A Method for Evaluating the Dynamic Sealing Efficiency of Underground Gas Storage Reconstructed by Aquifer

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ABSTRACT

There are very few living examples of engineering test cases in domestic aquifer underground gas storage construction, however, engineering test analysis can greatly reduce the risk of evaluation. This paper systematically introduced interference well test method application of aquifer gas storage construction in Huabei oilfield, and take the target of the D5 aquifer construction in Jizhong depression as an example to analyze the reasonable water injection, excited period and interference test results. Interference well test result shows that the target cap rock of D5 aquifer is sealed, the fault vertical sealing ability is good, the sealing condition of the reservoir is provided, and also the horizontal connectivity of the reservoir is good. The research results are directive and with reference value for the construction of aquifer underground gas storage in China.

KEYWORDS

Aquifer, Underground gas storage, Sealing ability, Interference well test

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INTRODUCTION

Aquifer underground gas storage (UGS) is the second UGS form in the world after depleted oil gas storage [1-3], it is mainly by injecting gas to the underground aquifer structure, by displacing the water in the reservoir, to build a gas storage place under impermeability cap rock [4-6]. International aquifer UGS constructed began in 1952, up to now has more than 80 aquifer gas storages, covers an area of about 15% of the total gas storages, and there is an increasing trend for aquifer UGS especially in countries and regions where lack of oil and gas fields which also already have formed a relatively comparatively advanced technology and experience in reconstruction of aquifer gas storage.

There is no completed aquifer UGS in our country at present, but the demand of aquifer gas storage in China is very urgent, especially under the giant demand for natural gas in the Beijing-Tianjin-Hebei region, only relying on limited depleted reservoir UGS is far from enough to satisfy the urgent need of growing seasonal peak shaving gas demand, the construction of aquifer gas storage is imperative. Aquifer UGS has certain characteristics such as large investment, high risk, the aquifer gas storage built in abroad mainly were integrity anticline that own good reservoir physical properties (porosity > 20%, permeability > 200 md), shallow buried depth (about 1000 meters), but the eastern part of our country is located in the fault basin tectonic setting, it is hard to find integrity anticlines buried depth less than 2000 meters and not develop fault, it brings more risks and challenges to aquifer gas storage [7-8].

Due to the lack of early evaluation data of aquifer UGS, it has big risks to rely on static data to evaluate the faults sealing ability and the cap rock sealing ability [9]. In this case, the dynamic interference well test results are more convincing and can greatly reduce the evaluation risk. Take the Jizhong depression D5 target as an example, this paper systematically introduced the design principle of interference well test, water injection and excited period determination method, result analysis, so as to provide beneficial reference for subsequent domestic aquifer gas storage construction.

INTERFERENCE TEST PRINCIPLE

During the onsite construction, the interference test can adopt two wells or more than two wells, but the basic unit is still a well-pair of two wells [10]. In this well-pair, one well is known as the "excited well" which change the working system in the test, from open to shut, or from shut to open as a certain production rate, thereby cause "excited" to the formation pressure; another well known as the "observation well", in the test this well will be shut to the static state, then down a high precision and high resolution pressure gauge into the downhole to record the change of the interference pressure spread from excited well.
During the onsite construction, multiple wells are often involved in the test construction in the same time. But no matter how many wells participate in the test, there is a basic principle must be follow: in the same time period, there can be multiple observation wells, but there can be only one excited well change working system to generate excited signal, otherwise will make data analysis disarray in next step.

PRACTICAL APPLICATION

Going to understand Jizhong depression D5 target cap rock sealing ability, fault sealing ability and formation fluid properties, to carry out the reservoir production capacity, to calculate the parameters such as reservoir physical properties and formation pressure, the interference well field test research is being taken on the only two wells D5 Well, D5-1 Well in target zone.

Overview of D5 Trap

D5 target is located in the middle of Litan sag in Jizhong depression, Dacheng county, Hebei province. The Litan sag distributes the north east direction, which is characterized by the Dacheng east fault control, and the gradual lifting of the fault depression from the southwest to the north east, and the sag area is 910km². The inner formations of the sag developed the Neogene, the Paleozoic, the Mesozoic, the upper Paleozoic Carboniferous-Permian, the lower Paleozoic Ordovician, the limestone formations, and the covering layer from the upper to lower. D5 target trap is an Ordovician-Paleogene inheritance anticline began to form in the late Mesozoic, inheritance and development in Paleogene, finalized in the late Paleogene. The target stratum of the D5 trap is Permian Shihezi formation sandstone (Figure 1).

D5 anticline is intact, and the top of the Permian Shihezi sandstone buried depth is 2307m, closure depth is 2512m, the closure height is 205m, and the trap area is 8.04km². The fault displacement in anticline area is small, the maximum fault displacement is less than 100m, anticline area including three block fault developed which separating the anticline into four block and extending the length of the 2 ~ 3km, secondly developed some local small fault.
Interference Test Program

In order to verify the fault sealing performance, cap rock vertical sealing property and reservoir characteristics between D5 Well and D5-1 Well, the impulse interference field test was carried out. Make D5-1 Well as excited well, D5 Well as observation well (Figure 2), Shihezi formation and the interbedded sand in upper cap rocks carry on with pulse water injection, monitoring the cap rock and adjacent D5 Well reservoir pressure response, thus acquiring reservoir characteristics and the status of the cap rock pressure response, calculating reservoir connected parameters (permeability, flow coefficient, pressure coefficient, elastic storage coefficient), evaluating the vertical and lateral sealing ability of the fault. The water injection operation and monitoring layer are as follows:

1. Water injection layer: Shihezi formation No. 2 sand group and No. 3 sand group (sandstone section 18-24#, 28-29#) of D5-1 Well, put the pressure gauge into the well to monitor the pressure.
(2) Monitoring layer: ① D5-1 Well Shihezi formation No. 1 sand group; ② D5-1 Well cap rock interbedded sand G sand group; ③ D5 Well Shihezi formation No. 3 sand group; ④ D5 Well Shihezi formation No. 1 sand group.

![Figure 2. D5 Aquifer Structural Interference Test Schematic Diagram.](image)

Table 1. Aquifer basic parameters of interferes well group.

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Permeability ×10⁻³ μm²</th>
<th>Water Viscosity mPa.s</th>
<th>Thickness m</th>
<th>System Compressibility MPa⁻¹</th>
<th>Porosity %</th>
<th>Volumetric Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>D5 Well</td>
<td>11.9</td>
<td>0.34</td>
<td>70.6</td>
<td>0.0011</td>
<td>9.42</td>
<td>1.03</td>
</tr>
<tr>
<td>D5-1CWell</td>
<td>9.65 (Local)</td>
<td>0.36</td>
<td>78.2</td>
<td>0.00148</td>
<td>6.07</td>
<td>1.0194</td>
</tr>
<tr>
<td>Average</td>
<td>10</td>
<td>0.36</td>
<td>78.2</td>
<td>0.00148</td>
<td>7.75</td>
<td>1.02</td>
</tr>
</tbody>
</table>

**Water Injection Rate and Pulse Period Determination**

1. Water injection rate
   According to the results of D5 Well and D5-1c Well early production test results, it is predicted that the daily water injection rate of D5-1c Well can reach 50m³/d.

2. Basic parameters selection
According to the interpretation results of D5 Well and D5-1c Well water formation test data, the basic parameters of the aquifer are determined by the logging interpretation results, as shown in Table1.

3. Interfere test time. $\triangle t_d$

The method of estimate test time for interference test is to determine the relationship between test flow $q$, excited production time $t$ and pressure gauge resolution $\delta_p$. When under certain $q_B$, the relationship with $\delta_p$ and $t$ is:

$$
\delta_p = \frac{qB\mu}{1.086Kh} E_i \left( \frac{69.44\phi\mu C_L^2}{Kt} \right)
$$

(1)

Where

- $\delta_p$: pressure gauge resolution, MPa
- $q$: daily water injection rate, m$^3$/d
- $B$: volume coefficient, l
- $\mu$: viscosity, mPas
- $K$: effective permeability, mD
- $Kh$: formation coefficient, mD.m
- $E_i$: exponential integral function

When selected $\delta_p$ as 0.0001 MPa, the minimum interference test time $\triangle t_d > 10t$ is required.

Interwell interference test time: according to the test requirements, use high resolution pressure gauge with the resolution of 0.0001 MPa, daily water injection rate as 50 m$^3$/d, substitute into equation (1) to calculate: excited production time $t =$ 3.6d. When $\delta_p$ selected as 0.0001 MPa, require minimum interference test time $\triangle t_d > 10t$, so at least 36 days, about 2 production pulse cycles test need to be done, one pulse cycle is for two weeks (production for a week, then shut-off for a week).

Vertical interference test time: (1) according to the cap rock sealing ability evaluation standard, when the cap rock permeability is between 0.001-0.01 mD, the porosity is between 2.5%-5%, the cap rock sealing ability is strong which can be used as the effective cap rock of the reservoir. (2) D5-1c Permian cap rock two sandstone layers of 2307-2313m and 2259.4-2262.6m, had been tested for formation testing respectively early, daily water production rate is 0.006 m$^3$/d and 0.026 m$^3$/d.
respectively, from that to estimate cover formation two sandstone layers’ permeability were 0.001mD, 0.004mD respectively, considering the vertical test isolation layer is pure compact mudstone, the permeability data may be lower. Under the principle of caution, considering cap rock test case and cap rock sealing ability evaluation standard, select permeability as 0.001mD, porosity as 5%, substitute into equation (1): $t = 11d$, when select $\delta p$ as 0.0001MPa, require minimum interference test time delta $\Delta t d > 10 t$, so at least 110 days test time, about 8 pulse period test need to be done.

