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Comparison of permeability models using mercury injection capillary pressure data on carbonate rock samples

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ABSTRACT

With the latest advances in carbonate reservoir characterization, new workflows have been proposed for consistent and accurate reservoir modeling where mercury injection capillary pressure (MICP) data is used primarily to determine petophysical properties. A dataset – obtained from carbonate formations from the Middle East region – containing 206 rock samples are used to evaluate the performance of nine permeability models. Numerical pressure derivative plots are proposed as a new approach to visually validate the accuracy of the mercury capillary pressure curves. As the order of the derivative increases, the data spreading increases as well proving an indication of the accuracy of the lab measurements. The compared permeability models are Purcell, Thomeer, Winland, Swanson, Pittman, Huet, Dastidar and Buiting–Clerke (two forms) permeability models. An accuracy index (ACI) is introduced to rank the permeability models along with a detailed statistical and graphical analysis. The ACI is computed by taking the arithmetic average of four different error measures after normalizing them. The error measures are the mean relative percent error (MRPE), the mean absolute relative percent error (MAPE), the coefficient of determination (R^2), and the root mean squares (RMS). In general, the comparative study shows that the permeability models can be grouped into three categories with respect to their performance using our dataset. The first group contains Swanson and Winland permeability models as the top-ranking permeability models with an average ACI of 0.91. The second category contains Buiting–Clerke, Thomeer, Dastidar and Pittman permeability models with an average ACI of 0.37. The last category has a single permeability model – Huet permeability model – with an ACI value of 0.02. This study provides a very thorough assessment of the performance and predictive capabilities of the compared permeability models in carbonate reservoirs using MICP data.

1. Introduction

Mercury intrusion – also called mercury porosimetry – experiment is widely used for the determination of total pore volumes and pore size distributions for porous materials were it is considered as a standard measure for such properties (León y León, 1998). It is a very powerful characterization tool that has major advantages over other techniques, primarily due to its simplicity, and quickness in which results are obtained. Capillary pressure profiles generated using mercury porosimetry has many pressure stabilization points that cover wide ranges of pore sizes. Irregular shape samples – including end cuts and rock ships – can also be used to generate capillary pressure profiles (Purcell, 1949).

Most mercury porosimeters consist of a sample cell, vacuum source with a gauge, mercury cleaning source, low pressure source with a gauge, high-pressure generator with a reservoir fluid and a gauge, in addition to a volume indicator (Allen, 1990). The test is carried out by applying a vacuum pump on a sample placed in a cell where all gases are evacuated. The pressure inside the sample subsequently drops to very low levels near vacuum conditions. Mercury is then slowly injected until it fills the whole sample chamber. Pressure is transmitted to the mercury by forcing a hydraulic fluid up to a desired pressure. Most porosimeters determine the intruded mercury volume by monitoring the drop in the interface level between the hydraulic fluid and mercury (Allen, 1990).

There are two main modes at which mercury porosimeters operate: incremental mode (stepwise) and continuous mode (scanning). In the continuous mode, mercury is forced into a sample at continuously increasing pressure. In the incremental model, however, pressure is increased in steps allowing enough time for mercury to reach equilibrium in every step (Allen, 1990; León y León, 1998; Giesche, 2006). León y León (1998) and Giesche (2006) presented a comprehensive comparison between the two methods; interested readers are advised to visit their papers.

