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Rock Stress Sensitivity and its Influence on Productivity of Overpressured Gas Reservoir: A Case Study in Yinggehai Basin, China

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Abstract: H gas reservoir is an overpressured gas reservoir with high temperature. It is generally believed that overpressured gas reservoir exist stress sensitivity effect due to uncompaction. Firstly, this study conducted lab core test to analysis stress sensitivity of rock by defined confining pressure and decreasing inner pressure. Test results show that the reservoir processes weak to medium stress sensibility. Then, according to mineral composition analysis and strain-stress curve comparison of the cores, stress sensibility is considered to be mainly caused by low hardness clay mineral. Finally, based on well testing data of well H-X-1, we used pseudo-pressure binomial deliverability equation considering stress sensitivity to discuss the influences of stress sensibility on productivity. Results show that the stronger the stress sensibility is, the more obviously productivity decreases. As stress sensibility of the block is weak to medium, it has little impact on productivity.

Keywords: Abnormal High Pressure, Gas Reservoir, Stress Sensitivity, Productivity, Yinggehai Basin

1. Introduction

With abnormal pressure and high temperature, H gas reservoir is located in Yinggehai Basin of western South China Sea. With a burial depth of 3000 meters, its temperature is above 140℃, and pressure is higher than 50MPa. Pressure coefficient is 1.88 to 2.09, and temperature gradient is 4.17℃/100m to 4.39℃/100m. Overburden pressure is about 70 MPa[1,2]. Current thinking suggests that in overpressure gas reservoir, rock is in under compaction condition. Therefore in depletion development process effective stress of rock skeleton greatly increases, which will cause prominent elastic-plastic deformation of the rock, and then produce stress sensibility [3,4].

Currently reservoir stress sensibility evaluation test mainly use method of defined inner pressure while changing confining pressure [5]. But this experiment is mainly used for overburden pressure correction of reservoir porosity and permeability [6]. Stress variation of underground reservoir is actually caused by pressure variation of pore fluid. So use more reasonable method of defined confining pressure while changing inner pressure [6]. About productivity evaluation, some steady and pseudo-steady productivity equations considering stress sensitivity are established [7,8]. However, those equations are established on pressure form, and need more calculation parameters, so the error is larger. This study use pseudo-pressure considering stress sensibility to evaluate productivity [9,10]. This method can linearize deliverability equation. Then get open flow capacity according to regression line, which can eliminate errors caused by reservoir parameters uncertainty.

2. Stress Sensitivity Test of Abnormal High Pressure Gas Reservoir

2.1. Experiment Process

To simulate stress variation of underground reservoir more truly, we use the method of defined confining pressure and changing fluid pressure. The experimental instrument is high temperature and high pressure core flow instrument (a temperature of 200℃ and a pressure of 70 MPa) produced by USA core company [6]. Permeability testing temperature is 140℃; Confining pressure is 70MPa; Initial pressure of gas reservoir is 55 to 5MPa, and net overburden pressure is 15 to 65MPa.

Firstly saturate core with nitrogen, and make two independent hydrostatic pressure systems in core holder, which means confining pressure and inner pressure. In the test, hold confining pressure unchanged. Firstly decreasing inner pressure gradually and get permeability under the corresponding pressure. When inner pressure falls to minimal designing point, increase it gradually and test the corresponding permeability until it rises to maximal designing point. Following figure (1) shows experimental flow chart.

