Rigorous upscaling of multiphase flow in fractured systems

EPSRC Research Proposal
CASE FOR SUPPORT

Rigorous upscaling of flow properties in fractured systems

Part 1 – Previous track record and relevant experience
Prof. Martin J. Blunt

Prof. Blunt is Professor of Petroleum Engineering at Imperial College London and is head of the Petroleum Engineering and Rock Mechanics Research Group (PERM). Before joining Imperial College in 1999, he was an Associate Professor of Petroleum Engineering at Stanford University in the US. He also worked for four years at BP’s Research Centre in Sunbury-on-Thames.

Prof. Blunt was principal investigator on the EPSRC proposal “Characterisation of multiphase flow properties using pore-scale modelling” that also attracted industrial funding from eight oil companies. This project is now continuing with entirely industrial support of £160,000 per year. The research used pore-scale modelling to predict multiphase transport properties [1-4] – this was an area once considered to be only of academic interest, but is now has potential commercial impact for the characterisation of flow properties in petroleum reservoir simulation. He was co-investigator on the EPSRC project “Pore-scale modelling of oil recovery by miscible gas injection” that developed new design criteria for the assessment of miscible injection projects [5]. He is currently co-investigator of the EPSRC project “Micro-mechanical studies of sand production problems in well bores” in collaboration with Schlumberger Cambridge Research and Prof. Chris Lawrence in the Department of Chemical Engineering at Imperial.

Most relevant to the current proposal is an industrially funded consortium “Improved simulation of faulted and fractured reservoirs.” The work is supported by the Department of Trade and Industry and eight oil companies that operate in the North Sea. This project is developing novel techniques to model flow in fractured hydrocarbon reservoirs that are more computationally efficient and accurate than current methods [6,7]. However, fundamental questions concerning the physical and mathematical basis of the models used have prompted consideration of a more in-depth study of flow in fractured systems that is the topic of this proposal.

Prof. Blunt’s research interests are in multiphase flow in porous media, with applications to improved oil recovery and contaminant transport and clean-up. He has published over 100 research papers and is on the editorial board of three international journals. He is one of the pioneers of streamline-based simulation that is now widely used in the oil industry [8]. Streamline methods are currently being applied to the study of fractured reservoirs [6]. One of his principal interests has been in the fundamentals of flow in fractured systems with applications to both hydrocarbon reservoir and groundwater problems. He was performed research covering many aspects of flow in fractures from laboratory experiments [9,10] and pore-scale modelling studies [11-13] to the development of innovative improved oil recovery schemes [14].

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Dr. Zohreh Tavassoli

Dr. Tavassoli is a post-doctoral Research Associate in Petroleum Engineering in the Department of Earth Science and Engineering at Imperial College London. She has a PhD in theoretical physics and has published several papers on the analysis of non-linear diffusion problems that are mathematically similar to the multiphase flow equations to be studied in this proposal [see full reference list in the CVs at the end of the proposal].

Recently she has been involved in the use of the integral method to analyse counter-current imbibition in fractured reservoirs [1,2] – theoretical expertise that is directly relevant to this project.


Department of Earth Science and Engineering, Imperial College

The department received the top rating for research (grade 5 A) in the last HEFC (Higher Education Funding Council) review. This is defined to mean excellence in research on an international scale. The Department comprises a large, interdisciplinary group of researchers investigating various aspects of earth science and engineering via theoretical, numerical and experimental work.
Part 2 – Description of proposed work

Background

Approximately one half of the world’s hydrocarbon reserves are contained in fractured reservoirs, with considerable reserves in the North Sea and the Middle East. However, often 80 – 95% of the oil in place is left underground, since most of the oil is retained in relatively low permeability matrix [1]. In nuclear waste containment, one key issue in considering long-term underground storage is how to predict the migration of radioactive species were they to escape. There is huge uncertainty associated with designing improved oil recovery schemes in fractured reservoirs and nuclear waste storage for two principal reasons: first the geological description of the fracture network is highly uncertain; and second the basic physical processes and their macroscopic description, particularly when they involve multiphase flow, are still not well established. This proposal will focus on the second of these issues.

