

# Cracking mechanism of shale cracks during fracturing

X J Zhao<sup>1,2,5</sup>, Q Zhan<sup>1,2</sup>, H Fan<sup>2</sup>, H B Zhao<sup>3</sup> and F J An<sup>4</sup>

<sup>1</sup>School of Aeronautics, Northwestern Polytechnical University, Xi'an, Shanxi, 710072, China

<sup>2</sup>School of Electronic Engineering, Xi'an Shiyou University, Xi'an, Shanxi, 710065, China

<sup>3</sup>Xi'an Center of Geological Survey, Shanxi Xi'an 710054, China

<sup>4</sup>Dongying Shengfeng Safety Service Corporation, Shandong Dongying 257000, China

E-mail: zhaoxsyu@qq.com; zhqu@xsyu.edu.cn; 723515507@qq.com; 315695573@qq.com; 94500732@qq.com

**Abstract.** In this paper, we set up a model for calculating the shale fracture pressure on the basis of Huang's model by the theory of elastic-plastic mechanics, rock mechanics and the application of the maximum tensile stress criterion, which takes into account such factors as the crustal stress field, chemical field, temperature field, tectonic stress field, the porosity of shale and seepage of drilling fluid and so on. Combined with the experimental data of field fracturing and the experimental results of three axis compression of shale core with different water contents, the results show that the error between the present study and the measured value is 3.85%, so the present study can provide technical support for drilling engineering.

## 1. Introduction

The shale formation is mainly composed of illite and mixed layer clay minerals, the horizontal bedding, crack and micro crack development of shale are obvious [1]. When the shale meets water, it can easily hydrate [2-4], the mechanical strength of it is reduced, the expansion stress is produced, and the pore pressure of the rock is increased [5]. Furthermore, water molecules in drilling fluids flow through the formation pores, then the additional stress field yields around the well wall [6], which leads to the decrease of the effective circumferential stress of the well. Besides, rock wall temperature changes can also cause wellbore instability, especially for the shale with high elastic modulus and low Poisson's ratio [7]. During the process of drilling fluid circulation, the thermal expansion of the surrounding rock of the shaft wall is not allowed to expand freely due to the limitation of wellbore liquid pressure and the surrounding rock of the shaft wall, so that the expansion stress will generate, which is the thermal stress affecting the shale fracture pressure [8].

At present, experts have proposed various methods for predicting formation fracturing pressure. Huang's model [9] is mainly for general reservoirs. It considers the relationship between overburden pressure and depth of rock strata, the influence of stress concentration on wellbore, the effect of tectonic stress of underground nonuniform distribution and the strength of strata and so on. Therefore, it can be applied to different deformations. Yan *et al* [10] established a fracture pressure model considering hydration based on Huang's model, which improved the prediction accuracy, but did not consider effect of perforation and natural fractures on the cracking of hydraulic cracks. Li *et al* [7]

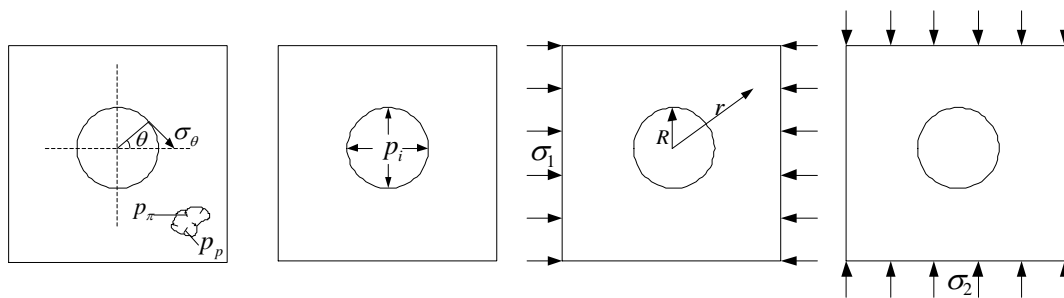


established a calculation model of fracture pressure on sandstone stratum coupling with temperature. Deng *et al* [11] established a model for calculating the fracture pressure considering the influence of high temperature and seepage, the prediction accuracy increased by 7%. However, this model is only fit for sandstone.

However, the fracture pressure model of shale considering the additional stress fields caused by the crustal stress field, chemical field, temperature field, tectonic stress field, the porosity of shale and seepage of drilling fluid is still absent. This paper is based on Hang's model, considering all these factors and established a new model for calculating the fracture pressure of shale.

