European Science Foundation (ESF)
Exploratory Workshop

'Recent Advances in Multiphase Flow and Transport in Porous Media'

Scientific Report

Convenors:

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1. **Introduction**

To design soil and groundwater remediation techniques and to make reliable predictions about the efficiency of these techniques, it is necessary to identify and understand multiphase flow and reactive transport processes at microscopic (pore scale) scale and to describe their manifestation at the macroscopic (core scale) level and field scale. Furthermore, while modelling at the field scale it is usually not feasible to take all core-scale heterogeneities into account. However, one has to incorporate the effects of such heterogeneities into field-scale descriptions. Current description of macroscopic multiphase flow behaviour is based on an empirical extension of Darcy's law supplemented with capillary pressure-saturation-relative permeability relationships. However, these empirical models are not always sufficient to account fully for the physics of the flow. Therefore, in general, more pore-level knowledge is required to obtain a better comprehension of the flow at the macroscopic scale. A very useful tool in this regard is a pore-scale network model, a percolation model or lattice-Boltzman model. For example, pore-scale multiphase flow models can describe the displacement of fluid-fluid interface(s) and effects of contact lengths in porous media. The connection of the flow physics between these two scales can be understood by upscaling. This is equivalent to the derivation of average flow properties on a larger scale based on some physical rules at smaller scales. Such a procedure may need several simplifying assumptions, mainly in regards to the pore structure. But, it provides important information on identification of relevant (or otherwise) multiphase flow phenomena.

Traditionally, P^c-S-K_r relationships have been derived under equilibrium flow conditions which typically takes time periods ranging from many days to weeks for particular soil samples depending on media properties, degree of saturation and possibly, types of heterogeneity present within the samples. However, flow processes at shorter durations, e.g., in the range of hours, do not actually occur under static conditions. This is because P^c-S relationships depend on the rate of change of fluid saturation, which again depend on gravity, viscous and capillary forces, area of fluid-fluid interfaces, sub-sample scale heterogeneities, etc. The dependence of P^c-S curves on the rate of change of saturation is known as the dynamic effect. Dynamic effects have been shown, both theoretically and experimentally, to be of importance.

The main focus of the workshop is on the identification and quantitative analysis of the followings:

- upscaling procedures of the pore-scale multiphase flow processes to the core scale
- upscaling procedures of the core-scale multiphase flow processes to field scale
- techniques for testing the upscaled theories with the aid of laboratory experiments
- dynamic effects in multi-phase flow processes

To achieve these goals, a number of leading scientists based at European institutes of international repute were invited to speak in the workshop. A number of young researchers of doctoral and post-doctoral levels were also invited to attend the workshop. The selection of the young participants was based on the merit of their research and its relevance to the workshop themes. Given the dynamic nature of the proposed workshop topics, preferences were given to speakers with more research experience. In total, we had around twenty speakers (young participants and leading experts) in the workshop. In correspondence with ESF aims and objectives, the workshop was based on an interdisciplinary approach and integrated fundamentals from a variety of engineering and pure science topics. The participants were from various branches of engineering, mainly, chemical, civil, environmental and petroleum engineering.

2. Scientific content and assessment of results

2.1 Pore Scale modelling

The workshop started with a session on pore-scale modelling for multiphase flow on June 23, 2003. **Per Valvatne** discussed the development of a library of pore-scale network models to predict flow properties in porous media that have disordered topology. He explained that a network from the library that most closely matches the geological structure of the sample of interest can be chosen and its properties can be tuned to match available experimental data. Then, predictions of single and multiphase flow processes can be made with no further adjustment of the model. However, it was also pointed out that aim of this work was not simply to match experiments. Instead, they proposed that easily acquired data needs to be used to predict difficult to measure properties, such as two and three-phase relative permeability. The variation of these properties in the field, due to wettability trends and different pore structures can then be predicted reliably using the methodology. **Laura J. Pyrak-Nolte** presented an experimental technique to measure interfacial area per volume as a function of capillary pressure and saturation. The methodology is based on wood's metal injection technique to determine IAV (interfacial area per volume) in sandstone undergoing imbibition. She explained that interfacial area per volume (IAV) plays an important role in scaling theories for the flow of multiple fluid phases in a porous medium. This is backed by a number of previous studies. Many investigations have shown that the values of capillary pressure and saturation do not uniquely specify the state of the system. IAV provides a natural yardstick for defining the role of scale in multiphase fluid properties. Laura J. Pyrak-Nolte presented results, which were aimed at investigating whether or not IAV provides a state-function-like description of the flow properties, and if so, what does this function look likes for synthetic micro-models. In addition, she discussed results from measurements of interfacial area per volume (IAV) in a natural three-dimensional porous medium, i.e. sandstone, for imbibition and drainage experiments.

