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Effect of pore framework and radius of pore throats on permeability estimation

Amir Maher Sayed Lala [a,*], Nahla A.A. El-Sayed [b]

[a] Geophysics Dept., Fac. of Science, Ain Shams Univ., Cairo, Egypt
[b] Egyptian Petroleum Research Institute, Cairo, Egypt

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ABSTRACT

The purpose of this study is to understand and develop a model pore geometry, petrophysical parameters of (porosity, pore throat radius and permeability), and reservoir performance characteristics. Number of both sandstone and limestone samples extracted from different oil fields in Egypt and Arabian Gulf were conducted for petrophysical study. This study used the pore throat size distribution derived from capillary pressure by mercury injection (MICP) to determine the pore throat parameter for all the studied samples, r_{35} and the amount of micro-porosity in the studied samples. The pore throat and micro-porosity cut-off were determined graphically from the two curves of cumulative flow capacity and storage capacity.

The idea that micro-porosity will hold a great part of irreducible water volume was verified by comparing the micro-porosity, with water saturation data determined from Dean and Stark technique which showed a good match between the two calculated values. It was used also to calibrate the T2-cutoff to enhance the permeability prediction from porosity using the NMR logging tool.

The all studied samples were discriminated based on permeability cutoff 10 md. For the measured permeability values higher than 10 md, the regression coefficient increased form when the permeability was plotted with macro-porosity instead of total porosity or with calculated permeability using Coates et al., equation model. For the calculated permeability values less than 10 md, there was very weak correlation between either the macro or total porosity with measured one.

In our work, we have introduced a radius of pore throat at mercury saturation of 35% (r_{35}) together with the pore space configuration parameters to enhance the permeability prediction. The r_{35} was assumed to present different pore throat parameters.

The present study showed that, pore throat size, (r_{35}) improves permeability estimation. The combination of pore space configuration and pore throat parameters in the new model has enhanced the relationship between porosity and permeability.

Finally, the validity of the new model represented by porosity and (r_{35}) was tested using 123 rock samples (sandstone and limestone). The estimated permeability using the new model was plotted against the measured permeability and revealing high coefficient of correlation.

1. Introduction

The reservoir rocks are composed solids and the pore voids. The solids are grains, cement and matrix. Geometrically, the pore voids are subdivided into two primary segments of pore spaces and pore throats. The pore spaces control the value of porosity, while the pore throats control the movement of subsurface fluids and therefore permeability. The porosity is a scalar parameter depending on the spectrum of pore sizes of various diameters and the mode of occurrence of cement and matrix, which in turn; are controlled by a spectrum of pore throats. It is thought that the producible fluids are contained in the larger pores while the bound fluids are held in the smaller and capillary pores and the smaller pores do not contribute to the fluid flow.

The permeability (non scalar parameter) and related parameters were extensively studied by many researchers such as, Timur (1968), Vernik (1994), Coates and Denoo (1981), Pittman (1971), El Sayed et al., 2005 and Coates et al. (1981 and 1997).

Timur (1968), developed a modified version of the original Kozeny equation as follows,

* Corresponding author.
E-mail address: amir77_lala@yahoo.com (A.M.S. Lala).

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$$Ka = \left[0.136 \times \left(\varphi^{4.4}/S_{wi}^2\right)\right] \quad (1)$$

where (Ka) is the absolute permeability in millidarcies, and (S_{wi}) is the irreducible water saturation (% pore space). This equation was successfully tested on 155 sandstone samples from various sedimentary basins (Vernik, 1994). In the Timur equation, the pore spaces are represented by micro-porosity (S_{wi}) and porosity (φ). The (S_{wi}) reflects the non-uniformity of pore size distribution which would be reflected in porosity-permeability relation.

Coates and Denoo (1981) introduced a new equation to predict permeability from porosity and water saruration. It is expressed as follows:

$$K = \left[\langle 100 \times \varphi_e^2 (1 - S_{wi})\rangle / S_{wi}\right]^2 \quad (2)$$

where (K) is the permeability in millidarcies, and (S_{wi}) is the irreducible water saturation (% pore space, fraction).

The equation has a new term ($1 - S_{wi}$) which represents the macro-porosity. The equation has a better representation of the pore space configuration.

The relationship between pore type and pore throat size is a fingerprint of the character of the reservoir. If a given reservoir rock will have such fingerprint, the permeability will increase as porosity increase. This is the ideal case of pore geometry configuration, but in other cases, this relationship is not systematic. Sandstone reservoirs having large pore types as predominant, while smaller pore throat sizes are present, the predicted permeability would be less than it should be, (large pore with small throat), if we consider only the pore spaces in prediction.

