Study on numerical analysis method of abnormal pressure formation in annulus A of CO_2 injection well

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Abstract. With the gradual development of CO_2 drive in oilfield, the existing CO_2 injection wells have A annulus pressure anomalies, and the A annulus pressure anomalies are very likely to cause damage to the wellbore integrity, and there is a greater safety risk to production and the environment. To address the problem of annulus pressure in CO_2 injection wells, a model of pressure equilibrium between tubing and A annulus and a model of mass conservation in the process of A annulus pressure relief have been established, and the effects of different oil jacket differential pressures, annulus liquid levels, leakage hole locations, equivalent diameter of leakage holes, and pressure relief time on the pressure in A annulus have been investigated, so as to form a method of evaluating the degree of leakage in A annulus. This method can provide theoretical guidance for the preliminary diagnosis of annulus with pressure in CO_2 injection wells, and has certain engineering reference significance for the control of annulus pressure in CO_2 injection wells.

Keywords: CO_2 injection well ; annular pressure ; pressure balance ; pressure relief ; conservation of mass.

1. Introduction

With the gradual development of oilfield CO_2 drive work[1], it is found that the existing CO_2 injection wells have A annulus pressure abnormality, and the A annulus abnormality with pressure is very easy to cause damage to the integrity of the wellbore[2], and there is a greater safety risk to production and the environment[3-5]. Some scholars have carried out a lot of research work on the temperature and pressure distribution of the wellbore during CO_2 injection. Lan Jianping[6] obtained the temperature and pressure distribution law of the wellbore during CO_2 injection by establishing a heat transfer flow model with coupled fluid properties in the wellbore. Xiao Bo[7] established a wellbore temperature-pressure coupling model for the phase change and physical property change in the CO_2 dry fracturing process. Qing Wang[8] explored the effects of CO_2 injection temperature and injection displacement on wellbore temperature and pressure. Wu[9] calculated the wellbore temperature and pressure of CO_2 injected wells in Jilin oilfield based on PR-EXP method. Zhang Yonggang[10] explained the gas flushing problem in Honghe oilfield based on the proposed CO_2 wellbore temperature and pressure coupling model. Domestic and foreign scholars conducted less research on the annular pressure banding problem of CO_2 injection wells, and more research related to the annular pressure banding of gas wells was carried out. Lian Zhanghua[11] combined elasto-plasticity mechanics and seepage mechanics to obtain the calculation method of A annular liquid surface height and annular pressure. Zhu Dajiang[12] established the diagnostic curve of A annulus test through the principle of pressure balance, and obtained the evaluation method for the leakage degree of A annulus. Hu[13] classified four types of annulus with pressure, and he concluded that the shallower the leakage aperture is, the faster the pressure rises and the higher the threat to the wellbore. Feng Ding[14] established the continuity equation and motion equation of gas seepage in the cement ring, and obtained the prediction model of annulus air leakage pressure. Guo Minling[15] established an annular pressure prediction model for non-leakage and leakage conditions, and he concluded that the closer the annulus is to the inside of the operating column, the faster the annular pressure grows. Xu Shenqi[16] studied the anomalous increase of annular pressure caused by gas flushing, and obtained a prediction model of annular liquid pressure considering gas seepage and gas-liquid two-phase flow. Zhang Hong[17] established the formation process of annular pressure considering gas seepage and PVT equations by taking into account the compressibility of the liquid in the annulus, and obtained an analytical calculation model of the annular pressure. Shu Gang[18] combined the A annulus pressure relief test process and the leakage point location calculation to form a new method of gas well annulus pressure banding diagnosis. Cong Ziyuan[19] combined the optimized CO_2 physical property calculation method to propose a prediction model of annulus band pressure in gas wells containing sour gas, and obtained the wellhead pressure change rule of A annulus band pressure and the phase distribution law in the wellbore. Zhou Lang[20] proposed the A annulus pressure recovery model for the problem of CO_2 driven annulus pressure in Jilin oilfield.

In this paper, with the background of A annulus pressure bringing problem of CO_2 injection wells in an oil field, the oil pipe and A annulus pressure equilibrium model and the mass conservation model of the pressure relief process were established respectively, and the relationship between the influence of different oil jacket differential pressure, annulus liquid level, leakage hole location, equivalent diameter of leakage holes, and time of pressure relief on the A annulus pressure was investigated, so as to form a method of evaluating the degree of leakage of the annulus of the oil jacket. This method can provide theoretical guidance for the preliminary diagnosis of annulus with pressure in CO_2 injection wells, and has some guiding significance for the control of annulus pressure in CO_2 injection wells.