The drying of liquid-saturated porous media is typically approached using macroscopic continuum models involving phenomenological coefficients. However important insights on these coefficients can be obtained by a more fundamental study at the pore- and pore-network levels. **A. K. Stubos** discussed these issues while presenting their pore scale modelling technique for isothermal drying in porous media. One novel aspect of recent research on multiphase flow is the inclusion of the wettability state of porous medium. Importance of such research can be realized in both groundwater aquifer remediation techniques involving NAPLs and also in oil reservoir gas injection processes such as WAG (water-alternating-gas). **Ken Sorbie** and **M.I.J. van Dijke** discussed these issues in detail. They also presented methodologies for pore-scale modelling of three-phase flow in porous media. Ken Sorbie noted that the conventional view at the pore scale for a strongly water wet system is that, at capillary equilibrium, the wetting phase (water) resides in the smallest pores the most non-wetting phase (gas) resides in the largest pores and the intermediate wetting phase (oil) occupies the middle sized pores. This view is broadly correct and leads to some predictions on the saturation dependencies of the transport properties such as the three-phase relative permeability (3PRP) and the three-phase capillary pressure (3PCP). However, if the system is not uniformly water wet, the possible range of three-phase pore occupancies widens considerably, although it does so in a complex but understandable manner. In the presentation, Ken Sorbie presented a review of the main findings from their work on this topic over the last few years and other outstanding issues. For example, he gave (a) a description of relative permeability where phases move but they are discontinuous; and (b) the issue of deriving genuine three-phase capillary entry conditions rather than using quasi two-phase entry conditions. **M.I.J. van Dijke** noted that one determining factor in pore-scale network modelling of multi-phase flow is the capillary entry pressure. The common assumption in three-phase flow has been that capillary entry conditions for piston-like displacement in three-phase flow are the same as those in two-phase flow, for example when gas displaces oil in the presence of water wetting films. In his presentation, M.I.J. van Dijke discussed a general formulating to determine the capillary entry pressure of two bulk phases in a pore of angular cross-section where also a third phase may be present. Their results indicated that the capillary entry pressures indeed depend on the pressure in the remaining third phase if the underlying cross-sectional fluid configurations contain this phase. However this dependence may disappear if layers of intermediate-wetting phase completely separate the wetting and the non-wetting phases. They showed that the general formula is also valid for determination of the capillary entry pressures associated with the spreading and retraction of these layers.

2.2 Dynamic effects

The discussion on dynamic effects started with a presentation from **Helge Dahle** in the afternoon of 23 June 2004. He presented a simple bundle of capillary tube model for investigating dynamic effects in P^c-S relationships. He explained that due to the simplicity of these models, they are ideal tools to provide understanding of the underlying mechanisms that lead to non-equilibrium effects. Next, **Twan Gielen** discussed a pore-scale network model to test the dynamic P^c-S relationship. His model consisted of a three-dimensional network of cylindrical tubes (pore throats) connected to each other by spherical pore bodies. The dependence of the dynamic coefficient on soil and fluid properties was discussed. His results showed that the dynamic effect may be important when a large pressure gradient is imposed on the fluids. **M. Al-Gharbi** presented another dynamic pore-scale model for simulating various types of fluid invasion in porous media. He explained that such a model can help us in predicting events that are observed in the microscopic experiments such as swelling of the wetting layers and meniscus oscillations. Besides, with the model it will be possible to address if multiphase flow involves significant transport of disconnected non-wetting phase, even at typical reservoir flow rates, or whether this phenomenon is restricted to low capillary numbers.

