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A New Development Strategy: Numerical simulation and Field Application of Advanced Gas Injection Approach in Shale Reservoirs

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ABSTRACT

The development of shale reservoirs relies on hydraulic fractures. The development process often faces the shortcomings of fast decreasing production rate and insufficient formation energy. The high permeability of gas makes gas injection into shale reservoirs an effective development strategy. In complex fractured reservoirs, reasonable timing of gas injection will significantly improve the development of the reservoir and effectively prevent the risk of gas intrusion. Currently, the shale reservoirs in Changqing Oilfield in the Ordos Basin of China face problems such as low reservoir pressure coefficients, poor physical properties, and obvious non-Darcy flow, which lead to low initial development production of the reservoirs. In this paper, we propose a new development strategy named advanced gas injection, where gas is injected in advance before the production of the production wells to improve the initial formation pressure and fluid physical properties and to realize the improvement of the fluid flow capacity. The advantages of the advanced gas injection strategy in shale reservoirs are analyzed using a shale numerical simulator, the model adopts the embedded discrete fracture model (EDFM) method to realize the fracture modeling, and the components adopt the results of the analysis of the actual extracted fluid components in the field. The simulation results show that advanced gas injection can significantly increase the oil production rate in the early stage of development, and the average oil production rate in the initial stage (three months) is increased by 10-35% compared with the lagging injection. However, the decline rate of production is faster, and this yield difference will be reduced in the subsequent production; further design of the follow-up development strategy is necessary.

Keywords: fractured shale reservoir, advanced gas injection, timing of gas injection

NONMENCLATURE

Abbreviations	
EDFM	Embedded discrete fracture model
WAG	Water-alternating-gas
SRV	Stimulated reservoir volume
Symbols	
P	Pressure
T	Temperature
x	Liquid phase mole fraction
y	Vapor phase mole fraction
ρ	Density
φ	Porosity
v	Velocity of phase
D	Diffusion coefficient
a	Attractive term in the Peng and Robinson (1976)
b	Repulsive terms in the Peng and Robinson (1976)
K	Balance constant
f	Fugacity
R	Gas constant
Fv	The vapor molar fraction

1. INTRODUCTION

Traditional water injection development technology is difficult to be applied in ultra-tight shale reservoirs, although there have been many attempts, such as water injection huff and puff, water injection imbibition, and water-alternating-gas injection (WAG)[1,2,3]. Gas migration in shale reservoirs with expansive minerals will be seriously affected during water injection, which limits

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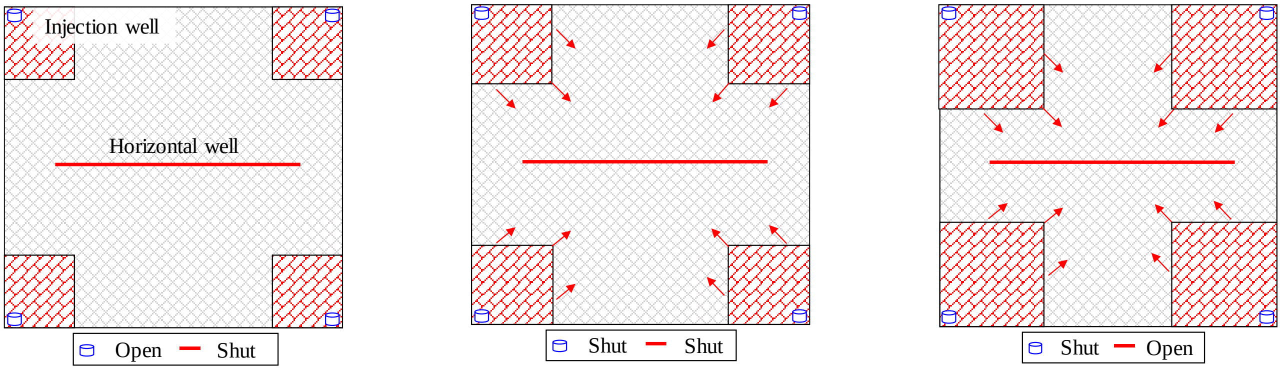
water injection development to a narrow range [4,5]. Gas injection is widely recommended as a more effective



