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Quantification of pore size distribution in reservoir rocks using MRI logging: A case study of South Pars Gas Field

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HIGHLIGHTS

- Observation of an acceptable correlation between MRI logging and mercury injection data.
- A high degree of similarity between T_2 distribution and PSD (R^2 = 0.85–0.91).
- An extra peak on pore size distribution curve marked the variation of clay bond water to range between 1e-6 and 1e-3 μm.

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ABSTRACT

Pore size distribution (PSD) is an important factor for controlling fluid transport through porous media. The study of PSD can be applicable in areas such as hydrocarbon storage, contaminant transport, prediction of multiphase flow, and analysis of the formation damage by mud infiltration. Nitrogen adsorption, centrifugation method, mercury injection, and X-ray computed tomography are commonly used to measure the distribution of pores. A core sample is occasionally not available because of the unconsolidated nature of reservoirs, high cost of coring operation, and program limitations. Magnetic resonance imaging logging (MRIL) is a proper logging technique that allows the direct measurement of the relaxation time of protons in pore fluids and correlating T_2 distribution to PSD using proper mathematical equations. It is nondestructive and fast and does not require core samples. In this paper, 8 core samples collected from the Dalan reservoir in South Pars Gas Field were studied by processing MRIL data and comparing them by PSD determined in the laboratory. By using the MRIL method, variation in PSD corresponding to the depth for the entire logged interval was determined. Moreover, a detailed mineralogical composition of the reservoir samples related to T_2 distribution was obtained. A good correlation between MRIL and mercury injection data was observed. High degree of similarity was also observed between T_2 distribution and PSD (R^2 = 0.85 to 0.91). Based on the findings from the MRIL method, the obtained values for clay bond water varied between 1E-6 and 1E-3 μm, a range that is comprehended from an extra peak on the PSD curve. The frequent pore radius was determined to be 1 μm.

1. Introduction

Fluid transport through porous media is governed by the geometry of pore structure, i.e., pore coordination number, pore size and throat size distributions, pore body-to-pore throat size and pore body-to-pore body aspect ratio (Takahashi et al., 2010). For the past several decades, the petroleum industry is aware that the determination of pore size distribution (PSD) for porous reservoir rocks facilitates a better understanding of fundamental flow processes in the porous matrix, and thus of petroleum reservoir performance in general (Burdine et al., 1950). The study of PSD has economically important applications in the petroleum industry, such as the determination of storage capacity of hydrocarbons, contaminant transport, waste storage, and rock durability (Fusi and Martinez-Martinez, 2013); prediction of multiphase flow through porous media (Dong et al., 2007); and analyses of damage due to invading particles and liquid phase of drilling fluid, deposition of wax, and asphaltene near wellbore and bacterial growth during MEOR and the determination of water saturation exponent (n) (Elgaghah, 2007).

Abbreviations: CPMG, Carr-Purcell-Meiboom-Gill; DDIF, Decay due to diffusion in internal field; GTEM, Temperature log; MRIL, Magnetic resonance imaging logging; NMR, Nuclear magnetic resonance; NMRL, Nuclear magnetic resonance logging; NPHI, Neutron porosity log; PSD, Pore size distribution; RHOB, Density log; Density logXRCT, X-ray computed tomography

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Nomenclature

A_{cs}	cross-sectional area of the adsorbate
D	molecular diffusion coefficient
D_h	hydraulic diameter
DT	sonic transit time log
G	field strength
L	distance of central mass of water portion to center of rotation
M	molecular weight of the adsorbate
N	Avogadro's number
P	pressure
P_0	initial pressure
P_c	capillary pressure
P_{Hg}	mercury pressure
r	pore throat size
r_e	central distance of capillary tube end
r_i	central distance of capillary tube end
S	pore surface
S_{wi}	irreducible water saturation
T	absolute temperature
T_1	longitudinal relaxation time
T_{1bulk}	T_1 relaxation time of pore fluid as it would be measured in a container so large that container effects would be negligible
T_2	transverse relaxation time
T_{2bulk}	T_2 relaxation time of pore fluid as it would be measured in a container so large that container effects would be negligible
$T_{2diffusion}$	T_2 relaxation time of the pore fluid as induced by diffusion in the magnetic field gradient
$T_{2surface}$	T_2 relaxation time of the pore fluid resulting from surface relaxation
TE	inter-echo spacing used in the CPMG sequence
V	volume of pore
W	weight
W_m	weight of adsorbate
γ	gyromagnetic ratio of a proton
θ	contact angle at the interface
ρ_2	surface relaxivity
ρ_g	gas density
σ	surface tension
$\sigma_{nw\text{-}w}$	wetting/nonwetting phase surface tension

