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Evaluation of regular-based pore networks for simulation of Newtonian two phase flow

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ABSTRACT

Pore network modelling is a well-established and powerful tool for investigating the pore-scale mechanisms in porous media. It can be used for simulation of vast areas involving fluid flow through porous media. The main constraint in this approach is to develop a network structure which is close enough to the real structure of the porous medium. Although recently proposed approaches can capture the real structure of a medium, acquiring a three-dimensional CT image or two-dimensional cross-section of the rock sample is quite expensive for many individual researchers. However, a pore network structure which adequately represents the porous medium and behaves similarly is sufficient for performing the simulations if the aim is to understand flow behaviour in porous media or to perform sensitivity analyses on fluid and rock properties, where. Early results of using regular-based networks in simulations were not promising. However, their inefficiency might be due to the over-simplified equations used in the simulations and ignorance of the presence of wetting layers. This study attempts to understand whether these networks can be a good representation of the porous medium when advanced equations are used in the calculations.

To achieve this aim, a simple regular cubic network was distorted by removing some of the throats randomly. The descriptive parameters of the network were tuned to match the macroscopic properties of the real porous medium. It was then used for simulation of primary drainage and the imbibition process using a quasi-static method. The tuning and validation processes were repeated for water-wet Bentheimer and Berea sandstones and a sample of carbonate rock. This study showed that if advanced equations and concepts (e.g. the shape factor and wetting layers) are used in calculations, the results of using a simple network can be adequately representative of the complexities of a real rock structure. Although the network obtained by tuning is not unique, however, these regular-based networks can be used for sensitivity analysis of pore-scale mechanism, with acceptable results, when a CT image or cross-section image of the rock is not available.

1. Introduction

The aim of pore network modelling is to substitute the complex void space of the porous medium with a network of interconnected pores. Fatt (Fatt, 1956a, 1956b, 1956c) pioneered the introduction of an idealised two-dimensional pore network model. However, further research in this area was postponed until the late 1970s, when great advances in computer technology occurred and numerical solutions of flow equations became readily available. In 1977, Chatzis and Dullien (Chatzis and Dullien, 1977) stated that two-dimensional networks were unable to predict the 3D flow behaviour of fluids in porous media, although they had been widely used before that time. By comparing the results of the regular networks with the experimental data obtained from sandstones, they showed that the regular networks comprised of circular capillaries could not be a realistic description of the real porous media.

Later, Jerauld and Salter (Jerauld and Salter, 1990) used a cubic lattice of circular capillaries to study the effect of pore structure on relative permeability and capillary pressure. Using this network, they were able to produce relative permeability curves with the same features as those seen in experiments. They reported that some throats could be removed from network in order to reduce

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the average coordination number of the network and match the coordination number of a given rock sample. Dixit et al. (Dixit et al., 1998a, 1998b) used a regular network for analysing relative permeability hysteresis observed in experiments. Although the network did not produce the exact relative permeability in experiments, it explained some trends observed in relative permeability hysteresis. They used the same network for investigating the wettability and its effects on oil recovery; however, in their network, the formation of oil layers during the imbibition stage in mixed-wet rocks was not modelled (Dixit et al., 1999).

Another approach for construction of a more realistic network was the random distribution of some points in the space. The network was constructed by triangulation of these points. However, little difference was observed by Jerauld and Salter when comparing the results of these types of networks to regular ones (Jerauld and Salter, 1990). In 1999, Fischer and Celia (Fischer and Celia, 1999) tuned the pore space distribution of a regular network to match capillary pressure data and predicted absolute and relative permeability. They used this method for a variety of soils, which worked moderately well. However, in some cases, the water relative permeability prediction was poor. In this study, the cross section of pores was assumed to be circular and also, the presence of wetting layers was ignored in the calculations.

Although these networks did not produce the exact relative permeability measured in the experiments they explained some trends observed in relative permeability hysteresis (Jerauld and Salter, 1990; Dixit et al., 1998a, 1998b; Fischer and Celia, 1999). Since these networks were not successful in prediction of experimental results, it became widely believed that regular-based networks cannot provide a good representation of real porous media (Blunt et al., 2002; Valvatne et al., 2005). However, the fundamental equations used in pore networks to calculate the capillary pressure and the conductance of pores and throats were not fully understood at that time. Thus, it is very difficult to understand if the main reason for the inefficiency of these networks was the regular-based structure or the simple equations, along with the many simplifying assumptions used in calculations.

