Relationship between pore throat and permeability of porous carbonate reservoir in the Middle East

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Abstract
A significant behavior of carbonate reservoirs is poor correlation between porosity and permeability. With the same porosity, the permeability can vary by three orders of magnitude or more. An accurate estimation of permeability for carbonate reservoir has been a challenge for many years. The aim of this study was to establish relationships between pore throat, porosity, and permeability. This study indicates that pore throat radius corresponding to a mercury saturation of 20% (R20) is the best permeability predictor for carbonates with complex porous pore networks. Quantitative analysis was made to achieve three different patterns of pore throat for 417 carbonate samples which cover all pore types of carbonate rocks. Different relationships between porosity, pore throat radius, and permeability have been identified in different patterns, which are utilized to predict more accurate permeability by different pore throat patterns.

Keywords Porous carbonate · Permeability · Pore throat · Porosity · MICP

Introduction
As the strong heterogeneity of carbonate reservoirs, the correlation between porosity and permeability is usually very poor or even none. The permeability estimation model usually builds on the correlation with porosity, water saturation, the grain size, and clay content (Qibin et al. 2015). All these parameters above are indirect indication of pore throat size (Wang and Taillang 2013). While mercury injection capillary pressure (MICP) curve is a direct reflection of pore throat size, many experts utilize MICP curve to explore the relation between pore throat and permeability (Hangyu et al. 2018; Fengfeng et al. 2020; Gao et al. 2013a; Ruibao et al. 2015). Purcel (Ahr et al. 2005) used the whole MICP curve to deduce the formula between permeability, porosity, and capillary pressure (Pc-2) and concluded that all the pore throat contributed to the permeability. Swanson (Al-Marzouqi et al. 2010) holds the viewpoint that pore throat contributes to the permeability only when the mercury saturation reached to a maximum percentage (Figure 1). Winland (Purcel 1949) believes that R35 (pore throat radius corresponding to a mercury saturation of 35%) correlates with permeability best based on the statistics of carbonates and clastic samples, which are widely used by many researchers. Katz and Thompson (Swanson 1981) think the injected mercury reached to the knee point (Figure 1) correlating with the large size of the pore throats, which controls the rock permeability. Warren thinks that R50 (Gunter et al. 2014) (pore throat radius corresponding to a mercury saturation of 50%) has the best correlation with permeability based on sandstone samples from different strata.

Figure 1 shows some of the researchers’ viewpoint. Some of the researchers above used sandstone samples to extract relationship between pore throat and permeability, but further study and experiments will be very necessary to test whether the relationship fits in carbonate rocks. Though some of the researchers covered carbonate samples in their research, but sample classification is missing based on the pore throat’s structure (Katz and Thompson 1986). For example, Swanson excluded the samples with duel-modal pore throat pattern, and only samples with homogeneity are kept in the experiment. So the results cannot be used in carbonate reservoir widely.

In this paper, carbonate rock samples are classified by pore throat structure patterns (single modal, dual modal, and triple modal), the relationships between pore throat radius and...
permeability are studied, and permeability is predicted separately by different pore throat patterns. Also, a whole set of pore throat radius (R5–R95) are calculated from MICP, from injected mercury saturation from 5 to 95% with 5% mercury saturation incremental interval to identify the best fit pore throat radius with permeability.

**Background**

M oilfield is located in southeastern Iraq, close to Iran-Iraq border, 50km north of Rumaila oilfield and Zubair oilfield (Warren and Pulham 2001). The whole Mesopotamia basin lies on Arabian plate on shore, which is divided into two tectonic units: Mesopotamia foredeep tectonic belt and stable Arabian platform (ZhiMin et al. 2018; Luo and Wang 1986). M oilfield, the giant carbonate oilfield whose main pay zone is bioclastic limestone of Mishrif formation in Cretaceous, is a north-south-oriented anticline lying in Mesopotamia foredeep tectonic belt (Cheng et al. 2017; Jin et al. 2013; Ma 2010; Gao et al. 2013b), with an area of 750km².

The sedimentary environment of Mesopotamia foredeep tectonic belt was passive continental margin belt in the Cretaceous, whose sedimentary evolution was controlled by both relative sea level fluctuation and Arabian plate’s uplift (Deng et al. 2014). High-quality reservoirs were developed in the mid-Cretaceous(Wang et al. 2016a; Wen et al. 2014; Hulea and Nicholls 2012), which are para-unconformity with Upper and Lower Cretaceous (Figure 2).

