

CAN NETWORK MODELLING PREDICT TWO-PHASE FLOW FUNCTIONS?

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ABSTRACT

Over the last two decades there has been an increase in activity on the pore-scale modelling of multiphase flow in porous media. Excellent progress has been made in many areas of pore scale modelling, particularly in (i) the representation of the rock itself and (ii) in our description of the pore-scale displacement physics (in model pore geometries). 3D voxelised images of actual rocks can be generated either numerically (e.g. from 2D thin sections) or from micro CT imaging. A simplified network involving more idealised nodes and bonds can then be extracted from this numerical rock model and this can be used in modelling pore scale displacement processes. Much progress has also been made in understanding these pore scale processes (i.e. piston-like displacement, snap-off events, layer formation/collapse, pore-body filling/drainage). These processes can be mathematically modelled accurately for pores of non-uniform wettability, if the geometry of the pore is sufficiently simple. In fact, in recent years these various pore-level processes in mixed and fractionally wet systems have been classified as “events” in an entire capillary dominated “phase space” which can be defined in a thermodynamically consistent manner. Advances in our understanding and ability to *compute* several two- (and three-) phase properties *a priori* have been impressive and the entire flooding cycle of primary drainage (PD), ageing/wetting change, and imbibition can be simulated.

In this paper, we review the successes of pore-scale network modelling and explain how it can be of great use in understanding and explaining many phenomena in flow through porous media. However, we also critically examine the issue of how *predictive* network modelling is in practice. Indeed, one of our conclusions on pore scale modelling in mixed wet systems is that we *cannot* predict two-phase functions reliably in “blind” tests. Interestingly, we make this statement not because we *do not* understand the pore-scale physics of the process, but because we *do* understand the physics. It is hoped that our comments will stimulate a more critical debate on the role of pore-scale modelling and its use in core analysis.

***A PRIORI* PETROPHYSICAL PREDICTION – AN INTRODUCTION**

Since the pioneering work of Fatt (1956), representing porous rocks and modelling fluid flow using pore-scale network models has been a part of our general activity in the study of flow through porous media. Since these early days, there have been many network modelling studies which had, as a main aim, the explanation of the macroscopic phenomena observed in multi-phase flow through porous media. For example, network

modelling has been used to analyse and explain hysteresis and the dispersion in two-phase flow experiments (Mohanty and Salter, 1982), to model mixed-wet systems and study the effects of wettability (McDougall and Sorbie, 1995; Dixit *et al*, 1999; Blunt, 1998; Patzek, 2001), and to explain hysteresis in water wet and mixed-wet systems (Dixit *et al*, 1998a, 1998b). Much of this early work using network models used idealised lattices of bonds and nodes, but more recently digital pore reconstruction methods have been developed based on various approaches, such as sedimentation modelling (Bakke and Øren, 1997), micro CT imaging of rocks (Lindquist *et al*, 2000; Arns *et al*, 2001) or reconstruction from 2D thin section images (Wu *et al* 2006, 2008). These approaches have been used to construct much more realistic looking digital rocks (and pore spaces) as a starting point for the calculation of petrophysical properties such as relative permeability, (k_{ro} and k_{rw}), capillary pressure ($P_{c,ow}$) and indeed residual oil (S_{or}). As a shorthand below, we denote relative permeability simply as k_r and oil/water capillary pressure as P_c .

As illustrated schematically in Figure 1, there are 4 main stages in the workflow to make an *a priori* prediction for relative permeability and capillary pressure ($k_r/P_c/S_{or}$):

- (i) **Construction:** The digital reconstruction of the rock from micro-CT imaging, sedimentation or reconstruction from 2D thin sections;
- (ii) **Extraction:** Network extraction from the digital rock;
- (iii) **Wetting:** Representation of wettability structure of the rock in the network model;
- (iv) **Physics:** The pore-scale physics simulation of k_r and P_c within the network model.

