Journal of Natural Gas Science and Engineering 33 (2016) 287–295

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

A method for hydrofracture propagation control based on non-uniform pore pressure field

Chenpeng Song [a], [b], *, Yiyu Lu [c], Hongmei Tang [a], [b], Yunzhong Jia [c], [d]

[a] Key Laboratory of Hydraulic and Waterway Engineering of the Ministry of Education, Chongqing Jiaotong University, Chongqing 400074, China
[b] National Engineering Research Center for Inland Waterway Regulation, Chongqing Jiaotong University, Chongqing 400074, China
[c] State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400044, China
[d] EMS Energy Institute, Energy and Mineral Engineering & G3 Center, The Pennsylvania State University, University Park, PA 16802, USA

ARTICLE INFO

Article history:
Received 11 December 2015
Received in revised form
6 May 2016
Accepted 8 May 2016
Available online 10 May 2016

Keywords:
Hydraulic fracturing
Coal seam
Pore pressure
Stress intensity factor
Crack propagation

ABSTRACT

Hydraulic fracturing technology, a technique for increasing productivity applicable in low-permeability oil-gas reservoir, has been used in the extraction of coal seam methane in underground coal mines. However, because of the more complex structure of coal seam compared with that of oil-gas reservoir, the hydrofracture propagation can easily extend to roof-floor rocks, limiting the range of permeability and making damages of roof-floor rocks in subsequent coal mining and support difficulty. How to control the hydrofracture propagation well-aligned in a large area of coal seam has become the key to long-time highly effective extraction of coal seam methane. Firstly, it starts with the perspective of stress field of crack tip, by means of thermal elasticity fracture mechanics theory, to get the stress intensity factor of hydrofracture tip while taking pore pressure into consideration. Next, a laboratory fracturing experiment using sandstone specimens was conducted to study the impact of non-uniform pore pressure on the direction of hydrofracture propagation. Lastly, a numerical simulation software RFPA^{2D}-Flow is adopted to further verify the theoretical and experimental results. The study shows that pore pressure can effectively increase the stress intensity factor of the crack tip, the more pressure of pore, the smaller the needed fluid pressure for hydrofracture propagation. In a large area, affected by the direction and distribution of pore pressure gradient, the hydrofracture will propagate along higher pore pressure area. A method is put forward for controlling hydrofracture propagation in underground coal mines accordingly. Meanwhile, the matching relationship between the space between boreholes and the water injection maintaining pressure and maintaining time are studied together, with methods and steps for calculating key fracture parameters established.

1. Introduction

China is rich in CBM (coal bed methane), with a located quantity of geological resource in coal bed reaching 36.81 trillion m^3, making it the third biggest country in this regard (Li, 2002; Li and Hua, 2006). To effectively extract CBM is an important part of the energy strategy and for achieving safe coal production in China. Nonetheless, the storage conditions for CBM are quite complex for over 70% of the coal seams are complicated and of low permeability, making the ground hydraulic fracturing technology for CBM extraction used in such major producing countries as the US, Russia and Australia inapplicable, as evidenced by the fact that ground extraction only accounted for 21.2% of the total extraction (Li et al., 2008; Guo et al., 2014; Lu et al., 2010). Currently, CBM extraction primarily takes place in underground, and such common permeability-increasing technologies as intensive drilling and hydraulic cutting, because of limited ability in increasing permeability, are bothered by problems like large drilling workload, low efficiency in extraction and long time of gas extraction (Liu et al., 2011; Herckenrath et al., 2015; Wang et al., 2014).

In recent years, chinese scholars have proposed a method of increasing permeability in underground coal mine by referring to hydraulic fracturing principle in the field of oil and natural gas (Song et al., 2014a, 2014b). This method aims to crush the coal by

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* Corresponding author. Key Laboratory of Hydraulic and Waterway Engineering of the Ministry of Education, Chongqing Jiaotong University, Chongqing 400074, China.

E-mail addresses: songchenpeng@163.com (C. Song), luyiyu@cqu.edu.cn (Y. Lu), hmtang6778@sina.com (H. Tang), yzj114@psu.edu (Y. Jia).

http://dx.doi.org/10.1016/j.jngse.2016.05.029
1875-5100/

pumping the high pressure water into coal bed through the drilling boreholes (from tunnels to coal seam), so as to expand and connect the existing cracks, form effective gas transport pathways, and thus improving the permeability in coal. Micro-seismic monitoring in field hydraulic fracturing in coal mine indicates that the expansion of hydrofracture in its initial phase could effectively handle coal seam fracture, increasing permeability of coal seam. However, as coal seam is far less thick than oil-gas reservoir and hydrofracture affected by stress orientation and coal seam angle, will propagate to the interface between coal seam and roof and floor board stratum, and it will enter the stratum through the interface, making the scope of permeability-increasing limited and the support of roof and floor board difficult while mining the coal in later phase (Hanson et al., 1980; Anderson, 1981). This will limit the strength of hydraulic fracturing method in its ability to pressure relief and increase permeability in a large spectrum. Thus, how to control the hydrofracture propagation well-aligned in a large spectrum of coal seam has become the key to hydraulic fracturing in underground coal mines.

As for the method for controlling hydrofracture propagation, fracturing for oil-gas reservoir and CBM ground is quite similar in techniques. The control method primarily uses horizontal drilling technology in which well track is effectively controlled by means of special downhole tools and measuring instruments, moving the drill towards the preset target through particular direction, which can substantially increase oil-gas production and reduce drilling cost (Lu et al., 2015; Noritis, 1991; Finfinger and Cervik, 1980). Nevertheless, constrained by tunnel space and coal seam geological conditions, it is impossible to adopt the horizontal drilling technology for hydraulic fracturing in underground coal mines. Our research team has proposed “water jet assisted hydraulic crack control method” (Xia et al., 2013). The method should be done as follows. Firstly, drilling a borehole in the coal seam and slotting with high pressure with water jet, this borehole was used to inject high pressure water. Then, four or more boreholes were drilled around the first borehole, these boreholes were also slotted by high pressure water jet. Finally, high pressure water will be injected into first borehole after sealing all boreholes. The slitting slotted by water jet could control crack initiation site and guide fracture’s propagation. But the effect is limited in field application. Hence, finding a way to control hydrofracture propagation in underground coal mine is an impending science and technical issue that shall be seriously addressed for the increase of the range of fracture and the output of CBM.

Therefore, this research studies the impact of non-uniform pore pressure field on hydrofracture propagation by combining theoretical analysis and laboratory test in following ways. Firstly, it starts with the perspective of stress field of crack tip, by means of thermal elasticity fracture mechanics theory, to get the stress intensity factor of hydrofracture tip while taking pore pressure into consideration. Next, a laboratory fracturing experiment using sandstone specimens was conducted to study the impact of non-uniform pore pressure on the direction of hydrofracture propagation. Lastly, a numerical simulation software RFPA^{2D}-Flow is adopted to further verify the theoretical and experimental results. A method for controlling hydrofracture based on pore pressure in underground coal mine was proposed according to the above mentioned analysis. Last, the matching relationship between the space between boreholes and the water injection maintaining pressure and maintaining time is studied, with key fracture parameters quantified.

2. Stress intensity factor of hydrofracture while considering pore pressure

When there is fluid in pores of coal, a poroelastic medium, the solid skeleton is affected by strength. This strength can be summed up as a volume force in which the force equals to grad p and p stands for the pore pressure in coal mass. Whereas it is necessary to point out that the volume force in elastic skeleton can not be attained through theoretic deduction, an analogy as follows can be applied: if fluid flow in the coal mass pores meets Darcy law, the volume force in the elastic skeleton can be achieved through classic thermoelastic theory (Detournay et al., 1989; Cherepanov, 1979). Here, p stands for $\alpha ET/(1-2\nu)$ in the solution (α is coefficient of thermal expansion,E is elasticity modulus,T is temperature,ν is Poisson’s ratio)According to this analogy, we are considering applying thermal elasticity fracture mechanics to solve the crack problem of porous materials in the event of pore pressure. Firstly, we need to be clear about the stress intensity factor of crack under the conditions of the given temperature field.

We think about the following physical model: suppose we have an isolated disc-shaped fracture whose length is $2a$. On lateral axis of the fracture (where $r<a,\ z=0$) is the scope for heat-source distribution, as shown in Fig. 1.

$$\frac{\partial\theta(r,z)}{\partial r}=\begin{cases}\dfrac{Q\left(r/a\right)}{\alpha} & If \quad 0<r<a, z=0\\ 0 & If \quad r>a, z=0\end{cases} \tag{1}$$

In the above formula, θ is the heat, α is the linear coefficient of thermal expansion, a is the half-length of the fracture, Q is the specific heat capacity and its unit is J/(m·K). To be clear, not as usual as J/(kg·K) to denote specific heat capacity. We used a similar expression J/(m·K). Which means amount of heat per unit length (meter) required to raise the temperature by 1 K. With this, the stress intensity factor on the crack tip shall be (Cherepanov, 1979):

$$K_1=-[(1+\nu)/(1-\nu)]\alpha T_\infty\sqrt{\pi a}\mu\int_0^1 sQ(s)ds \quad K_{II}=K_{III}=0 \tag{2}$$

If a constant heat is given in fracture, to say, $\theta=\theta_0$, the following can be drawn from formula (2):

$$K_I=-\frac{2(1+\nu)\alpha T_\infty Q_0\sqrt{\pi a}\mu}{\pi(1-\nu)} \quad K_{II}=K_{III}=0 \tag{3}$$

In that way, we got the stress intensity factor on the crack tip under the conditions of the given temperature field.

As mentioned above, stress intensity factor of hydrofracture under the condition of pore pressure is attained through the analogy. If in the unlimited porous space there is a $2a$ long disc-

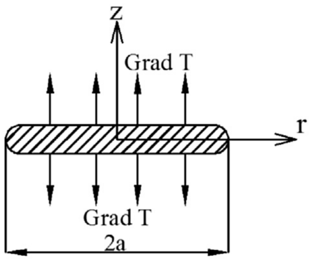

Fig. 1. Fracture model.