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Nomenclature

a_i	incremental volume of mercury at the *i*th capillary pressure, volume units
a_T	total incremental volume of mercury injected, volume units
ACI	accuracy index, fraction
B_v^{∞}	fraction of bulk volume occupied by mercury at infinite capillary pressure, fraction
B_v^Q	fraction of bulk volume with respect to *Q*, fraction
$\hat{B}_v^Q$	Laplace transformation of fractional bulk volume with respect to *Q*
D_λ	fractal dimension, dimensionless
F	Purcell lithology factor, dimensionless
F_g	Thomeer shape factor, dimensionless
F_p	Purcell integral parameter, psi^{-2}
F_s	Swanson parameter, psi^{-1}
k	absolute permeability, mD
k_a	air permeability, mD
k_m	permeability predicted by the models, mD
L	sample length, length unit
L_d	length of the shortest flow path, length unit
MAPE	mean absolute relative percent error, percentage
MICP	mercury injection capillary pressure
MRPE	mean relative percent error, percentage
P_c	capillary pressure, psi
P_d	entry pressure, psi
r	pore throat radius, μm
r_{apex}	pore throat radius at apex of MICP plot – Pittman parameter, μm
r_{35}	pore throat radius at 35% mercury saturation – Winland parameter, μm
R^2	coefficient of determination, fraction
RMS	root mean squares, mD
Q	natural log of capillary pressure where capillary pressure in psi
Q_d	natural log of entry pressure where entry pressure in psi
R_i	pore throat radius at the *i*th capillary pressure, μm
R_{WGM}	weighted geometric mean of pore throat radii – Dastidar parameter, μm
S	fraction of total pore space occupied by liquid, fraction
S_b	percent bulk volume occupied by mercury
$S_{b\infty}$	percent bulk volume occupied by mercury at infinite capillary pressure
S_{Hg}	fraction of total pore space occupied by mercury, fraction
S_w	wetting phase saturation, fraction
S_{wi}	irreducible wetting phase saturation, fraction
w_i	weight function defined at the *i*th capillary pressure, fraction
$\left(\frac{S_b}{P_c}\right)_A$	apex of a hyperbolic log–log plot of capillary pressure against mercury saturation, psi^{-1}

Greek symbol

λ	Brooks and Corey index, dimensionless
σ_{Hg-air}	interfacial tension for mercury-air system, dynes/cm
θ	contact angle, degrees
ϕ	porosity, fraction
ξ	parameter in Buiting-Clerke model equivalent to $2(\sigma_{Hg-air}cos\theta)$, psi μm

Pore size distributions computed using mercury intrusion experiments (Washburn, 1921) might not reflect the actual pore-size distribution of the tested porous medium depending on the amount of the "ink-bottle" pores that are present in the sample and how far those pores are located away from the injection plane. This is usually referred to as the impact of interconnected pores (Allen, 1990). Many researchers have studied this phenomenon and its impact on the hysteresis between the intrusion and extrusion curves using connectivity and percolation models (Mason and Morrow, 1984; Matthews et al., 1993; Mason and Mellor, 1995; Matthews et al., 1995; Rigby and Daut, 2002). In general, the presence of the interconnected pores tends to indicate a lower pore-size to what is actually present in the sample. Therefore, pore-size distributions determined using mercury porosimetry are always expected to be at the low side (Allen, 1990). While this is considered as a major limitation in the determination of the actual pore-size distribution, it provides a very good estimation of the connectivity of the sample and the pore-throat distribution – which is closely related to the permeability of the sample (Allen, 1990; Giesche, 2006).

The characterization of carbonate reservoirs is essential for accurate reservoir modeling. The presence of multi-pore systems in carbonates, however, makes their description from petrophysics point of view very complex (Clerke et al., 2008; Clerke, 2009; Gao et al., 2011). The modeling of permeability, a very important petrophysical parameter, is a very active research area, especially in carbonates. Numerous models have been reported in the literature utilizing various parameters derived from many sources (e.g., well testing and well logging) (Timur, 1982; Feitosa et al., 1994; Mohaghegh et al., 1997; Babadagli and Al-Salmi, 2004; Nooruddin and Hossain, 2011; Nooruddin et al., 2014). With the latest advances in characterizing carbonate reservoirs, new workflows have been proposed for consistent and accurate reservoir description and modeling of multi-modal pore systems where mercury injection capillary pressure are used mainly to determine grid cells properties (Sung et al., 2013; Nooruddin et al., 2014).

Researchers have reported that permeability estimation from MICP data can be categorized into two main categories (Gueguen and Palciausakas, 1994; Comisky et al., 2007). The first category contains permeability models that are derived based on the application of the percolation theory where fluid flow behavior through random porous media are modeled by using probabilistic principles (Fleming, 1983; Kesten, 2006). The other category covers permeability models derived based on the combination of Poiseuille and Darcy equations where porous media are considered as a bundle of capillary tubes.

The objective of this study is to compare models that are developed to estimate permeability values using parameters exclusively derived from mercury injection capillary pressure curves. The comparison is made on a recently-collected dataset from a carbonate formation located in the Middle East region. The performance of each model is evaluated using detailed statistical and graphical analysis. Before going into the details of the adopted methodology in this study, a brief literature review is presented with a description of the compared permeability models.

2. Literature review

In 1949, Purcell introduced for the first time a method to determine capillary pressure curves for porous media by forcing mercury into a core sample that is being held under vacuum