### 1.1. Influence of seepage and porosity on crustal stress field

On the infinite plane, a circular hole receives uniform internal pressure, at the same time, the infinite distance in the plane is subjected to two horizontal stresses ( $\sigma_1$  and  $\sigma_2$ ) and overlying pressure in the vertical direction. Considering that the rock is a small deformation elastic body, the principle of linear superposition is applicable to it. The stress state of the wall rock of the wellbore can be obtained by studying the stress contribution of the stress components to the wall rock of the wellbore, and then superimposing them. It is assumed that the strata are homogeneous isotropic and linear elastic porous materials, the rocks around the borehole are in a state of plane strain [2]. The stress model of the wellbore wall is shown in figure 1.  $R$  is the maximum borehole radius, m;  $r$  is the radius of borehole, m;  $\theta$  is the polar angle of the reverse clockwise rotation of the maximum radial direction in the radial direction.



**Figure 1.** Stress state around wellbore.

The wall rock of the borehole wall is porous medium, so the flow of fluid satisfies Darcy's law, the radial flow of drilling fluid filtrate in the stratum will generate additional stress field around wellbore rocks. Combined with drilling fluid column pressure and crustal stress, the distribution of the circumferential stress in the crustal stress field around the shaft wall in a vertical well is [2].

$$\sigma_{\theta} = -\frac{R^2}{r^2} p_i + \frac{(\sigma_1 + \sigma_2)}{2} \left( 1 + \frac{R^2}{r^2} \right) - \frac{(\sigma_1 - \sigma_2)}{2} \left( 1 + \frac{3R^4}{r^4} \right) \cos 2\theta + \delta \left[ \frac{\alpha'(1-2\mu)}{2(1-\mu)} \left( 1 + \frac{R^2}{r^2} \right) - \phi \right] (p_i - p_p) \quad (1)$$

$\sigma_{\theta}$  is the circumferential stress, MPa;  $p_i$  is the pressure of the liquid column of the drilling fluid, MPa;  $p_p$  is the pore pressure of the original formation, MPa;  $\alpha'$  is the effective stress coefficient;  $\mu$  is a Poisson ratio;  $\sigma_1$  is the maximum horizontal crustal stress, MPa;  $\sigma_2$  is the minimum horizontal crustal stress, MPa;  $\delta$  is the permeability coefficient;  $\phi$  is the porosity of shale.

When  $\delta=1$ , the wall of the well is permeable. When  $r=R$ , the circumferential stress on the surface of the wellbore is

$$\sigma_{\theta} = -p_i + (1 - 2\cos 2\theta)\sigma_1 + (1 + 2\cos 2\theta)\sigma_2 + \delta \left[ \frac{\alpha'(1-2\mu)}{2(1-\mu)} - \phi \right] (p_i - p_p) \quad (2)$$

The formation cracks produced by the fluid in the well are mostly vertical, the reason is that the tensile strength of the tangent stress exceed the tensile strength of the rock from compression to tension. When  $\theta = 0^\circ$  or  $\theta = 180^\circ$ ,  $\sigma_{\theta}$  is the minimum value.

$$\sigma_{\theta} = 3\sigma_2 - \sigma_1 - p_i + \left[ \frac{\alpha'(1-2\mu)}{2(1-\mu)} - \phi \right] (p_i - p_p) \quad (3)$$

### 1.2. Effect of chemical field on crustal stress field

When water-based drilling fluid encounters shale, under the action of water pressure difference, chemical potential difference and the pressure difference between the drilling fluid pressure and pore pressure, water molecules flow into the pores between the cracks and particles, they cause the transfer of water molecules and ions, at this time, hydration occurs [2]. Under certain conditions, the shaft wall can be considered as a semi permeable membrane, and the two sides are drilling fluid system and stratigraphic fluid system. On this basis, Chenevert and Pernot [12] put forward the calculation model of hydration stress. The calculation formula is

$$p_{\pi} = I_m \frac{R'T}{\bar{V}} \ln \frac{(A_w)_m}{(A_w)_{sh}} \times 10^{-6} \quad (4)$$

$p_{\pi}$  is hydration stress, MPa;  $I_m$  is the membrane permeable efficiency;  $R'$  is gas constant;  $T$  is the absolute temperature;  $\bar{V}$  is the partial molar volume of pure water;  $(A_w)_m$  is the activity of the formation liquid entering the stratum;  $(A_w)_{sh}$  is the activity of water in shale.