The discussion on dynamic effects continued in the morning session on 25 June 2003. **John L. Nieber** started the session and brought to the notice some results of recent mathematical analyses of the conventional model for variably saturated flow, the Richards equation. As he explained, the equation is unconditionally stable for homogeneous as well as heterogeneous unsaturated porous media. However, alternative models need to be sought to identify possible equation forms that would admit conditionally unstable flows. He noted that one such form is the dynamic capillary pressure-saturation relationship. John L. Nieber gave an overview of their work on mathematical and numerical analyses of gravity-driven unstable flows in unsaturated porous media. He also presented their research efforts towards characterizing the form and quantifying the parameters associated with the first-order relaxation model based on experimental evidence.

S. Majid Hassanizadeh presented a series of experiments involving water and PCE to determine dynamic effects. Quasi-static and dynamic capillary pressure curves, measured for primary drainage, main drainage and main imbibition cases, were presented. Theory suggests the dynamic drainage curves fall higher than corresponding quasi-static curves, and dynamic imbibition curves fall lower than corresponding quasi-static curves. The experimental results presented by S. M. Hassanizadeh clearly supported the theoretical indication and presence of dynamic effects. **Sabine Manthey** - presented a numerical study to determine dynamic effects on the macroscale in porous media with spatially correlated random heterogeneities. Her work suggested that a macroscopic dynamic coefficient could be determined. However the coefficient depends on the water saturation, variance of the intrinsic permeability, and size of the domain. **Zohreh Tavassoli** discussed an analytical model to analyse oil recovery processes during counter current imbibition. In their work, a wetting phase (water) is defined to displace the non-wetting phase under the influence of capillary forces such that the non-wetting phase moves in the opposite direction to the water. It was explained that this model can be used to for problems relating to water flooding in hydrocarbon reservoirs, or the displacement of non-aqueous phase liquid (NAPL) by water. It was shown that the formulation reproduces experimental data accurately.

