Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 6. Peering into the pore space: digital rock physics to improve oilfield management

1. Summary of the impact (indicative maximum 100 words)

Since Prof Blunt's appointment as a Professor of Petroleum Engineering at Imperial College in 1999, his Consortium on Pore-Scale Modelling has developed numerical tools to analyse the pore spaces of reservoir rocks, predict multiphase flow properties and determine field-scale impacts on oil recovery. This technology is now exploited by at least two start-up service companies with annual revenue of around $20 million, and is widely employed by major oil companies, leading to better reservoir management and improved oil and gas recovery. Statements submitted from just one company (Kuwait Oil Company, KOC) suggest a benefit of $100 million from efficiency savings and improved recovery in a just single field.

2. Underpinning research (indicative maximum 500 words)

Since 1999 a suite of numerical codes – and published algorithms and methodologies that have enabled other researchers to reproduce the methods – have been developed at Imperial College to simulate multiphase flow (oil, water and gas) in porous media and to predict averaged properties, typically measured in laboratory experiments, such as relative permeability and capillary pressure. The codes represent the rock as a disordered network of interconnected pores. In addition, a method was developed to generate a topologically representative network from a three-dimensional pore-space image. The development of micro-CT X-ray scanning to image rocks at a resolution of around 1 μm, combined with the numerical modelling technology developed at Imperial College, has enabled predictions to be made for different reservoir rocks. This can be performed for rock samples too small for conventional measurements, is much faster than the experiments and can explore a greater range of possible flow processes. This allows for better reservoir management, improving recovery while saving money in oil and gas field operations.

The key main research contributions have been: (i) development of algorithms to compute the displacement of fluids at the pore scale [1,2,4]; (ii) a method to analyse images of rocks [3] and from this extract a topologically representative network through which fluid flow is simulated [6]; (iii) demonstration of the predictive capabilities of this method through comparison with laboratory and field data [1,2,4]; and (iv) descriptions of case histories where using this approach to design optimal water injection could lead to improved oil recovery [5].

The research was performed by Prof Blunt (at Imperial from 1999 to present) and his research group, of which the main contributors were Dr Mohammad Piri (now Associate Professor at the University of Wyoming), Dr Per Valvatne (working for Shell as a reservoir engineer) and Hu Dong (founder and President of a start-up company iRock Technologies that exploits this technology). Prof Jackson (at the time a post-doc in the group) contributed to the understanding of field-scale consequences for oil recovery.

This research has been mentioned in Prof Blunt's citation for the Lester C. Uren Medal from the Society of Petroleum Engineers in 2011, awarded for contributions to petroleum engineering technology made before the age of 45 (www.spe.org). In addition, Prof Blunt was given the 2012 Darcy Award for Lifetime Achievement from the Society of Core Analysts, again based largely on this work (http://www.scaweb.org/about_awards.shtml).

The research was initially funded by two EPSRC proposals ("Characterisation of multiphase flow properties using pore-scale modelling" and "Pore-scale modelling of oil recovery by miscible gas

injection" EP/C536754/1). The research was also supported by a consortium of major oil companies, including Statoil, Schlumberger, Shell, BP, JOGMEC (Japan), Petrobras (Brazil), Saudi Aramco, Total and BG. Since 2004 the consortium has been entirely industrially funded with total support of around £150,000 per year.

3. References to the research (indicative maximum of six references)
* References that best indicate quality of underpinning research.

The results and some of our non-proprietary codes are placed on our website with all relevant papers: http://www3.imperial.ac.uk/earthscienceandengineering/research/perm/porescalemodelling

*[1] M.J. Blunt, M.D. Jackson, M. Piri, P.H. Valvatne, "Detailed physics, predictive capabilities and macroscopic consequences for pore-network models of multiphase flow", Advances in Water Resources, Vol 25, pp. 1069–1089, (2002) DOI: 10.1016/S0309-1708(02)00049-0

*[2] P.H. Valvatne, M.J. Blunt, "Predictive pore-scale modeling of two-phase flow in mixed wet media", Water Resources Research, Vol 40, Article no: W07406, (2004) DOI: 10.1029/2003WR002627

[3] H. Okabe, M.J. Blunt, "Prediction of permeability for porous media reconstructed using multiple-point statistics", Physical Review E, Vol 70, Article no: 066135, (2004), DOI: 10.1103/PhysRevE.70.066135

*[4] M. Piri, M.J. Blunt, "Three-dimensional mixed-wet random pore-scale network modeling of two- and three-phase flow in porous media. I. Model description", Physical Review E, Vol 71, Article no: 026301, (2005) DOI: 10.1103/PhysRevE.71.026301

[5] M.D. Jackson, P.H. Valvatne, M.J. Blunt, "Prediction of Wettability Variation Within an Oil/Water Transition Zone and Its Impact on Production", SPE Journal, Vol 10, Issue 2, pp. 185-195, (2005) DOI: 10.2118/77543-PA

[6] H. Dong, M.J. Blunt, "Pore-network extraction from micro-computerized-tomography images", Physical Review E, Vol 80, Article no: 036307, (2009) DOI: 10.1103/PhysRevE.80.036307

