently. Recently, it was shown that most reservoirs are mixed-wet (Anderson 1986, Delshad et al. 2003, Lenhard and Oostrom 1998) where available methods and techniques to evaluate capillary pressure curves are limited.

To advance on this topic, the current thesis deals with the modelling of capillary pressure curves in two-phase, mixed-wet reservoirs and proposes a way to evaluate capillary pressure experiments.

The proposed method aims to obtain both positive and negative imbibition capillary pressure curves using saturation profiles gained from a centrifuge experiment.

The saturation data of the core sample obtained from a centrifuge experiment is used to determine the following parameters: residual oil saturation, irreducible water saturation, pore size distribution indices as well as the capillary entry pressure for both phases. This process is performed using a combination of a correlation modelled and implemented in Maple with a support tool established in Visual Basic. A centrifuge experiment is simulated in Maple and imbibition capillary pressure hysteresis curves are produced using the concept by Skjæveland et al. (1998), which is the preferred correlation for mixed-wet reservoirs.

Artificially created centrifuge data is used in the model leading to reasonable results. Curve fitting is performed with high accuracy to match the model with lab data used to create the saturation profile.

Follow ups for field application of the developed Maple tool are given and an outlook for three phases is proposed.

Declaration of originality

The material presented in this thesis is entirely the result of my own independent research under the supervision of Professor Svein M. Skjæveland. All published or unpublished material used in this thesis has been given full acknowledgement.

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Nomenclature

Symbol	Description	Unit
a	pore size distribution index	[-]
b	fitting parameter	[-]
C	Land's trapping constant	[-]
c	capillary entry pressure	[Pa]
p	pressure	[Pa]
r	radius	[m]
S	saturation	[-]
S_1	saturation crossover point (P_{ci})	[-]
S_2	saturation crossover point (P_{cd})	[-]
ρ	density	[kg/m³]
ω	speed of rotation	[RPM]
$[k]$	scanning loop reversal No. k	[-]

Subscripts	Description
c	capillary
d	drainage
g	gas
i	Initial or imbibition
o	oil or oil-wet
r	Residual, irreducible
w	water or water-wet
0	zero point ($p_c=0$)

Superscripts	Description
dra	drainage
imb	imbibition
$*$	effective

Abbreviations

Acronyms	Description
FWL	Free Water Level
GFE	Gibbs Free Energy
MRI	Magnetic Resonance Imaging
PID	Proportional, Integral and Derivative Control System
PWC	Pumping While Centrifuging
RPM	Rounds Per Minute
SCAL	Special Core Analysis

1. Introduction

Capillary pressure is the governing factor behind multi-phase flow behavior (Green 2008) and capillary pressure curves are input to models predicting flow in hydrocarbon reservoirs. Reservoir simulation software uses capillary pressure as data input influencing the prediction of flow behavior which is often the basis for well planning and reservoir management techniques. Multi-phase flow predictions with inaccurate capillary pressure input will lead to prediction of incorrect watercuts, especially in heterogeneous reservoirs, and might lead to inefficient depletion plans with large scale investments in facilities that cannot process the produced fluids (Masalmeh, Abu Shiekah and Jing 2007). Besides flow effects, capillary pressure determines location and movement of fluid contacts due to improper well placement. The location of the fluid contacts then determines the oil in place and any contact movements can be crucial for production and incorrect prediction can lead to undesired coning effects. Estimates about recovery efficiencies of a reservoir can therefore just be made if capillary pressure effects are understood.

Transition zones in water-wet or oil-wet reservoirs are often assumed to be mixed-wet and can contain a large amount of the initial oil in place (Carnegie 2006, Masalmeh et al. 2007). The transition zone can vary between just a few meters up to a hundred meters depending on the reservoir characteristics (Masalmeh et al. 2007) and an error in the transition zone capillary pressure can lead to large-scale errors in STOIIP estimates. The height of the transition zone in a reservoir is determined by the earth's gravitational flied and may be compressed to a cm-scale in the centrifuge. However not only transitions are considered to be mixed-wet nowadays almost all reservoirs are considered to be water-wet (Anderson 1986, Delshad et al. 2003, Lenhard and Oostrom 1998). Until 2000 most reservoirs were considered to be water-wet and therefore most present techniques for capillary pressure interpretation have been developed for water- or oil-wet reservoirs. Nowadays it is essential to further improve the research that has been done for mixed-wet reservoirs.

This thesis describes the use of capillary pressure curves in mixed-wet, two-phase reservoirs and proposes a way to interpret capillary pressure experiments.

An additional limitation is that the majority of capillary pressure interpretation techniques have been developed for two phases while most reservoirs contain three phases in reality. To describe the flow in three-phase reservoirs where capillary

pressure occurs between oil and gas and oil and water, correlations for capillary pressure between each fluid interface have to be combined. The determination and interpretation of capillary pressure curves for three phases is subsequently more complex and requires combination of two capillary pressures. To find a correlation for three-phase flow, two-phase capillary effects have to be modelled first in a right way and the available methods reviewed.

Four main types of lab methods can be used to obtain capillary pressure curves: centrifuge, porous plate, membranes and mercury injection. In this thesis, centrifuge experiments are discussed in detail and are the basis of the work. Porous plate experiments are usually more precise but every capillary pressure point needs weeks or up to months to reach equilibrium. As improvement for the porous plate method the micro pore membrane technique can be used (Hammervold et al. 1998). In contrast, the mercury injection is quick and high capillary pressure values can be obtained. The main disadvantages are that the core is destroyed and mercury is a non-representative reservoir fluid. Centrifuge methods use representative reservoir fluids and are not as time consuming as porous plate methods (Green 2008). The problem with centrifuge experiments is that only negative imbition and drainage curves can be obtained. The positive capillary pressure region is cumbersome to obtain experimentally due to hysteresis effects and is often calculated using correlations.

This thesis shows a method to obtain both positive and negative imbibition capillary pressures and using results from a centrifuge experiment.

There are multiple techniques available in the literature on how to use the experimentally obtained capillary pressure data and interpret primary drainage curves. Drainage capillary pressure curves are easier to interpret, as no hysteresis effect needs to be considered which is essential when dealing with imbibition capillary pressure curves. Experimental methods available (e.g. Fleury et al. 1999) often avoid this hysteresis effect for imbibition by assuming uniform residual saturation of the core sample after the primary drainage or simply neglect it (e.g. Baldwin and Spinler 1997).

Besides experimental methods, correlations can be used to describe capillary pressure curves. As there are many correlations for capillary pressure curves in water-wet reservoirs (Skjæveland et al. 1998), the focus in the past was further work on correlations for mixed-wet reservoirs. Skjæveland et al. developed a widely used

correlation incorporating hysteresis effects (Abeysinghe, Fjelde & Lohne 2012a, Abeysinghe, Fjelde & Lohne 2012b, Bech, Fryman & Vejbæk 2005, Eigestand & Larsen 2000, El- Amin, Sun & Salama 2013, Hashmet et al. 2012, Kralik, Guice & Meissner 2010, Pirker, Mittermeier & Heinemann 2007).

In this thesis, it is discussed how to interpret and evaluate imbibition capillary pressure curves for mixed-wet reservoirs using a combination of a centrifuge experiment and a correlation for mixed-wet reservoirs (Skjæveland et al. 1998).

The main challenge is to find a way of including the hysteresis effect in the interpretation and evaluation process for imbibition capillary pressure curves. The idea is based on using the capillary pressure correlation for mix-wet reservoirs by Skjæveland et al. (1998).

The thesis contains an extensive literature review where the correlation for mixed-wet reservoirs by Skjæveland et al. will be explained. The correlation constitutes the basis of the modelling and was programmed in Maple. Following it will be explained how it is possible to combine the code with a capillary pressure centrifuge experiment and how it is modelled with Maple.

The model establishes saturation profiles at different speeds of the centrifuge along the whole core sample. The obtained saturation profiles from the program are compared through curve fitting with saturation profiles obtained from a centrifuge experiment. Using the adjusted correlation, irreducible water saturation, residual oil saturation, capillary entry pressure and pore size distribution can be obtained.

A base model is established in Maple to create drainage and imbibition capillary pressure bounding curves as well as scanning curves including hysteresis effects. This is done with the correlation by Sjkæveland et al. (1989). Subsequently a model to simulate a centrifuge experiment calculating capillary pressure accounting for centrifugal forces is created. Having the two equations to evaluate capillary pressure, it is possible to determine saturation and capillary pressure profiles. The saturation profiles can be evaluated in Maple but to evaluate the smallest error between two data sets Excel is used. To find the minimum error between the saturation lab data and the obtained data from the Maple program, residual saturations, pore size distribution indices as well as capillary entry pressure for wetting and non-wetting phase are adjusted with the Excel solver. With the new parameters it is possible to create imbibition capillary pressure curves which incorporate hysteresis.

2. Background information

To describe the flow of three phases, oil, gas and water in reservoir parameters have to be considered and they have a large influence on capillary pressures. The capillary pressures between oil and water and oil and gas need to be determined and then combined to an integrated system. To find a correlation that fits experiments and can describe three-phase flow, it is important to understand which factors affect the capillary pressure curve. Capillary pressure curves in two-phase are defined through residual oil saturation, irreducible water saturation, oil and water saturations, pore geometry, capillary entry pressure, permeability and porosity.

The outlook shows an overview of existing correlations for three phases in mixed-wet reservoirs and their limitations.

As the aim of this thesis is to obtain both positive and negative imbition capillary pressures in combination with results of a centrifuge the correlation for mixed-wet reservoirs by Skjæveland et al. (1998) is used as a basis. The used correlation is explained as well as available centrifuge methods which claim to obtain imbition capillary pressure curves.

At the beginning an extensive literature review was done and some of the important backgrounds regarding to this topic will be briefly mentioned.

This part of the thesis should help to understand the necessity of deriving capillary pressure curves. First general definitions of capillary pressure curves and residual saturations are presented. Furthermore the correlation by Skjæveland et al. (1998) is explained as it is used to interpret centrifuge experiments to determine capillary pressure curves. Then two different centrifuge techniques are introduced which claim to establish capillary pressure curves and will be discussed later.

2.1 Definition of drainage and imbibition

A capillary pressure curve for a mixed-wet reservoir is shown in Figure 1.
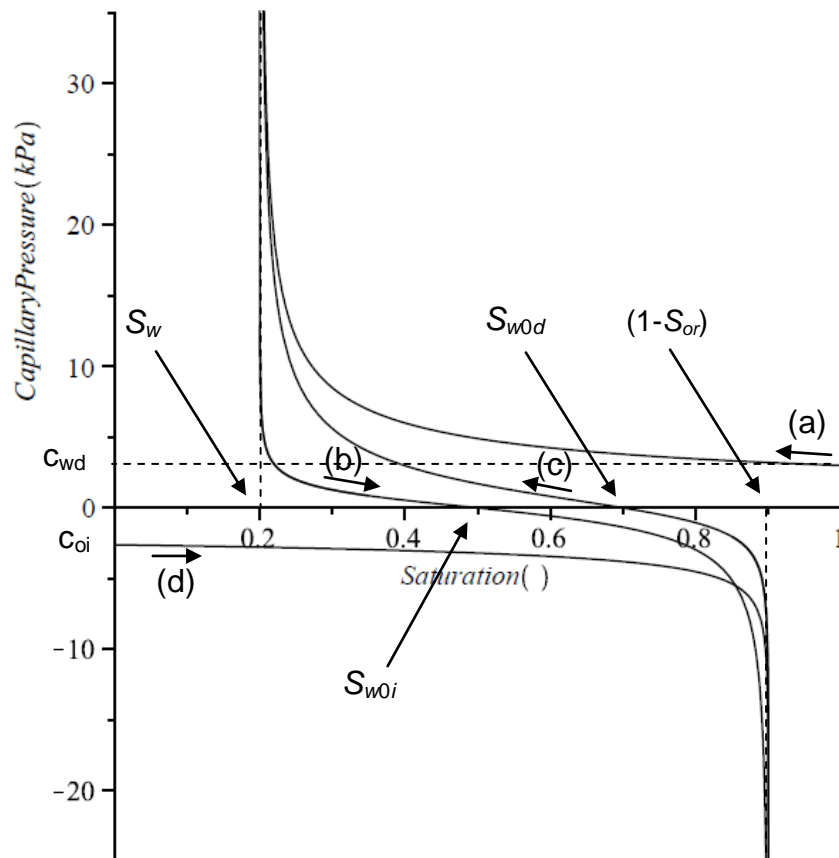
Figure 1 Schematic of bounding curves for mixed-wet reservoir: (a) primary drainage, (b) secondary imbibition, (c) secondary drainage and (d) primary imbibition.

Drainage is used to describe a process where the water saturation is decreasing. It is called spontaneous drainage if the capillary pressure is negative and it is called forced drainage when it is positive. Primary drainage is when the drainage process starts at 100 % wetting phase saturation.

Imbibition is used to describe a process where the water saturation is increasing. It is called spontaneous imbibition if the capillary pressure is positive and forced if it is negative. Primary imbibition describes the imbibition process starting at 100 % non-wetting phase saturation.

Bounding loop is the outer loop, starting at lowest irreducible water saturation and ending in the lowest residual oil saturation.

Scanning loops are all loops inside the bounding loop.

2.2 Residual saturations

To establish a correlation for two-phase capillary pressures, it is necessary to know the residual saturations of all phases. Incorrect residuals lead to wrong results in the capillary pressure models. In the literature there are different ways proposed to obtain the irreducible saturations.

The residual saturation, the fraction of the phase which cannot be recovered, depends on the pore structure and the contact angle between the different phases. Therefore depending on rock system and fluid system different techniques are proposed. An often used correlation to find residual saturations is the Land Correlation (Land 1967 and 1971) as a basis function and is adapted in different ways to fit the data.

Land assumes that during the imbibition process the non-wetting phase consists out of two different parts. One part is accepted to be the residual saturation and therefore does not account to flow and the other one is the mobile section, which is used as the actually non-wetting saturation. The mobile non-wetting phase saturation is obtained from the residual saturation and the residual gas saturation is received from laboratory measurements. The following relationship between initial and residual gas saturation was found:

$$\frac{1}{S_{gr}^*} - \frac{1}{S_{gi}^*} = C \; . \tag{1}$$

S_{gr}^* … effective residual gas saturation [-]

S_{gi}^* … effective initial gas saturation [-]

C … Land's trapping constant [-]

The trapping constant defines the trapping capacity of a rock. The effective saturations refer to the pore volume excluding the occupied pore volume of the irreducible wetting phase.

The correlation works well for water-wet sandstones. However there are also studies available that question the availability of Lands relationship, especially in unconsolidated sand packs. Other research projects claim that the Aissiaouri correlation works the best in this environment (Iglauer, 2009).

It is shown that Lands correlation in mixed-wet/ oil-wet reservoirs leads to incorrect results. Some research projects state that Lands correlation work, if SCAL (special

core analysis) data is available to adjust the correlation (Masalmeh, 2007). It is obvious that for every environment another correlation is needed.

Therefore Skjaeveland et al. (1998) adapted Lands correlation for mixed-wet reservoirs (chapter 2.4.).

Not only correlations can be used to determine residual saturations, but also different methods propose how the residuals can be analyzed with the help of core/sand pack experiments (Pentland 2010).

Three-phase measurements of residual saturations are more difficult than for two-phase reservoirs. Al-Mansoori (2009) observed that in three-phase flow in unconsolidated sand packs the residual gas saturation can be higher than the one in two-phase systems, where only water is present. That differs from measurements in consolidated media where the irreducible gas saturation is similar or lower than in a two-phase system. Also the amount of the residual oil is insensible to the initial oil saturation and more oil is trapped than in a comparable two-phase experiment. The reason for this observation can be explained by the piston-like displacement in unconsolidated two-phase water-wet reservoirs which leads to relatively little trapping and therefore to lower residual saturations (Al-Mansoori 2009). In consolidated media snap-off can occur as the throats are much smaller than the connecting pores. In water-wet media it can be observed that gas is often the non-wetting phase and therefore get trapped in the largest pores by snap-off.

The degree of trapping is independent of the present gas and initial oil saturation. As long as the initial oil saturation is not too little, the residual oil saturation in three-phase systems can be considered as stable. As already mentioned, the gas phase often gets trapped in the larger pores and therefore the trapping of the oil phase is reduced in a three-phase system compared to a two-phase flow. The determination of the residual saturations is therefore a prerequisite to establish reasonable capillary pressure curves (Al-Mansoori 2009, Iglauer 2009, Pentland 2010).

2.3   Two-phase capillary pressure correlations

One of the most widely used correlations in the industry was developed by Skjaeveland et al. and published in 1998 (Abeysinghe, Fjelde & Lohne 2012a, Abeysinghe, Fjelde & Lohne 2012b, Bech, Fryman & Vejbæk 2005, Eigestand & Larsen 2000, El- Amin, Sun & Salama 2013, Hashmet et al. 2012, Kralik, Guice & Meissner 2010, Pirker, Mittermeier & Heinemann 2007). The presented correlation is the basic concept to model centrifuge experiments in Maple, to obtain capillary pressure curves including hysteresis, saturation profiles and to solve for residual oil saturation, irreducible water saturation, capillary entry pressure as well as the pore size distribution index.

Skjæveland et al. developed a general capillary pressure correlation for two phases and a corresponding hysteresis loop scheme, which covers primary drainage, imbibition and secondary drainage. The authors chose the simple power-law presented by Brooks and Corey (1964 and 1967) as a basic equation for completely water-wet and oil-wet reservoir.

Equation for calculating the capillary pressure in a water-wet system is as followed:

$$P_c = \frac{c_w}{\left(\dfrac{S_w - S_{wr}}{1 - S_{wr}}\right)^{a_w}},\tag{2}$$

and correspondingly for an oil-wet system:

$$P_c = \frac{c_o}{\left(\dfrac{S_o - S_{or}}{1 - S_{or}}\right)^{a_0}}.\tag{3}$$

a … pore size distribution [-] S_{or} … residual oil saturation [-]

c … entry pressure [kPa] S_w … Water saturation [-]

P_c … capillary pressure [kPa] S_{wr} … irreducible water saturation [-]

S_o … oil saturation [-]

The basic idea is to sum the terms for water and oil branch up to a symmetrical form and is used to describe the capillary pressure of mixed-wet reservoir rocks.

The subsequent equation is used for modelling the imbibition curve in a mixed-wet reservoir:

$$P_{ci} = \frac{c_{wi}}{\left(\dfrac{S_w - S_{wr}}{1 - S_{wr}}\right)^{a_{wi}}} + \frac{c_{oi}}{\left(\dfrac{S_o - S_{or}}{1 - S_{or}}\right)^{a_{0i}}} .$$ (4)

a_{oi} … imbibition pore size distribution for the oil phase [-]

a_{wi} … imbibition pore size distribution for the water phase [-]

c_{oi} … imbibition entry pressure for the oil phase [kPa]

c_{wi} … imbibition entry pressure for the water phase [kPa]

P_{ci} … imbibition capillary pressure [kPa]

To model the drainage curve the index "*i*" is substituted by "*d*" and the saturation interval *S* going from S_{or} to S_{wr}. For simplicity it is assumed that the two set variables a_w, a_o, c_w, c_o, one set for drainage and one for imbibition, are constant.

To model the hysteresis loop a modification of Land's correlation is used to calculate the residual saturations:

$$\frac{1}{S_{or}[1]} - \frac{1}{S_o[1]} = C .$$ (5)

Where *C* is the Land's trapping constant and $S_o[1]$ the start- and $S_{or}[1]$ the end-point saturations of the imbibition process.

The following assumptions are used to establish the capillary pressure hysteresis loop:

- The first saturation reversal (direction change) starts from the primary drainage curve before the residual water saturation is reached. It is an imbibition scanning curve which ends at the residual oil saturation.

- A bounding imbibition curve starts at residual water saturation on the primary drainage curve and scans to the residual oil saturation.

- A closed hysteresis loop is defined when drainage and imbibition curve build a closed loop. For example when a second reversal from the residual oil saturation scans back to the residual water saturation.

- All scanning curves that have their origin on the bounding imbibition curve scan back to the residual water saturation and vice versa all the reversals on the bounding imbibition curve come back to the residual oil saturation.

- A scanning curve which starts from $S_w[k]$ will scan back to $S_w[k\text{-}1]$ and form a closed scanning loop. This loop can only be discontinued if a new reversal occurs before $S_w[k\text{-}1]$ is reached. If no new reversal occurs the curve scans back to $S_w[k\text{-}2]$.
- The shapes of the bounding and scanning curves are similar.

The first process in a reservoir is always the primary drainage which starts at 100 % water saturation. Therefore the first saturation reversal will form an imbibition curve with the origin on the primary drainage curve. The reversal saturation is a point where both the imbibition and the drainage curve meet and can be determined as followed

$$p_{cd}[0](S_w[1]) = p_{ci}[1](S_w[1]) \,. \tag{6}$$

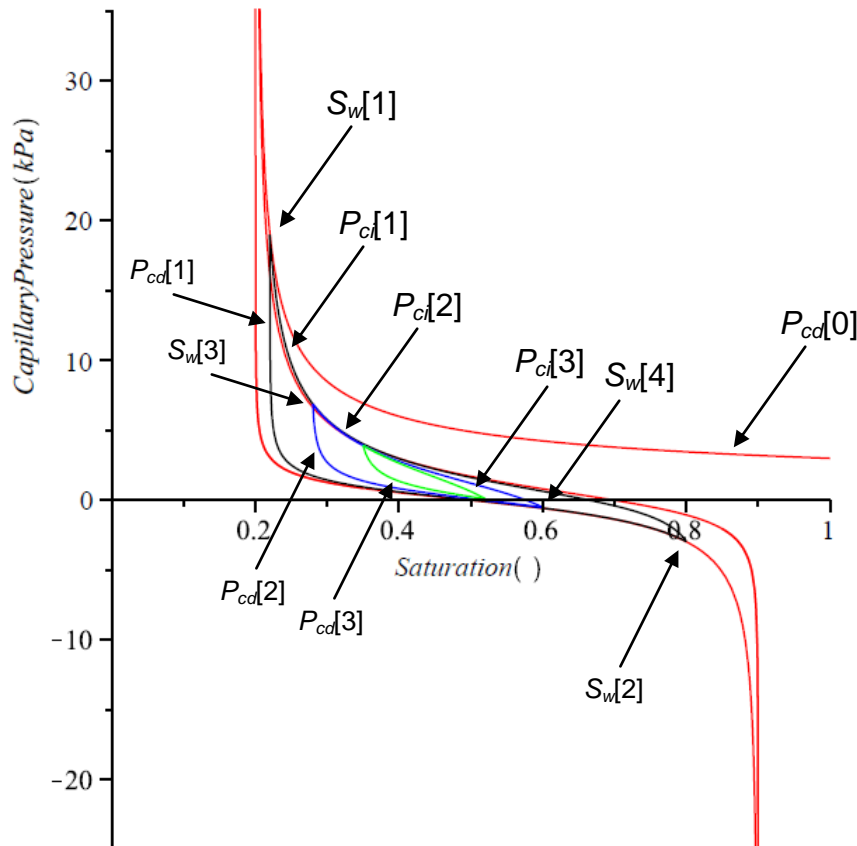**Figure 2** Capillary pressure curve – showing the saturation reversal points and the scanning curves. The mentioned reversal points where the imbibition curves starts are indicated as well as the drainage capillary pressure curves.

Where $P_{cd}[0]$ is the primary drainage curve and $P_{ci}[1]$ the imbibition curve. Figure 2 shows the first reversal for the imbibition curve which has its origin on the primary

drainage curve at the so called reversal point $S_w[1]$ and ends in the asymptote $S_{or}[1]$. Therefore the second reversal starts at a point on the first imbibition curve before reaching the residual saturation of the first reversal or at the residual oil saturation. Then the drainage curve scans back to the first reversal point to form a closed loop

$$p_{cd}[2](S_w[1]) = p_{ci}[0](S_w[1]) \,. \tag{7}$$

The reversal drainage scanning curve is created. This leads to a closed loop, as the imbibition curve from the first reversal and the drainage curve from the second reversal, are equal at the two reversal points (shown in Figure 2).

To explain the procedure generally the following two equations are used:

$$p_{ci}[1](S_w[1]) = p_{cd}[2](S_w[1]) \,, \tag{8}$$

$$p_{ci}[1](S_w[2]) = p_{cd}[2](S_w[2]) \,. \tag{9}$$

With these two equations the asymptotes $S_{wr}[2]$ and $S_{or}[2]$ for the second drainage curve are defined. The two equations are solved by estimating a value for $S_{wr}[2]$, as a first attempt the value of $S_{wr}[1]$ is used and then $S_{or}[2]$ can be calculated from Equation 8. Then Equation 9 is used to get a new value for $S_{wr}[2]$, the new value is inserted in the Equation 8. This iterative process continues until the values for $S_{wr}[2]$ and $S_{or}[2]$ converge.

In Figure 2 the third reversal is reached when the process follows the secondary drainage bounding curve until a third reversal occurs at $S_w[3]$. The process continues on the third imbibition bounding curve to the water saturation point of the second reversal. Before this point is reached, a fourth reversal could occur at $S_w[4]$. The process continuous until the last reversal $S_w[k]$ occurs, then the process scans back on the drainage curve of the last reversal n to the point $S_w[k\text{-}1]$ and continues on the following drainage curve ($p_{cd}[k\text{-}2]$) this goes on until the secondary drainage bounding curve is reached.

Further investigations of the correlation were performed and a modified correlation by Masalmeh et al. (2007) will be discussed.

2.3.1 Modified capillary pressure model

To model capillary transition zones, Masalmeh et al. (2007) modified the correlation by Skjaeveland et al. (1998). A third term is introduced which should account for the different shapes of capillary pressure curves:

$$P_{cd} = \frac{c_{wd}}{\left(\frac{S_w - S_{wc}}{1 - S_{wc}}\right)^{a_{wd}}} + \frac{c_{od}}{\left(\frac{1 - S_w - S_{or}}{1 - S_{or}}\right)^{a_{od}}} + b_d * \left(S^{dra}_{wcutoff} - S_w\right). \tag{10}$$

$S^{dra}_{wcutoff}$ … Cutoff water saturation for drainage [-]

b_d … fitting parameter [-]

Equation 10 describes the bounding drainage capillary pressure. Corresponding to describe the bounding imbibition curve the subscript "d" is changed to "i" and the superscript "dra" to "imb". In the extension b_d / b_i is zero for water saturation higher than $S^{dra}_{w\_cutoff}$ / lower than $S^{imb}_{w\_cutoff}$. The fitting parameter b is obtained from core data. The third term is used as the original model was not able to fit the experimental data, especially where the pore-size distribution is non-uniform (1/a describes the pore size distribution) and for measured imbibition capillary pressure curves. For calculating the scanning curves the following equation was used (the example is this time showed for the scanning imbibition curves):

$$P_{ci} = \frac{c_{wi}(S_{oi})}{\left(\frac{S_w - S_{wi}}{1 - S_{wi}}\right)^{a_{wi}(S_{oi})}} + \frac{c_{oi}(S_{oi})}{\left[\frac{1 - S_w - S_{or}(S_{oi})}{1 - S_{or}(S_{oi})}\right]^{a_{oi}(S_{oi})}}$$
$$+ b_i(S_{oi}) * \left(S^{imb}_{wcutoff} - Sw\right). \tag{11}$$

The fitting parameters can be determined as followed:

$$c_{wi}(S_{oi}) = c_{wi} + c_{wi1} * (1 - S_{oi} - S_{wc}),$$
$$a_{wi}(S_{oi}) = a_{wi} + a_{wi1} * (1 - S_{oi} - S_{wc}),$$
$$c_{oi}(S_{oi}) = c_{oi} + c_{oi1} * (1 - S_{oi} - S_{wc}),$$
$$a_{oi}(S_{oi}) = a_{oi} + a_{oi1} * (1 - S_{oi} - S_{wc}),$$
$$b_i(S_{oi}) = b_i + b_{i1} * (1 - S_{oi} - S_{wc}). \tag{12}$$

With the presented equations it is possible to calculate the desired capillary scanning curves and fit the experimental data. The extension was not developed for general use and is just applicable to a specific data set for which the fitting parameters are needed.

The original correlation by Skjæveland et al. (1998) without the extension has been widely used in the industry and showed good results in many cases (Abeysinghe, Fjelde & Lohne 2012a, Abeysinghe, Fjelde & Lohne 2012b, Bech, Fryman & Vejbæk 2005, Eigestand & Larsen 2000, El- Amin, Sun & Salama 2013, Hashmet et al. 2012, Kralik, Guice & Meissner 2010, Pirker, Mittermeier & Heinemann 2007). Finally it will be used to model the capillary pressure curves in combination with a centrifuge experiment.

2.4 Experimental methods for imbibition capillary pressure curves

Different experimental methods are available to establish capillary pressure curves. It was mentioned that four experimental methods can be used to obtain capillary pressure curves (centrifuge, porous plate, micro pore membrane and mercury injection). In this thesis only centrifuge experiments are used.

The advantages of the centrifuge method compared to others are usage of representative reservoir fluids and shorter duration (Green 2008). The disadvantage is that only negative imbibition and drainage curves can be obtained. The positive capillary pressure region is cumbersome to obtain experimentally due to hysteresis effects. Two recently used experimental methods (Spinler and Baldwin 1997 and Fleury et al. 1999) which claim to obtain positive imbibition capillary pressure curves, are presented and analyzed for their functionality.

In chapter three the problems occurring using these techniques are identified.

Spinler and Baldwin's experiment:

The aim of the experiment is to obtain positive and negative drainage and imbibition capillary pressure curves using centrifuge.

In porous media the oil/water saturation profile is obtained directly at a known pressure gradient measured from the free-water level.

With the centrifuge and the density differences of the two liquids, a pressure difference is created and leads to a capillary pressure. The main difficulty is to receive saturation information while the centrifuge rotates.

The oil phase is frozen while centrifuging and the water saturation can be mapped with the help of a magnetic resonance imaging (MRI) tool. As non-wetting phase octadecane ($\rho = 777$ kg/m³) with a freezing point of 27 °C was used and as wetting phase de-ionized water ($\rho = 1000$ kg/m³). The ambient temperature during the experiment was 23 °C, to prevent the water from evaporation (and the octadecane from melting) the plug was kept in a sealed plastic centrifuge for the whole time. The intensity map for water was converted to water saturation with the help of calibration curves. Little volume changes were adjusted with the water saturation. As soon as a uniform saturation state in the plug was reached, the average MRI values were plotted against the average water saturation. Depending on the core sample different methods are used to de-saturate. For the sandstone samples porous plate and for the chalk samples a centrifuge was used.

The next step is the determination of the capillary pressure and the pressure range. This can be done with the speed of the centrifuge, the distance from the position of the free water level and the length of the sample. Through an adjustment of the free water level, the positive and the negative part of the capillary scanning curves are determined. Using a centrifuge cell with a much larger bulk volume than the one of the pore volume of the plug, the movement of the water level was minimized and can be neglected, in the experiment.

To control the direction of the fluid and monitor the possibly occurring hysteresis effects it is necessary to prepare the plugs and define the sequence of the centrifuge steps. The plugs were sealed with Teflon on the sides. The fluid can only enter and exit the plug at the bottom and the top and flow is only in axial direction.

The following procedure is used to obtain capillary scanning curves:

1. A fully (100 %) saturated plug with wetting fluid is used.

2. The primary drainage curve was established, the centrifuge is started while the free water level is in contact with the plug.

3. The plug is prepared for the imbibition process:

   The plug is inverted (an inverted core holder is needed) and surrounded by non-wetting fluid and centrifuged. Then the plug is inverted again and the step is repeated to reach a uniform saturation profile over the whole plug at initial water saturation.

4. The plug is in contact with the free water level and centrifuged again, with contact to the free water level. The free water level is adjusted to be able to determine the positive and the negative part of the primary imbibition curve.

5. The plug is prepared for secondary drainage:

   The plug is inverted again and centrifuged in the wetting phase. Then the plug is inverted again. Repeat the step to obtain a uniform saturation profile over the whole plug at residual oil saturation.

6. The plug (in contact with the free water level) is centrifuged. Again the free fluid level needs to be adjusted that the positive and negative part of the secondary drainage curve can be determined.

7. To obtain more hysteresis curves the steps 3 to 7 have to be repeated.

The authors claim that with this improved centrifuge method many of the limitations of a normal centrifuge experiment can be reduced or even eliminated. For example time of the experiment, proper shape for capillary pressure curves, saturation equilibrium

and boundary conditions. However the main focus is on obtaining the negative and positive part of the drainage and imbibition capillary pressure curves.

<u>Fleury, Ringot & Poulain's experiment:</u>

Compared to standard centrifuge methods where the produced fluid (wetting or non-wetting) cannot stay in contact with the core sample, in this experiment the produced fluid is in contact with the sample all the time while centrifuging. This arrangement should make it possible to account for reversed flow when the pressure is decreased.

Depending on drainage or imbibition the oil-water contact (in contact with the sample) is held close to the bottom or top end of the sample. Depending on the capillary pressure the oil-water contact is maintained near the bottom or top end face of the sample. For drainage and imbibition (positive capillary pressure) it is the bottom end face. The speed is increased for drainage and decreased for the imbibition. For negative capillary pressure (forced imbibition and spontaneous drainage) the fluid contact is close to the top end face.

A pump is used to transfer oil in and out of the core holder while the centrifuge is running. The overspill water is channeled to a tank in the middle of the rotor. With the help of a PID (proportional, integral and derivative control) system it is possible to maintain the oil-water contact constant while centrifuging. If the level moves it is recorded by the level analyzer and the pump injects/removes the necessary amount of fluid into/from the core holder to keep the level at the desired and predefined position.
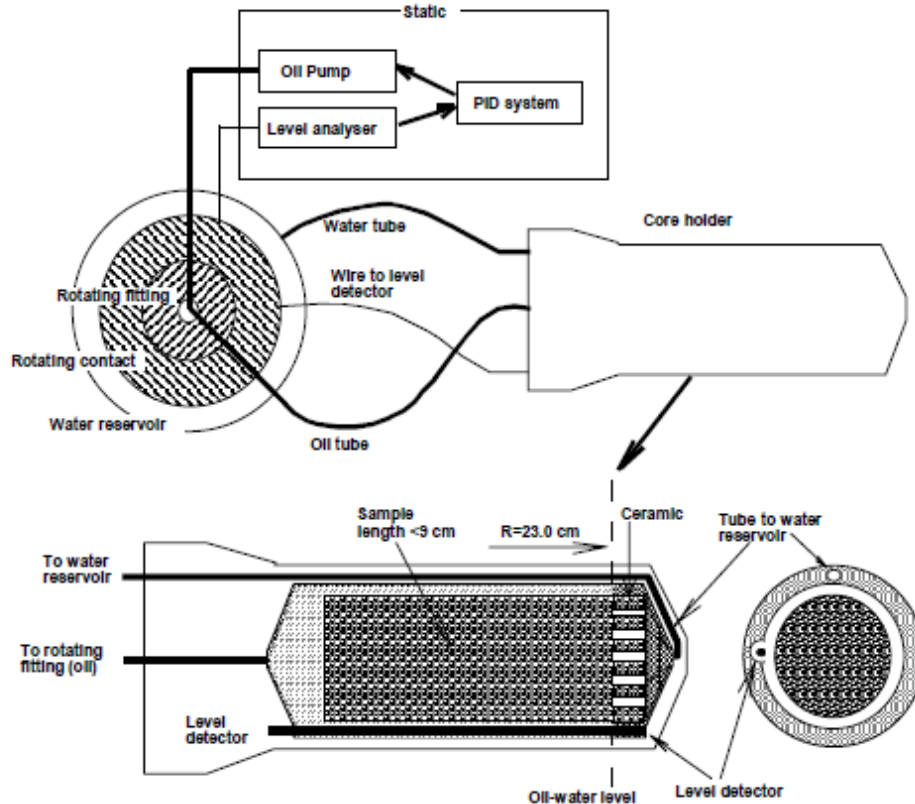
Figure 3 Schematic of centrifuge system (Fleury et al. 1999) – The schematic shows all the equipment which is needed for conducting this experiment. In the lower part on the left end of core holder the ceramic plate can be seen which makes it possible to establish a uniform saturation distribution after primary drainage (Fleury et al. 1999).

Figure 3 shows the schematics of the experimental devices showing all parts necessary to establish capillary pressure curves. The ceramic plate with a thickness of 1 cm is installed in the core holder. In this experiment it is installed at a radius of 23 cm. It is a semi-permeable filter which creates a uniform saturation distribution, which was chosen to be the residual saturation, after primary drainage. The functionality of the ceramic plate is explained subsequently.

The procedure:

1. The sample is fully saturated with brine and put into the core holder, all parts of the centrifuge up to the rotating fitting are filled with brine. Then the centrifuge is started at a minimum speed (200 RPM).

2. The pump implements oil into the core holder, preparing for primary drainage. With the help of the detector the oil-water contact is set close to the outer face of the sample.

3. Primary drainage: The speed of rotation is increased step by step.

4. At maximum speed of 3000 RPM the oil-water contact is moved 1 cm below bottom face to obtain a uniform saturation profile (this is done with the ceramic plate). After stabilization the level is set back to the bottom end of the core sample.

5. Then imbibition is implemented by decreasing the speed of rotation step by step.

6. At minimum speed of rotation the oil-water contact is set back to the top end of the sample.

7. Then the forced imbibition can be started.

There is no need to remove the core from the core holder at any point of the experiment. During the experiment data is recorded. Average saturation can be obtained from the pump. Speed of rotation gives the link to the capillary pressure. For monitoring purpose the position of the oil-water contact, the pressure of the rotating fitting as well as the temperature inside and outside the centrifuge are recorded.

The spontaneous imbibition curve can be obtained from the production at equilibrium at each change of speed. The positive imbibition capillary pressure at the inlet of the core sample (minimum radius) is calculated using the following equation:

$$Pc(R_{\min}) = \frac{1}{2} \Delta\rho\omega^2 \left(R_{\max}{}^2 - R_{\min}^2\right) . \tag{13}$$

R_{max} … maximal radius [m]

R_{min}… minimal radius [m]

$\Delta\rho$ … density difference between wetting and non-wetting phase [kg/m³]

ω … speed of rotation [RPM]

This equation assumes that the capillary pressure is zero at the outlet of the sample (maximum radius). The positive part of the imbibition curve is obtained in the same way as the primary drainage even if the physical processes are very different, the boundary conditions are identical and Equation 13 can be used. For deriving the secondary drainage the same procedure as for obtaining negative imbibition curves is used.
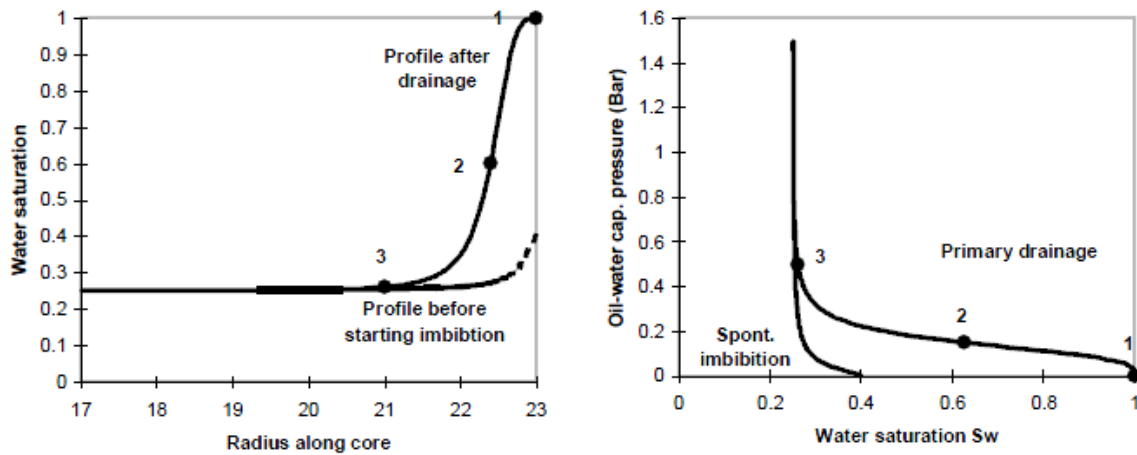
Figure 4 Effect of ceramic plate – The original profile after drainage is showed and then the profile after shifting the fluid level before starting the imbibition process. Obviously the saturation profile is after that procedure step uniform. Therefore it does not matter at which point along the core the imbibition curve has its origin, the curve will look the same (Fleury et al. 1999).

After primary drainage, hysteresis curves can occur. Fleury et al. consider that at any point on the primary drainage curve between point one and three in Figure 4 a hysteresis curve can occur. With the data from this experiment, if spontaneous imbibition immediately after primary drainage starts, the hysteresis curves cannot be determined. To overcome this problem, the ceramic plate is installed at the end of the core holder (Figure 3). With the help of this ceramic plate the free water level (P_c=0) is moved one centimeter "out" of the core sample (to a lager radius) which moves the part between 1 and 3 (Figure 4) out of the saturation profile. The entry pressure for oil is increased with the ceramic plate to around 3 bar and no oil will flow through the ceramic plate. This leads to a uniform residual saturation profile where no hysteresis effects can occur. Then the free water level can be set back to its original position and the outlet saturation will move back to its normal value.

3. Modelling of capillary pressure curves

To model capillary pressure curves, correlations have been developed and are applied in the industry. As mentioned, the correlation by Skjæveland et al. (1998) was preferred over other available correlations (Delshad et al. 2003, Lenhard and Oostrom 1998, Lomeland and Ebeltoft 2008) as it is rational and not fully empirical. In the correlation, the wetting branch and the non-wetting branch are summed up which can result in an either-or solution or a symmetrical solution and therefore different fractions of wettability are considered. If the reservoir is more oil-wet, the oil branch has a bigger influence than the water branch and is displayed through the shape of the curve. Respectively for a more water-wet reservoir it is the other way around.

Using the proposed correlation, a hysteresis scheme for capillary pressures curves in mix-wet reservoirs is modelled using Maple.

A first code of the model was established by Skjæveland et al. (1998) and is explained in chapter 2.4. The code was reconstructed to review what has been done 15 years ago and to be able to reuse the code. This code constitutes the basis of this thesis project and is used to further improve work on this topic.

It was discovered that one part explained in the paper is missing. As mentioned in chapter 2.4 an iterative process is needed to solve Equation 8 and Equation 9. It was not possible to insert the convergence test in the present code and a new code was established. The subsequent section explains the development of the code and difficulties that had to be overcome.

3.1 Base model development in Maple

Developing codes is a time intensive procedure and done stepwise, starting with sub-codes which are finally put together to establish a final program. In this case, two examples to understand the hysteresis logic are established initially and then the final program for modelling centrifuge experiments in combination with the correlation by Skjæveland et al. (1998) is created.

All codes use the same correlation by Skjæveland et al. (1998) to model capillary pressure curves and start in a similar way. First, the capillary pressure equations for drainage and imbition are defined and implemented, as explained in chapter 2.4. Land's equation and the corresponding constants (residual oil saturation, irreducible water saturation, pore size distributions and entry pressures) are specified as well.

With the given equations and data, the primary draining and imbition bounding curves can be established as shown in Figure 5.
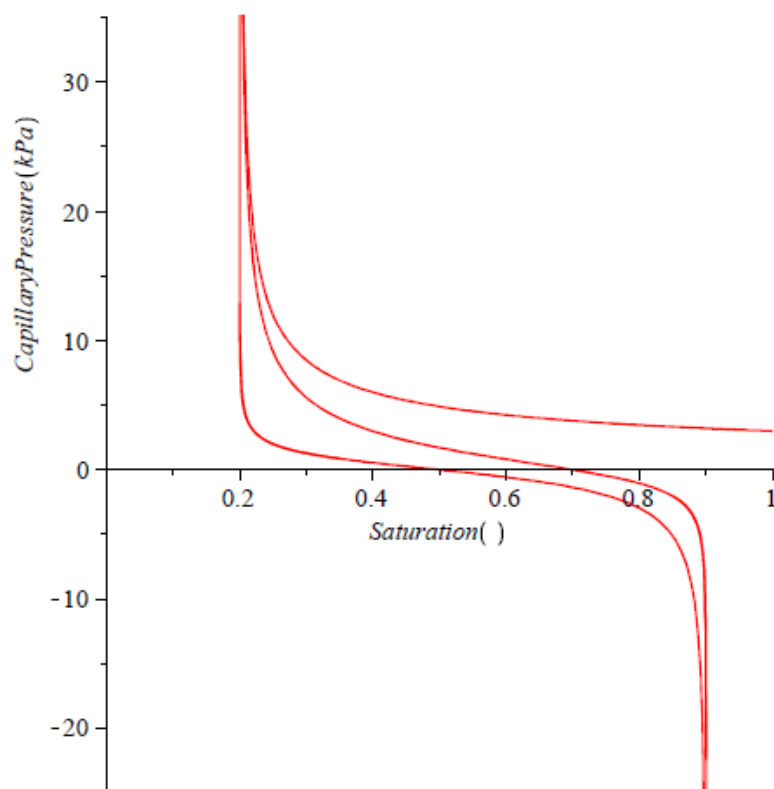

Figure 5 Bounding capillary pressure curves – for drainage and imbition. The bounding curves are created in all the codes programmed in Maple.

Following the explained basis, the codes start to vary between each other.

The first code (Example 1) is conducted to show how reversals can be modelled. Each reversal was conducted on its own with chosen reversal points, in this example

six reversals occur. The first reversal is an imbibition curve which has its origin on the primary drainage curve. The first normalized water saturation can be obtained by using the residual oil saturation for the ongoing reversals and the "flip-flop" process explained in chapter 2.4 is used to solve for the saturation values. The saturation values which are solved for with the iterative process are called minimum oil and minimum water saturation in the code. This minimum saturation is not the physical minimum saturation but a symbolic variable where the two branches have this saturation value for a certain reversal.

Figure 6 shows the final result of this program. The entire code can be seen in the Appendix A.1.
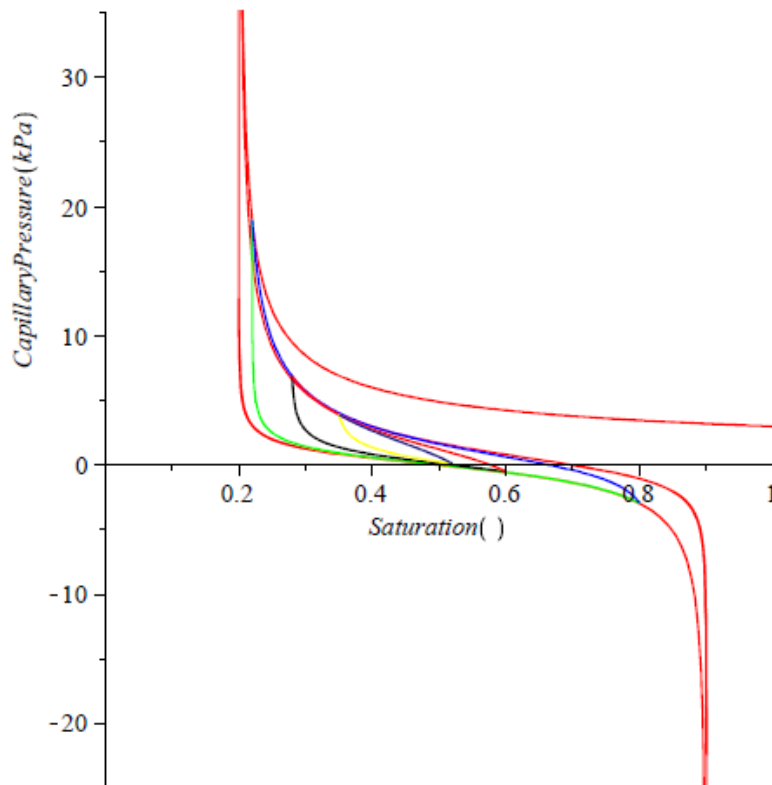
Figure 6 Example 1 – Six reversals occur until the process scans back to the secondary drainage bounding curve, as presented by Skjæveland et al. (1998).

The most important observation which can be drawn is for the second and third reversal where two iterations are needed until the saturation values converge. Starting with the fourth reversal, three iterations are needed to reach convergence.

To establish this code, saturation reversal points are predefined to generate the scanning curves. To create a more general solution, where an interval of possible saturation reversal is defined, various limitations have to be considered and reversals have to be obtained by trial and error.

The second example (Example 2) models at different saturation reversals points first imbibition and then secondary drainage curves. First the imbibition curve after the primary drainage curve with the origin on the primary drainage curve occurs. Then the secondary draining starts on the imbibition curve. In this code, an input interval for the saturation reversals is used and is therefore generally applicable. However it is not possible to artificially enforce a saturation reversal without evaluating first if it is feasible to occur at each point.

The spontaneous imbibition curves after primary drainage always start on the primary drainage curve, therefore no iteration process is needed to estimate the minimum oil and water saturation as the minimum oil saturation is equal to the residual oil saturation at each reversal point on the primary drainage curve.

To derive the drainage capillary pressure curve, the iterative process is needed to obtain values for the minimum saturations.
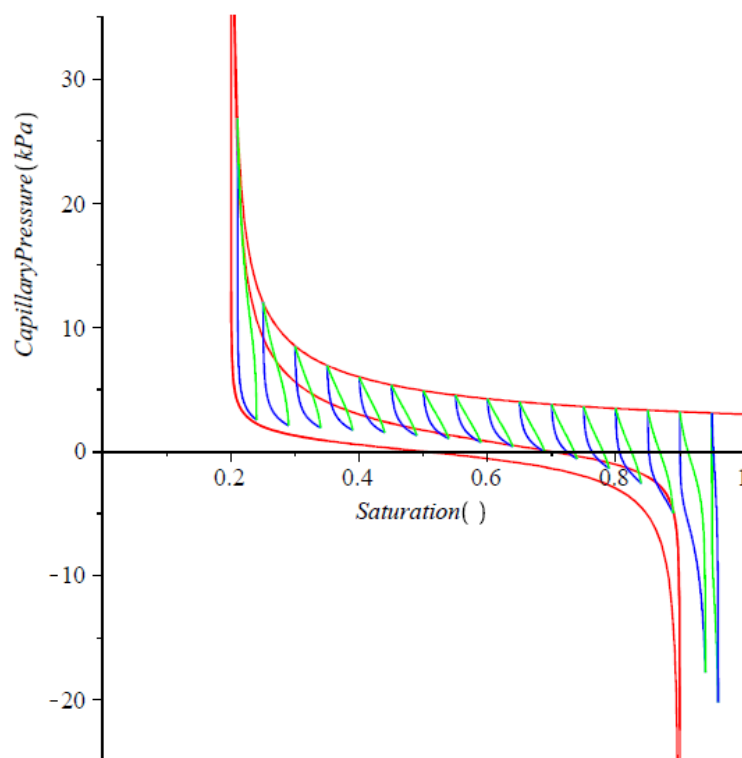
Figure 7 Example 2 – Display of various possible imbibition curves after primary drainage and secondary drainage curves. The reversal points are predefined.

Figure 7 shows possible occurring imbibition capillary pressure curves after primary drainage. For the reversal points, a predefined input interval is used. The full code can be seen in the Appendix A.2.

The most important is to find the number of necessary iterations until the minimum oil/water saturation for each drainage curve is reached. Every reversal needs three iteration steps until the values are considered converging.

The explanation of the produced programs shows on the one hand that using the correlation by Skjæveland et al. (1998) capillary pressure curves including hysteresis effect are established and on the other that test of convergence should not be neglected.

These codes are used to establish a program to simulate centrifuge experiments in Maple.

3.2 Evaluation of experimental centrifuge methods

A lot of material is available in the literature about interpretation of primary drainage capillary pressure curves but is limited for imbibition capillary pressure curves. As no hysteresis occurs for primary drainage it is easier to evaluate while with imbibition curves hysteresis effects have to be considered. Different methods are available dealing with imbibition capillary pressure assuming that the residual saturation of the core sample is uniform after primary drainage. In this case no hysteresis effect needs to be considered. In reality, the saturation distribution after primary drainage is not uniform and hysteresis effects occur and need to be considered. The hysteresis branches in the experiment depend on the position (radius) in the core.

One of the most commonly used methods in the industry to model hysteresis effects by Spinler and Baldwin ("Capillary pressure scanning curves by direct measurements of saturation", 1997) is found to be troublesome because they destroy the hysteresis effect and only get an averaged saturation. Re-producing their method was found to be impossible as the initial conditions and boundary effects were not available and a model cannot be built.