Considering interwell interference and vertical interference, the test is divided into seven pulse period, each pulse period has 7 days for water injection, then 7 days for suspension, daily injection rate is between 50-60m$^3$, cumulative water injection is 2722.6 m$^3$, water injection pressure is increased from 0.3 MPa to 1.6 MPa, the relationship between water injection pressure and injection rate of the excited well water injection layer No.3 sand group is shown in Figure 3.

Figure 3. Water Injection Pressure and Water Injection Rate.

Test Results Analysis

1. Horizontal connectivity of reservoir

D5 Well No.3 sand group reaction layer (Layer 9-14#) can receive clear interference signals from each pulse excited period, use Saphir interference well test interpretation software with interference well test module to analyze pulse interference curve matching (Figure 4), calculate connected parameters between D5 Well Layer No. 9-14 and D5-1 excited well, through the pressure model matching to calculate permeability for 25.5mD, which is higher than the single well test. The distance between two wells is 330 m, the reaction layers have a response delay time receive the excited layers pressure for an average of 40 minutes, the lateral pressure
response time is shorter, pressure response amplitude is obvious, the signal is clear, the reservoir connectivity is good, all this verify the fault between connected layers of two wells is lateral open.

Figure 4. History Matching Diagram of Interference Well Test Measured Pressure Curve.

Figure 5. The Measured Pressure Response of No.1 Sand Group (Layer 8#) in D5 Well Observation Layer.

Figure 5 shows the measured pressure response curve of D5 Well observation layer No.1 sand group (Layer 8#). D5 Well 8# reaction layer has received seven pulse signals, but the response amplitude is obviously stronger than D5 Well No.3 sand group reaction layer (Layer 9-14#), D5-1 Well 18-29# layer water injection pressure wave first achieves to D5 Well 9-14# layer, the good connecting relation
layer, the pressure response delay time of 8# layer is only late about 1 hour than the D5-1 Well excited layer water injection time.

The pressure response curve of D5 Well 8# layer has a normal performance in first cycle, the remaining six pulse cycles all behave abnormal, namely the pressure peak value decreases, and the pressure fluctuation amplitude also decreases gradually, analysis the reason for this is that D5 Well cementing quality is poor, D5 Well 9-14# layer pressure waves achieving to the upper 8# layer through the outside casing, the sand layer also received similar seven pulse cycles pressure response signals, but with 8# layer pressure increase, pressure wave break through 8# layer upper segments of the poor well cementing interval spillover to the upper layer, with repeated pulse, the inhibition of 8# layer and the upper layer of poor cementing interval is more and more weak, so the pressure of 8# layer is rise down slightly. Therefore, although the mudstone partition at the upper part of the reservoir is fractured by the fault, it is closed, and the 8# layer is not connected with the excited well D5-1 Well.

2. Cap Rock Vertical Sealing Ability

![Figure 6. D5-1 Well No.1 Sand Group Pressure Response Curve.](image)

![Figure 7. D5-1 Well Cap Rock Interbedded Sand G Sand Group Pressure Response Curve.](image)

D5-1 Well two vertical observation layers are G sand group (Layer 15 #) and No.2 sand group (Layer 16-17#), two sand groups both have impulse pressure response signals of seven cycles, but both sand groups showed various degrees of abnormal, pressure response curve is shown in Figure 6 - Figure 7.

The seven pulse signals in G sand group are not obtained from the excited layer No.3 sand group (Layer 18-29#), but are obtained from the thermal effect caused by the difference between the water injection temperature and the formation temperature. Analysis reasons are as follows: contrast excited sand layer measured pressure and observed G sand group pressure response curve show that two pressure change times are the same time, if the G sand group pressure signal is caused by excited layer, two layers are 65m apart, separated by the cap rock, the cap rock permeability is extremely low, delay time between the two measured pressure signals could not be such short; pressure response in G sand group is very small, if G sand group pressure signal is caused by excited layer, the pressure response
amplitude should be evident in a very short delay time, this indirectly verified the 15# layer and excited 18-29# layer is vertical disconnected. No. 2 sand group (Layer 16-17#) has an abnormal pressure pulse response as well as the 15# layer, formation pressure drop in water injection period, and formation pressure increase when shut off the well, the pressure signal is very weak, after comprehensive analysis, it is concluded that excited layer and 16# layer are vertically disconnected by the reason of heating effect of the water temperature difference in water injection. According to the synthesis, the overburden cap rock of the upper reservoir can be considered as sealing, and the fault vertical closure is good between the D5 Well and the D5-1 Well.

CONCLUSIONS

(1) The analysis of the interference test results show that the horizontal connectivity of the target reservoir D5 aquifer in Jizhong depression is good.

(2) The target cap rock of D5 aquifer in Jizhong depression has a good sealing ability, in the meanwhile, the fault between D5 Well and D5-1 Well has a good vertical closure.

REFERENCES