The PI, Prof. Blunt, and Dr. Stephan Matthai currently have a project ‘Improved Simulation of Faulted and Fractured Reservoirs’ that is funded by a consortium of eight major oil companies that operate in the North Sea. The project is concerned with the development of improved simulation software, namely discrete fracture models that can capture geologically realistic fracture networks and field-scale streamline-based simulation using a dual porosity approach. Working on the project, particularly on the field-scale modelling, has uncovered one major inadequacy in our understanding of fractured systems: we do not know how, rigorously, to upscale multiphase flow in a fracture network to a continuum description, even for the simplest processes. The constraints of an industrially supported project preclude the proper investigation of this topic without further funding.

We propose to study multiphase flow in fractured reservoirs using a combination of theory, numerical simulation and analysis of experiment. To illustrate the problem, consider counter-current imbibition. Here water flowing in the fracture network imbibes into a water-wet matrix due to capillary forces. Oil is expelled from the matrix into the fractures, with the oil and water flowing in opposite directions, Fig. 1. This is the principal mechanism by which oil is recovered during water flooding in a water-wet or mixed-wet fractured reservoirs. Despite a large body of experimental literature on this process [2] there are some key issues that are poorly understood:

1. Can counter-current imbibition be adequately described using a conventional quasi-static continuum description of multiphase flow? Recent work has suggested that since capillary and viscous forces are of equal magnitude a non-equilibrium description of the transport equations is necessary [3]. Related to this is the observation of hyper-diffusion in imbibition experiments, where the advancing water front moves faster than the expected square-root-of-time behaviour [4].

2. Several authors have matched the average recovery from counter-current imbibition experiments to empirical expressions [see, for instance, 2,5]. Recently the PI and the named investigator (Dr. Tavassoli) have analysed this problem analytically and have accurately predicted experimental results (see Fig. 2 [6,7]). While this is promising, the approach needs to be applied to more realistic situations where gravitational and viscous forces also play a role in the fluid displacement. Furthermore, it requires more rigorous testing against experiment and direct numerical simulation.

3. An average description of the flow can be applied at the large scale – Fig. 3 – this is the dual porosity approach [8,9]. At the field scale, transport occurs through a fracture network with exchange of fluid with the matrix. This exchange is given a functional form that will match experimental results or empirical models (step 2). However, at present there is debate about how to do this: to date researchers have performed upscaling from a two- or three-dimensional system to an effective zero-dimensional model [10,11]. In contrast, we will upscale to a one-dimensional transport equations along the flow direction (defined by streamlines). This difference of approach leads to radically different field-scale predictions of behaviour [12].

4. For more complex processes, where there may be flow through the matrix and transport mediated by other physical processes, such as gravity (see point 2 above), the appropriate form of the upscaled equations is not known. Also it there is no
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procedure to account for flow in geometrically complex systems – to date all the analysis has assumed a simplistic fracture geometry.

The upscaling methodology

![Image of fracture and matrix flow](image)

**Fig. 1.** Counter-current imbibition occurs when a water-saturated fracture surrounds a matrix block containing oil. Due to capillary forces, the water spontaneously enters the matrix displacing oil into the fractures. This process will be studied analytically and numerically. In addition, other fracture flow processes, such as gas gravity drainage and oil/water flows under the influence of gravity will be analysed.

![Comparison of analytical and experimental recoveries](image)

**Fig. 2.** Comparison of analytical and experimental recoveries for counter-current imbibition (Fig. 1) as a function of a dimensionless time [6,7]. We will extend this technique to study a variety of displacement processes, described in Fig. 1.

![Diagram of fracture, matrix, and streamlines](image)

**Fig. 3.** At the large scale, flow and transport can be described by a dual porosity approach. We consider a modification of this model: flow along streamlines captures the flow field in a highly heterogeneous fracture network, while transfer between fracture and matrix is accommodated by appropriate one-dimensional equations along streamlines. These equations capture the average recoveries seen experimentally and determined analytically or numerically (Fig. 2).
Programme and Methodology
The research programme will follow a methodology that addresses the issues outlined above.

**Step 1 – Analytic computations for recovery in fractured systems**
The integral method [13] has proved a successful technique to construct approximate analytical solutions to the highly non-linear transport equations that characterise multiphase flow in porous media. A functional form for the spatial variation of the saturation profile is assumed and the governing equations are then solved in weak (integral form). The time-dependent coefficients that describe the spatial variation are then found using only ordinary partial differential equations. We have used this method to study one-dimensional counter-current imbibition successfully [6,7], Fig. 2.

We propose to extend the analysis to study other multiphase processes that are important in fractured systems, namely gas gravity drainage and oil/water imbibition under the influence of gravitational effects. For gravity controlled displacements two-dimensional problems will be solved to account for the competition between capillary imbibition that occurs in all directions and the vertical movement due to gravity. Also the problems will be solved in systems of different geometry – this will be important when we upscale our results to the field where the fracture geometries are not as simplistic as indicated for our idealised analysis (compare Figs 1 and 3).

To validate the models we will compare against available experimental data – the PI has good links with some of the leading experimental groups in this area, including Stanford University [14]. In addition, direct numerical simulation of the processes will be performed using a state-of-the-art discrete fracture code, CSP [15]. Many of these processes have received considerable experimental attention, but lack a coherent theoretical framework that allows the results to be applied to predict field-scale recovery.

One issue associated with both the numerical and analytical work is the assignment of multiphase flow properties, namely relative permeability and capillary pressure. Again, where possible, properties will be obtained by experiment, but there are several cases where such information is extremely difficult to obtain, or unavailable. To obtain physically valid transport properties, the predictions from pore-scale modelling will be used – this will be particularly important for the analysis of mixed-wet systems [16], where it has been shown that pore-scale predictions can reconcile apparently surprising experimental results [17,18] and make startling recovery predictions at the field scale [19]. This aspect of the research will link with the PI’s industrially funded consortium on pore-scale modelling.

**Step 2 – Validation or extension of a dual porosity approach**
In Fig. 3 our conceptual model of fracture flow at the field scale is that there is a flowing, permeable section of the reservoir (called the fractures) in communication with less permeable reasons (the matrix) with which it exchanges fluid. Consider an incompressible two-phase system. The relevant flow equations are [12]:

\[
\phi_f \frac{\partial S_{wf}}{\partial t} + \mathbf{v}_f \cdot \nabla S_{wf} + \nabla \cdot \mathbf{g} = -T ; \quad \phi_m \frac{\partial S_{wm}}{\partial t} = T \tag{1}\]

where the subscript \(f\) stands for flowing or fracture and \(m\) for matrix, representing the stagnant fraction. \(\mathbf{v}_f\) is the total velocity and \(\mathbf{g}\) is the acceleration due to gravity. \(f_{wf}\) is the fractional flow in the flowing fraction ignoring gravity.

\(T\) is the transfer function that accounts for the exchange of fluid between fracture and matrix. Conceptually, at the large scale, we consider flow to oriented along streamlines that follow the instantaneous flow field, while the transfer acts as a source or sink term. Defining a time-of-flight: \(\tau(s) = \int_0^s \frac{1}{|\mathbf{v}_f|} ds\) we derive the following equations:
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\[
\frac{\partial S_m}{\partial t} + \frac{\partial S_w}{\partial t} + \frac{1}{\phi_f} \nabla \cdot \mathbf{g} = -\frac{T}{\phi_f}; \quad \frac{\partial S_m}{\partial t} = \frac{T}{\phi_m} \quad (2)
\]

We will derive appropriate forms for the transfer function \( T \) corresponding to our analytical solutions. The approach is fairly simple – we associate the recovery in the matrix (Fig. 2) with the local matrix saturation. We then re-write a time-dependent recovery as a function of matrix and fracture saturations. This enables us to derive a physically valid \( T(S_{wm}, S_{wf}) \) that is not an explicit function of time.

One issue is how to determine \( T \) for situations when the boundary conditions (essentially the fracture saturation) are non-uniform, in contrast to the uniform boundary conditions used in the experiments and the analytic analysis. As mentioned earlier there is some controversy in the literature over how to do this [10,11,20]. We will perform direct numerical simulation that accounts explicitly for both the fracture and matrix and compare the results with one-dimensional numerical and analytical solutions of the transport equations (2). In particular this will establish the correct formulation for non-uniform boundary conditions.

The construction of analytical solutions to equations (2) will constructed to provide benchmarks for numerical validation and give insight into the controlling processes. The traditional approach to tackle such problems is through Laplace transforming the equations, and this method will be pursued here. We have already had some success with this in the study of counter-current imbibition [12].

