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Single-phase and two-phase flow properties of mesaverde tight sandstone formation; random-network modeling approach

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ABSTRACT

3D random networks are constructed in order to represent the tight Mesaverde formation which is located in north Wyoming, USA. The porous-space is represented by pore bodies of different shapes and sizes which are connected to each other by pore throats of varying length and diameter. Pore bodies are randomly distributed in space and their connectivity varies based on the connectivity number distribution which is used in order to generate the network. Network representations are then validated using publicly available mercury porosimetry experiments.

The network modeling software solves the fundamental equations of two-phase immiscible flow incorporating wettability and contact angle variability. Quasi-static displacement is assumed. Single phase macroscopic properties (porosity, permeability) are calculated and whenever possible are compared to experimental data. Using this information drainage and imbibition capillary pressure, and relative permeability curves are predicted and (whenever possible) compared to experimental data.

The calculated information is grouped and compared to available literature information on typical behavior of tight formations. Capillary pressure curve for primary drainage process is predicted and compared to experimental mercury porosimetry in order to validate the virtual porous media by history matching. Relative permeability curves are also calculated and presented.

1. Introduction

Macroscopic properties of a porous medium of interest can be determined by knowing its microscopic properties: Microstructure of the medium, physical properties of the solid that grains are made of, and physical properties of the fluids inside the medium Dullien (1991); Øren and Bakke (2003). Petrophysical properties of the medium such as porosity, permeability and formation factor, and fluid transport properties such as capillary pressure, and relative permeability are calculated from the microscopic structure of the medium as well as the physical behavior of the fluids inside the medium. Consequently, it is important to find the relationship between the microstructure and macroscopic properties of interest. The aforementioned relationship can be industrially utilized in waste water treatment, pollutant transport, modeling of drug movement in live tissues, reservoir characterization, reservoir engineering, and enhanced oil recovery techniques Bashtani et al. (2013); Santos et al. (2008); Yegane et al. (2015).

It is necessary to quantitatively characterize the microstructure and pore-scale physics, and obtain the solution of the fluid transport equation (i.e. equations of motion) for the phenomenon of interest Dullien (1991); Øren and Bakke (2003). There are several methodologies for quantification of microstructure of a porous medium. Synchrotron X-ray computed microtomography (microCT) Coker et al. (1996); Coles et al. (1994); Dunsmuir et al. (1991) directly measures the microstructure of the medium in 3D by taking several high resolution images from the sample throughout its length. It is also possible to take SEM (Scanning electron microscope) images of several thin sections from the same porous medium and convert the obtained 2D structure into a 3D representation of the medium using statistical models Quiblier (1984); Scriven (1994). It is proven, however, that the reconstructed media using stochastic methods are often not an accurate representation of the real sample Øren and Bakke (2002).

Pore scale topology of unconventional reservoirs, especially tight sandstones, is extremely heterogeneous and completely different from conventional oil and gas reservoirs. Tight gas reservoirs are characterized by high capillary entry pressure, high irreducible water saturation, low to moderate porosity, and low permeability

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Nomenclature

Symbol	Unit	Description
F_d	-	Correction factor
G	-	Shape factor
K	*mD*	Permeability
n	-	Archie's n exponent
P	*kPa*	Pressure
P_c	*kPa*	Capillary pressure
P_{bt}	*kPa*	Breakthrough pressure
r	*m*	Radii of network element
R_1, R_2	*m*	Radii of curvature
RI	-	Resistivity Index
x	-	Estimated property value
x_{min}	-	Minimum boundary of x
x_{max}	-	Maximum boundary of x
β	*degree*	Corner half angle
γ	-	Weibull exponent
δ	-	Weibull exponent
θ	*degree*	Contact angle
σ	$\frac{mN}{m}$	Interfacial tension
ϕ	*fraction*	Porosity

Byrnes (1997); 2003); Dutton and of Texas at Austin. Bureau of Economic Geology (1993). According to the dual porosity mode, pore structure of tight gas reservoirs consists of secondary solution pores interconnected through narrow tortuous slots Soeder and Randolph (1987). These pore throats and the pore body connectivity associated with clays and slot-like pores control the flow inside the tight porous medium Aguilera (2008); Byrnes et al. (2009); Golab et al. (2010); Soeder and Randolph (1987).

Laboratory measurements for tight porous media are costly and time consuming. Moreover, studying the effect of a certain parameter in such complex pore structures is difficult because of the complicated experimental design. Due to high-end computer power available nowadays, it is possible to calculate single phase flow properties directly using the 3D representation of the porous medium obtained from micro-CT images. Porosity, permeability, formation factor, and conductivity are some of the single phase flow properties computed using the aforementioned method Ferreol and Rothman (1995); Øren and Bakke (2002); Widjajakusuma et al. (1999). On the other hand, substantial amount of CPU power is required in order to predict multiphase flow properties in such a detailed medium Bashtani et al. (2015); Dullien (1991); Øren and Bakke (2003).

