Similarity criteria and scale effect for physical simulation of coal and gas outburst

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Abstract. Based on the dimensional unity, analyzed mechanics, adsorption, desorption and seepage characteristics in the process of outburst by equation analysis method. Combining the existing experimental condition, proposed similarity model which could be more similar to practice and theory, and researched scale effect of outburst physical simulation. Analyzed the geometry size influences release area size, elastic energy, gas energy, broken power and throwing power in the process of outburst. Improved similar material of coal and gas outburst, considering seepage characteristic. The results show that realizing the consistency of the stress ratio scale and the gas pressure ratio is the key in the outburst similarity model. Scale effect plays an important role in the occurrence and development of outburst. In terms of energy contribution, gas can contribute more energy to outburst than elastic energy. Refer to energy dissipation, broken work is more than 95 % in outburst energy, and throwing work is only a small part in outburst energy.

1. Introduction
Coal and gas outburst is a complex dynamic disaster that occurs in coal mines, which seriously threatens the safe production of mines [1-5]. Regarding the theoretical research of coal and gas outburst, scholars from various countries have done some mechanism research and prediction models [6-8]. At present, there is no scientific and complete theory on coal and gas outburst mechanism. In recent years, the physical simulation test of coal and gas outburst has been developed rapidly. Yuan Liang, Yin Guangzhi, Liu Zegong, et al [9-13] have carried out large-scale coal and gas outburst tests, but they have similar theoretical directions for coal and gas outbursts. There is little research. Among them, Hu Yaoqing, et al [14] used the thermal-fluid-solid multi-field coupling relationship to calculate the seepage similarity model under the thermal-fluid-solid coupling. Zhang Shutong, et al [15,16] used dimensional analysis to derive similar models of physical and mechanical parameters from the perspective of mechanics, and discussed the law of similarity between physical dimensions, loads and material properties, but the relationship between stress and gas pressure is not detailed. Hu Shoutao [17] used equation analysis method to make similar changes to the basic equations of elastic mechanics. During the experiment, stress similarity, geometric similarity and dynamic similarity were mainly considered. Zhang Qinghe, et al [18] derived from the fluid-solid coupling model and the energy model, similar models have
different stress scales and gas pressure scales. The stress and gas pressure are placed in different dimensions, but from the perspective of dimensions, the dimension of pressure should be consistent with that of the earth's stress, which is MLT-2. In the physical simulation of coal and gas outbursts, most scholars mainly consider stress similarity and geometric similarity, but they are vague about the gas pressure and permeability involved in the experiment process, and lack comprehensive and accurate similarity theories to guide physics simulation experiments.

2. **Highlight the establishment of similar models**

To ensure that the outburst simulation experiment has a high consistency with the outburst prototype, it is necessary to simplify the similarity criterion of coal and gas outburst. In the experiment, priority is given to the rule of similarity that plays a dominant role. Which mainly involves stress environment dimension (P), spatial dimension (S) and material property dimension (M). Stress environment dimensions (P) include: ground stress, gas pressure; spatial dimensions (S) include: prominent hole diameter, tunnel diameter; material property dimensions (M) include: uniaxial compressive strength, elastic modulus, gas pressure, porosity, density, Poisson's ratio, adsorption constant, permeability and initial gas release velocity.

### 2.1. Mechanical similarity model:

(1) **Stress similarity model**

Mechanical similar conditions play a key role in emphasizing physical simulation. Try to ensure that the stress-strain relationship between the model material and the prototype material is similar. Ensure that under any strain, the ratio of the corresponding prototype stress to the model stress is equal. As far as coal and gas outburst is concerned, the stress-strain relationship is approximately regarded as a linear elastic similar material model before it fails, and both the prototype and the model should satisfy the statics equation. In the text, the subscript "p" represents the prototype, and the subscript "m" represents the model.