2.3 Upscaling techniques

Discussion on upscaling multiphase processes started on 24 June. **M. Sahimi** described a method for scale-up of the geological model of an oil reservoir based on the use of wavelet transformations. The wavelets systematically coarsen the fine-scale model of the reservoir where a detailed grid structure is not needed, while at the same time preserve the fine details of the geological model where most of the fluid flow in the reservoir occurs. The accuracy and efficiency of the method was demonstrated during the presentation. **Tom Hou** discussed a dynamic multiscale method for computing nonlinear partial differential equations with multiscale solutions. He explained that the main idea was to construct semi-analytic multiscale solutions local in space and time. This is then used to construct the coarse grid approximation to the global multiscale solution. Such approach overcomes the common difficulty associated with the memory effect in deriving the global averaged equations for incompressible flows with multiscale solutions. It provides an effective multiscale numerical method for computing two-phase flow through heterogeneous porous media and incompressible Euler or Navier-Stokes equations with multiscale solutions. **R. LeNormand** discussed the effect of heterogeneity on unsteady-state core-level displacements. He demonstrated that if the results are interpreted as if the core were homogeneous, significant errors in calculation of both the relative permeability (K_r) and capillary pressure (P^c) can occur. A series of high-resolution numerical simulations performed on heterogeneous permeability fields of various correlation lengths were described. Pressures and fractional flows calculated at the ends of the core, as well as saturations along the length of the core, mimicking in-situ measurements were presented. **M. Panfilov** presented a macroscale model of two-phase flow with interior structure and nonlinear mixing in heterogeneous porous media. He explained that for a particular type of phase structure formed by mobile interfaces in the form of meniscus, a new macroscale model is derived. The new elements of the model were: i) the relative permeabilities depend both on saturation and on a parameter responsible for the phase structure; ii) a new term describing vector field of capillary forces applied to meniscus appears in the momentum balance equation; iii) a supplementary equation describing the meniscus transport appears. The model was obtained within the framework of a phenomenological approach, with replacing the interior phase structure by a continuum capillary vector field, and with introducing coordination relationships for the velocity field. **Peter King** explained the need for upscaling in his presentation. This is an important part of reservoir modelling and involves going from the fine grid geological description of a reservoir and coarsening the grid cells so that flow simulation can take place. Mathematically this is equivalent to "integrating out" or "averaging out" the short-range fluctuations in the problem. This is very similar to the averaging out of random fluctuations in quantum field theory, which is used frequently in statistical physics. **Rainer Helmig** gave an overview of different kinds of techniques for upscaling multiphase flow processes (this was further discussed by **G. E. Pickup**). R. Helmig explained that for the description of multiphase flow processes, it is necessary to identify capillary pressure-saturation-relative permeability relationships relationship on each scale. An upscaling method for multiphase flow processes in heterogeneous porous media, which are dominated by capillary effects, was presented. Their results confirmed a number of issues, for example, (1) the macroscopic anisotropies are amplified by multiphase flow effects. The resulting anisotropies are no longer constant but depend on the saturation, (2) the residual saturation is spatially dependent (3) the effective parameters are subject to hysteresis effects. Their results indicate that upscaling methods need to take into account the relative permeability-saturation relationship and the capillary pressure-saturation relationship. Furthermore, it appears necessary to regard the relative permeability-saturation relationship as a tensor property rather than a scalar property. **Gilliane E. Pickup** discussed about multistage upscaling. She rightly pointed out that reservoirs are often composed of an assortment of rock types giving rise to permeability heterogeneities at a variety of length-scales. To predict fluid flow at the full-field scale, it is necessary to be aware of these different types of heterogeneity, to recognise, which are likely to have important effects on fluid flow, and to capture them by upscaling. In fact, it may be necessary to have a series of stages of upscaling to go from small-scales (mm or cm) to a full-field model. When there are two (or more) phases present, we also need to know how these heterogeneities interact with fluid forces. At small-scales, capillary effects may dominate, while at larger scales gravity effects may be important. She also pointed out in continuation of Helmig's presentation that while choosing a method, the effect of numerical dispersion also has to be considered. G. E. Pickup presented an upscaling study using a model of a North Sea oil reservoir in a deep marine depositional environment. The reservoir was produced by aquifer support, so we had a two-phase system. Geologists had identified 6 different genetic units (rocks types), including massive sandstone, inter-bedded sandstone and mudstone, and mudstone with injected sandstone. These units were modelled using different approaches, depending on the scale and magnitude of heterogeneities.

3. Final Programme

The workshop consisted of a number of sessions spread over three days. The presentations by the senior researchers were long talks of 40 minutes each with 20 minutes of discussion. The presentations by the young researchers were short talks of 20 minutes each with 10 minutes of discussion.

Monday, June 23, 2003

08:30-09:00	Registration
09:00-09:05	Welcome by S. M. Hassanizadeh
09:05-09:15	Introduction by Andreas N. Alexandrou (ESF Representative)
09:15-12:30	**Pore-scale Network Modelling I** Chair: Sahimi, M., University of Southern California, USA

09:15-09:55	Valvatne, P. Imperial College, UK	Predictive pore-scale modelling of multiphase flow in mixed-wet media
09:55-10:15	Discussion	
10:15-10:30	Tea Break	
10:30-	Pyrak-Nolte, L.	Measurement of Equilibrium Values

