Determination of petrophysical property cutoffs of tight lacustrine carbonate reservoir, Qaidam Basin, China

Introduction

An effective reservoir is a reservoir in which fluid can be stored and percolated, and a reservoir with industrial value output can be produced under the existing technological conditions (Cao et al. 2015). Effective reservoirs are generally distinguished by porosity and permeability. The lower limit of effective reservoir physical properties refers to the minimum of porosity and permeability. It is an important parameter for the evaluation of oil and gas resources and the formulation of development plan.

Some methods of determining the lower limit of physical properties of conventional reservoirs are not suitable for tight reservoirs because of the difference of filling mechanism and pore throat scale, and the limitation of test precision. In recent years, scholars have tried to determine the lower limit of physical properties of tight reservoirs. For instance, according to the relation of pressure difference and saturation in displacement experiment, the pore throat lower limit of the samples with the same saturation pressure difference and hydrocarbon generation pressure difference was selected as the pore throat lower limit of the 7th member of Yanchang formation (Wu et al. 2016). The value at the turning point of the diagram of displacement starting pressure and physical property was taken as the lower limit of physical property of the 7th member of Yanchang formation (Fu et al. 2014). The sum of double water film thickness and oil and gas molecular aggregates was used as the lower limit of effective pore throat of He-8 gas reservoir in Sulige Gasfield (Liu et al. 2016). The methods above are greatly influenced by the richness of data, the representativeness of samples and geological conditions in the study area. The fluid flow characteristics through porous medium is also less considered. In this study, an experimental method for determining the lower limit of reservoir physical properties was established by multiple centrifugation and nuclear magnetic resonance tests (NMR).

The Yingxi area is located at the northwest end of Yingxiongling structural belt, Qaidam Basin. The tectonic zoning belongs to the western depression. A number of wells have continued to make exploration breakthroughs since 2014. More than 100 million tons of oil and gas reserves were discovered in this area (Hanson et al. 2001). The exploration target horizon of the study area is the Paleogene Lower Ganchaigou Formation (E32), which is a set of shore-shallow to semi-deep lacustrine sediments. The rock composition is characterized by the mixed deposition of argillaceous, carbonate and clastic particles, and the carbonate content in the three components is relatively high (40%-80%). In addition, symbiotic salt minerals have also been found, such as gypsum, glauberite, halite and so on (Fan et al. 2019). Gas porosity of core samples is concentrated between 1% and 15%, with an average value of 3.87%, and permeability is mainly distributed between 0.01mD and 6mD, with an average value of 0.11mD, belonging to ultra-low porosity and ultra-low permeability reservoir. The main reservoir types are micro- and nano-scale dolomite intercrystalline pores. However the lower limit of effective physical properties for this type of reservoir has not been determined, which is the main problem to be solved in this study.

Method

Samples were taken from the drilling cores in Yingxi area, and 28 samples were selected from 7 wells at a sampling depth of 3100m-4050m (Figure 1). The purpose of this method is to distinguish the movable fluid from the irreducible fluid by multiple centrifugation and NMR tests, and to determine the lower limit of the pore throat radius of the movable fluid distribution according to the relation between the fluid and the pore throat, and to determine the lower limit of the physical property through the relation between the physical property and the pore throat radius. The steps are as follows. Firstly, the lithology and pore types of the samples were obtained by thin section observation and X-ray diffraction test. According to the results, samples with intercrystalline pore developed and dolomite content greater than 60% were selected for further experiments. Secondly, the approximate distribution range of pore throat of intercrystalline pore was obtained by SEM statistics of argon ion polished samples and mercury
injection tests. It can restrict the lower limit of pore throat of movable fluid distribution determined by multiple centrifugation and NMR tests.

Figure 1 Sedimentary environment and the location of Yingxi area, western Qaidam Basin

And then, the samples saturated with formation water were subjected to four centrifugation and NMR tests. The process of centrifugation can be considered as the process of gas drive. The higher the speed of centrifugation, the smaller the pore throat in which the movable fluid is drained by air. There is only irreducible fluid in the pores in the final state of the centrifugation. By comparing the nuclear magnetic $T_2$ relaxation spectrum accumulation curve of the initial fluid saturation state which reflects the overall characteristics of the movable fluid and the irreducible fluid and the nuclear magnetic $T_2$ relaxation spectrum accumulation curve of the final centrifugal state which reflects the characteristics of the irreducible fluid, the separation point of the two cumulative curves was determined (Figure 2). The separation point corresponds to a relaxation time. There is a linear relationship between $T_2$ relaxation time and pore throat radius. The NMR relaxation time $T_2$ can be converted to the pore throat radius $r$ only if the conversion coefficient $C$ is known ($r=C*T_2$)(Volokit et al. 2001). The pore throat radius corresponding to the separation point serves as the lower limit of pore throat of the movable fluids distribution, which is the minimum pore throat radius where the movable fluid no longer changes. The $C$ value of shale in Longmaxi formation in Sichuan Basin is 0.02 $\mu$m/ms (Gong et al. 2016). The composition and pore distribution of the tight lacustrine carbonate rocks are similar to that of the Longmaxi Formation. So the conversion coefficient $C$ used in this study is 0.02 $\mu$m/ms.