The main rock types of Mishrif formation are organic reef limestone (reef-building organisms are cyanophyta, coral, etc.) and bioclastic (rudist, foraminifer, etc.) and pelleted limestone (Nelson 2005). The main pore spaces are interparticle pore, intercrystal pore, moldic pore, and epigenetic freshwater solution vug. The carbonate ramp slope has a steady low angle less than 0.1° (Wright and Burchette, 1998) in shallow marine environment, with a broad reef shoal distribution of Mishrif formation which can be found across the research area (Pittman 1992; Jianping et al. 2015). The carbonate pore system of Mishrif formation is reformed by the superimposition of multi-stage diagenesis, as dissolution facilitated secondary interparticle pore, intercrystal pore, and moldic pore (Wang et al. 2016b; Zepu et al. 2016; Yikai et al. 2016); cementation in later stages diminished the storage space and throat size. For instance, the growth of sparry calcite dissolved interparticle space, while compaction and micritization also played a key role in lowering porosity and permeability.

**Data and methods**

**Data introduction**

All samples used in this paper are from Mishrif formation of M oilfield in the Middle East. Four hundred fifteen samples are chosen to cover all the rock types and pore throat structures. These samples have all been analyzed by lab experiments to get useful information such as mercury injection capillary pressure data, thin casting slices, and petrophysical data such as porosity and permeability. The porosity data varies from 2 to 34% with the median porosity 17%, while permeability varies from 0.001 to 3010mD with the median permeability 3.6mD. Both primary and secondary pore were well developed, including matrix micropore, intraparticle pore, moldic pore, intercrystal pore, and visceral foramen (Figure 3).

**Identification of pore throat patterns**

Microstructure and percolation capability depend on pore types and pore throat structures. Capillary pressure curve shape is controlled by both pore throat selection and size, which can form the basis to evaluate the storage capability of the rocks. Based on pore throat probability distribution chart, which are extracted from the capillary pressure curve, there are three patterns of pore throat distribution (PTSD): single modal, dual modal, and triple modal. The complex pore throat types and diagenesis differences within the same pore type caused strong micro-heterogeneity and poor correlation between porosity and permeability. After careful study and comparison of pore throat size of different modal, thin slices, pore, and permeability parameters, some findings have been summarized as below:

1) The pore system in carbonate rocks is complicated and with high heterogeneity, as there are three patterns of pore throat distribution: single modal (Figure 4A), dual modal

![Capillary pressure curve and key pore throat points](image)
The pore throat size varies with a wide range from 0.01 to 100 μm.

2) Different pore throat modal represents different rock and pore types. For single modal, the main rock type is micritic bioclastic limestone (Figure 5A) with a highly frequent bio-turbulence (Figure 5B). For dual-modal pattern, the cementation of mineral and calcite (Figure 5C) and dolomite is the reason to cause dual modal. Samples with triple modal are the most dispersed. Calcite, dolomite, and pyrrhotite (Figure 5D, E) were infilled in interparticle dissolved pore, dorsal foramen (Figure 5F).

3) Porosity and permeability correlations are different in the three pore throat patterns. In single modal, porosity and permeability correlate the best (Figure 4D) compared with the other two modals, but still not good enough for permeability estimation. In dual modal, permeability varies three orders of magnitude difference within the same porosity (Figure 4E). In triple-modal pattern, porosity and permeability correlated worst as there are four orders of magnitude difference within the same porosity (Figure 4F).

In summary, there are some connection between porosity and permeability, but it is not enough to use only porosity to predict permeability. While pore throat size is an indirect indicator for percolation ability of rocks, different pore throat size can be obtained from MICP. The next step will focus on finding out the best fit pore size with permeability.

Relation between pore throat, permeability, and permeability

The pore throat size is the key factor to control percolation capability in rocks. Based on the 415 samples, 19 different pore throat radii are extracted covering from 5 to 95% of mercury saturation during mercury injection process. Linear regressions between different pore throat radius and
permeability are made. It turns out that at 20% of mercury saturation, pore throat radius $R_{20}$ and permeability correlate the best, with the correlation coefficient 0.74 (Figure 6). $R_{20}$ will be utilized in the next step in analyzing how porosity and permeability will change along with the $R_{20}$ size.