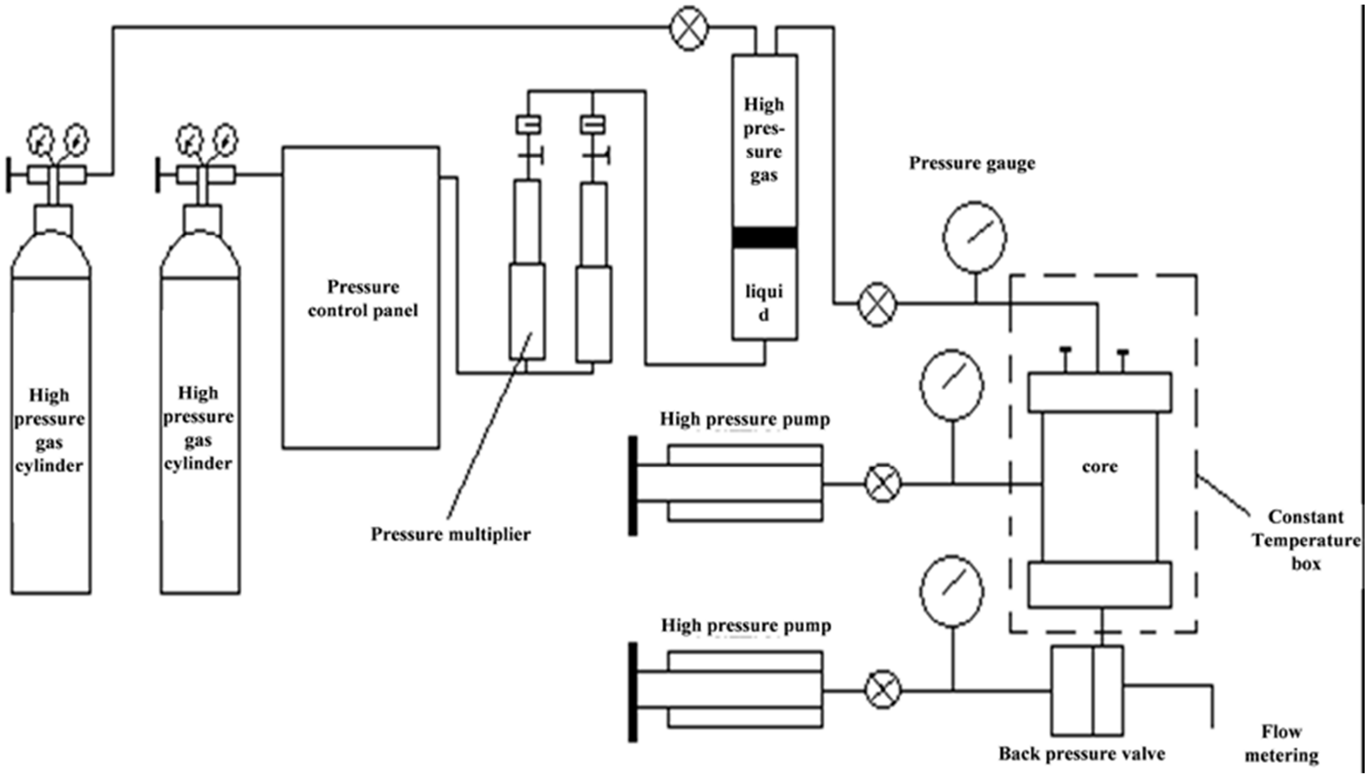
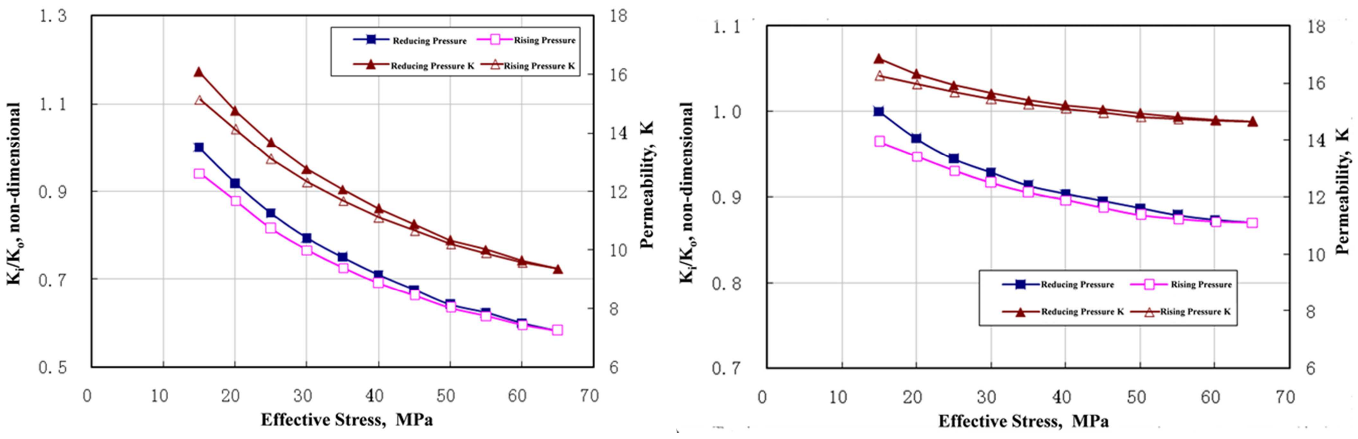


Figure 1. *Permeability stress sensibility test process on high temperature and high pressure core flow instrument.*

2.2. Experiment Result



(a)No.1 core (b)No.1-1 core

Figure 2. *Permeability variation of stress sensibility experiment.*

Experimental result (Figure 2) shows that: (1) pressure increasing curve and decreasing curve do not coincide. It means permeability variation is irreversible; (2) permeability decreases with increasing effective pressure. Decline rate is greater during early stage, and it becomes smaller during later stage. Therefore when develop abnormal high pressure gas reservoir, we should guarantee continuous flowing production and avoid shut in during producing to avoid irreversible change of rock, especially in early developing stage.

