FRACTURING TIGHT ROCKS BY ELEVATED PORE-WATER PRESSURE USING MICROWAVING AND ITS APPLICATIONS

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1. ABSTRACT

This paper proposes to fracture unconventional tight rocks with microwave (or electromagnetic wave (EM)) heating. The idea is based on the fact that when the temperature of water in a confined space, e.g., within a pore inside tight rock, increases, water cannot freely expand and consequently the pressure within water-filed pores quickly elevates to the point where it exceeds the rock's tensile strength and breaks the rock. Microwave heating can rapidly increase the temperature of water in the tight rock due to the relatively large dielectric loss of innate water. This method works well for rocks with low permeability where water pressure leak off during the rapid heating is negligible in practice. This paper presents both the theory and results of our preliminary laboratory tests of the microwaving heating method for tight rocks. The feasibility and benefits of using microwave or EM heating to fracture unconventional tight reservoir are also discussed. Furthermore, the test results demonstrate that microwaving of shales sometimes pulverizes them. When the sample is pulverized, it is likely that 100% of the light hydrocarbons are released. Hence, the proposed method also may provide insight into total recoverable light hydrocarbons per kilogram rock.

We propose to use microwave (or EM) heating to fracture tight rock and measure the tensile strength of the tight rocks. Tensile strength is a critical parameter needed to design and model hydraulic fracturing (or crack initiation and propagation) in oil and gas reservoirs, especially in shale reservoirs. The strength is estimated from the water-pore pressure (elevated through microwave heating) when the rock sample fails. Conventional methods for measuring rock tensile strength are time consuming and require precision "machined" samples and heavy mechanical instruments.

2. INTRODUCTION

Hydraulic fracturing from horizontal wells has been essential to commercially produce hydrocarbon from shale reservoirs and other tight reservoirs. The key reason is that the permeability of these reservoirs is extremely low. Permeability for tight reservoir is traditionally defined as less than 0.1 mD (Law and Curtis, 2002). The matrix permeabilities for shale reservoirs probably are less than 1 μD with many in the nD or less range (Luffel et al., 1993). The water-based fracturing fluids (that are now most commonly used in hydraulic fracturing) include about 99% fresh or recycled water, a precious resource for regions or locations lacking of water resources, such as the Middle East. Thus, development of water-free or water-efficient fracturing techniques is highly desirable.

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This paper proposes a method to fracture unconventional tight rocks using microwave (or electromagnetic (EM) wave) heating. This water-free method takes advantage of the extremely low permeability of these tight rocks. The idea is based on the fact that when the temperature of water in a confined space, e.g., within a tight rock, increases, water cannot freely expand its volume and consequently the water pressure within the water-filed pores quickly increases. When the pore-water pressure exceeds the rock's tensile strength, the rock fails. Microwave heating can rapidly increase the temperature of water in the rocks due to the relatively large dielectric loss of innate water. This method works well for rocks with low permeability where water pressure leak off during the rapid heating is negligible in practice. This paper presents both the theory and results of our initial laboratory tests for the microwaving heating method.

EM heating has long been recognized to cause differential heating of different minerals in the rocks and has been suggested for applications in energy related industries such as mineral processing, coalbed methane production, and oil-shale retorting and production. Differential heating by EM generates inhomogeneous strain in rocks and induces cracks

(Cooper and Simmons, 1977). The first publication of selective heating/transparency on different rock minerals by microwave was probably in 1984 (Chen et al., 1984). The experiments showed that most silicates, carbonates, and sulfates were almost transparent to microwave. In contrast, most sulfides arsenides and sulfosalts heat rapidly and to high temperature with only short-time exposure to microwave radiation. The effect was quickly recognized to be useful for rock grinding (Walkiewicz et al., 1989) and mineral separation (Kingman et al., 1998). Microwave heating was also known to pyrolyze coals (Fu and Blaustein, 1969) and to improve coal grindability (Lester et al., 2005). A recent experiment demonstrated that a short burst (3 s) of large power (15 kW) microwave induced fractures and increased cleat apertures in coal under isotropic stress (Kumar et al., 2011). EM heating has also been suggested early on to produce oil shale, tar sand, and coal (Bridges and Taflove, 1979). Specifically for oil shale, EM heating is proposed to retort kerogen into light hydrocarbon *in situ* so it can be produced. Fracturing oil shale was also suggested due to thermal gradient from inhomogeneous EM heating. The physics behind the majority of these applications includes two aspects: minerals heat adsorption ability and thermal expansion coefficient. EM heats some components of the formation very efficiently and the thermal expansiveness of minerals differs. Consequently, fractures are generated in the rocks when temperature increases. Shown in Table 1 are thermal expansiveness for some typical minerals and water. The thermal expansiveness is defined as $\frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$ in which V is the rock volume; T and p are the temperature and pressure, respectively. From Table 1, the thermal expansiveness of water is much larger than those of the rock minerals.