Figure 2 The separation point of the movable fluid and the irreducible fluid

Finally, the fitting experience formula of the median radius of pore throat in the process of mercury injection and porosity was established. The lower limit of effective porosity was gained by substituting
the lower limit of pore throat radius into the empirical formula, and the lower limit of effective permeability was acquired according to the relation of porosity and permeability.

**Distribution Range of Pore Throat**

The pore throat distribution range of the samples with carbonate intercrystalline pore in the lower Ganchaigou Formation of Yingxi area in the process of mercury injection was 11 nm to 220 nm, and the pore throat distribution range in the process of mercury ejection was 40 nm to 1500 nm. In conclusion, the pore throat distribution range of intercrystalline pores measured by mercury injection method was between 40nm and 220 nm. SEM was carried out to obtain the distribution of pore throats of the intercrystalline pores in tight carbonate samples with argon ion polishing. Secondary electronic images of intercrystalline pore throat section were taken, which are mostly triangular, serrated or irregular polygonal. Area calculation software was used to calculate the section area. Each pore throat radius was calculated as a circular equivalent. The equivalent pore throat radius of 32 typical intercrystalline pores was calculated with a distribution range of 50 nm - 300nm and an average value of 145.87nm. The NMR relaxation spectra of nine cores with saturated fluid were converted to pore throat radius distribution. It shows that the main pore size of tight lacustrine carbonate rocks in the lower Ganchaigou Formation is in the range of 40 nm to 500 nm. The pore size distribution curves are mostly unimodal-bimodal. The pores are mainly micropores (≤ 100nm), and the average proportion of micropores is 84%. The fluid saturation test results of NMR show that the overall irreducible fluid saturation of 9 samples is relatively high, with an average value of 83.6%.

The lower limit of the pore throat of 9 samples is distributed at 47 nm-510 nm, with an average value of 117 nm, mainly concentrates in the range of 47 nm-68 nm, which is consistent with the results of thin observation and SEM analysis. The samples within the range of lower limit mainly develop dolomite intercrystalline pores, in which the lower limit of the isolated intercrystalline pores sample is relatively low and the lower limit of the combined intercrystalline pores sample is relatively high.

**Lower Limit of Physical Property**

The lower limit of porosity was calculated by substituting the lower limit of pore throat of movable fluid distribution into the fitting formula of the median radius of pore throat and gas porosity. There is a positive correlation between gas porosity and the median radius of pore throat, with a correlation coefficient of 0.81. The range of the lower limit of porosity is 3.29%-7.77%, with an average value of 4.69%. There is no significant correlation between the lower limit of porosity and nuclear magnetic porosity of the post-saturation cores, while the lower limit of porosity is positively correlated with the median pore throat radius (correlation coefficient 0.78), which indicates that the effective reservoir space in the sample has nothing to do with the overall reservoir capability of the sample, and is mainly affected by the pore structure and pore throat distribution characteristics.

In this study, the inflection point of porosity and permeability fitting curve was used as the lower limit of permeability, which was 0.02mD. There is a good correlation between permeability and test pressure. The permeability and the test pressure curve reflects the rapid decrease of the permeability with the increase of the pressure when the gas permeability is less than 0.02 mD, indicating that the gas flow characteristics through porous medium of samples with permeability less than 0.02 mD and samples with permeability higher than 0.02mD are significantly different. Considering that samples with permeability below 0.1 mD are strongly affected by the slippage effect, the Klinkenberg permeability after eliminating the slippage effect still decreases rapidly with the increase of pressure, when the Kirschner permeability is less than 0.02 mD. Therefore, it is relatively reasonable to limit the permeability of tight carbonate rocks in the study area to 0.02 mD.

The degree of conformity of the lower limit of physical properties of the reservoir was tested by using log interpretation conclusion and corresponding gas test results. The porosity of effective reservoirs, defined as oil layer, water layer and oil-bearing water layer, is distributed in the range of 0.883%-23.35%, of which 87.3% are greater than the lower limit of porosity determined at this time.
Permeability of effective reservoirs is distributed in the range of 0.01mD - 95.8mD, of which 89.1% are greater than the lower limit of permeability determined at this time. The lower limit of the physical property of the tight carbonate rocks is in good agreement with the log interpretation, which can be used as the basis for the classification of effective reservoirs.

Conclusions

The dolomite intercrystalline pore reservoir of lacustrine carbonate rocks is dominated by nanoscale micropores, and intercrystalline pore throat section is mostly triangular, serrated and irregular polygonal. The distribution range of pore throat radius measured by mercury injection and SEM is from 40 nm to 300 nm. The distribution range of the main pore throat of the intercrystalline pore obtained by nuclear magnetic testing is 40 nm-500 nm, the lower limit of pore throat radius of movable fluid distribution is 47nm, the corresponding lower limit of porosity is 3.29%, and the lower limit of permeability is 0.02 mD.

References


