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ضغط بطانة البئر المتواصل (SCP) في آبار الغاز إستناداً إلى تشخيص قنوات ممر الغاز

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الخلاصة

ضغط بطانة البئر المتواصل (SCP) هو جانب أساسي لسلامة آبار الغاز وحماية البيئة. وتطلب جميع اللوائح والقوانين استبعاد (SCP). وتركز هذه الورقة على (SCP) التي تسببها حركة وهجرة الغاز في الحلقة بين بطانة البئر والاسمنت العازل. ونحن قد قمنا بنمذجة قنوات ممر الغاز في الجزء الاسمنتي وطورنا طريقة معدلة للتنبؤ بارتفاع أن ضغط تسرب الغاز وطول فترة تدعيم العازل يمكن أن تؤثر على كل من معدل الارتفاع والضغط الأقصى، بعد أن ناقشنا تدابير الوقاية. على وجه الخصوص إننا نقترح أن معدل الارتفاع والحد الأقصى لضغط الغلاف يجب أخذها في الاعتبار عند تحديد طول الازل الاسمنتي.

Prediction of SCP in Gas Wells Based on Gas Channeling-Path Characterization

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ABSTRACT

Sustained Casing Pressure (SCP) is a critical aspect to gas well safety and environmental protection. All regulations require SCP elimination. This paper focuses on the SCP which is caused by gas migration in cemented casing annulus. We modeled the gas channeling-path of cemented section and further developed a modified method to predict casing pressure rise. A field study was presented in the paper to verify the result of the prediction. We also analyzed the effects of the annular permeability, initial annular pressure, gas leakage pressure and the cementing isolation interval length on SCP. The annular equivalent permeability and initial annular pressure influence the rising rate of casing pressure without influencing the maximum casing pressure; while gas leakage pressure and the length of cementing isolation interval can influence both the rising rate and the maximum casing pressure. We discussed also the prevention measures. In particular, we suggest that the rising rate and the maximum of casing pressure should be considered while determining the cementing isolation interval.

Keywords: Annular equivalent permeability; gas channeling; gas well; prediction; sustained casing pressure.

INTRODUCTION

The abnormal casing pressure is a common and critical issue in gas wellproduction.When the casing pressure cannot be permanently bled off through needle valves at wellhead, the well is said to exhibit sustained casing pressure (SCP).The problem of SCP not only influences gas production performance, but also threatens worker safety and environment protection (Bourgoyne et al., 1999; Watson & Bachu, 2009; Peng et al., 2008; Zhang et al., 2011; Gu et al., 2013). According to the causes of abnormal annular pressure, there are two types of SCP. One is caused by high-temperature thermal expansion (Oudeman & kerem, 2006; Azzola et al., 2007; Hasan et al., 2010; Bellarby et al., 2013; Yang et al., 2013; Che et al., 2010), and the other is caused by migration of producing oil and gas incasing annulus (Somei, 1999; Xu & Wojtanowicz, 2001; Huerta et al., 2009; Zhu et al., 2012; Rocha-Valadez et al., 2014; Zhang et al., 2014). For the SCP caused by gas migration, Somei (1999) modeled gas migration as vertical flow through an annulus cemented to the surface, but because not all casings are cemented to the surface, the applicability of the model is limited. For cemented annulus that has mud columns, a new model was proposed by Xu & Wojtanowicz

(2001). The authors postulated that, gas would leak through the cement column, travel to the top of the mud column and accumulate in gas chamber, then lead to SCP. But they did not provide an analytical solution to their model. The model was also used by Kinik & Wojtanowicz (2011), who analyzed the Bleedoff-Buidup tests quantitatively to determine maximum possible emissions and their probabilistic risk. Based on the gas-liquid two-phase fluid dynamics theory, the gas migration model in the mud column above the cement was developed by Zhu et al., (2012), and then, he developed a coupled mathematical model of gas migration in a cemented annulus with a mud column. An analytical solution to Xu's model was developed by Rocha-Valadez (2014), who verified the model with five sets of field data. From this literature review, it can be seen that, although many researchers have studied the SCP problem and many of them have focused on the mechanism. However, to the author's knowledge, there is no report available in literature about the characterization of gas migration in cemented section. Previous work only briefly treated the cemented section as porous media with given permeability, and only few researchers have studied in depth, the mechanism of gas migration in the mud column above cement.

