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An analytical method to determine rock spallation temperature and degree of heterogeneity in thermal spallation drilling for geothermal energy

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ABSTRACT

Thermal spallation drilling is an alternative technology expected to be suitable for exploitation of geothermal energy in hard, polycrystalline rocks. The rock spallation temperature and degree of heterogeneity are two important parameters for spallation studies. The rock spallation temperature can offer guidance to provide a suitable temperature environment for different formations, and the degree of heterogeneity plays an important role in determining the spallability of rock. However, it is difficult to measure the rock's surface temperature at the onset of initial spallation and there is no universal method to determine the degree of heterogeneity of rock. This paper intends to provide a convenient analytical approach to approximate the rock spallation temperature and degree of heterogeneity for field applications. Based on the Weibull statistical theory of tensile failure, the rock temperature at spallation can be obtained by solving a set of over-determined equations. All other rock properties can be calculated based on the temperature, and then the degree of heterogeneity of rock can be determined. Compared with experimental data, the calculated rock spallation temperature and degree of heterogeneity are all within acceptable ranges. All results in this paper can provide implications for further study on thermal spallation drilling in geothermal reservoirs.

1. Introduction

As a renewable energy resource, geothermal energy offers considerable resource potential, low carbon emission and widespread distribution (Nasruddin et al., 2016; Lyu et al., 2017, 2018a; Sun et al., 2018). Drilling is the key procedure for geothermal energy exploration and development (Judzis et al., 2007; Wei et al., 2016). Traditionally, rock has been drilled and tunneled by imparting mechanical stresses to crush and ablate the rock in order to cause failure, which gives rise to bit wear and limits penetration rate (Lund et al., 2010; Rauenzahn and Tester, 1985). Consequently, alternative drilling methods may have the economic potential.

Thermal spallation drilling is a non-contact and efficient technology for hard rock formations, which has been applied extensively in the 20th century (Calaman and Rolseth, 1968; Browning et al., 1965; Williams, 1986). It uses downhole combustion to generate high temperature media, such as flame jet or laser, to heat the rock at the bottom of the hole. Then, non-uniform expansion stresses are induced by local heating within the rock (Heard, 1980; Li et al., 2014). Due to stresses, thermally-induced fragmentation occurs and disk-like rock fragments are formed in the heated rock's spallation zone. The entire thermal spallation process can be divided into three stages: the initiation stage, the expansion stage and the stripping stage (Fig. 1) (Yan et al., 1999; Tan et al., 2006; Wu and Liu, 2003; Nieckele et al., 2004).

In thermal spallation drilling, the fuel and oxidizer are usually injected to the downhole combustion chamber through coiled tubing, where the fuel and oxidizer are ignited to generate high temperature reaction products (Fig. 1). Since contact is avoided between the combustion chamber and the rock surface, longer life is obtained for the drilling tool, when compared to traditional rotary drilling equipment (Tester et al., 1994).

Thermal spallation drilling was commercially developed for drilling blast holes in the mining industry, starting in 1947, by the Linde Air Division of Union Carbide. These systems used a flame jet-piercing tool to drill blast holes for mining ore. By 1961, the tool had been used in the production of 140 million tons of crude taconite ore, as well as 25 million tons of granite, quartzite, syenite and sandstone (Calaman and Rolseth, 1962; Augustine and Potter, 2007). Research related to thermal spallation drilling mainly focuses on experimental studies on characteristics of rock under high temperature high pressure conditions, and numerical simulation of the initiated microcracks in the rock. Early work by Rauenzahn and Tester et al. established the basis for this study and focused on characterization of fundamental mechanisms of spall formation and ejection, and on modeling fluid flow and heat

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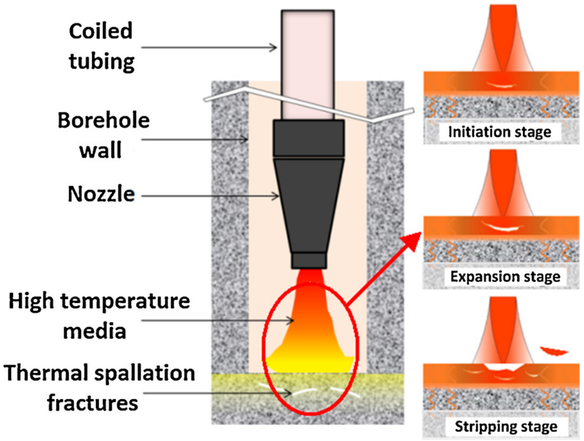

Fig. 1. Bottomhole assembly in thermal spallation drilling and thermal spallation process.

transfer process important for simulating drilling and quarrying conditions observed in practice (Rauenzahn, 1986; Rauenzahn and Tester,1991a). In addition, several analytical models have been developed based on buckling theory (Thirumalai, 1969; Weibull, 1950). Researchers also employed Weibull statistical failure theory to represent the relationship between microstructural heterogeneity and the rock's propensity to spall (Dey and Kranz, 1985; Rauenzahnf and Tester, 1991b). Walsh and Lomov (2013) described a numerical modeling tool designed to conduct explicit simulations of thermal spallation at the grain-scale. The model used an Eulerian-Godunov scheme to simulate solid and fluid mechanical behavior. Moreover, researchers from the Massachusetts Institute of Technology (MIT) and their partners proposed the fluid thermal spallation method, and applied for a patent (Schuler and Martin, 2013). In 2000, the Swiss Federal Institute of Technology in Zurich (ETH) began to research the flow field of fluid thermal spallation and develop the experimental device, and made some progress in characterizing temperature distribution characteristics (Stathopoulos et al., 2012; Stathopoulos et al., 2013; Rothenfluh et al., 2013a; Rothenfluh et al., 2013b). Song et al. also conducted basic numerical simulations associated with the flow field on hydrothermal jet drilling (Song et al., 2016, 2017a, 2017b, 2018; Lyu et al., 2018b, 2018c, 2018d).

Few investigations specifically consider rock heterogeneity. For example, Liu et al. used a statistical method to model rock heterogeneity. Results are in good agreement with those from homogenization modeling (Liu et al., 2004). Most researchers have focused on the thermophysical characteristics of the rock, especially granite. For example, Chen et al. (2017) designed and conducted an experimental program of creep tests to investigate the long-term behavior of granite under relevant repository conditions. Liu et al. (2017) performed deformation experiments on foliated granitic mylonites under high temperature and pressure conditions to investigate the effects of pre-existing fabric properties on the rheology of these rocks. Yang et al. (2017) carried out uniaxial compression tests to evaluate the effect of high temperature treatments on crack damage, strength and deformation failure behavior of granite.

In thermal spallation drilling, it is difficult to measure the rock surface temperature at the exact moment of initial spallation because of the very fast spallation process and interference of ejected spalls. Obtaining temperatures at spallation for different types of rock can help in providing a suitable temperature environment for each kind of rock to obtain the highest drilling efficiency. In addition, the degree of heterogeneity plays an important role in determining the spallability (Rauenzahn, 1986). To the best of our knowledge, there is no universal method to determine the degree of rock heterogeneity. This paper intends to provide a convenient, analytical approach to approximate rock spallation temperature and the degree of heterogeneity, for engineering application. Based on the Weibull statistical theory of tensile failure, the rock temperature at spallation can be obtained by solving a set of overdetermined equations. All other rock properties can be calculated based on the temperature, and then the degree of heterogeneity of rock can be determined. To validate this approach, a case study using granite has been performed.

2. Theoretical analysis and methodology

The Weibull statistical theory of tensile failure has been applied to rock spallation for several decades and proved to be able to better characterize rock heterogeneity compared with other methods (Liu et al., 2004). It correctly models the reported trends of increasing strength as sample volume diminishes, regardless of the type of stress applied (Manson and Smit, 1953). In the case of thermal spallation under high heat fluxes, the approximation that at most a few flaws are active in producing a chip seems valid. The Weibull fracture criterion, stated without derivation, is

$$G = 1 - \exp\left[- \int \left(\frac{\sigma}{\sigma_0} \right)^m dV \right] \tag{1}$$

where G is the cumulative probability that the rock will fail at stress levels below σ. σ_0 represents the Weibull rock strength for one unit volume, Pa. From this relationship, if the relevant volume can be obtained, then the stress and the temperature at "median" spalling conditions ($G = 0.5$) can be computed. m relates to the level of heterogeneity of the rock. If $m = \infty$ (a perfectly homogeneous material with equally spaced flaws of a single size), the rock will always fail at σ_0 (Rauenzahn, 1986).

In order to remove a given microscopic particle of rock from the surface, a flaw must extend and ultimately fail in the rock matrix somewhere in the vicinity of that particle. If one fixes the aspect ratio, or the diameter to thickness ratio of a chip, C_L, the volume that must include the critical flaw is a cone with its apex at the given particle and a radius at depth x of $C_L x/2$. Integration can be performed over all positive x values, and the resulting temperature rise at the surface is (Rauenzahn, 1986)

$$T_s = \left(\frac{(1-\nu)\sigma_0}{\beta E} \right) \left(\frac{u_r}{\alpha} \right)^{3/m} \left(\frac{1.386}{C_L^2 \pi} \right)^{1/m} \tag{2}$$

where T_s represents the surface temperature at spallation, K. ν represents Poisson's ratio (Fig. 2). β is the rock thermal expansion

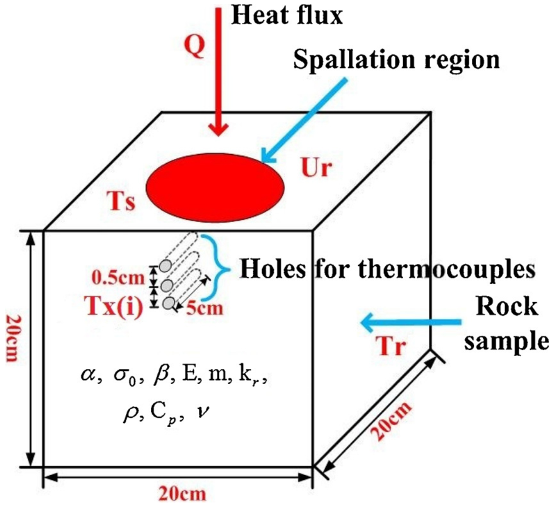

Fig. 2. Schematic diagram of a sample of granite and the relevant thermophysical parameters.