IN-SITU GAS PRESSURE CALCULATION PRINCIPLE OF PRESSURE-MAINTAINING COAL SAMPLES AND EXPERIMENTAL VERIFICATION IN DEEP COAL SEAMS

by

Ming-Zhong GAO[a,b], Yong-Cheng LI[a*], Jie SONG[a], Peng-Fei CUI[a], and Zong-Xin HAO[c]

[a] Guangdong Provincial Key Laboratory of Deep Earth Sciences and Geothermal Energy Exploitation and Utilization, Institute of Deep Earth Sciences and Green Energy, Shenzhen University, Shenzhen, China
[b] State Key Laboratory of Intelligent Construction and Healthy Operation and Maintenance of Deep Underground Engineering, College of Water Resource and Hydro Power, Sichuan University, Chengdu, China
[c] China Construction First Group the Fifth Construction Co., Ltd, Beijing, China

Original scientific paper
https://doi.org/10.2298/TSCI2502159G

Accurate determination of in-situ gas pressure in deep coal seams is the basic guarantee for safe production in coal mines, therefore, this paper is based on the in-situ pressure maintaining coring technology of deep coal seams, the gas pressure equilibrium process of pressure maintaining coal cores was simulated by carrying out decompression desorption experiments to validate the principle of in-situ gas pressure calculation for pressure maintaining coal samples of deep coal seams. The results of the study show that the theoretical values of in-situ gas pressure are in good agreement with the experimental values. The mean deviation is 0.126 MPa, 0.194 MPa, respectively, the average error is 5.085% and 8.319%, respectively. The experiments of desorption of pressure maintaining coal samples verified the reliability of the in-situ gas pressure calculation principle.

Key words: *deep coal seam, in-situ gas pressure, decompression desorption*

Introduction

Coal seam gas pressure is a key parameter for evaluating the risk of coal and gas protrusion and formulating measures for preventing and controlling gas disasters [1-3]. Based on the concept of *in-situ condition maintaining coring*, Xie *et al*. [4] team innovatively proposed *deep coal seam pressure maintaining gas coring principle and technology* [5], which can realize low disturbance confined coring of deep coal seams, and has the technical advantages of low disturbance, pressure maintaining confined coring, and measuring with drilling. It has the advantages of low disturbance, pressure maintaining confined coring and measurement with drilling. Based on this pressure maintaining coring technology, combined with the principle of gas pressure calculation, it can realize the accurate determination of in-situ gas pressure in deep coal seams. The gas desorption response characteristics of in-situ coal seams is the key to estimate the amount of gas loss during the coring process, and its accuracy will directly affect

* Corresponding author, e-mail: 1137458934@qq.com

the determination of in-situ coal seam gas pressure [6-8]. Unlike atmospheric pressure desorption, the gas pressure during coring or gas extraction often decreases gradually, which calls decompression desorption, theoretically, the adsorption and desorption process of coal samples is reversible, and the gas enters into the fissures from the matrix pores driven by the pressure difference when the coal samples are in decompression desorption, however, considering that the pressure gradient force of the decompression desorption state is weak, the rate of gas desorption is low [9-12].

At present, for the study of coal seam gas pressure calculation theory, there are fewer studies on the evolution of gas content before and after pressure preservation and confinement coring (desorption of coal samples under reduced pressure). Based on the principle and technology of pressure preservation and gas coring in deep coal seams [5, 13, 14], the author adjusted the principle of in-situ gas pressure calculation for deep coal seams in view of the technical difficulties of in-situ gas pressure measurement, and carried out the study of the evolution of desorption of pressure preservation coal samples. The in-situ gas pressure calculation principle was verified by decompression desorption experiment of the pressure holding coal samples.

Theoretical model of in-situ gas pressure calculation

In this paper, the principle of in-situ gas pressure calculation in deep coal seams based on pressure preserving coring [5] is based on the following basic assumptions: Law of mass conservation. No gas loss occurs in the pressure maintaining space, *i.g.*, the sum of gas content (adsorbed state/free state gas) in the coal samples and free gas content of free space remains constant; The adsorbed gas exists as a mono layer adsorption, which satisfies the Langmuir adsorption equation; The free state gas can be calculated by the gas equation of state.

Based on the Langmuir equation and the gas equation of state, the gas mass, m_0, per unit mass of sample could be calculated:

$$m_0 = \frac{abp}{1+bp}\frac{M_g}{V_M} + \phi\frac{M_g}{\rho_c \mathrm{R}T}p \tag{1}$$

where a, b are adsorption constants, p – the gas pressure of sample, M_g – the molar mass of gas, V_M – the molar volume of gas, R – the ideal gas constant, and T – the environmental temperature.

Therefore, before coring, the gas content m_{c0} of the pressurized coal sample:

$$m_{\mathrm{c0}} = m_c m_0 = m_c \frac{abp}{1+bp}\frac{M_g}{V_M} + \phi m_c \frac{M_g}{\rho_{\mathrm{c}} \mathrm{R}T}p \tag{2}$$

where m_c is the mass of sample.

After coring, the amount of gas contained in the pressure maintaining coal samples, m_{c1}, includes adsorbed gas in the samples, and free gas within the pore of the samples and confined space [15]:

$$m_{\mathrm{c1}} = m_c \frac{abp_1}{1+bp_1}\frac{M_g}{V_M} + \left(V_{\mathrm{con}} - \frac{m_c}{\rho_c} + \phi\frac{m_c}{\rho_c}\right)\frac{M_g}{\mathrm{R}T}P_1 \tag{3}$$

where m_{c1} is the gas content of sample after coring, P_1 – the gas pressure after depressurization and desorption, and V_{con} – the volume of confined space.

From the law of mass conservation: $m_{c0} = m_{c1}$, the in-situ gas pressure, P, can be calculated by conjugated formulas. The introduction of the gas compression factor, Z, to correct the ideal gas equation of state [16] is conducive to a more accurate calculation of the true free state gas content, which associates with coal seam temperature and gas pressure. In the in-situ

coal seam environment, the gas situation has deviated from the ideal state of gas, so the gas compression factor is considered for eqs. (2) and (3), and there are:

$$m_{c0}^{*} = m_c \frac{abp}{1+bp}\frac{M_g}{V_M} + \phi\frac{m_c}{\rho_c}\frac{M_g}{ZRT}p \tag{4}$$

$$m_{c2} = m_c \frac{abp_1}{1+bp_1}\frac{M_g}{V_M} + \left(V_{con} - \frac{m_c}{\rho_c} + \phi\frac{m_c}{\rho_c}\right)\frac{M_g}{ZRT}P_1 \tag{5}$$

where m_{co}^{*} is the gas content of sample before coring considering compression factor and m_{c2} – the gas content of sample after coring considering compression factor.

Similarly, $m_{c0}^{*} = m_{c2}$. Based on the principle of in-situ gas pressure calculation, we combine formula (2), (3). The significance of

$$\left(V_{con} - \frac{m_c}{\rho_c}\right)\frac{M_g}{RT}P_1$$

can be known as the amount of free-state gas content of the increased free volume in the pressure maintaining confined space at the pressure, P_1, corresponding to the experiments. It will be the amount of free gas captured by the flow meter, which operates at atmospheric pressure. So, there are:

$$\left(V_{con} - \frac{m_c}{\rho_c}\right)\frac{M_g}{RT}P_1 = \frac{M_g V_f}{RT}P_0 \tag{6}$$

where V_f is the cumulative gas-flow and P_0 – the atmospheric pressure.

Similarly, considering the gas compression factor for the eqs. (4) and (5), we have:

$$\left(V_{con} - \frac{m_c}{\rho_c}\right)\frac{M_g}{ZRT}P_1 = \frac{M_g V_f}{ZRT}P_0 \tag{7}$$

Analysis of the desorption characteristics of coal sample with different particle

Considering the different desorption effects of coal samples with different particle sizes in the re-balancing process of gas pressure, coal samples with particle sizes of 0.2~0.25, 1~3 mm were used. The isothermal adsorption data of coal samples were fitted with Langmuir function, as shown in fig. 1, the adsorption curves of coal samples with different particle sizes were similar, and the adsorption amount showed a positive correlation with the gas pressure, and the adsorption amount increased gradually with the increase of the gas pressure. The adsorption capacity was significantly reduced because the increase of particle size corresponded to the decrease of the outer surface area of coal particles, while the pore structure of coal became more complex. As in fig. 2, the desorption amount of coal samples increased and the adsorption amount decreased. The gas adsorption amount always dominates in process of pressure reduction, which indicates that it is relatively difficult to desorb the coal samples in the desorption stage of pressure reduction, and the small gradient pressure difference cannot effectively desorb the gas adsorbed inside the pores of the coal samples to the free space, and a large number of gas molecules are still adsorbed inside the coal samples. With the increase of the particle size of coal samples, the pore structure becomes more complex, which leads to the increase of the desorption diffusion path, and the macroscopic manifestation is that the desorption resistance becomes stronger, and the desorption effect is not obvious, *i.e.*, the desorption resistance shows a positive correlation with the particle size of coal samples.

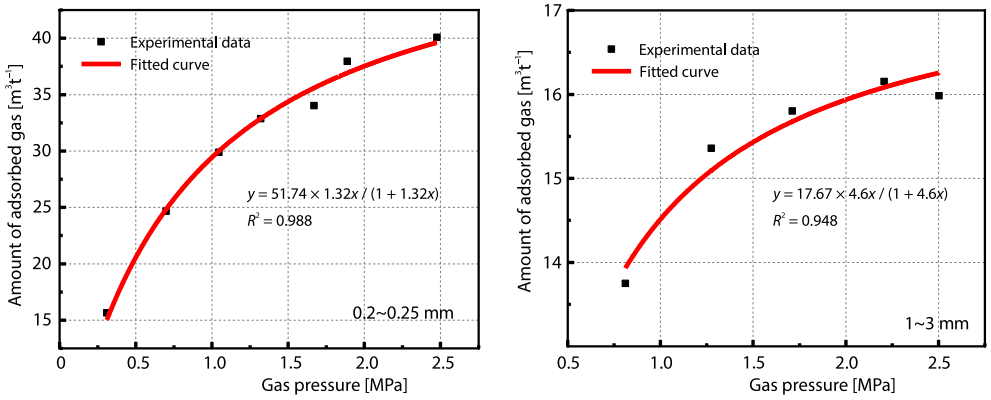

Figure 1. Isothermal adsorption curve

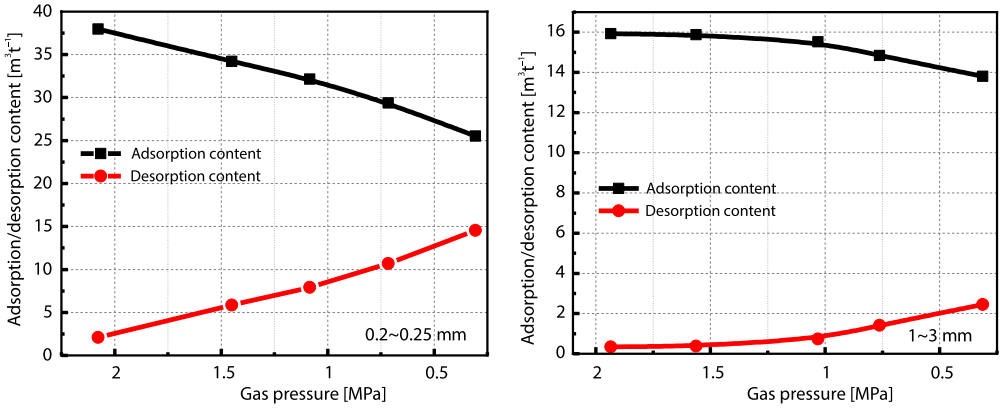

Figure 2. Response of decompression desorption

Based on the aforementioned experimental data of decompression desorption of pressure retaining coal samples, the in-situ gas pressure at the pressure of decompression desorption is calculated step by step in the order:

2 MPa → 1.5 MPa → 1 MPa → 0.74 MPa → 0.3 MPa → 0, respectively.

Comparing the gas content under the decompression equilibrium pressure, as shown in fig. 3, when the gas pressure decreases, the gas in the coal is continuously desorbed and released, and the free state gas content increases correspondingly. In the early stage of desorption, the adsorbed gas content is dominant, and the decrease of adsorbed gas content will directly affect the total gas content of the coal samples. The percentage of adsorbed gas content of 0.2~0.25 mm particle size coal samples decreases from 91.83-64.43%, and the change of the adsorbed gas content of the in-situ coal seam environment is larger, decreasing from the percentage of 91.82-36.84%, which indicates that the gas content change is gradually controlled by the free state gas.

According to the principle, the in-situ coal seam gas pressure before depressurization of different particle size pressure retaining coal samples is calculated, as shown in fig. 4. When the gas pressure in the pressure retaining confined space is shown as 0.306 MPa, the in-situ gas pressure calculated by the principle without considering the compression factor is 2.217 MPa,

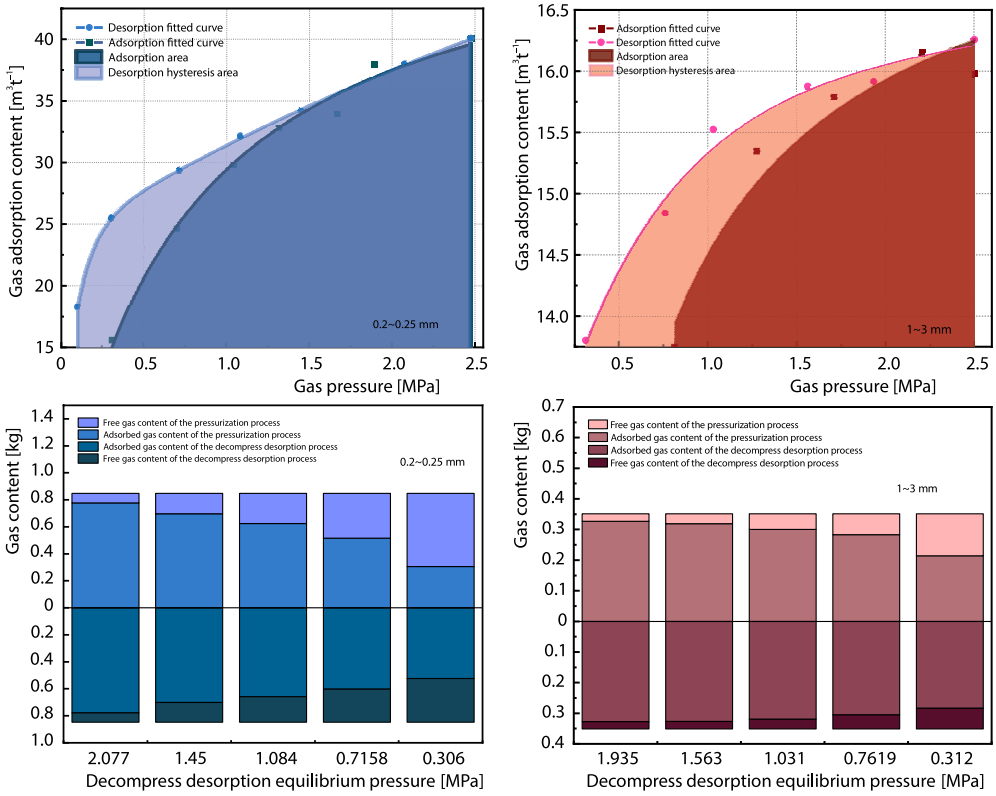

Figure 3. Comparison of gas content of pressurization and decompression desorption process

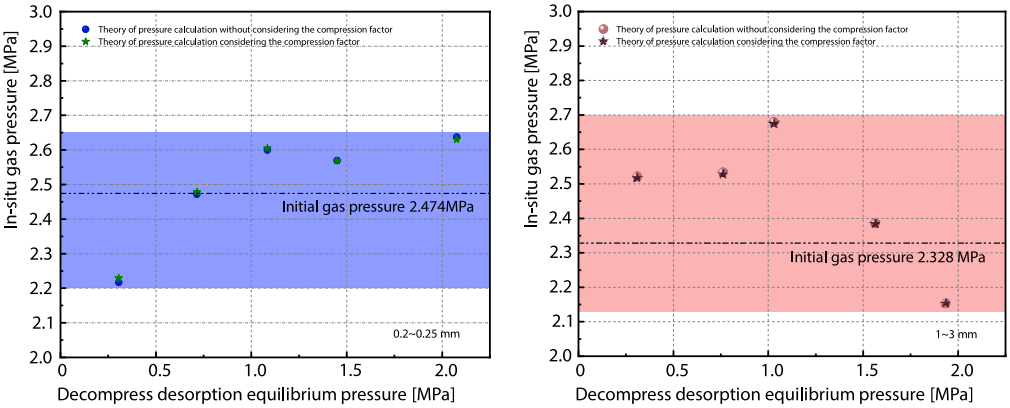

Figure 4. Comparison of results of in-situ gas pressure principle

while the principle with considering the compression factor is 2.229 MPa. According to the theoretical calculation, the deviation of the mean value between the principle without considering the compression factor and the real in-situ gas pressure of the coal samples with different particle sizes from 0.2~0.25 mm (taking the adsorption equilibrium pressure before decompression desorption) is 0.129 MPa, and the relative error is 0.129 MPa, with a relative error of 5.203%. The deviation between the theoretical and real in-situ gas pressure (the adsorption equilibrium

pressure before desorption is taken as 2.328 MPa) for the coal samples of 1~3 mm particle sizes without considering the compression factor is 0.197 MPa, with a relative error of 8.437%. The gas state deviates from the ideal state, and the consideration of the compression factor is favorable to the determination of the in situ gas pressure, in which the average error of the calculation principle of the consideration of the gas compression factor for the coal samples with grain size of 0.2~0.25 mm is 0.126 MPa, and the relative error is 5.085%; and the deviation of the mean value of the calculation principle of the consideration of the gas compression factor for the coal samples with grain size of 1~3 mm is 0.194 MPa, and the relative error is 8.319%.

Conclusion

In this paper, based on the free volume expansion of coal samples after coring, the free state gas content in the pressure maintaining confined space is corrected by considering the compression factor, and the adjusted principle of in-situ gas pressure calculation in deep coal seams is formed. For 0.2~0.25 mm and 1~3 mm grain size coal samples, the deviation of the theoretical mean value of the in-situ gas pressure calculation considering the compression factor principle is 0.126 MPa, 0.194 MPa, respectively; and the relative error is 5.085%, 8.319%, respectively, which shows experimental data verify the reliability of this theoretical model.

Nomenclature

a – adsorption constant, [m^3 per tonne]
b – adsorption constant, [MPa^{-1}]
p – gas pressure of sample, [Pa]
M_g – molar mass of gas, [gmol^{-1}]
m_0 – gas content of per unit mass, [g]
m_c – mass of sample, [g]
m_{c0} – gas content of sample before coring, [g]
m_{c1} – gas content of sample after coring, [g]
m_{c2} – gas content of sample after coring considering compression factor, [g]
m^*_{co} – gas content of sample before coring considering compression factor, [g]
P_0 – atmospheric pressure, [MPa]
P_1 – gas pressure after depressurization and desorption, [MPa]
R – ideal gas constant, [Jmol^{-1}K^{-1}]
T – environmental temperature, [K]
V_{con} – volume of confined space, [m^3]
V_f – cumulative gas-flow, [m^3]
V_M – molar volume of gas, [mLmol^{-1}]
Z – gas compression factor

Acknowledgment

This work was financially supported by the National Key Research and Development Program of China (2023YFF0615401), National Natural Science of China (52225403, U2013603) and Sichuan Science and Technology Program (2023NSFSC0004).

References

[1] Karacan, C., *et al*., Coal Mine Methane: A Review of Capture and Utilization Practices with Benefits to Mining Safety and to Greenhouse Gas Reduction, *International Journal of Coal Geology*, *86* (2011), 2-3, pp. 121-156
[2] Wang, L., *et al*., Safe Strategy for Coal and Gas Outburst Prevention in Deep-and-Thick Coal Seams Using a Soft Rock Protective Layer Mining, *Safety Science*, *129* (2020), ID104800
[3] Xie, H., *et al*., Theory, Technology and Engineering of Simultaneous Exploitation of Coal and Gas in China, *Journal of China Coal Society*, *39* (2014), 8, pp. 1391-1397
[4] Xie, H., *et al*., Study on Concept and Progress of in Situ Fidelity Coring of Deep Rocks, *Chinese Journal of Rock Mechanics and Engineering*, *39* (2020), 5, pp. 865-876
[5] Gao, M., *et al*., Principle and Technology of Coring with in-Situ Pressure and Gas Maintaining in Deep Coal Mine, *Journal of China Coal Society*, *46* (2021), 3, pp. 885-897
[6] Xie, H., *et al.*, Research Advances on the in-Situ Pressure-Preserved Coring and Gas Parameter Determination for Deep Coal Seams, *Coal Geology & Exploration*, *51* (2023), 8, pp. 1-12

[7] Gao, M., *et al*., Progress in Research on Deep in Situ Rock Mechanics, *Bulletin of National Natural Science Foundation of China*, *35* (2021), 6, pp. 895-903
[8] Zhang, Z., *et al*., Research on Permeability Characteristics of Raw Coal in Complete Stress-Strain Process under Different Gas Pressure, *Journal of China Coal Society*, *40* (2015), 4, pp. 836-842
[9] Zhang, S., *et al*., Theoretical Analysis of Coal-methane Adsorption/Desorption Mechanism and Its Reversibility Experimental Study, *Natural Gas Industry*, *25* (2005), 1, pp. 44-46
[10] Zhuang, L., *et al.*, Experimental Study of Methane Desorption Hysteresis Characteristics of Coal with Different Metamorphic Degrees, *Journal of Xi'an University of Science and Technology*, *40* (2020), 1, pp. 88-98
[11] Laicheng, L., *et al*., Experimental Study on Large Coal Sample Desorption under Successive Depressurization, *Coal Geology of China*, *27* (2015), 9, pp. 18-21
[12] Chen, X., *et al.*, Variation Characteristics of Expansion Energy of Desorption Gas in Process of Stepwise Decompression and Desorption, *Coal Science and Technology*, *50* (2022), 2, pp. 122-128
[13] Gao, M., *et al*., Technology and Application of in-Situ Pressure and Gas Maintaining Coring for Deep Coal Seam, *Coal Science and Technology*, *52* (2024), 4, pp. 143-154
[14] Li, F., *et al.*, Formation Mechanism of Core Discing During Drilling under Deep in-Situ Stress Environment: Numerical Simulation and Laboratory Testing, *Journal of Central South University*, *30* (2023), 10, pp. 3303-3321
[15] Cui, P., *et al*., A preliminary Study of Pressure-Preserved Coring Calculation Principle and Method for In-Situ Pressure in Deep Coal Seams, *Coal Geology & Exploration*, *51* (2023), 8, pp. 59-67
[16] Zeng, Q., *et al*., Experimental and Modelling Studies on High Pressure Methane Adsorbed on Coals, P*etroleum Science Bulletin*, *5* (2020), 1, pp. 78-92

Paper submitted: July 12, 2024
Paper revised: October 8, 2024
Paper accepted: November 21, 2024