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RESEARCH PAPER

Impact of wellbore fluid properties on trapped annular pressure in deepwater wells

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Abstract: To reduce the threat of trapped annular pressure on deepwater wells safe production, this study established a model of calculating trapped annular pressure, examined the influence of wellbore fluid properties on trapped annular pressure, and analyzed the sensitivities and engineering feasibilities of controllable factors. To realize the calculation of trapped annular pressure under multiple annuli with liquid, a volume balance equation set was built according to compatibility principle and a wellbore temperature computing model was built based on wellbore-formation coupled heat transfer. Annular pressure decreases as the expansion-compression ratio of annular fluid reduces. Decreasing annular saturation can eliminate annular pressure radically and then a formula was proposed to give extreme annular saturation. The increase of production fluid specific heat capacity and flow rate leads to enhancement of annular pressure. Annular pressure keeps a linear relation to production fluid hole bottom temperature and the wellhead temperature can reflect the value of annular pressure. The water ratio increase of production fluid causes dynamic increase of annular pressure. The sensitivity of annular saturation is much higher than other factors. Decreasing annular liquid thermal conductivity has relatively higher engineering feasibility. The annular pressure can be controlled effectively by developing subsea wellheads with the ability to release annular fluid, highly compressible materials and downhole thermal-insulated fluids.

Key words: deepwater wells; annular pressure; fluid properties; annular fluid; extreme annular saturation

Introduction

Abnormal annular pressure of deepwater wells can be divided into trapped annular pressure and[1] and sustained casing pressure[2]. Trapped annular pressure is caused by fluid thermal expansion (also named annular pressure build-up, shortened as APB), while gas channeling brings about sustained casing pressure (SCP). Multiple annuli containing liquid usually forms in deepwater wells because of limited cement technology[3] and uncertain formation information[4]. With drilling or completion fluid trapped in, these annuli would have annular pressure build-up after production. Wells in deep waters of Mexico Gulf, Brazil, West Africa and South China Sea[5–7] all have this problem to various extent. Different from land wells and offshore platform wells, the subsea wellhead of deepwater wells can't release annular pressure. A deepwater well in BP Marlin Oilfield was abandoned due to collapse of production casing, and trapped annular pressure is one of the main reasons[8]. The casing of Well Pompano A-31 in Mexico Gulf was deformed by trapped annular pressure, causing drilling pipe sticking[9]. In addition, pressure change in wellbore could break well sealing integrity, inducing sustained casing pressure[10].

Currently the research of APB in deepwater wells concentrates on pressure monitoring[11–12] and calculation optimization[13–15]. Some experiments of preventive measures[9, 16–17] and application analysis[18–19] have also been conducted. Hot formation fluid is the heat source led to wellbore temperature variation, and annular liquid is the pressure carrier, therefore, it is of great significance to study the impact of wellbore fluid properties on trapped annular pressure. In this study, a volume balance matrix based on volume consistency and interaction among multiple annuli and a model to calculate wellbore temperature based on wellbore-formation coupled heat transfer process have been established, the ratio of variable coefficient is advanced to evaluate the impact pattern of wellbore fluid properties, the sensitivity of controllable factors and engineering feasibility.

1. Calculation model of trapped annular pressure in deepwater wells

1.1. Trapped annular pressure in multiple annuli with liquid

Multiple annuli filled with remaining drilling or completion liquid would form in deepwater wells after cementing (Fig. 1). After this kind of well is put into production, the annulus cannot accommodate annular liquid any more because liquid

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expands due to temperature increase, and annulus pressure would rise to compress the liquid in it. According to volume consistency, the volume of liquid and annulus keep equality under the same temperature and pressure. Therefore a volume balance equation set can be established as equation (1):

$$\begin{cases}\left(k_{\mathrm{T}}\Delta p_{\mathrm{an1}}-\alpha_1\Delta T_1\right)V_{\mathrm{f1}}=\Delta V_{\mathrm{an1}}\left(T,p\right)\\ \left(k_{\mathrm{T}}\Delta p_{\mathrm{an2}}-\alpha_2\Delta T_2\right)V_{\mathrm{f2}}=\Delta V_{\mathrm{an2}}\left(T,p\right)\\ \vdots \\ \left(k_{\mathrm{T}}\Delta p_{\mathrm{an}i}-\alpha_i\Delta T_i\right)V_{\mathrm{f}i}=\Delta V_{\mathrm{an}i}\left(T,p\right)\end{cases} \tag{1}$$

