European Science Foundation (ESF) Exploratory Workshop

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

23-25 June 2003

BOOK OF ABSRACTS

Convenors:

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FOREWORD

The main focus of this workshop is on the identification and quantitative analysis of the following major issues:

1. Upscaling of pore-scale multiphase flow processes to the core scale;

2. Upscaling of core-scale multiphase flow processes to field scale;

3. Techniques for testing the upscaled theories with the aid of laboratory experiments;

4. Dynamic effects in multi-phase flow processes.

For the design of soil and groundwater remediation techniques and, for making reliable predictions about the efficiency of these techniques, it is necessary to identify and understand multiphase flow and transport processes at the microscopic (pore) scale and to describe their manifestation at the macroscopic (core) scale and field scale. Furthermore, while modeling at the field scale, it is usually not feasible to take all small scale heterogeneities into account. But one must incorporate the effects of such heterogeneities into field-scale descriptions. A number of presentations relate to various upscaling techniques and issues.

Current descriptions of macroscopic multiphase flow behaviour are based on an empirical extension of Darcy's law supplemented with assumed algebraic relationships among capillary pressure, relative permeability, and saturation. However, these empirical equations are not always sufficient to account fully for the physics of multiphase flow. In general, more pore-level knowledge of flow and transport processes will help with 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 a Lattice-Boltzman model. Results of research based such methods are presented in this workshop.

Traditionally, capillary pressure-relative permeability-saturation 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. There is ample experimental evidence that P^c-S relationships depend on the rate of change of fluid saturation. This dependence is known as the dynamic effect. Accounting for dynamic effects in P^c-S relationships may require the inclusion of a new term related to the time rate of saturation. This additional term is believed to be due to upscaling from pore to core and to field scale. A number research papers related to experimental and numerical studies of dynamic effects are presented here.

We greatly appreciate a financial support provided by the European Science Foundation (ESF) that has made this workshop possible. Also, we would like to thank David Oostveen and Ms. Margreet Evertman for providing valuable administrative and logistic support for the last one year.

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23 June 2003:

Workshop Session: Pore Scale Modelling

Predictive pore-scale modelling of multiphase flow in mixed-wet media

Per Valvatne[1]*, Mohammad Piri*[1]*, Xavier Lopez*[1] *and Martin Blunt*[1]

We show how to predict flow properties using pore-scale modelling with a library of networks that describe the disordered topology of different media. The network from the library that most closely matches the geological structure of the sample of interest is chosen and its properties are tuned to match readily available experimental data. Then predictions of single and multiphase properties are made with no further adjustment of the model.

We illustrate this approach through extensive comparison with data using only Berea sandstone and sand-pack networks. First we study the single-phase rheology of shear-thinning polymers. The beaker dependence of viscosity on shear rate is used to develop a pore-scale relationship between pressure drop and flow rate. For four different samples we successfully predict the variation of apparent viscosity with flow rate. The only adjustment to the networks needed is a length rescaling to match the absolute permeability of the experimental system. For multiphase flow, the pore-size distribution is adjusted to match mercury injection capillary pressure, keeping the rank order of pore sizes and the network topology fixed. We then predict a wide range of primary drainage relative permeabilities, including an extensive gas/oil dataset. For waterflooding we introduce a method for assigning contact angles to match measured wettability indices. For three mixed-wet datasets successful predictions of waterflood relative permeability and recovery are made. The network model can also compute three-phase permeabilities, and predictions are presented for steady-state experiments in Berea sandstone, and dynamic displacements in sand and bead-packs, including a mixed-wet sample.

The aim of this work is not simply to match experiments - we use easily acquired data to predict difficult to measure properties, such as two and three-phase relative permeability. Furthermore, the variation of these properties in the field, due to wettability trends and different pore structures can now be predicted reliably.