It is assumed that the structure of shale can make the fluid in the pores circulate in them and form the uniform pore pressure to the skeleton of the rock, so the effective stress is equal to the positive stress minus the pore pressure and the hydration stress. Therefore, the effective circumferential stress is as follows:

$$\sigma'_{\theta} = 3\sigma_2 - \sigma_1 - p_i + \left[ \frac{\alpha'(1-2\mu)}{2(1-\mu)} - \phi \right] (p_i - p_p) - p_p - p_{\pi} \quad (5)$$

### 1.3. Influence of temperature on crustal stress field

Boas [13] and Maury [14] put forward the idea that the thermal pressure caused by the temperature change of wellbore rock can cause the instability of the wellbore wall. The effect of temperature should be considered when the vertical depth of the open hole is more than 1 000 m. It is proved that the stress of 0.4 MPa is produced by  $1^\circ\text{C}$  increases in the temperature of the medium hardness rock [14]. According to the generalized Hoek's law and thermoelastic theory, the circumferential stress caused by the variation of the wellbore and the formation temperature is as follows:

$$\sigma_{\theta t} = \frac{E\alpha_m}{3(1-\mu)} \left[ \frac{1}{r^2} \int_R^r T_f(r,t) r dr + T_f(r,t) \right] \quad (6)$$

In the upper formula,  $T_f(r,t) = T(r,t) - T_0$ .  $T_f(r,t)$  is rock temperature change field around well;  $\sigma_{\theta t}$  is the temperature variable stress;  $T_0$  is the original formation temperature,  $^\circ\text{C}$ ;  $\alpha_m$  is the thermal expansion coefficient of rock volume;  $E$  is the elastic modulus of rock, GPa;  $t$  is the time, h.

When  $r = R$ , formula (6) can be written as:

$$\sigma_{\theta r} = \frac{E\alpha_m}{3(1-\mu)}[T_w - T_0]. \quad (7)$$

$T_w$  is the temperature of the wellbore,  $T_0$  is the original stratum temperature.

#### 1.4. Influence of tectonic stress field

According to the stress superposition criterion of small pore elastic deformation, under the influence of in-situ stress, seepage, temperature field and chemical field, the effective circumferential stress of the stress field around the borehole can be expressed as:

$$\sigma_{\theta}^z = 3\sigma_2 - \sigma_1 - p_i + \left[ \frac{\alpha'(1-2\mu)}{2(1-\mu)} - \phi \right] (p_i - p_p) - p_p - p_{\pi} + \frac{E\alpha_m}{3(1-\mu)}[T_w - T_0] \quad (8)$$

According to the maximum tensile stress criterion, the condition of stratum cracking is

$$\sigma_{\theta}^z = -S_t. \quad (9)$$

$S_t$  is the tensile strength of rock, MPa. When the condition is satisfied,  $p_i$  is the fracture pressure  $p_F$ .

If  $K = \frac{\alpha'(1-2\mu)}{2(1-\mu)} - \phi$ , formula (8) can be written as

$$p_F = \frac{1}{1-K} (3\sigma_2 - \sigma_1 + S_t - (1+K)p_p - p_{\pi} + \frac{E\alpha_m}{3(1-\mu)}[T_w - T_0]). \quad (10)$$

The main stress in the vertical direction is called the overlying stress  $\sigma_3$ , which is produced by the weight of the overlying strata and varies with the depth of the rock strata. The effective overlying pressure  $\sigma_3'$  is:

$$\sigma_3' = \sigma_3 - p_p, \text{ or } \sigma_3' = S - p_p. \quad (11)$$

According to the view of Huang [6], if tectonic pressure exists, the effective stresses added to the two horizontal main directions in general are not equal. They are expressed as

$$\sigma_1' = \frac{\mu}{1-\mu} \sigma_3' + \alpha \sigma_3' + p_p, \quad \sigma_2' = \frac{\mu}{1-\mu} \sigma_3' + \beta \sigma_3' + p_p. \quad (12)$$

Where  $\sigma_1'$  is the maximum horizontal effective stress, MPa;  $\sigma_2'$  is the minimum horizontal effective stress, MPa.

Submitting formula (12) into the formula (10), the shale stratum fracture pressure model is got.

$$p_F = \frac{1}{1-K} (S_t - p_{\pi} + \frac{E\alpha_m}{3(1-\mu)}[T_w - T_0]) + p_p + \frac{1}{1-K} (\frac{2\mu}{1-\mu} + 3\beta - \alpha) \sigma_3'. \quad (13)$$

Where  $p_F$  is the stratum fracture pressure, MPa;  $\alpha$ ,  $\beta$  are stress coefficients of geological structure.

## 2. Example calculation of shale fracture pressure

According to the crustal stress and measured fracture pressure parameters of oilfield [6,11,12,14], the basic parameters are selected as shown in tables 1 and 2.