As nuclear magnetic resonance has become a valuable tool in physics, chemistry, biology, and medicine, the invention of NMR logging tools has opened a new era in the formation evaluation and core analysis in the petroleum industry. The determination of NMR properties of fluids in porous media enables the characterization of reservoir rocks. Hence, these tools that use permanent magnets and pulsed radio frequencies facilitate the application of sophisticated laboratory techniques to permit formation evaluation in situ. A large amount of imperative petrophysical information can be extracted from NMR relaxation measurements, namely porosity, PSD, bound water, and permeability (Coates et al., 1999). Magnetic resonance imaging logging (MRIL) is a medical MRI or lab NMR equipment turned inside-out. The decaying "echo" signal from the hydrogen protons in resonance with the magnetic field produced by the permanent magnet placed at the center of an MRIL tool is picked up by an antenna. Contrary to the conventional neutron, bulk-density, and acoustic-travel-time porosity logging tools, which are affected by all components of a reservoir rock, the porosity measured by an MRIL tool contains no contribution from the matrix materials and does not need to be calibrated to formation lithology because only fluids are visible to MRI (Esmaili, 2014).

1.1. PSD determination methods

The methods used to quantify the PSD in rocks are explained as follows (Esmaili, 2014):

1.1.1. Nitrogen adsorption technique

In the nitrogen adsorption technique, the surface area is calculated by experimentally measuring nitrogen adsorption using the following BET equation:

$$\frac{1}{W\left(\left(\frac{P_0}{P}\right)-1\right)} = \frac{1}{W_m C} + \frac{C-1}{W_m C}\left(\frac{P}{P_0}\right) \tag{1}$$

where W is the weight of the adsorbed gas, P/P_0 is the relative pressure, W_m is the weight of the adsorbate as a monolayer, and C is the BET constant. By linear plotting of $\frac{1}{W\left(\left(\frac{P_0}{P}\right)-1\right)}$ versus $\frac{P}{P_0}$, the slope and intercept are $\frac{C-1}{W_m C}$ and $\frac{1}{W_m C}$ respectively. Hence,

$$W_m = \frac{1}{\text{slope} + \text{intercept}} \tag{2}$$

Thus, the total surface area S_t is

$$S_t = \frac{W_m N A_{cs}}{M} \tag{3}$$

where N is the Avogadro's number (6.023×10^{23}) and M and A_{cs} represent the molecular weight and the cross-sectional area of the adsorbate (16.2 $Å^2$ for nitrogen), respectively. By knowing the surface area and pore volume, a rough estimate of the pore radius can be obtained as follows:

$$d_{av} = \frac{6}{S_t} \tag{4}$$

1.1.2. Capillary pressure curve method

Another method to determine PSD is from the capillary pressure curve. This curve is plotted by gathering data from the centrifuge, porous plate, or mercury injection methods in the laboratory (Peters, 2006). The centrifuge method is based on drainage process by the centrifugal force generated by the rotation of the core sample, which has been saturated with a wetting fluid (usually water) (Esmaili, 2014).

Fig. 1 shows a simplified capillary tube model in the core sample, in which the non-wetting–wetting phase boundary (here air and water interface), and r_i and r_e represent the radial distances of capillary tube ends. It is assumed that the sample rotates at a rotational speed of ω.

The fluid in the capillary tube is exposed to capillary pressure, which is given by

$$P_c = \frac{4\sigma_{nw-w}}{D_h}\cos(\theta) \tag{5}$$

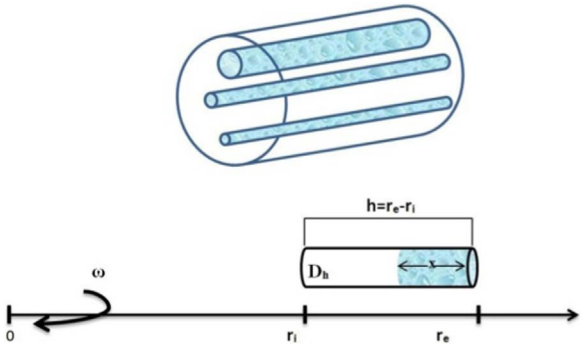

Fig. 1. A simplified capillary tube model.