2. Establishment of numerical analysis model

2.1 Pressure equilibrium model

As shown in Fig. 1, the A annulus pressure P_{c0} should be 0 when the anomalous pressure increase of A annulus due to formation temperature is ignored, and when the leakage occurs in the oil pipe, the gas gradually leaks into the A annulus and collects at the top under the action of the pressure inside the oil pipe. When the oil pipe and A annulus pressure equilibrium ($P_T = P_C$), the oil pipe and A annulus pressure to reach equilibrium, as shown in Fig. 1, the A annulus pressure profile gradually shifted to the right and the pressure in the oil pipe to reach equilibrium, based on the process of this paper to carry out the relevant research work.

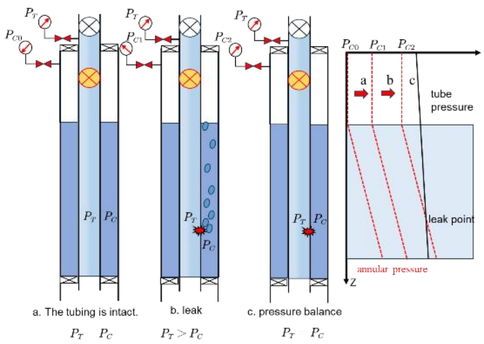


Fig. 1 Principle of pressure balance model

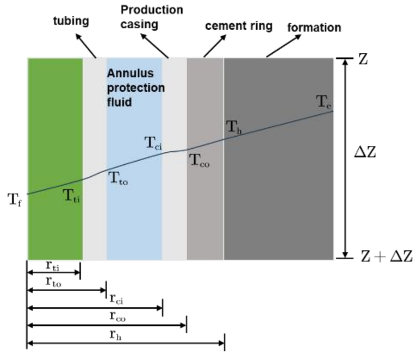


Fig. 2 Schematic diagram of radial heat transfer from wellbore of CO_2 injection well

Based on this principle, we make the following assumptions: ① Assume that the CO_2 injection wells are in a stable gas injection state during the process of reaching the pressure equilibrium; ② For the sake of simplifying the calculation, assume that there is only one leakage point of the equivalent diameter of the tubing; ③ In the same depth of the formation, the temperatures and pressures are equal, which means that the leakage flow and the heat transfer process are regarded as the one-dimensional flow and the one-dimensional heat transfer; ④ Neglect the vertical heat transfer, and only take into account the radial heat transfer effect between tubing-cement-floor. The radial heat transfer between the oil pipe and the cement and the formation is only considered. We divide the flow process of injected CO_2 gas in the oil pipe into infinitely small vertical segments (as shown in Fig. 2), and according to the equation of energy conservation, we can get the formula for calculating the temperature in the oil pipe:

$$\frac{dT_f}{dz}=C_J\frac{dp}{dz}+\frac{1}{C_{pm}}\frac{dH}{dz}=C_J\frac{dp}{dz}+\frac{1}{C_{pm}}\left(\frac{dQ}{dz}-g-v_t\frac{dv_t}{dz}\right) \tag{1}$$

Where: T_f - Fluid temperature, °C; z - Vertical position, m; C_J - Joule Thomson coefficient, $\mathrm{J/(kg\cdot ℃)}$; p - Pressure, Pa; C_{pm} - Specific pressure heat capacity, $\mathrm{J/(kg\cdot ℃)}$; H - Depth, m; Q - Heat exchange volume per unit mass, $\mathrm{J/kg}$; g - Gravitational acceleration, $\mathrm{m^2/s}$; v_t - Flow rate in the tube, m/s.

From the above analysis process can be seen, when a leak occurs at a certain point of the oil pipe A annulus pressure gradually rises until the pressure balance between the two sides of the leakage point, after the leakage point of the gas flow stops. This pressure equilibrium principle can be used to establish the leak depth prediction model. Therefore, this equilibrium process can be established as the pressure change of CO_2 gas flow in the oil pipe and the top pressure of the collected annular air in the A annulus to reach equilibrium with the static pressure of the annular liquid level. According to the law of conservation of momentum, the equations of steady state flow and frictional resistance of CO_2 in the oil pipe are:

$$\frac{dp}{dz}=\rho g-\frac{2f\rho v_t^2}{D_t}-\rho v_t\frac{dv_t}{dz} \tag{2}$$

$$f=\left[2\lg\left(\frac{\varepsilon/D_t}{3.707}-\frac{5.045}{Re}\lg\Lambda\right)\right]^{-2} \tag{3}$$

$$\Lambda=\frac{(\varepsilon/D_t)^{1.11}}{2.826}-\left(\frac{7.149}{Re}\right)^{0.898} \tag{4}$$

Where: ρ - fluid density, $\mathrm{kg/m^3}$; D_t - inner diameter of the oil pipe, m; ε - oil pipe wall roughness, m; Re - Reynolds number.

