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Original research paper

Experimental investigation of porosity and permeability change caused by salting out in tight sandstone gas reservoirs☆

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Abstract

Salt precipitation and its induced problems are increasingly prominent with the development of deep and ultra-deep tight sandstone gas reservoirs with high salinity formation water. In this paper, the change of porosity and permeability of a series of tight sandstone was measured, and then the morphology and occurrence state of crystalloid salt within the pore was observed by SEM. Meanwhile, high-pressure mercury injection analyzed the changes of pore size distribution. Experimental results show that salt precipitation could affect the porosity and permeability, which decreases by 53% and 65% after salt precipitation, respectively. The occurrence state of the crystalloid salt can be divided into three models: superposition growth along with the intergranular pore-fractures/natural micro-fractures, lamellar growth attached to the surface of the hydrophilic mineral like I/S interstratified mineral and the individual particles located in the corner of the pore. When the size of crystalloid salt is closer to the pore size distribution of tight sandstone, it will cause cracks and pore throat blockage easily. It is suggested that salt wash pretreatment should be carried out before analysis of tight sandstone with porosity less than 5%.

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Keywords: Salt precipitation; Tight sandstone; Porosity; Permeability; Formation damage

1. Introduction

Tight sandstone gas is an unconventional natural gas resource, which has a high proportion in the composition of unconventional oil and gas resources in China and has excellent potential for development [1,2]. Tight sandstone gas reservoirs are usually deeply buried. The rapid gas flow rate near the well area during gas reservoir development will accelerate formation water evaporation, which leads easily to the salting out within 5 m range of the reservoir near well zone [3,4] due to the high salinity of the formation water. The crystallization salt produced by salting out will block the percolation channel, reduce the percolation capacity and seriously affect the gas well productivity. Salting out occurs during production of a gas well in Beihai Oilfield, which results in the skin coefficient increasing with time [5,6].

At present, salting out studies mainly focus on laboratory experiments, salting out model establishment, salting out prediction and removal [7−17]. Laboratory experiments revealed the type of precipitate (NaCl), the kinetics of salting out evaporation in porous media, the preferred evaporation site of salting out in porous media, the effect of temperature/pressure on salting out, and the changes of physical properties of rock samples before and after salting out. These studies mainly focus on salting out of reservoirs with good pore and permeability properties ($K > 1 \times 10^{-3}$ μm^2, $\Phi > 10\%$).

In this paper, samples of tight sandstone with different pore types are selected, and the evaporation experiments of high

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salinity formation water in these tight cores are conducted to stimulate the process of salting out under the given temperature. Before and after the experiments of salting out, the porosity and permeability of these tight cores are measured. The effect of salt washing on the analysis of pore and permeability properties of tight sandstone is also discussed.

2. Samples and methods

2.1. The experimental sample

The experimental rock samples were taken from the western Sichuan outcrop, the N block in the East China Sea and the K block in the Tarim Basin. The porosity of tight sandstone in Western Sichuan is mostly between 14% and 20%, with an average of 16.23%. The porosity of tight sandstone in N block of East China Sea is mainly between 4% and 10%, with an average of 7.45%. The porosity in K block of Tarim Basin is mainly between 1% and 5%, with an average of 3.11%. Eight representative, tight sandstone cores selected from the 3 blocks, are divided into three types according to the porosity: relatively high porosity of TP_H:10% $< \Phi <$ 16%, relatively medium porosity of TP_M:5% $< \Phi <$ 10%, relatively low porosity of TP_L:1% $< \Phi <$ 5%. The basic physical parameters of these cores are shown in Table 1. Salt crystallization is mainly sodium chloride [18] according to the analysis results of ionic composition of formation water with high salinity in some gas reservoirs [19,20]. In this paper, the simulated formation water in K area with the salinity of 200 000 mg/L is prepared as experimental fluid.

2.2. The experimental method

2.2.1. Porosity and permeability testing

(1) The basic physical parameters of the cores are measured after drying.
(2) The simulated formation water solution is prepared and filtered.
(3) As shown in Fig. 1, the experimental cores are immersed in the simulated formation water solution for 24 h, and then the saturated formation water samples are heated and evaporated in an oven at 60 °C for 48 h.
(4) Measure the porosity and permeability of rock samples using the SCMS core measurement system.