In the course of our own research, we have had cause to examine each of these 4 steps in detail. Our overall conclusion is that it is *not* possible to *a priori* predict two-phase petrophysical properties (k_r , P_c and S_{or}) in non-strongly water wet (*sww*) rocks, that is, in rocks that are mixed or fractionally wetted (virtually all reservoir rocks) – and we have some doubts about *sww* rocks. Our argument for this conclusion is laid out in this paper using results from both the literature and our own work. In summary, we believe that the two-phase data has a limited **information content** which is expressible in a number of **parameters**. It is debatable how many parameters that the $k_r/P_c/S_{or}$ information on a given system contains, but to describe the end point saturation and analytical functions for P_c and both two-phase k_r , it is a minimum of ~ 5 and more realistic for an imbibition case ~ 8 parameters. We can think of these parameters as being the number of coefficients in say a set of Corey curves or other empirical model that “fits the data”. Analysing each of the 4 steps above – Construction \rightarrow Extraction \rightarrow Wetting \rightarrow Physics – we show that there are still inherently many more parameters required for a “prediction” than are actually contained in the data itself (*i.e.* in $k_r/P_c/S_{or}$). In fact, we estimate that between ~ 15 and ~ 26 parameters are required in the full work flow of an *a priori* prediction of ($k_r/P_c/S_{or}$) for a given rock from more elementary data. If this is correct, then the true concept of “prediction” is meaningless since more information is required than the data actually contains, that is, information is actually “lost” rather than generated in a so-called “prediction”.

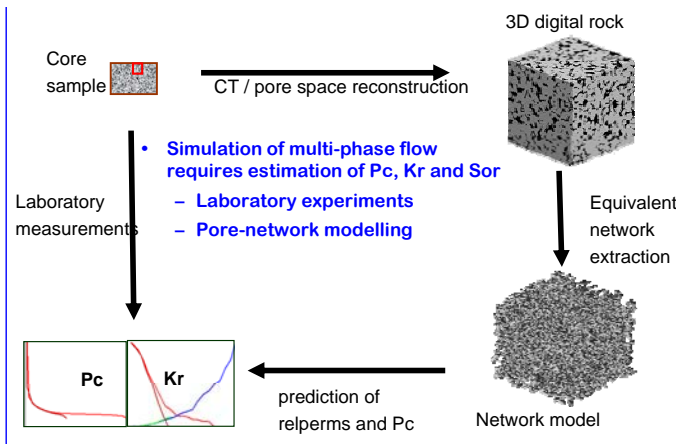


Figure 1: Schematic showing the procedure of going from rock measurements \rightarrow digital rock reconstruction \rightarrow network model \rightarrow calculation of petrophysical function (k_r and P_c) and how this can be compared with experiment.

PARAMETERS IN $k_r/P_c/S_{or}$ “A PRIORI” PREDICTION WORKFLOW

As noted above, the general workflow in making an *a priori* prediction of $k_r/P_c/S_{or}$ involves the 4 stages which we have summarised as Construction, Extraction, Wetting and Physics. Each of these stages is discussed in detail below:

Digital Rock Construction: The digital reconstruction of sandstone rocks has been a very active area of research over the last decade and genuine advances have been made in producing very realistic digital rock models (Øren and Bakke, 2002, 2003; Knackstedt *et al* 2004; Wu *et al*, 2006; Jiang *et al*, 2007). There is little doubt that, down to a resolution level of $\sim 1\mu\text{m}$, that the original rock can be accurately imaged because all of the statistical information on the “correct” original image (*e.g.* 2 point and multi point statistics, correlation structure) can be preserved. For example, Wu *et al* (2008) use a pore scale reconstruction method known as PAM (pore architecture models) based on a Monte Carlo Markov Chain (MCMC) reconstruction algorithm which uses 2D thin sections in 3 orthogonal directions as input. These workers validated their method by taking an original digital rock model extracted by micro-CT, assuming this model as “correct”, calculating various statistical functions, then carrying out various calculations such as permeability calculation (using lattice Boltzmann (LB) methods), network extraction (Jiang *et al*, 2007) and a network model calculation of drainage and imbibition relative permeabilities and capillary pressures were carried out (Wu *et al*, 2008). Various numerical thin sections of the “correct” 3D digital model (taken as being isotropic) were taken and used in the PAMs reconstruction of several new digital rocks as shown in Figure 2. All properties of the new reconstruction (statistical and derived) – including the derived relative permeabilities – were very close to those of the original reference model as shown in Figures 2(e) and 2(f) thus validating their method (Wu *et al*, 2008).

