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Pore-throat radius and tortuosity estimation from formation resistivity data for tight-gas sandstone reservoirs

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ABSTRACT

A new model is proposed for estimation of pore-throat aperture size from formation resistivity factor and permeability data. The model is validated with data from the Mesaverde sandstone using brine salinities ranging from 20,000 to 200,000 ppm. The data analyzed includes various basins such as Green River, Piceance, Sand Wash, Powder River, Uinta, Washakie and Wind River, available in the literature. For pore-throat radii analysis the methodology involves the use of log–log plots of pore-throat radius versus the product of formation resistivity factor and permeability ($r_T = a(FK)^b + c$). The model fits over 280 samples from the Mesaverde formation with coefficients of determination varying between 0.95 and 0.99 depending primarily on the type of model used for pore throat radius calculation. The brine salinity has some minor effects on the results. The model can provide better estimates of pore-throat radii if it is calibrated with experimental techniques such as mercury porosimetry. The results show pore-throat radii varying between 0.001 and 5 μm for the Mesaverde tight sandstone; however, most of the samples fall in a range between 0.01 and 1 μm.

For tortuosity analysis, the calculation involves the use of product of formation factor and porosity data. Results indicate that the estimated tortuosity values range mainly between 1 and 5. For samples with lower porosities (<5%), tortuosity values show a wider scatter (between 1 and 8); whereas for samples with larger porosities (>15%), the scattering in tortuosity decreases significantly. In general, for tortuosity calculation in tight gas sandstone formations, a square root model with a parameter (b_f) representing various types of connecting pores, i.e., sheet-like and tubular pores, is recommended.

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1. Introduction

1.1. Pore-throat radius

Pore throat radius is of significant and practical importance in conventional, tight and shale gas reservoirs for identifying flow units (discussed in Section 3) and for helping to distinguish between diffusion and viscous flow regimes. This makes pore throat radius an important parameter to study.

Pore-throat size distribution, first reported by Washburn (1921), has been widely studied by mercury injection at threshold entry pressure. Washburn's equation (Eq. (1)) relates the pore-throat radius to the surface tension and capillary pressure.

$$r_T = \frac{2\gamma\cos\theta}{P_c}. \tag{1}$$

Where γ is surface tension, θ contact angle and P_c capillary pressure, the pressure required to force mercury into a pore. Typical surface tension contact angle for mercury are $\gamma = 484$ dyn/cm and $\theta = 140°$ (Byrnes et al., 2009).

The technique is called Mercury Injection Capillary Pressure (MICP) test. In this method, a mercury porosimeter is used to generate pressure high enough to force mercury into all accessible pores and measure the volume of mercury entered to the pores. According to Washburn's equation a pore throat with radius as small as 1.8 nm should be accessible to mercury at 60,000 psi. The pore-throat in ultra-low permeability rock, especially in shale, is often so small that even high pressure mercury injection cannot access the full pore structure distribution Sodergeld et al. (2010).

In recent years, other techniques such as Scanning Electron Microscopy (SEM) and Nuclear Magnetic Resonance (NMR) methods have been widely used for pore size distribution analysis. NMR spectroscopy measures the response of hydrogen protons in a magnetic field. It gives the pore body size not the pore throat radius. The amplitude of NMR signal is proportional to the density of proton spin and therefore provides porosity estimation (Howard and Kenyon, 1992).

Nelson (2009) reviewed the pore throat size in sandstones and shales. He summarized that pore-throat diameter in conventional sandstones is generally greater than 2 μm, in tight gas sandstones it ranges from 0.03 to 2 μm, and for shales it varies from 0.005 to 0.1 μm.