The second method discussed by Fleury, Ringot and Poulain ("Positive imbibition capillary pressure curves using the centrifuge technique", 1999) uses a more solid experimental procedure. In this case they also assume an averaged saturation of the core sample and the core is prepared to have uniform residual water saturation.

Based on the limitations of the two methods a new way of interpreting imbibition capillary pressure curves will be presented. A centrifuge experiment is simulated in Maple using Skjæveland et al. (1998) correlation for mix-wet reservoirs.

Evaluation of Spinler and Baldwin's method:

In the procedure some of the steps have been found to be unreasonable and not clearly explained.

First of all, as it is necessary to invert the core holder after the primary drainage to start the imbibition process, the pressure continuity and the hysteresis effect are destroyed. Therefore the obtained capillary pressure curves are incorrect as the procedure does not account for hysteresis.

As mentioned by the authors, the original centrifuge method can only be used to determine the drainage or negative imbibition curves and cannot obtain scanning

curves. Their method does not model the occurring hysteresis effect in natural reservoirs properly.

Furthermore with this experiment only the average saturation of the core is obtained but the results are more representative if the saturation is obtained on different (predefined) radii of the core. Using such an advanced method, a detailed saturation profile can be generated over the whole core.

Also the positioning of the free water level to derive positive and negative parts of drainage/imbibition curves is questionable. In reality it is impossible to choose the position of the free water level. An experimental procedure cannot lead to representative results using techniques which cannot occur in a reservoir. As already mentioned it was tried to model their procedure in Maple but the pressure continuity is destroyed with the removal of the core. To program this method after each step, new initial data would be needed, but as there is no information about data when the core is inverted it is impossible to model this procedure. All these aspects show that this experiment cannot produce representative capillary pressure curves.

Evaluation of Fleury, Ringot and Poulain's method:

The presented procedure is comprehensive and well explained. Although hysteresis effects are considered, they are removed through establishing an artificially uniform saturation distribution at residual saturation after primary drainage. The uniform residual saturation profile can be obtained using a ceramic plate in the core holder. This idea was first presented by Szabo (1974). Removing the hysteresis effect makes it easier to interpret the experiment but in reality hysteresis is present and therefore it is necessary to find a method which takes this hysteresis into account.

Only average saturation is obtained, the amount of liquid pumped in and out during drainage/imbibition is compared. It is preferable to obtain a more detailed saturation profile and no information about the residual saturations is given.

In contrast to Spinler and Baldwin's method it is possible to model the method with Maple. This shows that moving the fluid level out of the sample establishes a uniform residual saturation profile after drainage. It does not matter at which position of the core the imbibition capillary pressure curve is expected to start, the curves are identically and they all start at the same reversal point which can be seen in Figure 8. The Maple program to model centrifuge experiments is used. The boundary conditions needed to be changed like it was discussed previously.
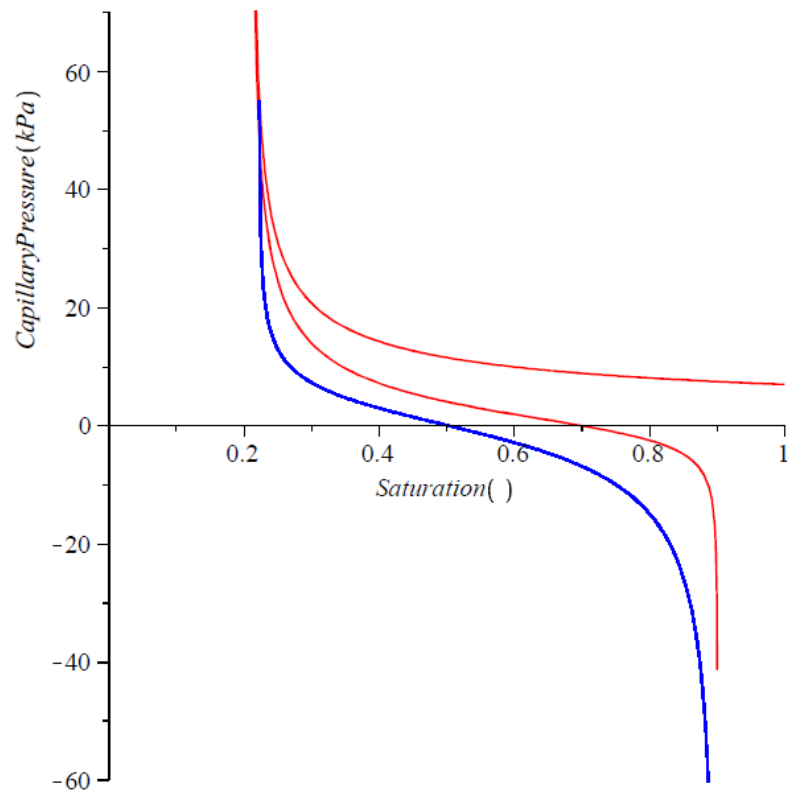
Figure 8 Imbibition curve – The imbibition curves after primary drainage for a uniform residual saturation profile is determined. 51 different points of the core have the same reversal saturation and the same imbibition capillary pressure curve.

Method comparison:

Primarily it will be discussed how the two presented papers deal with the hysteresis effect which occurs after primary drainage. Fleury et al. (1999) mention the problem and introduce a ceramic plate in the core holder, as it was explained, to avoid hysteresis effects. Spinler and Baldwin (1997) state that the procedure steps have to be repeated to obtain hysteresis curves but hysteresis cannot be determined as there is no relationship between the starting points of the curves and no pressure continuity in the procedure. With this experiment it is difficult to allocate where the measured imbibition curves occur along the primary drainage curve.

In contrast, Fleury et al. (1999) mention the problem when modelling imbibition capillary pressure curves. Hysteresis occurs after primary drainage along the whole primary drainage curve until the uniform residual saturation is reached. As soon as the saturation distribution is uniform after primary drainage, the capillary pressure imbibition curves are identical, independent of the location. Therefore different imbibition capillary pressure curves can be developed and need to be considered.

Spinler and Baldwin (1997) neglect hysteresis and do not take the effect of the imbibition capillary pressure curves into account, leading to incorrect imbibition capillary pressure curves. Fleury et al. (1999) consider the hysteresis effect, it is observed from the bounding imbibition curve which differs from the primary drainage curve. Still, none of them found a solution to include the hysteresis scanning curves in their experiments and results.

Another difference between the experiments is the procedure of obtaining capillary pressure curve data. Spinler and Baldwin (1997) invert the core holder after each drainage/imbibition process and destroy the continuity of the cycle and hysteresis as well. Fleury et al. (1999) found a way to overcome this problem using a "Pumping While Centrifuging" (PWC) system. This system makes it possible to measure drainage and imbibition curves without stopping the centrifuge and without inverting the core holder. The pump controls the position of the free fluid level and capillary pressure curves are obtained without stopping the centrifuge and manipulation of the sample. An advantage of this system is that the produced fluid is always in contact with the core allowing the fluid to flow into and out of the sample during the process. This makes the experiment much more accurate than a normal centrifuge experiment where no contact is established. This is also the case in Spinler and Baldwin's experiment (1997), where the produced fluid is collected in a separated tank.

One thing that the two experiments have in common is that the averaged saturation is obtained. This is not true in reality and it would be preferable to get a more accurate saturation profile of the core.

In general it can be said, that the experiment from Fleury et al. (1999) is more detailed and coherently explained. The experiment is possible to model in Maple compared to the one from Spinler and Baldwin (1997). In their explanation, important information is missing which would be needed to model their procedure. Information about initial and boundary conditions are difficult to obtain as the continuity is destroyed through the inversion of the core holder. Therefore new initial conditions are necessary at the beginning of each drainage/imbibition process. With the generated centrifuge procedure in Maple it is possible to model the effect of a uniform residual saturation profile after primary drainage. It can be observed that the idea by Fleury et al. (1999) is working to produce a single imbibition capillary pressure curve and that the code can be used to model centrifuge experiments.

3.3   Development of imbibition capillary pressure tool

A procedure was developed which makes it possible to obtain imbibition capillary pressure curves and determine the residual saturations, pore size distribution indices as well as the capillary entry pressures using saturation profiles gained from a centrifuge experiments for two-phase reservoirs.

The presented examples in chapter 3.1 are extended to model a centrifuge experiment which requires data from a centrifuge experiment. The sample dimensions and the used fluids are specified with the core dimensions chosen from the examples from Hermansen et al. (1991). Figure 9 indicates the length of r_1 and r_2 as it was classified in the paper by Hermansen et al. (1991), where the radii are defined as followed: r_1 = 0.0446 m and r_2 = 0.0938 m. In this case the free water level has to be considered, r_2 is set to the height of the free water level which is chosen at r = 0.093 m.
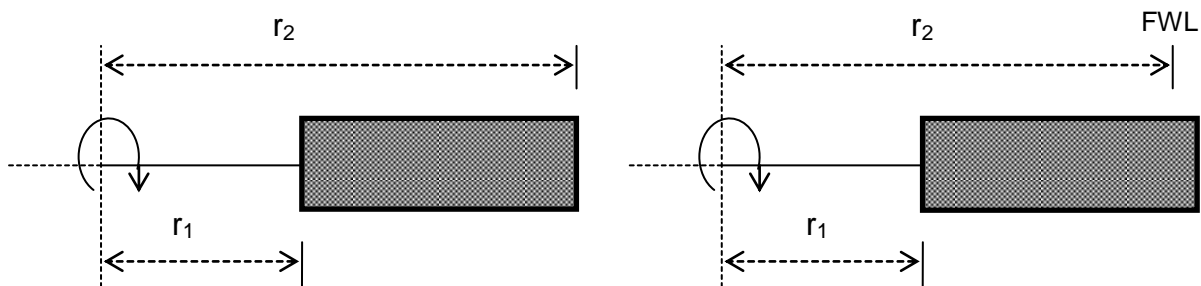

Figure 9 Centrifuge schematic – shows the length of r_1 and r_2. The plot on the right accounts for the free fluid level. The one on the left does not.

The next step is to define which types of fluid are used in the centrifuge experiment. It is decided to take the same fluids as Spinler and Baldwin (1997) used in their centrifuge experiment. The non-wetting phase was chosen to be octadecane with a density of 777 kg/m³. The wetting phase is chosen as de-ionized water (ρ = 1000 kg/m³). The chosen properties of the core sample and fluids (and their densities) can easily be changed in the program, depending on the experiment and the usage. This makes the model adaptable to different reservoir conditions.

After defining all the input parameters, the next step is to define the radius points where reversal points, residual oil and irreducible water saturation are defined. In the beginning 16 points are chosen, but to establish a smooth saturation profile, the point number is increased. Depending on the capillary entry pressure, between 47 and 51 points are needed to derive representative saturation profiles. For a higher capillary entry pressure, a larger portion of the core sample is fully saturated with the wetting

phase. A higher pressure is needed to displace the wetting phase. At each point in the core, saturation and capillary pressure values are evaluated using the correlation and an equation accounting for the centrifugal force. Then the frequency interval is chosen and the same range as for Spinler and Baldwin (1997) is used. The maximum speed is 5000 RPM (2001) and the capillary pressure and the saturation values are evaluated in 500 RPM steps.

The aim is to model a positive imbibition curve and the centrifuge starts at a speed of 5000 RPM after primary drainage. Then the speed is stepwise decreased to zero. At the starting speed, the reversal saturation, the residual oil saturation and the minimum water saturation for all radii are calculated. As it was explained, the minimum water/oil saturation are not the physical minimum, but are variables defined in Maple. The saturation values stay constant at each point of the core and are independent of the speed of the centrifuge. Therefore the capillary pressure imbibition curves have the same residual oil saturation, irreducible water saturation and reversal point for each point on the core sample at different speeds. This shows that the curves vary depending on the location in the core sample which is important to know. This is the reason why it is so important to account for hysteresis and shows as well that Spinler and Baldwind's method cannot work, as it is not known at which position of the core the capillary pressure curves are measured. It is necessary to be able to determine the imbibition capillary pressure curve at each point. The first step in the program is to define the reversal points, residual oil saturation and irreducible water saturation at each point of the core. In this example predefined points (between 47 and 51) are chosen to evaluate these parameters using two different equations for capillary pressure. The correlation (Equation 6) for mix-wet reservoirs by Skjæveland et al. (1998) is used and combined with an equation which accounts for the centrifugal force (Hermansen et al. 1991):

$$Pc(r) = \frac{1}{2} \Delta \rho \omega^2 (r_2^2 - r^2) . \qquad (14)$$

Pc (r) … capillary pressure at the position r on the core [kPa]

Δρ … density difference between the non-wetting and the wetting phase [kg/m^3]

ω … speed of the centrifuge [RPM]

r$_2$ … length between the end of the core sample to the spinning axis [m] (Figure 9)

r … predefined points along the core where the capillary pressure is determined [m]

The three parameters (reversal point, residual oil saturation and irreducible water saturation) are defined at every desired location (r). They are used to determine the imbibition capillary pressure and the saturation values over the whole core sample. Moreover a saturation profile and the imbibition capillary pressure curves are obtained at every point of the core sample and therefore accounting for the hysteresis effect.

This was done for two different data sets. In the first run, the recommended values by Skjæveland et al. (1998) for residual oil saturation, irreducible water saturation, the pore size distribution for oil and water and the capillary entry pressure for oil and water are used. The artificial centrifuge lab data is established and will be called "lab data" in the further work. As an actual physical centrifuge experiment is time consuming it was not possible for this project to run a real experiment first. Therefore the idea was to test the procedure with artificially produced data. An advantage of using artificial lab data is a better possibility of the evaluation of the tool. In this manner the correct solution to the inversion problem is known. For the second run, random values are chosen for the parameters and the model is ran again and new imbibition capillary pressure and saturation values are obtained. If centrifuge data is available, only the second run is required there is no need to create artificial lab data. After both runs are completed, the next step is to find a way of adjusting the correlation parameters to fit the measured values.

Three different methods can be used to adjust the parameters:

- method of the steepest descent
- use the excel solver to solve for the parameter
- Using Maple as an Add-in in Excel and use the Maple commands within Excel

As it is the most efficient method where an overview over all equations and used formulas is given, the Excel solver was chosen. The method of steepest descent would be more time consuming as six parameters have to be adjusted. Using Maple as an Add-in is another way which was applied, but it gets difficult to remain an overview as the equations become complex as links between the different cells are needed to use the Maple Add-in.

Using the problem solver, the error between the values of the saturation obtained from the lab data and the data from the calculation is obtained. Then the total error is calculated and is minimized by adjustment of the parameters by the Excel solver.

This is only possible if the saturation values from the calculation are generated in Excel itself. An equation using the parameters is necessary, that the solver can be used for curve fitting purposes. Therefore only the saturation values obtained from the "lab data" file are exported from Maple and imported into Excel. If the data is obtained from a real experiment, only the data has to be entered in the Excel tool. From the calculation-file, the capillary pressure at each radius is found and exported to Excel. For calculating the saturation values with the assumed parameters, a Macro is written in Visual Basic which makes it possible to generate the "composed saturation values".

The used Macro called "ComputeS" solves for the saturation values from the correlation (Equation 4). The values for the parameters are based on best engineering judgment and have to be the same used for determining the capillary pressure within the Maple model. Using the bisection method, it is solved iteratively for the saturation value at each point of the core sample. The maximum number of iterations as well as the tolerance are defined in the excel file and can be adjusted.

The squared error between the two saturation values is calculated and summed up to the total error. The total error is needed to use the problem solver. The problem solver is a regression routine using the generalized reduced gradient method to solve for non-linear problems (Microsoft, 2013).

The problem solver iterates to minimize the total error by changing the parameters (in this case, residual oil and irreducible water saturation, pore size distribution indices and the capillary entry pressures for both phases) until the minimum error is found. It is a simple and quick method with the accuracy and the results depending on the frequencies, discussed in the result section.

The saturation profile of the computed saturation are plotted before and after solving for the parameters and compared with the one obtained from the lab data. This makes it possible to visually evaluate the curve fitting.

4. Presentation of model output and results

It will be demonstrated that with the presented centrifuge model, the desired saturation profiles can be generated. The residual saturations, pore size distribution indices, capillary entry pressures and for each point along the core, an imbibition capillary pressure curve are obtained. The full model is presented in the Appendix A.3, the Excel tool in the Appendix A.4 and the Macro in the Appendix A.5. All the displayed outputs of Maple are produced from the same code, the "lab data" is used to show the results produced from Maple. Figure 10 shows the saturation profiles of the "lab data" at different speeds of the centrifuge.
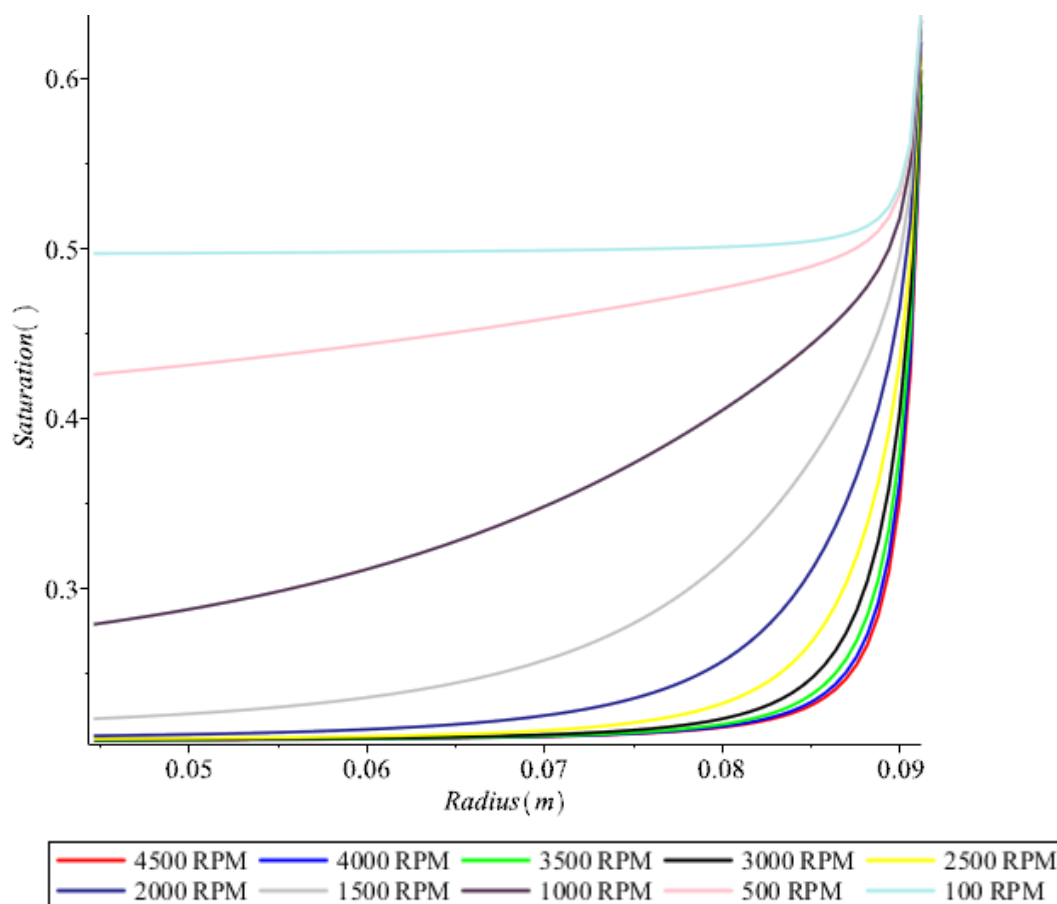
Figure 10 Saturation profile – each color represents the saturation profile at a different speed. The red curve is at the highest speed (ω = 4500 RPM) and the turquoise one for the lowest speed (ω = 100 RPM). It can be seen, that the water has fully filled the core at a speed of 100 RPM.

In Figure 10 it can clearly be seen that the saturation is a strong function of the radius.

The saturation profiles at the higher speeds are becoming close and the profiles less dependent on a further increase in speed. Figure 11 shows the saturation profiles for speeds between 1500 RPM and 4500 RPM in a zoomed in view.

Figure 11 Saturation profile zoom – In this figure a magnified view of the core sample from Figure 10 is shown. Now the saturation profiles at the higher speeds can be seen as well.

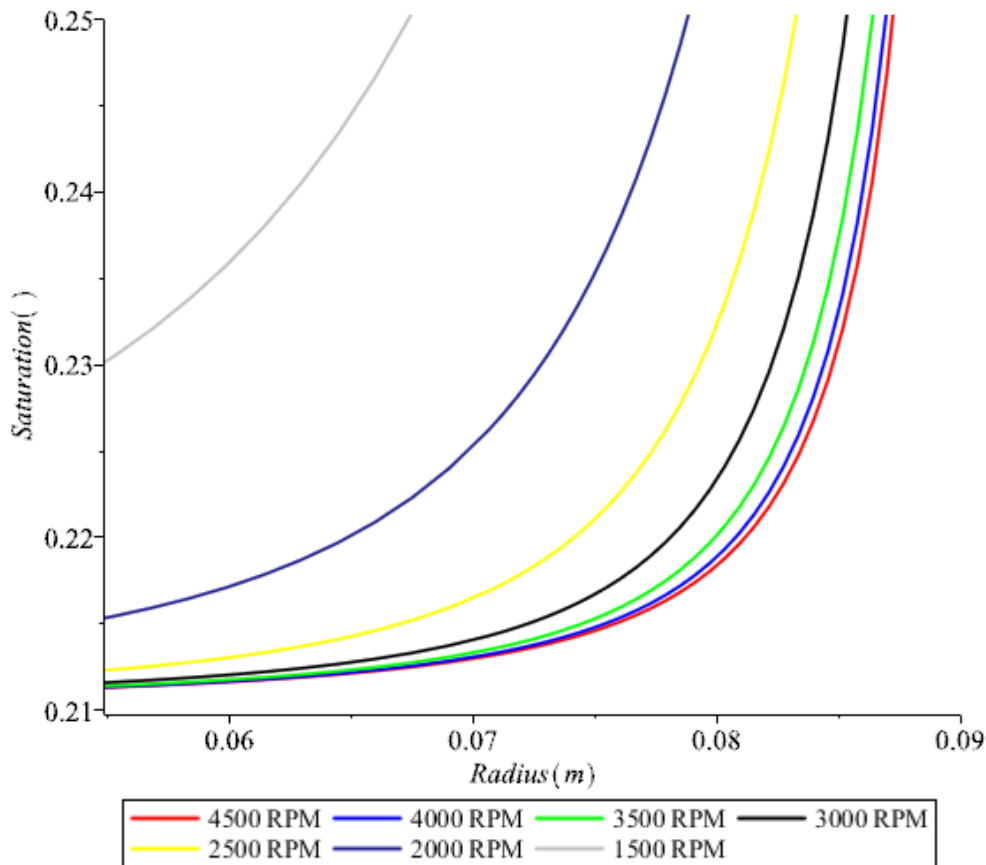In the region of the curvature, the density of the points is increased to have better resolution and establish a smooth curve.

From Figure 10 and Figure 11, it gets obvious that the saturation profiles are really close together at higher speeds. A curve indicates the movement of the fluid between each speed reduction. At higher speeds the core is mainly saturated with non-wetting phase and the water imbibes slowly into core. At a speed of 3000 RPM more and more water is sucked into the core and finally at a speed of 100 RPM the core is mainly water saturated.

The saturation profiles do not give any information about the hysteresis effect and therefore the capillary pressure profile has to be observed. In Figure 12 the capillary pressure curves of the primary drainage and imbibition are shown. It can be seen that the reversal for an imbibition curve can be at every point and that the imbibition curves can be determined using this model at every point.
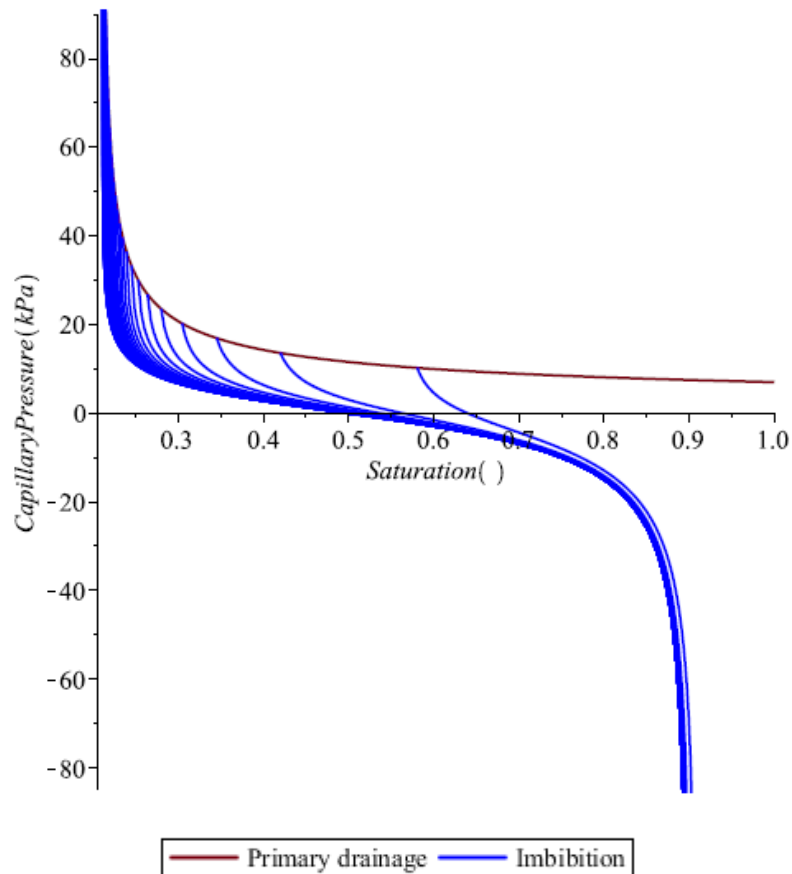
Figure 12 Capillary pressure profile – the red curve shows the primary drainage and the blue ones indicate the imbibition curves. Each reversal point is calculated with the chosen interval over the core.

As the reversal saturation point depends on the point of the core where it is determined, most of the imbibition curves start close to the irreducible water saturation. Many points in the core sample are close to irreducible water saturation as in this area a lot of radius points are needed to create a smooth saturation profile as already mentioned. It is possible to define even more imbibition curves, depending on the density of the chosen interval over the core. The location and the number of saturation values to determine have to be decided for each single experiment

Figure 13 shows the saturation range from 0.2 to 0.3. In this area, the imbibition curves do all have different origins on the primary drainage curves, which can hardly be seen in Figure 12 where it looks like they have the same origin.

