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HYDRAULIC FRACTURING OF LOW PERMEABILITY POROUS MEDIA CONTAINING WATER AT VERY HIGH PRESSURES: EFFECT OF SMALL TEMPERATURE VARIATION

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Abstract. *This article studies the possible inducement of hydraulic by small temperature variations in a rigid porous medium with ultra-low permeability, filled with high-pressure water. An experimental set-up was built in which a single pore is simulated as cylinder at very high pressure, maintaining the fluid over its critical temperature and pressure, so that hydraulic fracture may be induced by very small temperature variations, due to the water compressibility. A generalization of the Tait equation of state – able to account for small temperature variations – is proposed to explain that a small increase of temperature in a pore may cause a large pressure variation that eventually leads the solid matrix to failure. Results are in very good agreement with the proposed theoretical predictions.*

Keywords: *Low permeability porous media; Hydraulic fracture; Heat transfer; Thermodynamics; Enhanced geothermal systems; State law.*

1. INTRODUCTION

This article deals with the possibility of inducing the process of hydraulic fracturing in a low permeability rigid porous medium with the presence of natural pores filled with water at very high pressure through small temperature variations. Basically, although the concepts of porosity and permeability are associated, materials with the same porosity may have very different permeabilities. Porosity is a static quantity, while permeability can be enhanced and this work aims to verify the possibility of inducing the process of hydraulic fracturing when water at high pressure (filling the rigid porous matrix) is subjected to a small temperature increase. This process is known as hydraulic fracturing, when liquids or gases are pressurized within a confined area of a water well borehole to open existing bedrock fractures or part of the bedrock matrix to increase permeability.

This article aims to show, experimentally, that for a fluid over its critical temperature and pressure, very small temperature variations are sufficient to induce a hydraulic fracturing process. Essentially, at high pressures and temperatures, due to the fluid compressibility, a small increase of temperature in a pore may cause a large pressure variation that eventually leads the solid matrix to failure. If the fluid pressure inside a pore increases beyond a given limit, it can fracture the solid matrix. This phenomenon is explained by a proposed equation of state, a generalization of the Tait equation of state restricted to barotropic fluids, to account for small temperature variations.

In the XIX century, the concept of fracturing was already used by employing nitroglycerin to stimulate oil production in wells. The well-acidizing operation, used since the 1930s, consists of injecting acids to fracture the surrounding rocks provoking a flow channel to the well and enhancing its productivity. Hydraulic fracture was started in the 1940s for extracting natural gas and, in the 1950s, water (with additives) was already an important fracturing fluid. Recently hydraulic fracturing is being successfully employed in shale gas extraction (Montgomery and Smith, 2010). However, the additives are always reported as dangerous to the environment.

Another important phenomenon related to the flow of hot water in porous rocks is the energy generation using a process known as "Hot Dry Rock Technology" or "Hot Fractured Rock" (HFR) or "Enhanced Geothermal System" (EGS) (Zeng et al., 2014; Jiang et al., 2014; Hu et al., 2013). These systems require three basic factors: water, permeability of the rocks and heat. An appropriate location presenting a large mass of sub-horizontal hot rocks with adequate permeability should be selected. However, if the permeability is not sufficient it could be enhanced using hydraulic fracturing. Deepwater drilling into productive geothermal zones involves very high internal pressures due to very high depths.

This work aims to show that when a fluid is over its critical temperature and pressure hydraulic fracture may be induced by very small temperature variations; it is not concerned with the modeling of the fracture propagation or with the fluid flow. Essentially, a very small temperature increase (about 1 K) in a pore may cause a large pressure variation that eventually may lead the solid matrix to failure, due to compressibility. A fluid pressure increase beyond a given limit can lead the porous medium to fracture. The analysis considers a single pore filled with water surrounded by a rigid matrix. The procedure presented in this work could be an alternative to minimize the use of chemicals in fluids for fracturing shale rock, reducing the contamination of shallow water wells in the vicinity of the deep natural gas wells.

2. EXPERIMENTS: EFFECT OF SMALL TEMPERATURE VARIATIONS IN A SLIGHTLY DEFORMABLE VOLUME FILLED WITH WATER

The goal of this study is to present simple examples of how small temperature variations can affect pressure in a slightly deformable system filled with water. Essentially, the cylinder models a single pore filled with water surrounded by a rigid matrix.

The experiments were carried out employing a system originally conceived for testing composite repair systems in corroded pipelines (Costa Mattos et al., 2009; 2012). Considering an initial internal pressure p_0 at temperatures around 80°C (353.15 K), the hydrostatic tests were carried on using a hydrostatic testing system Flutrol FLUASF100-MS7, shown in Fig. 1. The hydrostatic testing system is connected to a 7.5 kW Schulz compressor, also depicted in Fig. 1

Figure 1. Hydrostatic testing system.

Figure 2 shows the pressure and temperature control system and specimen (cylinder). The electrical resistance is threaded at one extremity of the specimen and it is connected with the pressure water machine (depicted in Fig. 1) and the thermostat. The system allows controlling the temperature variation (using a type J thermocouple with accuracy of $\pm$ 0.75% $\times$ temp K). The pressure transducer accuracy (static error and total error band) is 0.5 bar. The mass of fluid inside the specimen is constant and the volume variation of the cylinder is very small. Both pressure and temperature are recorded simultaneously. API 5L grade B steel pipes were used to build the specimens for hydrostatic tests with 50.8 mm (2”) diameter and 5.54 mm wall thickness.

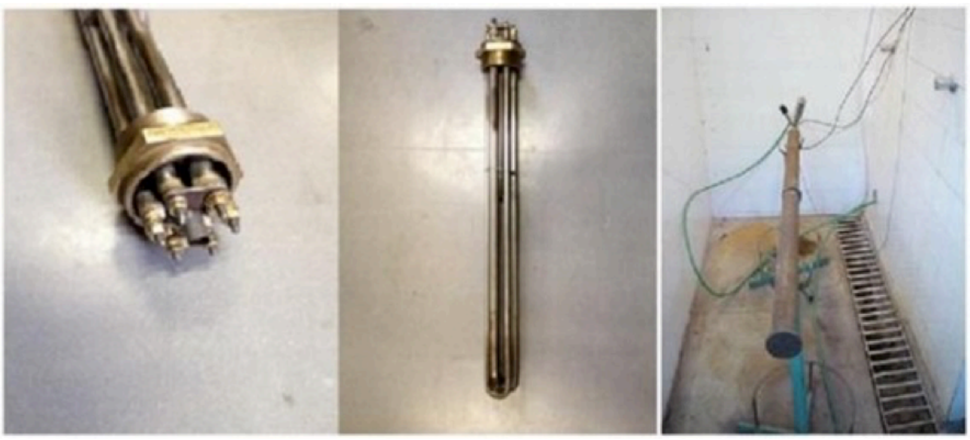

Figure 2. Pressure and temperature control system and specimen (cylinder).

Figure 3 shows the pressure variation obtained in a hydrostatic test performed in the closed system – a fixed mass of water inside the cylinder – described before. Peaks of pressure (up to 70 bars) can be verified, even with a limited temperature variation (always bellow 6 K). The pressure peaks depicted in Fig. 3 can be explained using an extension of the Tait equation proposed for small variations of temperature of liquid water at high pressures in the next section.