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Nomenclatures

Roman letters

b_f	A constant that depends on the type of connecting pores
c	Concentration
D	Diffusion coefficient
D_m	Molecular diffusion coefficient
D_e	Effective diffusion coefficient
F	Formation resistivity factor
i	Current density
k	Porous medium permeability to fluid
K_{el}	Specific electrical conductance
L	Length of core
L_e	Effective length
m	Cementation exponent
P	Pressure
q_{Diff}	Quantity of mass passing through unit cross-sectional area per unit time
r_T	Pore throat radius
R^2	Coefficient of determination
R_o	The electrical resistance of porous medium saturated with ionic solution (brine)
R_w	The electrical resistance of the ionic solution occupying the porous medium
T	Tortuosity factor
T_h	Hydraulic tortuosity factor
S_w	Brine saturation
S_{wi}	Irreducible water saturation
S_{wp}	Wetting phase saturation
V	Potential

Subscripts

c	Capillary
e	Effective
el	Electrical
T	Throat

Acronyms

BPD	Barrel Per Day
MICP	Mercury Injection Capillary Pressure
NMR	Nuclear Magnetic Resonance
OPR	Oil Production Rate

Greek symbols

θ	Contact angle
ϕ	Porosity (dimensionless)
γ	Surface tension
δ	Constrictivity factor
τ	Tortuosity

Other symbols

∇	Gradient operator

Besides Washburn's equation, various theoretical and experimental correlations have been developed for pore-throat radius estimation using rock's petrophysical data. Among these methods are Heid et al. (1950), Winland (see Kolodzie, 1980) and Aguilera's (2002) correlations which will be used in the current study. All these models correlate the pore-throat radius to the permeability and porosity of a porous medium. The details of these correlations are discussed later.

1.2. Tortuosity

Tortuosity is one of the most widely studied petrophysical parameters yet it is not very well understood (Brakel and Heertjes, 1974; Clennell, 1997; Cornell and Katz, 1953; Garrouch et al., 2001; Katsube, 2010). Introduced by Carman (1937), tortuosity accounts for the sinusoidal flow path through a porous medium. It is defined as the ratio of effective flow path to the macroscopic length (core length):

$$\tau = L_e/L. \tag{2}$$

As Carman (1937) pointed out, it is very important to understand the concept of tortuosity as it affects both permeability and the seepage velocity by a factor of (L_e/L). Therefore, the overall factor by which the flow is retarded in a tortuous path is proportional to the square of tortuosity, which is referred to as tortuosity factor (Clennell, 1997; Dullien, 1979):

$$T_h = \left(\frac{L_e}{L}\right)^2 = \tau^2. \tag{3}$$

Clennell (1997) review of tortuosity is one of the most comprehensive studies on this topic. In his paper, Clennell (1997) cleverly discussed all types of tortuosity including geometrical, hydraulic, diffusional and electrical tortuosities.

Garrouch et al. (2001) used Berea, Okesa, Tallant and Elgin sandstones to investigate the relationship between molecular diffusion and electrical conductivity, and corresponding tortuosity. They concluded that the Pirson's (1983) electrical tortuosity equation, a square root model (Eq. (4)), is analogous to Brakel and Heertjes (1974) diffusional tortuosity and provides the best agreement between the two types of electrical and diffusional tortuosities. Throughout this paper, we use Pirson's (1983) model and square root model interchangeably to refer to the following equation:

$$\tau = (F\phi)^{0.5}. \tag{4}$$

Where F is formation resistivity factor and ϕ is porosity. Pirson's (1958) suggested $\tau_e = (F\phi(1-S_{wi}))^{0.5}$ for effective tortuosity estimation; where S_{wi} is irreducible water saturation.

Katsube (2010) investigated a similar model of electrical tortuosity in more detail. He introduced an additional coefficient (b_f), (see equation below) to account for the shape of connecting pores.

$$\tau = (F\phi/b_f)^{0.5}. \tag{5}$$

1.3. Objective

Correlations are used for pore-throat estimation when MCIP data are not available or when the measurements are not viable.

Existing correlations in the literature are generally based on porosity and permeability but there are no correlations specifically developed for tight gas sandstone reservoirs.

In this paper, we use formation factor and permeability data along with correlations of pore throat radius available in the literature to develop new and simpler models for pore throat radius in terms of the product of formation resistivity factor and permeability for tight gas sandstone reservoirs. Also electrical tortuosity estimation is presented using various models. The recommended tortuosity model is a square root model, especially Katsube's (2010) model that uses a parameter (b_f), which represents various types of connecting pores discussed in detail later.

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