This paper focuses on the SCP caused by the annular gas channeling in gas wells. Based on the gas flow rules of the two types of channeling-path in cemented section, a characterization method of gas channeling in cemented section has been developed. Then we developed a modified SCP prediction model by taking spacer column, mud column, gas diffusivity and fluid compressibility into consideration. Meanwhile a field study is carried out to verify this model. In order to guide field operations, the influence rules of SCP are analyzed, and then we proposed some corresponding preventive measures. The result of this study will provide a theoretical method, and lay a basis for the prediction and management of SCP in gas wells.

GAS CHANNELING-PATH CHARACTERIZATION

Cementing isolation interval is composed of cement sheath and two cementing interfaces. Therefore, the channeling-path of gas in casing annulus also can be divided into two types; cement sheath which is a kind of porous media with secondary fracture and cracks in cementing interfaces, such as the micro-annulus. These two types of path combine with each other and finally compose the gas channeling-path in cementing isolation interval.

Gas channeling formulation in cementing isolation interval

The gas flow in cement sheath follows the steady linear seepage law. Therefore, we make the following assumptions: 1) the compressibility of cement sheath can be ignored; 2) the porosity of cement sheathis constant; 3) temperature is unchanged. The equations of flow velocity and flow rate of gas in cement sheath are as follows.

$$v = \frac{k_c}{2\mu_i L_{cc}} \frac{p_1^2 - p_2^2}{p_{sc}} \tag{1}$$

$$q = \frac{k_c A_c}{2L_{cc}} \frac{Z_{sc} T_{sc}}{p_{sc} T_{in} \mu Z_i} \left(p_1^2 - p_2^2 \right) \tag{2}$$

For the gas flow in micro-annulus, by assuming that the fluid is incompressible and flow pattern is a fully developed steady laminar flow, the flow equation can be deduced from the Poiseuille equation. The Navier-Stokes (N-S) equation in cylindrical coordinate is given by:

$$\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}-\frac{u_\theta^2}{r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}+u_z\frac{\partial u_r}{\partial z}=F_r-\frac{1}{\rho}\frac{\partial p}{\partial r}+\nu\left(\frac{\partial^2 u_r}{\partial r^2}+\frac{1}{r}\frac{\partial u_r}{\partial r}-\frac{u_r}{r^2}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta^2}+\frac{\partial^2 u_r}{\partial z^2}\right) \tag{3}$$

The flow velocity changes only in the *Z* direction and is zero in other two directions. We assume that the flow velocity in *Z* direction is u_z, which only changes in the r direction and does not change with time, that is $u_z = u_z(r)$. When we ignore the influence of mass force, the N-S equations can be simplified as follows:

$$\frac{1}{\mu}\frac{dp}{dz}=\left(\frac{d^2u_z}{dr^2}+\frac{1}{r}\frac{du_z}{dr}\right)=\frac{1}{r}\frac{d}{dr}\left(r\frac{du_z}{dr}\right) \tag{4}$$

Assuming the inside radius of micro-annulus is r_i, the outside radius is r_o, we obtain the boundary condition $u_z(r_i)$. Through the integration of Equation (4), we have the steady laminar flow equation of incompressible fluid in micro-annulus:

$$u_z=\frac{1}{4\mu}\cdot\frac{dp}{dz}\cdot[r^2-r_o^2-\left(r_i^2-r_o^2\right)\frac{\ln\left(r/r_o\right)}{\ln\left(r_i/r_o\right)}] \tag{5}$$

And by integrating Equation (5), we have the flow rate equation of gas in micro-annulus:

$$Q=\int_{r_i}^{r_o}u_z\cdot 2\pi r dr=\frac{\pi}{8\mu}\cdot\frac{dp}{dz}\cdot\left(r_o^2-r_i^2\right)\left[-r_o^2-r_i^2+\left(r_o^2-r_i^2\right)/\ln\left(r_o/r_i\right)\right] \tag{6}$$

But in fact, the interface of micro-annulus is rough in oil and gas well, which means that the permeability of real micro-annulus is lower than the ideal condition. So it is necessary to bring in a correction coefficient *c* related to the roughness of micro-annulus. Equation (6) follows the Darcy law and can be transformed to the following form of casing annulus; then we have:

$$k_h=-\frac{c\pi}{8A_c}\left(r_o^2-r_i^2\right)\left[-r_o^2-r_i^2+\left(r_o^2-r_i^2\right)/\ln\left(r_o/r_i\right)\right] \tag{7}$$