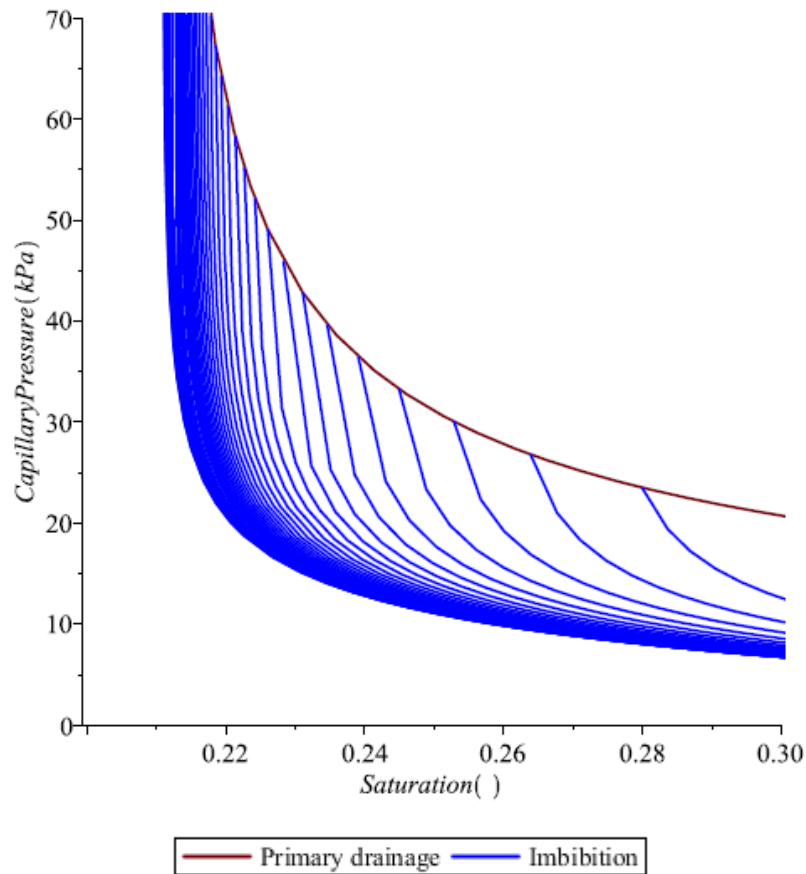**Figure 13** Capillary pressure profile between 0.2 and 0.3 – It can be seen that all imbibition capillary pressure curves are different even if their origin on the primary drainage curve is really close.

The presented curves are generated with the lab data and according to the varying input data the shape of the curve varies but the principle is the same.

As the lab data set was created, two different data sets representing the calculated data are chosen. Different data sets are compared to test the curve fitting tool within excel. Two cases are shown one with higher values and one with lower values than the original parameters.

Any first estimate is run in Maple, then the estimated values and the capillary pressure values are exported to Excel. If the values differ too much from the original data as, the solver cannot find a solution.

If the fit looks good and the curves are similar, the solver can be applied. Though if the curves are too different it is better to adjust the parameters first and as soon as a better fit is found, the new parameters are used again in Maple to produce new capillary pressure values. Then the new capillary pressure values are exported to Maple again and the curve fitting can be started. Figure 14 shows in which case the curve fitting works and in which not.
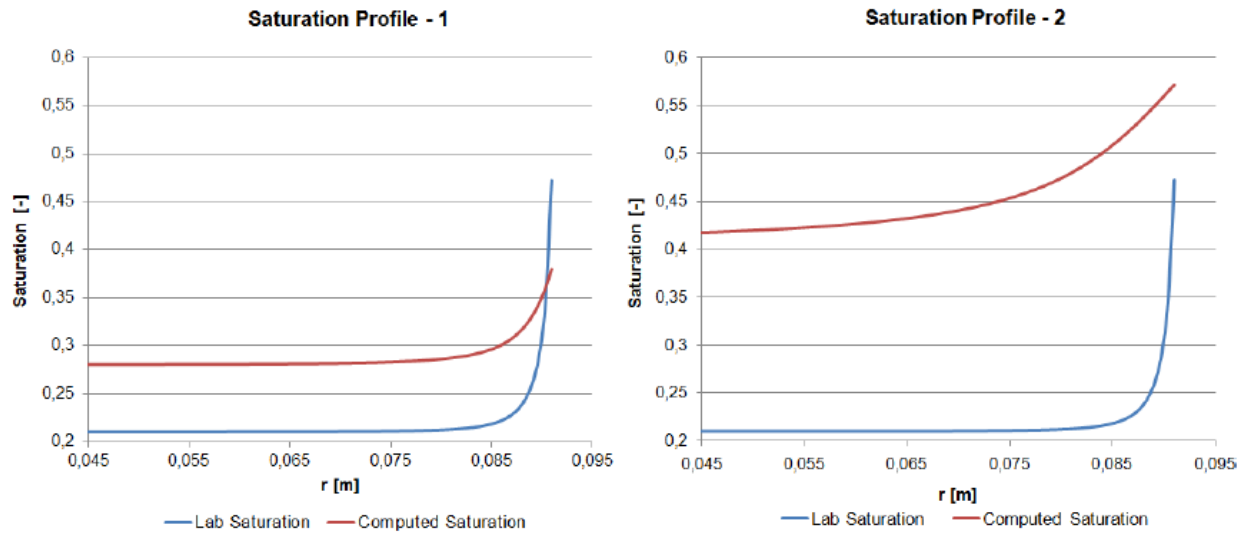
Figure 14 Comparison of saturation profiles – The saturation profile on the left side is from Case 1 (higher case) at a centrifuge speed of 3500 RPM. The saturation profile on the right side is at the same speed but without adjusting the parameters (the adjustment explained previously). The first estimate of the parameters was too far away from the original lab data and therefore the Excel solver cannot solve for it. After adjusting the parameters to reach a smaller difference between the red and the blue curve (left graph), the curve fitting process works without any problems.

The final values for running the curve fitting and obtaining the capillary entry pressures, pore size distribution indices and saturations are summarized in Table 1.

	Unit	Original	Case 1	Case 2
a_{wi}	[-]	0.25	0.30	0.20
a_{oi}	[-]	0.50	0.60	0.40
a_{wd}	[-]	0.25	0.30	0.20
a_{od}	[-]	0.50	0.60	0.40
c_{wi}	[kPa]	10.00	11.00	8.00
c_{wd}	[kPa]	7.00	8.00	5.00
S_{or}	[-]	0.10	0.13	0.10
S_{wr}	[-]	0.21	0.28	0.18
S_1	[-]	0.50	0.50	0.50
S_2	[-]	0.70	0.70	0.70

Table 1 Input parameter – Summary of the parameters entered in Maple and the set used for the imbibition are also used for the excel file.

It can be noticed that the capillary entry pressures for the oil phase are missing. They are determined using the correlation Equation (4) and the points S_1 and S_2. These are crossover points respectively from imbibition to drainage and from drainage to imbibition on the x-axis (saturation-axis). Solving for c_{oi} leads to

$$c_{oi} = -\frac{c_{wi}\left(\frac{-1 + S_1 + S_{or}}{-1 + S_{or}}\right)^{a_{oi}}}{\left(-\frac{S_1 - S_{wr}}{-1 + S_{wr}}\right)^{a_{wi}}}, \tag{15}$$

accordingly for c_{od} S_1 is substituted by S_2 and all subscripts "i" by "d".

This method is used in the Maple model as well. The crossover point is chosen to solve for the capillary entry pressure for the non-wetting phase. After the arrangements in 500 RPM steps, the lab data and calculated data are compared and the minimum error between the two data sets is evaluated with the Excel solver by adjusting the parameters. The results of the two cases will be discussed subsequently.

Case 1:

In this case the input parameters are higher than the original lab data. In Table 2 the original values (used to generate lab data) and the results of the parameters after running the solver at each speed are displayed. The used guess can be seen in Table 1.

	RPM orig.	500	1000	1500	2000	2500	3000	3500	4000	4500
S_{wr}	0.21	0.135	0.201	0.216	0.219	0.215	0.213	0.212	0.210	0.210
S_{or}	0.10	0.146	0.135	0.050*	0.078	0.117	0.099	0.090	0.213	0.221
a_{wi}	0.25	0.162	0.265	0.260	0.091	0.157	0.142	0.149	0.213	0.214
a_{oi}	0.60	0.570	0.221	0.623	0.554	0.586	0.625	0.646	0.641	0.660
c_w	10.0	11.00	10.99	11.00	10.99	10.99	10.96	11.00	11.00	11.00
S_1	0.50	0.506	0.526	0.593	0.516	0.595	0.664	0.731	0.646	0.714

Table 2 Results for case 1 – The results from case one (higher case) are embraced in the table to compare them.

* In this case, the program chooses S_{or} to be zero, as the residual saturation will never be zero, a restriction was given that it has to be greater than 0.05.

For the irreducible water saturation, the tool estimates almost the same water values except for speeds lower than 1000 RPM. The tool does not always yield the same results as for example for the residual oil saturation different values are obtained at each speed. It is similar for speeds of the centrifuge between 2000 RPM and 3500 RPM.

For the pore size distribution index, the evaluation tool leads in some cases to close results compared to the original values and in some slightly different. For the wetting phase, the parameters are quite similar at low and really high speeds of the centrifuge. For the oil phase it is roughly the same except for a speed of 1000 RPM.

Having a view on the results for the capillary entry pressure, it is conspicuous that they are very similar compared to the input parameter. The tool does not change the parameter to minimize the total error between the data sets.

For determining the crossing point and therefore the capillary entry pressure for the non-wetting phase, the highest variations can be noticed especially as the same value was used for the lab and the calculation data. It can be observed that the values tend to increase with an increase of the speed of the centrifuge. To make a judgment if the tool works for curve fitting purpose the saturation profiles are visualized in Figure 15.

Figure 15 shows the produced saturation profiles from the lab data compared to the saturation profiles obtained by the centrifuge model and the Excel tool. The dark red curves are at the lowest speed of 500 RPM where almost the whole wetting phase is already sucked into the core.

In general, the visual fit looks accurate with some deviations that can be seen. At some speeds both curves are almost identical, for example at a speed of 1000 RPM and at high speeds of 4000 RPM and 4500 RPM. Checking the deviation of the values the match for the speed of 1000 RPM is quite good as well except for the value for the non-wetting pore size distribution index. At higher speeds the calculated data is not matching the irreducible non-wetting saturation and the capillary entry pressure of the non-wetting phase. Still, the saturation profile looks really good.
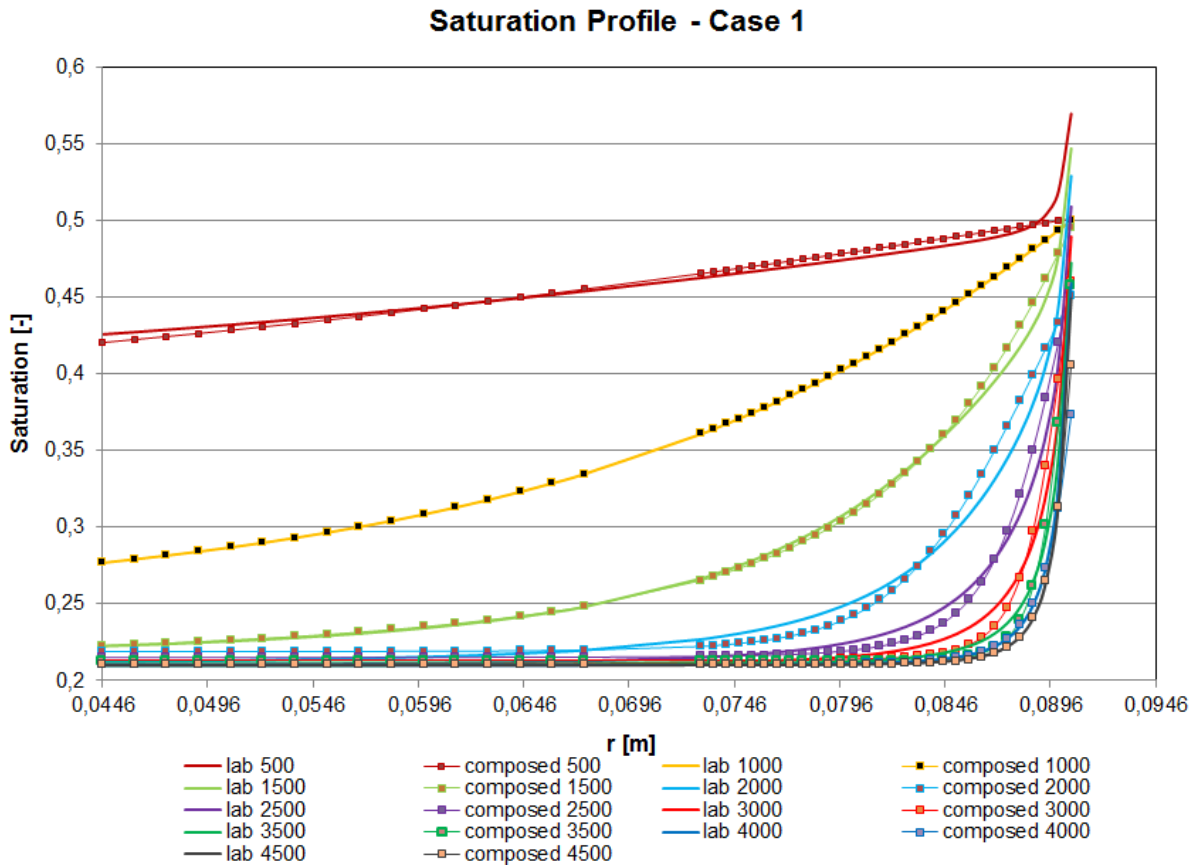
Figure 15 Saturation profiles case 1 – All saturation profiles for both the lab data case and the adjusted calculated data are displayed. The curves for the same speed are displayed in the same color. The thicker line without points represents the lab data and the other line with dots the calculated data.

Case 2:

In this case the used input parameters are lower than the original lab data. In Table 3 the original and the parameters after running the solver at each centrifuge speed are displayed. The estimate can be seen in Table 1.

	RPM orig.	500	1000	1500	2000	2500	3000	3500	4000	4500
S_{wr}	0.21	0.404	0.191	0.202	0.216	0.215	0.213	0.212	0.210	/
S_{or}	0.10	0.096	0.170	0.138	0.105	0.106	0.106	0.087	0.179	/
a_{wi}	0.25	0.287	0.602	0.450	0.245	0.222	0.210	0.213	0.251	/
a_{oi}	0.60	0.413	0.298	0.309	0.386	0.435	0.412	0.499	0.654	/
c_w	10.0	8.003	7.899	8.007	7.998	7.977	8.002	8.009	8.019	/
S_1	0.50	0.527	0.539	0.584	0.608	0.678	0.770	0.834	0.762	/

Table 3 Results for Case 2 – The results from Case 2 (lower case) are embraced in the table to compare them. "/" means it was not possible to evaluate the parameters at this speed.

Evaluating the results in Table 3, the values are quite similar to the first case. The same abnormalities can be observed for each parameter. Again, the values for wetting phase capillary entry pressure are fairly constant, the value for the crossing saturation point (therefore non-wetting phase capillary entry pressure) tends to increase with increasing rotation speed and the most consistent values are obtained for irreducible water saturation.

At a speed of 4500 RPM, the tool has troubles although it is possible to determine values for the parameters, the Macro "composeS" is not able to determine the saturation values anymore. The problem occurs because the curve is really sharp and the tool has troubles to determine the values at these points.

This case is visualized in Figure 16 and the curve fitting can be observed.
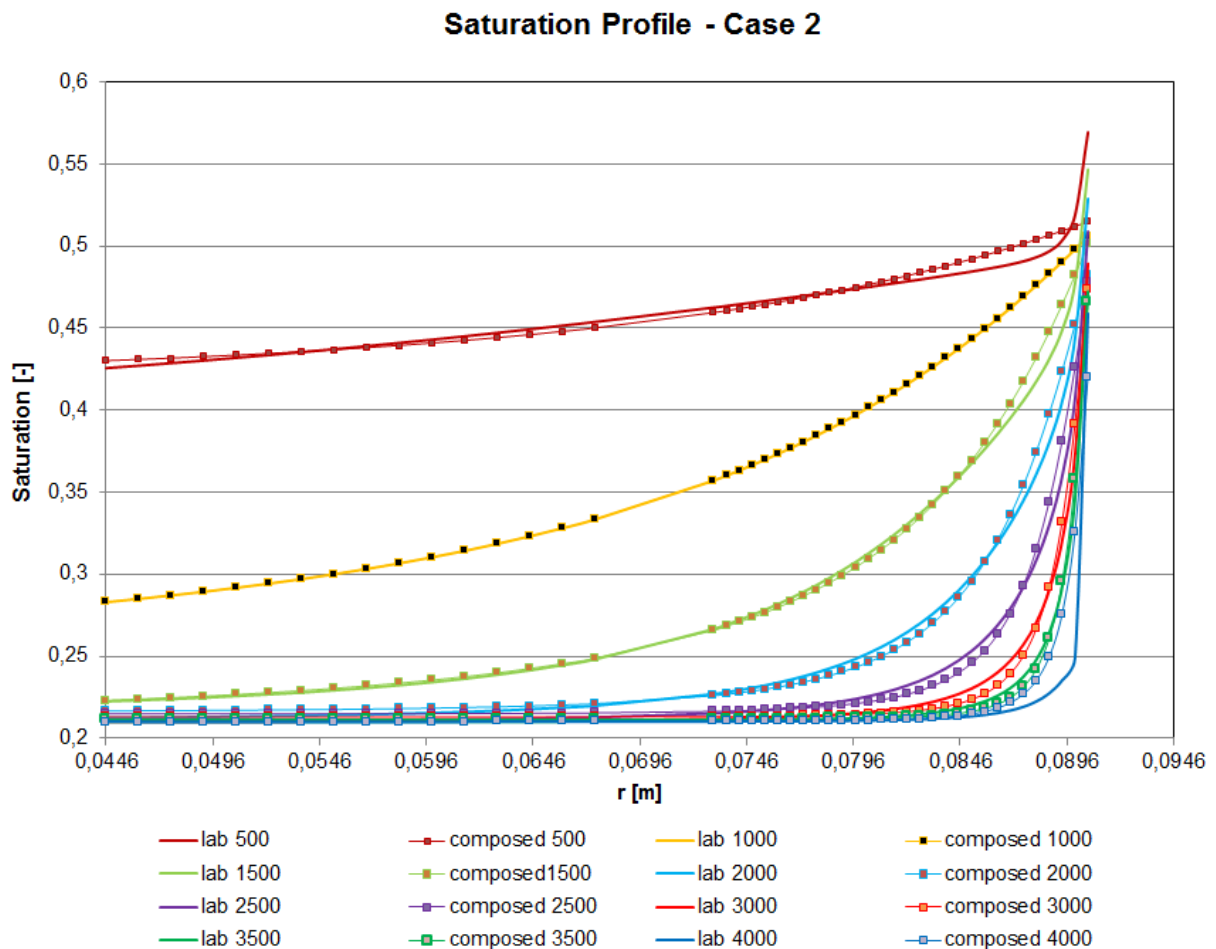

Figure 16 Saturation profiles Case 2 – All saturation profiles for both the lab data case and the adjusted calculated data are displayed. The curves for each speed are displayed in the same color. The thicker line with no points represents the lab data and the line with dots the composed data

Looking at Figure 16 most fits show minor deviation. At speeds of 1000 RPM, 2500 RPM and 3500 RPM it achieves most exact matches. Comparing the obtained parameters of these speeds to the lab data, it looks like the fit for 1000 RPM does not fit really well. The deviations for the both pore size distribution indices are higher as well as the obtained residual non-wetting saturation. The fit for 2500 RPM is better, still the pore size distribution index for the non-wetting phase is too low and as the crossing point saturation is increasing with speed it gets too high. At 3500 RPM, the match is fairly good, only for the crossing saturation point a high difference can be noticed which leads to a change in capillary entry pressure for the non-wetting phase.

A direct comparison of the deviation of each parameter compared to the used one to create the lab data are shown in Table 4 and Table 5.

		500	1000	1500	2000	2500	3000	3500	4000	4500
S_{wr}	[%]	35.73	4.46	3.83	4.46	2.42	1.63	0.96	0.11	0.09
S_{or}	%	45.92	34.73	50.00	22.04	16.51	1.03	9.79	87.17	120.70
a_{wi}	%	35.38	6.06	89.18	64.07	37.19	43.08	40.45	14.78	14.12
a_{oi}	%	5.00	63.24	1.17	7.76	2.33	4.18	7.72	6.90	9.93
c_w	%	9.96	9.85	10.13	9.91	9.88	9.63	10.01	9.99	9.98
S_1	%	1.24	5.22	13.87	2.96	18.99	32.83	46.17	29.14	42.77

Table 4 Deviation Case 1 – The deviation of each parameter for the first case referring to the used values creating the lab data are shown.

		500	1000	1500	2000	2500	3000	3500	4000	4500
S_{wr}	%	92.29	9.19	3.81	2.62	2.24	1.39	0.76	0.11	/
S_{or}	%	3.71	69.52	38.35	5.25	2.55	6.26	14.42	79.41	/
a_{wi}	%	14.87	140.99	80.39	1.88	11.48	16.01	14.62	0.54	/
a_{oi}	%	31.17	50.25	48.44	35.70	27.50	31.27	16.86	9.07	/
c_w	%	19.97	21.01	19.93	20.01	20.23	19.98	19.91	19.80	/
S_1	%	5.41	7.75	16.85	21.51	35.53	54.03	66.73	52.41	/

Table 5 Deviation Case 2 – The deviation of each parameter for the second case referring to the used values creating the lab data are shown.

It can be seen that the deviation varies from 0.11 % to 140 %. Extreme cases appear at the high speed or at low speed of the imbibition process. For example the highest deviations for irreducible wetting phase saturation is always at a speed of 500 RPM

and except of one speed for all other speeds for both cases the deviation is less than 5 %. The input parameters are equal to 0.18 and 0.28 (see Table 2) and for both cases the S_{wr} is really close to the original input parameter.

The comparison between the visual and the numerical results should show that both results have to be evaluated to get a better understanding of the results. As the curve fitting is based on a mathematical (generalized reduced gradient) iteration method to find the smallest error, the parameters are not adjusted based on physical reasoning (for example in Case 1 S_{or} is adjusted to zero, which is physically not possible). The parameters are adjusted to find the smallest error which is shown to generally lead to reasonable results.

The parameters are obtained for each speed separately and no general solution for one case is evaluated. It would be desirable to create a tool which considers the results of all speeds and try to find one best fit for all curves. For now an average of each parameter is calculated for each case and the results are shown in Table 6.

	Case 1	Case 2
S_{wr}	0.20	0.23
S_{or}	0.12	0.12
a_{wi}	0.21	0.31
a_{oi}	0.57	0.43
c_w	10.99	7.99
S_1	0.61	0.66

Table 6 Averaged parameters – To establish parameters for one case and not for each speed the average of each parameter is taken.

The average of the estimated parameters results in a reasonable solution. Case 1 is really close to the chosen input parameters. Even if the average values for the second case are slightly higher, the results before showed that the fit is really good.

The summary of the results should give an overview of the possibilities of this tool and what can be done with it. The usage and possible improvements will be evaluated in the discussion.

5. Discussion

The importance of finding evaluation methods for capillary pressure curves has been highlighted in the introduction. With the correlation by Skjæveland et al. (1998), a way to model and establish capillary pressure curves with consideration of the hysteresis effect is available. In addition, the determination of residual saturations, pore size distribution indices as well as capillary entry pressures is essential in the context of capillary pressure modelling and can be performed with the designed tool.

It is shown that the widely used method by Spinler and Baldwin (1997) to derive capillary pressure curves does not reach their claimed results. The detailed evaluation leads to the conclusion that with this technique, continuous capillary pressure curves cannot be produced. Likewise the hysteresis effect is not considered in the method and the use of the method leads to incorrect capillary pressure curves. The alternative method introduced by Fleury et al. (1999) uses a uniform saturation profile at residual saturation to avoid hysteresis. Figure 8 shows that with a uniform residual saturation profile after primary drainage all imbibition curves will be identical and start at the same point on the primary drainage curve.

With the limitations highlighted it is shown that no reasonable experimental way to establish imbibition capillary pressure curves for two-phase is available. Hence, a new method is proposed where the combination of a centrifuge experiment and the capillary pressure correlation are used to establish hysteresis imbibition capillary pressure curves as well as to derive the residual saturations, capillary entry pressures and pore size distribution indices for both phases.

The proposed model has been developed using artificially created "lab data" to test the procedure and its functionality. Based on the established model as a follow up, it is recommended to test the method with real saturation profiles obtained from a centrifuge experiment with the known limitations.

Furthermore it would be desirable to enter boundary conditions for the parameters (saturation values, pore size distribution indices and capillary entry pressures) and make the tool more automatic. Suggested add-ins would be on the one hand that the program could tell if a parameters deviation is too high to find a curve match with the solver. On the other hand it would be helpful to set boundaries for the tool that a parameter stays within physical limits and does not converge to a mathematical fit which is unreasonable.

It has to be considered that Excel runs iterations to find the minimum error between two data sets and adjusts the values in the way the minimum error is reached and some deviation in the results from the calculated lab data is expected. Nevertheless, it can be observed from the results that the tool works with high accuracy for curve fitting purpose. It was already mentioned in the result section that the curve fitting and adjusting for the parameters is done for each speed independently. As a follow up, a method which accounts for all different centrifuge speeds and iterates to find the "best fit" for all parameters based on available data and not only for one speed is recommended. In the proposed tool, the average value is calculated and was found as a good match.

6. Conclusion

The importance of the evaluation of methods and techniques which can be used in mixed-wet reservoirs is highlighted throughout this thesis. Only a limited amount of methods and techniques are available to determine capillary pressure curves in mixed-wet reservoirs because most reservoirs were considered to be water-wet or oil-wet until the early 2000s. Nowadays the view has changed and reservoirs are considered to be mixed-wet. To incorporate mixed wettability, recently used methods are reviewed to find a way to determine imbibition capillary pressure curves after primary drainage. It was explained that most available techniques are especially troublesome due to the occurring hysteresis effect.