Stress sensibility intensity of abnormal high pressure reservoir is generally presented by stress sensibility coefficient and permeability damage ratio. Definition of stress sensibility coefficient is showed in equation (1), in which α is stress sensibility coefficient and its unit is MPa^{-1}. The bigger α is, the more intense stress sensibility is. When α=0 , stress sensibility disappear[8]. According to equation (1) [15,16], there lies in an exponential relationship between permeability and pressure drop. Logarithmic both sides of the equation (2), Using stress sensibility data, can get relationship curve of $\ln K \sim \Delta p$. And the slope of line fitting by the curve is α.

$$\alpha = \frac{1}{K}\frac{\partial K}{\partial p} \tag{1}$$

$$K = K_i e^{-\alpha(p_i - p)} \tag{2}$$

Calculation equation of permeability damage ratio [6] is as following equation (3). D_k is permeability damage ratio. When $D_k \leq 0.3$, reservoir performs weak stress sensibility; when $0.3 < D_k < 0.7$, reservoir performs middle stress sensibility; when $D_k \geq 0.7$, reservoir performs strong stress sensibility [8].

$$D_k = \frac{K_i - K}{K_i} \times 100\% \tag{3}$$

Based on permeability of initial effective overburden pressure, normalize test data of core stress sensibility experiment. We can get variation curves of dimensionless permeability (Figure 3) and stress sensibility evaluation result table (Table 1). The table shows that stress sensibility coefficient of permeability is 0.001 to 0.0104, and average value is 0.05; when reservoir pressure falls from 55MPa to 5MPa (pressure differential is 50MPa), reservoir permeability damage ratio is 8.95% to 41.25%. If reservoir pressure declines 10MPa [17], reservoir permeability damage ratio D_{k10} is 3.01% to 16.67%. According to industry standard, stress sensibility degree of core permeability is weak to middle [8].

Table 1. *Stress sensibility evaluation result of core permeability.*

Core NO.	φ (%)	K (mD)	α (MPa-1)	D_K (%)	D_{K10} (%)
NO.1	18.45	13.3	0.0104	41.25	15.63
NO.X1-3	20.55	10.05	0.0018	9.08	3.36
NO.1-1	22.18	17.32	0.0027	13.53	5.29
NO.X1-1	11.34	20.52	0.0021	9.62	3.01
NO.1-2	16.09	20.88	0.0018	8.95	3.16
NO.4	24.07	23.05	0.0042	19.23	6.92
NO.5	20.59	6.49	0.0062	27.56	9.62
NO.6	19.55	1.8	0.0095	38.33	16.67

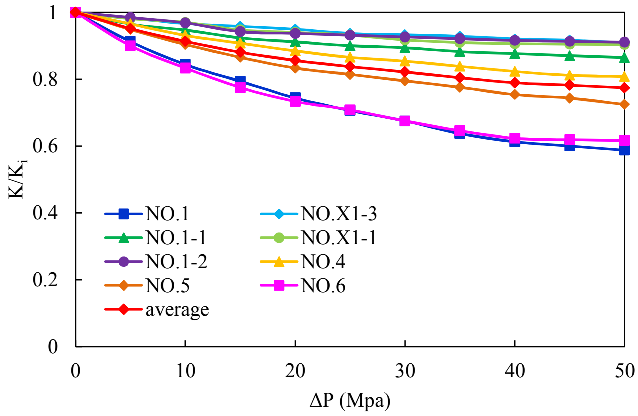
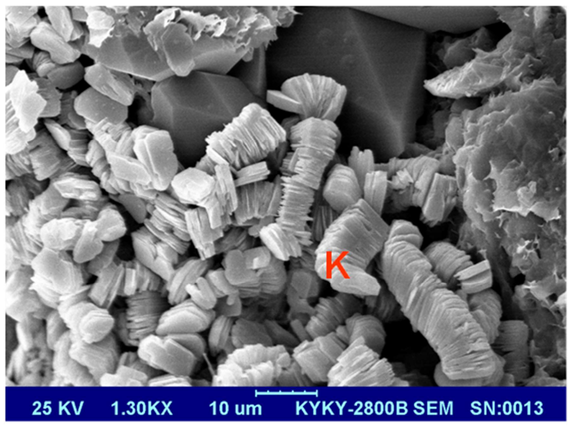
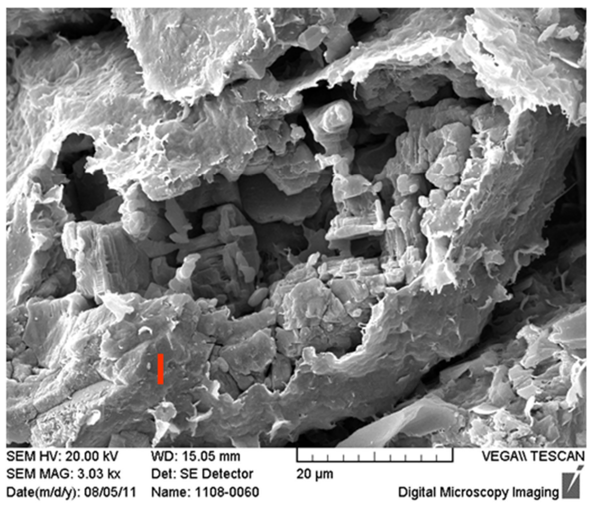