With the development of more advanced technology, new techniques have been proposed for improving the extraction of actual rock void space. One of these methods is the construction of 3D images from a series of 2D cross sections (Lin and Cohen, 1982; Holt et al., 1996). Another method for acquiring a three-dimensional image of pore space is the use of X-ray microtomography. This is a more accurate method but it is not readily available nor cost effective (Dunsmuir et al., 1991; Spanne et al., 1994; Hazlett et al., 1998; Coker et al., 1996). The geological reconstruction of a porous medium simulates the sedimentation process in sandstone rocks and captures the developed void space (Bryant et al., 1993a, 1993b; Bryant and Blunt, 1992). However, the pore size distribution of the rock and some information about the connectivity of the rock is also required in this method. Moreover, it can only be applied for simulation of sandstones, since carbonated rocks are formed during a very complex diagenesis procedure which is hard to simulate. Nevertheless, geological reconstruction of rock structure successfully predicted the macroscopic properties of rock for the first time, which was a significant improvement in pore network modelling. However, in addition to using complicated pore network structures, these models used more complicated and advanced equations for calculation of both capillary pressure and conductance. The presence of wetting layers and their contribution in fluid conductance were some other features that were introduced in these networks.

Currently, the technology for acquiring a 3D image of the rock and extracting the equivalent pore network model is available in certain research groups around the world (Blunt et al., 2013; Knackstedt et al., 2010, 2012; Singh et al., 2016; Iglauer et al., 2012). In some cases, the macroscopic flow properties are even calculated directly on 3D images of the rock sample, using Navier–Stokes solvers (Menke et al., 2016). Therefore, many of the recent papers published in the area of pore network modelling use the real structure of the rock sample to perform pore network simulations (Tanino and Blunt, 2012; Muljadi et al., 2015). However, these facilities are not readily available for many individual researchers in other institutes around the world. These researchers require a pore network modelling tool which can adequately represent the porous media to be used for simulation and gaining a better understanding of pore-scale mechanisms. This tool should be simple enough for performing simulations and inserting new ideas and findings. At the same time, it should be complex enough to mimic the real porous media.

For many years, researchers used the extracted network of Berea sandstone constructed by Oren et al (Øren and Bakke, 2002). for performing simulations and sensitivity analyses when a real 3D image of the rock was not available. However, the permeability of these networks is quite high and their use for simulation of the fluid flow in tight rocks with lower permeability is uncertain. Usually, in order to reduce the permeability of the system, the lengths of pores and throats are reduced by a factor equal to $\sqrt{K^{exp}/K^{net}}$, in which K^{exp} is the desired permeability and K^{net} is the permeability of the pore network, based on Berea sandstone. The re-scaled network has the same permeability as the experimental system, although it has the same structure as before. In other words, the average coordination number of the system is still high and the highly connected structure of Berea sandstone is untouched, which might affect the results (Valvatne et al., 2005; Lopez and Blunt, 2004). Other researchers have used the same process to build a sophisticated random pore network quite similar to Berea sandstone and used it for studying the fluid flow in the porous medium (Piri and Blunt, 2005).

It is widely believed that the rescaled pore network structure of Berea sandstone is a good representation of porous media. However, this triggers the idea that maybe building an artificial pore network with lower connections, lower coordination number and smaller pores and throats could be as efficient as scaling the lengths of pores and throats in a high permeability pore network. Using this network would be easier for researchers who want to test their ideas and formulations using pore network modelling but do not want to get involved in understanding a very complex network. Moreover, they can check the effect of network properties on fluid flow by changing the network parameters, such as porosity, coordination number (degree of connectivity) and pore size distribution. To test this idea, the regular-based network models and their performance was studied to see if they can provide a good representation of real porous media. It has been shown elsewhere that it is easy to use this artificial regular-based pore network structure for calculation of fluid flow properties or to change the governing formulations, for example to simulate non-Newtonian fluid flow (Aghabozorgi et al., 2015).

As mentioned above, many of the regular based networks used in the literature, were very simple and comprised of circular capillaries. The cross section of pores and throats was assumed to be circular, so the presence of wetting layers and their conductance was ignored, despite their significant contribution to fluid flow. Furthermore, the capillary pressure and fluid conductance were calculated based on very simple equations available in that time. Therefore, the aim of this paper is to show whether employing recently developed equations and new concepts (e.g. irregular cross sections and wetting layers) can improve the performance of regular-based networks. Although the uncertainty associated with regular-based networks is very large and they cannot be used for