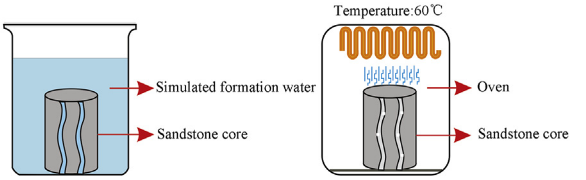

Fig. 1. Schematic diagram of evaporation of sampled saturated by formation water.

2.2.2. Salting out occurrence and pore size change analysis

After salting out, six experimental cores salting out were analyzed by using alpha Quanta 450 environmental scanning electron microscope.

The morphology, size and occurrence position of salt crystallization were observed. A tight sandstone core was cut into two sections. 9250 automatic mercury injection meter was used to test two sections of them. The capillary pressure curves are used to analyze the change of pore size of the core before and after salting out.

3. Experimental results and analysis

3.1. Change of porosity and permeability

As shown in Figs. 2 and 3, the porosity and permeability of six tight sandstone cores after salting out have been reduced to varying degrees. Among them, the porosity and permeability of TP_H cores have been reduced by 16% and 10%, and the porosity and permeability of low TP_M cores have been reduced by 13% and 26% respectively, and the porosity and permeability of low TP_M cores have been reduced by 49% and 57% respectively. These show that the smaller the porosity of tight sandstone is, the lower the permeability is, and the more substantial the decrease of porosity and permeability caused by salting out is.

3.2. Salt crystal morphology and microscopic distribution

From the scanning electron microscopy (Fig. 4) of the salted tight sandstone, it can be seen that salting out occurs in three types of occurrence modes, i.e., growth pattern (Fig. 4a) along intergranular pore/natural micro-fracture clusters, growth pattern (Fig. 4b) on the surface of hydrophilic clay

Table 1
Basic physical properties of experimental samples.

Core number	Lengh/mm	Diameter/mm	Mass/g	Porosity/%	Permeability/(× 10^{-3} μm^2)	Core type
LT-1	52.34	25.10	57.99	16.18	0.0930	TP_H
LT-2	50.50	25.10	55.00	15.98	0.0860	
DH-1	35.91	24.68	41.42	7.39	0.0723	TP_M
DH-2	46.75	24.76	55.43	8.97	0.0907	
KS-1	22.05	24.25	27.56	2.81	0.0128	TP_L
KS-2	28.25	24.16	34.65	3.40	0.0329	
KS-3	26.56	24.22	31.85	3.50	0.0420	
KS-4	27.63	24.18	33.06	3.16	0.0312	

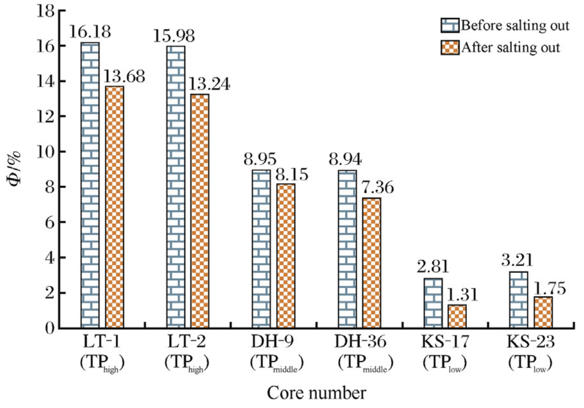

Fig. 2. Effects of the salt precipitation on the porosity of tight sandstone.

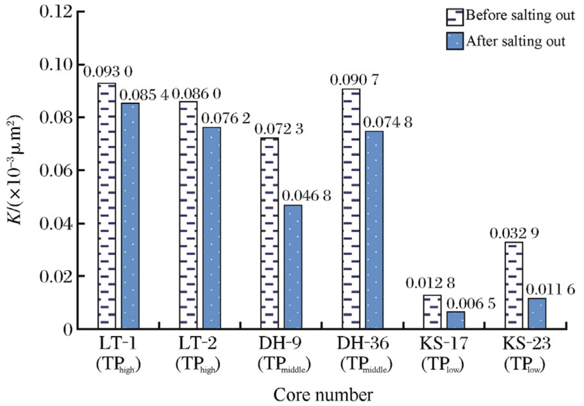

Fig. 3. Effects of the salt precipitation on the permeability of tight sandstone.

minerals such as illite/Mongolian interlayer, and growth pattern (Fig. 4c) at the corner of the pore. When microfractures or intergranular pore develop in the reservoir rock, these pore fractures become the dominant flow path of gas–liquid and the fast channel of preferential water evaporation, providing a good evaporation environment for gas flow and liquid evaporation. Also, the fluid saturation in these slots is usually higher, resulting in higher salinization. Scanning electron microscopy (SEM) reveals that the main types of clay minerals are illite/montmorillonite and chlorite. Among them, illite/montmorillonite is a hydrophilic clay mineral, so the solution is more readily adsorbed on the surface of such clay minerals and evaporates to form continuous layered salt crystals on the surface. When salting out occurs at the corner of the pore, crystalline salts grow at the corner or on the surface of quartz with natural single crystals of about 3–5 micron in length. Such crystalline salts may come from evaporation of pore water or retained water, or salt transport.

3.3. Variation of pore throat radius distribution in tight sandstone

Figs. 5 and 6 show the pore distribution of mercury injection analysis of KS-3 and KS-4 tight sandstone cores before and after salting out. The pore sizes are divided into four types in order to facilitate the analysis of the effect of salting out on the pore size of tight sandstone. These are macropore (pore size is greater than 100 nm), mesopore (pore size is 50–100 nm), transition pore (pore size is 10–50 nm) and micropore (pore size is less than 10 nm) [21]. The mercury intrusion test results show that the pore volume of KS-3 before salting out is between (40.88–1218) $\times 10^{-5}$ mg/L, and after salting out, the pore volume is between (85.12–92.55) $\times 10^{-5}$ mg/L. The pores are dominated by macropore and micropore. After salting out, the proportion of macropore and micropore decreases, and the volume of macropore decreases the most, which indicates that salting out occupies most of the pore space. The volume of pre-salting mercury injection method for KS-4 is between (1.71–1889) $\times 10^{-5}$ mg/L, and the pore volume of post-salting mercury injection method is between (37.34–162) $\times 10^{-5}$ mg/L. The pore volume of a core is

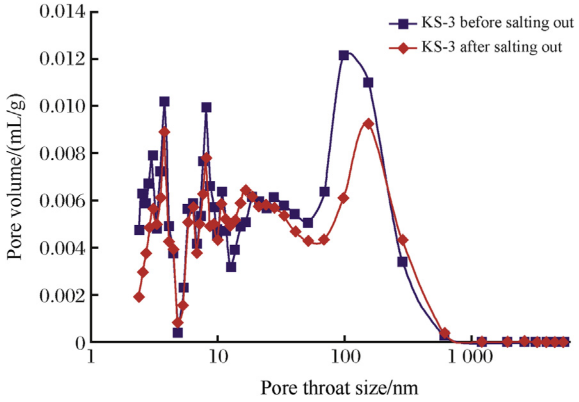

Fig. 5. Pore distribution of KS-3 core before and after salt precipitation.

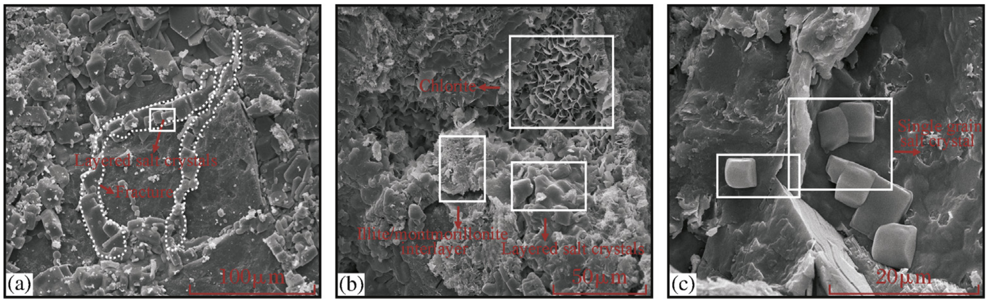

Fig. 4. Occurrence state of crystalloid salt within the pore throat.

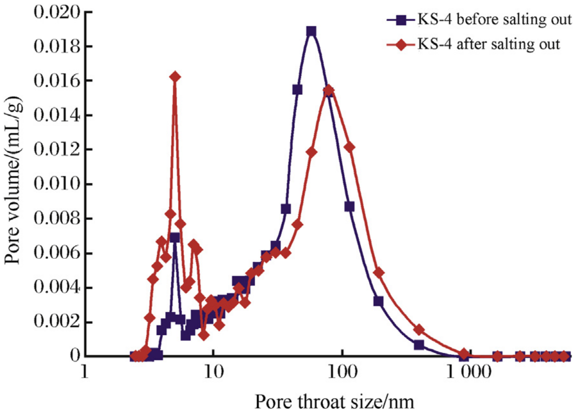

Fig. 6. Pore distribution of KS-4 core before and after salt precipitation.

mainly mesoporous and microporous. After salting out, the pore volume of mesopore tends to decrease, but the peak value of micropore increases, which indicates that the proportion of micropore increases by filling and cutting the mesopore with salt crystallization [22].

4. Discussion

4.1. Salting out mechanism analysis of tight sandstone gas reservoir

The pore structure and fracture of porous media strongly determine transport and precipitation patterns of salt in porous media strongly depend on the [14,23]. The characteristics of tight sandstone, such as high capillary pressure and abundant clay minerals in natural fractures, determine that the salting out mechanism of tight sandstone is different from that of conventional sandstone. In the process of formation water evaporation, the gas first enters the larger pore, and the smaller pore has strong water binding capacity but keeps saturated state. When the salinity increases due to the evaporation of the solution in the larger pore and the concentration gradient exists between the smaller pore solution and the larger pore solution, the smaller pore solution will migrate to the larger pore, and finally, the smaller pore will more naturally reach the salt solution limit [24]. However, after the final evaporation and salting out of the solution, the larger pore contains more crystalline salts because it stores more solutions and the solution migration caused by the concentration gradient. The pore distribution characteristics of Figs. 5 and 6 also show that crystalline salts have a more severe influence on the larger pore. Fracture is the main flow channel of tight sandstone reservoir. The liquid evaporation in a reservoir is mainly the result of gas carrying and high-temperature evaporation. In a fractured reservoir, gas flow rate increases, resulting in rapid evaporation of the solution to induce rapid production of crystalline salts and filling of fractures [25].

In tight sandstone reservoirs, salt crystallization occurs mainly in stratified cluster crystalline salts and single crystalline salts. The stratified cluster crystalline salts mainly occur in the iso-high permeability evaporation zone in cracks or thick pore throats, and the single crystalline salts mainly occur in the corner or grooves of the small pore throats. In the actual production process, crystalline salts in clusters are stable, and migration does not occur smoothly. Generally, it is mainly to reduce the cross-section of the flow channels. Under a given pressure difference, the single-grained will migrate and block the throat due to its weak binding force on the pore wall, which severely reduces the flow capacity of tight sandstone.

4.2. The influencing factors of salting out

Salting out phenomenon in pore throat of tight rock is related to liquid salinity, distribution of flow field and properties of mineral interface [26–29]. The main factors affecting the distribution of salt crystallization include:

(1) Heterogeneity of flow path of a reservoir. Micro-cracks are the dominant flow path (Fig. 4a). The more developed the cracks are, the stronger the gas flow ability is, the easier the liquid evaporates, and the more naturally the liquid reaches the saturated state to form salt crystallization. With high water content in the cracks, the crystalline salts produced by salting out grow rapidly in layers, have a stable structure and sufficient thickness, plug the cracks and significantly reduce their transport capacity.

(2) The occurrence and content of the hydrophilic clay minerals. Crystalline salts mainly distribute on the surface of the clay minerals in the pore throat, but no crystalline salts exist on the surface of chlorite (Fig. 4b). This is because the surface of the interlayer minerals is hydrophilic and super absorbent [30]. At high temperature, water evaporation causes crystalline salts to stay on the surface of the interlayer minerals. In addition, the illite/montmorillonite has an intricate surface, on which crystalline salts grow in clusters of “film-attached” layers, resulting in a decrease in pore volume.

(3) Pore shape of a rock. Some single salt crystalline are distributed in the corner of the pores (Fig. 4c), because the liquid is easily retained and evaporated to inducing salting out occurs in situ.

(4) The salinity of formation water. The higher salinity of formation water, the more salt crystals will be produced after evaporation and salting out.

4.3. Effect of salt washing on the physical property of tight sandstone cores

Salting out may occur in the process of drilling tight sandstone cores from underground to surface, which may influence the analysis results of physical properties. Thirty-nine tight sandstones in K block of Tarim Basin are selected to wash the salt and test the porosity and permeability of tight cores using the method for the repeated-pressure saturation establishing [31]. Fig. 7 is the relationship between pore and permeability of the cores.

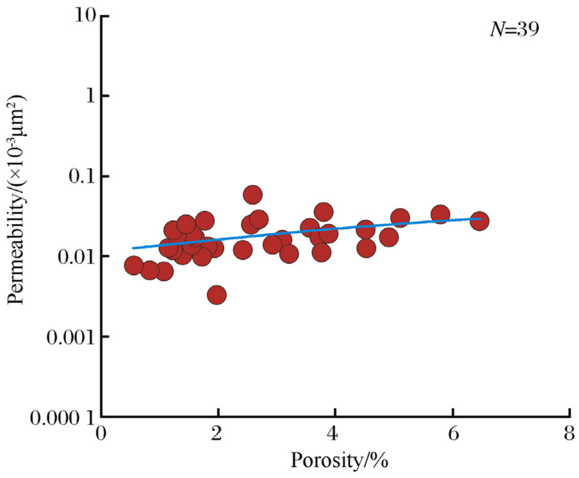

Fig. 7. Curve of the relationship between porosity and permeability.

The results of porosity and permeability test before and after salt washing (Figs. 8 and 9) show that the average porosity before salt washing is 2.54%, and after salt washing, the average porosity is 3.17%, which increases by 25%. The average permeability after salt washing is $0.0217 \times 10^{-3}\ \mu m^2$, which is 23% higher than that ($0.0176 \times 10^{-3}\ \mu m^2$) before salt washing. The smaller the porosity and permeability of tight sandstone, the more obvious the change of porosity and permeability after salt washing. For tight cores with the porosity greater than 5%, the effect of salting out on porosity is not significant. Therefore, it is necessary to carry out salt washing treatment before conducting flow or rock electricity experiments of tight sandstone containing high salinity formation water [32].

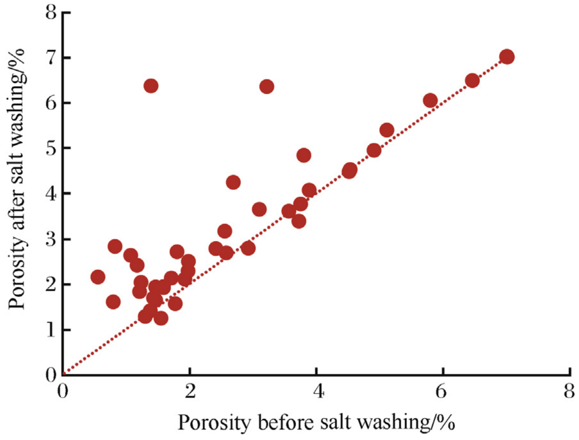

Fig. 8. Change the porosity before and after salt washing.

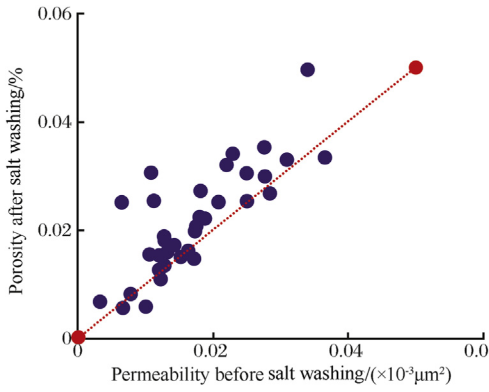

Fig. 9. Change the permeability before and after salt washing.

5. Conclusions

(1) After salting out, the porosity and permeability of tight sandstone may decrease by 53% and 65%.
(2) Salting out can be divided into three types: growth along intergranular pore fracture/natural micro-fracture cluster superposition, layer growth on the surface of hydrophilic clay minerals such as illite/montmorillonite interlayer, and growth of single grain at the corner of pores.
(3) After salting out, the volumes of all kinds of pores in tight sandstone can decrease.
(4) For tight sandstone with porosity less than 5%, salt washing should be carried out before core laboratory analysis experiments.

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Conflict of interest

The authors declare no conflict of interest.

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