(a) Injection period (b) Soaking period (c) Production period

Fig.1 The diagram of advance gas injection

way to EOR. The high permeability and miscible ability of the gas phase make gas injection development more potential. At the same time, the interaction between gas and oil, such as dissolution, improves the physical properties of oil and makes it easier to migrate [6,7]. The effect of the above advantages will be further enhanced under a larger contact area of the oil and gas system. Multi-cluster volume fracturing technology of horizontal well have been widely used in shale reservoir development [8]. The complex fracture network as the intermediate medium effectively communicates the multi-scale pores and well.

Currently, the formation pressure coefficients of ultra-low permeability shale reservoirs in the Changqing oilfield in China range from 0.6 to 0.8, which are significantly lower than those of shale reservoirs in other typical regions. In the process of field development, although a large number of hydraulic fractures have been formed through volume fracturing, the lack of formation energy restricts the production of the field. In this paper, based on the current questions of shale oil production in Changqing, China, and the exposed problems, a new gas injection strategy is proposed to inject gas ahead of time in the early stage of reservoir development, which can significantly improve the reservoir energy and fluid properties, thus providing more excellent oil production(Fig.1), but this development method has not yet been verified in practice for complex fractured reservoirs, and its applicability needs to be further analyzed by numerical simulation.

2. RESERVOIRS MODEL

2.1 Physical model

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Fig.2 shows the multistage fractured shale reservoir model. The stimulated reservoir volume (SRV) contains 18 hydraulic fracturing fractures with different half-lengths. There are four injection vertical wells and a horizontal well in the corners and center of the model, and the well pattern model refers to the typical shale reservoir field. The fractures were modeled using modified EDFM with unstructured grids. The grid number is 80×80×1, the grid scale is 10m×10m×20m, the initial pressure is 37.5MPa, the initial temperature is 130°C. The length of horizontal well is 600m.

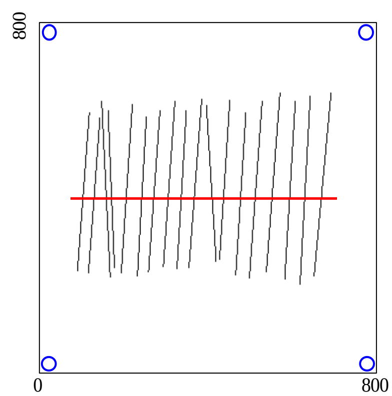


Fig.2 Physical model in this paper

2.2 mathematical model

The numerical simulator for shale reservoirs is programing using MATLAB programming, the mass conservation equation is shown in equation (1)-(2), q_{well} is the source term of well, $q_{f\text{-}ml}$ is the total flow flux between non-neighbor connections. q^{w} is the water phase. The implicit equation adopts the finite volume method (FVM) and Newton-Raphson iteration for discretization and solution, and the embedded discrete fracture model (EDFM) is used for fracture modeling. The fluids are actual mine components and parameters are shown in Table2-3.

$$\frac{\partial}{\partial t}\left[\phi\left(\rho_L S_L x_i+\rho_V S_V y_i\right)+q_{i,ads}\right]+\nabla\cdot\left(\rho_L x_i \vec{v}_L+\rho_V y_i \vec{v}_V\right)$$
$$+\nabla\cdot\left[D_{eff,i}\nabla\left(\rho_V y_i\right)\right]+q_i^{\,w}+q_{i,f-m}=0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\phi\rho_w S_w\right)+\nabla\cdot\left(\rho_w \vec{v}_w\right)+q^w+q^w_{f-m}=0 \tag{2}$$