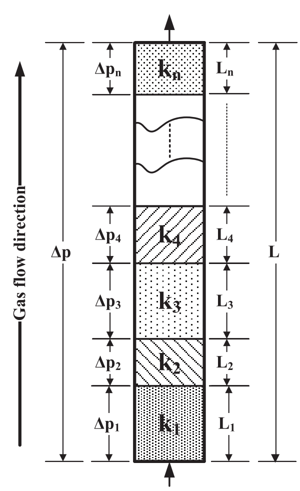


Fig.1. The schematic of gas channeling incementing isolation interval

Equivalent permeability of cementing isolation interval

According to gas flow rules in cementing isolation interval, the process can be equivalent to gas flow in different intervals with different permeability (Figure 1). The gas flow satisfies the continuity principle, when flowing in vertical direction, so the flow rates per unit area of all intervals are equal $Q_1 = Q_2 = \dots = Q_n = Q$,but the head loss of gas flow through each interval is different. According to the Darcy law, the flow rates per unit area of all intervals satisfy:

$$\frac{k_1 \Delta p_1}{\mu L_1} = \frac{k_2 \Delta p_2}{\mu L_2} = \dots \dots = \frac{k_n \Delta p_n}{\mu L_n} = Q$$

$$\text{and } \Delta p_i = \frac{Q \mu L_i}{k_i}, \quad i = 1, 2, \dots \dots, n \tag{8}$$

$k_1, k_2, k_3 \dots k_n$ are the permeability of intervals, $\Delta p_1, \Delta p_2, \Delta p_3 \dots \dots \Delta p_n$ are the head losses of intervals, $L_1, L_2, L_3 \dots L_n$ are the height of intervals.

Therefore, the gas channeling in cementing isolation intervals can be assumed to the flow in a homogeneous permeability medium with the height of $L = \sum_{i=1}^{n} L_i$, and with the same flow rate Q under the head loss $\Delta p = \sum_{i=1}^{n} \Delta p_i$, so the homogeneous permeability will be the equivalent permeability of gas channeling in the cementing isolation intervals:

$$Q = \frac{k_e}{\mu} \frac{\sum_{i=1}^{n} \Delta p_i}{\sum_{i=1}^{n} L_i}, \quad i = 1, 2, \dots \dots, n \tag{9}$$

Using Equation (8) and (9), we have:

$$k_e = \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n} \frac{L_i}{k_i}}, \quad i = 1, 2, \dots \dots, n \tag{10}$$

According to Equation (10), if there are only two types of channeling-path in cementing isolation interval, then the equivalent permeability of gas flow can be written as:

$$k_e = \frac{L_c}{\frac{L_{cc}}{k_c} + \frac{L_{ch}}{k_h}} \tag{11}$$

PREDICTION MODEL OF CASING PRESSURE

Model formulation

The steady linear seepage flow can be expressed in the form of Darcy law no matter what type of channeling-path it is. Therefore, the prediction model of casing pressures also established in the form of Darcy law, and we should make the following assumptions Xu & Wojtanowicz (2001), ① Annular pressure is established on micro-time steps, both annular pressure and flow rate in wellhead are constant in every micro-time step; ② The gas leakage pressure is constant. ③ The migration time of gas in drilling fluid is very short, thus can be neglected. The annular gas channeling model is shown in Figure 2.

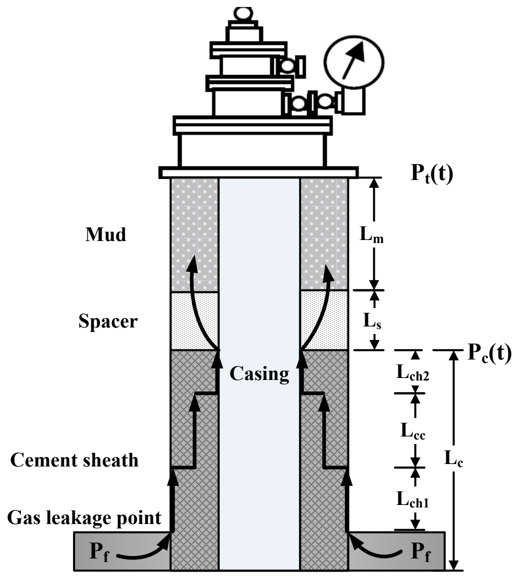


Fig.2. The schematic of annular gas channeling model

At n-th time step the pressure at the top of cement is:

$$p_c^n = p_t^{n-1} + 0.0098\left(\rho_m L_m^{n-1} + \rho_s L_s^{n-1}\right) \tag{12}$$