When the pressure equilibrium is reached, the pressure on the side of the leakage point of the A ring can be calculated as:

$$P_c=p_{Ac}+\rho_l g h_l \tag{5}$$

Where: p_c - pressure on one side of the leakage point of A annulus, Pa; p_{Ac} - pressure at the top of A annulus, Pa; ρ_l - density of annulus protection liquid, $\mathrm{kg/m^3}$; h_l - level of A annulus measured by the echo method, m.

Combined with the above equation according to the principle of pressure balance, can be obtained:

$$p_{in} + \rho g h - \frac{2fh\rho v_t^2}{D_t} = p_{Ac} + \rho_l g h_l \tag{6}$$

The injection pressure p_{in} is a known parameter, the stabilised annular pressure can be measured with a pressure gauge, and the annular level h_l can be measured by the echo method.

Therefore, based on the pressure balance equation, the leakage position of the oil pipe can be solved. Since the physical parameters of CO_2 change with temperature and pressure, in order to accurately solve the physical parameters of CO_2, the NIST database [21] was used to obtain the density, viscosity, and constant-pressure specific heat data at different temperatures and pressures.

2.2 Annular pressure relief mass conservation model

In the process of A annulus pressure relief, the gas in the tubing will flow into the annulus from the leakage hole, and at the same time, the gas in the annulus in the pressure relief process will also be released into the atmosphere from the A annulus wellhead valve. Based on the above process to establish the physical model shown in Figure 3, take the volume of the A ring air body for the control body, the height of the control body for the height of the liquid level in the annulus h, considering the A ring air body leakage process, the pressure relief process of the tubing pressure, the inlet for the leakage holes, the outlet for the valve diameter of DN50, for the sake of model calculations, assuming that there is only one equivalent aperture of the leakage holes, the initial total mass of the ring air body in the figure M (kg), The inlet pressure is the tubing pressure P, the inlet back pressure is the annulus pressure P_{cas}, the outlet pressure is the atmospheric pressure P_a, and the outlet back pressure is the annulus pressure P_{cas}.

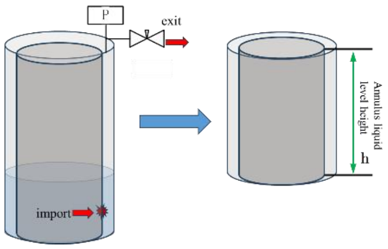


Fig. 3 Schematic diagram of pressure relief model

Considering the above physical model, the mass conservation equation is satisfied inside and outside the annular control, assuming that carbon dioxide does not undergo a phase change during constant volume leakage:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = q_{\mathrm{in}} - q_{\mathrm{out}} \tag{7}$$

Discrete the above equation in d_t time can be obtained as: $M(n+1) = M(n) + q_{in} \cdot \mathrm{d}t - q_{out} \cdot \mathrm{d}t$, $M_{(n+1)}$ and $M_{(n)}$ represent the mass of CO_2 in the annular control body at t_n and t_{n+1} moments, By calculating the residual mass of each time step, the residual molar mass of the whole control body is calculated, and the iterative solution is obtained step by step.

The calculation of mass flow parameters of downhole leakage hole and wellhead valve is based on the small hole leakage model, and the CO_2 leakage process is regarded as adiabatic isentropic flow, and the leakage process is a critical flow when the outlet pressure and the medium pressure in the pipe satisfy the pressure $\frac{P_b}{P} \le \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$, and the mass flow rate is calculated according to the following formula:

$$q_{\text{out}} = C_d P A_{\text{hole}} \sqrt{\frac{2}{ZRT} \frac{k}{k+1} \left(\frac{2}{k+1} \right)^{\frac{2}{k-1}}} \tag{8}$$

Otherwise the leakage process is subcritical flow and the mass flow rate is calculated according to the following equation:

$$q_{\text{out}} = C_d P A_{\text{hole}} \sqrt{\frac{2}{ZRT} \frac{k}{k-1} [\left(\frac{P_b}{P} \right)^{\frac{2}{k}} - \left(\frac{P_b}{P} \right)^{\frac{k+1}{k}}} \tag{9}$$

Where: k-CO_2 adiabatic index 1.3; C_d-leakage resistance coefficient, 0.62; A_{hole}-leakage port area, m^3; Z-compression factor; R-gas constant.