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Measurement of Equilibrium Values of Interfacial Area per Volume on Micro-Models and Sandstone

Laura J. Pyrak-Nolte[1,2], Jiangtao Cheng[1], Daiquan[2] Chen and Nicholas Giordano[1]

Recent theoretical developments suggest that interfacial area per volume (IAV) plays an important role in scaling theories for the flow of multiple fluid phases in a porous medium. Many investigations have shown that the values of capillary pressure (Pcap) and saturation (S) do not uniquely specify the state of the system. A single value of relative volume saturation can correspond to infinitely different distributions of two phases within the volume. IAV provides a natural yard-stick for defining the role of scale in multiphase fluid properties. The dimensional units of interfacial area per volume is a spatial frequency (inverse length) that breaks scale invariance. In this study, we investigate 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, we present results from measurements of interfacial area per volume (IAV) in a natural three-dimensional porous medium, i.e. sandstone, for imbibition and drainage experiments. Measurements of interfacial area per volume as a function of capillary pressure and saturation were made on micro-models of pore structures. Photo-projection lithography was used to make transparent micro-models that were 600 μm x 600 μm with an aperture of 1.08 μm and in-plane features as small as 6 microns. Two phase flow measurements were performed on the micro-models using nitrogen gas and decane for a series of drainage and imbibition cycles. The initially decane-saturated micro-models were invaded with nitrogen by the application of pressure in increments. At each pressure increment, the system was allowed to equilibrate, and the saturation and distribution of each phase was digitally imaged and analyzed. We observed that the Pcap - S - IAV surface appears to be a smooth, single valued surface. The value of the IAV is measured to within a typical 5% experimental error in analyzing the digital photo-micrographs. We also observed that the magnitude of IAV was significantly different between the two types of models. Correlated micro-models exhibited values of IAV that were smaller by about a factor of 2, than that found for the uncorrelated micro-model. We have used a Wood's metal injection technique to determine IAV in sandstone undergoing imbibition. Measurements were performed on sandstone samples measuring 52 mm in diameter and ranging from 25 mm to 100 mm in length. Wood's metal was used to represent a non-wetting fluid and ethylene glycol (EG) was used to represent a wetting phase fluid. The imbibition experiments were performed for pressure drops ranging from 0 MPa to 0.68 MPa. To determine the IAV for a sample injected with Wood's metal, images of the Wood's-metal-injected core were taken with a Scanning Electron Microscope (SEM). A custom computer code was used to analyze each SEM image to isolate the rock phase, the wetting phase (EG) and the non-wetting phase, and to calculate the interface between each of the two phases. Analysis of the images of the metal-injected sample found that interfacial length per area (ILA) values for the sandstone ranged from 0 to 150 per cm for the rock-metal interface and decreased from 680 to 20 per cm for the ethylene glycol - rock interface for pressures that ranged from 0 MPa to 0.68 MPa. For the metal-ethylene glycol interface, ILA values ranged from 0 to 7.5 per cm for the same pressure range. The investigation also found a break-though pressure between 0.027 and 0.034 MPa where metal saturation increased rapidly. Drainage and scanning drainage experiments are currently underway.

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Pore network modelling of isothermal drying in porous media

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The drying of liquid-saturated porous media is typically approached using macroscopic continuum models involving phenomenological coefficients. Insight on these coefficients can be obtained by a more fundamental study at the pore- and pore-network levels. In a first step, we present a model based on a pore-network representation of porous media that accounts for various processes at the pore-scale. These include mass transfer by advection and diffusion in the gas phase, viscous flow in liquid and gas phases and capillary effects at the gas-liquid menisci in the pore throats. We consider isothermal drying in a rectilinear horizontal geometry, with no-flow conditions in all but one boundary, at which a purge gas is injected at a constant rate. The problem is mainly characterized by two dimensionless parameters, a diffusion-based capillary number, Ca, and a Peclet number, Pe, in addition to the various geometrical parameters of the pore network. Results on the evolution of the liquid saturation, the trapped liquid islands and the drying rate are obtained as a function of time and the dimensionless parameters. For fixed parameter values, the drying front does not in general obey invasion percolation rules. However, as drying progresses, and depending on the relative magnitude of the capillary and Peclet numbers, a transition to a percolation-controlled problem occurs. Effects of capillarity and mass transfer on saturation profiles and drying rates are discussed.

In a further step, we attempt to quantify liquid film effects on the isothermal drying of porous media. In the approach taken, capillarity-driven film flow transports liquid to an evaporation interface, far from the interface of liquid clusters. Through a transformation, we map the drying problem with liquid films, to the Laplace equation around the percolating clusters. From its solution, all properties of drying problem are obtained in terms of the capillary number. We find that film flow can be an important mechanism in drying, consistent with experimental evidence.