Because of the pressure at leak point is constant, according to Darcy law we get the flow rate at the top of cement as:

$$q_c^n = \frac{0.00864 k_e A_c T_{sc}}{2 p_{sc} T L_c \mu_i Z_i}[p_f^2 - \left(p_c^n\right)^2] \tag{13}$$

During this period of time, the volume of gas is:

$$\Delta V_g^m = q_c^n \Delta t \tag{14}$$

For all time steps, the cumulative gas at the top of the annular is:

$$n_t^n = \sum_{k=1}^{n} \Delta n^k = \frac{\sum_{k=1}^{n} q_c^k p_c^k \Delta t}{Z_i R T_{wb}} \tag{15}$$

and k=1,2,3…n.

Considering the diffusivity of gas and the compressibility offluid, we can get the following equations:

$$p_t^n(V_t^{n-1}+\Delta V_t^n)=n_t^n ZRT_{wh} \tag{16}$$

$$\begin{aligned}\Delta V_t^n &= \Delta V_m^n + \Delta V_s^n\\ \Delta V_m^n &= c_m V_m^{n-1}(p_t^n - p_t^{n-1})\\ \Delta V_s^n &= c_s V_s^{n-1}(p_t^n - p_t^{n-1})\end{aligned} \tag{17}$$

Using equations (12), (13), (15), (17)and (16), we get the prediction casing pressure at n-th time step as:

$$p_t^n=\frac{1}{2}\left(p_t^{n-1}-\frac{V_t^{n-1}}{c_mV_m^{n-1}+c_sV_s^{n-1}}+\sqrt{\left(p_t^{n-1}-\frac{V_t^{n-1}}{c_mV_m^{n-1}+c_sV_s^{n-1}}\right)^2+\frac{4T_{wh}\sum_{k=1}^{n}q_c^k p_c^k\Delta t}{c_mV_m^{n-1}T_{wb}}}\right) \tag{18}$$

Model validation

We select a high-pressure gas well from awestern oilfield of China as an example, and the abnormal pressure has appeared in B-annulus of this well. The casing program of the example well is shown in Figure 3.Based on the well history and logging data, the well parameters used in calculation has been determined (Table 1).