Solving equation (1) can get the pressure of each annulus. The annulus volume change is a function of pressure and temperature. Considering interaction of annuli, the radial change of annulus caused by temperature and pressure can be described as the following[20]:

$$\Delta r_{\mathrm{t}}=\frac{\alpha_{\mathrm{s}}(1+\mu)}{r(1-\mu)}\int_a^r\Delta T_{\mathrm{d}}r\mathrm{d}r+\frac{\alpha_{\mathrm{s}}r(1+\mu)(1-2\mu)}{2(1-\mu)}\Delta T_{\mathrm{d}}+\frac{\alpha_{\mathrm{s}}a^2(1+\mu)}{2r(1-\mu)}\Delta T_{\mathrm{d}} \tag{2}$$

$$\Delta r_{\mathrm{p}}=\frac{1}{E\left(b^2-a^2\right)}\left[r(1-\mu)\left(a^2p_{\mathrm{i}}-b^2p_{\mathrm{o}}\right)-\frac{a^2b^2}{r}(1+\mu)\left(p_{\mathrm{i}}-p_{\mathrm{o}}\right)\right] \tag{3}$$

So the annulus volume change is:

$$\Delta V_{\mathrm{an}}=\pi\int_{Z_{\mathrm{i}}}^{Z_{\mathrm{o}}}\left(r_{\mathrm{o}}+\Delta r_{\mathrm{to}}+\Delta r_{\mathrm{po}}\right)^2-\left(r_{\mathrm{i}}+\Delta r_{\mathrm{ti}}+\Delta r_{\mathrm{pi}}\right)^2\mathrm{d}z-V_{\mathrm{an}} \tag{4}$$

1.2. Temperature change of annulus after production

Semi-steady approach and transient approach are two basic approaches to calculate wellbore temperature. Featuring simple computation and high accuracy[20], semi-steady approach has been widely applied in paraffin control[1, 21], gas flooding[22] and super-critical carbon dioxide[23]. Based on semi-steady approach, the energy of micro-unit as shown in Fig. 1 conforms to energy conservation law:

$$-W_{\mathrm{f}}C_{\mathrm{f}}\mathrm{d}T_{\mathrm{f}}+\left(\Phi_{\mathrm{ki}}-\Phi_{\mathrm{ko}}\right)+\left(p_{\mathrm{zi}}-p_{\mathrm{zo}}\right)\frac{W_{\mathrm{f}}}{\rho_{\mathrm{f}}}+W_{\mathrm{f}}g\mathrm{d}z\cos\theta-\Phi_{\mathrm{r}}=0 \tag{5}$$

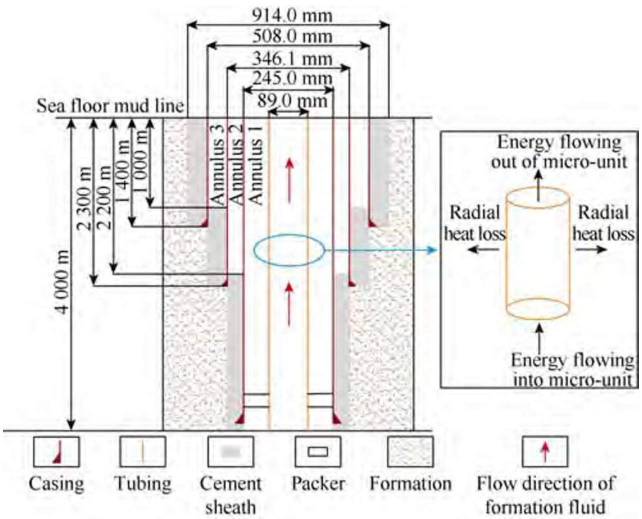

Fig. 1. Sketch map of deepwater wells.

The pressure drop in equation (5) comprises gravitational and frictional drop:

$$p_{\mathrm{zi}}-p_{\mathrm{zo}}=-\rho_{\mathrm{f}}g\cos\theta\mathrm{d}z+\frac{2f\rho_{\mathrm{f}}v_{\mathrm{f}}^2}{d_{\mathrm{to}}}\mathrm{d}z \tag{6}$$

f in equation (6) is dimensionless hydraulic friction coefficient[24]:

$$f^{-0.5}=-2\lg\left\{\frac{R_{\mathrm{a}}/d_{\mathrm{to}}}{3.706\,5}-\frac{5.045\,2}{Re}\lg\left[\frac{\left(R_{\mathrm{a}}/d_{\mathrm{to}}\right)^{1.109\,8}}{2.825\,7}+\frac{5.850\,6}{Re^{0.898\,1}}\right]\right\} \tag{7}$$

The heat transfer between wellbore and formation complies with radial heat conservation law, so radial heat loss is:

$$\Phi_{\mathrm{r}}=\frac{2\pi\lambda_{\mathrm{e}}\left(T_{\mathrm{f}}-T_{\mathrm{e}}\right)}{T_{\mathrm{D}}+2\pi\lambda_{\mathrm{e}}R_{\mathrm{to}}}\mathrm{d}z \tag{8}$$

Dimensionless formation temperature T_{D} in equation (8) can be computed by Ramey equation, Butlere equation, Chiu equation and Hasan equation. Previous studies show[25] Hasan equation has higher accuracy in the whole production period, and this equation also works well in wellbore temperature calculation[26] and trapped annular pressure analysis[27]. Therefore, Hasan equation was adopted to calculate dimensionless formation temperature T_{D} in this study:

$$T_D=\begin{cases}1.1281\sqrt{t_D}\left(1-0.3\sqrt{t_D}\right) & t_D\le 1.5\\ \left(0.4063+0.5\ln t_D\right)\left(1+0.6/t_D\right) & t_D>1.5\end{cases} \tag{9}$$

Combine equations (5), (6) and (8) to calculate annular temperature:

$$T_{\mathrm{an}}=\frac{T_{\mathrm{f}}\left(1+T_{\mathrm{D}}\right)+2\pi\lambda_{\mathrm{e}}T_{\mathrm{e}}\left(R_{\mathrm{to}}-R_{\mathrm{an}}\right)}{T_{\mathrm{D}}+2\pi\lambda_{\mathrm{e}}R_{\mathrm{to}}} \tag{10}$$

where

$$T_{\mathrm{f}}=T_0+g_{\mathrm{f}}\left(A+h-z\right)+A\frac{fv_{\mathrm{f}}^2}{r_{\mathrm{to}}C_{\mathrm{f}}}+C\mathrm{e}^{-\frac{z}{A}}$$

$$A=\frac{W_{\mathrm{f}}C_{\mathrm{f}}\left(T_{\mathrm{D}}+2\pi\lambda_{\mathrm{e}}R_{\mathrm{to}}\right)}{2\pi\lambda_{\mathrm{e}}}$$

Then the average temperature change of annulus is:

$$\Delta T=\frac{\int_{z_{\mathrm{i}}}^{z_{\mathrm{o}}}T_{\mathrm{an}}\mathrm{d}z}{z_{\mathrm{o}}-z_{\mathrm{i}}}-T_{\mathrm{an0}} \tag{11}$$

2. Impact of annular liquid

A deepwater well located in West Africa produces a mixture of oil and water. Its structure is given in Fig. 1 and related parameters are listed in Table 1. The pressure in Annulus A can be released during test and production, so pressure in Annulus B is chosen to analyze the impact of wellbore fluid on trapped annular pressure.

2.1. Annular liquid isobaric expansion coefficient and isothermal compressibility

Fig. 2 shows that annular pressure decreases with the fall of isobaric expansion coefficient and the rise isothermal compressibility. Ratio of expansion and compressibility is defined as: