Well test analysis method for CO₂ content gas reservoirs of Ying-Qiong Basin

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Abstract: Mid-deep formations of Ying-Qiong Basin are characterized as deep, tight, high-temperature, and overpressure, the fluids in which generally contain CO₂, so high-pressure physical property parameters of natural gas and stress sensitivity of low permeability reservoir should be considered in the well testing method. Thus, based on the Standing-Katz chart, the high-pressure natural gas physical property parameter calculation method is optimized that are suitable for reservoirs containing CO₂, and taking the influence of pressure on seepage into account, a well testing analysis model considering stress sensitivity is established. Results show that when CO₂ content is lower than 5%, the most properly high-pressure natural gas physical property parameter calculation method is LXF method, when CO₂ content is higher than 5%, the most properly method is BB method. During radial flow period, the pressure derivative curves of drawdown test goes upwards gradually with the duration of production, and the greater is the stress sensitivity factor, the shorter is the distance between the pressure curves and the pressure derivative curves. While as for buildup test, the pressure derivative curves goes downwards gradually with duration of shut-in, and the greater is the stress sensitivity factor, the greater is the distance between the pressure curves and the pressure derivative curves.

Key words: Ying-Qiong Basin; Natural gas; CO₂; Well testing; Stress sensitivity.

1. Introduction
Median-deep reservoir in Ying-Qiong Basin is typical ultrahigh temperature and pressure reservoir in offshore areas of China, with pressure coefficient generally above 1.8 and temperature of about 200℃, being the significant field and new increase mode of reserves for gas exploration in western South China Sea [1]. For reservoirs with abnormal high pressure and low permeability, with decreasing formation pore pressure during recovery process, the stress condition of reservoir medium will be changed obviously, causing rocks remarkable elastic deformation and plastic rupture in, and physical parameters (such as porosity and permeability) in immediate vicinity of wellbore decreased quickly, namely stress sensitivity effect[2-10], which will seriously affect development and production of gasfield and should be figured out if there is this type reservoir during prospecting well operation. Besides, the fluid components of high temperature and pressure gas reservoir in Ying-Qiong Basin generally contain CO₂, so the conventional calculation method for PVT parameters is not applicable in
high temperature and pressure settings [11-12], which will seriously affect pretesting deliverability estimation, post welltesting interpretation and reservoir assessment. Aiming at these problems above, calculation method of gas deviation factor for high temperature and pressure gas reservoir containing CO\textsubscript{2} has been optimized based on laboratory results, establishing welltesting interpretation method with stress-sensitive effect considered. This new method has been applied and gotten good results, providing theoretical foundation for accurately assessing the median-deep reservoir in Ying-Qiong Basin.

2. Calculation of gas deviation factor for high temperature and pressure gas reservoir with high CO\textsubscript{2} content

High-temperature physical parameters of gas reservoirs can be obtained by experimental determination, chart method and analytical model method. Experimental determination is characterized by long experiment period, high cost and inconvenience of quick result gains; chart method is difficult for computer application and not very practical; analytical model method is applicable to programming calculation, mainly including HY, DAK, DPR, LXF and BB method, but whether each method is applicable under high temperature and pressure condition needs to be further analyzed. Therefore, based on the Standing-Katz plate, analysis of each method is carried out under different pseudoreduced pressure and its error to obtain application condition for different methods (Table1). If CO\textsubscript{2} content of high temperature and pressure gas less than 5%, LXF method is recommended to evaluate deviation factor; if that more than 5%, BB method is recommended. For gas reservoir without hydrocarbons, it should be calibrated by Wichert-Aziz, Car-Kobayshi-Burrows or Guoxuqiang method.