It was shown that the available experiments produce incorrect imbibition capillary pressure curves as hysteresis effect is not considered or artificially removed. These experiments should not be used as they lead to inaccurate results which have a major influence on predicting flow behavior and well performance. However it is important to find a way of modelling imbibition capillary pressure curves. Therefore this new method, a combination of a centrifuge experiment and a correlation for capillary pressure is used. The correlation by Skjæveland et al. (1998) was chosen as it is comprehensive and widely used.

With the presented tool, not only capillary pressure curves can be ascertained.

To use the correlation by Skjæveland et al. (1998) to derive capillary pressure curves residual saturations, pore size distribution indices and capillary entry pressures need to be known. If the saturation profile of a core obtained by a centrifuge experiment for example, is available, the presented tool can be used to derive imbibition capillary pressure curves as well as the mentioned parameters.

The use of this technique leads to accurate results for the parameters and the curve fitting purpose. The tool has been designed based on artificial data and shall as a follow up be tested on real centrifuge data and used to determine capillary pressure curves for two-phase flow in mixed-wet reservoirs.

This tool constitutes a base program to model imbibition capillary pressure curves and the possible improvements to automate this tool have been discussed.

This tool is only applicable in two-phase flow and to model three phase flow, it can be extended as the research on three-phase capillary pressure correlations establishes reasonable models.

7. Outlook for three-phase capillary pressure correlation

As highlighted in the introduction, most reservoirs contain three phases but the majority of capillary pressure evaluation techniques have been developed for two phases due to high complexity by adding a third phase. Three-phase capillary pressure curves used to be predicted from two-phase capillary pressure curves which is demonstrated to not work. In three-phase flow, the fluid distribution as well as the displacement process at the pore scale is more difficult than for two-phases. It has to be considered that the dynamics of two different transition zones (oil-gas and oil-water) have to be modelled. Currently, the impact from one movement of a transition zone to the other one is not known. There are infinite possibilities of displacement paths of two independent saturations which makes it really difficult to predict the movement of the flow (Helland and Skjæveland 2004).

Three-phase capillary pressure correlation is a complex research field which attracts attention. Publications about this topic have been made and research is ongoing to find a correlation. Helland and Skjæveland published a suggestion for a three-phase capillary pressure correlation in mixed-wet reservoirs in 2004. They propose a correlation based on Skjæveland et al. (1998) to compute capillary pressure curves for three-phase flow.

In three phase flow, infinite possible ways are available to relate the three phases and therefore an infinite number of unique saturation trajectories exist. Helland and Skjæveland (2004) assume a process-based approach which implements that the processes are known for the saturation trajectories. The saturation change is structured into "classes of processes". Depending if the saturation is increasing (I), decreasing (D) or constant (C) the phases are classified. Further classification notation, a three-letter symbol is one class. The first letter denotes the direction of water saturation, the second of oil saturation and the third one for gas saturation change. The formulation for the three-phase correlation for each process class is done with the sum of the Brooks-Corey terms for oil and water saturation. This leads to the following equations for all classes of processes.

For the process classes XDI and XID:

$$P_{cgo} = c_g \left(1 - S_g\right)^{-a_g} + c_o (1 - S_o)^{-a_o} . \tag{16}$$

For the process classes IXD and DXI:

$$P_{cgw} = c_g \left(1 - S_g\right)^{-a_g} + c_w (1 - S_w)^{-a_w} . \tag{17}$$

For the process classes DIX and IDX:

$$P_{cow} = c_o (1 - S_o)^{-a_o} + c_w (1 - S_w)^{-a_w} . \tag{18}$$

The X can either stand for I, D or C in all six terms.

It is a reasonable method to start, still the saturation paths are not controlled and the particular direction of the pathway is unknown. It is recommended to combine this method with the one of Yuan and Pope (2012).

Yuan and Popes (2012) approach is independent on phase identification, Gibbs free energy (GFE) is used to control the system. The minimum GFE is reached at a local equilibrium at fixed mole number, pressure and temperature. Using GFE the direction of the pathway can be predicted. Finding the minimum GFE for a system is difficult and Yuan and Pope (2012) assume to measure relative permeability at known thermodynamic states and interpolate with molar GFE of each phase between the states.

Measuring residuals saturations is much more difficult for three phases than in two phases. A lot of different scenarios could occur, for example, all three phases saturations increase, all decrease, one increase - two decrease, two increase - one decrease, one constant - two change and many more.

Yuan and Pope (2012) propose a capillary pressure model consonant with the relative permeability model as well as it should be a continuous function. All parameters of the correlation should be a function of GFE of each phase which leads to independency of phase label.

To implement this method in three-phase reservoirs further research is necessary. There are still many unknowns like how to obtain GFE for the phases, how to combine them, how to interpret the values to receive the pathway. There is an ongoing research project to use GFE in combination with a correlation for capillary pressure curves at the University of Austin in Texas. The aim is to find a way of using GFE to determine imbibition capillary pressure curves including hysteresis in three-phase flow.

8. References

Abeysinghe, K.P., Fjelde, I. and Lohne, A. 2012a. Acceleration of oil production in mixed- wet reservoirs by alteration of relative permeability curves using surfactants. Paper SPE 155626 presented at the SPE EOR Conference at Oil and Gas West, Muscat, Oman, 16 - 18 April.

Abeysinghe, K.P., Fjelde, I. and Lohne, A. 2012b. Dependency of remaining oil saturtaion on wettability and capillary number. Paper SPE 160883 presented at the SPE Saudi Arabia Section technical Symposium and Exhibition, Al- Khobar, 8 - 11 April.

Al-Mansoori, S.K., Pentland, C.H., Iglauer, S. and Blunt, M.J. 2009. Three- phase measurements of non-wetting phase trapping in unconsolidated sand packs. Paper SPE 1239994 presented at the SPE Annual Technical Conference and Exhibition, New Orleans Louisiana, USA, 4 - 7 October.

Baldwin, B.A. and Spinler, E.A. 1997. Capillary pressure scanning curves by direct measurements of saturation. Paper SCA-9705 presented at Society of Core Analyst Meeting 1997.

Baldwin, B.A. and Spinler, E.A. 2001. Method for laboratory measurement of capillary pressure in reservoir rock. US Patent No. 6178807 B1.

Bech, N., Frykman, P. and Vejbæk, O.V. 2005. Modelling of initial saturation distribution in oil/water reservoirs in Imbibition Equilibrium. Paper SPE 95365 presented at the SPE Annual Technical Conference and Exhibition, Dallas, Texas, 9 - 12 October.

Brooks, R.H. and Corey, A.T. 1964. Hydraulic properties of porous media. Hydraulic paper No.3, Colorado State University.

Brooks, R.H. and Corey, A.T. 1967. Properties of porous media affecting fluid flow. Journal of the Irrigation and Drainage Division, Proc. of ASCE, 92, No. IR2, pp. 61 - 88.

Carnegie, A.J. 2006. Understanding the pressure gradients improves production from oil/water transition carbonate zones. Paper SPE 99240 presented at the SPE/DOE Symposium on Improved Oil Recovery, Tulsa, Oklahoma, USA, 22 - 26 April.

Delshad, M., Lenhard, R.J., Oostrom M. and Pope, G.A. 2003. A mixed-wet hysteretic relative permeability and capillary pressure model for reservoir simulations. SPE Reservoir Evaluation & Engineering Journal, vol. 6, no. 5, pp. 328 - 334, SPE 86916.

Eigestand, G.T. and Larsen, J.A. 2000. Numerical modelling of capillary transition zones. Paper SPE 64374 presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Brisbane, Australia, 16 - 18 October.

El- Amin, M.F., Sun, S. and Salama, A. 2013. Enhanced oil recovery by nanoparticles injection: modelling and simulation. Paper SPE 164333 presented at the SPE Middle East Oil and Gas Show and Conference, Manama, Bahrain, 10 - 13 March.

Excel®, 2010. Redmond, Washington: Microsoft Coorporation.

Fleury, M., Ringot, G. and Poulain, P. 1999. Positive imbibition capillary pressure curves using the centrifuge technique. Paper SCA-9913 presented at the International Sympoisum of the Society of Core Analysts, Denver, U.S.A, 1 - 5 August.

Green, D.P., Dick, J.R, McAloon, M., Cano-Barrita, P.F.J., Burger, J. and Balcom, B. 2008. Oil/water imbition and drainage capillary pressure determined by MRI on a wide sampling of rocks. Paper presented at Society of Core Analysts, Abu Dhabi, UAE, 29 October - 2 November.

Hammervold, W.L., Knusten, Ø., Iversen, J.E. and Skjæveland, S.M. 1998. Capillary pressure scanning curves by mircopore membrane technique. Journal of Petroleum Science and Engineering, vol. 20, pp. 253 - 258.

Hashmet, M.R., Tan, I.M., Majidaei, S. and Mushtaq, M. 2012. Simultaneous determination of capillary pressure and relative permeabilities. Paper presented at the SPE Saudi Arabia Section technical Symposium and Exhibition, Al- Khobar, Saudi Arabia, 8 - 11 April.

Helland, J.O. and Sklæveland, S.M. 2004. Three-phase capillary pressure correlation for mixed-wet reservoirs. Paper presented at the SPE International Petroleum Conference, Puebla, Mexico, 8 - 9 November.

Hermansen, H., Eliassen, Ø., Guo, Y. and Skjæveland, S.M. 1991. Capillary pressure from centrifuge - a new, direct method. Paper presented at The Second European Core Analysos Symposium (Eurocas II), London, 20 - 22 May.

Iglauer, S., Wuelling, W., Pentland, C.H., Al-Mabsoori S.K. and Blunt, M.J. 2011. Capillary- trapping capacity of sandstones and sand packs. SPE Journal, vol. 16, no. 4, pp. 778 - 783, SPE-115697.

Kralik, J.G., Guice, K. and Meissner, J.P. 2010. Methods and tools for the development of consistent reservoir rock type based relative permeability and capillary pressure models for reservoir simulation. Paper SPE 137357 presented at the Abu Dhabi International Petroleum Exhibition and Conference, UAE, 1 - 4 November.

Land, C.S. 1971. Comparison of calculated with experimental imbibition relative permeability. Paper SPE 3360 presented at the SPE Rocky Mountain Regional Meeting, Billings, Mont., 2 - 4 June.

Land, C.S. 1967. Calculation of imbibition relative permeability for two- and three-phase flow from rock properties. Paper SPE 1942 presented at the SPE 42nd Annual Fall meeting, Houston, Texas, 1 - 4 October.

Lenhard, R.J. and Oostrom, M. 1998. A parametric model for predicting relative permeability-saturation-capillary pressure relationships for oil-water systems in porous media with mixed wettability. Transport in Porous Media, vol. 31, pp. 109 - 131.

Lomeland, F. and Ebeltoft, E. 2008. A new versatile capillary pressure correlation. Paper SCA2008-08 presented at the International Symposium of the Society of Core Analysts, Abu Dhabi, UAE, 29. October - 2. November.

Maple^{TM}, version 16. 2012. Waterloo, Ontario: Maplesoft^{TM}.

Masalmeh, S.K., Abu Shiekah, I. and Jing, X.D. 2007. Improved characterization and modelling of capillary transition zones in carbonate reservoirs. SPE Reservoir Evaluation & Engineering, vol. 10, no. 2, pp. 191-204, SPE-109094-PA-P.

Microsoft. 2013. Solver Uses Generalized Reduced Gradient Algorithm. http://support.microsoft.com/kb/82890 (accessed 28 May 2013).

Pentland, C.H., Itsekiri, E., Al Mansoori, S.K., Iglauer, S., Bijelic, B. and Blunt, M.J. 2010. Measurement of nonwetting- phase trapping in sandpacks. SPE Journal, vol. 15, no.2, pp. 274 - 281, SPE-115697-PA-A.

Pirker, B., Mittermeier, G.M. and Heinemann, Z.E. 2007. Numerically derived type curves for assessing matrix recovery factors. Paper SPE 107074 presented at the SPE Europec/EAGE Annual Conference and Exhibition, London, United Kingdom, 11 - 14 June.

Skjaeveland, S.M., Siqveland, L.M. and Kjosavik, A. 1998. Capillary pressure correlation for mix-wet reservoirs. Paper SPE 39497 presented at the SPE Indian Oil and Gas Conference and Exhibition, New Delhi, 10 - 12 February.

Szabo M.T. 1974. New methods for measuring imbibition capillary pressure and electrical resistivity curves by centrifuge. SPE Journal, vol. 14, no.3, pp. 243 - 252, SPE 3038-PA.

Yuan, C. and Pope, G.A. 2012. A new method to model realtive permeability in compositional simulators to avoid discontinuous changes caused by phase-identification problems. SPE Journal, vol. 17, no. 4, pp. 1221 - 1230, SPE 142093-PA.

Appendix A.

A.1   Example 1

Example 1

```
> restart:
> with(plots):
```

General definitions for drainiage and imbibition capillary pressure curves

```
> Swn:=(S-Swr)/(1-Swr):
  Son:=(1-S-Sor)/(1-Sor):
> pcpi:= cwi/Swn^awi:   pcmi:= coi/Son^aoi:
  pcpd:= cwd/Swn^awd:   pcmd:= cod/Son^aod:
> Pci:= unapply(pcpi+pcmi,S):
  Pcd:= unapply(pcpd+pcmd,S):
  PcD1:= unapply(pcpd,S):
```

Nomenclature:
Swn ... normalized water saturation, Son...normalized oil saturation
pcpi,pcpd ... capillary pressrue positive part of imbibition/drainage
pcmi,pcmd ... capillary pressrue minus part of imbibition/drainage
Pci ... capillary pressure imbibtion, Pcd...capillary pressure drainage
PcD1 ... capillary pressure of primary drainage
cwi,cwd ... entry pressure for water (i for imbibition entry pre and d for drainage entry pre)
coi,cod ... entry pressure for oil (i for imbibition entry pre and d for drainage entry pre)
1/a ... poresize distribution (w...water,o...oil)

Determine coi and cod

```
> coi:=solve(Pci(S1)=0,coi):
  cod:=solve(Pcd(S2)=0,cod):
```

S1 and S2 is the crossover points between respectively primary imbibition and secondary drainage and the "S-axis". Pc(S) is of course zero.

Lands Equation

```
> C:=1/Sor-1/(1-Swr):
```

C...Land's trapping constant
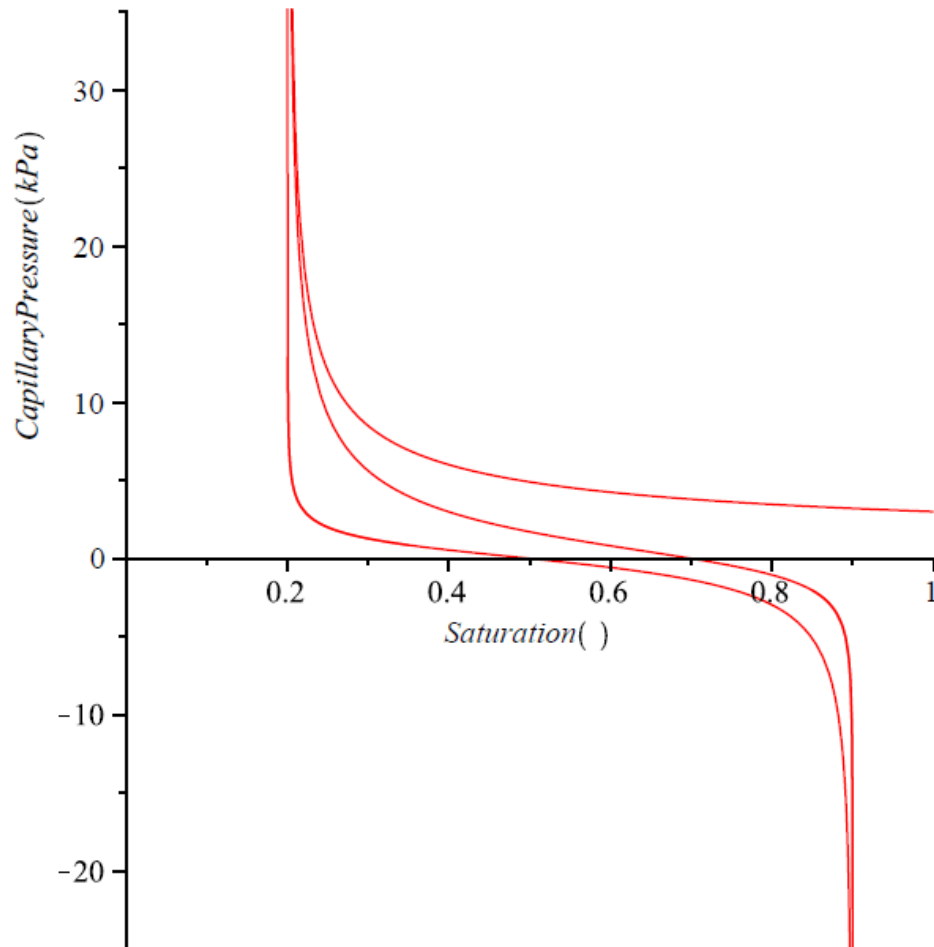Using Land's equation to determine asymptotes when imbibition starts from primary drainage curve .

Defining Constants

```
> awi:=0.25: aoi:=0.5: cwi:=2:
  awd:=0.5: aod:=0.25: cwd:=3:
  Sor:=0.1: Swr:=0.2:
  S1:=0.5: S2:=0.7:
```

Plot of primary drainage and imbibiton bounding loop

```
> fpci:= plot(Pci,(Swr-0.05)..(Swr+0.15),0..35,numpoints=500,
  labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
  fpci1:= plot(Pci,Swr..1,-25..25,numpoints=100,labels=[Saturation
  ( ),CapillaryPressure (kPa)],thickness=1,labeldirections=
  [horizontal,vertical]):
  fpcd:= plot(Pcd, Swr..1,-25..25,numpoints=100,labels=[Saturation
  ( ),CapillaryPressure (kPa)],thickness=1,labeldirections=
  [horizontal,vertical]):
  fpcd1:= plot(Pcd, (1-Sor-0.05)..(1-Sor+0.05),-25..25,numpoints=
  500,labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
  fpcD1:= plot(PcD1, 0..1,labels=[Saturation ( ),CapillaryPressure
  (kPa)],thickness=1,labeldirections=[horizontal,vertical]):
```

```
> display(fpci1,fpci,fpcd,fpcd1,fpcD1);
```


Reversion

1. Reversal

The first reversal will be an imbibition curve (Pcim[1]) which has its origin on the primary drainage curve (PcD1). The reversal saturation (Srev[1]) is a point on both PcD1 and Pcim[1].
Therefore it is solved for: PcD1(Srev[1])=Pcim[1](Srev[1])

```
> Srev[1]:=0.22:
> SorD[1]:=1/(C+(1/(1-Srev[1]))):
```

This is the residual oil saturation if the spontanous imbibition occurs on the primary drainage curve at the saturtation S=Srev[1]. This is the lowest water saturation experienced.

Calulate the normalized saturations for the first reveral

S_nw ... normalised water saturation
Sw_min1[1] ... asymptote for the positive branch of the imbibition curve
S_no ... normalised water saturation for the negative branch
SorD[1] ... asymptote for the negative branch

```
> S_nw[1]:=(S-Sw_min1[1])/(1-Sw_min1[1]):
> S_no[1]:=(1-S-SorD[1])/(1-SorD[1]):
> Pcim[1]:=cwi/S_nw[1]^awi+coi/S_no[1]^aoi:
  Pcim[1]:=unapply(Pcim[1],S):
> Sw_min1[1]:=solve(Pcim[1](Srev[1])=PcD1(Srev[1]),Sw_min1[1]):
```
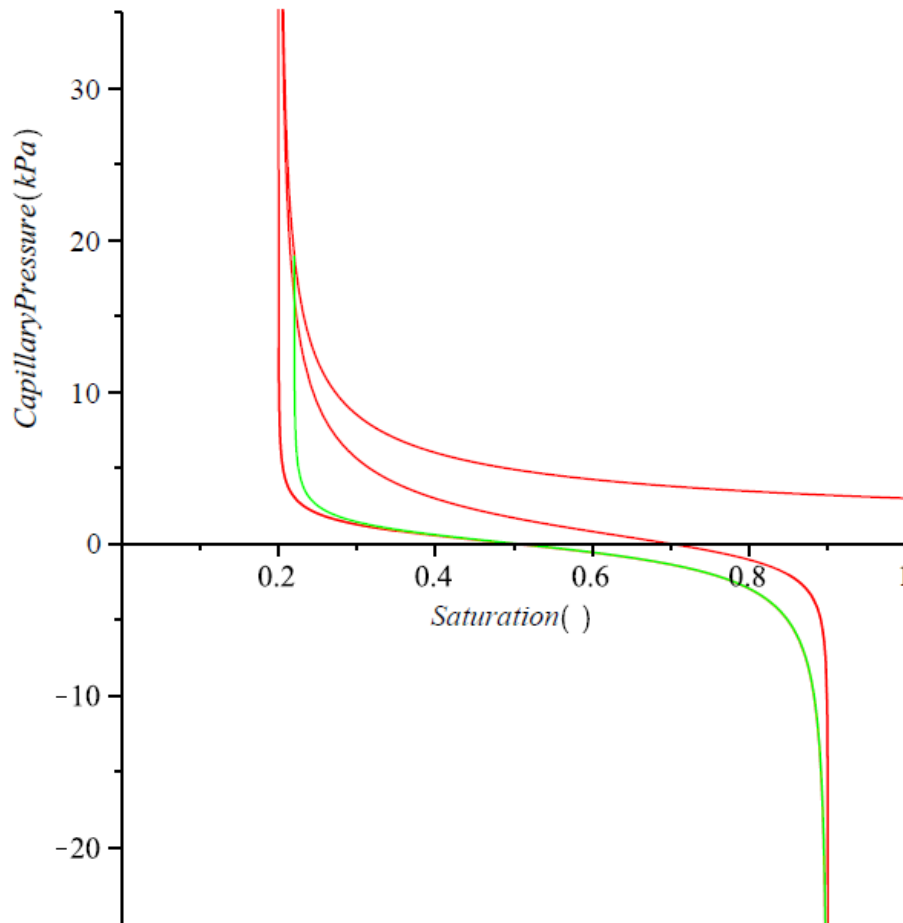
```
> fpcir1:=plot(Pcim[1],Srev[1]..0.99,-25..10,numpoints=300,color=
  green,labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=
  1,labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcir1);
```


2.Reversal

the secound reversal starts at the point Srev[2]. the secound reversal is a drainage cuvre starting on the imbibition curve from the first reversal and ending on the primary drainage curve (PcD1), the drainage curve has to scann back to to Srev[1] to close the loop.

First we have to assume that Sw_min2=Sw_min1 to start the process, as we have tow unkown this time, Sw_min2 and So_min2. We have 2 equations which we have to flip-flop until they converge.

epsw,epso,b,a are varibales which help to store results to test the loop on convergence

The two equations to be solved for are:

Pcim[1](Srev[2])=Pcdr[2](Srev[2])

Pcim[1](Srev[1])=Pcdr[2](Srev[1])

```
> Srev[2]:=0.8:
> Sw_min2[1]:=Sw_min1[1]:
> epsw[1]:=2:
  epso[1]:=2:
  b[0]:=1:
  a[0]:=1:
  for i from 1 to 10 do
```

```
    S_nw:=(S-Sw_min2[i])/(1-Sw_min2[i]):
    S_no:= (1-S-So_min2[i])/(1-So_min2[i]):
    Pcdr[2]:= cwd/S_nw^awd+cod/S_no^aod:
    Pcdr[2]:= unapply(Pcdr[2],S):
    So_min2[i]:=solve(Pcim[1](Srev[2])=Pcdr[2](Srev[2]),So_min2[i]):
    a[i]:=So_min2[i]:
    S_nw:= (S-Sw_min2[i+1])/(1-Sw_min2[i+1]):
    S_no:= (1-S-So_min2[i])/(1-So_min2[i]):
    Pcdr[2]:= cwd/S_nw^awd+cod/S_no^aod:
    Pcdr[2]:= unapply(Pcdr[2],S):
    Sw_min2[i+1]:= solve(Pcim[1](Srev[1])=Pcdr[2](Srev[1]),Sw_min2
    [i+1]):
    b[i]:=Sw_min2[i+1]:
    epso[i]:=abs(a[i]-a[i-1]):
    epsw[i]:=abs(b[i]-b[i-1]):
    eps[i]:=epsw[i]+epso[i]:
    print(eps[i]);
    if (eps[i]<0.002)
    then
    print(i);
    i:=11
    fi:
    od:
```
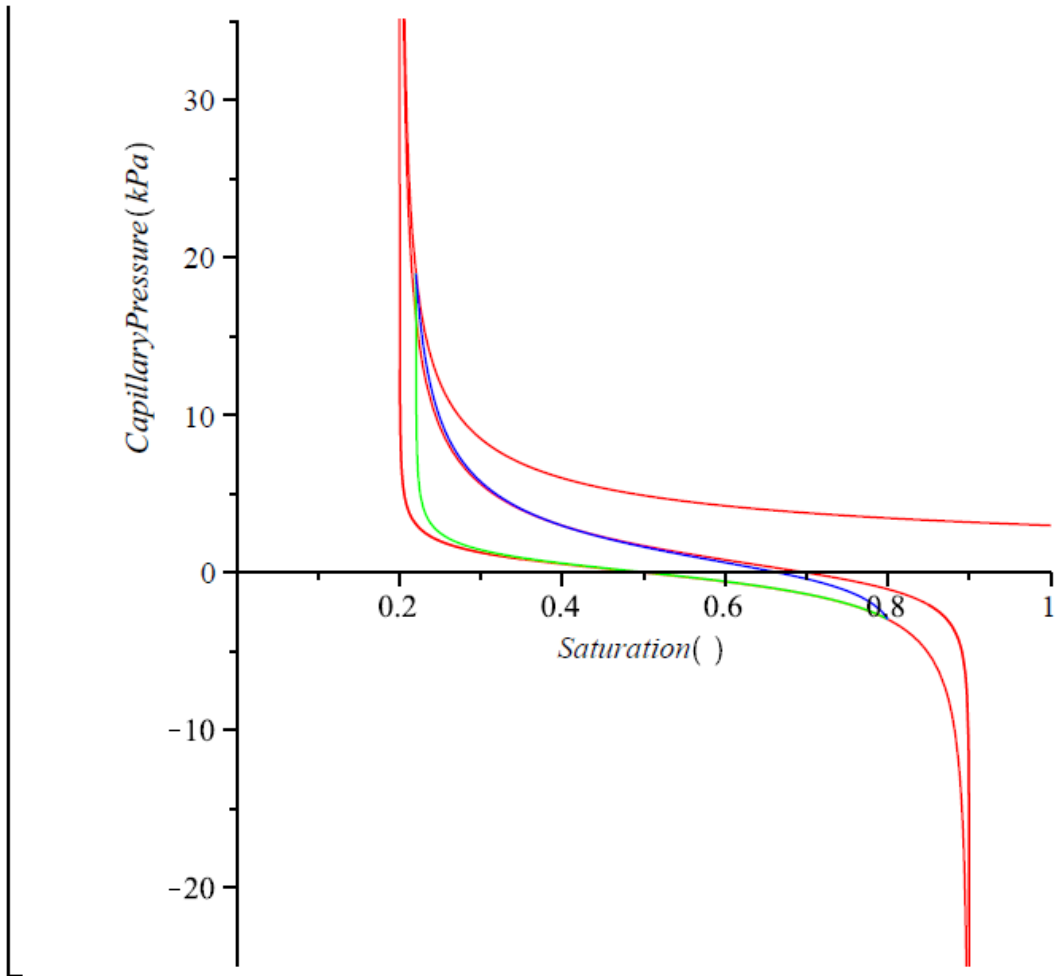
$$1.617240443$$
$$0.0001604736$$
$$2 \tag{1}$$

```
> Sw_min2[3]:
> fpcdr[2]:=plot(Pcdr[2],Srev[1]..Srev[2], color=blue,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
> fpcim[1]:=plot(Pcim[1],Srev[1]..Srev[2], color=green,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcim[1],fpcdr[2]);
```

3. Reversal

The third reversal starts on the Pcdr[2] curve before the Srev[1] point is reached and is an imbibition curve. The imbibiton curve starts at Srev[3] .