On last issue is to determine the circumstances under which the dual porosity formulation is an appropriate description of the flow at the large scale. The combination of analytical results and numerical simulations will be used to determine whether or not this is an appropriate macroscopic formulation of the transport equations. In particular, a dual permeability model, that admits flow in the matrix, may be necessary when there is significant viscous-mediated transport in both fracture and matrix.

**Step 3 – Field-scale upscaling in realistic fracture geometries**

So far our work will only have been applied to situations with simplistic fracture geometries – either a fracture that completely surrounds a single matrix block, or a single straight fracture surrounded by matrix. The reality is that flow occurs in a geologically complex fracture network with transfer of fluids to the matrix across many fracture surfaces of different size, shape and orientation, Fig. 3.

We will use a combination of direct simulation and analytical analysis to estimate the behaviour in complex fracture geometries. The emphasis will not be on running a large number of complex simulations; more it will be on deriving what properties affect the transfer – such as the effective fracture surface area and average fracture spacing. The aim will be to derive transfer functions with physically meaningful parameters that can be derived from knowledge of the fracture geometry in a field of interest.

For example, our recent work has derived a scaling group for the variation of imbibition rate with the viscosity of both oil and water [7,21] – this relation could be tested against numerical simulation for situations outside the simplistic cases studied analytically. The same approach could be used to suggest and confirm scaling groups that include geometrical parameters to describe the amount of surface over which there is transfer and the typical flow path length in the matrix. It could be that the overall transfer could be decomposed into summation of processes with different rate constants, with the spectrum of rate constants representing the hierarchical structure of the fracture network. This approach would be conceptually similar to that used to study anomalous dispersion in heterogeneous (typically unfractured) aquifers [22].

**Relevance to beneficiaries**

This work will have a direct benefit to oilfield operators, allowing more accurate modelling of flow
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processes, leading to improved design of reservoir management schemes and ultimately leading to enhanced oil and gas recovery. As mentioned before, this proposal is related to the project ‘Improved Simulation of Faulted and Fractured Reservoirs’ which is concerned with the development of improved simulation software for predicting hydrocarbon recovery from fractured reservoirs. Through the consortium, it is planned that the upscaled results, in the form of novel transfer functions, will be implemented into research and commercial reservoir simulation codes, allowing immediate industrial applications of the work.

Similarly, in the prediction of migration of contaminants, such as nuclear waste, in fractured bedrock, this work will provide rigorously upscaled transport equations to account for multiphase flow situations, as occur in the unsaturated zone, or when the contaminant is present in its own phase.

Dissemination and exploitation
The fracture simulation consortium has project meetings every six months where the results of the work are presented to industrial contacts. It is anticipated that the research results from this proposal would be presented at these meetings, as well as at the yearly affiliates meeting of the Petroleum Engineering and Rock Mechanics Research Group, to which all our industrial sponsors and collaborators are invited. The research will be published in leading academic journals, such as Water Resources Research, Advances in Water Resources, Transport in Porous Media and SPE Journal – the targeting of the hydrology literature will allow the ideas to be disseminated outside the rather narrow academic confines of the oil industry. The PI and named investigator both have good track records of publications in these journals. The work will be presented at major national and international conferences. Again the research will be presented to both the oil and water resources communities.

Justification of resources
Support is requested for the named investigator for a period of three years. In addition, funds to buy a computer, to allow the numerical work to be performed are required. It is expected that the results of this work will be presented at one national and one international conference each year and travel funds to allow this are requested. National conferences include the Fundamentals of Fluid Flow Meeting yearly in December at the BP Institute in Cambridge. International meetings include the Annual Meeting of the Society of Petroleum Engineers and meetings of the American Geophysical Union.

Time-scale and project planning
The chart below indicates how the various tasks in the project will be allocated.

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<tr>
<th>Task</th>
<th>Time (months)</th>
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<td>Step 1 – Analytical solutions</td>
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<td>Counter-current imbibition</td>
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<td>Gas gravity drainage</td>
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<td>Step 2 – Dual porosity models</td>
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<td>Analytical models</td>
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<td>Numerical simulation</td>
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<td>Step 3 – Complex systems</td>
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<td>Analytical models</td>
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<td>Numerical simulation</td>
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<td>Are the equations correct?</td>
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<td>Preparation of papers/presentations</td>
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<td>Project Management</td>
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References
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Annex
CVs of the Principal Investigator and Named Researcher

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Education
1985  BA Natural Sciences, Cambridge University (First Class Honours)
1988  PhD, Theoretical Physics, Cambridge University.
       “The Growth and Properties of Fractal Boundaries.”

Employment
1988-1992  Research Physicist, BP Research, Sunbury-on-Thames
1992-1999  Faculty member, Department of Petroleum Engineering, Stanford University:
           Assistant Professor 1992-1995; Associate Professor 1995-1999; sabbatical at
           Imperial College 1998-1999.
1999-present  Professor of Petroleum Engineering and head of the Petroleum Engineering and
           Rock Mechanics research group (PERM), Imperial College London.

Honours and Awards
1985  Research Scholarship, Trinity College Cambridge
1985  Clerk Maxwell and ver Heyden de Lancey Prizes, Cambridge University
1991  Tallow Chandlers Prize, BP
1996  Teaching award, School of Earth Sciences, Stanford University
1996  Cedric Ferguson Medal, Society of Petroleum Engineers
2001  Distinguished Lecturer, Society of Petroleum Engineers

Research interests
Flow in porous media, reservoir engineering, flow in fractured systems, streamline-based
simulation and pore-scale modelling.

Journal Publications 2001 – date
    nonaqueous phase liquid dissolution developed using a pore network model,” Journal of
    pressure, relative permeability, and in situ saturation in a rock fracture using computed
    Opinion in Colloid and Interface Science, 6(3) 197-207 (2001).
5.  M J Blunt, “Constraints on contact angles for multiple phases in thermodynamic
6.  H S Al-Hadhrami and M J Blunt, “Thermally Induced Wettability Alteration to Improve Oil
    Recovery in Fractured Reservoirs” SPE Reservoir Engineering and Evaluation, 4 179-186 June
7.  R G Hughes and M J Blunt, “Pore-Scale Modeling of Multiphase Flow in Fractures and
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WORK EXPERIENCE
Research Associate, Imperial College, London, UK Nov 2001-Present
Centre for Petroleum Studies, Dept. of Earth Science and Engineering
Project Sponsored by British Petroleum (BP).
• Studying Errors in History Matching and investigating uncertainties in the management of oil reservoirs by adopting Bayesian Statistics, in order to develop better methods for performance prediction of a reservoir and optimize business and investment decisions.
• Developed a methodology to study counter-current imbibition process for flow in hydrocarbon-fractured reservoir. Successfully constructed an analytical model, which matches the experimental data.
• Invited to present my work at the European Science Foundation on Advances in Multiphase Flow and Transport in Porous Media and also at the Department of Petroleum Engineering, Stanford University.

EPSRC Research Fellow, University of Surrey, Surrey, UK Oct 2000-Oct 2001
Department of Physics
• Investigated the process of protein crystallisation in order to get a better understanding of the structure of proteins.
• Used numerical methods to develop a model that simulated nucleation and growth of globular proteins and crystal growth, especially around phase transitions.

Graduate Teaching Assistant, Brunel University, Middlesex, UK Sep 1997-Jun 2000
• Lectured and tutored physical science and engineering undergraduate students.
• Responsible for developing and delivering lectures, setting and grading examinations.
• Supervised/demonstrated physics laboratory experiments.

EDUCATION
PhD in Mathematical Physics, Brunel University, Middlesex, UK Jan 1997-Sep 2000
Awarded Soudavar Scholarship by Brunel University
Thesis Title: Statistical Mechanics of Non-Equilibrium Systems.
• Investigated and analysed different non-equilibrium systems including models of fragmentation, chemisorption with precursor layer diffusion, nucleation and growth, and growth of droplets.
• Developed mathematical models to describe these physical processes.

MSc (Distinction) Condensed Matter Physics, National University of Iran (Now Shahid-Beheshti University), Tehran, Iran Jan 1992-Jan 1994
Awarded prize for being the Best Graduating Student.
Thesis Title: Analysis of the electronic structure in solids.

BSc (First Class Honours) Physics, Shahid-Beheshti University, Tehran, Iran Oct 1987-Oct 1991
Awarded prize for being the Best Graduating Student.
PUBLICATIONS