Research Article

Research on Structural Characteristics of Dynamic Nuclear Zone in Dynamic System of Coal and Rock

Hai Rong1,2, Bing Liang2, Hongwei Zhang1,2, and Feng Zhu1

1College of Mining, Liaoning Technical University, Fuxin, Liaoning Province, China
2School of Mechanics and Engineering, Liaoning Technical University, Fuxin, Liaoning Province, China

Correspondence should be addressed to Hai Rong; ronghai1988@163.com

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In order to calculate the concrete scale range of coal and rock mass in rockburst of different degrees of danger and to prevent and control rockburst in coal mines, the concept of dynamic system of coal and rock is put forward in this paper. The model of the relationship between the occurrence of rockburst and dynamic system is built at the same time, which could be used to analyze the rockburst risk of coal and rock in different scales. The calculation method of dynamic nuclear zone scale and its evaluation system and quantitative indicators are put forward based on the energy release process of dynamic system of coal and rock. Combined with the fracturing technology of liquid CO2, the accuracy of the calculation method for the radius of dynamic nuclear zone is verified in a coal mine in Shanxi Province. The degree of coincidence between the results of the two methods is 96.9%–97.5%, which shows that the calculation method for the radius of dynamic nuclear zone has high reliability and practicability. This method can be widely used in forecasting the risk of rockburst. The liquid CO2 fracturing method can be well used to simulate the blasting source of rockburst at the same time and can be applied to more mines in the future.

1. Introduction

The shallow coal resources account for 47% of the total coal reserves in China which have been nearly exhausted after a long period of mining [1]. At the International Coal Summit 2013 held in Beijing, China, Xie, an academician of the Chinese Academy of Engineering predicted that China’s total coal annual output will reach 3 to 3.5 billion tons by 2030, and this output level will continue for several years to come [1]. It means that in order to meet China’s annual demand for coal resources, more coal mines in China will reach the “deep mining” level in the near future. Coal and rock will bear higher stress and energy when the coal mine reaches the “deep mining” level, providing a more conducive environment for the occurrence of rockburst [2–5]. Rockburst is one of the most common and destructive mine dynamic disasters, which poses a serious threat to the safety of coal mine workers and the efficient production of coal mines [6]. Therefore, accurate evaluation and prediction is particularly important for the establishment of mine rockburst prevention and control systems.

Many theories and methods have been formulated for the evaluation and prediction of coal mine impact pressure, and good application results have been obtained in many mines. In order to identify the information that can be used to predict dynamic disasters, Vazaios et al. [7] investigated the failure and fracturing processes and the mechanisms of energy storage and rapid release resulting in rockbursting by finite-discrete element method and examined the impact of rock structure on rockbursting under high in situ stresses by integrating DFN geometries. Wang et al. [8] regarded the rock strength index, energy release index, and surrounding rock stress as the basic factors of rockburst, and a new Bayesian multi-index model to predict and evaluate rockbursts was built, which was observed to predict rockbursts more effectively than the current methods. Wang and Kaunda [9] indicated that the rockburst consequence could be quantified with plastic strain work and released energy in numerical models, and they thought the rock mass damage under soft loading stiffness had larger magnitude of plastic strain work and released energy than that under stiff loading stiffness. Sousa et al. [10] focused on the analysis of
a database of in situ cases of rockburst, the in situ rockburst database was further analyzed using different DM techniques ranging from ANNs to naive Bayes classifiers in order to build influence diagrams, list the factors that interact in the occurrence of rockburst, and understand the relationships between these factors. Zhang et al. [11] revealed the power sources and energy accumulation conditions of rockburst under natural geological conditions by applying the geodynamic division method and predicted the dangerous locations of rockburst in the Shenhua Xinjiang mining area in China. Pan et al. [12, 13] proposed the charge induction monitoring theory and developed a working charge induction monitoring system. Experiments have shown the system is accurate in monitoring the spatial and temporal changes of the coal surface charge with a range of applied stress during the mining process. Dou et al. [14] studied the relationship and difference between rockburst, rock bursting, and mine earthquake and proposed 3 mechanical models of rockburst in coal mine. They identified 4 categories of scientific problems that need to be addressed in the study of rockburst and pointed out the direction of improving the level of rockburst prevention and control. Jiang et al. [15] put forward a method based on the stress superposition to assess rockburst risk after fully considering the influence of various factors on the increment of the geostatic stress. He considered this method more intuitive and quantified for the evaluation of rockburst. Pan et al. [16] aimed to identify the inducing factors of rockburst in their research. They proposed the theory of the source monitoring and evaluation and established the evaluation model based on weight comprehensive and different-load sources of coal bump. The authors believed that the method can effectively reflect the current degree of risk and the future development trend of rockburst. The weight is calculated according to the contribution rate of coal bump monitoring index by the entropy weight method that could reduce the influence of subjective factors. Based on the impact tendency of coal, Li et al. [17] studied the relevant information before the damage of coal and revealed the fact that the amplitude of the main frequency of acoustic emission increases with the increase of coal impact tendency and the stress value of coal is negatively correlated with the acoustic emission signal “b.” The “hierarchical monitoring application” model of rockburst was established by Lv et al. [18] He applied the model to the Xinzhouyao coal mine, Datong mining area, and believed that the complementarity between the hierarchical monitoring technology and other monitoring technologies is strong. The technology can enable effective comprehensive dynamic monitoring of the mine. Peng et al. [19] established the rockburst risk preevaluation index based on the corresponding influence factors, constructed the dynamic preevaluation system and verified the rationality of the system in practice.

When the structure of coal and rock is destroyed, the accumulated energy will be released in the form of waves, which will be accompanied by microseismic signals [20]. The occurrence of rockburst is the unity of time and space. Since there is often a high-energy microseismic event in the process of rockburst, the accurate prediction of the high-energy microseismic event is the key to rockburst prediction [19]. Therefore, the analysis of microseismic events should be focused on their locations and energy, especially “high-energy” microseismic events above the critical energy of rockbursts.

When a high-energy microseismic event occurs, there is greater potential danger of damage to the coal and rock nearby [21]. After a period of energy accumulation, the coal and rock mass in the nearby areas are in danger of rockburst or high-energy microseismic events occurring again. According to statistical analysis, $10^6$ J is regarded as the critical energy of rockburst in China. We should focus on the microseismic events above the critical energy of rockburst for each mine with rockburst danger.

2. Model Construction and Energy Source for Dynamic System of Coal and Rock

2.1. Concept and Model Construction for Dynamic System of Coal and Rock

Different geological dynamic environments have been formed due to tectonic movements, which resulted in different stress distribution and energy accumulation of rock mass. When the mining activity reaches a zone of high stress or energy accumulation, the risk of coal and rock structure instability, energy release, rockburst, and other mine dynamic disasters is increased. We define the coal and rock system in this zone as “dynamic system of coal and rock,” and the basic power source of rockburst is the energy released from dynamic system of coal and rock. In the dynamic system of coal and rock, there are many factors that affect its stability, of which energy factor is the most important. Determining the source and scale of the dynamic system of coal and rock will be helpful to the prediction and prevention of rockburst.

The occurrence of rockburst originates from the difference between the released energy and absorbed energy when the coal and rock are destroyed, reaching or exceeding a certain critical value. The difference in energy depends on the relative spatial relationship between mining work and dynamic system of coal and rock, which leads to the different dynamic appearance of rockburst. We constructed the model of the relationship between rockburst and dynamic system of coal and rock and formulated the corresponding relationship criteria, as shown in Figure 1.

According to the degree of energy accumulation and the influence range, dynamic system of coal and rock can be divided into four zones: the dynamic nuclear zone, the damage zone, the injury zone and the influence zone. Rockburst can also be categorised into four grades: coal gun, coal pour out or press out, rockburst and serious rockburst. When mining activity reaches the influence range, injury zone, damage zone and dynamic nuclear zone, the corresponding dynamic behavior will be coal gun, coal pour out or press out, rockburst and serious rockburst respectively.

Therefore, to prevent and control rockburst, it is important for us to study the structure of dynamic system of coal and rock and determine the calculation method of each
Under the influence of external forces such as tectonic movements and mining activities, the coal and rock in the mine will deform, and the deformation of the coal and rock will be accompanied by the continuous accumulation of energy. Once the external force on the coal and rock disappears, the accumulated energy in the coal and rock will be released while the coal and rock restore their original shape [23, 24]. When rockburst is absent, dynamic system of coal and rock continuously accumulates energy. Under the influence of mining disturbance, when the total energy of dynamic system is greater than the background energy, the energy will be released. If the released energy $\Delta U$ is greater than the critical energy, the rockburst will occur.

\begin{align}
U_Z &= \int_{i=1}^{n} [\gamma_i^2 H_i^2 + 2(\mu^2/(1-\mu)^2)\gamma_i^2 H_i^2] \frac{2E_i}{2E_i}, \\
U_G &= \int_{i=1}^{n} [(k_1^2 + k_2^2 + k_3^2)\gamma_i^2 H_i^2 - 2\mu(k_1k_2 + k_2k_3 + k_3k_1)\gamma_i^2 H_i^2] \frac{2E_i}{2E_i}, \\
U_C &= (1 + m_1)U_Z + (1 + m_2)U_G, \\
V &= \frac{4}{3}\pi R^3.
\end{align}

Under the influence of external forces such as tectonics are different, and the ability of energy transfer and storage in geological bodies is also different. Natural geological condition and mining effect are the two sources that the energy of dynamic system of coal and rock comes from. Dynamic system of coal and rock located in the tectonic environment and the modern stress field, with dynamic conditions for forming energy accumulation. Through the work such as mining and excavation, the stress of the system will be increasing, the energy will be superimposing, and the system will maintain dynamic equilibrium. At the same time, mining activities will change the energy of the dynamic system, release energy into the system, destroy the structure of the system, and cause dynamic disasters such as dynamic emergence or rockburst.

Total energy of dynamic system is made up of energy under gravity stress field $U_Z$, energy under tectonic stress field $U_G$, and energy under mining induced stress field $U_C$, as shown in formulas (1)–(4) [22]. In this paper, dynamic system is regarded as a spheroid, which the scale radius is $R$, and the volume is $V$, as shown in formula (5). The scale of dynamic system is related to the stored energy and the released energy. Therefore, the actual scale of dynamic system can be determined according to the energy value of rockburst and “high-energy” microseismic events. In this paper, the radius of the dynamic nuclear zone, the damage zone, the injury zone, and the influence zone are expressed by $R$, $R_p$, $R_o$, and $R_v$ respectively. The three-dimensional model of dynamic system of coal and rock is shown in Figure 2.

\begin{align}
U &= U_Z + U_G + U_C, \\
U_Z &= \int_{i=1}^{n} [\gamma_i^2 H_i^2 + 2(\mu^2/(1-\mu)^2)\gamma_i^2 H_i^2 - 2\mu(2(\mu(1-\mu))\gamma_i^2 H_i^2 + (\mu^2/(1-\mu)^2)\gamma_i^2 H_i^2)] \
U_G &= \int_{i=1}^{n} [(k_1^2 + k_2^2 + k_3^2)\gamma_i^2 H_i^2 - 2\mu(k_1k_2 + k_2k_3 + k_3k_1)\gamma_i^2 H_i^2] \
U_C &= (1 + m_1)U_Z + (1 + m_2)U_G, \\
V &= \frac{4}{3}\pi R^3.
\end{align}

(1) Energy under gravity stress field
Under the gravity stress field, the energy stored in dynamic system is related to the mining depth. With the increase of the mining depth, the weight of overlying strata increases, and the energy stored in the system increases.

(2) Energy under tectonic stress field
The energy stored in rock is related to the elastic deformation of the rock mass, and the greater the elastic deformation, the more the energy stored. Dynamic system of coal and rock under tectonic
stress field is also experiencing elastic deformation; dynamic system accumulates energy with the increase of elastic deformation. When the stress reaches the ultimate strength of the rock, the rock will be destroyed. For dynamic system of coal and rock, this part of energy is produced by the combined action of gravity stress field energy and tectonic stress field energy. The energy released from dynamic system of coal and rock is equal to the energy difference between tectonic stress field and gravity stress field, as shown in the following equation:

\[ \Delta U = U_G - U_Z. \] (6)

(3) Energy under mining induced stress field

Due to the influence of mining engineering, the stress state of coal and rock will change, and the energy of dynamic system will also change accordingly. Because of difference in mining areas, mines, coal seams, structures, and stress conditions, the mode of rockburst is different. Therefore, \( m_1 \) and \( m_2 \) should be confirmed by theoretical calculation, numerical calculation, analogue material simulation, etc.

3. Calculation for the Scale of Dynamic Nuclear Zone


The energy of dynamic system is mainly concentrated in the “dynamic nuclear zone.” Similar to the unloading blasting process of coal, at the instance when rockburst or high-energy microseismic event occurs, the “dynamic nuclear zone” of dynamic system will form a huge impact load, which satisfies the von Mises yield criterion. Under the action of the impact load, the outer wall of the “dynamic nuclear zone” of dynamic system is deformed rapidly. The coal and rock mass at the junction of the “dynamic nuclear zone” and the “destroyed area” will generate a shock wave rapidly, which immediately propagates and dissipates to the outer region. In this process, the coal and rock in the “dynamic nuclear zone” is completely broken, as shown in Figure 3. Under the action of the shock wave, the coal and rock mass in a certain range outside the “dynamic nuclear zone” will receive the compressive stress far greater than the dynamic compressive strength of the coal and rock themselves. In this process, the coal and rock in this section will break up under the strong compressive stress, forming a “ring damage zone.” The “damage zone” of dynamic system is formed outside the “dynamic nuclear zone,” as shown in Figure 4.

In the “damage zone” of dynamic system, shock wave is the main form of energy and the strength of which is far greater than the dynamic compressive strength of coal and rock, as shown in Figure 5. Compression failure will occur in coal and rock, the failure criterion of coal in this section is based on the dynamic compressive strength of coal itself, and the boundary condition is that shock wave strength is equal to the dynamic compressive strength of coal itself.

3.2. Calculation of Dynamic Nuclear Zone Radius of Coal Rock Dynamic System.

The energy of dynamic system is mainly concentrated in the “dynamic nuclear zone.” The energy released when rockburst or high-energy microseismic events are monitored by microseismic system and other equipment is provided by the “dynamic nuclear zone” of dynamic system. Under the influence of geological dynamic conditions, the energy of dynamic system mainly comes from tectonic stress field. After the energy transfer and supplement between dynamic system and the outside world, the dynamic system maintains a balanced state. After a rockburst accident occurs, there is still some residual energy in...
The dynamic system. If the energy accumulated in the dynamic system is enough to support the next rockburst accident, the rockburst will reoccur when induced by mining activities and other factors. The radius \( R \) of the “dynamic nuclear zone” of the dynamic system can be deduced and calculated according to formulas (2), (3), and (5)–(7) under the model conditions of the “spherical” dynamic system, as shown in formula (8).

The calculation method of radius \( R \) of “dynamic nuclear zone” in dynamic system needs to be verified by other experimental methods such as liquid CO\(_2\) fracturing technology.

\[
\Delta U = \frac{2\pi y^2 H^2 R^3}{3E} \times \left[ k_1^2 + k_2^2 + k_3^2 - 2\mu (k_1 k_2 + k_2 k_3 + k_1 k_3) - 1 + \frac{2\mu^2}{(1-\mu)} \right],
\]

(7)

\[
R = \sqrt[3]{\frac{3E(1-\mu)\Delta U}{2\pi [2\mu^2 (k_1 k_2 + k_1 k_3 + k_2 k_3 + 1) - \mu (2k_1 k_2 + 2k_1 k_3 + 2k_2 k_3 + k_1 k_2 + k_1 k_3 + k_2 k_3 - 1) + k_1^2 + k_2^2 + k_3^2 - 1] y^2 H^2}}
\]

(8)

### 4. Principle and Equipment of Liquid CO\(_2\) Fracturing


CO\(_2\) fracturing device is a new type of fracturing equipment for coal mining, which mainly comprises of a filling valve, a heating pipe, a main pipe, a sealing gasket, a shearing piece, and a discharge head. Structure and composition of CO\(_2\) fracturing device are shown in Figure 6. The filling valves, the main manifolds, and the discharge heads are reusable, made of high-strength metals, whereas the heating pipes, the gaskets, and the shears are consumables. After taking a fracturing device filled with liquid CO\(_2\) to the borehole, the heating pipe will be turned on by the initiator. The liquid CO\(_2\) in the main pipe gasifies rapidly. The pressure in the main pipe builds up, until the pressure release mechanism breaks the shear fragment, releasing a large volume of CO\(_2\) gas to fracture the coal.

#### 4.2. Mechanism of Liquid CO\(_2\) Fracturing.

Under standard temperature and pressure, CO\(_2\) is a colorless, odorless, and noncombustible gas. When the temperature of liquid CO\(_2\) exceeds 31.1°C while the pressure is held above 7.35 MPa, CO\(_2\) enters the supercritical state. Above the critical temperature, the gaseous substance will remain in its original state and will not continue to liquefy, even if the pressure is higher. CO\(_2\) in its supercritical state is neither gas nor liquid, but presents as a state between gas and liquid, and has the characteristics of both.

When the liquid CO\(_2\) fracturing technology is applied, the fracturing only occurs in the interior of the medium, and there is no free surface in blasting. Most of the gas emitted by
5. Field Verification of Radius Calculation Method for Dynamic Nuclear Zone

5.1. Experimental Layout and Mechanical Parameters of Coal and Rock. We conducted an industrial test on coal pillar side of 5939 roadway, panel 8939, in a coal mine of Shanxi Province by using the ZLQ-53/800 CO₂ fracturing equipment. Its specifications are shown in Table 1. 9 holes with different diameters were drilled, with 3 at 60 mm, 3 at 65 mm, and 3 at 90 mm. According to the degree of coal failure and pressure relief effect, the optimal drilling diameter of CO₂ fracturing is obtained, and the accuracy of radius calculation method for dynamic nuclear zone of dynamic system is verified.

5.2. Determination of Fracturing Effect Parameters. In order to determine the fracture range of liquid CO₂ in panel 8939, we relied on the distributed optical fiber sensing technology to monitor the fracturing effect and influence range. Fibers that carry optical signals are used to sense and transmit measurement results. It is immune to electromagnetic interference, highly sensitive, waterproof and moisture-proof, and capable of long-range and wide-area monitoring. The infrastructure is easy to install, has good material quality, and lasts for a long time. Distributed optical fiber sensing technology is based on Brillouin optical time-domain analysis technology, which can measure the strain of each point in the optical fiber in a distributed way to achieve precise, continuous, and universal monitoring, as shown in Figure 8.

After grouting and sealing, the distributed sensing fiber optic cables and the pressure testing tube are consolidated together with the surrounding coal body to coordinate deformation. We set liquid CO₂ fracturing hole under the fiber optic cable; when coal deformation occurs after pressure relief, fiber optic will sense the deformation of the test tube strain, and then calculate the pressure pipestress distribution curve, according to the stress and strain coefficient of the pressure. Distributed sensing fiber optic cables arranged beside pressure pipes will bend and stretch under the action of surrounding coal. This stretching deformation area is the influence area of coal pressure relief deformation, as shown in Figure 9.

We set a distributed optical fiber monitoring hole at the winch hole location in roadway 5939 near the stopping line.
The winch hole is 1.4 m away from the coal wall, 1.2 m away from the bottom plate. The angle between the optical fiber monitoring hole and the coal wall is 5 degrees. The hole has an elevation angle of 1 degree, a diameter of 65 mm, and a depth of 50 m.

After the completion of the optical fiber hole, we arranged a 50 m long distributed optical fiber sensing cable. Since the fiber optic cables are laid on an inclined surface, the construction is only carried out at 1207 m ∼ 1235 m on the panel for the safety of roadway. A total of 9 liquid CO₂ blasting holes were drilled in 20 cm below the fiber to analyze and monitor the effect of coal fracturing.

5.3. Analysis of Fracturing Effect. The strain of the sensing cable mainly reflects the deformation characteristics of the coal around the borehole along the radial direction of the fiber. Figure 10 shows the strain distribution curve of sensing cable in the monitoring hole. Generally, tensile strain is defined as a positive value and the compressive strain as a negative value. The cable is generally under tensile strain, which indicates that the tension around the borehole occurs along the radial direction of the optical fiber.

The ZLQ53/800 type fracturer is used to construct a drilling hole with a diameter of 60 mm, the distance between the fracturer and the hole wall is 7 mm. The monitoring data showed the maximum strain of coal is about 143.1 με, and the influence radius is about 2.0 m. When the diameter is 65 mm, and the distance is 12 mm, the maximum strain of coal is about 147.8 με, and the influence radius is about 2.6 m. When the diameter is 90 mm, and the distance is 37 mm, the maximum strain of coal is about 127.6 με, and the influence radius is about 1.6 m, as shown in Table 3 and Figure 10. Comparison of the effect before and after 5# drilling blasting is shown in Figure 11. Therefore, according to the experimental results, a drilling hole with a diameter of 65 mm and a distance of 12 mm leads to the best fracturing results, which is considered as the optimal scheme.

According to the fracturing effect enumerated in Table 3, the maximum influence radius of fracturing is 2.0 m for drilling hole with a diameter of 60 mm. According to formula (10), the blasting release energy of liquid CO₂ fracturer

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Table 1: Specifications of liquid CO₂ fracturing instrument.

<table>
<thead>
<tr>
<th>Model</th>
<th>External diameter (mm)</th>
<th>Internal diameter (mm)</th>
<th>Length of main pipe (mm)</th>
<th>Length of reel (mm)</th>
<th>Shear strength (MPa)</th>
<th>Gas loading (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZLQ53/800</td>
<td>53</td>
<td>37</td>
<td>800</td>
<td>250</td>
<td>300</td>
<td>0.530</td>
</tr>
</tbody>
</table>

Table 2: Physical and mechanical indexes of coal seam on panel 8939.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Uniaxial tensile strength (MPa)</th>
<th>Uniaxial compressive strength (MPa)</th>
<th>Hardness</th>
<th>Modulus of elasticity (GPa)</th>
<th>Poisson ratio</th>
<th>Internal friction angle (°)</th>
<th>Cohesive force (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1.34</td>
<td>32.27</td>
<td>3.23</td>
<td>3.66</td>
<td>0.20</td>
<td>29.89</td>
<td>3.67</td>
</tr>
</tbody>
</table>

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Figure 8: Test principle diagram of pressure relief influence range.

Figure 9: Borehole layout plan.

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of panel 8939. The winch hole is 1.4 m away from the coal wall, 1.2 m away from the bottom plate. The angle between the optical fiber monitoring hole and the coal wall is 5 degrees. The hole has an elevation angle of 1 degree, a diameter of 65 mm, and a depth of 50 m.
According to the released energy and formula (8), the radius range of dynamic nuclear zone of dynamic system is $1.72 \, \text{m} \sim 2.17 \, \text{m}$, with an average value of $1.95 \, \text{m}$. The difference between the measurements is $0.05 \, \text{m}$. The maximum influence radius of fracturing is $2.6 \, \text{m}$ for drilling hole with a diameter of $65 \, \text{mm}$. According to formula (10), the blasting release energy of liquid CO$_2$ fracturer is $3.0 \times 10^5 \, \text{J} \sim 6.1 \times 10^5 \, \text{J}$. According to the released energy and formula (8), the radius range of dynamic nuclear zone of dynamic system is $1.37 \, \text{m} \sim 1.73 \, \text{m}$, with an average value of $1.55 \, \text{m}$. The difference between the measurements is $0.05 \, \text{m}$. The maximum influence radius of fracturing is $1.6 \, \text{m}$ for drilling hole with a diameter of $90 \, \text{mm}$. According to formula (10), the blasting release energy of liquid CO$_2$ fracturer is $3.0 \times 10^5 \, \text{J} \sim 6.1 \times 10^5 \, \text{J}$. According to the released energy and formula (8), the radius range of dynamic nuclear zone of dynamic system is $1.37 \, \text{m} \sim 1.73 \, \text{m}$, with an average value of $1.55 \, \text{m}$. The difference between the measurements is $0.05 \, \text{m}$. Monitoring effect of different types of hole is shown in Table 4. The maximum strain value data in Table 4 used to support the findings of the radius of dynamic nuclear zone are included within the article.

### Table 3: Monitoring effect of different types of hole.

<table>
<thead>
<tr>
<th>Drill number</th>
<th>Borehole diameter (mm)</th>
<th>Maximum strain value ($\mu e$)</th>
<th>Maximum impact area (radius) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1#</td>
<td>60</td>
<td>143.1</td>
<td>2.0</td>
</tr>
<tr>
<td>2#</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3#</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4#</td>
<td>65</td>
<td>147.8</td>
<td>2.6</td>
</tr>
<tr>
<td>5#</td>
<td>65</td>
<td>147.8</td>
<td>2.6</td>
</tr>
<tr>
<td>6#</td>
<td>65</td>
<td>147.8</td>
<td>2.6</td>
</tr>
<tr>
<td>7#</td>
<td>90</td>
<td>127.6</td>
<td>1.6</td>
</tr>
<tr>
<td>8#</td>
<td>90</td>
<td>127.6</td>
<td>1.6</td>
</tr>
<tr>
<td>9#</td>
<td>90</td>
<td>127.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Figure 11: Effect diagram of 5# borehole before and after blasting: (a) before blasting, (b) after blasting.
The dynamic nuclear zone radius of the dynamic system is obtained by theoretical calculation, which is subsequently compared to the measurement result. The difference between them is 0.05 m–0.07 m, and the coincidence is 96.9%–97.5%. Good consistency is achieved.

6. Conclusions

(1) In this paper, the concept of dynamic system of coal and rock is put forward, and the relationship between dynamic system of coal and rock and rockburst appearance model is constructed. The dynamic system is divided into four regions: the dynamic nuclear zone, the damage zone, the injury zone, and the influence zone. The relationship between space structure of dynamic system and rockburst appearance is revealed. The energy source of coal and rock dynamic system is clarified.

(2) A method for calculating the radius of dynamic nuclear zone of dynamic system is proposed, and the corresponding evaluation system is established.

(3) The accuracy of the calculation method for the radius of dynamic nuclear zone of dynamic system is verified by the fracturing experimental data of liquid CO₂. The result shows that the degree of coincidence is 96.9%–97.5%, and good consistency is obtained. The method has high reliability and practicability and can be widely used in the rockburst prediction and risk assessment.

(4) The liquid CO₂ fracturing method can be used to simulate the blasting source of rockburst effectively, which could be widely applied in the future.

Nomenclature

- **R**: Radius of dynamic nuclear zone
- **R₀**: Radius of damage zone
- **R₅**: Radius of injury zone
- **R₆**: Radius of influence zone
- **U**: The total energy of dynamic system of coal and rock
- **U₂**: The energy under gravity stress field
- **U₃**: The energy under tectonic stress field
- **U₅**: The energy required for coal and rock failure
- **σ**: The uniaxial compressive strength
- **π**: The constant pi
- **L**: The Influence radius of fracture initiation
- **θ**: The angle of the influence zone, random number between [π/4, π/2]
- **V₅**: The volume of failure fractured coal
- **ΔU**: The released energy
- **V**: The volume of dynamic nuclear zone
- **U**: The radius of dynamic nuclear zone
- **R**: The radius of dynamic nuclear zone
- **C**: The energy under mining induced stress field
- **G**: The energy under tectonic stress field
- **Z**: The energy under gravity stress field
- **S**: The energy required for coal and rock failure
- **E**: The depth of the location of the unit
- **μ**: Poisson’s ratio of the unit
- **κ**: The density of unit bulk
- **π**: The modulus of elasticity of the unit
- **k₁**: The ratio of maximum principal stress to vertical stress
- **k₂**: The ratio of intermediate principal stress to vertical stress
- **k₃**: The ratio of minimum principal stress to vertical stress
- **m₁**: The stress increasing coefficient of coal and rock under gravity stress field
- **m₂**: The stress increasing coefficient of coal and rock under tectonic stress field
- **ν**: The ratio of minimum principal stress to vertical stress
- **μ**: Poisson’s ratio of the unit
- **κ**: The density of unit bulk
- **π**: The modulus of elasticity of the unit
- **k₁**: The ratio of maximum principal stress to vertical stress
- **k₂**: The ratio of intermediate principal stress to vertical stress
- **k₃**: The ratio of minimum principal stress to vertical stress

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


[23] M. G. Qian, P. W. Shi, and J. L. Xu, Mining Pressure and Strata Control, China University of Mining and Technology Press, Xuzhou, China, 2010.

