Impact Objectives

- To capture submillimetre-scale features in geological media under representative stress conditions
- To inform the design of fracking and thermal stimulation operations
- To provide data to enable validation of Darcy simulators with unprecedented rigour

Going with the flow

__Drs Yukie Tanino__ and __Amer Syed__ are investigating the initiation and propagation of rock fractures and fluid flow through them. Below, they share some thoughts on their latest project and the important role collaboration played in this work

From left: Dr Yukie Tanino and Dr Amer Syed

How did you become involved in this field of research?

YT: My undergraduate and postgraduate research was on flow and mass transport in cylinder arrays under conditions relevant to vegetated surface waters (the cylinders represented aquatic plant stems). I became involved in the field of petroleum engineering as a postdoctoral research associate at Imperial College London, where I extended my expertise from single phase to multiphase flows.

AS: I have been working on different aspects of brittle fracture mechanics since I was an undergraduate student of mechanical engineering. During the initial stages of my career, my focus was solely on the mechanics of brittle fracture in elastic materials for engineering and aerospace applications. My PhD project gave me the opportunity to expand my expertise into soft rock mechanics, which brought exciting new challenges with it. Rocks are very heterogeneous in terms of their material constitution compared to metals/alloys and hence the mechanics of fracture are less predictable and not well understood. One of the main reasons for this is the sensitivity of rock mechanics on the stress state. Until recently, there was no experimental technique that enabled direct observation of crack initiation and propagation while the rock is held under triaxial stress conditions. During my discussion with Dr Tanino in 2015, who by then had established contact with our collaborators at the US National Institute of Standards and Technology (NIST) and was planning in situ imaging of corefloods to study capillary imbibition in rocks, the idea of imaging crack initiation and propagation in rocks with neutron imaging was formulated, which led to the development of the current project.

Your latest project is focused on dynamic, in situ imaging of capillary imbibition. What did this involve, and what do you envisage the technology could enable in the future?

YT: The experiment itself is – at least conceptually – quite simple. First, we injected oil into brine-saturated rock samples (cores) to establish initial oil saturation. This step represents oil migration from source rock into reservoirs. The samples were then, if necessary, left in that state until adsorption and other surface chemistry processes reached equilibrium. In the laboratory, the establishment of initial oil saturation can take several weeks to several months depending on the permeability of the rock sample and oil composition. Subsequently, one end of the sample was placed in contact with water, allowing water to imbibe into the core from that end and propagate towards the opposite end of the sample. Neutron tomograms were obtained at selected time intervals to capture the water saturation within the core as imbibition progressed. This line of research will lead to a physically meaningful, predictive model for capillary-driven, two-phase flow in porous media under the full range of possible wettability and initial fluid distribution and fracture properties.

In what ways did collaboration with other institutes contribute to the success of this work?

AS: NIST's Center for Neutron Research was the ideal place to carry out this research for three key reasons. First, as a user facility that hosts teams throughout the year it has both the infrastructure and the expertise to enable visitors to set up and carry out experiments within the standard beam time allocation of two to seven days. In addition to training and staff time, the Center also provides consumables, glassware, and access to an extensive set of general laboratory equipment and tools. Second, the facility has recently been retrofitted to allow simultaneous X-ray/neutron imaging – the first of its kind, to our knowledge. X-rays provide greater sensitivity to the porous rock structure and the neutrons provide greater sensitivity to hydrogenous liquids like oil. Finally, the project benefits greatly from the scientific input of Drs David Jacobson, Jacob LaManna and Daniel Hussey of the Neutron Physics Group at NIST, who manage the scientific activities in the neutron imaging facility.

Exploring reservoir fractures

*Researchers based at **University of Aberdeen** have been conducting neutron and X-ray imaging of geological materials to gain insight into the propagation of fractures and flow through them in order to enable more efficient recovery of hydrocarbons*

For more than a century, oil has been known as black gold – a name befitting its staggering amount of uses in the modern age. Oil is located in reservoirs deep underground and extracting it is usually separated into three stages: primary, secondary and tertiary. Our focus here is on the first two stages. Primary oil recovery is limited to hydrocarbons that naturally rise to the surface, or methods that use artificial lift devices, such as pump jacks, whereas secondary oil recovery involves techniques such as gas injection and waterflooding. The latter method involves the injection of water into a reservoir that subsequently displaces the oil towards production wells from which it can be extracted.

Dr Yukie Tanino from the University of Aberdeen explains that in hydrocarbon-bearing geological reservoirs, fractures are ubiquitous for a number of reasons. Some reservoirs naturally contain these fractures, whereas others are induced to enhance oil recovery. During primary recovery the fractures serve as high permeability pathways for oil to reach production wells. However, during secondary recovery, injected fluid preferentially flows through the fractures, leaving behind a large fraction of the oil in the rock matrix. Then, more gradually, the water in the fractures enters the rock matrix by imbibition, buoyancy, and molecular diffusion, displacing the oil that was left behind.

'A good understanding of fractures, such as how they are formed, how fluids travel through them, and how fluids move in and out of them into the adjacent rock matrix will allow operators to better predict how much oil will flow through which regions of an oil reservoir. This will in turn enable more accurate predictions of how much oil will arrive at production wells and when,' explains Tanino.