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Pore scale modelling of three-phase flow in porous media of non-uniform wettability

K.S. Sorbie[1], M.I.J. van Dijke[1]

There has been much interest and research activity in recent years on the simultaneous flow of three phases through porous media. This work has been stimulated by developments both in groundwater aquifer remediation involving NAPLs and also in oil reservoir gas injection processes such as WAG (water-alternating-gas). One novel aspect of recent research by several groups is that the issue of wettability state of the porous medium has been considered. 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).

When 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 this paper, we present a review of the main findings from our work on this topic over the last few years. Firstly, we describe our general analytical theory of three-phase pore occupancy in systems of arbitrary wettability in very simple pore systems. We then go on to describe the full implementation of the displacement mechanisms in a 3D pore scale network simulator. This leads to the prediction of new "multiple" displacements during capillary dominated WAG type processes, which are also observed in micromodel experiments. The calculations from the full three-phase network model are compared with the results from our simpler analytical model and agreement is seen under certain circumstances, which we explain. We also show some direct comparisons between the (2D) three-phase micromodel experimental observations and the pore-scale calculations and good agreement is found. Finally, we will review some current outstanding issues on the pore scale modelling of three-phase flow through non-uniformly wetted pore systems which are still not fully resolved and are the subject of current research. These include (a) the 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. Some future challenges are outlined and some relevant experiments are proposed which can test recent theory.

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Three-phase capillary entry conditions - layers of the intermediate-wetting phase

M.I.J. van Dijke[1] *and K.S. Sorbie*[1]

One of the determining factors 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. Using the method of Mayer, Stowe and Princen (MS-P), we have derived a general formula 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 (van Dijke and Sorbie, J. Coll. Interface Sci. 260 (2003) 385). We have found that the capillary entry pressures do depend on the pressure in the remaining third phase if the underlying cross-sectional fluid configurations contain this phase. This dependence only vanishes when layers of the intermediate-wetting phase completely separate the wetting and the non-wetting phases. Extending the previous findings, we show that the general formula is also valid for determination of the capillary entry pressures associated with the spreading and retraction of these layers. Numerical examples of the interdependence of the radii of curvature, which are equivalent to the capillary entry pressures, are given. For pores of triangular cross-section effects on the gas-oil capillary entry pressures of the oil spreading coefficient, the degree of wettability and the pore aspect ratio have been investigated. In most cases strong and non-monotonic dependence of the effective gas-oil radius on the oil-water arc meniscus is found, which reflects the dependence of the capillary entry pressure on the pressure in the water wetting film.

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Workshop Session: Dynamic effects and pore-scale network modelling

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A bundle of capillary tubes model to investigate dynamic effects in the capillary pressure-saturation relationship

H.K. Dahle[1], M.A. Celia[2], S.M. Hassanizadeh[3]

Recent theoretical and experimental developments suggest that the equilibrium capillary-pressure-saturation relationship should be enhanced by a dynamic term. Furthermore, thermodynamic considerations based on volume averaging theory imply that the dynamic term should be proportional to the time-derivative of saturation.
In this work we will use a bundle of capillary tubes model to investigate possible dynamic effects in the Pc-S relationship. These models can provide understanding of the underlying mechanisms that lead to non-equilibrium effects. In particular we interpret these effects to be partly due to viscosity. In addition this model may be used to quantify the magnitude of dynamic effects.

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Study of capillary pressure-saturation relationships using a dynamic pore-scale network model

Twan Gielen[1], Hans Nordhaug[2], Helge Dahle[2], Majid Hassanizadeh[1] and Michael Celia[3]

Current theories of multiphase flow rely on capillary pressure-saturation relationships that are commonly measured under static conditions. Recently, new multiphase flow theories have been proposed that include a new capillary pressure-saturation relationship that is valid under dynamic conditions. In this relationship, the difference between the two fluid phase pressures is referred to as dynamic capillary pressure. The dynamic capillary pressure is assumed to be a function of saturation and its time rate of change:

$$P^c_{dynamic} = P^n - P^w = P^c_{static} - \tau \frac{\partial S^w}{\partial t}$$

The dynamic effect is governed by the coefficient t that, in general, may be a function of saturation.

In this work, we test this relationship using a pore-scale network model. Our model consists of a three-dimensional network of cylindrical tubes (pore throats) connected to each other by spherical pore bodies. We perform numerical experiments wherein both static and dynamic procedures for measurement of capillary pressure-saturation curves are simulated. We show that the dynamic correction term may indeed be important when a large pressure gradient is imposed on the fluids. We determine the value of the coefficient t and investigate its dependence on soil and fluid properties.

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Pore-scale modelling of rate dependence of two-phase flow in porous media

M. Al-Gharbi[1] *and M. Blunt*[1]

The pore scale network is a representation of the void space of the reservoir rock. Wide voids of the reservoir rocks are represented by the pore bodies which are interconnected by narrow spaces called pore throats. Flow through these networks is simulated using one of two types of model. The majority of the existing pore network models are quasi-static models. At each stage in the displacement, a fixed capillary pressure is imposed on the network and the final static position of fluid-fluid interfaces is determined. However, there are several cases where the quasi-static displacement is not valid such as fracture flow (high flow rate), gas condensate reservoirs (low interfacial tension) and polymer injection (high viscosities). Therefore, studying dynamic fluid displacements through the reservoir pores becomes important. Dynamic network models that explicitly account for viscous forces are the second type of model, but are much less frequently used. Indeed, to date, no pore-scale model has been able to account properly for basic rate-dependent phenomena observed in micromodel experiments, such as the swelling of wetting layers and snap-off.

The aim of this research is developing a fully dynamic pore-scale model for modeling various types of fluid invasion, including reasonable assumptions and accurate formulas, which may help us in predicting the events that are observed in the microscopic experiments such as swelling of the wetting layers and meniscus oscillations.

With this model, we hope that we will be able to address whether or not 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.

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24 June 2003:

Workshop Session: Upscaling multiphase flow processes

Use of multi-resolution wavelet transformations in upscaling of heterogeneous reservoirs

M. Sahimi[1]

We describe 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. In addition, unlike almost all the current scale-up methods, the wavelet-based method is applicable to fractured reservoirs. The accuracy and efficiency of the method is demonstrated by its applications to three problems, namely, the computation of the effective permeabilities of the coarsened blocks; the pressure transient analysis for a given reservoir, and simulation of miscible displacements over a while range of the values of the mobility ratio of the displacing and displaced fluids.

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Multiscale Modeling and Computation of Flow Through Heterogeneous Media

T. Y. Hou[1]

Many problems of fundamental and practical importance contain multiple scale solutions. Composite materials, flow and transport in porous media, and turbulent flow are examples of this type. Direct numerical simulations of these multiscale problems are extremely difficult due to the range of length scales in the underlying physical problems. Here, we introduce a dynamic multiscale method for computing nonlinear partial differential equations with multiscale solutions. The main idea is to construct semi-analytic multiscale solutions local in space and time, and use them 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. In a related effort, we introduce a new class of numerical methods to solve the stochastically forced Navier-Stokes equations. We will demonstrate that our numerical method can be used to compute accurately high order statitstical quantites more efficiently than the traditional Monte-Carlo method.

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Up-scaling of relative permeabilities at core and reservoir scales

R. Lenormand[1]

In this seminar, I first discuss the effect of heterogeneity on unsteady-state core-level displacements. I show that if the results are interpreted as if the core were homogeneous, significant errors in calculation of both the relative permeability (Kr) and capillary pressure (Pc) can occur. I describe a series of high-resolution numerical simulations performed on heterogeneous permeability fields of various correlation lengths. Pressures and fractional flows were calculated at the ends of the core, as well as saturations along the length of the core, mimicking in-situ measurements. For each grid block in the high-resolution simulation, simple Corey exponent Kr curves were used and Pc was set to zero. First, the results are interpreted as if the sample were homogeneous using JBN analysis. With this approach, it is impossible to fit the saturation profiles within the core. This is due to the effects of heterogeneity and the inability for a single Kr curve to capture the smearing of the invading front at all length scales. The saturation profiles can be fitted by history matching only when a pseudo-Pc is included even though at the local scale P^c=0. Surprisingly, this numerical pseudo-Pc has the same shape as a real laboratory capillary pressure curve. Finally, I show how tracer tests on core samples can be used to quantify the effect of heterogeneity and decouple the effects of heterogeneity from the effects of petrophysical properties. This result is generalized for upscaling applications at reservoir scale.

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Macroscale models of two-phase flow with interior structure and nonlinear mixing in heterogeneous porous media

M. Panfilov[1]

A two-phase flow in porous media is characterized by various geometrical phase structures within porous space. 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 are: 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 is 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. The homogenisation technique as an alternative tool to derive the model is also discussed. The closing relations for the model are obtained by a microscale network modelling. For a large class of processes the model may be transformed into a single saturation-transport equation, which is however different from the traditional Buckley-Leverett model. The capillary phenomena are described in terms of convective transport with keeping equation hyperbolicity. Various analytical and numerical solutions are obtained and compared with the classical model. An experimental method to determine the dynamic capillary function is suggested.

In the case of a medium with heterogeneous stochastic permeability, the obtained model is used to study the dynamic mixing phenomena under fluid displacement. A macroscale model of first order is obtained by two-scale stochastic homogenisation with keeping the hydrodynamic dispersion effects. It is shown that in two-phase systems, the mixing is described both by nonlinear dispersion and by convective term renormalization. The two-phase dispersion tensor is shown to be a non-monotonous function of saturation, viscosity ratio and capillary number. The results obtained are completed with a direct 3D numerical simulation of two-phase displacement in a heterogeneous medium.

The two-phase dispersion effect is related with hydrodynamic instability. To describe instability in terms of two-phase dispersion, we have obtained a homogenized model for the initial stage of a Cauchy problem describing fluid displacement. The dispersion effect is shown to infinitely grow in the unstable case. In contrast, in the case of a highly viscous displacing fluid, an anti-dispersion effect arises, which has another grow rate than that of dispersion. Due to this, both the effects are equilibrated since a moment, giving rise to travelling-wave solutions.

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Probability Upscaling

P. King[1], I. Neuweiler[1]

Upscaling is an essential part of reservoir modelling. It 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. In this talk the need for upscaling will be given as well as the more technical details of current research ideas into applying these field theory ideas to practical upscaling problems.

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Upscaling of two-phase-flow processes in porous media

R. Helmig[1] *S. Manthey*[1] *and H. Eichel*[1]

In heterogeneous porous media, the influence of the capillary and gravity forces is scale-dependent. For the description of, for example, DNAPL-infiltration processes, it is necessary to identify the relative permeability-saturation relationship and the capillary pressure-saturation relationship on each scale. In this presentation, we first give a short overview of the different kinds of upscaling techniques. Moreover, the scale-dependent processes will be shown. In detail, an upscaling method for multiphase flow processes in heterogenous porous media which are dominated by capillary effects will be presented. Capillary effects are dominant when small-scale (cm to dm) heterogenities are considered. The concept is applied to examples where the multiphase flow equation is solved for geostatistically generated heterogeneity fields with a percolation model. The computation confirmed experiments and analytical solutions:

- The macroscopic anisotropies are amplified by multiphase flow effects. The resulting anisotropies are no longer constant but depend on the saturation
- The residual saturation is spatially dependent
- The effective parameters are subject to hysteresis effects

These results imply 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. With the help of an experiment, we will show the influence of the different upscaling techniques on the simulation results and discuss the uncertainties of the different model concepts.

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Multi-Stage Upscaling

G. E. Pickup[1], K. D Stephen[1], J. Ma[1], and J. D. Clark, [1,2]

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, we may require 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. We have carried out 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. The smallest-scale models were constructed at the bed-scale, with cells of about 1 cm. We used 3 stages of upscaling to reach the full-field model.

There are many different upscaling methods, including permeability averaging, single-phase pressure solution methods, and two-phase upscaling, using both steady-state and dynamic methods. When choosing a method, the effect of numerical dispersion also has to be considered. This spreads out the front as the grid size increases. Two-phase dynamic upscaling can compensate for this, but it is difficult to apply and is time-consuming. We carried out a series of tests on a fine-scale 1D model to determine a combination of two-phase upscaling methods which was both feasible to apply and reasonably accurate. The optimum combination was: the capillary equilibrium method for stage one, dynamic upscaling for stage 2, and the viscous-dominated steady-state method for stage 3. This approach was then applied to our field-scale model.

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Nonlinear Two-Phase Mixing in Heterogeneous Porous Media

N.Jamaleddine[1]*, M. Panfilov*[1]

Abstract. For two-phase immiscible flow through a heterogeneous porous medium in gravity field but with neglected capillary pressure, a macroscale model of first order is derived by a two-scale homogenization method with capturing the effects of fluid mixing. The mixing is manifested in the form of a nonlinear hydrodynamic dispersion and a transport velocity shift. The dispersion tensor is shown to be a nonlinear function of saturation. In the case of flow without gravity this function is proportional to the fractional flow derivative and depends on the viscosity ratio. For a flow which is 1D at the macroscale, the dispersion operator remains 3D and can be calculated in a analytical way. In the case of gravity induced flow, the longitudinal dispersion as the function of saturation is negative within some interval of saturation values. Numerical simulations of the microscale problem justifies the theoretical results of homogenization.

[1]LAEGO - ENS de Géologie - INP de Lorraine, France

25 June 2003:

Workshop session: Dynamic effects and continuum scale modelling

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Dynamic Capillary Pressure Mechanism for Instability in Gravity-Driven Unstable Flow; Overview of Progress and Quantification of Model Parameters

John L. Nieber[1], Aleksey Sheshukov[1], Andrey Egorov [2], Rafail Dautov[2]

The results of recent mathematical analyses have shown that the conventional model for variably-saturated flow, the Richards equation, is unconditionally stable for homogeneous as well as heterogeneous unsaturated porous media. In response to this result, alternative models have been sought to identify possible equation forms that would admit conditionally unstable flows. Just such an alternative form has been identified in a model that employs a generalized dynamic capillary pressure-saturation relationship. One specific form of this dynamic capillary pressure-saturation relationship is expressed by the first-order relaxation model described by Hassanizadeh and Gray (1993). In this presentation we will present an overview of our work on the mathematical and numerical analyses of gravity-driven unstable flows in unsaturated porous media. While continuing to work on these mathematical and numerical analyses, our newest research effort is toward characterizing the form and quantifying the parameters associated with the first-order relaxation model based on experimental evidence. In previous work we examined the effect of the magnitude of the relaxation coefficient, but we had not as yet directly related the coefficient to experimental observations. In the second part of this presentation we will suggest a rational saturation dependent form for the relaxation coefficient, and attempt to quantify the magnitude of the coefficient based on experimental observations.

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Experimental evidence of dynamic capillary pressure effects in two-phase flow

Oubbol Oung[1],S. Majid Hassanizadeh[2],Adam Bezuijen[1]

There is compelling experimental evidence reported in the unsaturated flow literature that capillary pressure is perhaps not only a function of saturation but may also depend on the rate of flow. This is known as the dynamic or non-equilibrium effect. In this work, we report on a recent series of experiments involving water and PCE. Quasi-static as well as dynamic capillary pressure curves are measured for primary drainage, main drainage and main imbibition cases. As suggested by the theory, dynamic drainage curves fall higher than corresponding quasi-static curves, and dynamic imbibition curves fall lower than corresponding quasi-static curves. The data are used to estimate the dynamic capillary pressure coefficient.

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Dynamic effects on the macroscale in porous media with spatially correlated random heterogeneities

Sabine Manthey[1]

Based on thermodynamic theories Hassanizadeh and Gray (1993) have shown that by volume averaging conservation equations formulated for the pore scale, a dynamic capillary pressure-saturation relationship is introduced. Applying numerical experiments it will be investigated whether the same holds true for upscaling the P^c-S on the macroscale. The static and dynamic P^c-S curves are computed for spatially correlated random fields with log normal distributions with the two-phase module of the simulator MUFTE_UG. Subsequently the damping coefficient τ is quantified. Preliminary work suggests that a macroscopic τ can be identified. It depends on the water saturation. It will be attempted to show further dependencies e.g. on the variance of the intrinsic permeability.

Reference:

S. M. Hassanizadeh and W. G. Gray, 1993: Thermodynamic Basis of Capillary Pressure in Porous Media, Water Resources Research 29(10): 3389 - 3405.

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Semi-Analytic Analysis of Counter-Current Imbibition

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We study counter-current imbibition, where a wetting phase (water) displaces a non-wetting phase under the influence of capillary forces, such that the two phases move in opposite directions. We use an approximate analytical approach to derive an expression for saturation profile when the viscosity of the non-wetting phase is non-negligible. Our approach is applicable to water flooding in hydrocarbon reservoirs, or the displacement of non-aqueous phase liquid (NAPL) by water. We find the recovery of the non-wetting phase as a function of time for one-dimensional flow. We compare our predictions with experimental results from the literature. Our formulation reproduces experimental data accurately, and is superior to previously proposed empirical models. The use of this expression for field-scale dual porosity modelling of flow in fractured systems is discussed.

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