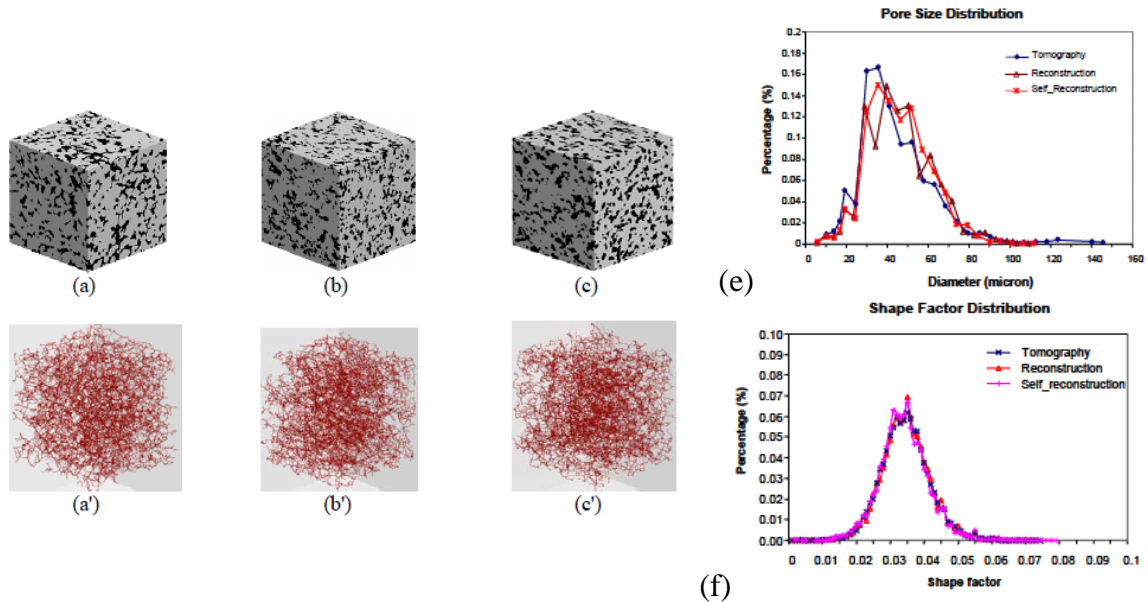


Figure 2: (a) The 3D reference (CT) image of sandstone; (a') the extracted network from 3D image (a); (b) The first cycle reconstruction of sandstone and (b') pore network extraction; (c) the second cycle reconstruction (Self-reconstruction) of sandstone and (c') the extracted pore network. Comparison of (e) pore size distribution and (f) shape factor distribution curves for the original reference 3D image, the reference image and the “self reconstruction” (from Wu et al, 2008).

However, every reconstruction method – either by experimental micro-CT scanning, sedimentation modelling or from thin section – requires some intervention which results in “parameters”. These parameters arise as a result of image processing and come from sources such as thresholding and image clean up steps that must be carried out. No method goes from a CT scan or a 2D thin-section completely with *zero* parametric input or decisions. However, we believe that this is the *least* parameterised step in the process and we estimate that there are only $\sim 2 - 4$ parameters in this stage for simple clastic rocks (not for carbonates which we discuss later). Broadly speaking, it appears that if we can reproduce the Minkowski functionals of a rock (Lehmann *et al*, 2008; Latief *et al*, 2010; Vogel and Roth, 2001), then the digital image of the rock is a good topological representation of the original rock sample. In particular, obtaining the connectivity function of the rock (Specific Euler number vs. pore size) seems to be particularly important because it captures the correct correlation structure of how the big pores and little pores are topologically arranged and connected (; Vogel and Roth, 2001; Wu *et al*, 2008). **Construction parameter count** = $\sim 2 - 4$ (E.g. thresholding level for rock/pore space partition, beam hardening parameter in micro-CT image construction, image “clean up” parameter, etc.).