**Prototype:**

\[
\frac{\partial \sigma_x}{\partial x_p} + \frac{\partial \tau_{xy}}{\partial y_p} + \frac{\partial \tau_{xz}}{\partial z_p} + X_p = 0
\]

\[
\frac{\partial \sigma_y}{\partial y_p} + \frac{\partial \tau_{yx}}{\partial x_p} + \frac{\partial \tau_{yz}}{\partial z_p} + Y_p = 0
\]

\[
\frac{\partial \sigma_z}{\partial z_p} + \frac{\partial \tau_{zx}}{\partial x_p} + \frac{\partial \tau_{zy}}{\partial y_p} + Z_p = 0
\]

**Model:**

\[
\frac{\partial \sigma_x}{\partial x_m} + \frac{\partial \tau_{xy}}{\partial y_m} + \frac{\partial \tau_{xz}}{\partial z_m} + X_m = 0
\]

\[
\frac{\partial \sigma_y}{\partial y_m} + \frac{\partial \tau_{yx}}{\partial x_m} + \frac{\partial \tau_{yz}}{\partial z_m} + Y_m = 0
\]

\[
\frac{\partial \sigma_z}{\partial z_m} + \frac{\partial \tau_{zx}}{\partial x_m} + \frac{\partial \tau_{zy}}{\partial y_m} + Z_m = 0
\]

\[
C_\sigma = \left(\frac{\sigma_x}{\sigma_x}\right)_p = \left(\frac{\sigma_y}{\sigma_y}\right)_p = \left(\frac{\tau_{xy}}{\tau_{xy}}\right)_p = \left(\frac{\tau_{xz}}{\tau_{xz}}\right)_p, \quad C_i = \frac{x_p}{x_m} = \frac{y_p}{y_m} = \frac{z_p}{z_m}, \quad C_f = \frac{X_p}{X_m} = \frac{Y_p}{Y_m} = \frac{Z_p}{Z_m}
\]  

Where, \(C_\sigma\) is stress similarity constant; \(C_i\) is geometric similarity constant; \(C_f\) is body force similarity constant.

Substituting formula (3) into formula (1), we can get:
Comparing formula (2) and formula (4), we get:
\[ \frac{C_x C_i}{C_y} = 1, \quad \frac{C_y C_i}{C_z} = 1 \rightarrow C_i = C_y \]

(2) Similar deformation conditions
According to the elastic theory, the relationship between stress, strain, elastic modulus and Poisson's ratio can be derived:
\[
\begin{align*}
\varepsilon_x &= \frac{1}{E} \left[ \sigma_x - \mu (\sigma_y + \sigma_z) \right] \\
\varepsilon_y &= \frac{1}{E} \left[ \sigma_y - \mu (\sigma_x + \sigma_z) \right] \\
\varepsilon_z &= \frac{1}{E} \left[ \sigma_z - \mu (\sigma_x + \sigma_y) \right]
\end{align*}
\]

(5)

Where, \( \varepsilon_x, \varepsilon_y, \varepsilon_z \) are the strain components in the x, y, and z directions; E is elastic modulus; \( \mu \) is Poisson's ratio.

Similar derivations can be used to obtain similar constants for Poisson's ratio and elastic modulus:
\[
\begin{align*}
C_\mu &= 1, \quad C_x C_\mu = C_y \\
C_\varepsilon &= 1, \quad C_\mu = 1, \quad C_x = C_y
\end{align*}
\]

(3) Destroy similar conditions
The destruction of coal and rock can be described by Mohr-Coulomb Criterion, taking the Mohr circle envelope as a straight line, so that the Mohr circle envelope of the prototype and the model can be similar. At this time, the mechanical characteristics of the material can be expressed by the ratio of its compressive strength to tensile strength, so that similar failure conditions can be derived:
\[
\begin{bmatrix}
\sigma_c \\
\sigma_t
\end{bmatrix}_p = \begin{bmatrix}
\sigma_c \\
\sigma_t
\end{bmatrix}_m
\]

(6)

where, \( \sigma_c \) is compressive strength; \( \sigma_t \) is tensile strength; c is cohesion; \( \varphi \) is internal friction angle.

2.2. Seepage similarity model
During the outburst process, the coal body deformation, failure and instability in the preparation stage need to satisfy the homogeneous continuum solid-gas coupling mathematical model:
2.3. Similar model of adsorption and desorption

When emphasizing the simulation experiment, the gas adsorption and desorption capacity of similar materials has an important influence on the results of the simulation experiment. Therefore, it is necessary to determine a reasonable similar ratio of adsorption and desorption. Through the equation analysis method, the Langmuir calculation formula is analyze:

\[
\theta = \frac{abp}{1 + bp}
\]  

Where, \( \theta \) is adsorption capacity; \( a \) is adsorption constant, limit adsorption capacity at test temperature, \( \text{cm}^3/\text{g} \); \( b \) is adsorption constant, \( \text{MPa}^{-1} \); \( p \) is absolute gas pressure of coal seam, \( \text{MPa} \).

\[
\pi = abp, \quad \pi = bp \quad \text{We can get} \quad C_s = 1, \quad C_p C_p = 1.
\]

For coal and gas outbursts, stress, gas pressure, and coal and rock physical and mechanical properties are the main parameters that determine its occurrence and development. Therefore, first consider the model model to meet the following conditions:

\[
\frac{\partial}{\partial x} \left( K_x \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial P}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_z \frac{\partial P}{\partial z} \right) = 2 \frac{\partial}{\partial x} \left( \frac{\partial \rho \mu}{\partial x} \right) + W
\]

\[
\nabla \cdot \left[ \nabla \left( \frac{1}{G} \left( \frac{\partial^2 u}{\partial x^2} \right) + X - \rho \frac{\partial u}{\partial x} \right) \right] = 0
\]

\[
\nabla \cdot \left[ \nabla \left( \frac{1}{G} \left( \frac{\partial^2 u}{\partial y^2} \right) + Y - \rho \frac{\partial u}{\partial y} \right) \right] = 0
\]

\[
\nabla \cdot \left[ \nabla \left( \frac{1}{G} \left( \frac{\partial^2 u}{\partial z^2} \right) + Z - \rho \frac{\partial u}{\partial z} \right) \right] = 0
\]

(7)

Where, \( P = p^2 \); \( S(\rho) = \frac{n}{p} + \frac{ab}{p(1 + bp)} \); \( K_x, K_y, K_z \) is the permeability coefficient of the three coordinate axis directions; \( W \) is terms of source and convergence; \( G \) is modulus of elasticity in shear; \( \nabla = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \) is laplacian operator; \( \lambda = \frac{\mu E}{(1 + \mu)(1 - 2\mu)} \) is lame constant; \( e \) is volumetric strain.

Using equation analysis method can get:

\[
C_G \frac{C_u}{C_i} = C_G \frac{C_e}{C_i} = \frac{C_e}{C_i} = \frac{C_p}{C_i} = C_g
\]

(8)

According to \( C_p C_e / C_i^2 = C_i \) and \( C_g = C_p C_e \), in the same gravity field, then the acceleration of gravity is the same, \( C_g = 1 \). According to \( C_u = C_i C_e \), we can get \( C_i^2 = C_i C_e \). According to \( C_e = 1 \), we can get similarity constant for exercise time \( C_i = \sqrt{C_i} \).

\[
\frac{C_k C_p}{C_i^2} = \frac{C_k C_p}{C_i^2} = \frac{C_k C_p}{C_i^2} = \frac{C_s}{C_i} = \frac{C_p}{C_i} = C_w
\]

(9)

According to \( C_k C_p / C_s = C_w \), \( C_s = C_i \) and \( C_p = C_k C_i \), we can get permeability coefficient similarity constant, \( C_k = \sqrt{C_i} / C_i \).

2.3. Similar model of adsorption and desorption

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\theta = \frac{abp}{1 + bp}
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Where, \( \theta \) is adsorption capacity; \( a \) is adsorption constant, limit adsorption capacity at test temperature, \( \text{cm}^3/\text{g} \); \( b \) is adsorption constant, \( \text{MPa}^{-1} \); \( p \) is absolute gas pressure of coal seam, \( \text{MPa} \).

\[
\theta = \frac{C_k C_p C_r (abp)}{1 + C_k C_r (bp)}
\]

(11)

\[
\pi = abp, \quad \pi = bp \quad \text{We can get} \quad C_s = 1, \quad C_p C_p = 1.
\]

For coal and gas outbursts, stress, gas pressure, and coal and rock physical and mechanical properties are the main parameters that determine its occurrence and development. Therefore, first consider the model model to meet the following conditions:
First satisfy the dimensionless similarity constant: \( C_i = C_p = C_g = 1 \); Mechanical similarity constant: \( \frac{C_p C_i}{C_p} = 1 \), \( C_r = C_\sigma \), \( C_E = C_\sigma \); seepage similarity constant: \( C_K = \frac{C_i}{C_p} \); time similarity constant: \( C_t = \sqrt{C_i} \); adsorption and desorption similarity constant: \( C_a = 1 \), \( C_b C_p = 1 \).

In the actual physical simulation experiment of coal and gas outburst, \( C_p = 1 \) can be achieved by the ratio of similar materials, so \( C_g = C_r = C_i \), \( C_K = \frac{C_i}{C_p} \), \( C_t = \sqrt{C_i} \), \( C_a = 1 \), \( C_b C_p = 1 \). \( C_a = C_g = C_i \) is the key to similar models and conducting prominent physical simulation experiments. When geometric size \( C_i = 1 \), it is impossible and meaningless to carry out prominent simulation experiments; on the other hand, when \( C_a = C_p = 1 \), it realizes the complete similarity of stress and gas pressure, but it cannot meet the requirements of geometric size. At this time, the problem becomes the influence of geometric size on coal and gas outburst.

3. Model validation
Relying on the similar model, the physical simulation experiment of coal and gas outburst was carried out. The prototype of the coal and gas outburst accident is the 11-2 coal seam "4.19" outburst accident in Huainan Dingji Coal Mine. The coal thickness is 2.2m, the buried depth is 870m, and the gas pressure is 0.5MPa. The firmness coefficient is 0.3, the adsorption constant a is 15.12cm\(^3\)/g, the initial release velocity is 7, and the amount of outburst coal is 35t. The protruding holes are wedge-shaped, with a width of 3 to 4 m and a depth of 6 to 7 m. The accumulated coal is 4 to 6 m away from the working face. There is no obvious sorting phenomenon. It is a type of extrusion with stress as the main controlling factor. The simulation experiment was carried out under the conditions of geometric similarity ratio 1:12, stress similarity ratio 1:1, and gas pressure similarity ratio 1:1. The specific parameters are set to stress 16MPa, air pressure 0.5MPa, firmness coefficient 0.34, adsorption constant 14.98cm\(^3\)/g, and initial release velocity 9. The mass of outburst coal is 18.09kg, and the amount of reduced outburst coal is 33.2t. Under this test condition, the simulation test has obvious prominent phenomenon. Outburst pulverized coal is sortable, which verifies the accuracy of the model.

4. The influence of size effect on coal and gas outburst
Coal and rock masses are elastically deformed due to their own weight stress, tectonic stress and mining stress, which makes the coal mass have high elastic potential. At the same time, a large amount of adsorbed gas and free gas occur in the coal seam, making it have a higher gas internal energy. Excavation disturbance is an important factor that induces coal and gas outburst, and the size of coal seam excavation often has an important influence on coal and gas outburst. Combined with outburst physical simulation experiments, under the premise of keeping the basic physical and mechanical parameters of coal consistent, the influence of size effect on coal and gas outburst is mainly manifested in the evolution of energy, including the volume of energy release zone, elastic energy, and gas internal energy, Breaking power and throwing power. Regarding the energy law of coal and gas outburst, predecessors...
have carried out a lot of research. This article is based on the energy model proposed by Hu Qianting [2] and improved it to carry out research on the influence of size effect.

Elastic energy:
\[
W_1 = \frac{\pi(1-2\mu)\sigma_0^2 R_p}{E} \int \left( \frac{R_{p1}}{R_p} \right)^3 - 1 + \frac{3k_s}{1-a_2} \ln \frac{R_{p1}}{R_p} + \frac{2.25k_s^2}{3(1-a_2)^2} \left( 1 - \frac{R_p^2}{R_{p1}^2} \right) d \cos \psi
\] (12)

Gas internal energy:
\[
W_2 = \eta V_p \ln \left( \frac{p_g}{p_s} \right) + k_0 \int_0^{r_{max}} \int_{\eta}^{R_p} \int_{\eta}^{r_{max}} \sqrt{r^2 - r_0^2} \left( 1 - a_2 \right) r^2 d\psi d\theta dr
\] (13)

Crushing energy:
\[
A_1 = 46.914\gamma V_p f^{1.437} \nu^{1.679}
\] (14)

Handling work:
\[
A_2 = \frac{mv^2}{2} = \frac{1}{2} \gamma V_p v^2
\] (15)

The scale effect study was carried out based on a coal and gas outburst accident in Houxi Coal Mine in Chongqing in 2015. The location of the accident was K3 coal seam 1311 heading face, which was 237 m away from +445 Qishimen (111 m from the branch of 1311 transportation lane). The outburst coal seam was K3 coal seam with a thickness of 2.0 m and a buried depth of about 353 m. The parameters are shown in Table 1.

| Driving footage /m | Support pressure concentration factor \(\eta\) | Internal friction angle \(\mu\) | Protodyakonov coefficient \(k\) | Elastic modulus \(E\) /MPa | Poisson's ratio \(\nu\) | Porosity \(\gamma\) /\% | In-situ stress \(\sigma_0\) /MPa | Gas pressure \(p_g\) /MPa | Throw speed \(v\) /ms\(^{-1}\) |
|-------------------|-----------------------------|------------------|------------------|-------------------------|------------------|------------------|----------------------|------------------|------------------|
| 1                 | 3                           | 25               | 0.2              | 1623                    | 0.36             | 0.09             | 12.5                 | 2.304            | 1                |

Using matlab programming, the energy of coal and gas outburst under different roadway sizes can be calculated separately, and the influence of scale effect on coal and gas outburst can be further analyzed. The volume of the energy release zone, gas internal energy, crushing work and throwing work show an exponential trend with the increase of the roadway section radius. When the roadway section radius is 2 m, the volume of the energy release zone contained in coal and gas outburst is 13.5177 m\(^3\), and the elastic energy It is 0.3782 kJ, and the gas internal energy is 1915.9 kJ; when the tunnel section radius is 0.8 m, the energy release zone volume is 1.73779m\(^3\), the elastic energy is 0.055 kJ, and the gas internal energy is 246.3291 kJ. Through calculation, it is found that the contribution of gas internal energy to coal and gas outburst is much greater than elastic energy, which shows that elastic energy only provides a small part of the energy for outburst, while gas internal energy plays a control role in coal and gas outburst. In terms of power dissipation, when the roadway section radius is 2m, the breaking power is 1843.6 kJ and the throwing power is 9.8003 kJ; when the roadway section radius is 0.8m, the breaking power is 237.0301 kJ and the throwing power is 1.26 kJ.

Through the above calculation results, we can find that in terms of energy dissipation, the crushing work accounts for more than 95% of the outburst energy of coal and gas. From this, we get the evolution law of coal and gas outburst energy under different roadway radius sizes.

5. Conclusion
(1) A similar model of coal and gas outburst is established through equation analysis.
(2) The influence of the scale effect on coal and gas outburst is analyzed, and the relationship between the volume of the energy release zone, elastic energy, gas internal energy, crushing work and throwing work, and the roadway section radius is found, which has a little meaning for establishing a reasonable model size.
(3) On the basis of similar models and scale effects, researches on similar materials and prominent simulation experiments have been carried out. In this paper, the relationship between ground stress and...
gas pressure is considered together. It should be noted that the relationship between stress and geometry still needs in-depth research.

Acknowledgments
The study was supported by National Key R&D Program of China (2018YFC0808305), Chongqing Technological Innovation Leading Talent Support Program (CSTCKJXLC14).

References
[1] Yuan Liang. Control of coal and gas outbursts in Huainan mines in China: A review[J]. Journal of Rock Mechanics and Geotechnical Engineering, 2016,8(4): 559-567.
[2] Hu Qianting, Zhou Shining, Zhou Xinquan. Mechanical mechanism of coal and gas outburst process[M]. Science Press,2008,1368-1372.
[3] Pan Yishan. Integrated study on compound dynamic disaster of coal-gas outburst and rockburst[J]. Journal of China Coal Society, 2016(01): 105-112.
[4] Yu Qixiang, Cheng Yuanping. Coal mine gas control[M]. China University of Mining and Technology Press,2012.
[5] Jin Hongwei. Experiment and mechanism analysis of the developing process of coal and gas outburst[J]. Journal of China Coal Society, 2012(S1): 98-103.
[6] Guo Pinkun. Research on laminar spallation mechanism of coal and gas outburst Propagation[D]. China University of Mining and Technology, 2014.
[7] Tu Qingyi, Cheng Yuanping, Guo Pinkun, et al. Experimental study of coal and gas outbursts related to gas-enriched areas[J]. Rock Mechanics & Rock Engineering, 2016,49(9): 1-13.
[8] Tang Jun, Jiang Chenglin, Chen Yujia, et al. Line prediction technology for forecasting coal and gas outbursts during coal roadway tunneling[J]. Journal of Natural Gas Science & Engineering, 2016,34: 412-418.
[9] Wang Hanpeng, Zhang Qinghe, Yuan Liang, et al. Coal and gas outburst simulation system based on CSIRO model[J]. Chinese Journal of Rock Mechanics and Engineering, 2015(11): 2301-2308.
[10] Wang Hanpeng, Zhang Qinghe, Yuan Liang, et al. Development of a similar material for methane-bearing coal and its application to outburst experiment[J]. Rock and Soil Mechanics, 2015(06): 1676-1682.
[11] Gao Kui, Liu Zegong, Liu Jian. Effect of geostress on coal and gas outburst in the uncovering tectonic soft coal by cross-cut[J]. Chinese Journal of Rock Mechanics and Engineering, 2015(2): 305-312.
[12] Gao Kui, Liu Zegong, Liu Jian. Effect of gas on coal and gas outburst induced by rock cross-cut tectonic soft coal uncovering[J]. China Safety Science Journal, 2015,25(3): 102-107.
[13] Liu Dong, Xu Jiang, Yin Guangzhi et al. Development and application of multifield coupling testing system for dynamic disaster in coal mine[J]. Chinese Journal of Rock Mechanics and Engineering, 2013(05): 966-975.
[14] Hu Yaoqing, Zhao Yangsheng, Yang Dong. Simulation theory and method of 3D solid-liquid coupling[J]. Journal of Liaoning Technical University, 2007(02): 204-206.
[15] Zhang Shutong. Research on similarity of materials and systems for coal and gas outburst simulation test[D]. Anhui University of Science & Technology, 2015.
[16] Zhang Shutong, Dai Linchao, Wang Bo, et al. Experiment study on mixture ratio of similar material for simulation of coal and gas outburst[J]. Coal Science and Technology, 2015(06): 76-80.
[17] Hu Shoutao. The research on similar simulation test and characteristics of energy of coal and gas outburst [D]. China University of Mining & Technology, Beijing, 2016.
[18] Zhang Qinghe, Yuan Liang, Wang Hanpeng, et al. Establishment and analysis of similarity criteria for physical simulation of coal and gas outburst[J]. Journal of China Coal Society, 2016(11): 2773-2779.