FRACTURES AND FLUID FLOW IN, OUT, AND THROUGH THEM

There are two key questions: Where do fractures initiate in rocks and how does the rate of oil transport vary with fracture properties? To address these questions, Tanino and her team established a collaborative project that was first initiated through support from the Carnegie Trust for the Universities of Scotland and then followed by a 12-month project funded by the UK Engineering and Physical Sciences Research Council (EPSRC). In the ongoing EPSRC project, for which Tanino is Principal Investigator and Dr Amer Syed Co-Investigator, the two questions are being addressed separately.

2D slice of reconstructed X-ray tomogram

With regard to the first question, the team placed different rocks under increasing triaxial stress and monitored crack initiation and propagation. 'Materials are intrinsically heterogeneous but are composed of small homogenous constituents that are separated by a boundary,' says Syed. 'When materials are subjected to stresses – such as those created by gas injection and waterflooding – the boundaries rupture, resulting in the formation of a crack. This in turn reduces the strength of the material.' While this process is well documented in metal alloys, such as steel, in rocks it is still unclear how the cracks (or fractures) form. Thus the team are focused on addressing the fundamental mechanics of crack propagation.

To gain insight into the second question, the team visualised imbibition of water from a single, idealised fracture of infinite aperture into rock by capillary imbibition. Future work will combine the two efforts and consider imbibition and flow through 'real' fractures generated within rock and their dependence on the finite aperture size and geometry of the fractures.

ADVANTAGES OF NEUTRON AND X-RAY IMAGING

One key method of achieving this is to ascertain a means of observing the processes that occur in the subsurface when they are subjected to specific stress field. To do this, it is essential that such stresses can be reproduced in the laboratory. Traditional techniques, such as scanning electron microscopy (SEM) and

Direct, in situ observations of pore space and fluid distribution in them are key to understanding fracture initiation and flow and transport in fractured reservoirs

transmission electron microscopy (TEM) only provide images of the rock in 2D, and the techniques limit the observation of rock under stress due to the design and setup of SEM and TEM experiments. Thus, these techniques cannot be used to observe processes that depend on the pore structure of the rocks.

With this in mind, the team employed both X-ray and neutron imaging which, in contrast, offer unique and complementary observations of pore structure in 3D – under stress conditions that are representative of the subsurface. 'Direct, in situ observations of pore space and fluid distribution in them are key to understanding fracture initiation and flow and transport in fractured reservoirs,' explains Tanino.

THE VALUE OF PARTNERSHIP

In achieving the specific aims of the project, collaboration has proved vital. This research is being carried out at the National Institute of Standards and Technology (NIST)'s neutron imaging facility in Maryland, USA, which has involved the scientific input of Drs David Jacobson, Jacob LaManna and Daniel Hussey of the NIST's Neutron Physics Group. The fact that the flow experiments are very long in duration – where sample preparation can last between one and two months and the imbibition can continue for many months – has necessitated lab space that the team could occupy for many months at a time. 'Our NIST collaborators have generously provided us with lab space – as well as high specification pumps which we would not have been able to ship from Scotland to the USA – to do these experiments,' says Tanino.

The fluid phenomenon that the team have been studying is not confined to specific materials, making the findings relevant to a wide range of disciplines beyond that of petroleum engineering. In addition, the project demonstrates the capability of combining X-ray and neutron tomography to simultaneously image the aqueous phases and the solid grains within a real rock, with real oil, in real time.

SOLID RESULTS

The global attention fracking has been receiving recently regarding its possible pitfalls also warrants consideration. Once the project is completed, several high quality videos of fluid flow through rock will be produced, which will serve as an effective tool for communicating the nature of fluid flow through geological materials (be they soil or shale) to the public. 'The videos will be used in outreach activities, which will encourage interest in STEM and, in the long term, contribute towards addressing our chronic shortage of engineers – a need that has been highlighted by the UK Parliament and by the Royal Academy of Engineering,' Tanino says.

Ultimately this line of work will lay the foundation for developing the next generation of predictive models that capture the dependence of fracture flow on variables such as oil composition, mineralogy and temperature. Up until now, experiments have focused on imbibition in an idealised laboratory model of an open fracture under conditions in which the flow is controlled by the properties of the rock matrix. The next stage is to extend the experimental conditions over the full range of fracture and fracture/matrix properties, specifically the consideration of varying dimensions, porosity, permeability and aperture roughness and geometry.

Crucially, by improving scientific understanding, the team are supporting the discovery and development of significant improvements in the secondary yield from oil fields, thereby improving the utilisation of natural energy resources – something that will benefit people around the world.

Project Insights

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PRINCIPAL INVESTIGATOR BIO

Dr Yukie Tanino is a Lecturer in the School of Engineering at University of Aberdeen. Her research interests are in the fluid dynamics of, and mass transport in, obstructed flows such as is found in geological reservoirs, production wells, and flood plains. Tanino leads the Subsurface Flow and Transport Laboratory at Aberdeen, and currently supervises/co-supervises 13 PhD students in the Schools of Engineering and Geosciences. Recently, her group has received support from the EPSRC, Royal Society, Carnegie Trust for the Universities of Scotland, COREX (UK) Ltd, Mexican National Council for Science and Technology, Society of Petrophysicists and Well Log Analysts, and Aberdeen Formation Evaluation Society.

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