Figure 3. *Stress sensibility experimental result of core permeability.*

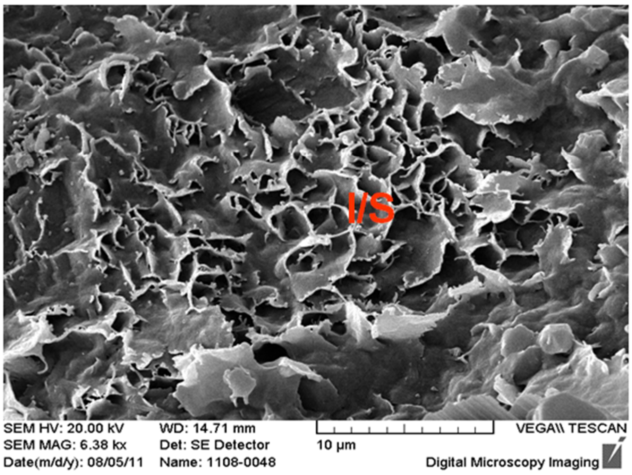
2.3. Reasons Discussion of Stress Sensibility



(a)Inter granular pore filling by book kaolinite (K) (magnifying 1300 times)



(b)Particle surface coated by flake/filiform illite (magnifying 1510 times)



(c)I/S formation with honeycomb particle surface (magnifying 6380 times)

Figure 4. *Scanning electron microscope graph of clay mineral.*

Table 1 shows that stress sensibility of permeability in No.1 core is 0.0077 higher than No.1-1 core, and permeability damage ratio is 27.72% higher than No.1-1 core. According to X-ray diffraction, get mineral composition and relative clay mineral content table of No.1 and No. 1-1 core (Table 2, Table 3). Table 2 shows that quartz content of No. 1 core is 7.03% lower than No. 1-1 core; feldspar content of No.1 core is 7.04% higher than No. 1-1 core; clay mineral content is 1.35% higher than No. 1-1 core, thereinto relative kaolinite content is 7.6% higher than No. 1-1 core. Mechanical property of quartz and feldspar is stable, and compressive strength is high [18,19]. Mechanical property of clay mineral is relatively poor, and compressive strength is relatively low [18,19]. However occurrence of the clay mineral is special (Figure 4), under compression particle is easily to drop and transport, then throat is blocked and permeability changes irreversibly. Clay content of No.1 core is higher than No. 1-1 core, so that stress sensibility of No.1 core is more intense than No. 1-1 core.

Table 2. *Test result of core mineral composition.*

Well	core /depth, m	φ (%)	K (mD)	Mineral content (%)					
				clay	quartz	orthoclase	plagioclase	dolomite	siderite
X-4	1, 2864.89	18.45	13.3	12.31	55	14.24	14.83	2.06	1.56
	1-1, 2864.72	22.18	17.32	10.96	62.03	3.99	18.04	2.41	2.57

Table 3. *Analysis result of relative clay content.*

Well	core	φ (%)	K (mD)	Relative clay content (%)			
				illite	illite/smectite	kaolinite	chlorite
X-4	1	18.45	13.3	37.8	10.5	51.6	0.0
	1-1	22.18	17.32	47.8	9.2	43.0	0.0

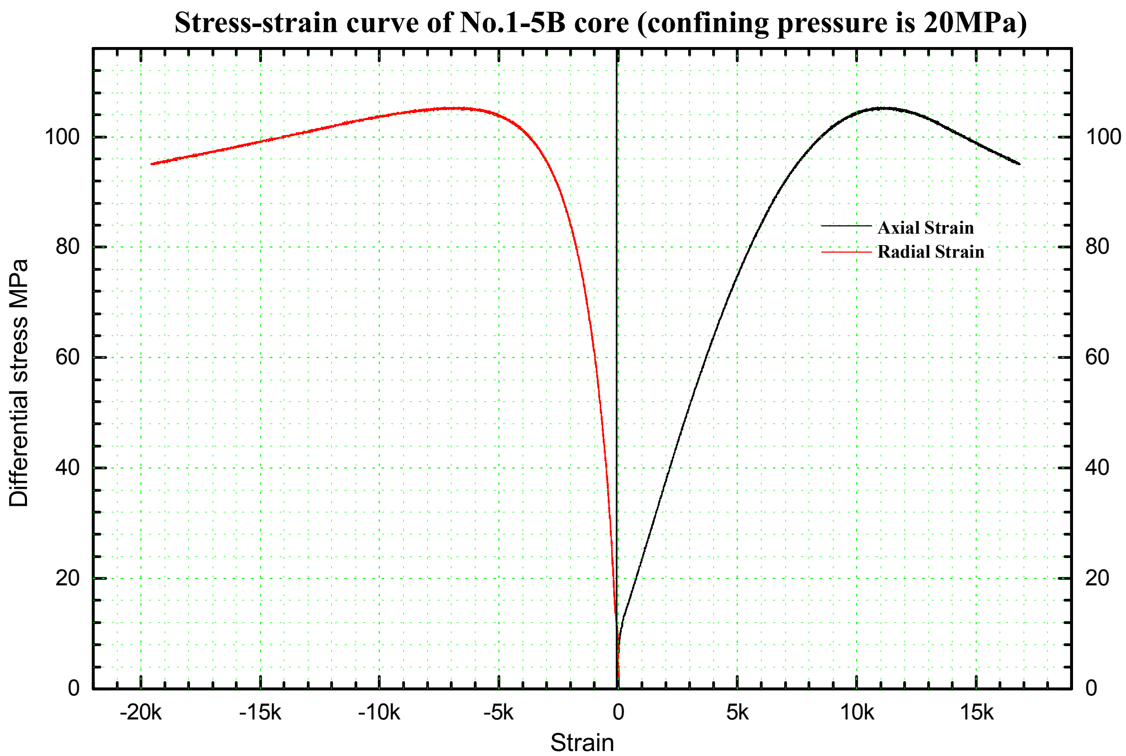


Figure 5. *Stress-strain curve of sandstone.*

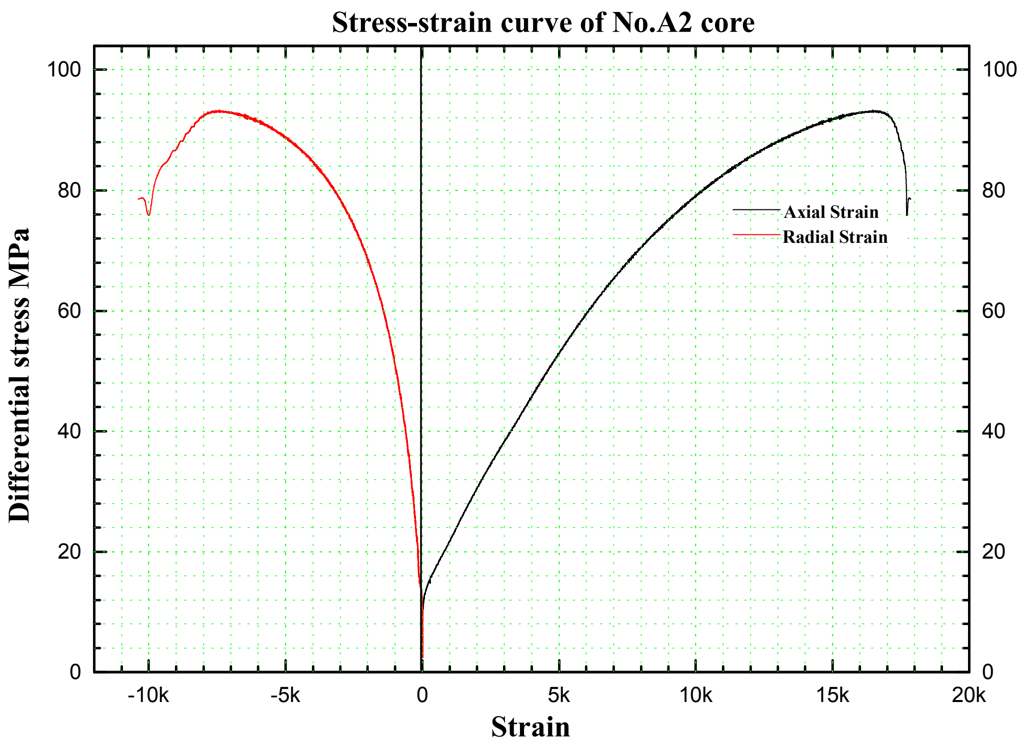


Figure 6. *Stress-strain curve of gray silty mudstone.*

Rock deformation process includes: elastic deformation-plastic deformation- failure [18]. In elastic deformation range, permeability and porosity variation of rock is reversible. While plastic deformation occurs, permeability and porosity variation is irreversible [17]. Stress-strain curve (Figure 5) of the sandstone shows that when differential stress is less than 70MPa, slope of axial stress-strain curve is basically a definite value, indicating elastic deformation. However, in stress-strain curve (Figure 6) of the silty mudstone, when differential stress is less than 70MPa, slope of axial stress-strain curve is gradually increasing with the strain increasing, indicating plastic deformation. So that plastic deformation of the rock is mainly caused by plastic deformation of low hardness clay mineral.