At the same time the CO_2 gas mass in the annulus was calculated from the real gas equation of state:

$$p = \frac{RT}{v-b} - \frac{a}{v^2} \tag{10}$$

Where: a - reflect the strength of molecular mutual attraction constant, for carbon dioxide a = 0.365; b - molecules can not move freely space, and molecular volume, for carbon dioxide b = 4.28 × 10^{-5}; (v - b)- molecules can move freely space; a / v^2 - indicates that the molecules are attracted to each other making the pressure of the actual gas decrease.

3. Engineering Applications

Based on the above pressure balance model and the calculation process of the annulus pressure relief mass conservation model substituted into the basic data of a well in the oilfield (as shown in Table 1) to analyse the relationship between the leakage point location, differential pressure of the oil jacket, the annulus liquid level, the leakage aperture size and the time of the pressure relief, and to calculate the leakage point location of the well as shown in Fig. 4, when the annulus static liquid level of the well is at the wellhead, the leakage location obtained by this paper's pressure balance equation is 660m below the well.

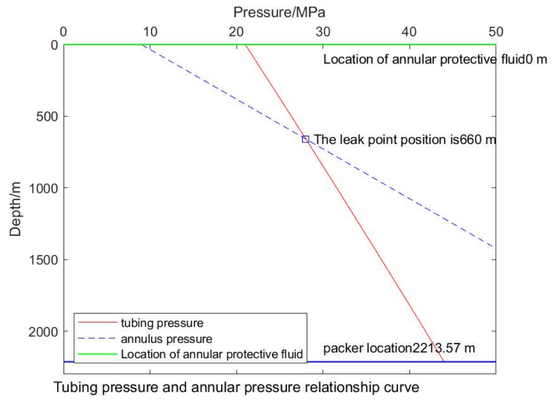


Fig. 4 Prediction results of leakage location of a well in an oil field

Table 1 Table of basic parameters of a well in an oil field

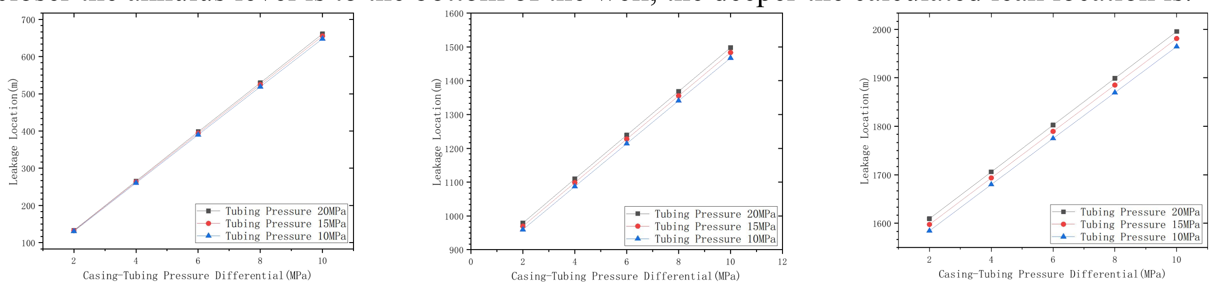
Parameter	Value
Tube specification(mm)	Φ73×5.51
Casing specification(mm)	Φ139.7×7.72
Formation temperature gradient(°C/100 m)	1.84
Wellhead injection temperature(°C)	-20
Packer depth(m)	2213.57
Level of annular protective fluid(m)	0
Gas injection volume(t/h)	3
Density of annular protective fluid(g/cm^3)	1.05

4. parameter sensitivity analysis

According to the method established in this paper, the basic data of a well in the above oilfield are inputted to carry out parametric analysis on the relationship between different leakage locations, differential pressure in the oil jacket, liquid level in the annulus, leakage aperture size, and time of pressure relief, so as to make clear the connection between various factors.

4.1 The influence of leakage point position and oil jacket pressure difference on annular pressure

Figure 5 shows the relationship between different leakage locations, oil jacket differential pressure and annulus level. From Fig. 5(a), it can be seen that when the depth of the annulus level is 0m, i.e., the A annulus level has reached the wellhead, at this time, when the oil jacket differential pressure is the same, the leakage positions calculated by the model are almost equal, indicating that when the annulus level is 0m, the influence of the oil jacket differential pressure on the leakage position is insignificant; from Fig. 5(c), it can be seen that when the depth of the annulus level is 1,000m, and the pressure of the oil tubing is 20MPa, the calculated oil jacket differential pressure gradually increases with the depth of leakage position, indicating that the closer the leakage position is to the wellbore, the smaller the growth of the annulus pressure is. increases, the calculated oil jacket differential pressure increases gradually, indicating that the closer the leak location is to the bottom of the well, the smaller the growth of the annulus pressure. Comparing with Fig. 5, it can be seen that when the tubing pressure is 20MPa and the oil jacket differential pressure is 2MPa, the closer the annulus level is to the bottom of the well, the deeper the calculated leak location is.