Network Extraction and Geometrical Idealisation: The digital rock image is as close to the reality of rock structure that we are likely to get and it would be very convenient if accurate detailed two phase interfacial fluid mechanics could be performed on this grid. Some simpler single phase *a priori* calculations are possible such as the calculation of permeability or dispersivity (Zaretskiy *et al*, 2010) but, at the present time, reliable two

phase calculations cannot be made on these digital models that can be compared meaningfully with experiment. However, some techniques look promising for making such calculations in the future (*e.g.* level set or phase field methods Dorn *et al*, 2009).

Given the above problems, then the network extraction stage is a very important step in the predictive workflow. An example of this is shown in Figure 3 where a medial axis network has been extracted from a PAM digital model (Jiang *et al*, 2007); this network is just the topological “backbone” skeleton of the extracted network. The actual volumetric and geometric details of the “nodes” (pore bodies) and “bonds” (pore throats) must be grafted onto this backbone and one specific way of doing this is shown in Figure 3. Finally, we must make certain choices about how the actual idealised geometrical network elements will be handles as follows:

- Will a partitioning be made into nodes (pore bodies) and bonds (pore throats) or will a bonds-only network be used? Either case can give good agreement with experiment but the inclusion of nodes introduces pore-body filling events which are complex and dealt with quite empirically (*i.e.* they are parameterised);
- What type of geometry will be used for the pore elements? The bond cross section may be taken as mixtures of circles-squares-triangles (CST) (Valvatne and Blunt, 2004) or “star shape” (SS) pores may be used (Ryazanov *et al*, 2009). Incidentally, it is known that the choice of pore shapes does make a difference in the final result $k_r/P_c/S_{or}$, as shown by Ryazanov *et al* (2010);
- The precise transfer from the digital rock local “shape factors” to the idealised geometry (*e.g.* CST, SS) involves some decisions, that is, parameters.

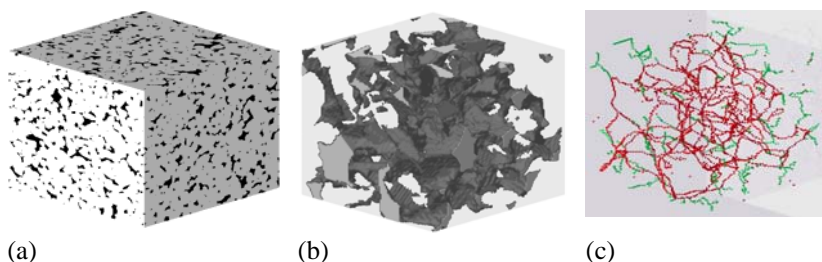


Figure 3: (a) the 3D digital rock constructed by the PAMs approach (Wu *et al*, 2006), (b) the rendering of the actual pore structure in this image and (c) the medial axis backbone skeleton of this image (Jiang *et al*, 2007).

In our view, the network extraction stage of the process from the digital rock is more “parameterised” than the construction of the original numerical rock image itself and involves a number of decisions/idealisation/choices, as discussed above. Examining this process, we estimate that the network extraction stage of the process involves $\sim 4 - 6$ parameters. **Extraction parameter count = $\sim 4 - 6$.** Examples, 1 parameter for extraction “algorithm choice”, 1 for decision about idealised geometries, 2 parameters in these geometries (shape factors, proportion of CST, etc.), 1 on pore body/throat assignment, etc. NB there are further ancillary choices/parameters depending on decisions made at this stage *e.g.* with pore body filling model (see below).