From all 415 samples, the scatter plot (Figure 7a) of porosity and permeability is plotted and divided into seven intervals (Table 1) sorted by the size of $R_{20}$ (pore throat radius at mercury saturation of 20%). For each interval, the average permeability (Figure 7b) is calculated to get clearer trends of how porosity and permeability change along with pore throat radius.

As shown in Figure 7 a and b, some conclusion can be drawn: (1) There is strong positive correlation between

![Fig. 3](image-url) Main pore types in Mishrif formation

![Fig. 4](image-url) Pore throat characteristics in Mishrif formation
permeability and pore throat radius for all samples. Permeability keeps increasing with R20. Both the max value and max average value of permeability are in interval RVII, which is the maximal pore throat zone. (2) There is a poor correlation between porosity and permeability. With the same porosity, there are 1–4 orders of magnitude difference of permeability. (3) The max permeability zone is in interval RVII with an average permeability of 100mD. The maximal permeability exceeds 1000mD, with the average porosity around 20% within porosity interval 14–24%. This means that permeability does not keep increasing with porosity. (4) When pore throat radius exceeds 2um, there is an obvious better correlation between permeability and pore throat radius; however, there is a negative correlation between permeability and porosity.

Unlike the turbidite reservoirs, the correlation between porosity and permeability of carbonate reservoir usually is very poor. The reason is that the diagenesis process had different reconstruction effect on storage and percolation capability of the reservoir, while the pore throat size and connectivity directly indicate the quality of percolation pathway. This research identifies that the pore throat radius (R20) is the main controlling factor of permeability and clarifies the micro-distributing characteristics of the reservoir. This provides positive evidence to evaluate reservoir quality and classification more accurately.

Fig. 5 Reservoir micro-characteristics in Mishrif formation

Fig. 6 Correlation coefficient of permeability and pore

![Graph showing correlation coefficient of permeability and pore throat radius](image)
Discussion

Reservoir engineers and petrophysicists are interested in how permeability and porosity relate to pore throat size and pore throat distribution, primarily so they can estimate permeability (Pittman 1992). Regression analysis has frequently been used as the main tool with which to correlate porosity and permeability values (Jamialahmadi and Javadpour 2000). Regressions have been made between porosity, permeability, and R20 (Table 2) by three different pore throat patterns in the “Identification of pore throat patterns” section.

| Pore throat radius (microns) | Interval | Mean porosity (%) | Mean permeability (mD) | Porosity range (%) | Permeability range (mD) |
|-----------------------------|----------|-------------------|------------------------|-------------------|-----------------------|
| 0–0.1                       | RI       | 0.075             | 2.149                  | 2.63–23.6         | 0.0007–0.5            |
| 0.1–0.5                     | RII      | 0.139             | 3.544                  | 4.15–26.9         | 0.01–80               |
| 0.5–1                       | RIII     | 0.179             | 11.277                 | 7.5–28.3          | 0.3–110               |
| 1–2                         | RIV      | 0.229             | 17.537                 | 6.5–30            | 6–101                 |
| 2–5                         | RV       | 0.257             | 50                     | 15–37             | 5–800                 |
| 5–10                        | RVI      | 0.216             | 186                    | 8–34              | 7–3121                |
| 10–21                       | RVII     | 0.210             | 234.7                  | 16–26             | 8–881                 |

Fig. 7 Crossplot of permeability and R20 of Mishrif formation

| Pore throat pattern | Equations                           | Correlation coefficient |
|---------------------|-------------------------------------|-------------------------|
| Single modal        | $\log_{10} K = 2.076 \log_{10} R20 + 0.913 \log_{10} \phi + 2.297$ | 0.824                   |
| Dual nodal          | $\log_{10} K = 3.0377 \log_{10} R20 + 0.787 \log_{10} \phi + 2.648$ | 0.881                   |
| Triple modal        | $\log_{10} K = 2.307 \log_{10} R20 + 0.557 \log_{10} \phi + 3.265$ | 0.791                   |

Conclusion

There is a good correlation between pore throat radius and permeability. Pore throat and permeability correlate the best when mercury saturation reaches 20%. Porosity and permeability correlate differently in different pore throat pattern. With the increment of pore throat radius, porosity and permeability show different trends. Statistically, as the increment of pore throat radius, permeability keeps increasing, while porosity shows different trend. Three different patterns have been identified for pore throat: single modal, dual modal, and triple modal. Regressions have been made between...
porosity, permeability, and pore throat radius by different pore throat patterns.

**Declarations**

**Conflict of interest** The authors declare that they have no competing interests.

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