The two equations to be solved for are:

Pcim[3](Srev[2])=Pcdr[2](Srev[2])
Pcim[3](Srev[3])=Pcdr[2](Srev[3])

```
> Srev[3]:=0.28:
> Sw_min3[1]:=Sw_min2[3]:
> epsw[1]:=2:
  epso[1]:=2:
  b[0]:=1:
  a[0]:=1:
  for i from 1 to 10 do
  S_nw:=(S-Sw_min3[i])/(1-Sw_min3[i]):
  S_no:= (1-S-So_min3[i])/(1-So_min3[i]):
  Pcim[3]:= cwi/S_nw^awi+coi/S_no^aoi:
  Pcim[3]:= unapply(Pcim[3],S):
  So_min3[i]:=solve(Pcim[3](Srev[2])=Pcdr[2](Srev[2]),So_min3[i]):
  a[i]:=So_min3[i]:
  S_nw:= (S-Sw_min3[i+1])/(1-Sw_min3[i+1]):
  S_no:= (1-S-So_min3[i])/(1-So_min3[i]):
```

```
Pcim[3] := cwi/S_nw^awi+coi/S_no^aoi:
Pcim[3] := unapply(Pcim[3],S):
Sw_min3[i+1] := solve(Pcim[3](Srev[3])=Pcdr[2](Srev[3]),Sw_min3
[i+1]):
b[i]:=Sw_min3[i+1]:
epso[i]:=abs(a[i]-a[i-1]):
epsw[i]:=abs(b[i]-b[i-1]):
eps[i]:=epsw[i]+epso[i]:
print(eps[i]);
if (eps[i]<0.002)
then
print(i);
i:=11;
fi:
od:
```
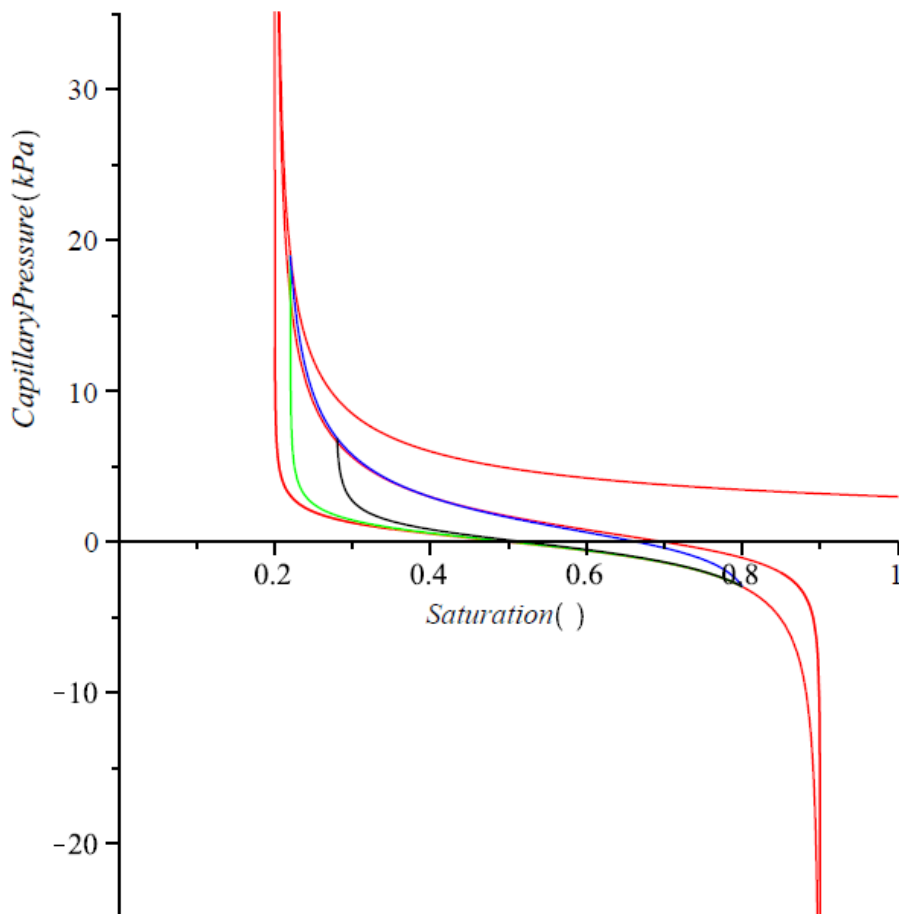
$$1.622294593$$
$$0.00082583161$$
$$2 \qquad\qquad\qquad\qquad (2)$$

```
> Sw_min3[3]:
> fpcim[3]:=plot(Pcim[3],Srev[3]..Srev[2], color=black,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcim[1],fpcdr[2],fpcim[3]);
```

4.Reversal
Darainage curve, Starts on the Pcim[3] curve at Srev[4].
The two equations to be solved for are:
Pcim[3](Srev[4])=Pcdr[4](Srev[4])
Pcim[3](Srev[3])=Pcdr[4](Srev[3])

```
> Srev[4]:=0.6:
> Sw_min4[1]:=Sw_min3[3]:
> epsw[1]:=2:
  epso[1]:=2:
  b[0]:=1:
  a[0]:=1:
  for i from 1 to 10 do
  S_nw:=(S-Sw_min4[i])/(1-Sw_min4[i]):
  S_no:= (1-S-So_min4[i])/(1-So_min4[i]):
  Pcdr[4]:= cwd/S_nw^awd+cod/S_no^aod:
  Pcdr[4]:= unapply(Pcdr[4],S):
  So_min4[i]:=solve(Pcim[3](Srev[4])=Pcdr[4](Srev[4])):
  a[i]:=So_min4[i]:
  S_nw:= (S-Sw_min4[i+1])/(1-Sw_min4[i+1]):
  S_no:= (1-S-So_min4[i])/(1-So_min4[i]):
  Pcdr[4]:= cwd/S_nw^awd+cod/S_no^aod:
  Pcdr[4]:= unapply(Pcdr[4],S):
  Sw_min4[i+1]:= solve(Pcim[3](Srev[3])=Pcdr[4](Srev[3])):
  b[i]:=Sw_min4[i+1]:
  epso[i]:=abs(a[i]-a[i-1]):
  epsw[i]:=abs(b[i]-b[i-1]):
  eps[i]:=epsw[i]+epso[i]:
  print(eps[i]);
  if (eps[i]<0.002)
  then
  print(i);
  i:=11 fi:
  od:
```

$$1.441088072$$
$$0.0111632787$$
$$0.0000232858$$
$$3 \tag{3}$$

```
> Sw_min4[4]:
> fpcdr[4]:=plot(Pcdr[4],Srev[3]..Srev[4], color=red, labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
  fpcim[3]:=plot(Pcim[3],Srev[3]..Srev[4], color=black,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcim[1],fpcdr[2],fpcim[3],
  fpcdr[4]);
```
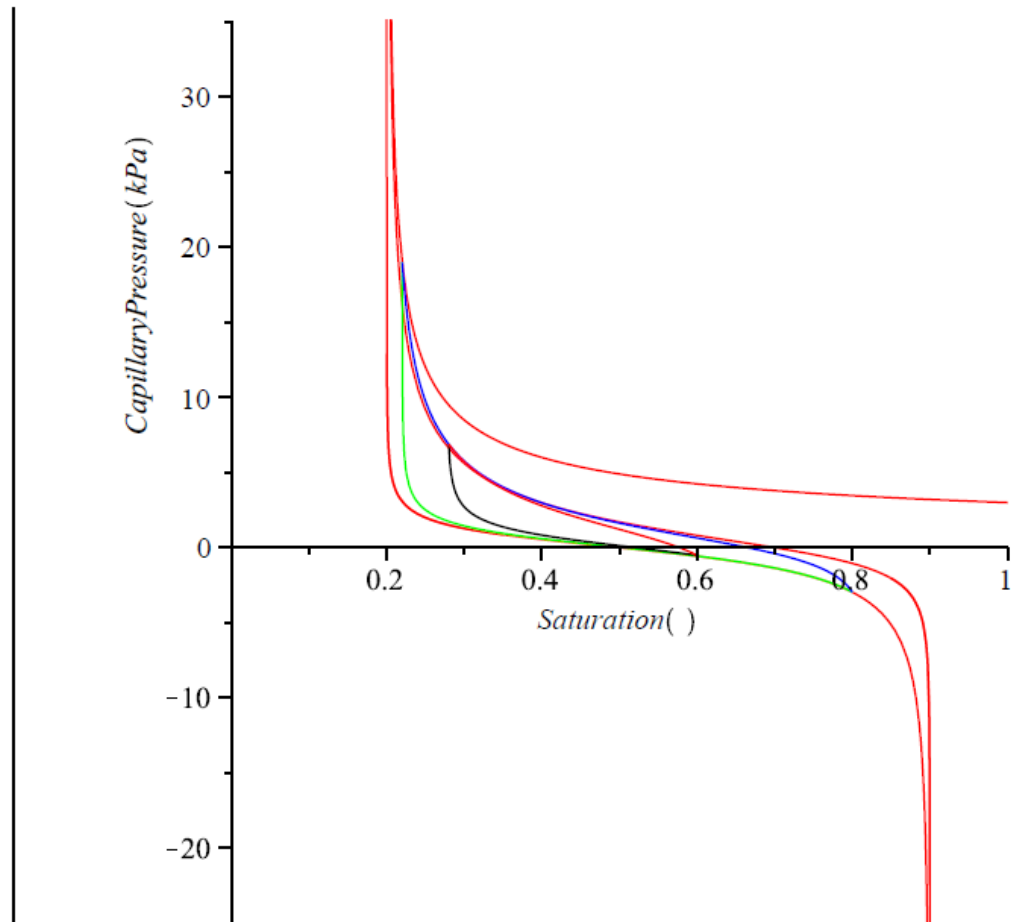
```
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcim[1],fpcdr[2],fpcim[3],
  fpcdr[4], view=[0.25..0.65,-10..15]):
```

Reversal 5

The fifth reversal starts on the Pcdr[4] curve before the Srev[3] point is reached and is an imbibition curve. The imbibiton curve starts at Srev[3] .

The two equations to be solved for are:

Pcim[5](Srev[4])=Pcdr[4](Srev[4])

Pcim[5](Srev[5])=Pcdr[4](Srev[5])

```
> Srev[5]:=0.35:
> Sw_min5[1]:=Sw_min4[4]:
> epsw[1]:=2:
  epso[1]:=2:
  b[0]:=1:
  a[0]:=1:
  for i from 1 to 10 do
  S_nw:=(S-Sw_min5[i])/(1-Sw_min5[i]):
  S_no:= (1-S-So_min5[i])/(1-So_min5[i]):
  Pcim[5]:= cwi/S_nw^awi+coi/S_no^aoi:
  Pcim[5]:= unapply(Pcim[5],S):
  So_min5[i]:=solve(Pcim[5](Srev[4])=Pcdr[4](Srev[4]),So_min5[i]):
  a[i]:=So_min5[i]:
  S_nw:= (S-Sw_min5[i+1])/(1-Sw_min5[i+1]):
```

```
S_no:= (1-S-So_min5[i])/(1-So_min5[i]):
Pcim[5]:= cwi/S_nw^awi+coi/S_no^aoi:
Pcim[5]:= unapply(Pcim[5],S):
Sw_min5[i+1]:= solve(Pcim[5](Srev[5])=Pcdr[4](Srev[5]),Sw_min5
[i+1]):
b[i]:=Sw_min5[i+1]:
epso[i]:=abs(a[i]-a[i-1]):
epsw[i]:=abs(b[i]-b[i-1]):
eps[i]:=epsw[i]+epso[i]:
print(eps[i]);
if (eps[i]<0.002)
then
print(i);
i:=11 fi:
od:
```

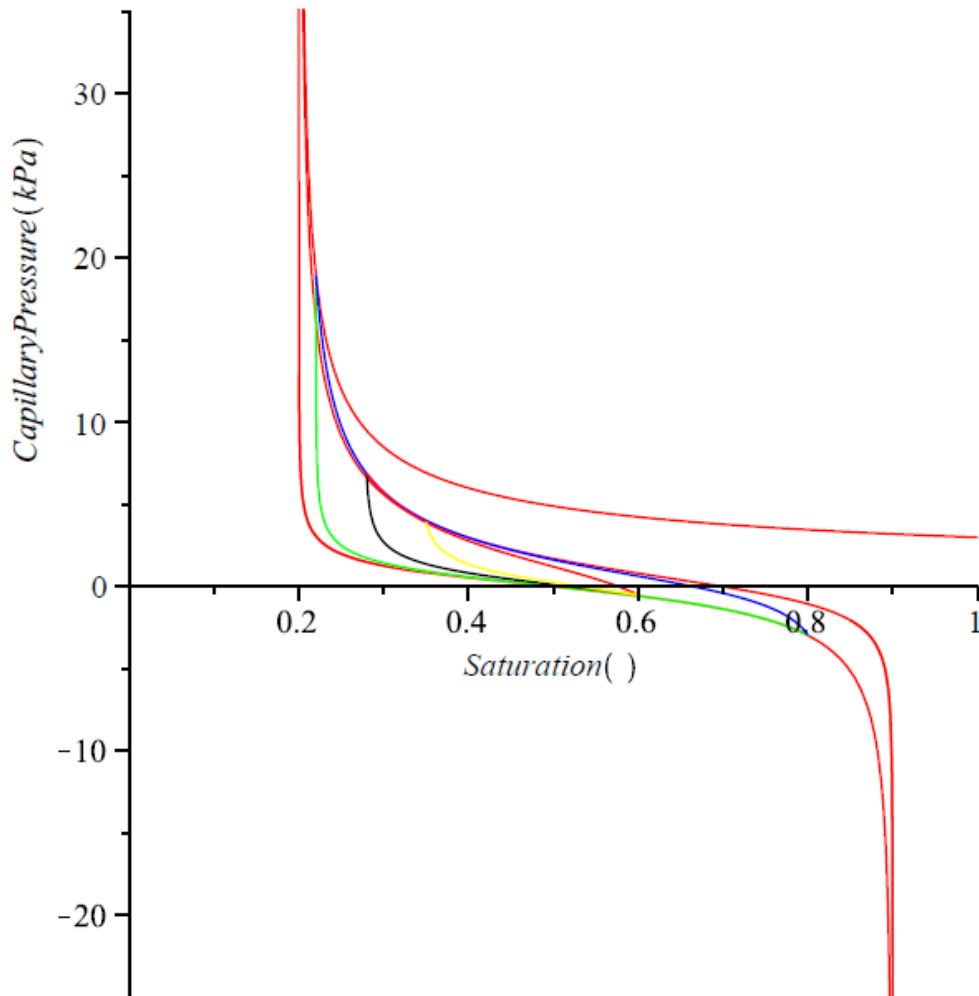$$1.578037657$$
$$0.04369505698$$
$$0.0000685697$$
$$3 \tag{4}$$

```
> fpcim[5]:=plot(Pcim[5],Srev[5]..Srev[4], color=yellow,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcim[1],fpcdr[2],fpcim[3],
  fpcdr[4],fpcim[5]);
```

Reversal 6
Darainage curve, Starts on the Pcim[5] curve at Srev[6]
The two equations to be solved for are:
Pcim[5](Srev[6])=Pcdr[6](Srev[6])
Pcim[5](Srev[5])=Pcdr[6](Srev[5])

```
> Srev[6]:=0.52:
> Sw_min6[1]:=Sw_min5[4]:
> epsw[1]:=2:
  epso[1]:=2:
  b[0]:=1:
  a[0]:=1:
  for i from 1 to 10 do
  S_nw:=(S-Sw_min6[i])/(1-Sw_min6[i]):
  S_no:= (1-S-So_min6[i])/(1-So_min6[i]):
  Pcdr[6]:= cwd/S_nw^awd+cod/S_no^aod:
  Pcdr[6]:= unapply(Pcdr[6],S):
  So_min6[i]:=solve(Pcim[5](Srev[6])=Pcdr[6](Srev[6])):
  a[i]:=So_min4[i]:
  S_nw:= (S-Sw_min6[i+1])/(1-Sw_min6[i+1]):
  S_no:= (1-S-So_min6[i])/(1-So_min6[i]):
  Pcdr[6]:= cwd/S_nw^awd+cod/S_no^aod:
  Pcdr[6]:= unapply(Pcdr[6],S):
  Sw_min6[i+1]:= solve(Pcim[5](Srev[5])=Pcdr[6](Srev[5])):
  b[i]:=Sw_min6[i+1]:
  epso[i]:=abs(a[i]-a[i-1]):
  epsw[i]:=abs(b[i]-b[i-1]):
  eps[i]:=epsw[i]+epso[i]:
  print(eps[i]);
  if (eps[i]<0.002)
  then
  print(i);
  i:=11 fi:
  od:
```

$$1.430863836$$
$$0.0142699025$$
$$0.0001045167$$
$$3$$

(5)

```
> fpcdr[6]:=plot(Pcdr[6],Srev[5]..Srev[6], color=orange,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
  fpcim[5]:=plot(Pcim[5],Srev[5]..Srev[6], color=yellow,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcim[1],fpcdr[2],fpcim[3],
  fpcdr[4],fpcim[5],fpcdr[6]);
```
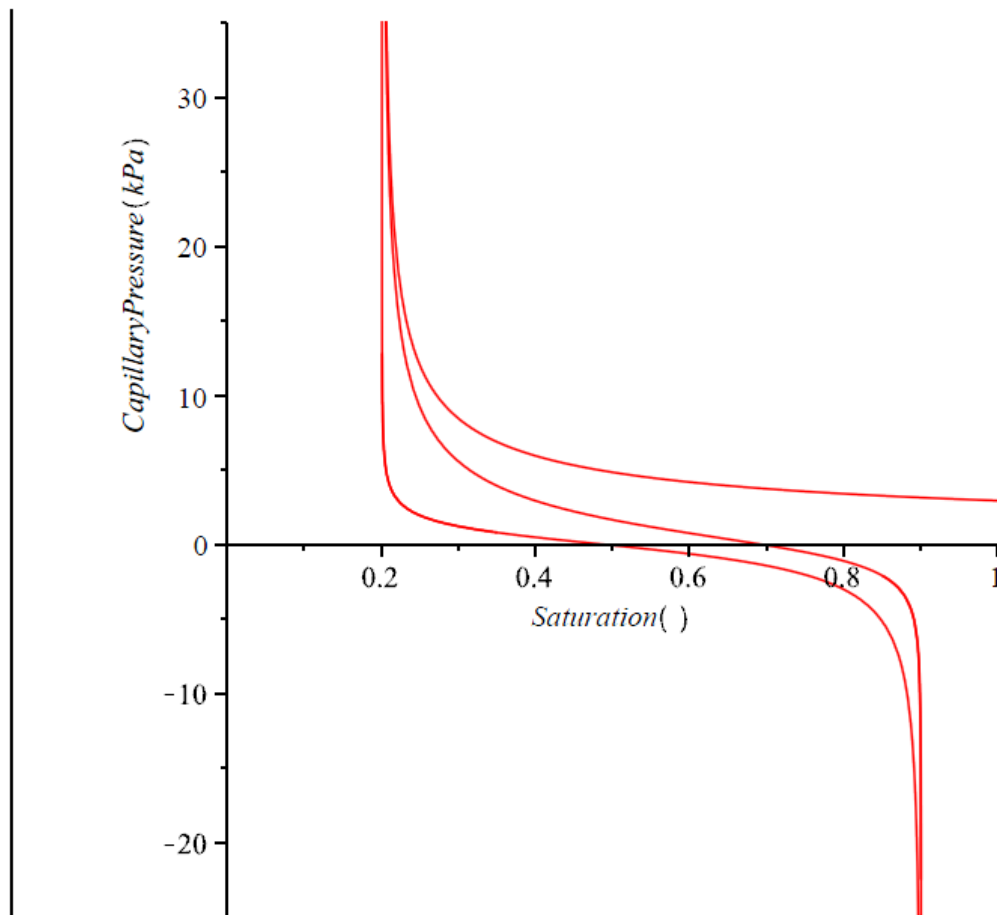
```
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcim[1],fpcdr[2],fpcim[3],
  fpcdr[4],fpcim[5],fpcdr[6], view=[0.18..0.82,-10..20]):
>
```
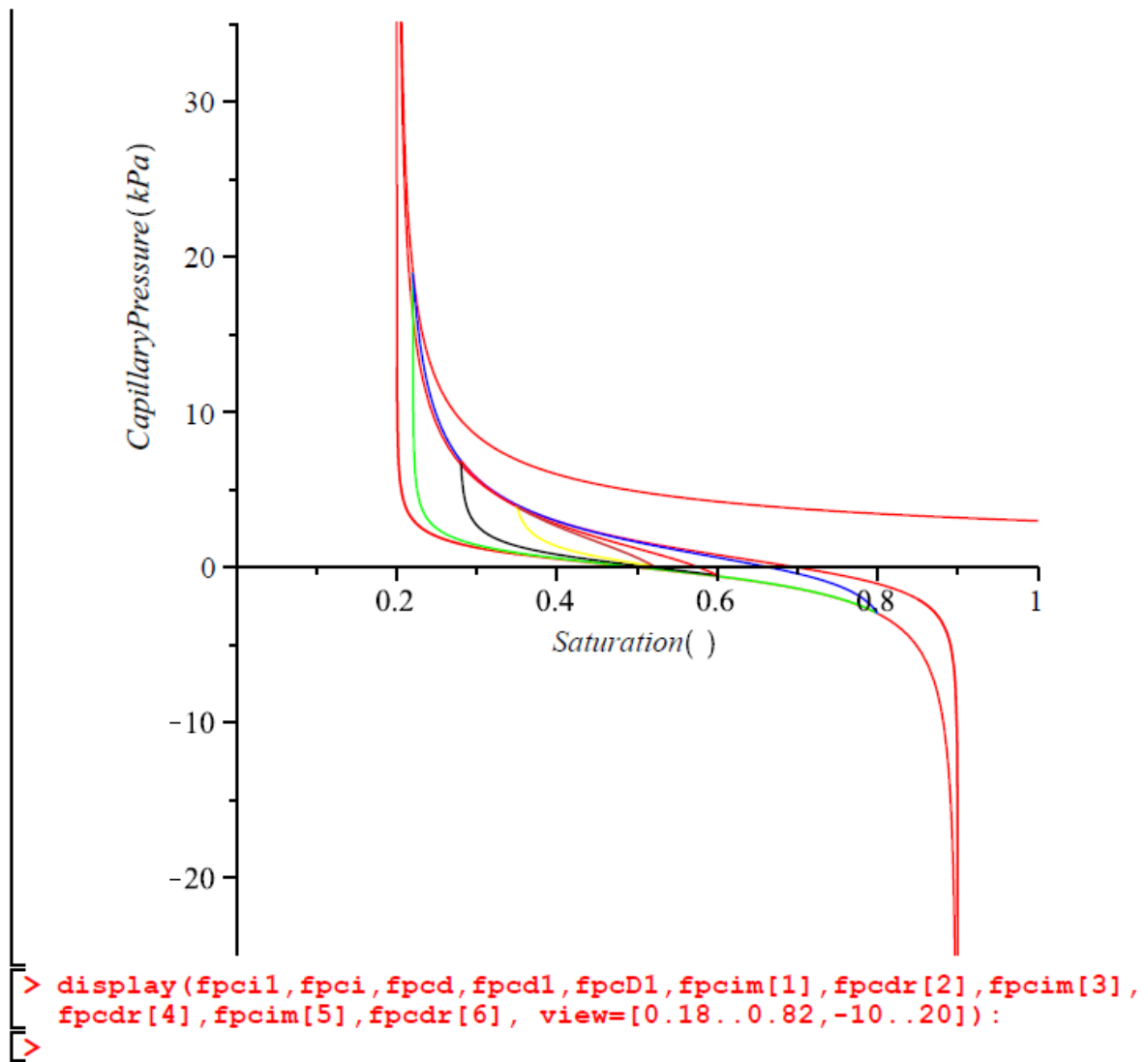
A.2   Example 2

```
> restart:
```

Example 2

```
> with(plots):
> with(RealDomain):
```

General Definitions for drainiage and imbibition capillary pressure curves

```
> Swn:=(S-Swr)/(1-Swr):
  Son:=(1-S-Sor)/(1-Sor):
> pcpi:= cwi/Swn^awi:   pcmi:= coi/Son^aoi:
  pcpd:= cwd/Swn^awd:   pcmd:= cod/Son^aod:
> Pci:= unapply(pcpi+pcmi,S):
  Pcd:= unapply(pcpd+pcmd,S):
  PcD1:= unapply(pcpd,S):
```

Swn ... normalized water saturation. Son ... normalized oil saturation
pcpi,pcpd ...c apillary pressrue positive part of imbibition/drainage
pcmi,pcmd ... capillary pressrue minus part of imbibition/drainage
Pci ... capillary pressure imbibtion. Pcd ... capillary pressure drainage
PcD1 ... capillary pressure of primary drainage
cwi,cwd ... entry pressure for water (i for imbibition entry pre and d for drainage entry pre)
coi,cod ... entry pressure for oil (i for imbibition entry pre and d for drainage entry pre)
1/a .. .poresize distribution (w...water,o...oil)

Determine coi and cod

```
> coi:=solve(Pci(S1)=0,coi):
  cod:=solve(Pcd(S2)=0,cod):
```

S1 and S2 is the crossover points between respectively primary imbibition and secondary drainage and
the "S-axis". Pc(S) is of course zero.

