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Effects of pore geometry and rock properties on water saturation of a carbonate reservoir

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A R T I C L E I N F O

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A B S T R A C T

Capillary pressure analysis is an important piece of every reservoir rock study. Mercury injection capillary pressure (MICP) is one of the best methods for pore geometry analysis among different techniques for obtaining the capillary pressure data. Pore-facies analysis is a useful method for classifying the carbonate reservoir rocks directly according to their pore system characteristics using the MICP curves. One of the challenging subjects in every carbonate reservoir study is the characterization of reservoir fluids behavior in the pore network.

The purpose of this study is determining the effect of the rock properties and pore geometry on water saturation in the carbonate reservoir rocks. Two types of reservoir rock classification were performed based on the MICP and air–water capillary pressure data. The results show that the reservoir rock samples with specific depositional texture, pore type and cement content show distinct capillary and water saturation behavior. Therefore, the pore geometry of rock samples has a strong effect on the fluid movements and entrapment in the reservoir rock. In turn, it is the result of depositional texture and diagenetic features. Although understanding the relationship between the rock properties and capillary behavior and determining the controlling parameters in fluid behavior in the pore network is very difficult and time consuming in carbonate reservoirs with such a complicated pore system, it is possible by detailed capillary pressure and petrographic studies.

1. Introduction

The pore system, including the pore throats and the pore types, is the main controlling parameter in the fluid movements and entrapment in carbonate reservoir rocks. In turn, it is the result of the interactions between the depositional rock texture and diagenetic overprint. Thus the pore system could be considered as a parameter that links the geological properties and dynamic characteristics in the reservoir rock. In other words, the depositional and diaganetic processes in carbonate successions control the reservoir quality by making the pore system and governing its variations. The porosity as a parameter which connects the rock properties to fluid behavior needs to be characterized precisely. Capillary pressure analysis is a common method for pore system characterization which includes drainage and imbibition tests. There are several experimental techniques available for the capillary pressure measurements, including mercury injection, porous plate, centrifuge tests which have been the subject of many investigations (Wardlaw, 1976; Krause et al., 1987; Kopaska-Merkel and Friedman, 1989; Jing and Van Wunnik, 1998; Shafer and Lasswell, 2007). Mercury injection is a fast and convenient method in capillary pressure measurements with the ability of pore geometry characterization which has been frequently used in reservoir rock studies. The MICP method and petrographic analysis are the best instruments for the pore throats and pore types studies, respectively. The discrepancy between the results of the MICP analysis and other types of capillary pressure tests has been considered by many authors (e.g. Newsham et al., 2003, 2004; Saller and Hamon, 2005; Masalmeh and Jing, 2006, 2007). The main reasons for the discrepancies are the differences in the laboratory procedures and the experimental fluids and conditions. Accordingly, the accuracy of converting the mercury injection data to other types of capillary pressure systems is in doubt.

In this paper, the compatibility of the reservoir rock classification based on the MICP curves and the air–water capillary pressure curves has been studied for the purpose of determining the effect of pore system characteristics, including pore types and pore geometry on water saturation in the reservoir rock samples. The pore-facies analysis was carried out applying the MICP curves. The reservoir rocks were classified according to their pore geometry and then the rock properties including the rock textures and pore types were defined in each pore-facies. The next step was the classification of the core samples which were available from the centrifuge tests, according to the geological properties and the water saturation behavior.

The study was performed using the core plug samples from the reservoir interval in five wells in a gas field in the Persian Gulf.

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The main purposes of this study are (1) identifying the effect of the geological properties including depositional textures, pore types and the cement content on variations in the pore geometry (in the first classification) and fluid saturation (in second classification) in the reservoir rock; and (2) observing the compatibility of pore geometry defined classes and water saturation based classes in order to determine the effect of the pore system characteristics on the fluid movements and saturation behavior.

2. Material and methods

High pressure Mercury intrusion tests were performed on core plug samples up to 60,000 psi maximum pressure using an automatic system (Micromeritics AutoPore Mercury Porosimeter). A pressure table comprising 117 points evenly spaced in logarithmic space was used.

Air-displacing-water data were acquired at 4 capillary pressure increments up to 137.7 psi (in the laboratory air–water system). In this test, soxhlet cleaned samples were used. The plugs were loaded into a centrifuge and subjected to non-stop centrifugation under air. Sample saturations were determined by weighing the samples at each pressure step, after 12 h rotational time. Based on the experimental results, capillary pressure curves were determined.

Gas–water (=gas displacing water) capillary pressure curves at overburden pressure were measured according to the following procedure: (1) Soxlet Cleaned samples were saturated with brine (Initial Water Saturation: 100%); (2) the samples were then placed in "Hassler" cells, and a confining pressure of 2474.8 psi was applied; and (3) four steps of capillary pressure were then performed, reading at each step the volume of water displaced by nitrogen (nitrogen filtered and dehumidified).