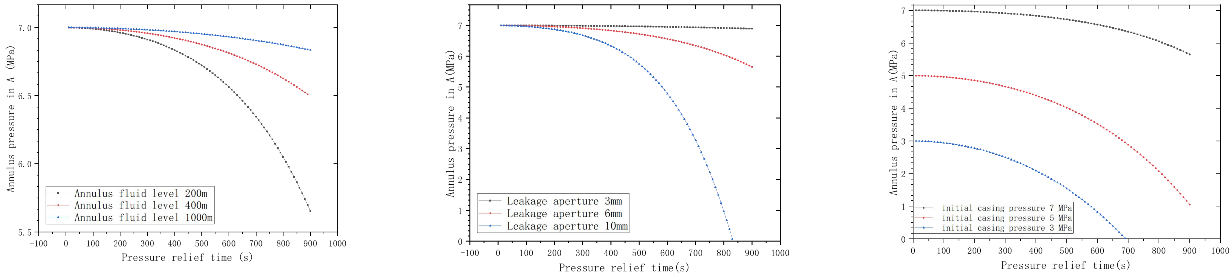


a. Annulus fluid level: 0m b. Annulus fluid level: 500m c. Annulus fluid level: 1000m

Fig. 5 Relationship between leakage location, annulus level and differential pressure of the oil jacket

4.2 The influence of leakage point size and pressure relief time on annular pressure

Figure 6 shows the relationship between different leak sizes, initial casing pressure and annulus level. From Fig. 6(a), it can be seen that when the leakage hole size is 6mm and the initial casing pressure is 7MPa, under the same pressure relief time, the closer the annulus liquid level is to the wellhead, the faster the annulus pressure decreases, which indicates that under the same annulus pressure, the higher the liquid level is, the lower the mass content of gas in the annulus, and the shorter the relief time is required. From Fig. 6(b), it can be seen that when the liquid level in the annulus is 200m and the initial casing pressure is 7MPa, the smaller the equivalent diameter of the downhole leakage point is, the less obvious the reduction of the annulus pressure is under the same relief time, which indicates that the diameter of the downhole leakage point is one of the key influencing factors of the annulus pressure relief speed. From Fig. 6(c), it can be seen that when the level of the annulus is 200m and the leakage hole diameter is 6mm, the higher the initial annulus pressure is, the less obvious the reduction of the annulus pressure is under the same relief time, which indicates that the higher the initial annulus pressure is, the more the gas mass content in the annulus is, and the longer the relief time is required.



a. Leakage aperture: 6 mm, initial casing pressure: 7 MPa

b. Annulus fluid level: 200 m, initial casing pressure: 7 MPa

c. Annulus fluid level: 200 m, leakage aperture: 6 mm

Fig. 6 Relationship between leakage size, initial jacket pressure and annulus level

5. Summary

Based on the pressure equilibrium model of tubing and A annulus and the mass conservation model of the pressure relief process established in this paper, and based on the basic data of a well in an oil field, the relationship between the influence of different oil jacket differential pressures, annulus level, leakage hole location, equivalent diameter of leakage holes, and time of pressure relief on the pressure of A annulus is obtained, and a method of evaluating the degree of leakage of the annulus of the oil jacket is formed, and it is found that in parametric studies:

(1) The method established in this paper can be used to make preliminary downhole leakage location prediction for a well in an oil field, and it can realize surface diagnosis based on the downhole pressure equilibrium state;

(2) The closer the height of the static liquid level in the annulus is to the wellhead, the oil jacket pressure difference has little effect on the leakage location prediction results in the model calculations, and when the static liquid level in the annulus is closer to the bottom of the well, the closer the leakage location is to the bottom of the well under the pressure equilibrium state as the oil jacket pressure difference increases.

(3) In the process of pressure relief in the annulus, the closer the liquid level in the annulus is to the wellhead, the shorter the pressure relief time is, which indicates that the gas mass content in the annulus is the key influencing factor of pressure relief time.

(4) The larger the initial pressure in the annulus, the smaller the downhole leak equivalent aperture is, and the longer the pressure relief time is required.

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