By synthesized analyses, stress sensibility of reservoir rock is mainly influenced by clay mineral. The higher clay mineral content, the more complex occurrence is, and more intense stress sensibility is.

3. Production Evaluation of Abnormal High Pressure Gas Reservoir

Based on non-Darcy flow equation of gas reservoir, considering stress sensibility with different permeability, this paper builds production equation of gas reservoir [9, 10].

Define pseudo-pressure of stress sensibility as follows [10]:

$$m(p) = \int_{p_{sc}}^{p} \frac{\exp(-\alpha(p_i - p))\rho_g}{\mu_g} dp \tag{4}$$

High speed non-Darcy flow of gas in porous media can be mathematical depicted as follows [9,10]:

$$\frac{dp}{dr} = \frac{1000\mu_g}{K(p)} \frac{m_g}{2\pi rh\rho_g} + \beta_g \rho_g \left(\frac{m_g}{2\pi rh\rho_g}\right)^2 \tag{5}$$

Turbulence coefficient [9, 10]is:

$$\beta_g = \frac{1.88\times10^{10}}{K^{1.47}\phi^{0.53}} \tag{6}$$

Transform equation (5) and integrate both sides of the equation. Considering skin effect and turn mass flow into volume flow [9,10], then take equation (4) into it, we can get:

$$m(P_R) - m(P_{wf}) = \frac{1000\rho_{sc}}{2\pi K_i h}\left(\ln\frac{r_e}{r_w} + s\right)Q_g + \frac{\rho_{sc}^2 \int_r^{r_e} \frac{\beta_g \exp[-\alpha(p_i - p)]}{\mu_g r^2} dr}{4\pi^2 h^2} Q_g^2 \tag{7}$$

Take non-Darcy coefficient [9] (equation 8) into equation (7):

$$D = \frac{4.9487\times10^{-18}\beta_g M_g p_{sc} K}{h r_w T_{sc} \mu_g} \tag{8}$$

We can get:

$$m(P_R)-m(P_{wf})=\frac{1000\rho_{sc}}{2\pi K_i h}(\ln\frac{r_e}{r_w}+s)Q_g+(\frac{\rho_{sc}^2 r_w T_{sc}}{1.98\times10^{-7}\pi^2 hM_g p_{sc}K_i}\int_r^{r_e}\frac{D}{r^2}dr)\ Q_g^2 \quad (9)$$

Assume:

$$A=\frac{1000\rho_{sc}}{2\pi K_i h}(\ln\frac{r_e}{r_w}+s) \quad (10)$$

$$B=\frac{\rho_{sc}^2 r_w T_{sc}}{1.98\times10^{-7}\pi^2 hM_g p_{sc}K_i}\int_r^{r_e}\frac{D}{r^2}dr \quad (11)$$

We can get:

$$m(p_R)-m(p_{wf})=AQ_g+BQ_g^2 \quad (12)$$

Equation (12) is binomial deliverability equation considering stress sensibility of gas reservoir. Coefficient A cannot reflect reservoir stress sensibility, while coefficient B can reflect effect of reservoir stress sensibility comprehensively [10].

Absolute open flow potential is:

$$Q_{AOF}=\frac{-A+\sqrt{A^2+4B[m(p_R)-m(p_{sc})]}}{2B} \quad (13)$$

DST (Drill Stem Testing) data of well H-X-1 is shown in table 4. Stress sensibility data is shown in table 1. Firstly calculate pseudo-pressure considering stress sensibility under different stress sensibility coefficient by numerical integration method (Figure 7). Then through linearity regression to the $\frac{m(p_R)-m(p_{wf})}{Q_g}$ ～Q_g relationship curve (Figure 8) under different stress sensibility coefficient in the Cartesian coordinates. Use slope and intercept of the line to get constant A and B in the deliverability equation. Then get IPR curves (Figure 9) and absolutely open flow capacity Q_{AOF} (Table 5) under different stress sensibility coefficient. With reference to the figures we can see that the more intense the stress sensibility is, the more obviously the productivity decreases. Without regard of stress sensibility, open flow capacity is 861.66 x $10^4 m^3/d$; consider stress sensibility of No.1 core, open flow capacity is 769.21 x $10^4 m^3/d$, and productivity loss is 10.73%; consider average stress sensibility, open flow capacity is 822.17 x $10^4 m^3/d$, and productivity loss is 4.58%. On the whole, stress sensibility has little impact on productivity.

Table 4. *Stable well testing data of well H-X-1 in H formation.*

well	Testing method	Sand body	Perforation interval m	Effective thickness m	choke mm	production(m^3/d) oil	gas	water	Bottom hole pressure MPa	Extrapolation pressure MPa	Producing pressure drop MPa
H-X-1	DST1	H_1 Ⅰ$_a$	2976.0～2998.9 3003.5～3010.0	27.2	6.35	14.1	239192	trace	51.826	52.702	0.876
					8.73	27.2	436849	trace	51.320	52.702	1.382
					11.11	36.0	589906	trace	50.833	52.702	1.869
					13.49	48.8	794066	trace	50.330	52.702	2.372
					19.05	52.8	1211654	trace	49.470	52.702	3.232

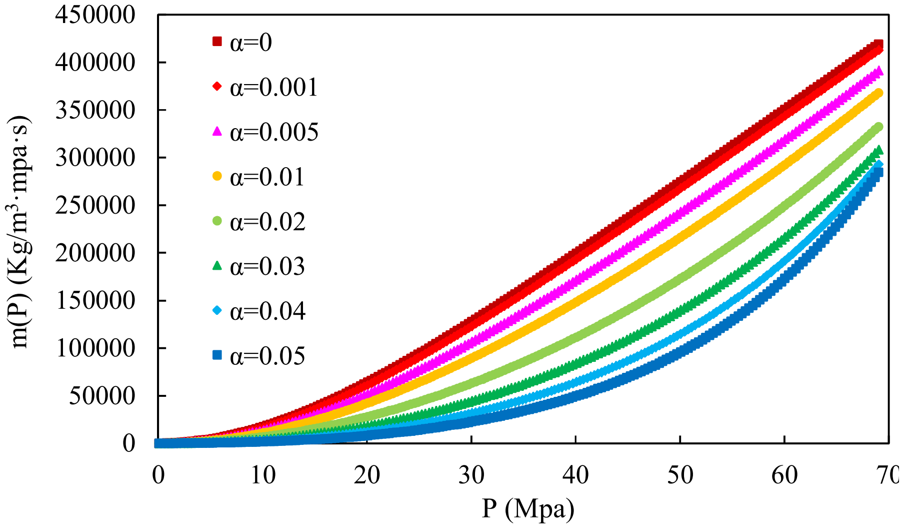


Figure 7. *Relationship curve of pseudo-pressure and pressure under different stress sensibility coefficient.*

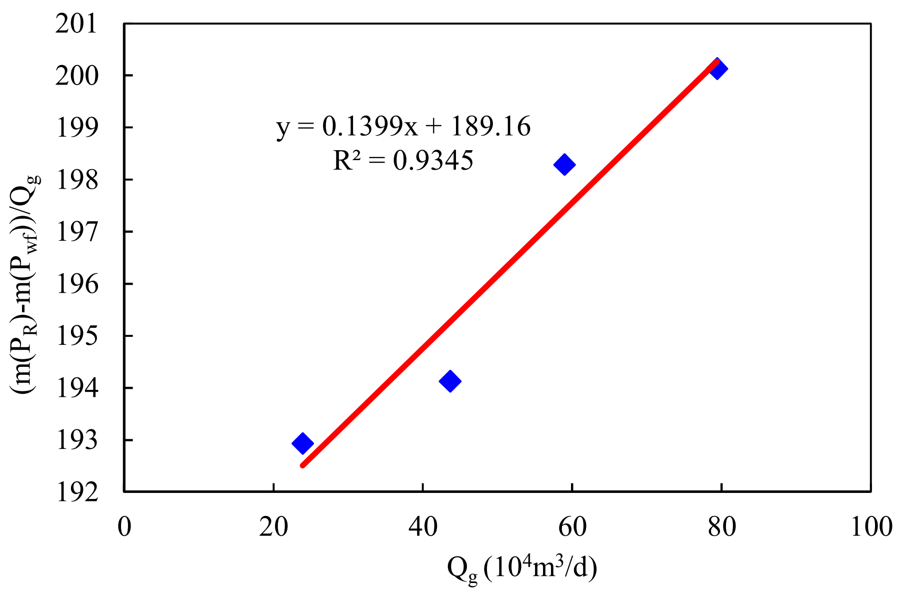


Figure 8. *Binomial deliverability equation with pseudo-pressure considering stress sensibility(α=0.01).*

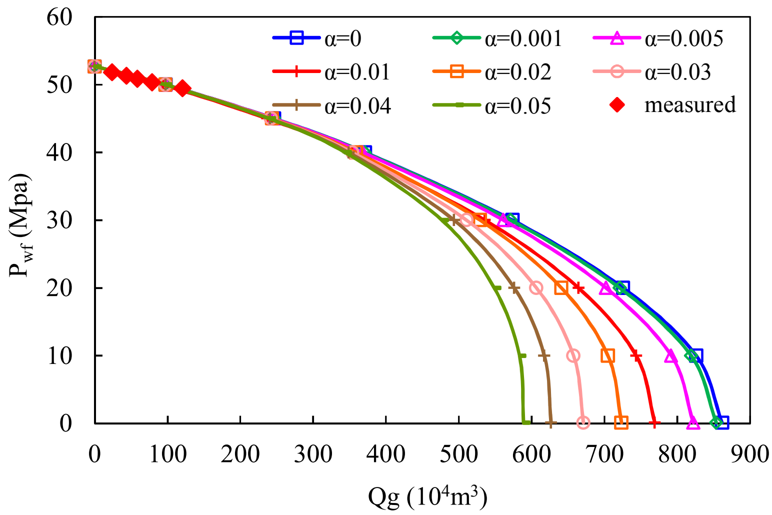


Figure 9. *IPR curves under different stress sensibility coefficient.*

Table 5. *Deliverability calculation result with pseudo-pressure considering stress sensibility.*

Equation	Q_{AOF}	α	D_k
	$10^4m^3/d$	Mpa^{-1}	%
$m(P_R)-m(P_{wf})=0.1725q^2+192.6q$	861.66	0.000	0.00
$m(P_R)-m(P_{wf})=0.1691q^2+192.28q$	853.46	0.001	0.95
$m(P_R)-m(P_{wf})=0.1559q^2+190.96q$	822.17	0.005	4.58
$m(P_R)-m(P_{wf})=0.1399q^2+189.16q$	769.21	0.01	10.73
$m(P_R)-m(P_{wf})=0.1091q^2+185.34q$	723.55	0.02	16.03
$m(P_R)-m(P_{wf})=0.00801q^2+181.53q$	671.04	0.03	22.12
$m(P_R)-m(P_{wf})=0.0525q^2+178.01q$	626.68	0.04	27.27
$m(P_R)-m(P_{wf})=0.0262q^2+174.96q$	588.80	0.05	31.67

4. Conclusion and Proposals

(1)With defined confining pressure and changing inner pressure, stress sensibility test results show that permeability of the block declines as effective stress increases. It declines quickly in the initial stage, and tends to decline slowly in the later stage. Permeability variation is irreversible, and stress sensibility degree is weak to middle;

(2)X-ray diffraction indicates that cores with intense stress sensibility always have higher clay content; rock stress-strain test indicates elastic deformation occurs in sandstone within overburden pressure, while plastic deformation occurs in silty mudstone. In summary, stress sensibility is mainly caused by low hardness clay mineral;

(3)Binomial deliverability equation of pseudo-pressure considering stress sensitivity indicates that the more intense reservoir stress sensibility is, the more obviously productivity decreases. In the test, the average stress sensibility reduces 5% of the productivity, and stress sensibility has little impact on productivity.

Nomenclature

α —Stress sensibility coefficient, MPa^{-1}; D_k —Permeability damage ratio; p —Formation pressure, MPa ; p_i —Initial formation pressure, MPa ; p_{wf} —Bottom hole pressure, MPa ; p_{sc} —Atmospheric pressure, $m(p)$ —Pseudo pressure, $MPa^2/(mPa{\cdot}s)$; $m(P_R)$ —Pseudo pressure of formation pressure, $MPa^2/(mPa{\cdot}s)$; $m(p_{wf})$ —Pseudo pressure of bottom hole pressure, $MPa^2/(mPa{\cdot}s)$; $m(P_{sc})$ —Pseudo pressure of atmospheric pressure, $MPa^2/(mPa{\cdot}s)$; T —Formation temperature, K ; μ_g —Gas viscosity, $mPa{\cdot}s$; Z —Gaseous z-factor; ρ_g —Gas density, Kg/m^3 ; D —Non-Darcy flow factor, $(10^4 m^3/d)^{-1}$; β —Turbulent coefficient, m^{-1} ; h —Net pay thickness, m ; S —Skin factor; ϕ —Porosity; ϕ_i —Initial porosity; K —Permeability, md ; K_i —Original Permeability, md ; r_w —Well bore radius, m ; r_e —Well controlled radius, m ; Q_g —Gas production, m^3/d ; Q_{AOF} —Open flow capacity, $10^4\ m^3/d$; A 、 B —Coefficient. M_g —The molar mass of the gas, $kg/kmol$

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