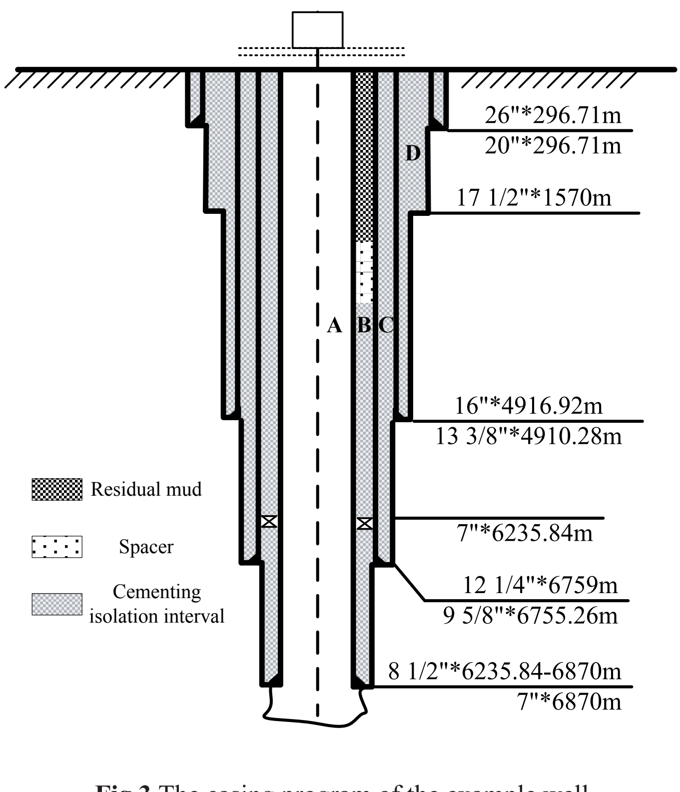


Fig.3. The casing program of the example well

Table1. Field data and parameters

	Value		Value		Value
D_1	0.2159m	D_2	0.1778m	T_{wb}	71.88℃
T_{in}	123.66℃	T_{sc}	20℃		20℃
p_{sc}	0.1MPa	μ_i	0.015mPaat	Z_i	0.92
L_{in}	6870m	L_c	3670m	L_s	300m
L_m	2900m	k_c	0.426mD	k_h	4.2mD
L_{ch}	1300m	L_{cc}	2370m	ρ_m	2.0g/cm^{-3}
ρ_s	2.3g/cm^{-3}	c_m	1.5g10^{-4}MPa^{-1}	c_s	1.0g10^{-4}MPa^{-1}
p_f	112MPa	p_t^0	2.3MPa		

By using the prediction model, the annular pressure in B-annulus is calculated, and then compared with the testing data. When testing starts, open the needle valve of B-annulus to bled off the casing pressure, and then close the needle valve, the casing pressure being stable at 2.3MPa. The production is stable and the pressure of A-annulus is stable at 39MPa in the testing. The comparison result of prediction and testing is shown in Figure 4.

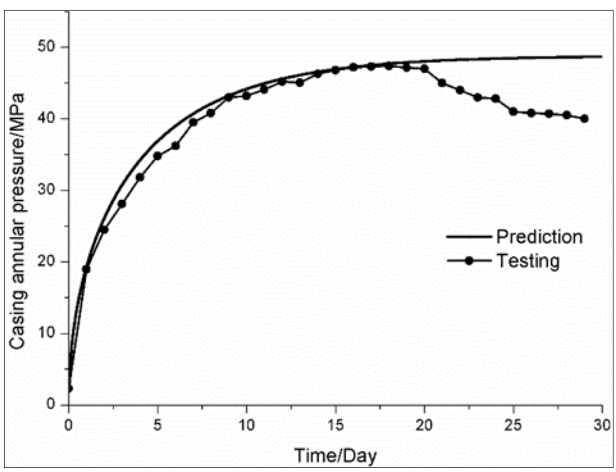


Fig.4. Comparison result of casing pressure prediction and testing

As we can see clearly from Figure 4, the predicted casing pressure of B-annulus is in good agreement with the testing data at the initial stage. However, being different from the prediction result, the testing data goes down gradually since they reach the maximum, and the testing data is less than the prediction value at the end. By contrast, the pressure of annulus-A is stable during the whole testing. We think the difference between prediction and testing may be caused by the sealing failure of outer casing. According to the above results, the accuracy of the prediction model can be validated.

DISCUSSION

Analysis of the influence rules on casing pressure

Firstly, by using the calculation method of equivalent permeability of gas channeling in cementing isolation interval, the annular equivalent permeability under different length ratio of two channeling-paths was calculated. The result is shown in Figure 5.

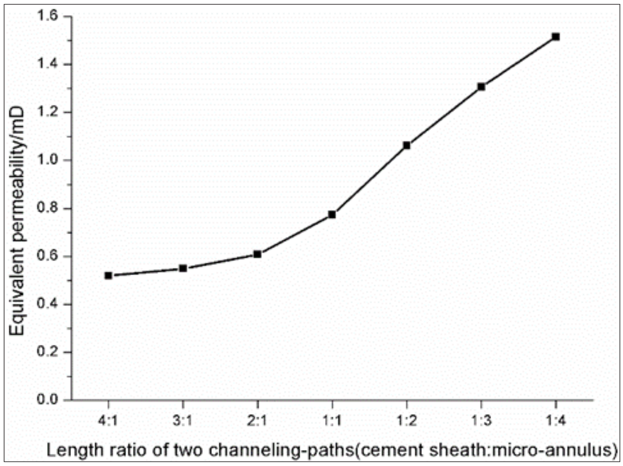
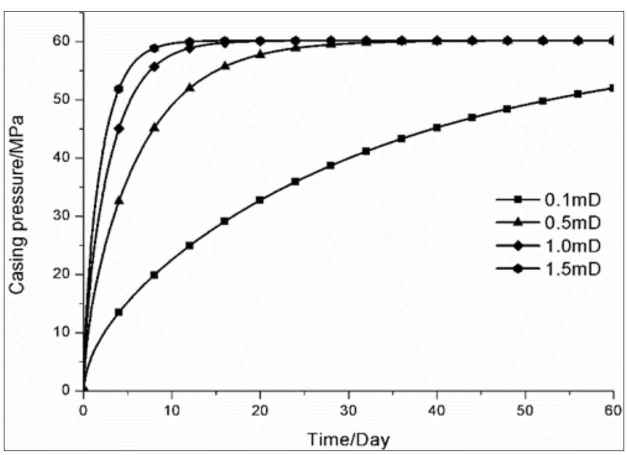