Alternatively, the microstructure of a 3D porous media can be represented by a network of pore bodies connected to each other by pore throats Fatt (1956); Øren and Bakke (2003). The pore bodies and throats can have various shape, size, and length. The Total number of connections per pore is called connectivity (coordination) number. The overall average of the connectivity number over the whole medium is defined as the average connectivity number Bashtani et al. (2015); Blunt et al. (2002). The main advantage of network modeling technique is its capability to directly relate the macroscopic behavior of the porous medium to the underlying pore-scale physics Dullien (1991); Øren and Bakke (2003).

The first network model was able to predict capillary pressure and relative permeability curves of primary drainage utilizing 2D regular lattice network in which the radius of pore bodies were randomly assigned Fatt (1956). Later on, it was replaced by the 3D network model because of the more accurate pore structure representation that a 3 dimensional medium offered Chatzis and Dullien (1977). 3D random network model allow for the existence of bi-continua in the bulk of pore space; A basic necessity for multi phase flow prediction Dullien (1991). Extensive studies were conducted based on regular lattice networks on the topology, pore body, and throat radius distribution, and their spatial dispersion Chatzis and Dullien (1977); Grattoni and Dawe (1994); Jerauld and Salter (1990). However, the aforementioned studies lack the ability to reflect the real pore structure and geometry of the rock because of the limitation of regular lattice network. As a result of recent studies, network models nowadays are improved and have the ability to predict single phase and immiscible multiphase flow properties including capillary pressure, relative permeability, and resistivity index curve of conventional formations Øren and Bakke (2002); 2003); Oren et al. (1998); Patzek (2001); Piri and Blunt (2005a); 2005b); Valvatne and Blunt (2004).

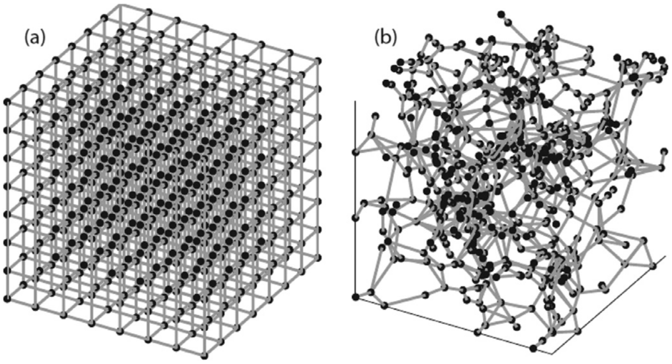

Fig. 1. (A) Regular generated network with constant connectivity number of 6 Valvatne and Blunt (2004). (B) 3D voxel based representation of pore space using a random generated network Bakke and Øren (1997).

A network can be generated having either micro-CT images of the real porous medium Sok et al. (2002) or the statistical information about the pore space: pore body, pore throat, and connectivity number distribution Blunt et al. (2002). It is also possible to reconstruct the pore space having the grain size distribution of the medium and macroscopic properties of the pore space, porosity and permeability for instance, for calibration purposes. It is worth mentioning that using micro-CT images for network reconstruction is the best method for replication of the real sample, provided that the resolution is sufficient Sok et al. (2002).

Elements of the network (i.e. pore bodies and throats) can be placed in space uniformly or randomly. The uniform placement of elements leads to a cuboid shaped network. Maximum connectivity number for this type of placement is 6 since each pore can potentially be connected to 6 other pores surrounding it. Random element placement, on the other hand, can lead to higher connectivity numbers which could lead to a more detailed representation of the microstructure of porous space Bashtani et al. (2015). Fig. 1 illustrates both uniform and random generated networks. The term *random network* in this paper refers to a network in which the pore bodies are randomly distributed throughout the space.

The network model allows the pressure of one fluid to increase step by step in order to obtain the two phase fluid configuration after each pressure jump. Employing capillary equilibrium, and Young-Laplace equation leads to obtaining two phase fluid configuration of each pressure difference step for each network element (i.e. pore bodies and pore throats). Flow of each phase at each pressure step is calculated using the hydraulic conductance empirical equation Blunt et al. (2002); Patzek (2001). Assuming stationary fluid interface after each step, the pressure profile through the network can be calculated using the mass balance equation. Finally, macroscopic properties such as total and relative permeability can be computed having the relationship between the injection rate and pressure gradient through the network at each step Blunt et al. (2002).

The objective of this research is to employ random network modeling techniques for reconstruction of physically equivalent 3D pore networks of tight porous media based on the Mesaverde tight formation, predict the single phase and miscible two phase flow properties, and compare the network model predictions with lab-