Lands Equation

```
> C:=1/Sor-1/(1-Swr):
```

C ... Land's trapping constant
Using Land's equation to determine asymptotes when imbibition starts from primary drainage curve .

Defining Constants

```
> awi:=0.25: aoi:=0.5: cwi:=2:
  awd:=0.5: aod:=0.25: cwd:=3:
  Sor:=0.1: Swr:=0.2:
  S1:=0.5: S2:=0.7:
```

Plot of primary drainage and imbibiton bounding loop

```
> fpci:= plot(Pci,(Swr-0.05)..(Swr+0.15),0..35,numpoints=
  500,labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
  fpci1:= plot(Pci,Swr..1,-25..25,numpoints=100,labels=[Saturation
  ( ),CapillaryPressure (kPa)],thickness=1,labeldirections=
  [horizontal,vertical]):
  fpcd:= plot(Pcd, Swr..1,-25..25,numpoints=100,labels=[Saturation
  ( ),CapillaryPressure (kPa)],thickness=1,labeldirections=
  [horizontal,vertical]):
  fpcd1:= plot(Pcd, (1-Sor-0.05)..(1-Sor+0.05),-25..25,numpoints=
  500,labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
  fpcD1:= plot(PcD1, 0..1,labels=[Saturation ( ),CapillaryPressure
  (kPa)],thickness=1,labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1);
```

The first 2 reversals have different datapoints, which was found out by trail and error. The other reversals (3 to 30) it was possible to see a realtionship and general input data was created.

Reversal

First 2 reversal

have different input values then the other reversals:

1. Reversal

```
> Srev[1]:=0.95:
> SorD[1]:=1/(C+(1/(1-Srev[1]))):
```

This is the residual oil saturation if the process (primary drainage) i reversed from S=Srev[1]. This is the lowest water saturation experienced.

Calulate the normalized saturations for the first reveral:

S_nw ... normalised water saturation

Sw_min1[1] ... asymptote for the positive branch of the imbibition curve

S_no ... normalised water saturation for the negative branch

SorD[1] ... asymptote for the negative branch

```
> S_nw[1]:=(S-Sw_min1[1])/(1-Sw_min1[1]):
> S_no[1]:=(1-S-SorD[1])/(1-SorD[1]):
> Pcim[1]:=cwi/S_nw[1]^awi+coi/S_no[1]^aoi:
  Pcim[1]:=unapply(Pcim[1],S):
> Sw_min1[1]:=solve(Pcim[1](Srev[1])=PcD1(Srev[1]),Sw_min1[1]):
```
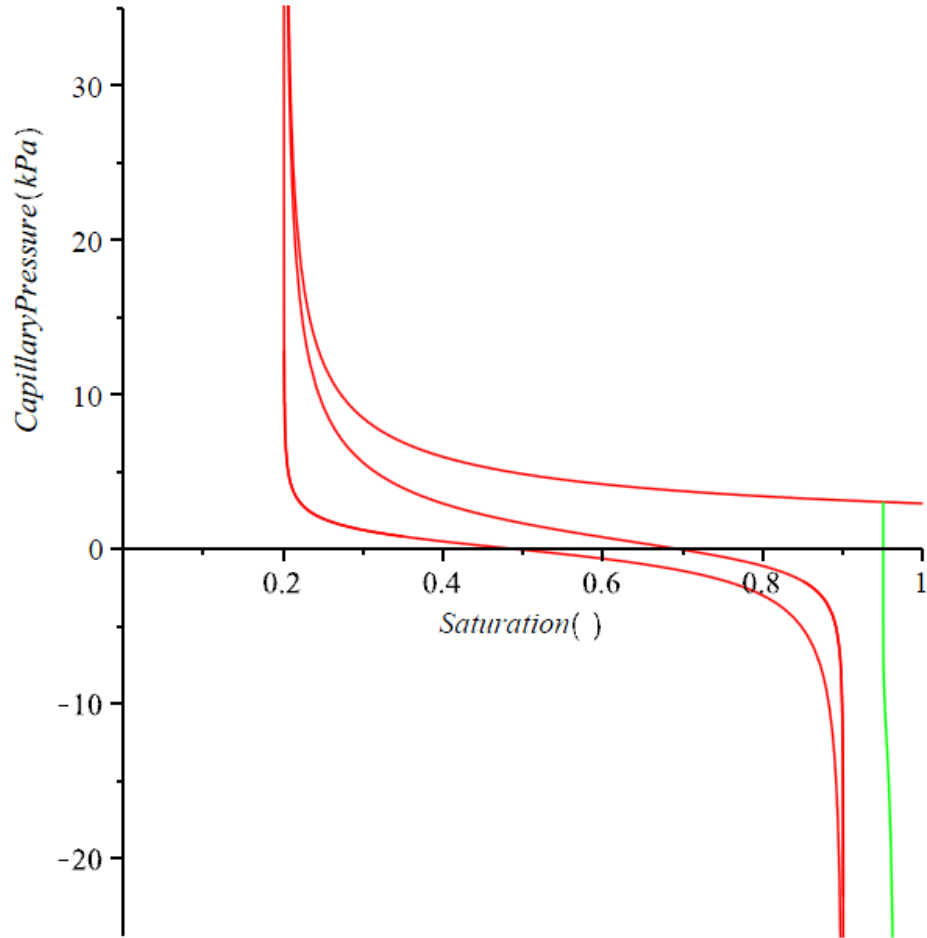
```
> fpcir1:=plot(Pcim[1],Srev[1]..0.99,-25..10,numpoints=300,color=
  green,labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=
  1,labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcir1);
```


2.Reversal
```
> Srev[2]:=0.96:
> Sw_min2[1]:=Sw_min1[1]:
> epsw[1]:=2:
  epso[1]:=2:
  b[0]:=1:
  a[0]:=1:
  for i from 1 to 10 do
  S_nw:=(S-Sw_min2[i])/(1-Sw_min2[i]):
  S_no:= (1-S-So_min2[i])/(1-So_min2[i]):
  Pcdr[2]:= cwd/S_nw^awd+cod/S_no^aod:
  Pcdr[2]:= unapply(Pcdr[2],S):
  So_min2[i]:=solve(Pcim[1](Srev[2])=Pcdr[2](Srev[2]),So_min2[i]):
  a[i]:=So_min2[i]:
  S_nw:= (S-Sw_min2[i+1])/(1-Sw_min2[i+1]):
  S_no:= (1-S-So_min2[i])/(1-So_min2[i]):
  Pcdr[2]:= cwd/S_nw^awd+cod/S_no^aod:
  Pcdr[2]:= unapply(Pcdr[2],S):
```

```
  Sw_min2[i+1]:= solve(Pcim[1](Srev[1])=Pcdr[2](Srev[1]),Sw_min2
  [i+1]):
  b[i]:=Sw_min2[i+1]:
  epso[i]:=abs(a[i]-a[i-1]):
  epsw[i]:=abs(b[i]-b[i-1]):
  eps[i]:=epsw[i]+epso[i]:
  #print(eps[i]);
  if (eps[i]<0.002)
  then
  #print(i);
  i:=11
  fi:
  od:
> fpcdr2:=plot(Pcdr[2],Srev[1]..Srev[2], color=blue,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
  fpcir1:=plot(Pcim[1],Srev[1]..Srev[2],color=green,labels=
  [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcir1,fpcdr2);
```
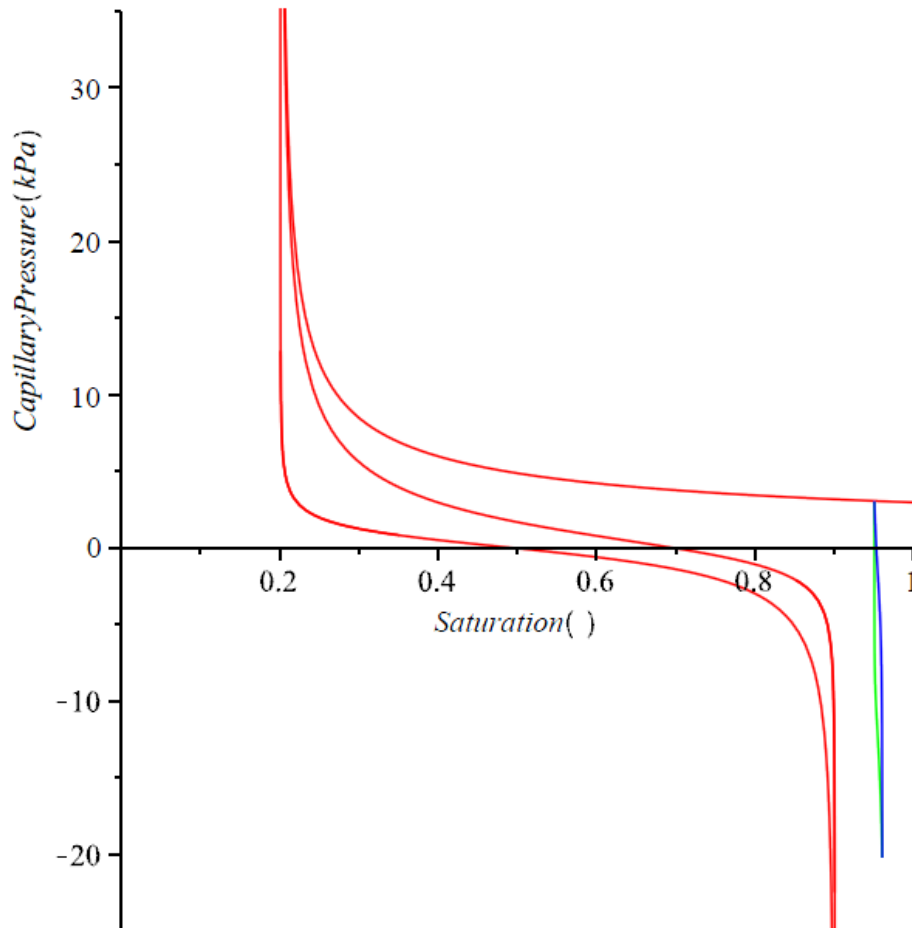

Datapoints

```
> k:=0.1:
```

```
> for i from 3 to 38 do
  if type(i,odd) then
  Srev[i]:=1-k;
  k:=k+0.05:
  else
  Srev[i]:= Srev[i-3]-0.01:
  fi:
  od:
> #for i from 3 to 38 do
  #print(Srev = Srev[i]):
  #od:
```
From 3th to the 30th reversal
```
> for j from 3 to 30 do
  #print("j" = j);

  #print(Srev = Srev[j]);

  if type(j,odd) then

  Srev[j]:
  SorD[j]:=1/(C+(1/(1-Srev[j]))):
  S_nw[j]:=(S-Sw_mini[j])/(1-Sw_mini[j]):
  S_no[j]:=(1-S-SorD[j])/(1-SorD[j]):
  Pcim[j]:=cwi/S_nw[j]^awi+coi/S_no[j]^aoi:
  Pcim[j]:=unapply(Pcim[j],S);
  Sw_mini[j]:=solve(Pcim[j](Srev[j])=PcD1(Srev[j]),Sw_mini[j]);
  #print(Sw_mini = Sw_mini[j]);
  #print("-----------------------------------");
  fpcir[j]:=plot(Pcim[j],Srev[j]..0.99,-25..10,numpoints=300,color=
  blue,labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):

  else

  #print(Srev = Srev[j]);
  epsw[1]:=2:
  epso[1]:=2:
  b[0]:=1:
  a[0]:=1:
  Sw_min[j,1]:=Sw_mini[j-1];

  for i from 1 to 10 do
  S_nw:=(S-Sw_min[j,i])/(1-Sw_min[j,i]);
  S_no:=(1-S-So_min[j,i])/(1-So_min[j,i]);
  Pcdr[j]:= cwd/S_nw^awd+cod/S_no^aod;
  Pcdr[j]:= unapply(Pcdr[j],S);
  So_min[j,i]:=solve(Pcim[j-1](Srev[j])=Pcdr[j](Srev[j]),So_min[j,
  i]);
  a[i]:=So_min[j,i];
  S_nw:= (S-Sw_min[j,i+1])/(1-Sw_min[j,i+1]);
  S_no:= (1-S-So_min[j,i])/(1-So_min[j,i]);
  Pcdr[j]:= cwd/S_nw^awd+cod/S_no^aod;
  Pcdr[j]:= unapply(Pcdr[j],S);
  Sw_min[j,i+1]:= solve(Pcim[j-1](Srev[j-1])=Pcdr[j](Srev[j-1]),
  Sw_min[j,i+1]);
  b[i]:=Sw_min[j,i+1];
```

```
epso[i]:=abs(a[i]-a[i-1]);
epsw[i]:=abs(b[i]-b[i-1]);
eps[i]:=epsw[i]+epso[i];
#print(eps = eps[i]);

if (eps[i]<0.002) then
#print("number of iterations:",i);
Sw_min[j]:=Sw_min[j,i];
So_min[j]:=So_min[j,i];
i:=11;
fi:

fpcdr[j]:=plot(Pcdr[j],Srev[j-1]..Srev[j], color=green,labels=
[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
labeldirections=[horizontal,vertical]):
fpcir[j-1]:=plot(Pcim[j-1],Srev[j-1]..Srev[j], color=blue,labels=
[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
labeldirections=[horizontal,vertical]):
od;

#print(Sw_min = Sw_min[j]);
#print(So_min = So_min[j]);
#print("---------------------------------");
fi:
od;
> display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcir1,fpcdr2,fpcir[3],fpcdr
[4],fpcir[5],fpcdr[6],fpcir[7],fpcdr[8],fpcir[9],fpcdr[10],fpcir
[11],fpcdr[12],fpcir[13],fpcdr[14],fpcir[15],fpcdr[16],fpcir[17],
fpcdr[18],fpcir[19],fpcdr[20],fpcir[21],fpcdr[22],fpcir[23],fpcdr
[24],fpcir[25],fpcdr[26],fpcir[27],fpcdr[28],fpcir[29],fpcdr[30])
;
```
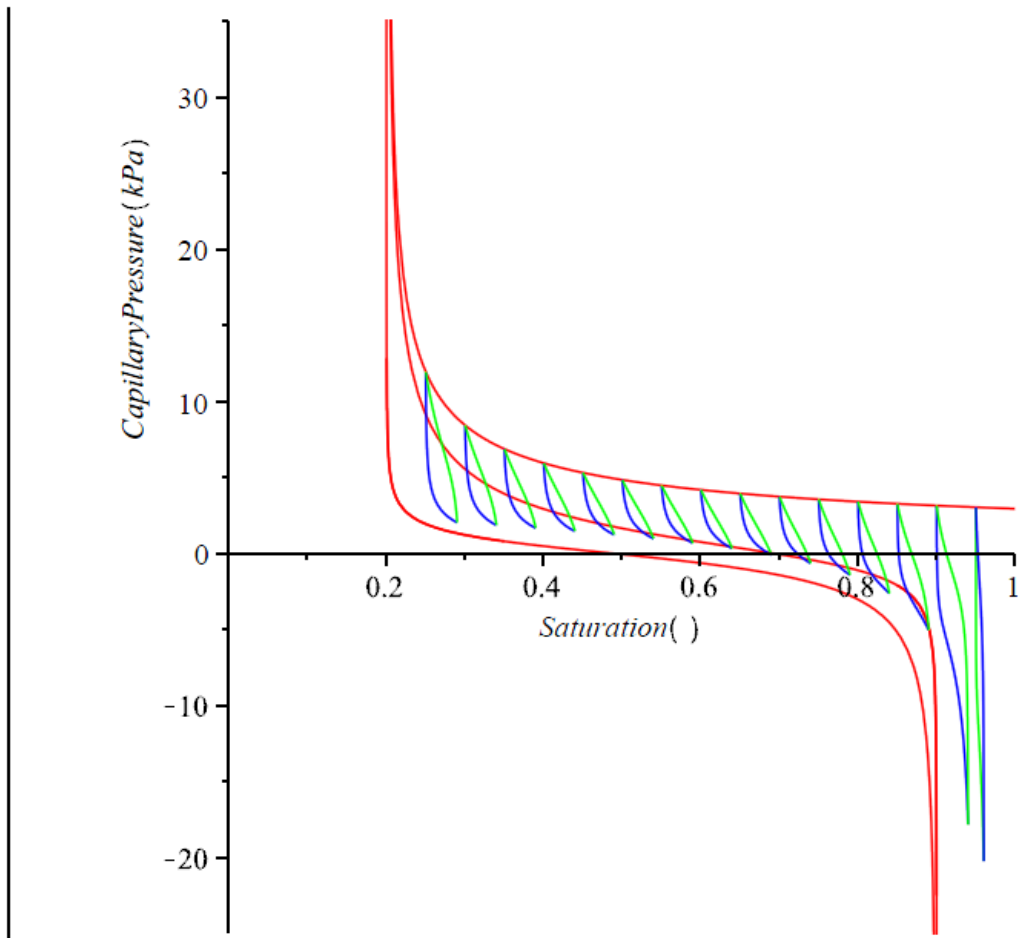
Last possible reversal:

```
> Srev[31]:=0.21:
  SorD[31]:=1/(C+(1/(1-Srev[31]))):
  S_nw[31]:=(S-Sw_mini[31])/(1-Sw_mini[31]):
  S_no[31]:=(1-S-SorD[31])/(1-SorD[31]):
  Pcim[31]:=cwi/S_nw[31]^awi+coi/S_no[31]^aoi:
  Pcim[31]:=unapply(Pcim[31],S):
  Sw_mini[31]:=solve(Pcim[31](Srev[31])=PcD1(Srev[31]),Sw_mini[31])
  :
  #print(Sw_mini = Sw_mini[31]):
  #print("---------------------------------");
  fpcir[31]:=plot(Pcim[31],Srev[31]..0.99,-25..10,numpoints=300,
  color=blue):
> Srev[32]:=0.24:
> Sw_min[32,1]:=Sw_mini[31]:
> epsw[1]:=2:
  epso[1]:=2:
  b[0]:=1:
  a[0]:=1:
  for i from 1 to 10 do
  S_nw:=(S-Sw_min[32,i])/(1-Sw_min[32,i]):
  S_no:= (1-S-So_min[32,i])/(1-So_min[32,i]):
```

```
   Pcdr[32]:= cwd/S_nw^awd+cod/S_no^aod:
   Pcdr[32]:= unapply(Pcdr[32],S):
   So_min[32,i]:=solve(Pcim[31](Srev[32])=Pcdr[32](Srev[32]),So_min
   [32,i]):
   a[i]:=So_min[32,i]:
   S_nw:= (S-Sw_min[32,i+1])/(1-Sw_min[32,i+1]):
   S_no:= (1-S-So_min[32,i])/(1-So_min[32,i]):
   Pcdr[32]:= cwd/S_nw^awd+cod/S_no^aod:
   Pcdr[32]:= unapply(Pcdr[32],S):
   Sw_min[32,i+1]:= solve(Pcim[31](Srev[31])=Pcdr[32](Srev[31]),
   Sw_min[32,i+1]):
   b[i]:=Sw_min[32,i+1]:
   epso[i]:=abs(a[i]-a[i-1]):
   epsw[i]:=abs(b[i]-b[i-1]):
   eps[i]:=epsw[i]+epso[i]:
   #print(eps[i]);
   if (eps[i]<0.002)
   then
   #print(i);
   i:=11
   fi:
   Sw_min[32]:=Sw_min[32,i];
   So_min[32]:=So_min[32,i];
   #print(Sw_min = Sw_min[32]);
   #print(So_min = So_min[32]);
   od:
>  fpcdr[32]:=plot(Pcdr[32],Srev[31]..Srev[32], color=green,labels=
   [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
   labeldirections=[horizontal,vertical]):
   fpcir[31]:=plot(Pcim[31],Srev[31]..Srev[32], color=blue,labels=
   [Saturation ( ),CapillaryPressure (kPa)],thickness=1,
   labeldirections=[horizontal,vertical]):
>  display(fpci1,fpci,fpcd,fpcd1,fpcD1,fpcir1,fpcdr2,fpcir[3],fpcdr
   [4],fpcir[5],fpcdr[6],fpcir[7],fpcdr[8],fpcir[9],fpcdr[10],fpcir
   [11],fpcdr[12],fpcir[13],fpcdr[14],fpcir[15],fpcdr[16],fpcir[17],
   fpcdr[18],fpcir[19],fpcdr[20],fpcir[21],fpcdr[22],fpcir[23],fpcdr
   [24],fpcir[25],fpcdr[26],fpcir[27],fpcdr[28],fpcir[29],fpcdr[30],
   fpcir[31],fpcdr[32]);
```

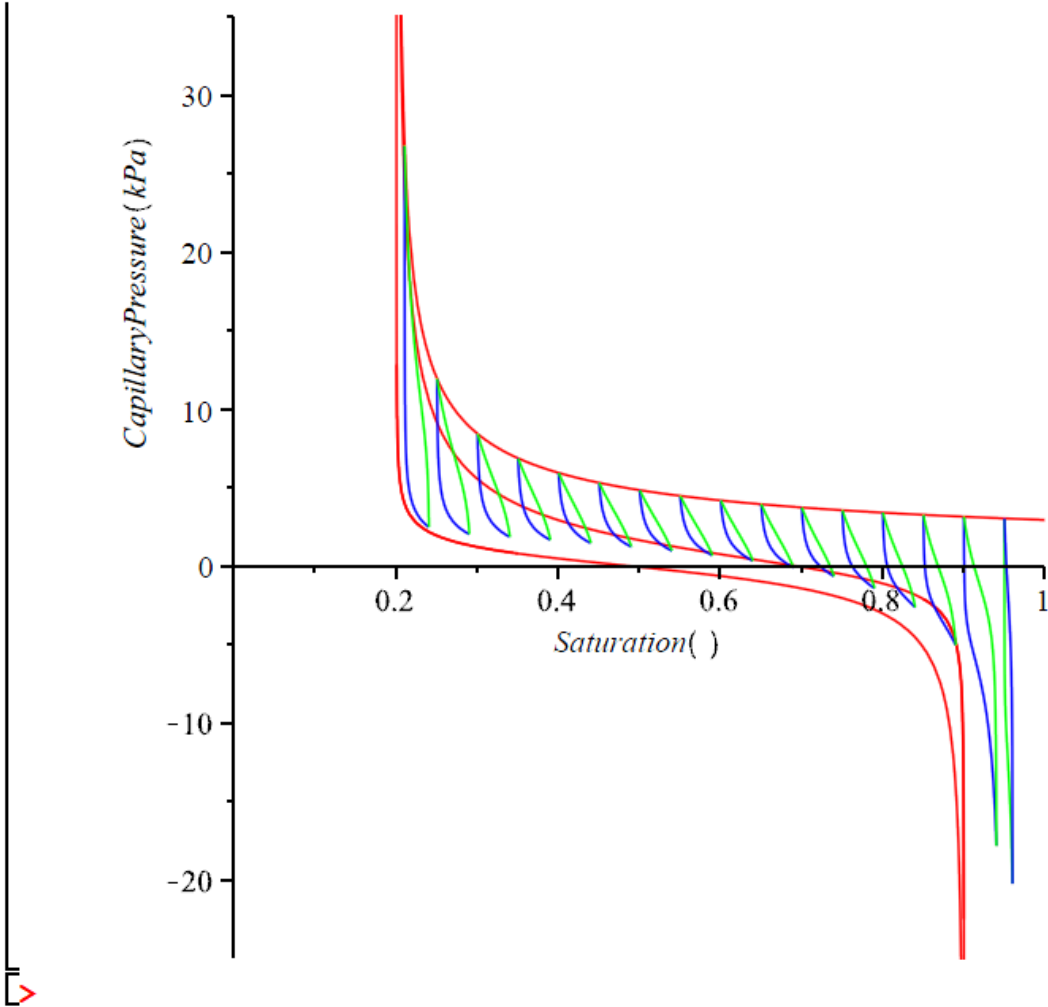## A.3 Centrifuge Mode

```
> restart:
```

Centrifuge Experiment

```
> with(RealDomain):
  with(LinearAlgebra):
  with(ExcelTools):
> with(plots):
```

General Definitions for drainiage and imbibition capillary pressure curves

```
> Swn:=(S-Swr)/(1-Swr):
  Son:=(1-S-Sor)/(1-Sor):
> pcpi:= cwi/Swn^awi:   pcmi:= coi/Son^aoi:
  pcpd:= cwd/Swn^awd:   pcmd:= cod/Son^aod:
> Pci:= unapply(pcpi+pcmi,S):
  Pcd:= unapply(pcpd+pcmd,S):
  PcD1:= unapply(pcpd,S):
```

Swn ... normalized water saturation, Son ... normalized oil saturation
pcpi,pcpd ...c apillary pressrue positive part of imbibition/drainage
pcmi,pcmd ... capillary pressrue minus part of imbibition/drainage
Pci ... capillary pressure imbibtion, Pcd ... capillary pressure drainage
PcD1 ... capillary pressure of primary drainage
cwi,cwd ... entry pressure for water (i for imbibition entry pre and d for drainage entry pre)
coi,cod ... entry pressure for oil (i for imbibition entry pre and d for drainage entry pre)
1/a .. .poresize distribution (w...water,o...oil)

Determine coi and cod

```
> coi:=solve(Pci(S1)=0,coi):
  cod:=solve(Pcd(S2)=0,cod):
```

S1 and S2 is the crossover points between respectively primary imbibition and secondary drainage and the "S-axis". Pc(S) is of course zero.

