Application of numerical modelling and flow experiments to optimize the design of microfluidic devices representing porous media

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Understanding transport phenomena and governing mechanisms of different physical and chemical processes at the pore-scale is crucial for a wide range of applications including hydrocarbon recovery, CO_2 sequestration and contaminant hydrology. Microfluidic devices, also known as micromodels, coupled with visualization techniques allow the investigation of these processes at pore-scale [1, 2]. For the fabrication of micromodels, glass substrates are often preferred over silicon wafer and certain polymers due to their high transparency, thermal stability, hardness and chemical resistance. Recently, we have developed a laser-based process that can be used for the rapid prototyping of micromodels using glass substrates [3]. Using this technique, we can fabricate porous structures containing fine elements, e.g. pores and channels with the width as small as 14 µm (measured at Full-Width-Half-Maximum). Additionally, the process enables control of the depth of individual pores and channels.

It is desirable to have uniform migration of a front invading a pore pattern in micromodels. Control over the flow dynamics of a migrating front can be achieved by optimising the design of the inlet buffer. In our previous study, numerical simulations showed that the geometry of inlet buffers affects the distribution of fluids present in a micromodel and a triangular buffer can offer a more uniform distribution than a rectangular buffer [4]. In the present study, we integrate micromodel flow experiments and pore-scale numerical simulations to design and optimise micromodel fabrication. Simulations are particularly useful for guiding the prototyping of micromodels, since the geometry and dimensions of micro-channels and pores in the structure have a significant effect on fluid flow dynamics. In this work, we investigate the fluid displacement front, saturation distribution, and the influence of the micromodel imperfections on the bulk flow using a commercial computational fluid dynamics (CFD) code. Additionally, a set of dynamic fluid flow tests are performed on the fabricated micromodels with different inlet designs. Throughout these experiments, a 5.3 Megapixel colour camera is used to capture and visualize displacement events.

In this research, qualitative (flow images) and quantitative (flow rate) results from the dynamic flow tests of the fabricated micromodels are compared with predictions of the pore-scale numerical simulations. This promotes the validity of the numerical modelling assumptions and improves the predictions of the models. Moreover, integrating experimental results with numerical simulations pinpoints critically important features of the microfluidic pattern that have an impact on the fluid flow behaviour. This will help to identify optimal design of inlet buffers as well as the improvement of the fabrication of micromodels in order to avoid any unwanted artefacts in the experimental results.

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