Representing Wettability in Network Models: The wettability of the reservoir rock is known to have a profound effect on virtually all multi-phase petrophysical properties and the literature on this is vast. At the micro scale, some qualitative notion of the local wetting can be seen in ESEM images such as those shown in Figure 4. The range of

macroscopic tests to determine the wetting state of a rock are relative crude and include calculating the USBM index (I_{USBM}), the Amott-Harvey index (I_{AH}), measuring rates and quantities of spontaneous imbibition of oil and water and/or simply looking at the form of k_r and P_c . Using the petrophysical quantities (k_r and P_c) themselves to assess wettability is sometimes done in reservoir studies where a campaign of petrophysical data collection has already been carried out.

ESEM Showing Wettability State of Clay and Quartz

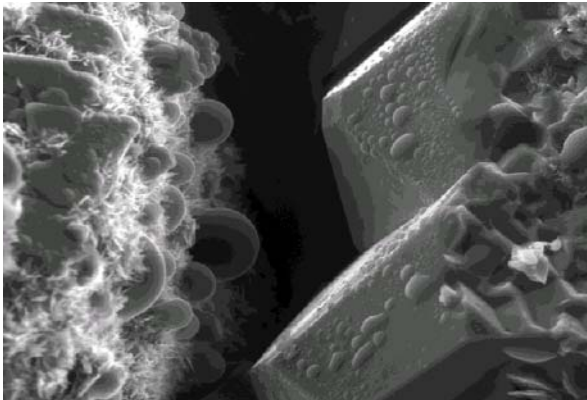


Figure 4: Environmental scanning electron microscope (ESEM) image of water droplets condensing onto a North Sea sandstone showing the differential wetting of the illitic clays (oil wet) and the quartz (weakly water wet) (J. Buckman, Heriot-Watt University, Edinburgh, UK).

The current practice for representing the wettability of idealised pore elements (*e.g.* triangular pores, CST, SS) in pore-scale network modelling was laid down in the classic paper by Kovsek *et al* (1993). In this model oil invades a geometrical (*e.g.* triangular) strongly water-wet pore in a primary drainage (PD) process according to the usual Young-Laplace law displacing water. After the water is displaced, the oil resides in the main pore body with (bulk) water in the corners and a thin film of water on the rock surface (see Figures 5(a) and 5(b)). After some time, various processes (“ageing”) can collapse the water film thus changing the wettability of the oil-contacted surface of the pore from s_{ww} to a different wetting state ($\theta_{\text{a,ow}}$ and $\theta_{\text{r,ow}}$) \rightarrow weakly water wet or to some degree of oil wettability (see Figure 5(c)).

The degree to which this wetting change affects the surface of the pore depends on the precise geometry of the pore, the mineralogy of the pore surface, and the final capillary pressure to which the primary drainage was carried out. Also, a number of decisions about the wetting state must be made in order to allocate numerical values in all of the pore scale displacement processes, as follows:

- In exactly which *fraction* (denoted α ; McDougall and Sorbie, 1995; Dixit *et al*, 1999) of the oil occupied pores should we change the surface wetting? Is it the larger pores, the smaller pores or pores of all sizes? For example, there are theoretical reasons why this could be a mixed-wet system with the larger pores being oil wet (MWL) (see McDougall and Sorbie, 1995; Dixit *et al*, 2000; Høiland *et al*, 2007; Skauge *et al*, 2007) and reasons why it may be otherwise (see Figure 6);
- Which values should we allocate to the advancing and receding contact angles ($\theta_{\text{a,ow}}$ and $\theta_{\text{r,ow}}$) on these changed pore surfaces? What should the distributions of the contact angle be since they are probably not uniform all through the region of altered wettability? (see Figure 6);

- The choices we make here are intimately connected with the earlier choices made about the local geometry of the pores (*e.g.* CST, SS) and so how do we make this “joint choice” in the absence of any real quantitative experimental data ?

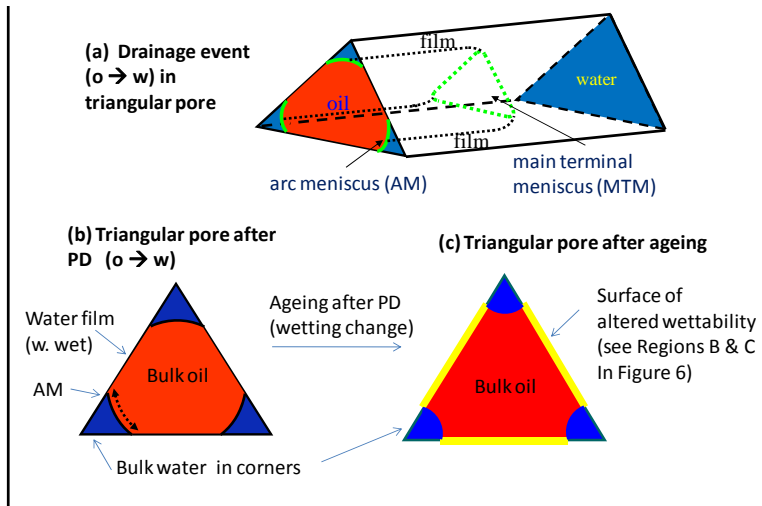


Figure 5: (a) Primary drainage (PD) in a water wet triangular pore showing the bulk corner occupancy by water, arc menisci (AM) and water films; (b) bulk oil occupancy after PD; and (c) oil/water occupancy of triangular pore and changed wettability of oil contacted pore surface after ageing.

An even larger conceptual uncertainty about the process of allocating wettability is that, while the Kovsek-type model appears to be very plausible and theoretically well founded, it has never been fully validated for reservoir crude oil/brine/ rock (COBR) systems. In addition, even if this model is broadly conceptually correct in terms of the pore scale physics involved (as the current authors believe), the degree of approximation that is being made in its application in an idealised model is very difficult, if not impossible, to estimate.

We believe that the representation of wettability is probably the most significant single issue in the *a priori* prediction process because it results in more parameterisation than any of the other 3 stages (Construction, Extraction or Physics). For this reason, we break down the pore-network model parameter list for wettability in more detail as follows:

“Structure” of Wettability (MWL, MWS, fraction α ..)	=	2 – 3
$\theta_{a,ow}$ distribution	=	1 – 2
$\theta_{r,ow}$ distribution	=	1 – 2
Layer parameters	=	1 – 2
Final $P_{c,ow}$ or S_{wi} / S_{or} distribution	=	2 – 3

Wetting parameter count = ~7 – 12

Pore-Scale Physics: In all the pore-scale network models describing mixed and fractionally wet two- and three- phase systems, the assumption of local capillary dominated displacement is used. Thus, we need to understand and be able to model all of the capillary displacement events that occur in drainage and imbibition in pores of non-uniform wettability (*i.e.* piston like drainage/imbibition displacements, snap-off events caused by fluid layer and corner growth, and oil layer formation and collapse events. This subject has been studied in great detail for systems in arbitrary wetting states by a wide range of authors (McDougall and Sorbie, 1995; Blunt, 1997, 1998; Øren *et al* 1998; Valvatne and Blunt, 2004; Hui and Blunt, 2000; van Dijke and Sorbie, 2006)

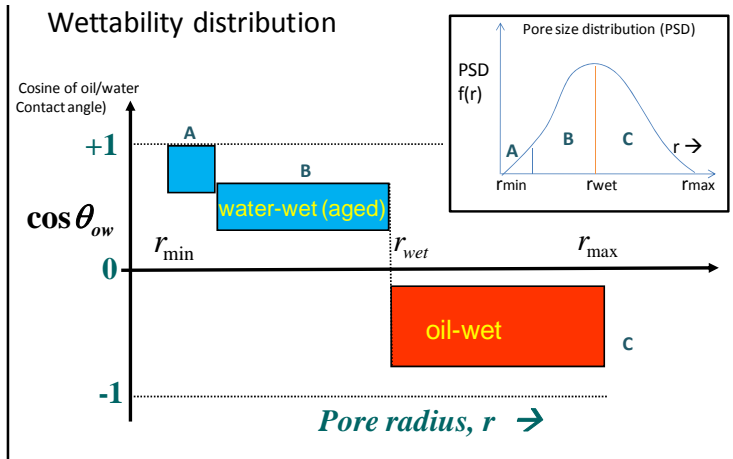


Figure 6: Representation of the wettability distributions within the pore space for a MWL pore size distribution (PSD inset). Region A is the strongly water-wet, pores which remain water filled from primary drainage (PD), at initial water saturation S_{wi} . Regions B and C were oil occupied at the end of PD and this part of the pore space experienced a wetting change to water wet (region B with range of $\cos \theta_{ow} > 0$) or oil wet (region C with range of $\cos \theta_{ow} < 0$).

We will not discuss these various processes in any detail here because, once a geometrical network and its wetting state have been established, this is not a source of many additional parameters. There are some empirical numerical decisions that must be made (e.g. the precise version/parameterisation of a pore body filling events in imbibition, Lenormand *et al*, 1983; Blunt, 1997) but the parameter count is not very high in the Physics stage of the *a priori* process. **Physics parameter count = ~2 – 4.**

EXAMPLES AND CONCERNS

Having talked quite generally about the *a priori* predictive workflow for two-phase petrophysics, we present two specific very simple examples from the literature where there are genuine concerns about this predictive ability. We choose these because the authors are trying to predict quite simple quantities, viz. (1) relative permeabilities and S_{wi} for a strongly water wet (sww) rock, and (2) residual gas saturation to water, S_{grw} .

Example 1: Figure 7 shows a well known prediction of Oak’s oil/water relative permeability data for primary drainage (PD) in strongly water wet Berea sandstone which has been carried out by various workers (e.g. Valvatne and Blunt, 2004; Ryazanov *et al*, 2009). Note the closeness of the “predictions” of both network models in Figure 7 (ICL = Imperial College London, and HWU = Heriot-Watt U.) to Oak’s experimental data. At first sight, this looks like an excellent prediction. However, in both cases the S_{wi} in the k_{rw} curve is not “predicted”; this quantity is actually input from the amount of clay which is assigned to the Berea rock. But this is not a prediction, it is simply input – it is just a “parameter” of the sort discussed above. To our knowledge, even for a strongly water wet system, no one has produced a genuine prediction of the full two-phase drainage curves: k_r/P_c and resulting “ S_{wi} ”.

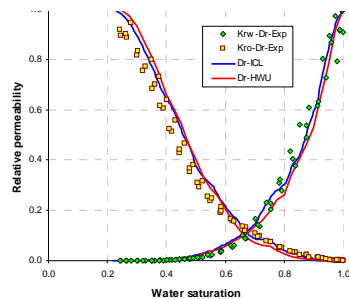


Figure 7: Comparison of calculated drainage relative permeabilities for both HWU and ICL models with Oak’s water wet data (Berea PB network).

Example 2: Secondly, we refer to the very detailed study of Caubit et al (2008) who set out to test *a priori* pore network model predictions of residual gas saturation to water, S_{grw} , in “blind” tests. Despite the large amount of imaging data for digital rock construction, good network extraction tools and network simulators, the models were unable to predict S_{grw} for any of the rock samples studied. Caubit et al attributed this difficulty to the inability of the models to capture micro-porosity and heterogeneities which in turn led to an inability to predict. They finally concluded that .. “the combined techniques of imagery and PNM [pore network modelling] cannot currently be considered as an industrial tool on the whole range of rock investigated in petroleum engineering” (Caubit et al, 2008).

APPROPRIATE USE OF NETWORK MODELS AND THE WAY FORWARD

Although we have some misgivings about the ability of network modelling to *predict* two-phase petrophysical quantities ($k_r/P_c/S_{or}$), network modelling can be used for a wide range of very useful purposes in two- and three-phase petrophysics, as follows:

- (i) **Single Phase Predictions:** Network models can be applied for the genuine prediction of single phase static and (some) flow properties, *e.g.* permeability, electrical properties, and (potentially) dispersion. It may also have a role in the interpretation of NMR responses such as T_1/T_2 distributions;
- (ii) **Explanation:** network modelling can *explain* many global trends in two- and three-phase behaviour (*e.g.* the broad effect of wettability on residual oil and, k_r/P_c) (McDougall and Sorbie, 1995; Blunt, 1997, 1998; Øren and Bakke, 2002, 2003), the observed hysteresis trends in oil/water relative permeability (Mohanty and Salter, 1982; Dixit *et al*, 1998a, 1998b), rationalising the meaning of USBM and Amott wetting tests in terms of the pore scale physics (Dixit *et al*, 2000; Høiland et al, 2007, Skauge *et al*, 2007));
- (iii) **Interpolation and Extrapolation:** network models can be “matched” or “anchored” to two-phase experimental ($k_r/P_c/S_{or}$) data and then used to interpolate or extrapolate this data for a range of related but varying conditions. This is a key step in multi-stage upscaling of two-phase flow from pore \rightarrow core \rightarrow gridblock scale. An excellent example of this approach is presented in the study by Lerdahl *et al*, (2005).
- (iv) **Understanding and Calculating Three-Phase Properties from Two- Phase Data:** Reliable three-phase data is *much* more difficult than two-phase data to obtain and it is very rarely measured. Network modelling has been used to extend our understanding of the underlying physics of three-phase displacements such as WAG (Mani and Mohanty, 1998; Fenwick and Blunt, 1998; Piri and Blunt, 2002; van Dijke Sorbie, 2002; van Dijke *et al*, 2004) In addition, network models can be matched to two- phase data and then be used to calculate three-phase properties such as phase displacement paths (when gas \rightarrow oil and water), three-phase relative permeabilities and three-phase capillary pressures. An example of this was presented by Svirsky *et al* (2007).
- (v) **Role of Mineralogy:** Another advance in which pore scale modelling may have an important role is in the use of identified local mineral properties from the construction phase to obtain the local mineralogy of all surface sites within the

rock. This is an advantage for study of possible wettability changes during oil injection/ageing or geochemical reactions during CO₂ injection, or for defining local wetting property changes during low salinity injection.

- (vi) **Structure of Residual Oil:** Another important role of pore scale modelling is in establishing the possible **structure** of residual oil, for example as a function of wettability of the rock. Indeed, this is the precise objective of another paper at this SCA conference (Sorbie *et al.*, 2011). If the S_{or} structure is understood, then this in turn will help us to design more effective EOR type processes for chemical and/or gas injection.

SUMMARY AND CONCLUSIONS

In this paper, we have laid out the workflow which must be followed in order to make a genuine *a priori* prediction of two-phase petrophysical quantities ($k_r/P_c/S_{or}$), which comprises Construction, Extraction, Wetting and Physics stages. We note that the petrophysical data itself only contains a certain amount of information which we code as a number of parameters such as end point saturations and the coefficients in a Corey or other empirical fit to this data. This number of parameters in a typical laboratory dataset might be a minimum of ~5 and a maximum of ~8 parameters. Thus, any “predictive” network model would have to have the same (or less) number of parameters. We analyse each step of the workflow and we conclude that the parameter count is as summarised in Table 1. The various stages result in the requirement for ~15 - ~26 parameters, which is much more than the data actually contains. We therefore conclude that pore scale network modelling of mixed-wet systems cannot *a priori* predict two-phase petrophysical data, ($k_r/P_c/S_{or}$), in a meaningful manner.

However, pore scale modelling can be used in a wide range of other very useful and constructive ways which bring great understanding of multi-phase fluid flow through porous media. We suggest a variety of useful ways in which this technology can contribute greatly to core scale petrophysical studies and scale up of fluid flow.

Table 1: Estimated number of parameters required for each stage of the *a priori* 2 phase petrophysical prediction workflow.

Stage	Parameter Count	Comment
Construction of digital rock	2 - 4	Probably least parameterised stage in workflow
Extraction of network	4 - 6	Several decisions must be made in this stage
Wetting assignment of the network	7 - 12	Most complex and least validated stage
Physics of the pore scale displacement	2 - 4	Quite well understood for simple pore geometries
	Min. no. parameters = 15 Max. no. parameters = 26	

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