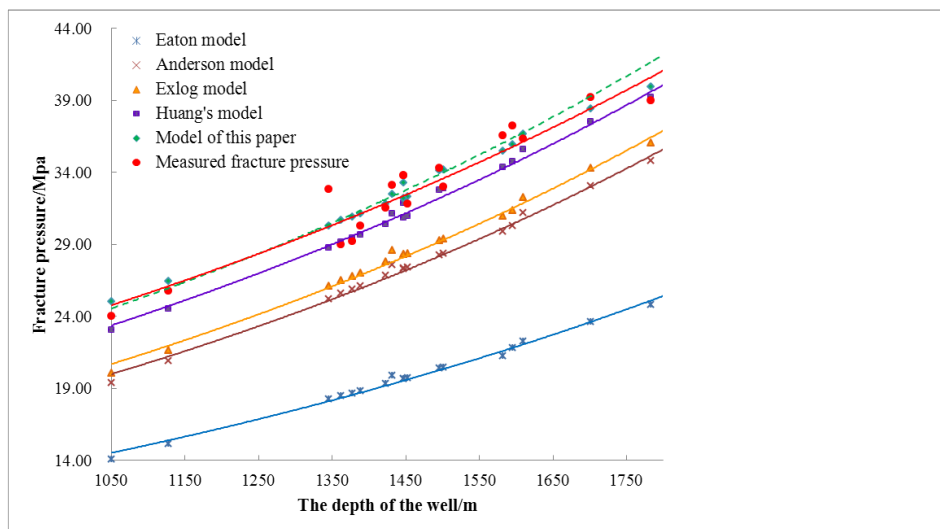
**Table 1.** Conventional parameters of shale formation.

Membrane permeable efficiency $I_m$	Gas constant $R'$	Absolute temperature $T / K$	Partial volume of water $\bar{V}$	molar of pure liquid	the activity of the formation liquid entering the stratum $(A_w)_m / m^3 mol^{-1}$
0.1	8.314	363	$1.8 \times 10^{-5}$		0.78
the activity of water in shale $(A_w)_{sh}$	Shale porosity $\phi$	Poisson ratio $\mu$	Structural coefficient $\alpha ; \beta$	stress	Effective stress coefficient $\alpha'$
0.915	0.1811	0.25	1.4; 0.46		0.7

**Table 2.** Ground stress and fracture pressure model in oil field.

Oil field	Well No.	Average depth of well /m	Measured fracture pressure $p_f$ /MPa	Stratum pressure $p_p$ /MPa	Tensile strength $S_t$ /MPa	Effective overlying stress $\sigma_3$ /MPa	Predicted rupture pressure /Mpa				
							Eaton model	Anderson model	Exlog model	Huang's model	Model of this paper
QY	Y2 <sup>#</sup>	1782.7	39.00	14.80	4.9	24.51	24.79	34.80	36.07	39.20	39.96
	Y4 <sup>#</sup>	1700.9	39.20	14.21	4.9	23.13	23.65	33.08	34.28	37.51	38.43
	Y14 <sup>#</sup>	1609.9	36.36	13.43	4.9	21.75	22.30	31.17	32.30	35.63	36.70
	Y13 <sup>#</sup>	1582	36.55	12.64	4.9	21.15	21.27	29.90	31.00	34.38	35.51
	Y11 <sup>#</sup>	1495.8	34.30	12.54	4.9	19.26	20.40	28.25	29.26	32.76	34.12
HCH	C1 <sup>#</sup>	1050.8	24.01	8.72	3.92	13.10	14.06	19.41	20.10	23.07	25.06
	C33 <sup>#</sup>	1127.2	25.77	9.41	3.92	14.11	15.16	20.92	21.65	24.56	26.43
MLB	186 <sup>#</sup>	1452.7	31.85	12.05	3.92	18.84	19.74	27.42	28.40	30.97	32.30
	93 <sup>#</sup>	1446.7	33.81	12.05	3.92	18.71	19.68	27.32	28.29	30.86	32.22
	188 <sup>#</sup>	1432	33.12	12.15	3.92	18.94	19.87	27.61	28.60	31.15	32.48
MLZ	98 <sup>#</sup>	1345.4	32.83	11.27	3.92	17.08	18.24	25.21	26.10	28.78	30.32
	207 <sup>#</sup>	1447.4	33.81	12.05	4.9	18.73	19.69	27.33	28.31	31.86	33.27
	256 <sup>#</sup>	1388	30.28	11.56	3.92	17.82	18.84	26.10	27.03	29.66	31.12
	209 <sup>#</sup>	1595.7	37.24	13.33	4.9	20.77	21.81	30.27	31.35	34.76	35.93
	303 <sup>#</sup>	1501.5	33.03	12.54	4.9	19.38	20.45	28.36	29.37	32.87	34.20
MLN	39 <sup>#</sup>	1377	29.20	11.47	3.92	17.68	18.68	25.89	26.81	29.46	30.93
	75 <sup>#</sup>	1361.5	29.01	11.37	3.92	17.45	18.49	25.61	26.52	29.18	30.67
	84 <sup>#</sup>	1423	31.56	11.86	3.92	18.40	19.36	26.87	27.83	30.43	31.81