Lands Equation

```
> C:=1/Sor-1/(1-Swr):
```

C ... Land's trapping constant
Using Land's equation to determine asymptotes when imbibition starts from primary drainage curve .

Defining Constants

```
> awi:=0.25: aoi:=0.5: cwi:=10:
  awd:=0.5: aod:=0.25: cwd:=7:
  Sor:=0.1: Swr:=0.21:
  S1:=0.5: S2:=0.7:
  coi:cod:
```

Plot of primary drainage and imbibiton bounding loop

```
> fpci:= plot(Pci,(Swr-0.05)..(Swr+0.15),0..35,numpoints=
  500,labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
  fpci1:= plot(Pci,Swr..1,-25..25,numpoints=100,labels=[Saturation
  ( ),CapillaryPressure (kPa)],thickness=1,labeldirections=
  [horizontal,vertical]):
  fpcd:= plot(Pcd, Swr..1,-25..25,numpoints=100,labels=[Saturation
  ( ),CapillaryPressure (kPa)],thickness=1,labeldirections=
  [horizontal,vertical]):
  fpcd1:= plot(Pcd, (1-Sor-0.05)..(1-Sor+0.05),-25..25,numpoints=
  500,labels=[Saturation ( ),CapillaryPressure (kPa)],thickness=1,
  labeldirections=[horizontal,vertical]):
```

```
  fpcD1:= plot(PcD1, 0..1,labels=[Saturation ( ),CapillaryPressure
  (kPa)],thickness=1,labeldirections=[horizontal,vertical]):
> display(fpci1,fpci,fpcd,fpcd1,fpcD1);
```


Staring the centrifuge procedure

Input values, the values for r2 (a little different as in my case r2 should be the FWL and not the end of the core), r1 and dealta_rho are taken from the Hermansen et al (1991). Using r2 and r1 the different loctions (r) are evaluated, there should be as many as passible saturation reversals therefore the 54 points are chosen.

Defining parameters:

```
> r2:=0.0930:
  r1:=0.0446:
  r3:=0.069:
  rho_oct:=777:
  roh_wa:=1000:
  deltarho:=roh_wa-rho_oct:
```

Defining radius:

Locations at the core where the capillary pressure and staturation should be determined.

```
> for j from 1 to 54 do
  if j < 38 then
  r[j]:=r2-((r2-r1)/80)*j:
```

```
  #print(j = r[j]);
  else
  r[j]:=r3-((r3-r1)/16)*(j-38):
  #print(j = r[j]);
  fi:
  od:
```

Defining centrifuge speed:

Speeds at which the capillary pressure and saturation values should be determined at each position. In this case in 500 RPM steps.

```
> for j from 1 to 10 do
  omega[j]:=5000-500*(j-1):
  od:
> omega[11]:=100:
```

Calculation part Srev, Pcim, SorD and Sw_min at 5000RPM:

```
> for i from 3 to 54 do
  #print(r= r[i]);
  Pc[i]:=(((1/2)*(2*Pi*omega[1]/60)^2*deltarho*(r2^2-r[i]^2))/1000)
  ;
  Srev[i]:=fsolve(PcD1(S)=Pc[i],S);
  #print("Srev=", Srev[i]);
  SorD[i]:=1/(C+(1/(1-Srev[i])));
  S_nw[i]:=(S-Sw_min[i])/(1-Sw_min[i]);
  S_no[i]:=(1-S-SorD[i])/(1-SorD[i]);
  Pcim[i]:=cwi/S_nw[i]^awi+coi/S_no[i]^aoi:
  Pcim[i]:=unapply(Pcim[i],S);
  Sw_min[i]:=fsolve(Pcim[i](Srev[i])=Pc[i],Sw_min[i]);
  #print("Sw_min=", Sw_min[i]);
  # ("--------------------------")
  od:
```

Calculation for the spontaneous imbibition capillary pressure curves for every point from 3 to 54 (1 and 2 the core is 100% saturated) at the predefined centrifuge speeds:

```
> for j from 2 to 11 do

  #print("j=", j);
  for i from 3 to 54 do
  #print("r=", r[i]);
  Pc[i]:=((1/2)*(2*Pi*omega[j]/60)^2*deltarho*(r2^2-r[i]^2))/1000;
  Pcim[i]:=cwi/S_nw[i]^awi+coi/S_no[i]^aoi:
  Pcim[i]:=unapply(Pcim[i],S);
  Sny[i]:=solve(Pcim[i](S)=Pc[i],S);
  #print("Sny=", Sny[i]);
  #print("-------------------------");
  fpcir[j,i]:=plot(Pcim[i],Srev[i]..0.99, color=blue,labels=
  [Saturation( ), CapillaryPressure (kPa)],labeldirections=
  [horizontal,vertical]):
  od:

  #print("_____END j_____", j);
  smst[j]:=array(3..54);

  col[j]:=array(1..16);
  col[2]:='red':
  col[3]:='blue':
  col[4]:='green':
  col[5]:='black':
```

```
col[6]:='yellow':
col[7]:='navy':
col[8]:='grey':
col[9]:='violet':
col[10]:='pink':
col[11]:='turquoise':

# loop to plot values
for i from 3 to 54 do
smst[j][i]:=r[i],Sny[i] od:
fsmsv[j]:=pointplot(smst[j],connect=true,color=col[j],labels=
[Radius(m),Saturation( )],labeldirections=[horizontal,vertical]):

#  prepare values to export to excel
A[j]:=Matrix(52,2,[r[3],Sny[3],r[4],Sny[4],r[5],Sny[5],r[6],Sny
[6],r[7],Sny[7],r[8],Sny[8],r[9],Sny[9],r[10],Sny[10],r[11],Sny
[11],r[12],Sny[12],r[13],Sny[13],r[14],Sny[14],r[15],Sny[15],r
[16],Sny[16],r[17],Sny[17],r[18],Sny[18],r[19],Sny[19],r[20],Sny
[20],r[21],Sny[21],r[22],Sny[22],r[23],Sny[23],r[24],Sny[24],r
[25],Sny[25],r[26],Sny[26],r[27],Sny[27],r[28],Sny[28],r[29],Sny
[29],r[30],Sny[30],r[31],Sny[31],r[32],Sny[32],r[33],Sny[33],r
[34],Sny[34],r[35],Sny[35],r[36],Sny[36],r[37],Sny[37],r[38],Sny
[38],r[39],Sny[39],r[40],Sny[40],r[41],Sny[41],r[42],Sny[42],r
[43],Sny[43],r[44],Sny[44],r[45],Sny[45],r[46],Sny[46],r[47],Sny
[47],r[48],Sny[48],r[49],Sny[49],r[50],Sny[50],r[51],Sny[51],r
[52],Sny[52],r[53],Sny[53],r[54],Sny[54]]);
od:

> display(fsmsv[2],fsmsv[3],fsmsv[4],fsmsv[5],fsmsv[6],fsmsv[7],
  fsmsv[8],fsmsv[9],fsmsv[10],fsmsv[11]);
```
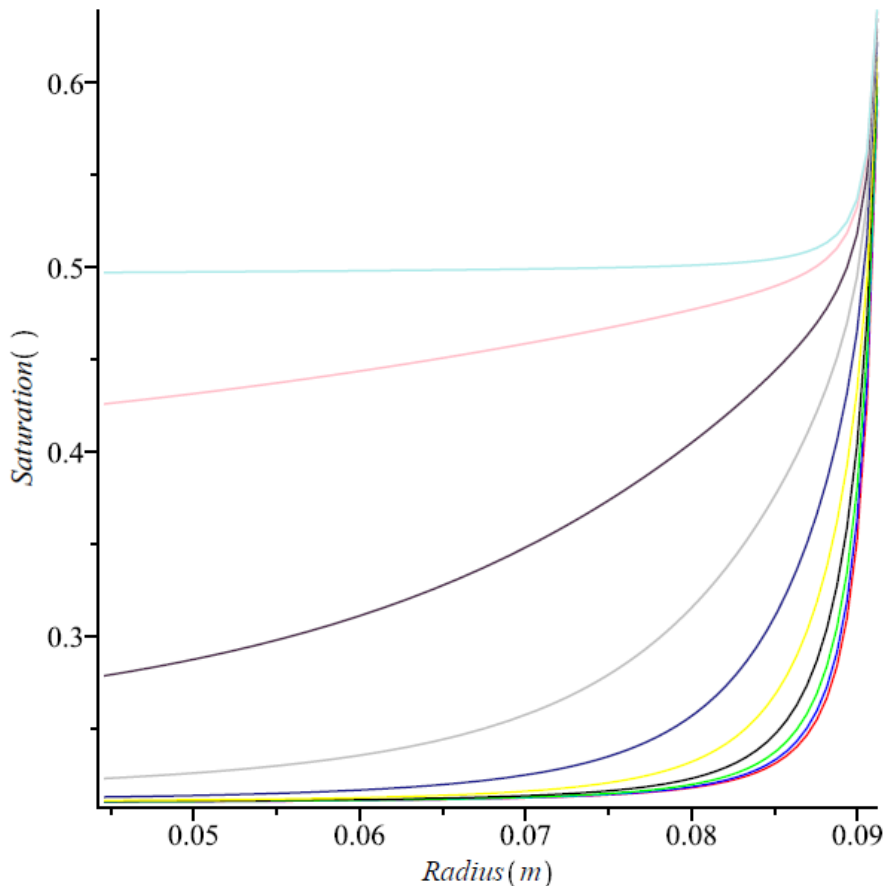
```
> display(fsmsv[2],fsmsv[3],fsmsv[4],fsmsv[5],fsmsv[6],fsmsv[7],
  fsmsv[8],fsmsv[9],fsmsv[10],fsmsv[11],view=[0.055..0.09,0.21.
  .0.25]):
> display(fpcD1,fpcd,fpcir[2,3],fpcir[2,4],fpcir[2,5],fpcir[2,6],
  fpcir[2,7],fpcir[2,8],fpcir[2,9],fpcir[2,10],fpcir[2,11],fpcir[2,
  12],fpcir[2,13],fpcir[2,14],fpcir[2,15],fpcir[2,16],fpcir[2,17],
  fpcir[2,18],fpcir[2,19],fpcir[2,20],fpcir[2,21],fpcir[2,22],fpcir
  [2,23],fpcir[2,24],fpcir[2,25],fpcir[2,26],fpcir[2,27],fpcir[2,
  28],fpcir[2,29],fpcir[2,30],fpcir[2,31],fpcir[2,32],fpcir[2,33],
  fpcir[2,34],fpcir[2,35],fpcir[2,36],fpcir[2,37],fpcir[2,38],fpcir
  [2,39],fpcir[2,40],fpcir[2,41],fpcir[2,42],fpcir[2,43],fpcir[2,
  44],fpcir[2,45],fpcir[2,46],fpcir[2,47],fpcir[2,48],fpcir[2,49],
  fpcir[2,50],fpcir[2,51],fpcir[2,52],fpcir[2,53],fpcir[2,54],view=
  [0.1..1,-70..70]);
```

```
> display(fpcD1,fpcd,fpcir[2,3],fpcir[2,4],fpcir[2,5],fpcir[2,6],
  fpcir[2,7],fpcir[2,8],fpcir[2,9],fpcir[2,10],fpcir[2,11],fpcir[2,
  12],fpcir[2,13],fpcir[2,14],fpcir[2,15],fpcir[2,16],fpcir[2,17],
  fpcir[2,18],fpcir[2,19],fpcir[2,20],fpcir[2,21],fpcir[2,22],fpcir
  [2,23],fpcir[2,24],fpcir[2,25],fpcir[2,26],fpcir[2,27],fpcir[2,
  28],fpcir[2,29],fpcir[2,30],fpcir[2,31],fpcir[2,32],fpcir[2,33],
  fpcir[2,34],fpcir[2,35],fpcir[2,36],fpcir[2,37],fpcir[2,38],fpcir
  [2,39],fpcir[2,40],fpcir[2,41],fpcir[2,42],fpcir[2,43],fpcir[2,
  44],fpcir[2,45],fpcir[2,46],fpcir[2,47],fpcir[2,48],fpcir[2,49],
  fpcir[2,50],fpcir[2,51],fpcir[2,52],fpcir[2,53],fpcir[2,54],view=
  [0.2..0.9,-10..70]):
> display(fpcD1,fpcd,fpcir[3,3],fpcir[3,4],fpcir[3,5],fpcir[3,6],
  fpcir[3,7],fpcir[3,8],fpcir[3,9],fpcir[3,10],fpcir[3,11],fpcir[3,
  12],fpcir[3,13],fpcir[3,14],fpcir[3,15],fpcir[3,16],fpcir[3,17],
  fpcir[3,18],fpcir[3,19],fpcir[3,20],fpcir[3,21],fpcir[3,22],fpcir
  [3,23],fpcir[3,24],fpcir[3,25],fpcir[3,26],fpcir[3,27],fpcir[3,
  28],fpcir[3,29],fpcir[3,30],fpcir[3,31],fpcir[3,32],fpcir[3,33],
  fpcir[3,34],fpcir[3,35],fpcir[3,36],fpcir[3,37],fpcir[3,38],fpcir
  [3,39],fpcir[3,40],fpcir[3,41],fpcir[3,42],fpcir[3,43],fpcir[3,
  44],fpcir[3,45],fpcir[3,46],fpcir[3,47],fpcir[3,48],fpcir[3,49],
  fpcir[3,50],fpcir[3,51],fpcir[3,52],fpcir[3,53],fpcir[3,54],view=
  [0.2..0.3,-10..70]):
> display(fpcD1,fpcd,fpcir[4,3],fpcir[4,4],fpcir[4,5],fpcir[4,6],
  fpcir[4,7],fpcir[4,8],fpcir[4,9],fpcir[4,10],fpcir[4,11],fpcir[4,
  12],fpcir[4,13],fpcir[4,14],fpcir[4,15],fpcir[4,16],fpcir[4,17],
  fpcir[4,18],fpcir[4,19],fpcir[4,20],fpcir[4,21],fpcir[4,22],fpcir
  [4,23],fpcir[4,24],fpcir[4,25],fpcir[4,26],fpcir[4,27],fpcir[4,
  28],fpcir[4,29],fpcir[4,30],fpcir[4,31],fpcir[4,32],fpcir[4,33],
  fpcir[4,34],fpcir[4,35],fpcir[4,36],fpcir[4,37],fpcir[4,38],fpcir
  [4,39],fpcir[4,40],fpcir[4,41],fpcir[4,42],fpcir[4,43],fpcir[4,
  44],fpcir[4,45],fpcir[4,46],fpcir[4,47],fpcir[4,48],fpcir[4,49],
  fpcir[4,50],fpcir[4,51],fpcir[4,52],fpcir[4,53],fpcir[4,54],view=
  [0.2..0.22,-10..200]):
> Export(A[2]);
> Export(A[3]);
> Export(A[4]);
> Export(A[5]);
> Export(A[6]);
> Export(A[7]);
> Export(A[8]);
> Export(A[9]);
> Export(A[10]);
```

A.4   Excel Tool

This part of the appendix should show how the Excel tool is build (the alignment was slightly changed for the Appendix).

Information

Tuning of parameters in capillary pressure correlation to laboratory data
Using build in Excel function **Solver** and user defined function **ComputeS**.
Solver: regression routine using Generalized Reduced Gradient method to determine
tuning parameters.
ComputeS: computes saturation corresponding to given capillary pressure value iteratively
(bisecting intervals).

Instructions

- Values in **blue** cells obtained by experiment, they are never changed during tuning procedue.
- Values in **red** cells, iteration parameters used by iterative function ComputeS.
- Initial guess for values of tuning parameters in **green** cells, values change as .
  computations proceed
- After computations the tuned parameters are written to **green** cells.
- Values in **brown** cells are used by function ComputeS and must not be changed by user.

In Excel build in Solver the cells containing tuning parameters (a subset of the **green** cells)
 must be selected. In addition the error cell (**yellow**) must be selected.

In Solver panel make all active tuning parameters non-negative.

NB!! For tuning of primary drainage curve, set S1 = 1, Sor = 0 and c1 equal to the measured
treshold pressure. Use Swr, and a1 as tuning parameters.

Parameters for computation of capillary pressure

	computed	guess	true
Swr	0,21470577	0,18	0,21
a1	0,2212936	0,2	0,25
c1	7,97698703	8	10
Sor	0,1025492	0,1	0,1
a2	0,43495496	0,4	0,6
S1	0,67766566	0,5	0,5

Parameters used in iterative solver (ComputeS)

tol =	1,00E-05	←	Iteration tolerence (ComputeS)
maxit =	100	←	Max number of iterations (ComputeS)

w   2500   RPM

r	Input Pc		Input saturation	Computed S	sqr of diff	Error
0,09058	3,3951022	3,3951022	0,50895345	0,477676058	0,00097828	0,00272226
0,089975	4,22989177	4,22989177	0,407355842	0,426149311	0,00035319	
0,08937	5,05908695	5,05908695	0,359838886	0,381198839	0,00045625	
0,088765	5,88268774	5,88268774	0,330039266	0,344314398	0,00020378	
0,08816	6,70069413	6,70069413	0,308660761	0,315284373	4,3872E-05	
0,087555	7,51310615	7,51310615	0,292298906	0,292979079	4,6264E-07	
0,08695	8,31992375	8,31992375	0,279352421	0,276021078	1,1098E-05	
0,086345	9,12114697	9,12114697	0,268911949	0,263151599	3,3182E-05	
0,08574	9,91677579	9,91677579	0,260388182	0,253348879	4,9552E-05	
0,085135	10,7068102	10,7068102	0,253365853	0,245831415	5,6768E-05	
0,08453	11,4912503	11,4912503	0,247537359	0,240017922	5,6542E-05	
0,083925	12,2700959	12,2700959	0,24266803	0,23548078	5,1657E-05	
0,08332	13,0433472	13,0433472	0,238575564	0,231906721	4,4473E-05	
0,082715	13,8110041	13,8110041	0,235116624	0,229065412	3,6617E-05	
0,08211	14,5730666	14,5730666	0,232177507	0,226786423	2,9064E-05	
0,081505	15,3295347	15,3295347	0,229667369	0,22494295	2,232E-05	
0,0809	16,0804083	16,0804083	0,227513169	0,223439644	1,6594E-05	
0,080295	16,8256876	16,8256876	0,225655847	0,222204415	1,1912E-05	
0,07969	17,5653726	17,5653726	0,224047383	0,221182142	8,2096E-06	
0,079085	18,299463	18,299463	0,222648533	0,22033036	5,3739E-06	
0,07848	19,0279594	19,0279594	0,221427058	0,219616126	3,2795E-06	
0,077875	19,7508611	19,7508611	0,220356352	0,219013599	1,803E-06	
0,07727	20,4681685	20,4681685	0,219414346	0,218502452	8,3155E-07	
0,076665	21,1798811	21,1798811	0,218582657	0,218066499	2,6642E-07	
0,07606	21,8859996	21,8859996	0,2178459	0,217692799	2,344E-08	
0,075455	22,5865242	22,5865242	0,217191147	0,217370949	3,2329E-08	
0,07485	23,2814541	23,2814541	0,216607488	0,217092495	2,3523E-07	
0,074245	23,9707889	23,9707889	0,216085679	0,216850565	5,8505E-07	
0,07364	24,6545305	24,6545305	0,21561786	0,216639512	1,0438E-06	
0,073035	25,332676	25,332676	0,21519732	0,216454686	1,581E-06	
0,07243	26,0052295	26,0052295	0,214818311	0,216292243	2,1725E-06	
0,071825	26,6721869	26,6721869	0,214475892	0,216148974	2,7992E-06	
0,07122	27,3335497	27,3335497	0,214165801	0,216022197	3,4462E-06	
0,070615	27,98932	27,98932	0,213884352	0,215909663	4,1019E-06	
0,069	29,7124438	29,7124438	0,213250219	0,215665426	5,8332E-06	
0,067475	31,3029485	31,3029485	0,212775749	0,215491726	7,3765E-06	
0,06595	32,857909	32,857909	0,212392658	0,215357643	8,7911E-06	
0,064425	34,3773241	34,3773241	0,212080064	0,215252662	1,0065E-05	
0,0629	35,8611934	35,8611934	0,211822524	0,215169405	1,1202E-05	
0,061375	37,3095196	37,3095196	0,211608463	0,215102603	1,2209E-05	
0,05985	38,7223	38,7223	0,211429093	0,21504843	1,31E-05	
0,058325	40,0995309	40,0995309	0,21127767	0,21500407	1,3886E-05	
0,0568	41,4412191	41,4412191	0,211148959	0,21496742	1,4581E-05	

0,055275	42,7473618	42,7473618	0,211038859	**0,214936891**	1,5195E-05
0,05375	44,0179537	44,0179537	0,210944124	**0,214911267**	1,5738E-05
0,052225	45,2530096	45,2530096	0,210862168	**0,21488961**	1,622E-05
0,0507	46,4525145	46,4525145	0,21079091	**0,214871186**	1,6649E-05
0,049175	47,616475	47,616475	0,210728666	**0,21485542**	1,703E-05
0,04765	48,7448859	48,7448859	0,210674061	**0,214841854**	1,737E-05
0,046125	49,837769	49,837769	0,210625967	**0,21483012**	1,7675E-05
0,0446	50,8950716	50,8950716	0,210583452	**0,214819924**	1,7948E-05

Saturation Profile
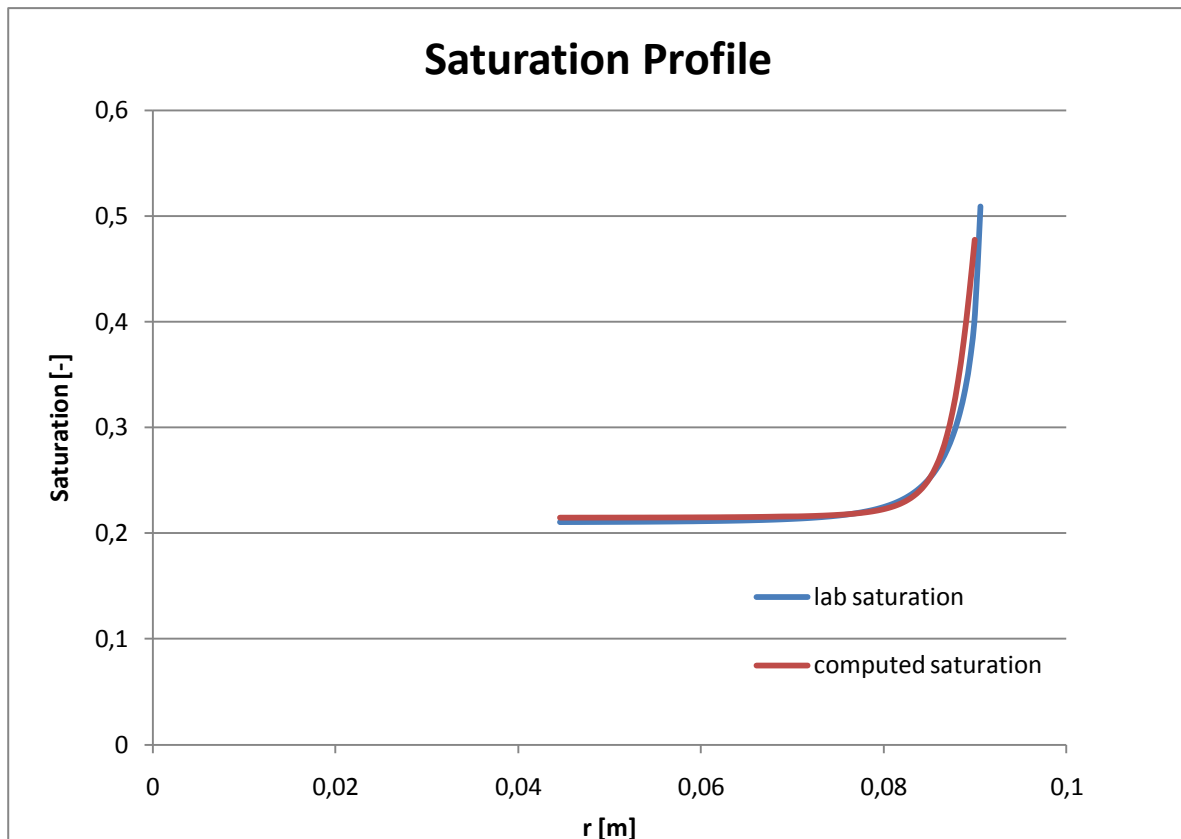
A.5　Macro – ComputeS

The Macro to evaluate the saturation values in Excel is introduced:

```vba
Function ComputeS(Pc As Double) As Double
'Compute saturation S given value Pc of capillary pressure
'Iterative method: bisecting interval

Dim S As Double
Dim i As Integer
Dim Err As Double

'Input Parameters for computing Pc specified in Data sheet
  Swr = Worksheets("Data").Cells(4, 3).Value
  a1 = Worksheets("Data").Cells(5, 3).Value
  c1 = Worksheets("Data").Cells(6, 3).Value
  Sor = Worksheets("Data").Cells(7, 3).Value
  a2 = Worksheets("Data").Cells(8, 3).Value
  S1 = Worksheets("Data").Cells(9, 3).Value

  S11 = (S1 + Sor - 1) / (Sor - 1)
  S22 = (Swr - S1) / (Swr - 1)

  c2 = -c1 * (S11 ^ a2) * (S22) ^ (-a1)

'Parameters for iteration procedure (bisecting interval)
  tol = Worksheets("Data").Cells(13, 3).Value
  maxit = Worksheets("Data").Cells(14, 3).Value

'Start values for iterations
  Smin = Swr
  Smax = 1 - Sor

'Start iterations
  i = 0
  Do While i < maxit
  i = i + 1

  S = 0.5 * (Smax + Smin)

  S1 = (S - Swr) / (1 - Swr)
  S2 = (1 - S - Sor) / (1 - Sor)

  ComputedPc = c1 * S1 ^ (-a1) + c2 * S2 ^ (-a2)

  Err = Pc - ComputedPc
```

```
      If Err < 0 Then
        DErr = -Err
      Else
        DErr = Err
      End If

      If DErr > tol Then

        If Err < 0 Then
          Smin = S
        Else
          Smax = S
        End If

      Else

        ComputeS = S
        Exit Do

      End If

  Loop

'  If i > maxit - 1 Then
'    MsgBox "NB!! no convergence"
'  End If

End Function
```