4. Details of the impact (indicative maximum 750 words)

Codes developed from the research have been used commercially, both directly and in modified form. Numerical Rocks, a company spun out from Statoil (the Norwegian state oil company) in 2005, and which merged with an Australian Group, Digicore in 2011 to form LithIcon, uses the same concepts for network modelling and employs the network extraction algorithm developed at Imperial [6]. Lithicon now employs over 50 people worldwide and has an annual turnover in excess of $15 million. Lithicon's Chief Technical Officer writes [A]: "*the importance of this work cannot be overstated: Predictive capabilities are the main reason why companies such as Shell, Chevron, ADCO, Total and Statoil are users of digital rock services. In addition, Imperial College has published algorithms and methodologies that have enabled other researchers and companies to reproduce the methods and enabled internal quality control of digital rock analysis. This has contributed significantly to the rapid growth of digital rock services in the petroleum industry.*"

iRock Technologies is a start-up company, based in Beijing, that exploits the technology developed at Imperial College. The CEO is Dr Hu Dong, a former researcher in Prof Blunt's research group at Imperial, while Prof Blunt himself is Chief Scientist. To quote from their website: "*iRock Technologies provides digital special core analysis (SCAL) software and services to national and international oil companies. We leverage years of research from the Imperial College Consortium*

on Pore Scale Modeling to provide comprehensive reservoir insights that can affordably improve recovery factor for oil and gas companies worldwide." iRock Technologies works with the China National Petroleum Corporation and other major companies to assess conventional and unconventional (shale) hydrocarbon reservoirs. The company was founded in 2010 and employs 20 people with an annual turnover of more than $4 million [B].

The methods have also been used directly internally in several major oil and service companies, including Chevron, KOC (Kuwait), Shell, BG and Schlumberger. The research continues with total current industrial funding of £220,000 per year from Total [C], Petrobras, JOGMEC, Statoil and BG.

The research has been applied to predict flow properties in hydrocarbon reservoirs that are difficult or impossible to measure directly. It allows a much more detailed and accurate characterization of oil, water and gas flow, allowing better design of oil and gas recovery. This has resulted in savings in operating costs and additional hydrocarbon recovery, and helped inform management decisions for oilfield development [C]. In addition, the technology is now being used to appraise unconventional resources, such as shale gas [B].

One example of the use of this technology, reported in the Society of Petroleum Engineers conference proceedings, paper SPE 163331, [D] was to manage the pressure decline in a large oil reservoir (Marratt) in the Middle East, operated by KOC (Kuwait Oil Company) while avoiding problems associated with the precipitation of asphaltenes (tar-like components of the oil that restrict flow). **The use of digital rock technology led to savings of over $25 million in the cost of production operations to KOC, and boosted recovery by 10 million barrels (worth around $100 million)**. The same ideas are now being applied the world's largest sandstone reservoir (Greater Burgan; the second largest oilfield in the world) operated by the same company [E]. This is just one of dozens of uses of the technology worldwide: these were discussed, for instance, at the 2013 Annual Symposium of the Society of Core Analysts [F].

As other examples, the Principal Reservoir Engineer at Shell confirms savings of *"$3-4 million*" for just for one reservoir alone using this technology and points to recovery improvements of around 500 million barrels for transition zone carbonate reservoirs, which are difficult to describe and manage using conventional technology [G].

A senior Petrophysicist at BG also points to recovery improvements in this type of reservoir and cites our work on the Panna field (offshore India) as an example of the use of the technology: he presented this case study to engineers in Brazil in May 2012 [H].

5. Sources to corroborate the impact

[A] Chief Technical Officer, Lithicon to confirm use of code

[B] iRock Technologies: www.irocktech.com, quotation from http://www.irocktech.com/index.php?option=com_content&view=article&id=95&Itemid=69. Archived here https://www.imperial.ac.uk/ref/webarchive/t1f on 29/10/2013

[C] Reservoir Engineer, Total S.A to confirm on going development of code

[D] A Al-Qattan, M J Blunt, O Gharbi, A Badamchizadeh, J M Al-Kanderi, M Al-Jadi, H H Dashti, V Chimmalgi, D J Bond and F Skoreyko, "Evaluation of the Effect of Asphaltene Deposition in the Reservoir for the Development of the Magwa Marrat Reservoir," (2012) (SPE 163331, proceedings of the SPE Kuwait International Petroleum Conference and Exhibition, Kuwait City, Kuwait, 10-12 December 2012 DOI: 10.2118/163331-MS

[E] Senior Reservoir Engineer, Kuwait Oil Company (KOC) to confirm use of digital rock technology by KoC and its resultant savings

[F] http://www.scaweb.org/assets/symposium_2013/Preliminary%20Agenda%202013.pdf Also available here

[G] Principal Reservoir Engineer, Shell (China) Ltd to confirm savings by Shell (Now: Shell Global R&D Manager)

[H] Senior Petrophysicist, BG Group to confirm recovery improvements due to use of code