11:10	Purdue University, USA	of Interfacial Area per Volume on Micro-Models and Sandstone
11:10-11:30	Discussion	
11:30-12:10	Stubos, T National Institute for Scientific Research 'DEMOKRITOS', Greece	Pore network modelling of isothermal drying in porous media
12:10-12:30	Discussion	
12:30-13:30	Lunch	
13:30-15:00	**Pore-scale Network Modelling II** Chair: Pyrak-Nolte, L., Purdue University, USA.	
13:30-14:10	Sorbie, K. Heriot-Watt University, UK	Pore scale modelling of three-phase flow in porous media of non-uniform wettability
14:10-14:30	Discussion	
14:30-14:50	M.I.J. van Dijke Heriot-Watt University, UK	Three-phase capillary entry conditions - layers of the intermediate-wetting phase
14:50-15:00	Discussion	
15:00-15:30	Tea Break	
15:30-17:30	**Dynamic effects and Pore-scale Network Modelling** Chair: Nieber, J.L., University of Minnesota, St. Paul, USA	
15:30-16:10	Dahle, H.K. University of Bergen, Norway	A bundle of capillary tubes model to investigate dynamic effects in the capillary pressure-saturation relationship
16:10-16:30	Discussion	
16:30-16:50	Gielen, T. W. J. Delft University of Technology, The Netherlands	Study of capillary pressure-saturation relationships using dynamic pore-scale network model
16:50-17:00	Discussion	
17:00-17:20	Al-Gharbi, M. Imperial College, London, UK	Pore-scale modelling of rate dependence of two-phase flow in porous media
17:20-17:30	Discussion	
18:30-	Workshop Dinner	

Tuesday, June 24, 2003

09:00-12:15	**Upscaling Multiphase Flow Processes I**	
	Chair: Sorbie, K., Heriot-Watt University, UK	
09:00-09:40	Sahimi, M. University of Southern California, USA	Use of multi-resolution wavelet transformations in upscaling of heterogeneous reservoirs
09:40-10:00	Discussion	
10:00-10:40	Hou, T. Y. California Institute of Technology, USA	Multiscale Modeling and Computation of Flow Through Heterogeneous Media
10:40-11:00	Discussion	
11:00-11:15	Tea Break	
11:15-11:55	Lenormand, R. Institut Français du Pétrole, France	Up-scaling of relative permeabilities at core and reservoir scales
11:55-12:15	Discussion	
12:15-13:30	Lunch	
13:30-15:30	**Upscaling Multiphase Flow Processes II**	
	Chair: Hilpert, M., John Hopkins University, USA	
13:30-14:10	Panfilov, M. INP de Lorraine - ENSG - LAEGO, France	Macroscale models of two-phase flow in heterogeneous media
14:10-14:30	Discussion	
14:30-15:10	King, P. R. Imperial College, UK	Probability Upscaling
15:10-15:30	Discussion	
15:30-16:00	Tea Break	
16:00-17:30	**Upscaling Multiphase Flow Processes III**	
	Chair: King, P.R., Imperial College, UK	
16:00-16:40	Helmig, R. University of Stuttgart, Germany	Upscaling of two-phase-flow processes in porous media
16:40-17:00	Discussion	
17:00-17:20	Pickup, G.E. Heriot-Watt University, UK	Multi-Stage Upscaling
17:20-17:30	Discussion	

Wednesday, June 25, 2003

Dynamic Effects and Continuum-scale Modelling

09:00-11:45

Chair: Dahle, H.K., University of Bergen, Norway

09:00-9:40	Nieber, J. University of Minnesota, St. Paul, USA	Dynamic Capillary Pressure Mechanism for Instability in Gravity-Driven Unstable Flow; Overview of Progress and Quantification of Model Parameters
9:40-10:00	Discussion	
10:00-10:20	Hassanizadeh, S.M. Delft University of Technology, The Netherlands	Experimental evidence of dynamic capillary pressure effects in two-phase flow
10:20-10:30	Discussion	
10:30-10:45	Tea Break	
10:45-11:05	Manthey, S. University of Stuttgart, Germany	Dynamic effects on the macroscale in porous media with spatially correlated random heterogeneities
11:05-11:15	Discussion	
11:15-11:35	Tavassoli, Z. Imperial College, UK	Semi-Analytic Analysis of Counter-Current Imbibition
11:35-11:45	Discussion	

11:45-12:45 Closing Remarks / Discussion

12:45- Lunch

4. Final List of participants

	Participants (alphabetical order)	Mailing Address
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