Reservoir energy response mechanism during shale gas accumulation in Longmaxi Formation

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Abstract. In order to explore the microscopic energy response mechanism of the shale gas accumulation process in the Longmaxi Formation, the energy balance theory is taken as the core. Based on the tectonic evolution and hydrocarbon generation history simulation, the elastic energy and gas elasticity of the Longmaxi Formation shale reservoir block are discussed. Can wait for energy response characteristics. It is meaningful to quantify the energy changes in the development of shale gas reservoirs. The results show that the accumulation of shale gas is controlled by the evolution of different energy systems in the geological history process. The accumulation of shale gas is controlled by the changing process of different energy systems in the geological history process; the dynamic balance of energy system changes the shale gas accumulation effect. The shale gas from the sedimentary-diagenetic-hydrocarbon generation stage, the gas reservoir energy mainly shows three major evolution stages.

Keywords: Longmaxi Formation, energy, shale gas, reservoir-forming coupling.

1. Introduction

Energy balance theory believes that energy will neither be produced nor disappeared, it can only be transformed from one form to another, or transferred from one object to another, and its total amount during the process of transformation or transfer constant. The accumulation of unconventional gas is maintained by the energy balance system, the core of which is the efficient energy transfer and its geological selection process. Wu Caifang et al. and Qin Yongjing proposed the concept and scientific issues of energy dynamic balance during coalbed methane accumulation, and believed that this balance is the essential feature of the gas reservoir and is controlled by the complex geological selection process of its formation and evolution. The core is energy Effective transmission and geological selection process, and shale gas accumulation is also maintained in the energy balance system [1-3].

In the process of oil and gas accumulation, there are similarities between coalbed methane accumulation and shale gas accumulation in the mechanisms of organic matter hydrocarbon generation, reservoir transformation, and gas reservoir preservation. In this paper, through the geological survey and rock physical property experiments of the Longmaxi Formation in the southern Sichuan area, the elastic
energy calculation Eq. of the three-phase material of the reservoir [3] is used to quantitatively study the evolution process of the elastic energy of the three-phase solid, liquid and gas in the shale reservoir. Combined with the history of sedimentary evolution, the energy response mechanism during shale gas accumulation of Longmaxi Formation was studied from multiple angles, which provided theoretical support for quantitatively elucidating the characteristics of reservoir energy changes after the temperature and pressure conditions changed during shale gas development.

2. Shale gas accumulation factors and Relationship

The formation of shale gas is controlled by the evolution of different energy systems during the geological history (Figure 1). Under the action of three macro-kinetic factors including tectonic dynamic energy, thermodynamic energy and groundwater dynamic energy, the elastic energy of the three-phase material of solid, liquid and gas in the shale reservoir keeps changing. Specifically, the consumption of reservoir elastic energy reflects the destruction process of shale gas reservoirs, while the accumulation of reservoir elastic energy reflects the formation process of shale gas reservoirs. This dynamic balance change feature of the energy system balances the shale gas accumulation effect. Therefore, the formation elastic energy is essentially the link between the shale gas accumulation dynamics and the shale gas accumulation effect, and is also the key to interpreting the shale gas accumulation process.

![Fig. 1 Shale gas accumulation factors and relationship](image)

3. Shale reservoir energy calculation model

The energy stored in the thermodynamic system is called the stored energy of the system, including the thermodynamic energy, macro kinetic energy, and macro potential energy determined by the thermal state of the system itself (Chen Wenwei et al., 1999). The specific manifestation of stored energy in shale reservoirs is formation elastic energy, referred to as shale elastic energy, which is the result of the coupling effect of various dynamic factors in geological history.

3.1. Shale layer elastic energy overall composition

The elastic energy of the shale layer includes the elastic energy of the shale base block and the gas elastic energy, and the overall relationship can be expressed as Eq. 1:

$$E = E_{\text{shale}} + E_{\text{gas}}$$  \hspace{1cm} (1)

In the Eq., $E$ is the overall elastic energy, kJ/m$^3$; $E_{\text{shale}}$ is the elastic energy of shale base block, KJ/m$^3$; $E_{\text{gas}}$ is gas elastic energy, KJ/m$^3$.

The supercritical temperature of methane, the main component of shale gas, is 293K, and the supercritical pressure is 1.68MPa. During the entire process of shale gas adsorption, desorption, diffusion, migration, and accumulation, the formation pressure field continuously consumes the potential energy of the formation water pressure field and increases the kinetic energy of the shale gas molecules. When the formation pressure potential energy in the system reaches a relative equilibrium
state, the average velocity of fluid molecules in shale also reaches a relatively stable state. Once the system conditions change, such as the change of formation pressure, formation temperature, and the increase or decrease of the material in the formation or the mutual transformation of the material phase state, the equilibrium state of the system will be broken, the formation energy output or gain input, and even between the energy states The conversion of each other, and then reach a new balance.

3.2. Mathematical model of shale elastic energy

3.2.1. Mathematical model of base block elastic energy. The elastic energy of the base block is closely related to the physical properties of the shale reservoir itself, reflecting the relationship between the mechanical properties of the shale layer and the occurrence of oil and gas. According to the principle of elastic mechanics, the volume expansion coefficient of solids is (Kuang Shenglu et al., 2003) (Eq. 2):

$$\alpha = \frac{\Delta V}{V \cdot \Delta T}$$  \hspace{1cm} (2)

In the Eq., $\alpha$ is the volumetric thermal expansion coefficient, $10^{-4}$/K; V is the original volume of the solid, m$^3$; $\Delta V$ is the volume change during the temperature change, m$^3$; $\Delta T$ is the temperature change, K.

The solid compression coefficient can be described by the following Eq. (Kuang Shenglu et al., 2003) (Eq. 3):

$$\beta = \frac{\Delta V}{V \cdot \Delta P}$$  \hspace{1cm} (3)

In the Eq., $\beta$ is the volumetric thermal expansion coefficient, $10^{-4}$/K; V is the original volume of the solid, m$^3$; $\Delta V$ is the volume change during the pressure change, m$^3$; $\Delta P$ is the pressure change, MPa.

Under the triaxial confining pressure, the shale block is in an elastic state, and its stored energy is (Xian Xuefu et al., 2001) (Eq. 4):

$$E = \frac{1}{2E} \left[ \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_1 \sigma_3) \right]$$  \hspace{1cm} (4)

In the Eq., E is the elastic modulus, MPa; $\nu$ is the Poisson's ratio of the shale rock mass, dimensionless; $\sigma_1$ is the maximum horizontal principal stress, MPa; $\sigma_2$ is the minimum horizontal principal stress, MPa; $\sigma_3$ is the vertical stress, MPa.

In the original stress state, $\sigma_1 + \sigma_2 + \sigma_3=P_0$, so the energy expression of shale can be obtained (Eq. 5):

$$E = 3P_0^2(1-2\nu)/2E$$ \hspace{1cm} (5)

3.2.2. Mathematical model of gas elastic energy. The natural gas stored in shale has the energy to work outward when the temperature and pressure change. This energy is called gas elastic energy, which is directly related to the gas content of shale gas and the temperature and pressure changes before and after expansion.

①Mathematical model of free aeroelastic performance

In the original formation state, the temperature and pressure changes belong to a changeable process. Combined with the multivariable process Eq. in the gas thermodynamic Eq., the elastic energy Eq. of free methane is obtained (Eq. 6):

$$E(\text{Free}) = \frac{\beta RT_0(1 + \alpha \Delta T)(1 - \beta \Delta P)}{k - 1} \left( 1 - \frac{P_0}{P} \right)^{\frac{k - 1}{k}}$$  \hspace{1cm} (6)

In the Eq., $\alpha$ is the thermal expansion coefficient of the gas when the temperature is from $T_0$ to $T$, $10^{-4}$/K; where, $T$ is the ambient temperature after the gas state changes, K; $\beta$ is the compression coefficient of the gas when the pressure is from $P_0$ to P, $10^{-4}$/K; R is the molar gas constant, and its value is 8.314J/(mol•K); $P_0$ is the fluid pressure before the gas state changes, MPa; P is the fluid pressure after...
the gas state changes; \( \triangle T = T - T_0 \), the amount of temperature change, K; \( \triangle P = P - P_0 \), the pressure change, MPa; \( K \) is the variable index, \( k = C_p/C_v \), where \( C_p \) is the constant pressure heat capacity of the gas, and \( C_v \) is the gas Constant volume heat capacity, for methane, \( k = 1.30 \).

If the changeable process is handled according to the ideal gas at low pressure, Eq. 7 can be derived:

\[
\frac{T_0}{T} = \left( \frac{V}{V_0} \right)^{k-1} = \left( \frac{P_0}{P} \right)^{\frac{k-1}{k}}
\]  

(7)

Where \( T_0 \) is the temperature in the original gas state, K; \( V_0 \) is the volume in the original gas state, m\(^3\); \( P_0 \) is the pressure in the original gas state, MPa; \( T \) is the temperature after the gas state changes, K; \( V \) is the gas The volume after the state change, m\(^3\); \( P \) is the pressure after the gas state changes, MPa.

Substituting Eq. 7 into Eq. 6, the expression of free aeroelastic energy is obtained as shown in Eq. 8:

\[
E(Free) = \frac{\beta R T_0 (1 + \alpha \Delta T)(1 - \beta \Delta P)}{k-1} \frac{P}{P_0} \frac{\Delta T}{T}
\]  

(8)

Adsonption aeroelasticity mathematical model

For the convenience of calculation, the simplified Eq. 9 derived from Zhou Shining and Lin Baiquan (1999) was used to calculate the adsorption gas content of the shale layer.

\[
V(Adsorption) = \alpha \sqrt{P}
\]  

(9)

In the Eq., \( P \) is the fluid pressure of the shale reservoir; \( \alpha \) is the gas content coefficient, and its value is \( 3.16 \times 10^{-3} \) m\(^3\)/(t\cdot Pa\(^{0.5}\)).

When there is a slight change (decrease) in the reservoir fluid pressure, the calculated expression of the desorbed gas volume is Eq. 10:

\[
dV = \frac{\alpha}{2\nu \sqrt{P}} dP
\]  

(10)

In the Eq., \( \nu \) is the molar volume of methane in the standard state, \( 22.4 \times 10^{-3} \) m\(^3\)/mol.

According to the variable process, the elastic energy per mole of desorbed gas can be expressed by Eq. 8. Therefore, the methane desorbed by the pressure reduction has an elastic energy of Eq. 11:

\[
dE = E(Free) \frac{\alpha}{2\nu} dP
\]  

(11)

Therefore, the integral can get the expression of adsorption aeroelastic energy as Eq. 12:

\[
E(Adsorption) = \int_{P_0}^{P} E \frac{\alpha}{2\nu \sqrt{P}} dP = E \frac{\alpha}{\nu} \left( \sqrt{P_0} - \sqrt{P} \right)
\]  

(12)

Therefore, when the temperature and pressure change, the gas elastic energy of the shale reservoir can be expressed as Eq. 13:

\[
E(Total) = E(Free) + E(Adsorption) = E \left[ 1 + \frac{\alpha}{\nu} \left( \sqrt{P_0} - \sqrt{P} \right) \right]
\]  

(13)

4. Reservoir energy variation characteristics of Longmaxi Formation

Shale gas is a tight rock layer with low permeability and low porosity. Hydrocarbons generated during the geological history rely on free gas bound in the pores to form high elastic energy and the adsorption capacity of shale reservoirs. The complex heterogeneity of the reservoir makes the shale gas accumulation control mechanism distinct from conventional natural gas reservoirs, and the multi-phase geological process experienced by the Sichuan Basin makes the formation energy system extremely complicated [3-5]. Among them, the experiment used the Longmaxi outcrop samples exposed in Changning County, Sichuan Province to conduct research. The key mechanical parameters such as elastic modulus \( E \), Poisson’s ratio \( \nu \), and in-situ stress \( P_0 \) were used to carry out shale triaxiality at the Coalbed Methane Laboratory of China University of Mining and Technology. Obtained by mechanical experiments.
4.1. Shale block elastic energy characteristics

The elastic energy of the shale reservoir block of Longmaxi Formation is calculated according to Eq. 5, and the elastic energy change characteristics of the shale reservoir with the change of burial depth are obtained (Figure 2). The results show that as the burial depth increases, the elastic energy of the shale block gradually increases. In the early stage of sedimentation, with the increase of the burial depth, the elastic energy of the shale reservoir block increases slowly; after the burial depth exceeds 2000m, with the increase of the burial depth, the elastic energy of the shale reservoir block increases approximately linearly.

![Fig. 2 Relationship between the elastic energy of the shale matrix of the Longmaxi Formation and the burial depth](image)

4.2. Shale gas elastic energy characteristics

When the burial depth of shale reservoir changes, the macroscopic performance is the change of reservoir temperature and pressure, and the microscopic performance is the change of gas elastic energy. According to Eq. 8, the free aeroelastic energy of the Longmaxi Formation shale reservoir can be calculated, and according to Eq. 12, the adsorbed aeroelastic energy of the Longmaxi Formation shale reservoir can be calculated. The results show that the free aeroelastic energy and adsorbed aeroelastic energy of shale reservoir can be divided into three stages. In the first stage, when the reservoir uplift is less than 3200m, the change in free aeroelastic energy gradually decreases, and the adsorption aeroelastic energy gradually increases; in the second stage, when the reservoir uplift is between 3200-4400m, the free gas and The changes of the adsorbed gas elastic energy increase rapidly; in the third stage, when the reservoir uplift is greater than 4400m, the changes of the free gas and the adsorbed gas elastic energy decrease rapidly (Figure 3).
4.3. Energy change characteristics of shale reservoirs under different reservoir conditions

Based on the previous research results on the compressibility of methane and water under different temperature and pressure conditions, the pressure gradient is selected as 2.5MPa/hm, 2.0MPa/hm, the temperature gradient is selected as 2.5℃/hm, 2.0℃/hm, and the elastic energy change $\Delta E$ of shale-based reservoir under different burial depth conditions is obtained.

The results show (Figure 4 and Figure 5) that during the geological history of shale reservoirs, when the burial depth decreases, the temperature and pressure decrease at the same time, and the reservoir energy decreases continuously with the burial depth. It is good for shale gas accumulation, and the pressure reduction is not conducive to shale gas accumulation. The energy change during the shale reservoir uplift is a coupling effect under the joint control of temperature and pressure. Generally speaking, as the temperature and pressure continue to decrease, the reservoir energy changes can be divided into three different stages, the main control factors in different stages are in dynamic changes. In the first stage, the uplift height is less than 3200m. As the uplift height gradually increases, the reservoir energy decrease value is small, and the amount of reservoir energy change per unit uplift height gradually decreases. In the second stage, the uplift height is between 3200m and 4400m. As the uplift height increases, the reservoir energy decreases rapidly, and the amount of change decreases rapidly from $787.584 \text{ KJ/m}^3$ to $14479.7 \text{ KJ/m}^3$; in the third stage, the uplift height is between 4400m and 5000m, and as the uplift height changes, the reservoir energy continues to decrease, but the amount of energy change per unit lift height gradually decreases. At the same time, the reservoir energy change trend is the same for different temperature gradients and pressure gradients. The smaller the temperature gradient and pressure gradient, the smaller the reservoir energy variation.
5. Conclusion

Through the research in this article, the following conclusions are obtained:

(1) The formation of shale gas is controlled by the evolution of different energy systems in the process of geological history, the macrodynamic energy can control the coupling process of reservoir deposition-burial-reform, and the formation of shale gas is controlled by the process of geological history. The constantly changing process of the energy system.

(2) The dynamic balance of the energy system is characterized by the elastic energy of the formation of three-phase elastic energy of solid, liquid and gas, which balances the shale gas accumulation effect. The shale gas changes from sedimentation to diagenesis to hydrocarbon generation. At various stages, the energy of the gas reservoir mainly shows three different stages of evolution.
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