Table.1 Horizontal well model of shale reservoir

Parameter	Value	Units
Initial pressure	37.5	MPa
Initial temperature	130	℃
Initial water saturation	0	-
Permeability of Matrix	0.1	mD
Porosity of matrix	6.3	%
Injection pressure	45	MPa
Production pressure	20.66	MPa

Table.2 Thermodynamic properties of pseudo-components after PVTi fitting

components	Z_i	T_{ci}	P_{ci}	ω_i	V_c	MW_i	$[P]_i$
CO_2	0.22	306	7.38	0.228	0.094	44	78
C_1	58.26	184	4.60	0.012	0.099	16	77
C_{2-5}	12.58	365	4.29	0.135	0.183	40	137.6
C_{6-10}	4.96	557	2.69	0.322	0.434	111	319.9
C_{11+}	5.62	708	1.72	0.650	0.655	204	536.2
C_{20+}	3.24	847	1.29	0.820	0.990	327	839.2
C_{30+}	15.85	919	0.96	0.980	1.330	428	1141.3

Z_i、T_{ci}、P_{ci}、ω_i 、V_c 、MW_i 、$[P]_i$ are total molar fraction; critical temperature, K; critical pressure, MPa; eccentric factor; critical volume, ($10^3 m^3$/mol); molecular weight, g/mol; parachor parameter.

In this paper, Peng-Robinson equation of state (PR-EOS)[9] is used as follow:

$$P=\frac{RT}{V_m-b}-\frac{a}{V_m\left(V_m+b\right)+bV_m-b^2} \tag{3}$$

Where *T* is temperature, K. *P* is pressure, MPa. V_m is the molar volume, mol/m^3. *R* is gas constant, J/(mol K). *a* and *b* represent the attractive and repulsive terms, respectively.

In the non-ideal system at equilibrium, *Ki* is usually related to the fugacity coefficient. At the same time, the *K* value is updated according to the calculation results:

$$K_i=\frac{y_i}{x_i}=\frac{\varphi_L^i p_L}{\varphi_V^i p_V} \tag{4}$$

$$K_i^{n+1}=\frac{f_i^{L(n)}}{f_i^{V(n)}}K_i^n \tag{5}$$

Where the superscripts *n* is the iteration level, K_i is the equilibrium ratio. f_i^V and f_i^L are the fugacities of component *i* in the vapor-liquid phase, respectively, MPa.

Wilson's correlation[10] is usually used to generate the initial guess of K_i.

$$K_i=\frac{p_{ci}}{p}\exp\left[5.37\left(1+\omega_i\right)\left(1-\frac{T_{ci}}{T}\right)\right] \tag{6}$$

Where $P_{c,i}$ is the critical pressure of component *i*, MPa. $T_{c,i}$ is the critical temperature of component *i*. ω_i is the acentric factor.

Vapor-liquid equilibrium calculation for *xi* and *yi* used Rachford-Rice (R-R) equation [11].

$$\sum_{i=1}^{Nc}\frac{\left(K_i-1\right)z_i}{1+F_v\left(K_i-1\right)}=0 \tag{7}$$

Where z_i is the overall mole fraction of component *i*, and F_v is the vapor molar fraction.

The bubble point pressure needs to satisfy:

$$\sum z_i K_i=1 \tag{8}$$

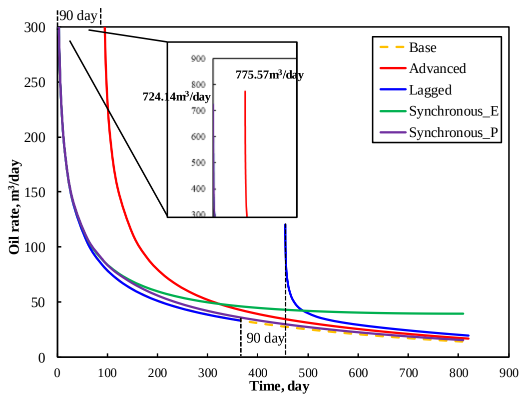
The dew point pressure needs to satisfy:

$$\sum z_i/K_i=1 \tag{9}$$

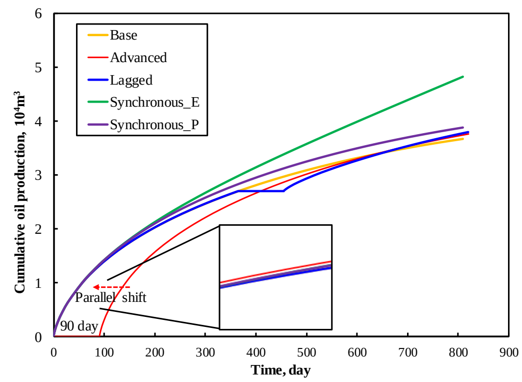
3. RESULTS

In this paper, the numerical simulation of gas injection development of shale reservoir is carried out, which is aimed at the reservoirs' production performance during the early development stage. The injection strategies include constant pressure injection (50MPa injection pressure for three months) and constant injection rate (2.6·103m^3/day for ten days).

As shown in Fig 3-4, under constant injection pressure, the advanced gas injection scheme, despite its time cost, allows the pressure wave to reach the producing wells faster than synchronized and lagged injection, significantly increasing the oil production rate in the early stages of production. After 2 years of production, the cumulative oil production from synchronized gas injection was slightly higher than that from advanced and lagged injection, but the oil production rate decline was faster. At the same time, the lagged injection scheme has a more significant pressure differential between the average reservoir pressure and the injection pressure, which allows the reservoir to inject more CO_2 and thus maintain a higher average formation pressure.

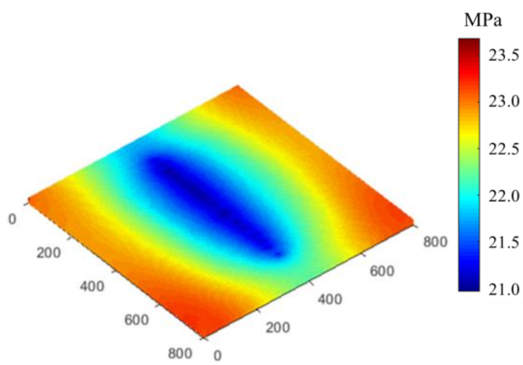


(a)oil rate

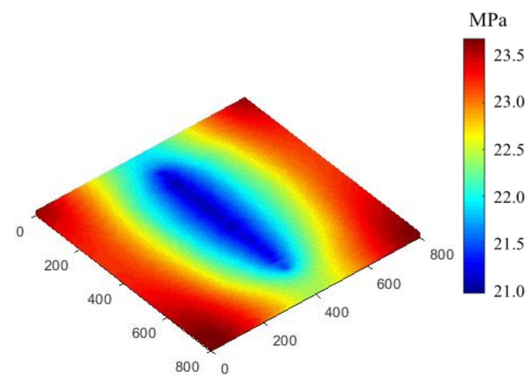


(b)cumulative oil production

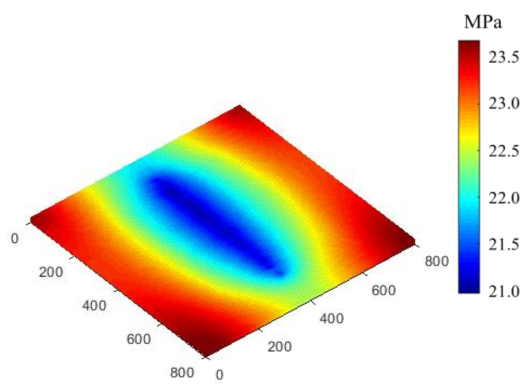
Fig.3 Effect of gas injection timing on yield (constant injection pressure). Left: oil production rate. Left: oil rate. Right: cumulative oil production. Base, Advanced, Lagged, Synchronous_E, Synchronous_P refer to the development strategy of natural energy depletion, advanced injection, lagged injection, synchronous injection (the whole period of development), synchronous injection(90 day), respectively