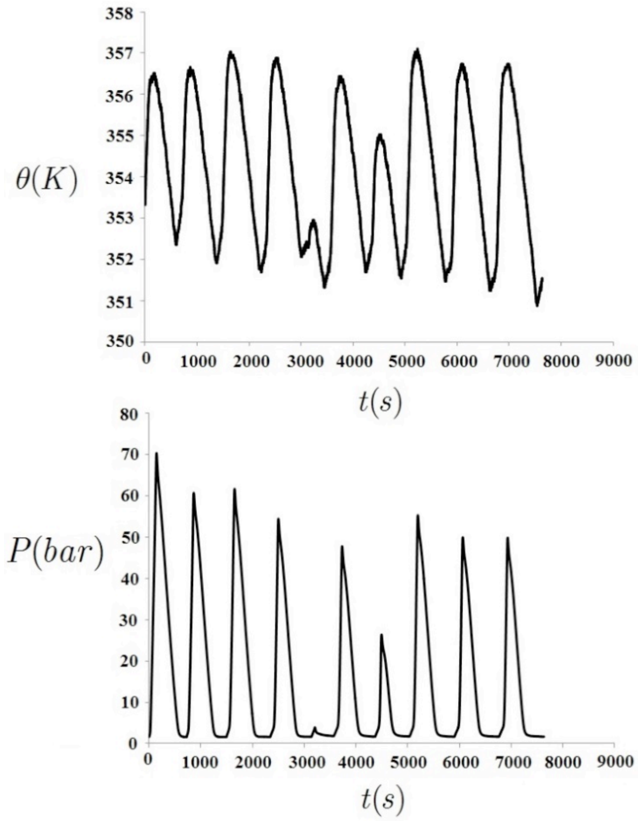

Figure 3. Pressure peaks induced by small temperature variations.

3. GENERAL MODELLING

The first and second laws of thermodynamics may be stated as

$$\rho\dot{e} = -div(\boldsymbol{q}) + \boldsymbol{T} : \boldsymbol{D}$$
$$d = (d_1 + d_2) \geq 0 \quad \text{with} \quad d_1 = \boldsymbol{T} : \boldsymbol{D} - \rho(\dot{\psi} + s\dot{\theta}) \quad \text{and} \quad d_2 = -\frac{1}{\theta}\boldsymbol{q} \cdot \boldsymbol{grad}\big(\theta\big) \tag{1}$$

where the material time derivative of ( ) is denoted by $\dot{(\ )}$; is the mass density by ρ; Cauchy stress tensor by $\boldsymbol{T}$; the deformation rate tensor by $\boldsymbol{D}$; the internal energy per unit mass by e, the absolute temperature by θ; the total entropy per unit mass by s; the Helmholtz free energy per unit mass by $\psi = (e - \theta s)$; the heat flux vector by $\boldsymbol{q}$ and the rate of energy dissipation per unit volume by d. This local version of the second law does not exclude the possibility of unusual behaviours such as a decreasing temperature when heat is added to the medium; this could be achieved by restricting this study to fluids that always satisfy a further constraint on the intrinsic and thermal dissipation, respectively: $d_1 \geq 0$ and $d_2 \geq 0$.

Considering a particular family of compressible fluids in which the stress is considered to be equal in all directions for any given strain rate, the free energy is a differentiable function of the absolute temperature and of the density: $\psi = \psi(\rho,\theta)$. At this point it is important to introduce a dissipation potential ϕ which is a differentiable, convex and isotropic function of $\dot{\rho}$ and θ. The potential ϕ is a convex and differentiable function of $\dot{\rho}$ and θ such that the intrinsic dissipation d_1 and the thermal dissipation d_2 are supposed to have the following form

$$d_1 = \dot{\rho}\frac{\partial \phi}{\partial \dot{\rho}} \qquad \phi = \phi(\dot{\rho},\theta); \quad \phi(\dot{\rho},\theta) \geq 0 \quad \forall\ (\dot{\rho},\theta) \qquad \phi(\dot{\rho} = 0,\theta) = 0$$
$$d_2 = \frac{\boldsymbol{q} \cdot \boldsymbol{q}}{\theta k} \tag{2}$$

in which k is the thermal conductivity. If $\phi \equiv 0$ (and, therefore $d_1 = 0$) the fluid will be called *Pascalian.* The first equation of Eq. (2) implies that $d_1 = 0$ when $\dot{\rho} = 0$.

4. A GENERALIZATION OF THE TAIT EQUATION TO ACCOUNT FOR SMALL TEMPERATURE VARIATIONS

At this point, using the abstract framework proposed by Da Costa Mattos et al. (2015), the following expressions for the thermodynamic potentials ψ and ϕ are proposed:

$$\psi(\rho,\theta) = \left[\frac{(p_o + B)}{\gamma - 1}\rho^{\gamma-1}\left(\frac{1}{\rho_o}[1 - \eta(\theta - \theta_o)]^{-1}\right)^{\gamma} + B\rho^{-1}\right] \qquad \phi \equiv 0 \tag{3}$$

where p_o and ρ_o are the thermodynamic pressure and density at a reference state; and B, γ and η are positive parameters. The thermodynamic pressure is then given by (Da Costa Mattos et al., 2015)

$$p = (p_o + B)\left(\frac{\rho}{\rho_o}\left[1 - \eta(\theta - \theta_o)\right]^{-1}\right)^{\gamma} - B \Rightarrow \frac{\rho}{\rho_o} = \left[\frac{p + B}{p_o + B}\right]^{(1/\gamma)}\left[1 - \eta(\theta - \theta_o)\right] \tag{4}$$

Now the Tait equation of state will be generalized to include very small temperature variations (eq. (4)). The original Tait equation of state models water as a compressible, barotropic liquid, its bulk modulus being an affine function of pressure. The Tait equation is a highly non-linear equation involving only density and pressure as variables, given by

$$p = (p_o + B)\left(\frac{\rho}{\rho_o}\right)^{\gamma} - B \Rightarrow \rho = \rho_o\left[\frac{p + B}{p_o + B}\right]^{(1/\gamma)} \tag{5}$$

where p and ρ denote the pressure and the density, respectively; p_0 and ρ_0 are the pressure and density at a reference state; and B and γ are positive parameters.

Eq. (4) is an alternative constitutive equation – namely a generalization of the Tait equation (Eq. (5)) – accounting for very small temperature variations from a reference temperature θ_0, but, eventually, η can be a positive pressure-dependent parameter. It is important to note that the pressure peaks observed experimentally – and shown in Fig. 3 – can be explained using eq. (4) proposed for small variations of temperature of liquid water at high pressures.

At this point some comments about the parameters B and γ that appear in the Tait equation must be made. Farhat et al. (2008) state that a reasonable approximation for these parameters is: $B = 2.9 \times 10^3$ bar and $\gamma = 7.15$. It should be noted that these parameters are pressure-dependent and a careful analysis must be performed before using average constant values.

Table 1 presents the variation of density and bulk modulus of water for a pressure of 1 atm (1.01325 bar).

Table 1. Variation of some water properties with temperature at 1 atm.

Temperature θ (K)	Density ρ (Kg/m^3)	Bulk Modulus K (bar)
283.15 (10ºC)	1000	19900
293.15 (20ºC)	998	22100
303.15 (30ºC)	996	22600
313.15 (40ºC)	992	22900
323.15 (50ºC)	988	22900
333.15 (60ºC)	983	22800
343.15 (70ºC)	978	22400
353.15 (80ºC)	972	22000
363.15 (90ºC)	965	21400
373.15 (100ºC)	958	20700

The results presented in Table 1 can be better visualized in Fig. 4 that depicts the variation of density with temperature, with $\rho \times \theta$ at the left-hand side and $(\rho / \rho_0) \times (\theta - \theta_0)$ at the right-hand side. It can be observed a very small variation of density with temperature, in the considered temperature range.

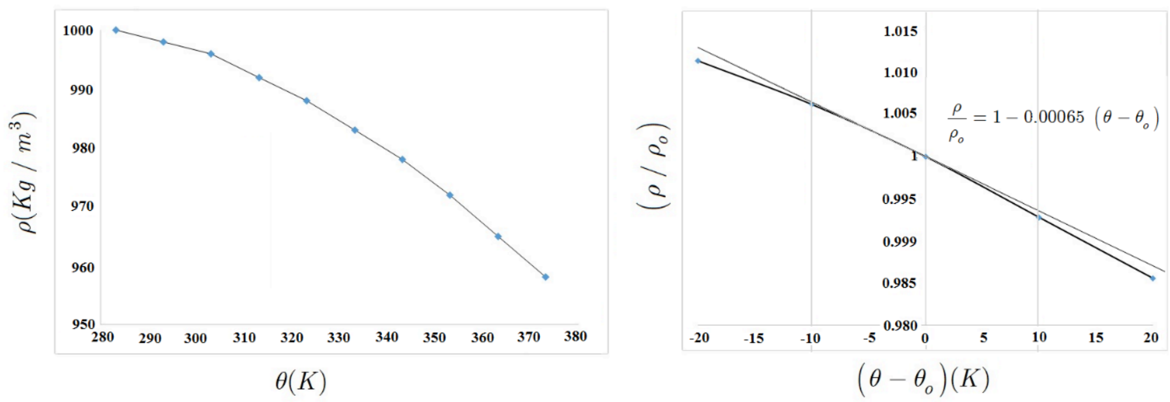

Figure 4. Variation of density with temperature. Water at a constant pressure of 1 atm.

The curves $\rho \times \theta$ and $(\rho / \rho_0) \times (\theta - \theta_0)$ presented in Fig. 4 can be useful to identify the additional parameter η that appears in Eq. (4). Taking θ_0 = 353.15 K (80^{o}C) and ρ_0 = 972 (kg/m^3), for a temperature variation of less than 10 K, the curve can be approximated by the linear equation $(\rho / \rho_0) = 1 - \eta(\theta - \theta_0)$ (see eq. (4)), with $\eta = 0.00065$ K^{-1}. Hence, assuming small temperature variations from the reference temperature θ_0, it is reasonable to assume a constant value $\eta = 6.5 \times 10^{-4}$ K^{-1}. Therefore, although the curve $\rho \times \theta$ presents a non-linear behaviour, it can be approximated by a linear function in the neighbourhood of the reference temperature θ_0.

Once the parameters η and γ are defined, the parameter B can be identified experimentally using Eq. (4), Table 1 and the definition of the bulk modulus K

$$K = \rho \frac{\partial p}{\partial \rho} = \gamma(p_0 + B)\left(\frac{\rho}{\rho_0}\left[1 - \eta(\theta - \theta_0)\right]^{-1}\right)^{\gamma} \tag{6}$$

The value of B, assuming $\gamma = 7.15$ and $\eta = 6.5 \times 10^{-4}$ K^{-1}, is 3075 bar, what is in reasonable agreement with the value suggested by Farhat et al. (2008). However, since all these parameters are in reality pressure-sensitive, it is suggested to use corrected average values for higher pressures. The average parameters suggested for a reasonable approximation for pressures up to 100 bar are presented in Table 2.

Table 2. Water. Average material parameters suggested for pressures up to 100 bar.

B (bar)	γ	η (K^{-1})
2.9×10^3	Between 5 and 6	6.5×10^{-4}

Figures 5 and 6 show a comparison between experimental and predicted pressures for the experimental temperature history depicted in Fig. 3, for two limit values of the parameter γ, using eq. (4) and assuming that $(\rho / \rho_O) \approx 1$. It is important to note that the approximations are quite reasonable, besides the simplicity of eq. (4).

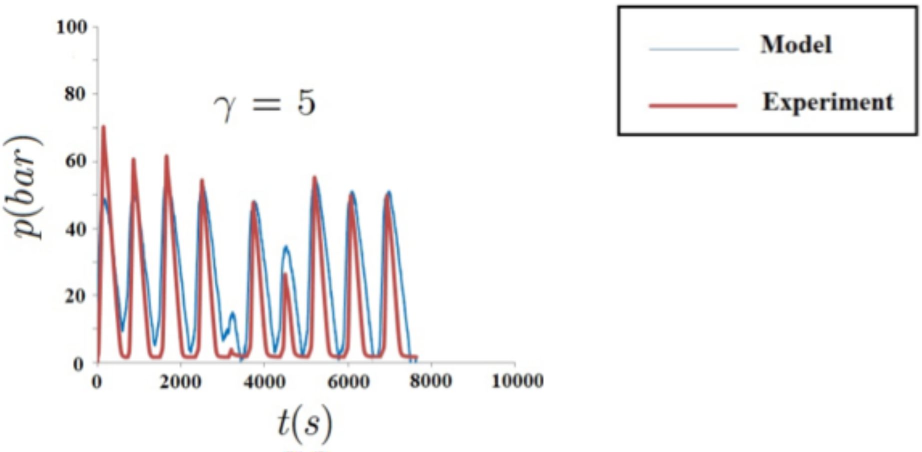

Figure 6. Model prediction of pressure history for $\gamma = 5$.

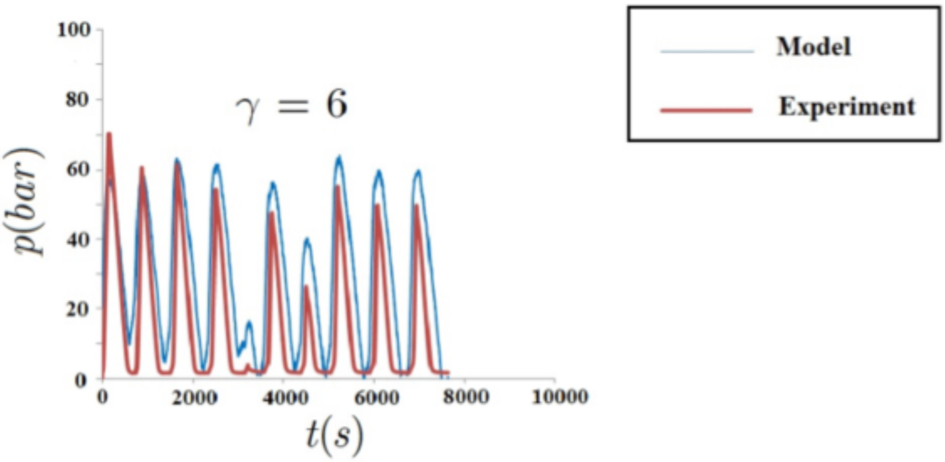

Figure 6. Model prediction of pressure history for $\gamma = 6$.

Of course, in the case of a closed region (constant mass of fluid), the density ρ tends to increase when a higher pressure is applied: $(\rho / \rho_0) > 1$. However, for a very rigid medium, the density variation is very small (Da Costa Mattos et al., 2015). So, the following equation can be used by engineers and designers

$$p = \frac{(p_0 + B)}{\left[1 - \eta(\theta - \theta_0)\right]^{\gamma}} - B \tag{7}$$

5. CONCLUSIONS

This paper analysis the possibility of inducing the process of hydraulic fracturing in a low permeability rigid porous medium with the presence of natural pores filled with water through small temperature variations. Such kind of procedure may be interesting, for instance, in Enhanced Geothermal System (EGS). Since the analysis may be extended to other fluids, it could be a reasonable alternative to minimize the use of chemical in fluids for fracturing shale rock, reducing the contamination of shallow water wells in the vicinity of the deep natural gas wells.

Due to the fluid compressibility and depending of the fluid temperature and pressure, it is shown, both theoretically and experimentally, that a small increase of temperature in a pore may cause a pressure surge that may eventually lead the solid matrix to failure.

Although the complete set of governing equations is highly nonlinear (see Da Costa Mattos et al., 2015) and the numerical approximation of a general non-isothermal compressive fluid flow is very complex, a simple and effective algebraic equation (Eq. (7)) can be used to estimate the pressure surge in a pore due to a small temperature variation. The theoretical predictions using such a simple equation are in good agreement with experiments, even for reasonable complex pressure histories.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE