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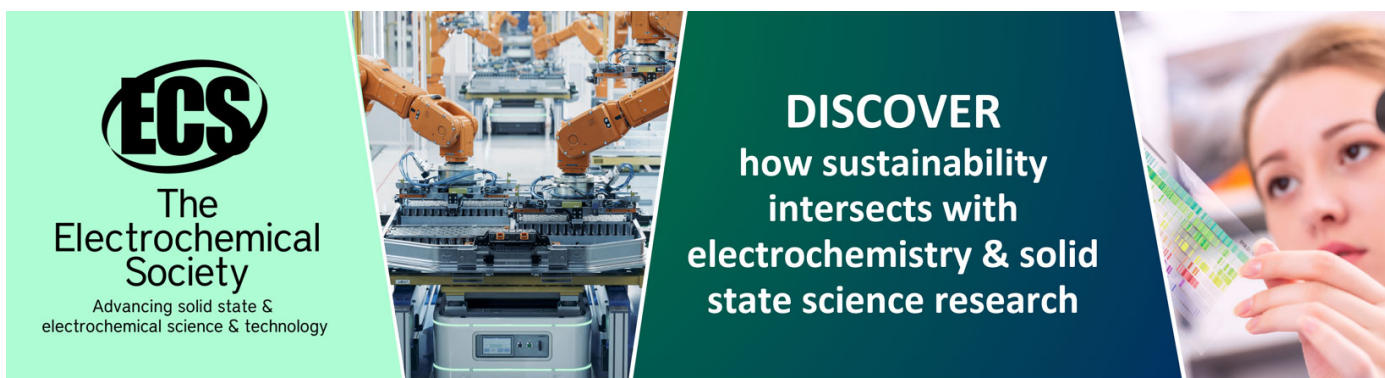
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Experimental analysis of factors influencing the development effect of multilayer gas well

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Abstract. Sulige gas field is characterized by complex pore structure, poor reservoir properties and low output of single-layer production. Therefore, in order to obtain higher economic profit, multi-layer commingling development is adopted in this type of gas field. According to the basic characteristics of the upper Paleozoic reservoir in Sulige gas field, there is a positive correlation between the output contribution rate of each production layer and its physical parameters and effective thickness. In order to directly analyze the inter-layer output law and its influencing factors of gas wells, a variety of formation models are designed, and the experiment of single-layer development and multi-layer combined development is carried out. It is found that permeability and original formation pressure are the main factors affecting the development effect of multi-layer well. The original formation pressure has the greatest influence on the ultimate recovery, while the permeability has the strongest influence on the average daily output and the yield contribution rate of productive layer. According to the similarity theory, the mathematical model between the gas productivity index per meter per well and permeability is fitted. Finally, the mathematical model is applied to 18 gas wells of the S-af area of sulige gas field, and the calculation accuracy reaches a high level. The validity and practicability of the formula is verified, which can provide the basis for subsequent production.

1. Introduction

Sulige gas field is located in the north of Yishan slope of Ordos Basin. The main production layers are Permian lower Shihezi formation and Shanxi formation. The reservoir with an average porosity of 8.5% and an average permeability of 0.55mD is a typical tight sandstone gas reservoir [1-3].

Due to the complexity of the pore structure and the poor physical properties of the reservoir, the single-layer productivity of the production well is low, and it is difficult to achieve industrial productivity. In order to increase the productivity of a single well and obtain higher economic profit, multi-layer development is often used to gas production in this type of gas field [4].

In the years of production practice, the research on underground pipe string and multi-layer commingled development mode in this area has been deepened and has gained a mature understanding [5]. However, there is still a large research space in the production rules and influencing factors of multi-layer production wells.

This paper is aimed at the inter-layer production of the multi-level well in sulige gas field. Based on the dynamics production and the reservoir characteristics, through the simulation experiment, we



analysis and study the main influence factors of multilayer commingled producing, in order to optimize the work system and improve the economic profit of gas reservoir development.

2. Study on the law of interlayer production of commingled producing well

Sulige gas field is a large gas field with multiple layers vertically superimposed and widely distributed on the plane. The effective sand body of the reservoir has poor continuity and connectivity, and the pressure system is complex. An independent sand body is often a pressure system, so the inter-well interference phenomenon in the existing well network is relatively weak. In the longitudinal, due to the poor reservoir physical properties and the small original formation pressure range, large pressure difference should be established during production. Once the well put into production, all layers will reach dynamic equilibrium in a relatively short time in the wellbore, and there will be no reverse osmosis phenomenon [6]. Therefore, there is no obvious interlayer interference phenomenon when several sand layers of gas wells are put into production at the same time.

According to the gas production profile test, under the condition of similar pressure difference in production, the production distribution and variation are determined by the physical properties, gas content and effective thickness of the reservoir [7]. Take the Well-S-af-ak-33 as an example, the change law of gas production and yield contribution rate in each production layer as in Table 1. In the early production, the higher gas carbonitriding layer suppressed the lower permeability layer, however, as the production progressed, the pressure of the high permeability layer decreased, and the recoverable reserves are reduced. However, the pressure in the low permeability layer decreases less and there are still a lot of reserves have not been utilized. Therefore, the difference of permeability can be compensated by the difference of pressure and residual reserves, which makes the yield contribution rate rise.

Table 1. The result of gas production profile test of Well-S-af-ak-33.

Formation	Parameter types	Result of gas production profile test in 2009	Result of gas production profile test in 2010	Effective thickness (m)	Porosity (%)	Permeability (mD)	Gas saturation (%)
Upper He 8	Gas production (m^3/d)	11244.43	9207.13	3.8	9.29	0.419	71.54
	Gas production ratio (%)	72.25	62.67				
Lower He 8	Gas production (m^3/d)	1289.25	5485.26	4.9	8.52	0.246	70.03
	Gas production ratio (%)	8.28	37.33				
Shan1	Gas production (m^3/d)	3029.77	0.00	2.2	9.03	0.331	68.28
	Gas production ratio (%)	19.7	0.00				

By analyzing the data of each layer in Gas production profile testing, it is found that the yield contribution rate is positively correlated with the physical parameters and the effective thickness. The productive layer with high porosity, permeability and gas saturation or the layer with general physical properties but with relatively thick effective thickness, the yield contribution rate is larger and the cumulative gas production volume is higher than other layers. The productive layer with relatively poor properties but high effective thickness, most of them show an upward trend of yield contribution rate in the middle and late production, which can provide the guarantee of stable production for the middle and later production.

3. Laboratory analysis of factors affecting development effect of commingled producing well

In order to directly analyze the inter-layer output law and its influencing factors of gas wells, it is necessary to devise multi-layer development simulation experiments. The experimental device consists

of pump, parallel core gripper, cylinder, pressure control and monitoring system, and gas-liquid separation and measurement system. Porosity and permeability were tested for the experimental samples collected at sulige gas field (Table 2). According to the basic characteristics of the upper Paleozoic reservoir in sulige gas field, a variety of formation models are designed, and the experiment of single-layer development and multi-layer combined development is carried out [8].

Table 2. Statistical table of core physical properties.

NO.	Length (cm)	Diameter (cm)	Porosity (%)	Permeability (mD)
1	3.274	2.482	9.29	1.460
2	3.297	2.487	8.93	1.156
3	3.338	2.508	9.45	1.523
4	3.382	2.493	7.63	0.315
5	3.318	2.489	7.35	0.158

3.1. The effect of single factor on single-layer development

The experiment is conducted under the situation of different formation pressure, permeability, water saturation, rock confining pressure and gas recovery speed, and the influence degree of each factor on the single layer exploitation effect is analyzed. According to the influence degree to the recovery percent, the sequence is from strong to weak: formation pressure, permeability, water saturation, gas recovery rate, rock confining pressure. The degree of influence on unit time flow is from strong to weak: permeability, formation pressure, water saturation, rock confining pressure. It can be seen from the experimental results that permeability and formation pressure are the main factors influencing the development effect (Figure 1).

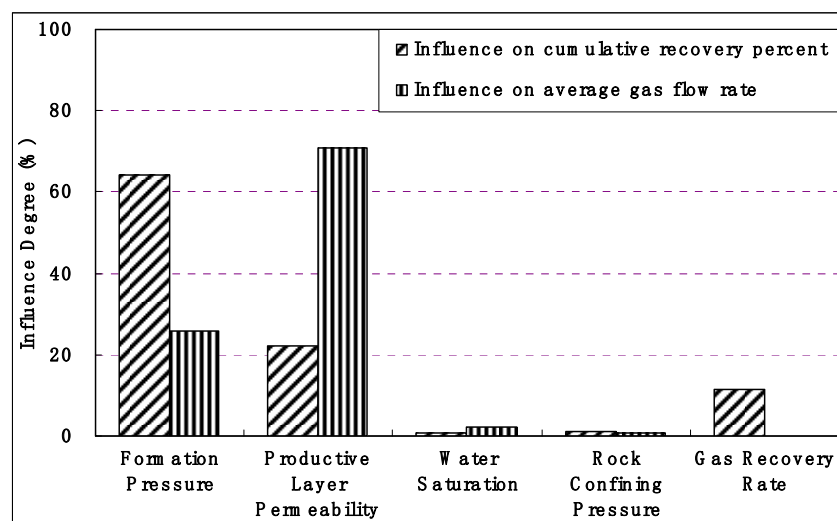


Figure 1. Rank of the influence degree of each factor on development effect.

3.2. The effect of formation pressure on the multi-layer combined development

The No. 1 and No. 3 samples with similar permeability are selected to carry out simulation development experiments under different experimental environments of original formation pressure. In the first group of experiment, the simulated original formation pressure of each samples is respectively 33.27MPa and 30.25MPa, and the simulated original formation pressure ratio is 1.1. In the second group of experiments, the simulated original formation pressure of each samples is respectively 33.27MPa and 25.62MPa, and the simulated original formation pressure ratio is 1.3. With

the continuation of the experiment time, the pressure keep falling, and the corresponding experiment time is 21min when the abandonment pressure is reached.

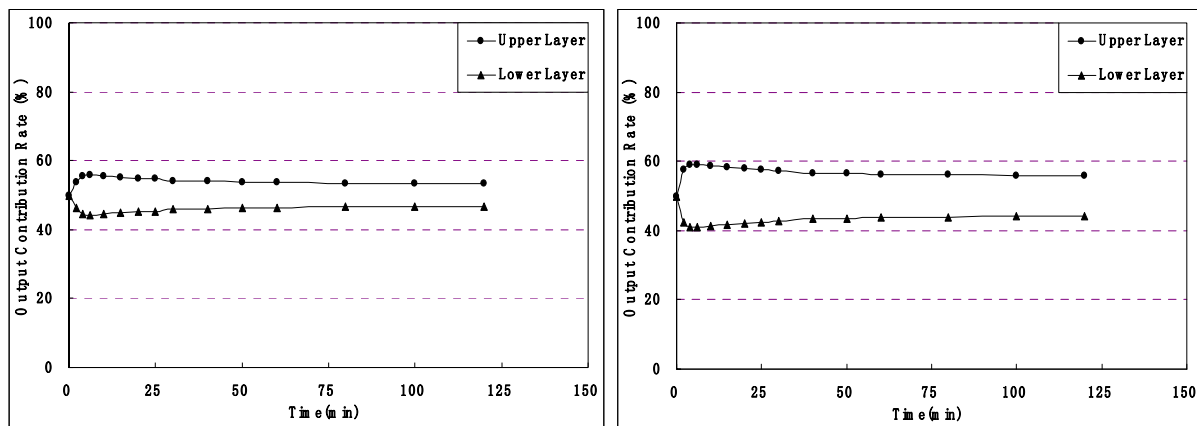
When the simulated original formation pressure ratio is 1.1, the average gas flow rate of the upper and lower producing layers is 78.75ml/min and 64.39ml/min, and the cumulative flow rate is respectively 1653.7ml and 1352.2ml. When the abandonment pressure is reached, the corresponding cumulative recovery percent is respectively 63.81% and 58.47%. In the process of simulated development experiment, the pressure of upper producing layer is higher, and the output contribution rate, as well as the development effect, is always higher than that of low pressure layer.

When the simulated original formation pressure ratio is 1.3, the upper producing layer has high pressure, and the average flow rate, cumulative flow rate and ultimate recovery rate are all higher than the lower layer. Compared with the simulated formation pressure ratio of 1.1, when the simulated formation pressure ratio is 1.3, the output contribution rate of the high-pressure layer is more obvious and the development effect is more advantageous.

It can be seen that, when the physical properties of each layer are similar, the greater the difference of original formation pressure, the more obvious the difference of development effect [9-11] (Table 3, Figure 2).

Table 3. The development effect of different formation pressure in different productive layer.

The simulated formation pressure ratio of 1.1				The simulated formation pressure ratio of 1.3			
layer	Average gas flow rate (ml/min)	Cumulative flow rate (ml)	Cumulative recovery percent(%)	layer	Average gas flow rate (ml/min)	Cumulative flow rate (ml)	Cumulative recovery percent(%)
upper	78.75	1653.7	63.81	upper	78.58	1650.2	63.76
lower	64.39	1352.2	58.47	lower	59.48	1186.0	56.82



(a) The simulated formation pressure ratio of 1.1 (b) The simulated formation pressure ratio of 1.3

Figure 2. The effect of formation pressure on the development of multi-layer combined development.

3.3. The effect of permeability on the multi-layer combined development

The No. 2, 4 and 5 samples are selected to carry out simulation development experiments under the experimental environment with similar original formation pressure. In the first group of experiment, the permeability of each samples is respectively 1.156mD and 0.315mD, and the permeability ratio is 3.7. In the second group of experiments, the permeability of each sample is respectively 1.156mD and 0.158mD, and the permeability ratio is 7.3. With the continuation of the experiment time, the pressure keep falling. When reached the abandonment pressure, the corresponding time of the two groups of experiments is 36min and 126min, 36 min and 210min, respectively.

When the permeability ratio is 3.7, the average gas flow rate of the upper and lower producing layers is 44.82ml/min and 12.33ml/min, and the cumulative flow rate is respectively 1613.5ml and 1553.2ml. When the abandonment pressure is reached, the corresponding cumulative recovery percent is respectively 64.75% and 60.28%. In this experimental model, the permeability of upper producing layer is higher, and the output contribution rate, as well as the development effect, is always higher than that of low permeability layer.

When the permeability ratio is 7.3, the upper producing layer has high permeability, and the average flow rate, cumulative flow rate and ultimate recovery rate are all higher than the lower layer which has low permeability. Compared with the permeability ratio of 3.7, when the permeability ratio is 7.3, the output contribution rate of the high permeability layer is more obvious and the development effect is more advantageous.

It is evident that, when the original formation pressure of each layer are similar, the greater the difference of permeability ratio, the more obvious the difference of development effect [12-13] (Table 4, Figure 3).

Table 4. The development effect of different permeability in different productive layer.

The permeability ratio is 3.7				The permeability ratio is 7.3			
layer	Average gas flow rate (ml/min)	Cumulative flow rate (ml)	Cumulative recovery percent(%)	layer	Average gas flow rate (ml/min)	Cumulative flow rate (ml)	Cumulative recovery percent(%)
upper	44.82	1613.5	64.75	upper	44.91	1616.7	64.92
lower	12.33	1553.2	60.28	lower	7.03	1475.6	57.97

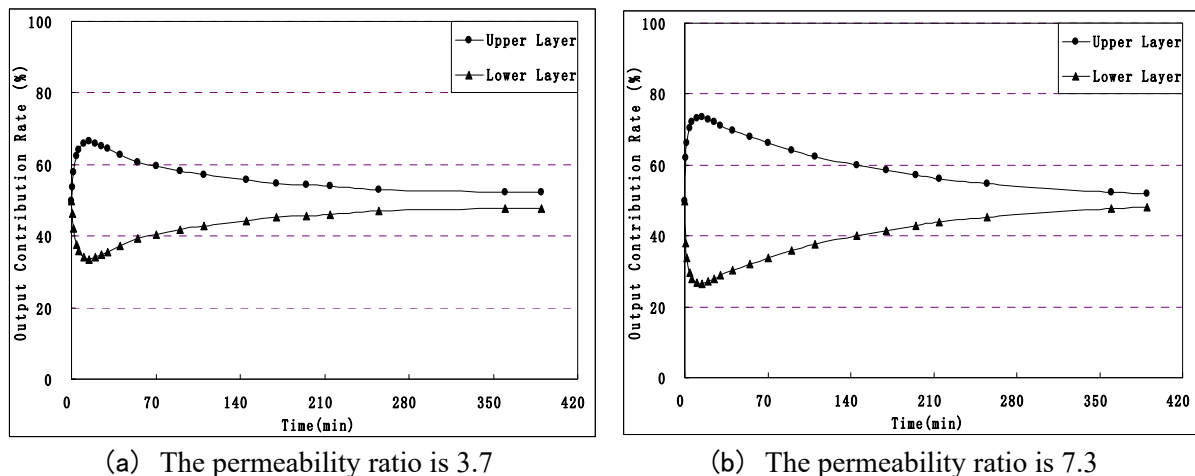


Figure 3. The effect of permeability on the development of multi-layer combined development.

3.4. The quantitative relationship between single well productivity and its main controlling factors

In the simulated development experiment, when the experimental pressure reaches the formation abandoned pressure, the recovery percent can be considered as the final recovery percent in the field actual production. The gas flow rate per unit time can be converted into the average daily gas output per well in practical production by using the similarity theory. According to the influence degree of each factor on the development effect, it is considered that for single well recovery percent, the original formation pressure has the greatest influence degree, followed by permeability. For the average daily output of single well, the permeability has the strongest influence on it [14-15].

It is found from the experiment that the effect of reservoir properties on output contribution rate is stronger than that of formation pressure. What's more each producing layers of sulige gas field has the characteristics of similar original formation pressure. Therefore, the gas productivity index per meter

per well in the experimental environment is calculated by using the experimental data. Finally, according to the similarity theory, the mathematical model between the gas productivity index per meter per well and permeability is fitted by using the mathematical methods such as statistics and regression.

$$\ln J = \ln \sum_{i=1}^n (10.303K_i + 3.527) - 1.213 \sqrt{\frac{\sum_{i=1}^n (K_i - K_{avr})^2}{n}} / K_{avr} \quad (1)$$

In the formula:

J —the gas recovery index per meter per well;

n —the number of producing layers of the single well;

K_i —permeability of any producing layer of a single well;

K_{avr} —average permeability of all producing layers in a single well.

4. Mathematical model validation

The mathematical model of gas productivity index per meter is applied to 18 gas wells of the S-af area of sulige gas field, and the calculated results are compared with the actual production data to verify the accuracy of the mathematical model. There are only 4 wells wrongly calculated, and the prediction accuracy reaches 77.78%. The validity and practicability of the formula is verified, and it can provide the basis for subsequent production (Table 5).

Table 5. The calculative value and actual value of gas recovery index per meter in S-af area.

Well	Gas recovery index per meter		Predicted results
	Calculation	Actuality	
Well-S-af-ah-38	35.192	36.069	T
Well-S-af-ag-37	24.459	22.091	T
Well-S-af-ad-36	30.848	22.365	F
Well-S-af-ah-33	20.746	20.746	T
Well-S-af-af-41	19.347	19.725	T
Well-S-af-ad-40	28.460	26.357	T
Well-S-af-af-30	49.603	43.687	T
Well-S-af-ak-37	21.170	30.021	F
Well-S-af-ag-41	21.331	23.434	T
Well-S-af-ah-41	20.377	14.285	F
Well-S-af-ac-43	28.633	35.703	T
Well-S-af-ak-44	33.100	30.082	T
Well-S-af-ab-41	36.574	37.689	T
Well-S-af-bl-36	31.903	37.849	T
Well-S-af-ac-38	41.229	36.068	T
Well-S-af-ac-41	17.497	15.904	T
Well-S-af-aa-37	18.318	19.630	T
Well-S-af-ab-32	27.601	17.075	F

5. Conclusions

(1) There is a positive correlation between the output contribution rate of each production layer and its physical parameters and effective thickness. The production layer with high permeability or thick effective thickness usually has a high output contribution rate. Some reservoirs, which has low permeability but a thick effective thickness, often show an upward trend of the production contribution rate in the middle and late production stages.

(2) Permeability and original formation pressure are the main factors affecting the development effect of multi-layer well. The original formation pressure has the greatest influence on the single well recovery percent, while the permeability has the strongest influence on average daily output of single well. For the output contribution rate of each production layers, the effect of reservoir permeability is stronger than formation pressure.

(3) The data of gas productivity index per meter per well in the experimental environment is calculated and the mathematical model of gas productivity index per meter per well is founded. The formula is applied to 18 gas wells of the S-af area of sulige gas field, and the calculation accuracy reaches 77.78%. It can provide the basis for subsequent production.

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