Micro-porosity usually contributing to total porosity, but is not effective in fluid conduction due to its smaller pore throat radius than the radius of the fluid molecules. Micro-pores will be filled with bound water and will never be invaded by oil, as the hydrocarbon column would have to be greater to charge a rock composed of this pore type. Micro-porosity occurs in sandstone and carbonate reservoirs and affects their fluid flow properties and their log responses.

Initial investigations of micro-porosity were limited to routine examination of thin sections, pore casts, and pore-cast thin sections. These techniques provide the best means of visually locating concentrations of micro-pores (Pittman, 1971). However, micro-pores are too small to be studied adequately with conventional light microscopes. Other authors or researchers measured porosity on core plugs and considered it to be the total porosity. A thin section from the core plug is prepared and point counted; the difference between plug porosity and thin section porosity is the micro-porosity.

Other authors or researchers used the capillary pressure obtained by mercury injection to study the pore network distribution and used the end of capillary pressure curve to define the amount of irreducible water saturation (micro-porosity). This practice is not the proper technique because it depends on the upper limit of capillary pressure used in the experiment. In the up-to-date apparatus, the capillary pressure reaches up to 60,000 psi, the straight end of the capillary pressure curve is not present now, but a steadily inclined curve is obtained. At the end of the curve, the mercury saturation reaches 100% of the pore spaces.

The NMR reflects the pore size distribution and through a selective cutoff, the micro-porosity is separated from macro-porosity. In the case of even relationship between pore type and throat size (large pore space is associated with large pore throat size), the estimation of micro-porosity would be correct. In the case of uneven relationship between pore type and throat size the estimated micro-porosity would be much less; as parts of large pores are kept behind small throat but it is represented in the domain of large pores in the image of NMR.

In the case of uneven relationship between pore type and throat size, the definition of micro-porosity based on the pore size will lead to an error in estimating the micro-porosity. The error in estimating micro-porosity will affect the prediction of permeability from the porosity in the uncored wells. Also it will affect the recognition of low resistivity pay.

Finally, we define the micro-porosity based on a pore throat cutoff which separates the volumes of pores controlled by large pore throats and volumes of pores that are controlled by small pore throats. The volumes of pores that are controlled by large pore throat will be termed macro-porosity and that are controlled by small pore throats will be termed micro-porosity (El Sayed et al., 2005). In this approach, pore size has no effect as it is controlled by a certain pore throat. This approach helps recognize abnormal relationship between porosity and permeability in case of oversize pores. It detects the presence of high irreducible water saturation in rocks which flow oil free of water.

Coates et al. (1997) developed an equation to estimate the permeability from the results of NMR logging tool as,

$$K = (10^4)(\varphi^4)\left[(\textit{macro-porosity}/\textit{micro-porosity})^2\right] \quad (3)$$

The equation treated the porosity as two segments, macro-porosity (contribute to the fluid flow) and micro-porosity does not contribute to the fluid flow (irreducible fluids).

In our study, Coates et al. (1997) equation was used to estimate the permeability for the studied samples. The equation has three terms for porosity and thus it has the best representation of porosity among the other published equations. It is widely used in the oil industry to predict permeability from pore size distribution of NMR logging tools. So, testing and validating the equation is very important for permeability prediction and reservoir evaluation.

In the present work, the mercury injection capillary pressure curve was used to obtain measured pore throat sizes and the radii at various levels of mercury saturation. The pore throat size distribution was used to obtain pore throat parameters for all the studied samples, (r_{35}).

Storage and flow capacity curves allow the determination of the pore throat cutoff, macro porosity and micro porosity through the pore network. In addition, the size of the pore throats that control the two parts of pore volume can be determined.

Trials have been made in predicting rock permeability from the capillary pressure estimated pore throat size distribution parameter; (r_{35}). The r_{35} represent the specific pore throat size that control the pore volumes saturated with 35% of mercury and reflect the difference in reservoir quality. We apply pore throat cutoff to NMR log in order to calibrate the T2-cutoff and discriminate the volumes of pores controlled by larger pore throats (macro-porosity) and volumes of pores which are controlled by smaller pore throats (micro-porosity). We also derived a pore throat parameter in conjunction with the porosity and pore space configuration parameters to investigate the enhancement of the permeability prediction. Then the estimated permeability using the new model was plotted against the measured permeability on additional new 123 samples (sandstone and limestone) to test the validity of the new obtained model to other reservoir rocks.

2. Methodology

The laboratory methods used to measure the present petrophysical parameters such as porosity, permeability and pore throat radii obtained from mercury injection capillary pressure curves for our studied samples have been discussed before in (Lala and El Sayed, 2015).