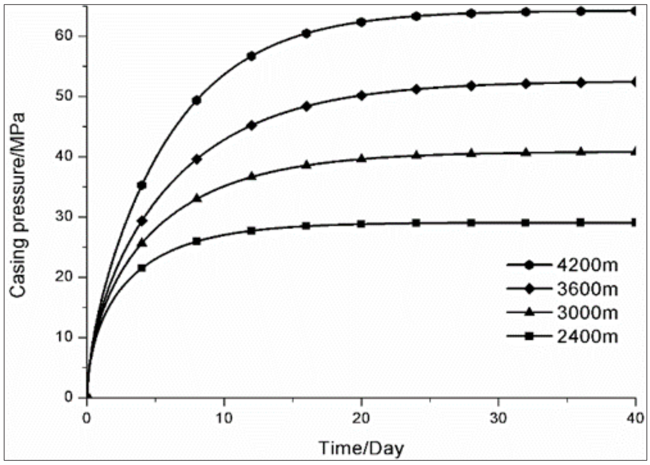
Fig.5. The equivalent permeability under different length ratio of two channeling-paths

Because the permeability in micro-annulus is much bigger than in cement sheath, it can be seen from Figure 5, that the equivalent permeability is low within a small range, when the length of channeling-path in cement sheath has a greater percentage. But, when the length of channeling-path in micro-annulus has a greater percentage, the annular equivalent permeability is high within a big range.

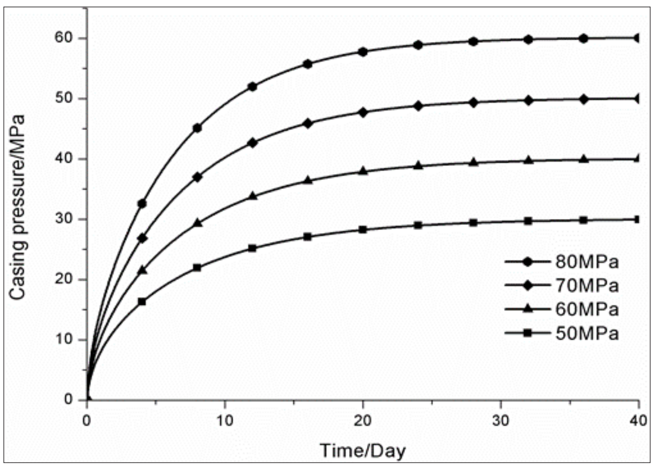
By using the casing pressure prediction model, the relationship between annular equivalent permeability, gas leakage pressure, initial pressure in wellhead and casing pressure in wellhead were analyzed. The results are shown in Figure 6.



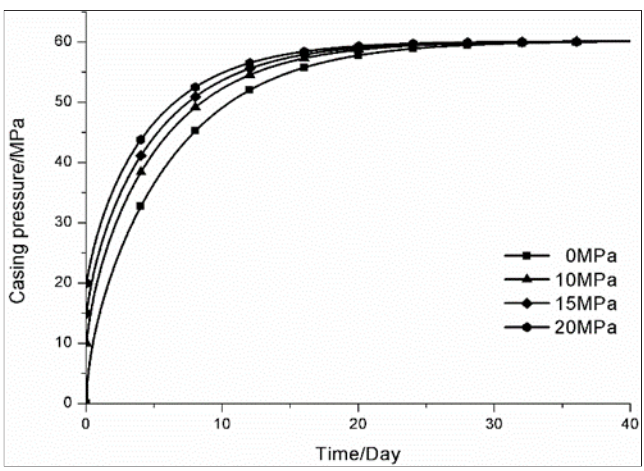
(a) Annular equivalent permeability



(b) Gas leakage pressure



(c) Length of cementing isolation interval



(d) Initial annular pressure

Fig.6. Influence law curves of different factors on casing pressure

From Figure 6(a) and 6(d) we can see that the annular equivalent permeability and initial annular pressure mainly influence the rise rate of casing pressure without influencing the maximum of casing pressure; the higher the annular equivalent permeability is, the faster the annular pressure rise; the lower the initial annular pressure is, the faster the annular pressure riseand vice versa. As shown in the Figure 6(b) and 6(c), the gas leakage pressure and the length of cementing isolation interval have significant influence on both the rise rate and the maximum of casing pressure; the higher the gas leakage pressure is, the faster the annular pressure rise, the higher is the annular pressure; the longer the length of cementing isolation interval is, the faster the annular pressure raises and, the higher is the casing pressure. Whenthe pressure on the top of long cementing isolation interval is low, or the gas leakage pressure is high, these will bring about a large head loss between two sides of cementing isolation interval, and lead to a great gas channeling speed and, ultimately the casing pressure rises faster with a higher value.

Preventive measures of sustained casing pressure

Excessively high annular pressure can cause sealing failure of casing (outside the annular) and tubing (inside the annular) or destruction of cement sheath. So it is necessary to limit the allowable maximum of annular working pressure to ensure wellbore integrity in production (Shi et al., 2012; Li et al., 2013). American Petroleum Institute API-RP90 (API, 2006) provides a method to determine the maximum allowable annular working pressure. In order to keep the annular pressure under the allowable maximum, we should prevent the subsequent operation, which causes micro-annulus and cement sheath destruction, avoiding the formation of channeling-path, which has high annular permeability. Moreover, low cement sheath body permeability helps to delay the rise of annular pressure. In addition, high-pressure gas wells are often cemented to the surface, but according to the relationship between the length of cementing isolation section and annular pressure, actuallythis is bad for SCP management. Also the length of cementing isolation interval is not the shorter the better. By calculating the equivalent permeability under same conditions, we concluded that the longer the length of effective cementing isolation interval, the lower the equivalent permeability. From the study above, the rising rate and the maximum of casing pressure should be considered, while determining the cementing isolation interval. Meanwhile, we should strengthen the casing pressure surveillance in production and make timely and effective pressure release plans.

CONCLUSIONS

Channeling-path of annular gas can be divided into two types, cement sheath which is a kind of porous media with secondary fracture and cracks in cementing interfaces. These two types of path combined with each other composed the gas channeling-path in cementing isolation intervals. Based on the gas flow rules in channeling-paths, a characterization method of annular channeling-path was developed.

By assuming that the formation gas migratesup through cementing isolation interval and mud column to the surface, we also developed a modifiedprediction model for casing pressure. According to the validation with field data, the model is rational.

Annular equivalent permeability and initial annular pressure mainly influence the rate of casing pressure rise without influencing the maximum of casing pressure rise; gas leakage pressure and the length of cementing isolation interval influence both the rate and the maximum of casing pressure rise. The length of cementing isolation interval should be determined under the consideration of the rise rate and the maximum of casing pressure.

NOMENCLATURE AND UNITS

A_c-area of cement sheath, m^2; k_c-permeability of cement sheath, mD; k_h- permeability of micro-annulus, mD; k_e-equivalent permeability of casing annulus, mD; L_c-length of cementing isolation interval, m; L_{cc}-length of cement sheath, m; L_{ch}-length of micro-annulus, m; c_m-mud compressibility, MPa^{-1}; c_s-spacer compressibility, MPa^{-1}; L_m-length of mud column, m; L_s-length of spacer column, m; L_{in}-depth of gas leakage point, m; ρ_m-density of mud, g/cm^3; ρ_s-density of spacer, g/cm^3; p_f-gas leakage pressure, MPa; p_c-pressure at the top of cement, MPa; p_t-annular pressure in wellhead, MPa; p_t^0-initial annular pressure in wellhead, MPa; T_{in}-gas leakage temperature, K; T_{wh}- temperature in wellhead, K; T_{wb}-average wellbore temperature, K; T_{sc}-standard temperature, K; μ-gas viscosity, $mPa \cdot s$; p_{sc}-standard pressure, MPa; Z_i-gas-law deviation factor; p_1-inlet pressure, MPa; p_2-outlet pressure, MPa; D_1-outer diameter of annulus, m; D_2-inner diameter of annulus, m; r_i-inside radius of micro-annulus, m; r_o-outside radius of micro-annulus, m; c-correction coefficient, $0 < c \le 1$; Δt-time step, day; q_c-flow rate at the cement top, m^3/day; V_t-volume of accumulated gas, m^3; V_m-volume of mud column, m^3; V_s-volume of spacer column, m^3.

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