Several hundreds of thin sections from the pay zones of the two wells in a carbonate reservoir in the Persian Gulf were selected for the study. Thin section petrography is based on the modified Dunham (1962) classification scheme for the carbonate textures. Eighty core plug samples were selected for mercury injection and air–water capillary pressure analysis from the producing intervals, described, photographed and made into thin sections. Samples were impregnated with blue-dyed epoxy to describe pore types, texture, grain or crystal size, cement types and volume and other diagenetic features. The cement types and pore types in some samples also were characterized with the scanning electron microscope (SEM).

3. Pore-facies analysis

The pore-facies analysis is a new generation of reservoir rock classification which is based on the pore system characteristics. All pore geometry related properties such as pore throats and pore types characteristics can be included in the pore-facies analysis and the result of the facies analysis is applicable in the reservoir modeling.

In this study, the pore-facies analysis was performed by the parameterization and classification of MICP curves (Chehrazi et al., 2011). MICP curves are the best instruments for pore geometry analysis and this special ability makes them powerful in reservoir rock characterization (e.g. Purcell, 1949; Dullien and Dhawan, 1974; Wardlaw, 1976; Schowalter, 1979; Van Brakel, 1981; Jennings, 1987; Melas and Friedman, 1992; Luo and Machel, 1995) and rock typing analysis (Porras, 1998; Leal et al., 2001; Porras and Campos, 2001; Varavur et al., 2005; Skalinski et al., 2006; Lehmann et al., 2008; Skalinski et al., 2010).

There are some valuable properties such as pore throat size distribution (PTSD) and pore throat sorting (PTS) that become possible to characterize by mercury injection analysis which are described in the following section. This applicability is related to the nature of the experimental fluid (mercury). It does not show interaction with the reservoir rock and the applied pressure in this method which is capable of attaining injection pressures as great as 60,000 psi, thus providing coverage of the entire range of mercury saturation and pore throat size.

In this study, MICP curves were applied for the reservoir rock classification because of the following purposes: (1) the importance of the pore system in controlling the fluids distribution in the carbonate reservoir rock; (2) the applicability of the mercury injection analysis in pore geometry characterization; and (3) observing the effect of the variations in carbonate rock textures and pore types on MICP curves and the MICP curve defined classes.

For the pore-facies analysis, MICP curves were parameterized and then were classified according to the extracted parameters using clustering analysis. Each pore-facies includes the most similar capillary pressure curves. The average value of the extracted parameters and other petrophysical properties such as permeability, reservoir quality index (RQI) and flow zone indicator (FZI) based on the modified Kozeny–Carman equation (Amaefule et al., 1993) were determined in each pore-facies (Table 1).

3.1. MICP curves parameterization and classification

The MICP curves were parameterized and then were classified based on the extracted parameters. These parameters are pore throat radius at different mercury saturations (35%, 50% and 75%), displacement pressure (Pd) or entry pressure, threshold pressure (Tp) (the pressure which mercury makes a connected network), Swanson's parameter (the maximum value of S/Pc ratio which is determined at all pressures and corresponding mercury saturations), pore throat sorting (the average value of the capillary pressure at 16%, 50% and 84% mercury saturation) (PTS), and height above free water level at 50% and 75% non-wetting phase saturations.

Pore throat sorting (PTS) corresponds with the degree of sorting of pore throats in the rock sample (Jennings, 1987). It is

Table 1
Pore facies classification. The average values of the extracted parameters from the MICP curves, some petrophysical properties and the main rock fabrics and pore types in each pore facies.

Pore Facies	K (md)	PHI (%)	Pd (kPa)	Tp (kPa)	Sp	H 50% (m)	H 75% (m)	PTS	RQI (μm)	FZI (μm)	R 50% (μm)	R 75% (μm)	Dominant rock fabrics and pore types
1	409.5	23.5	49.51	71.27	0.77	2.61	4.79	25.21	1.26	4.40	5.88	3.22	Dolo-grainstone with well connected interparticle porosity
2	151.5	23.2	90.6	123.8	0.36	6.24	12.05	64.67	0.70	1.96	2.45	1.3	Grainstone with interparticle porosity and intergranular cement
3	6.65	23.4	120.4	188.9	0.2	10.73	23.6	127.7	0.16	0.81	1.5	0.74	Grainstone with well-sorted moldic porosity
4	1.96	18.5	494.2	856.1	0.05	41.1	71.1	428.8	0.10	0.86	0.38	0.24	Grainstone with progressively filled moldic porosity
5	0.49	14.0	50.44	62.44	0.15	21.35	132.6	534.9	0.054	0.33	0.69	0.11	Grainstone with unsorted moldic and vuggy porosity
6	0.43	21.3	860.8	1821.3	0.04	145.6	275	1175	0.032	0.14	0.13	0.06	Grainstone with totally plugged pore system

Pd: displacement pressure, Tp: threshold pressure, Sp: Swanson's parameter $(S\%/Pc)_{max}$, H 50%: height above free water level at 50% saturation, PTS: pore throat sorting, R 50%: pore throat radius at 50% saturation.