| PVT model | Recommended application range in literatures | Recommended application conditions |
|-----------|---------------------------------------------|-----------------------------------|
| LXF method | 1.05<T\textsubscript{pr}≤3.0, 0.2<P\textsubscript{pr}≤30 (calculation by partitioned segmentation) | With low overall error When T\textsubscript{pr}>1.05, obvious step at partition |
| DAK method | 1.0<T\textsubscript{pr}≤3.0, 0.2<P\textsubscript{pr}≤30 | When T\textsubscript{pr}=1.05, accuracy decreases When T\textsubscript{pr}>1.05, error higher than that of LXF method |
| DPR method | 1.05<T\textsubscript{pr}≤3.0, 0.2<P\textsubscript{pr}≤3 | 0.2<P\textsubscript{pr}≤30, little accuracy difference from DAK method |
| HY method | 1.2<T\textsubscript{pr}≤3.0, 0.1<P\textsubscript{pr}≤24.0 | With higher accuracy when 2.4>T\textsubscript{pr}>1.2 |
| BB method | 1.05<T\textsubscript{pr}≤2.4, 1<P\textsubscript{pr}≤15 | Rich in CO\textsubscript{2} |

3. Test model of gas wells with stress sensitivity considered

3.1. Assumptions

Assumptions are: 1) one straight well in the center of homogeneous gas reservoir with circular boundary, under production of constant rate; 2) reservoirs with horizontal isopachous thickness, isotropy, overlying and underlying favorable interlayers, and homogeneous distribution of formation pressure under primary condition; 3) reservoir rock slightly compressible, with constant compressibility coefficient; 4) formation permeability changing with effective stress; 5) fluid in formation as isothermal flow; 6) taking wellbore storage effect and skin factor into account; 7) no gravity and capillary force.
3.2. Establishment of mathematical model of seepage flow

Exponential function of permeability changing with stress:

\[ k = k_0 e^{-\gamma (\psi, \psi)} \]  

(1)

Combined with motion equation, state equation and formula (1), mathematical governing equation of radial seepage flow is established for stress-sensitive reservoir:

\[ \frac{1}{r} \frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial r^2} + \gamma^* \left( \frac{\partial \psi}{\partial r} \right)^2 = \frac{\phi \mu C(p)}{k_i} e^{\gamma^* (\psi, \psi)} \frac{\partial \psi}{\partial t} \]  

(2)

In the formula: \( \gamma^* = \frac{\partial \psi}{\partial p} = \gamma \frac{\mu Z}{2p} \).

Primary condition:

\[ \psi \left( r, 0 \right) = \psi_i \]  

(3)

The inner boundary condition of wellbore storage effect and skin factors is:

\[ r e^{-\gamma^* (\psi, \psi)} \frac{\partial \psi}{\partial r} \bigg|_{r = r_{we}} = \frac{q_s p_s T}{\pi k_i h T_{sc} Z_{sc}} + C \frac{\mu}{2\pi k_i h} \frac{\partial \psi_w}{\partial t} \]  

(4)

In the formula: \( r_{we} = r_w e^{-s} \) is effective radius.

Boundary conditions:

For infinitely large formation,

\[ \lim_{r \to \infty} \psi \left( r, t \right) = \psi_i \]  

(5)

For formations with circular constant pressure outer boundary,

\[ \psi \left( r, t \right) \bigg|_{r = R_e} = \psi_i \]  

(6)

For formations with circular closed outer boundary,

\[ \frac{\partial \psi}{\partial r} \bigg|_{r = R_e} = 0 \]  

(7)

In the formula: \( R_e \) is the outer boundary radius of gas reservoir.

Formula (2) \( \sim \) (7) constitute welltesting mathematical model of stress-sensitive gas reservoir.

3.3. Model resolution

By normalizing welltesting mathematical model of deformed media homogeneous gas reservoir, dimensionless welltesting model of deformed media gas reservoir is established (Table2):
\[
\begin{align*}
&\frac{1}{r_D} \frac{\partial \psi_D}{\partial r_D} + \frac{\partial^2 \psi_D}{\partial r_D^2} - \gamma_D \left( \frac{\partial \psi_D}{\partial r_D} \right)^2 = e^{-S} \frac{\partial \psi_D}{\partial t_D} \\
&\left. \psi_D \left( r_D, t_D \right) \right|_{r_D=0} = 0 \\
&\left. r_D e^{-\gamma_D \phi_D} \frac{\partial \psi_D}{\partial r_D} \right|_{r_D \to \infty} = -1 + C_D \left( \frac{\partial \psi_{wd}}{\partial t_D} \right) \\
&\lim_{r_D \to \infty} \left. \psi_D \left( r_D, t_D \right) \right|_{r_D=0} = \text{Infinitely large formation} \\
&\left. \frac{\partial \psi_D}{\partial r_D} \right|_{r_D=R_D} = \text{Bounded constant pressure} \\
&\left. \frac{\partial \psi_D}{\partial r_D} \right|_{r_D=R_D} = \text{Bounded confinement}
\end{align*}
\]

(8)

**Table 2. Definition of dimensionless variable**

| Name                              | Expression                                                                 | Name                              | Expression                                                                 |
|-----------------------------------|---------------------------------------------------------------------------|-----------------------------------|---------------------------------------------------------------------------|
| Dimensionless formation pressure  | \( \psi_D = \frac{\pi k_w h T_w}{q_w P_t} (\psi_i - \psi) \)             | Dimensionless bottomhole pressure | \( \psi_{wd} = \frac{\pi k_w h T_w}{q_w P_t} (\psi_i - \psi_w) \)          |
| Dimensionless time                | \( t_D = \frac{k_0}{\mu C_i C_r} t \)                                   | Dimensionless radius              | \( r_D = \frac{r}{r_w} = r_w e^{-s}, R_D = \frac{R_s}{r_w} \)              |
| Dimensionless stress-sensitive coefficient | \( \gamma_D^* = \frac{\gamma \mu Z_i q_w P_t}{2 p_i \pi k_w h T_w} \) | Dimensionless wellbore storage coefficient | \( C_D = \frac{C}{2 \pi h_0 C_i C_r} \)                                      |

Setting \( \psi_D = -\frac{1}{\gamma_D^*} \ln \left[ 1 - \gamma_D^* \xi_D \left( r_D, t_D \right) \right] \), which is substituted into into the equation system (8):

\[
\begin{align*}
&\frac{1}{r_D} \frac{\partial \xi_D}{\partial r_D} + \frac{\partial^2 \xi_D}{\partial r_D^2} = \frac{e^{-S}}{1 - \gamma_D^* \xi_D} \frac{\partial \xi_D}{\partial t_D} \\
&\left. \frac{\partial \xi_D}{\partial r_D} \right|_{r_D=0} = 0 \\
&\lim_{r_D \to \infty} \left. \xi_D \left( r_D, t_D \right) \right|_{r_D=0} = 0 \quad \text{Infinitely large formation} \\
&\left. \frac{\partial \xi_D}{\partial r_D} \right|_{r_D=R_D} = 0 \quad \text{Bounded constant pressure} \\
&\left. \frac{\partial \xi_D}{\partial r_D} \right|_{r_D=R_D} = 0 \quad \text{Bounded confinement}
\end{align*}
\]

(9)

Equation system (9) is transformed by perturbation method as follows:
Due to minor order of magnitude of Dimensionless stress-sensitive coefficient, zeroth order perturbation solution is adopted to carry out Laplace transformation:

\[ \xi_D = \xi_{D0} + \gamma_D \xi_{D1} + (\gamma_D)^2 \xi_{D2} + \ldots \quad (10) \]

\[-\frac{1}{\gamma_D^*} \ln \left[ 1 + \gamma_D^* \xi_D \right] = \xi_D + \frac{1}{2} (\gamma_D)^2 \xi_D^2 + \ldots \quad (11)\]

\[ \frac{1}{1 - \gamma_D^* \xi_D} = 1 + \gamma_D^* \xi_D + (\gamma_D^* \xi_D)^2 + \ldots \quad (12) \]

For formula (13) various solutions under different boundary conditions are as follows: Solution for infinitely large formation,

\[ \xi_D = \frac{K_0 \left( \sqrt{u} \right) + S \sqrt{u} K_1 \left( \sqrt{u} \right)}{u \left( \sqrt{u} K_1 \left( \sqrt{u} \right) + C_2 u \left[ K_0 \left( \sqrt{u} \right) + S \sqrt{u} K_1 \left( \sqrt{u} \right) \right] \right)} \quad (14) \]

Solution for circular constant pressure outer boundary,

\[ \xi_D = \frac{1 + S \cdot f(u)}{u f(u) + C_2 u \left[ 1 + S \cdot f(u) \right]} \quad (15) \]

In the formula: \( f(u) = \frac{K_1 \left( \sqrt{u} \right) I_0 \left( \sqrt{u} R_2 \right) + K_0 \left( \sqrt{u} R_0 \right) I_1 \left( \sqrt{u} \right)}{K_0 \left( \sqrt{u} \right) I_0 \left( \sqrt{u} R_0 \right) - K_0 \left( \sqrt{u} R_0 \right) I_0 \left( \sqrt{u} \right) \left( \sqrt{u} \right)} \).

Solution for circular closed outer boundary,

\[ \xi_D = \frac{1 + S \cdot f(u)}{u f(u) + C_2 u \left[ 1 + S \cdot f(u) \right]} \quad (16) \]
In the formula:  
\[ f(u) = \frac{K_i\left(\sqrt{u}\right)I_1\left(\sqrt{u}R_d\right) - K_i\left(\sqrt{u}R_D\right)I_1\left(\sqrt{u}\right)}{K_0\left(\sqrt{u}\right)I_1\left(\sqrt{u}R_D\right) + K_i\left(\sqrt{u}R_D\right)I_0\left(\sqrt{u}\right)} \].

Formula (14), (15) and (16) are processed as follows, to obtain solution of gas reservoir with circular outer boundary:

\[ \psi_D = -\frac{1}{\gamma_D^*} \ln \left[ 1 - \gamma_D^* \frac{r_D}{r_D} (t_D, t_D) \right] \]  
(17)

3.4. Characteristics of typical curves

According to the established welltesting theoretical model of stress-sensitive reservoirs, reservoir pressure buildup curve is calculated for deformed reservoir media under condition of infinitely large outer boundary (Fig.1). It shows difference from conventional reservoir: 1) with increasing stress-sensitive coefficient, both stress-sensitive reservoir pressure and derivative curves are upward deviated; 2) with increasing stress-sensitive coefficient, the peak value in transition section increase gradually and appears later; 3) pressure derivative curve during radial flow period is slightly more than 0.5 and falls to 0.5 gradually over time.

![Fig.1 well test curve of pressure buildup in straight well with infinite boundary within homogeneous gas reservoir with stress sensitivity considered](image)

The pressure buildup and drawdown curves in conventional reservoir will overlap under production time long enough, but for stress-sensitive gas reservoir the curves will not overlap and the longer the production time, the more significant the difference, with pressure buildup curve always above pressure drawdown curve. It indicates that during production stress sensitivity resulted in damage on permeability, and the extent and extent of the damage would increase with production time, causing gradually remarkable difference between pressure buildup and drawdown curves, which is consistent with the experimental results. If welltesting model of conventional reservoir is adopted to interpret the data of deformed media gas reservoir, the interpretation results of pressure drawdown will be different from those of pressure buildup.
4. Practical applications

DST and coring in testing intervals have been carried out for exploratory well A in Ying-Qiong basin, and the analysis of stress sensitivity in Table 3 shows that stress-sensitive coefficient is 0.0013–0.0022, with average value of 0.0019. Calculation results of established model shows that the stress-sensitive coefficient is 0.0049, which is basically the same with experimental results.

Table 3. Experimental results of stress sensitivity in Well A

| Core No. | Cored intervals (m) | Experimental Modes | Damage rate (%) | Stress-sensitive coefficient (formation pressure drop is 0) (MPa$^{-1}$) | Stress-sensitive coefficient (formation pressure drop falls to its half) (MPa$^{-1}$) |
|----------|---------------------|--------------------|----------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| C2       | 2862.92-2863.92     | Variable confining pressure | 9.6            | 0.0018                                                                          | 0.0021                                                                          |
| C3       | 2862.92-2863.92     | Variable hole pressure  | 9.0            | 0.0017                                                                          | 0.0022                                                                          |
| C4       | 2862.92-2863.92     | Analog overpressure    | 7.2            | 0.0014                                                                          | 0.0017                                                                          |
| C5       | 2862.92-2863.92     | Ultrahigh temperature and pressure | 7.8        | 0.0013                                                                          | 0.0017                                                                          |
| D3       | 2860.90-2861.94     | Variable confining pressure of bound water | 9.4           | 0.0018                                                                          | 0.0017                                                                          |
| D4       | 2860.90-2861.94     | Variable confining pressure | 7.6            | 0.0014                                                                          | 0.0017                                                                          |
|          | Average value       |                     |                | 0.0016                                                                          | 0.0019                                                                          |
Fig. 3 log-log overlay plot (a) and semi-log overlay plot (b) of DST well test interpretation in Well A

Table 4. Fitting results of DST welltest interpretation in Well A

| C (m³/MPa) | Cᵢ/Cᵢ | Δt (h) | Skin factor | K (10⁻³μm²) | Stress sensitivity coefficient (1/MPa) |
|------------|--------|--------|-------------|--------------|--------------------------------------|
| 0.022      | 999    | 0.00348| 4           | 0.69         | 0.0049                               |

Fig. 4 shows that the model is of good imitative effect and high accuracy, and the stress-sensitive coefficient is close to experimental results, indicating that the well testing method established in this paper could evaluate reservoirs more accurately.

5. Conclusion

(1) Calculation method of gas deviation factor, which is applicable to high temperature and pressure gas reservoir, is optimized by Standing-Katz plate. If CO₂ content of high temperature and pressure gas less than 5%, LXF method is recommended to evaluate deviation factor; if that more than 5%, BB method is recommended.

(2) For drawdown testing, the pressure derivative curve during radial flow period will rise, deviating from level 0.5, and formation capacity will decrease gradually when well-opening production.

(3) For buildup testing, the pressure derivative curve during radial flow period will migrate downward after subjected to stress sensitivity, tending to level 0.5, and formation capacity will recovery gradually when shut-in pressure buildup.

References

[1] Wang Zhenfeng, Pei Jianxiang, Hao Defeng, et al. Development conditions, sedimentary characteristics of Miocene large gravity flow reservoirs and the favorable gas exploration directions in Ying-Qiong basin [J]. China Offshore Oil and Gas, 2015, 27(4): 13-21.

[2] Fatt I, Davis D H. Reduction in permeability with overburden pressure [J]. Journal of Petroleum Technology, 1952, 4(12): 16-16.

[3] Hao Chunshan, Li Zhiping, Yang Manping et al. Research on deformation mechanism and petrophyiscalcharacteristics of deformable media [J]. Journal of Southwest Petroleum University (Science & Technology Edition), 2003, 25(4): 19-21.

[4] Luo Ruilan. A study of deformation and percolation mechanism of deep gas reservoir and its application [D]. China University of Petroleum (Beijing), 2006.

[5] Fan Xueping, Xu Xiangrong. Experimental and mechanism research about permeability damage with the change of stress [J]. Petroleum Exploration and Development, 2002, 29(2): 117-119.

[6] Liu Jianjun, Liu Xiangui. The effect of effective pressure on porosity and permeability of low
permeability porous media [J]. Journal of Geomechanics, 2001, 7(1): 41-44.

[7] Xiang Yang, Xiang Dan, Du Wenbo. An experimental study of simulating high-speed production in tightsandstone gas reservoir [J]. Journal of Chengdu University of Technology (Science & Technology Edition), 2002, 29(6): 617-620.

[8] Raghavan R, Scorer J D, Miller F G. An Investigation by Numerical Methods of the Effect of Pressure-Dependent Rock and Fluid Properties on Well Flow Tests [J]. SPE Journal, 1972, 12(3): 267-275.

[9] Samaniego V F, Brigham W E, Miller F G. An Investigation of Transient Flow of Reservoir Fluids Considering Pressure-Dependent Rock and Fluid Properties [J]. SPE Journal, 1977, 17(2): 141-150.

[10] Rosalind Archer. Impact of Stress Sensitive Permeability on Production Data Analysis [C]. SPE Unconventional Reservoirs Conference.10-12 February 2008, Keystone, Colorado, USA.

[11] Wang Gang, Yang Shenglai, Wu Xiaoyun, et al. Study on deviation factor of CO2 rich gas [J]. Oil Drilling & Production Technology, 2010, 32(1): 53-56.

[12] Hu Yue, Du Jianfen, Guo Ping, et al. Experimental study on deviation factor of CO2 rich gas [J]. Journal of Yangtze University (Natural Science Edition), 2009, 6(2): 192-194.