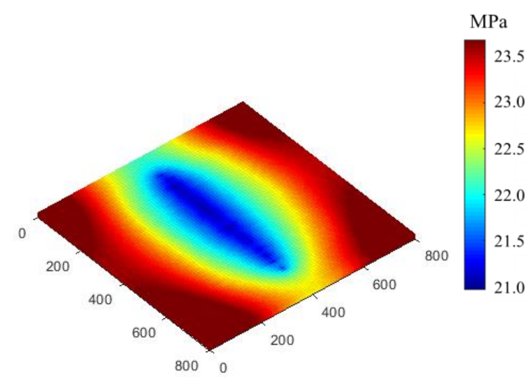
(a)Lagged injection



(b) Synchronous injection (90 day)



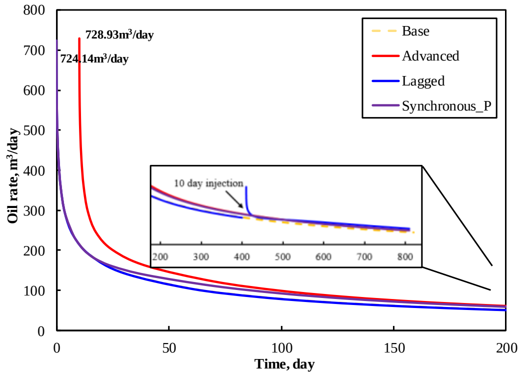
(c) Advanced injection



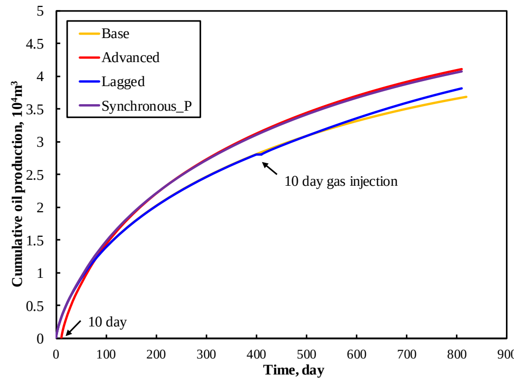
(d)Lagged injection

Fig. 4 Reservoir pressure profiles after 2 years of production with different injection timing

Constant gas injection gas is often used in the actual development of the field. Fig 5-6 show the production and reservoir pressure profiles at different injection timing, respectively. At a constant injection rate, the cumulative oil production of the advanced injection and synchronized gas injection is better than that of lagged gas injection. The advanced injection has the highest oil production rate in the early stage of development. However, the average reservoir pressure is lower, and a reasonable time should be chosen for the subsequent development program design.

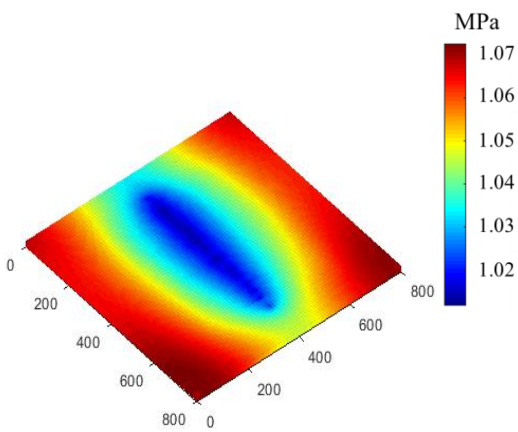


(a)

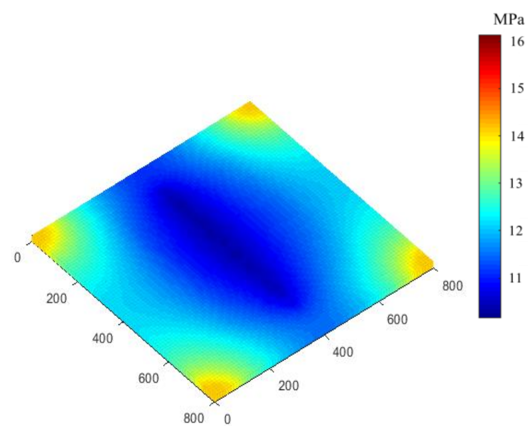


(b)

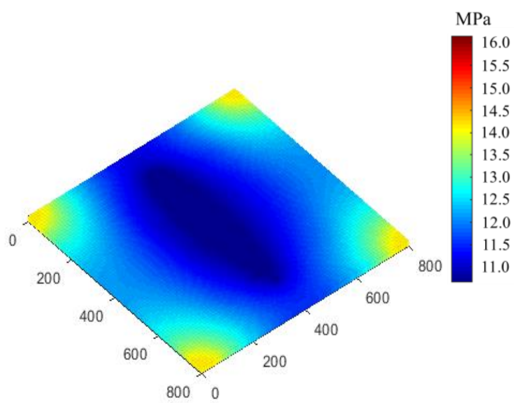
Fig.5 Effect of gas injection timing on yield (constant gas injection rate). Left: oil production rate. Right: cumulative oil production.



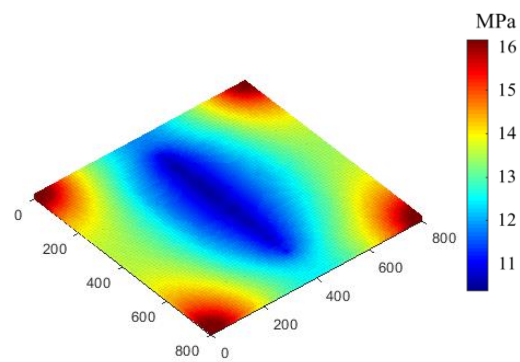
(a)Lagged injection



(b) Synchronous injection (90 day)



(c) Advanced injection



(d)Lagged injection

Fig.6 Reservoir pressure profiles after 2 years of production with different injection timing

4. DISCUSSION

In this paper, the theoretical advantages and feasibility of advanced gas injection are analyzed. Although this method can shorten the response time of gas injection, the applicability of fractured reservoirs needs to be further analyzed. Currently, advanced water injection technology has achieved quite good results in low permeability reservoirs in Ordos Basin, China. However, the ultra-tight reservoirs in Ordos Basin in China face the problems of low formation pressure coefficient, poor physical property and insufficient formation energy. The application of water injection technology system in ultra-low permeability reservoir is limited, and the development of ultra-low permeability reservoir is severely restricted by poor water absorption capacity and slow pressure conduction velocity. The high permeability of gas phase makes gas injection an effective alternative method for ultra-low permeability reservoir development, but it also faces more significant problems, such as optimization of production parameters and gas invasion risk.

The following points are proposed as potential key factors in advance gas injection development:

(1) The direction and density of natural fractures are in fractured formations.

(2) The difference of injection medium. Different injection media have different interactions with oil, which may lead to different oil displacement efficiency.

(3) Applicability of advanced gas injection about reservoir physical properties.

(4) Production system evaluation.

The next step will be to further verify the development effect of advanced gas injection in the actual field.

5. CONCLUSIONS

Advanced gas injection is a promising potential development strategy for shale reservoir development. In the preliminary simulations in this paper, advanced gas injection demonstrated higher oil production rates in the early period of development, which is very important for development. However, this strategy also requires further analysis the effect on production, such as gas injection time, and the adaptability of overdraft in different reservoir conditions needs to be further analyzed.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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