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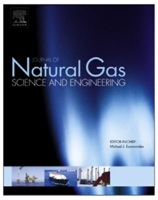

Theoretical analysis and experimental research on the energy dissipation of rock crushing based on fractal theory

Yong Deng [a, b], Mian Chen [a, b, *], Yan Jin [a, b], Daiwu Zou [a, b]

[a] College of Petroleum Engineering, China University of Petroleum, Beijing 102249, China
[b] State Key Laboratory of Petroleum Resources and Prospecting, Beijing 102249, China

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ABSTRACT

The relationship between energy consumption and the rock fragment size distribution is a basic question in rock fragmentation. Based on fractal rock mechanics and fracture mechanics theory, a new model of energy consumption during rock fragmentation is proposed. Moreover, dynamic uniaxial compressive tests on granite and sandstone under five different impact velocities are conducted with the split Hopkinson pressure bar (SHPB) device, the fragment size distribution of broken rock is obtained by sieving and the energy dissipation in the process is analyzed. The results from the tests show that fragments resulting from rock breakage under impact loading exhibit fractal features; the larger the fractal dimension, the higher the degree of rock fragmentation. Notably, the energy consumption density is inversely correlated with the average size of the rock fragments: with an increasing energy consumption density, the average size decreases significantly and the fracture surface area increases accordingly. Additionally, the SHPB tests enable determination of the fracture surface energy of granite and sandstone, and the energy consumption density is calculated based on the theoretical model and found to be in good agreement with the experimental results.

1. Introduction

With shallow oil and gas resources gradually decreasing, the target of oil and gas exploration and development has turned to deep strata in the form of deep and ultra-deep wells, which poses a serious challenge to underground rock engineering and deep drilling engineering. The use of impact energy to drill, a concept that has long been proposed, can enhance the efficiency of rock breaking and meet the demand of deep well drilling (Xu and Yu, 1984; Wang, 1999).

Research and experiments have indicated that the impact drilling technique is an effective and feasible method to break up rock in deep hard formations, offering great potential in geotechnical engineering and mining of petroleum and natural gas (Wiercigroch et al., 2005; H. Li et al., 2010; Akbari et al., 2011; Franca, 2011; Li et al., 2015). The dynamic fragmentation of rock is essentially a process of energy consumption, and energy dissipation analysis is essential to elucidate the mechanism of rock dynamic crushing. Furthermore, energy consumption is not only one of the important indicators to evaluate rock breaking efficiency but also forms a useful metric when optimizing the rate of impact drilling. A series of studies on the energy dissipation characteristics of rock crushing have been performed by a number of domestic and foreign scholars, and valuable research results have been obtained. For example, Hustrulid and Fairhurst (1971a,b, 1972a,b) investigated the energy transfer efficiency of percussive drilling and derived the minimum impact force for optimal energy transfer; Carpinteri et al. (2004) carried out an experimental investigation on concrete specimens under crushing and fragmentation over a large scale range to evaluate the influence of fragment size distribution on energy density dissipation. They concluded that energy density dissipation was proportional to the characteristic size of rock fragments using fractal concepts, but did not obtain a specific functional expression between the dissipated energy and rock fragment size distribution. Lundberg and Okrouhilk (2006); Lundberg and Collet (2010) studied the energy efficiency and the influence of loading waveform on energy transfer efficiency in the percussive drilling process and theoretically obtained the optimum waveform that can produce an energy transfer efficiency equal to 1 (though this was not

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* Corresponding author. College of Petroleum Engineering, China University of Petroleum, Beijing 102249, China.
E-mail addresses: dengyong2012@yeah.net (Y. Deng), chenmiancup@163.com (M. Chen).

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available in practice). Marian et al. (2008) investigated the vibrational energy transfer for percussive drilling and proposed a new method of vibrational energy transfer from high-frequency low-amplitude to low-frequency high-amplitude mechanical vibrations. Sadrai et al. (2011) developed a high-velocity impact comminution apparatus to study the energy efficiency of rock breakage; experimental results suggested that energy efficiency of rock breakage can be improved by two or three times using high velocity impact for the same energy input level. Li et al. (1988) carried out experiments to study the effects of duration and amplitude of stress wave on energy dissipation in sandstone; the results showed that energy absorption per unit volume of rock increased with increasing duration and amplitude of the stress wave, but that excessive duration and amplitude in stress waves would lead to additional energy loss. Xu et al. (2010) studied the effects of confining pressure on energy dissipation of rock under cyclic impact loads; the results indicated that energy absorption increased with increasing number of cyclic impacts but decreased with increasing confining pressure under the same strain rate.

The theoretical and experimental studies on energy dissipation of rock fragmentation cited above primarily concentrated on the relationships among energy consumption, stress waveform, strain rate and confining pressure (see, e.g., Hustrulid and Fairhurst, 1971a,b, 1972a,b; Lundberg and Okrouhilk, 2006; 2010; Li et al., 1988; Xu et al., 2010). However, there has been little research on the quantitative relation between energy consumption and fragment size distribution (Carpinteri et al., 2004; Li et al., 2009). Therefore, this paper is focused on developing a quantitative relationship between energy consumption and rock fragment distribution by means of fractal rock mechanics and fracture mechanics theory and presents a theoretical analysis and results of indoor experiments. Dynamic uniaxial compressive tests on granite and sandstone under five different impact velocities are performed using the large diameter split Hopkinson pressure bar (SHPB) device. Energy density absorption and fracture surface energy of test granite and sandstone under SHPB test are obtained, and the test results indicate that the energy consumption density of rock crushing under impact load is basically consistent with the theoretically derived value, which demonstrates the validity of the theoretical model.

2. Fractal energy consumption model of rock crushing

Fractal geometry was originally developed by Mandelbrot to describe highly irregular and self-similar objects (Mandelbrot, 1982); subsequently, fractal theory was applied to many other scientific fields (Perfect, 1997; Lai and Wang, 2015; Hu et al., 2016). In the field of rock fragmentation, numerous studies have showed that rock fragments exhibit fractal features that reflect the energy dissipation process (Nagahama, 1993; Xie, 1996; Carpinteri et al., 2004). Macroscopic breakage of rock material under a load is characterized by a small group of fragments, whereas minor fracture consists of smaller crack evolution and aggregation, and this similar behavior leads the broken fragments and energy dissipation process to exhibit self-similarity. Using the basic definition of a fractal (Turcotte, 1986), the number of fragments (N) with size is larger than r exhibits a power function correlation with r; that is:

$$N(r) = C_0 r^{-D_f} \tag{1}$$

where D_f is the fractal dimension, r is the size of fragments in mm, and C_0 is a proportionality coefficient.

It can be concluded from the equation above that the cumulative distribution of fragments with size smaller than r is

$$P(r) = 1 - \left(\frac{r_{\min}}{r}\right)^{D_f} \tag{2}$$

Then, the total fracture surface area of fragments can be obtained by integration:

$$A = \int_{r_{\min}}^{r_{\max}} N_t \left(4\pi r^2\right) \mathrm{d}P(r) \tag{3}$$

where N_t is the total number of rock fragments, r_{min} is the minimum size of fragments, and r_{max} is the maximum size of fragments.

Inserting Equation (2) into Equation (3), the total surface area can be written as:

$$\begin{aligned} A &= 4\pi N_t \frac{D_f}{D_f - 2} r_{\min}^{D_f} \left(\frac{1}{r_{\min}^{D_f-2}} - \frac{1}{r_{\max}^{D_f-2}}\right) \\ &\cong \begin{cases} 4\pi N_t \dfrac{D_f}{D_f - 2} r_{\min}^2, D_f > 2 \\ 4\pi N_t \dfrac{D_f}{2 - D_f} r_{\min}^{D_f} r_{\max}^{2-D_f}, D_f < 2 \end{cases} \end{aligned} \tag{4}$$

Similarly, the total volume of rock fragments can also be obtained by integration:

$$\begin{aligned} \mathrm{V} &= \int_{r_{\min}}^{r_{\max}} N_t \left(\frac{4}{3}\pi r^3\right) \mathrm{d}P(r) \\ &= \frac{4}{3}\pi N_t \frac{D_f}{3 - D_f} r_{\min}^{D_f} \left(r_{\max}^{3-D_f} - r_{\min}^{3-D_f}\right) \cong \frac{4}{3}\pi N_t \frac{D_f}{3 - D_f} r_{\min}^{D_f} r_{\max}^{3-D_f} \end{aligned} \tag{5}$$

Rock breaking is the process of new free surface formation. According to fracture mechanics theory (Griffith, 1921; S.Y. Li et al., 2010), the energy dissipated to produce the new free surface in the fragmentation process is provided by the product of the surface energy E_s and the total fracture surface area (the effect of initial surface area is negligible when the particle size after fragmentation is far smaller than the initial size of the rock):

$$W = E_s A = \begin{cases} 3E_s V \left(\dfrac{3 - D_f}{D_f - 2} \cdot r_{\min}^{2-D_f} \cdot r_{\max}^{D_f-3}\right), D_f > 2 \\ 3E_s V \left(\dfrac{3 - D_f}{2 - D_f} \cdot \dfrac{1}{r_{\max}}\right), D_f < 2 \end{cases} \tag{6}$$

Then, the energy required for rock breaking per unit volume is defined as the energy consumption density:

$$E_v = \frac{W}{V} = \begin{cases} 3E_s \left(\dfrac{3 - D_f}{D_f - 2} \cdot r_{\min}^{2-D_f} \cdot r_{\max}^{D_f-3}\right), D_f > 2 \\ 3E_s \left(\dfrac{3 - D_f}{2 - D_f} \cdot \dfrac{1}{r_{\max}}\right), D_f < 2 \end{cases} \tag{7}$$

Equation (7) is the fractal energy consumption density model of rock crushing, which can be directly determined by the rock fracture surface energy and fragment-size distribution.