According to the formula (13), the calculation results of the fracture pressure of shale are shown in figure 2.

**Figure 2.** The relation curve of fracture pressure and depth of well.

The calculation model is compared with other classic models as shown in figure 2. It can be seen that the fracture pressure of shale gradually rises with the rise of the well depth. The shale fracture pressure calculated by the present study is higher than that of other models at the same well depth. The reason is that the model of this paper not only considers the effect of these factors: the relationship between the overlying stress, the depth of the rock layer, stress concentration in wellbore wall, the effect of tectonic stress on underground nonuniform distribution and rock stratum strength, but also considers the additional stresses caused by percolation of drilling fluid, the hydration stress, the thermal stress caused by the temperature difference in the wellbore. The results show that the prediction error of the model of this paper is 3.85% compared with the measured results. The predicted results of this model are in good agreement with the actual fracture pressure. So the density of the equivalent drilling fluid calculated is more practical.

### 3. Summary

- Combined with the theory of elastic mechanics and rock mechanics, the application of the maximum tensile stress criterion, the present study established a model of shale fracture pressure. Based on Huang's model, the model of the present study has considered the additional influence of seepage of drilling fluid, hydration stress, shale porosity, temperature variable stress and tectonic stress and so on. Compared with the measured results, the error of this model is 3.85%, so the calculation accuracy is improved.
- Based on the stress superposition principle of small deformations on elastic material with pores, the present study made the linear superposition of crustal stress, tectonic stress, additional stresses caused by seepage and temperature and hydration stress. However, the interaction between them has not been considered yet, which needs to be studied in the subsequent work.

### Acknowledgment

The present work is supported by National Natural Science Foundation of China (Grant No. 51674200, 51704233 and 51704237), and the special research project of Shanxi Provincial Department of education (Brittleness analysis of drilling rig system based on improved extension theory and FAHP).

### References

- [1] Liu X J, *et al* 1997 Study on the stability of well wall in mudstone strata *Natural Gas Industry* **17** 45-8
- [2] Qu Z and Wang P 2016 *Creep Damage Instability Study of Shale* (Science Press, Beijing) 30-45
- [3] Wang P, Qu Z, Huang H, *et al* 2016 Creep experimental study of brittle shale triaxial state under aqueous *Science Technology & Engineering* **16** 66-71
- [4] Wang P, Qu Z and Huang H 2015 Experimental study of the effect of formation water salinity on creep laws of the hard brittle shale *Petroleum Drilling Techniques* **43** 63-8
- [5] Wen K M, Chen P, Li X Q, *et al* 2015 The Influence between shale hydration and rock stress distribution relationship *Science Technology & Engineering* **15** 43-6
- [6] Huang R 1982 Initiation and propagation of fractures in hydraulic fracturing *Petroleum Exploration and Development* **1982** 65-77
- [7] Li S G, Deng J G, Yu B H, *et al* 2005 Formation fracture pressure calculation in high temperatures wells *Chinese Journal of Rock Mechanics & Engineering* **24** 5669-73
- [8] Maury V and Guenot A 1995 Practical advantages of mud cooling systems for drilling *SPE* 25732 **1995** 42-8
- [9] Huang R 1984 A model for predicting formation fracture pressure *Journal of the University of Petroleum China* **1984** 16-28
- [10] Yan X, Hu Y Q, Li N, *et al* 2015 Calculation model of breakdown pressure in shale formation *Lithologic Reservoirs* **27** 109-13
- [11] Deng J 2009 Formation fracture pressure prediction method in high temperature and high

- pressure formations *Petroleum Drilling Techniques* **37** 43-6
- [12] Chenevert M E and Pernot V 1998 Control of shale swelling pressures using inhibitive water-base muds *SPE* 49263 27-30
- [13] Boas B M V 1992 Temperature profile of a fluid flowing within a well *SPE* 21133 439-46
- [14] Maury V and Guenot A 1995 Practical advantages of mud cooling systems for drilling *SPE* 25732 42-8