While all the above applications have been based on the heterogeneous mineral responses to EM heating, this paper focuses on the pore-water pressure increase in tight rocks due to EM wave heating and demonstrates that the latter is a very effective mechanism to breaks tight rock. We also developed the theory for calculating pore-water pressure elevation when water is heated. To our knowledge, this work is probably the first one to systematically investigate rock fracturing or failure induced by microwave-heated pore-water using both theoretical and experimental means.

As a specific application of the rock fracturing mechanism discussed above, this paper demonstrates that microwave heating can be used to measure tensile strength of tight rocks. Tensile strength is the maximum stress a rock can withstand under stretch before failing. It is important for engineering applications involving potential rock tensile failure (Goodman, 1898; S. and Hsu, 2001). In oil and gas related applications, the tensile strength, for example, is a key parameter in both designing hydraulic fracturing to stimulate unconventional reservoir and determining wellbore stability during drilling (Fjær et al., 2008). Laboratory techniques to measure the rock tensile strength include the direct uniaxial tensile test and indirect tests, while the former is theoretically the simplest, but in fact difficult to carry out in practice (Nova and Zaninetti, 1990). Among indirect tests, the mostly commonly used one is the Brazilian test involving diametrical compression of thin rock discs (Bieniawski and Hawkes, 1978). As will be discussed later in this paper, our microwave heating method is relatively easy to implement, does not require large instruments, and can be used for irregular samples.

This paper is organized as follows. We first discuss our theory for calculating pore-water pressure elevation when water is heated and the method to estimate the tensile strength. We then present some initial experimental results, and, finally, we discuss the potential advantages of using microwave heating as a technology to fracture tight rock.

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Table 1. Thermal Expansion coefficient of typical minerals found in shales. The data are at 293°K (or 20°C) unless noted.

Rock Type	Thermal Expansion Coef, ($1/^oK$)	Reference
Berea Sandstone (dry)	1.5×10^{-6}	(Jaeger et al., 2007)
Boom Clay (wet)	3.3×10^{-6}	(Jaeger et al., 2007)
Calcite	13.1×10^{-6}	(Rosnnnolrz and Surru)
Water	6.6×10^{-5}	(Jaeger et al., 2007)
Pyrite	9.7×10^{-6} (40^oC)	(Press, 1949)

3. METHOD

3.1 Outline of Method

When water is heated, its temperature elevation leads to pressure and/or volume change. As water is heated in tight rocks of low permeability, its volume expansion is confined by the rock matrix and thus cannot expand freely. As the result, the water pressure increases rapidly. In this section, we first

consider how water changes with temperature in free space, based on the equation of state of water. We then consider the case when water expansion is restricted to a confined space, e.g., a rock pore, to calculate how it responds to temperature increase. The following two scenarios are considered herein: an ideal one where the rock matrix, the solid phase, is completely rigid and does not compress and a realistic one where the rock matrix is compliant, compressing as pore-pressure increases.

We then relate the tensile strength measured using elevated pore-water pressure method to the traditional pulling method. Finally, we discuss how EM heats a rock with water through dielectric loss of materials.

3.2 Equation of State for water

The water pressure increase attributed to heating water in the rock sample is obtained from the equation of state (EOS). The EOS for water can be expressed as:

$$z = \frac{p_w V_w}{R T_w} \tag{1}$$

where R = 0.461526 kJ·kg^{-1}·°K^{-1} is the specific gas constant of ordinary water (Cooper, 2007), T_w is the temperature in degrees Kelvin, p_w is the pressure in MPa, and V_w is the volume of water in m^3, and z is sometimes referred to as the compressibility factor. It is more convenient to use molar density of water in our calculation, so we convert Eq. (1) to

$$z = \frac{p_w}{R T_w \rho_w} \tag{2}$$

where ρ_w is the density in kg/m^3.

As a most important substance, water has been thoroughly studied and many different formulations for water EOS have been proposed. Here we use the EOS published by the International Association for the Properties of Water and Steam (IAPWS) (Cooper, 2007; Wagner and Pruß, 2002) based on experimental data, covering the following temperature and pressure ranges:

$$0°\mathrm{C} \le T \le 800°\mathrm{C}, \quad p \le 100\ \mathrm{MPa} \tag{3a}$$

$$800°\mathrm{C} \le T \le 2{,}000°\mathrm{C}, \quad p \le 50\ \mathrm{MPa} \tag{3b}$$

These temperature and pressure ranges cover the full range of application and experiments discussed and anticipated. The IAPWS formula for Eq. (2) contains several dozens of parameters and is generally handled using a computer program. We developed a computer program using Matlab for this purpose based on an open source program (Holmgren, 2006). The program can calculate the required properties for water in the pressure and temperature range defined by (3a) and (3b).

The EOS of water in small pores may deviate from the above equation. The correction requires significant amount of experimental data to evaluate. Thus, we use the EOS discussed above in this study as the first step, which is not expected to introduce significant errors for practical applications.

3.3 Pore-water pressure increase with constant water density

First we consider an ideal scenario where the rock is strong enough so that rock does not deform under an elevated water pressure. In this case, the water volume in the pore does not change and the density of water remains constant. The net outcome of temperature increase is to raise the water pressure. This temperature-dependent pressure can be obtained from the water EOS directly at constant water density.

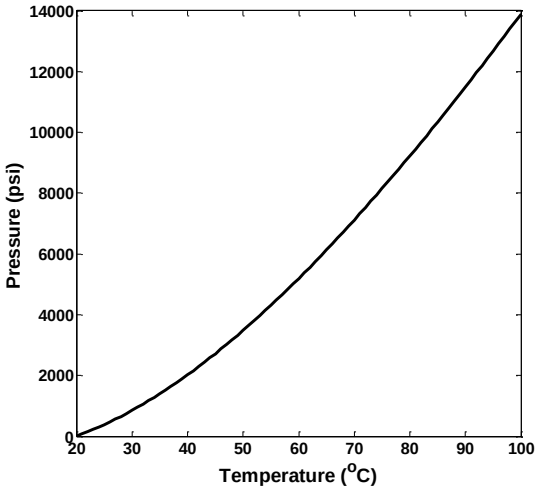

Fig. 1. Temperature-dependent pressure for water in a rock without leak off and volume expansion with initial condition at 1 ATM and 20°C.

The calculated pressure build-up, as a function of temperature, is shown in Fig. 1, with initial condition of water at room condition of 1 ATM and 20°C. In this ideal situation, the pressure increases rapidly. The tensile strength of shale rock is approximately

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1,000 psi (Lin, 1983). From Fig. 1, it can be seen that the pressure reaches this value when the temperature increases only approximately 10°C. We note that for an infinite bulk modulus the pressure increase does not depend on the volume of water in the rock as long as the water filled porosity is not zero.

3.4 Pore-water pressure change in compliant rock

In this section, we consider that the rock solid-phase is compressible under the pressure exerted by the heated water. This allows the water to expand when heated. The rock compressibility and the associated water expansion reduce the rate of pressure build-up due to the water heating.

Fig. 2 illustrates schematically how the elevated water pressure in multiple pores compresses the rock matrix. All the rocks considered in this paper are tight with fine grains and small pores. The perturbations to the *in situ* stress field due to the presence of the water-filled pores are localized to within a few radii of the pore (Jaeger et al., 2007) . Therefore, change in the bulk rock volume owing to the elevation of the pore-water pressure can be practically ignored. In this case, the volume change of the rock matrix caused by the water compression should be equal to the expansion of the trapped water volume, or

$$dV_m = -dV_w \tag{4}$$

where d indicates the volume change; V_m and V_w are the volume of matrix (solid phase) and water, respectively. The pressure exerted on the rock matrix, p_m, equals the pore pressure from the water, p_w. The differential form of this equality is

$$dp_m = dp_w \tag{5}$$

Under the pressure, the volume change of the rock matrix depends on the matrix (solid phase) modulus K_m as

$$K_m = -V_m^0 \frac{dp_m}{dV_m} \tag{6}$$

where V_m^0 is the initial rock solid-phase volume, i.e., the rock solid-phase volume at time zero. From Eqs. (4), (5) and (6), we obtain

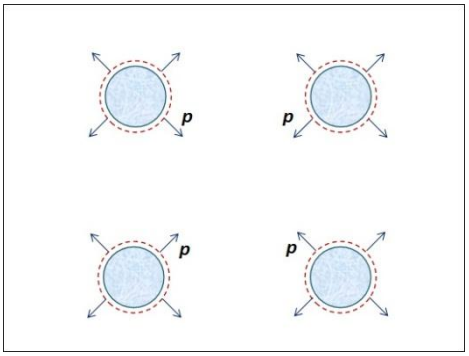

Fig. 2. Schematic illustrating the effect of elevated pore pressure due to the expansion of water on the compressible rock matrix. Dashed circles depict minor pore expansion.

$$dp_w = \frac{K_m}{V_m^0} dV_w \tag{7}$$

Using the following relationships

$$V_w^0 = x_w V_r^0 \tag{8a}$$

$$V_m^0 = (1 - x_w) V_r^0 \tag{8b}$$

where x_w is the water content defined as the volumetric fraction[1] of water to the total rock and V_r^0 is the initial bulk volume of a rock sample, Eq. (7) becomes

$$dp_w = \frac{K_m}{(1 - x_w) V_r^0} dV_w . \tag{9}$$

Further using

$$dp_w = p_w^t - p_w^0 \tag{10a}$$

$$dV_w = V_w^t - V_w^0 \tag{10b}$$

where the superscript t and 0 indicate time t and time t = 0, Eq. (9) becomes

$$p_w^t = p_w^0 + \frac{K_m x_w}{(1 - x_w)} \left(\frac{V_w^t}{V_w^0} - 1\right). \tag{11}$$

The water volume can be converted to density and Eq. (11) becomes

[1] This includes water in pores as well as water in shale interlayers and may not be equal to the water saturation in the "conventional" pore space.

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$$p_w^t = p_w^0 + \frac{K_m x_w}{(1-x_w)}\left(\frac{\rho_w^0}{\rho_w^t} - 1\right). \qquad (12)$$

Eq. (12) shows that the pressure of the heated water depends on the water density, the water volume fraction and the bulk modulus (specifically, the rock matrix solid-phase modulus). The water density is a function of temperature and pressure according to Eq. (2). Therefore, we can combine Eq. (12) and Eq. (2) to obtain the water pressure at a given temperature when the rock bulk modulus and water content are known.

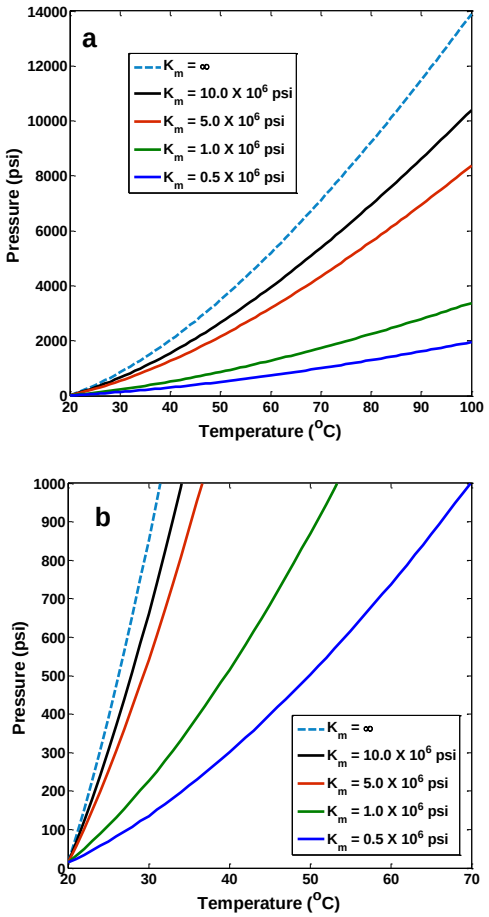

Fig. 3. Pressure dependence on the temperature of the water inside the rock pores with different moduli as shown in the legend. Fib 3b is a blow-up to show the smaller pressure range. The total water volume is 10% of the bulk rock volume.

Again, the analytical form of Eq. (2) contains many parameters; hence, a Matlab program was developed to solve Eqs. (2) and (12) using bisection method (Arfken and Weber, 2013). The calculation error was set to be within one psi for pressure.

Shown in Fig. 3a is the water pressure build-up for several different bulk moduli for a rock with 10 p.u. water at initial condition of 1 ATM and 20^{o}C, corresponding to the laboratory condition. It indicates that the rate of pressure build-up significantly depends on the rock's modulus. Smaller bulk moduli allow the water volume to increase more, and as a result, the pressure build-up with temperature increase is less. Fig. 3b shows an enlarged section of Fig. 3a which is relevant to our experiment. In Fig. 4, the density change for water in the pore is plotted according to the temperature, corresponding to Fig. 3. If the water volume is only 10% of the rock volume, then a 4% change of water density will only result in about 0.4% solid-phase volume change of the rock matrix.

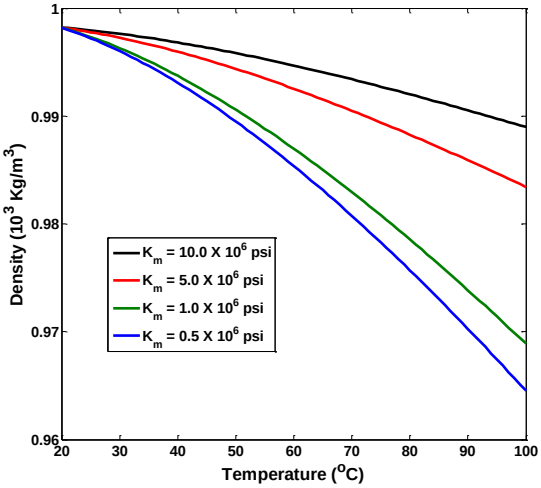

Fig. 4. Density of water in the rock pores versus temperature for different rock matrix moduli, corresponding to Fig. 3a.

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3.5 Pore-water pressure change at reservoir condition

Fig. 3 illustrates the pore-water pressure build-up when water is heated at the laboratory condition. In the subsurface, the initial temperature and pressure of pore-water are higher; therefore the starting water density in Eq. (12) is different from laboratory condition. In addition, the rock matrix bulk modulus under a larger overburden stress is larger than that at the laboratory condition (Coyner, 1984; Jizba, 1991; Liu et al., 2009). These certainly change the pore-water pressure build-up rate when water is heated.

Shown in Fig. 5 are calculated pore-water pressure build-up according to water temperature increase at the initial conditions T = 140°C, p = 4000 psi. This condition corresponds to a reservoir depth of approximately 9,000 ft with overburden stress approximately 9,000 psi. The typical bulk modulus of shale measured at this pressure is expected to be 3 ~ 5 × 10^6 psi (Coyner, 1984). From Fig. 5, the pore pressure elevates to between 9,000 and 10,500 psi when the water is heated for 40 degrees.

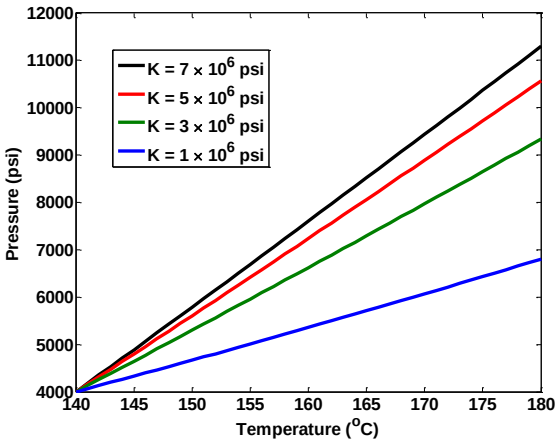

Fig. 5. Pore-water pressure (a) and water density (b) dependence on the temperature at reservoir condition with different moduli as shown in the legend. The total water volume is 10% of the bulk rock volume.

3.6 Tensile strength relationship

This section presents the relationship of measuring tensile strength using elevated pore pressure and a traditional test. The rock tensile strength measured using this method equals to the pore pressure at the point where rock fails by the pore pressure. On the other hand, in a traditional tensile test, a tensile stress equals to the largest stress a rock can withstand while being stretched before failing.

In unconventional rocks, the portion of water-filled pores is small; therefore, it is justifiable to ignore interactions between individual pores when investigating stress distributions near a pore. Also for simplicity, we study a two-dimensional problem with a pore being represented by a circle with radius R as illustrated in Fig. 6.

For the case shown in Fig. 6, the largest tensile stress occurs along y axis. Thus, we focus on tensile stress distribution along y axis, given by (Jaeger et al., 2007)

$$\sigma_x = \sigma_1\left(1+\frac{1}{2}\left(\frac{R}{y}\right)^2+\frac{3}{2}\left(\frac{R}{y}\right)^4\right)+p_w\left(\frac{R}{y}\right)^2 \quad (13)$$

The above equation is applied to the region $y \geq R$. It is obvious from Eq. (13) that the maximum tensile stress occurs at point A (x = 0, y = R) and A' (x = 0, y = -R) in Fig. 6 and is

$$\sigma_x^{max} = 3\sigma_1 + p_w \quad (14)$$

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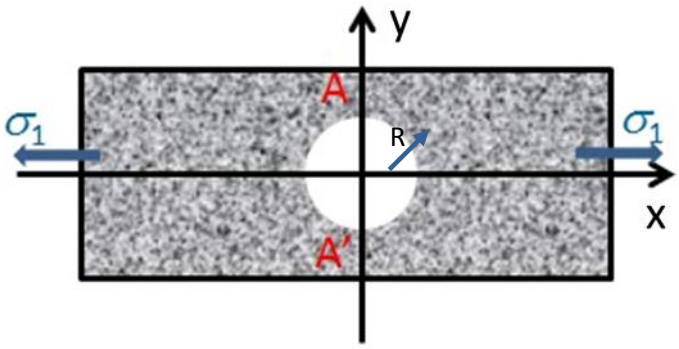

Fig.6. Stress distribution near a circular pore with radius R in an infinite two-dimensional medium under far-field tensile stress σ_1. The pore pressure inside the pore is p_w.

A rock sample under test fails when the maximum stress exceeds the "tensile strength" of the rock, the rupture stress, σ_c is

$$\sigma_x^{max} = \sigma_c \tag{15}$$

which is an intrinsic property of the rock matrix.

For traditional tensile tests obtained with the "pull" method, the tensile strength, S_{tr}, is determined (with no pore pressure, p_w = 0) and equals the stress σ_1 when the corresponding rock sample fails. Thus, we have from Eqs. (14) and (15),

$$S_{tr} = \frac{1}{3}\sigma_c \tag{16}$$

For the microwave heating tests, the tensile strength, S_{mw}, is determined (with no external forces, σ_1 = 0) from the pore pressure, p_w when the corresponding rock sample breaks. From Eqs. (14) and (15), we have

$$S_{mw} = \sigma_c \tag{17}$$

From Eqs (16) and (17), we obtain

$$\frac{S_{mw}}{S_{tr}} = 3 \tag{18}$$

Therefore, the tensile strength measured from microwave heating test, assuming round pores, is three times larger than that from traditional tensile tests. For a three-dimensional problem with a spherical pore, the factor 3 in Eqs. (14) and (18) should be replaced by 4 (Jaeger et al., 2007). While these results are obtained under idealized conditions, they indicate that rock tensile strength measured with microwave heating could be significantly larger than that from the traditional measurements, as a result of different rock micromechanical models assumed for the two different test conditions. Note that the interpretation of the traditional "pulling" method is based on the continuum mechanics and an assumption of macroscopic homogeneity of the rock sample. Consequently, it does not consider the stress concentration near a pore when determining the tensile strength.

3.6 *Microwaving tight rock samples*

Microwave radiation quickly heats materials with substantial dielectric loss. An estimate of power dissipated into the homogeneous materials is given by

$$P_{av} = \frac{1}{2}\omega\varepsilon_0\varepsilon_r^{''}\int_V E\cdot E^* \, dV \, . \tag{19}$$

where P_{av} is the average power, ω is the microwave frequency, E is the electric field strength, E* is the conjugate of electric strength, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m, and $\varepsilon_r^{''}$ is the relative dielectric loss which is part of relative complex dielectric permittivity, ε_r^*

$$\varepsilon_r^* = \varepsilon_r^{'} + i\varepsilon_r^{''} \, . \tag{20}$$

$\varepsilon_r^{'}$ is the relative dielectric constant. Eq. (19) is integration over the entire rock sample. If the rock sample contains several different minerals and water, to calculate the power adsorbed by the rock, one needs to consider all of the rock's constituents. If we know the fraction composition of minerals and their dielectric loss, Eq. (19) becomes

$$P_{av} = \frac{1}{2}\omega\varepsilon_0\sum_i(\varepsilon_{r,i}^{''}\int_V E\cdot E^* \, dV) \tag{21}$$

where the summation i is over all the dielectric loss components from minerals and fluids.

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Table 2. Relative dielectric constants of typical minerals in shale. The number listed in the parenthesis in the first column is the frequency the measurement was conducted.

Rock/Mineral	Dielectric Const. (ε_r')	Dielectric Loss (ε_r'')
20 Ohm salt water[a] (1.1 GHz)	79	5.6
1 Ohm salt water[a] (1.1 GHz)	77	21
0.1 Ohm salt water[a] (1.1 GHz)	59	167
Dolomite[b] (1 GHz)	7.41	1.80E-03
Calcite[b] (1 GHz)	8.94	4.20E-04
Quartz[b] (1 GHz)	3.89	5.33E-04
Pyrite[c] (2.45 GHz)	83	17

[a] Shen, 1985; [b] Church, 1988; [c] Peng, 2014.

The wavelength of the microwaves that we used is approximately 11 cm which is much larger than the mineral grain size and pore size; therefore, the electric field E over different components can be considered the same. As the result, integration over the space in Eq. (21) is the same for all of the rock's

constituents. This significantly simplifies the calculation and then Eq. (21) becomes:

$$P_{av} = \frac{1}{2}\omega\varepsilon_0 \int_V E \cdot E^* \, dV \sum_i \varepsilon''_{r,i} \qquad (22)$$

Some typical dielectric constants are listed in Table 2 (Church et al., 1988; Peng et al., 2014; Shen, 1985).

4. Experiments

Samples and preparation. Microwaving tests were performed on a tight Tennessee sandstone, five Mancos outcrop shale plugs, and clay disks. Saturation of the dry Tennessee sandstone sample was achieved by first vacuuming the plug for more than 40 hours and then imbibing 2% KCl solution under vacuum condition. The plugs were in the solution for a week before the microwaving experiment. The montmorillonite clay was from Panther Creek, Colorado. A clay disk was made by pressing the powder at pressure of 70,000 psi using an Angstrom 4451AE Briquet Press.

Water content determination. Water content was measured using low field NMR (2 MHz or 13 MHz) by comparing the measured NMR signal from the sample to known amount of water. The NMR signal was acquired using a CPMG spin echo method (Carr and Purcell, 1954; Meiboom and Gill, 1958).

Microwaving. A Monowave-300 microwave from Anton Paar was used for the majority of microwave experiments. For all experiments on Monowave-300, a constant power mode with output power at 200 watts was used. The maximum microwave exposure time was set to be 40 sec. The microwaving experiment was immediately terminated when rock failure was detected. Rock failure was detected from the sound with an attached microphone to the microwave. Some qualitative microwaving tests were performed with a common household microwave (Hamilton Beach Household Microwave, Model P100N30AP_F4). Sample temperatures were measured using an infrared thermometer.

Brazilian Test. To compare with microwave heating test results, indirect (Brazilian) tensile strength measurement was also carried out following the ASTM standard protocol (ASTM-D3967).

In the Brazilian test, a disc of material is subjected to two strip load at the disc periphery. The applied load is p. The disc-specimen has a diameter of D and a thickness of L. According to ASTM and ISRM, the tensile strength of rock, σ_t, can be calculated as

$$\sigma_t = \frac{2p}{\pi DL} \qquad (22)$$

where p is the maximum applied load indicated by the testing machine.

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Fig. 7. Tight Tennessee sandstone before and after microwaving. 20.1 seconds microwaving completely obliterated the rock plug.

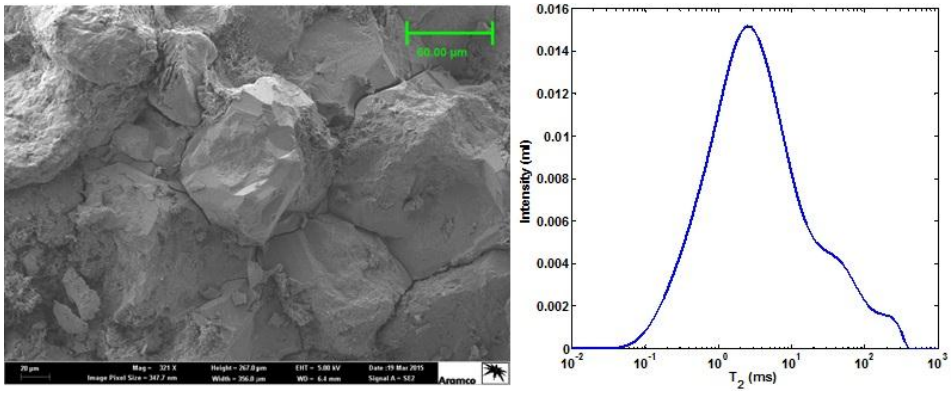

Fig. 8. SEM image of a fresh, broken surface of the Tennessee sandstone (see Fig. 6) and NMR T_2 spectrum of fluid in the sample before microwaving experiment.

5. Results

5.1 Microwaving tight Tennessee sandstone

Fig. 7 shows a tight Tennessee sandstone sample before and after microwaving. The grain size is approximately 60 to 70 μm from the SEM images (Fig. 8 left). The plug was initially dry and had no NMR detectable water content. After vacuum saturation, it contained 6 p.u. (percent unit, i.e. volumetric percent of water in the core plug) water based on the NMR measurement, shown on the right in Fig. 8. No permeability measurements were made, but the sample is extremely tight under visual and microscopic examination. Immediately after microwaving, the sample temperature was 51°C, measured with an infrared thermometer. The rock matrix contains 97.4% quartz and traces of muscovite and clay, from XRD analysis. The matrix moduli for sandstone varies from 4.1×10^6 psi to 6.0×10^6 psi (Jaeger et al., 2007). Using these matrix moduli, a water content of 6 p.u. from NMR measurement, and the initial room pressure of 14.5 psi, we obtain the pressure build up shown in Fig. 9 for the temperature range of interest from 20°C to 100°C. We interpret the "tensile strength" of this sample to be the heated pore-water pressure at 51°C to be between 1,500 and 1,800 psi.

As previously indicated we also carried out Brazilian test and obtained tensile strengths on the same Tennessee sandstone. The measured tensile strength is 434 psi. Using relationship Eq. (18) and the related discussion, we expect the microwave measured tensile strength would be approximately between 1,300 and 1736 psi, which generally is consistent with microwave heating test results (1500 to 1800 psi). Since the relationship between the two measured strengths was obtained under idealized conditions, it needs to be further verified with more test results.

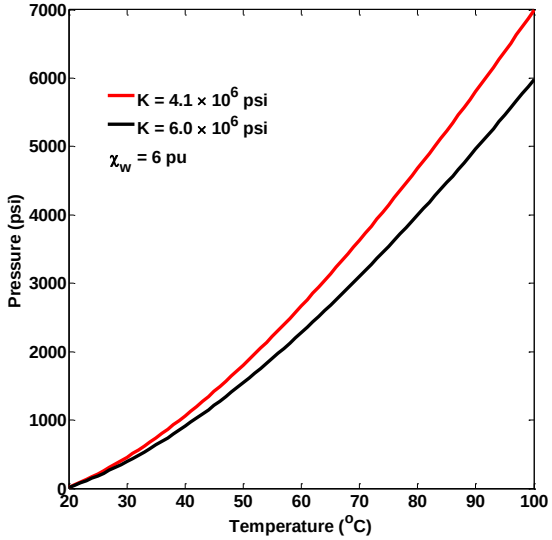

Fig. 9. Pore-water pressure build-up due to microwave heating for tight Tennessee sandstone with water content of 6 p.u. and matrix modulus $K = 4.1 \times 10^6$ psi in red and $K = 6.0 \times 10^6$ psi in black. The pore-water pressure, between 1500 to 1800 psi at temperature 51°C when rock failed, is interpreted as the tensile strength of this rock.

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5.2 Microwaving shales and pressed clay disk

Organic-rich shales generally consist of significant amounts of quartz and/or carbonate, clay, and organic matter. In addition, shales usually contain small amount (1~2 wt%) of pyrite, which has a dielectric

loss of more than 10, in contrast to less than 0.1 for most other minerals and TOC. Therefore, the interpretation of microwave heating of shales is more complicated than that of tight sandstones. Here we show some initial microwave heating experiments on shale samples. Quantitative estimate of tensile strength in shale samples will be reported in later publications.

Fig. 10 shows the Mancos outcrop shale plug on the left and results after 35 s of heating with a common microwave on the right. The water content in this sample is 3.3 p.u.. Microwaving completely obliterated this plug. Fig. 11 shows the microwaving result for a different Mancos outcrop plug. This plug contains 2.1 % water. Microwaving left about half of the plug intact (far right in the picture). Subsequent NMR testing on this half found no observable water signal. This supports our thesis that increased water pressure is responsible for the pulverizing the tight rocks.

Fig. 12 shows results of microwaving on clay disk pressed from Montmorillonite powder under 70,000 psi. This clay contains 6 %t water by weight. It took only 9 s to fracture the disk in the Hamilton Beach Household Microwave. In contrast, 30 s microwaving did not have much effect on a clay disk pressed from Kaolinite (data not shown) which exhibited no NMR detectable water.

Fig. 10. Mancos outcrop shale plug before (left) and after microwaving (right).

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Fig. 11. Mancos outcrop shale plug before (left) and after microwaving (right). Half of the plug was intact after microwaving.

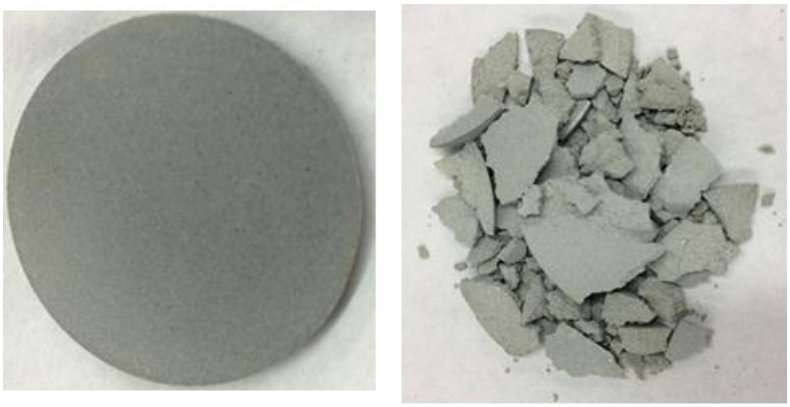

Fig. 12. Left: clay disk pressed from Montmorillonite powder at 70,000 psi; Right: after 5 seconds microwaving in the household microwave.

6. Discussion

The microwaving experiments on the tight sandstone and shales illustrate that the elevation of pore-water pressure is the mechanism to effectively pulverize or fracture the tight rocks in laboratory. The same mechanism, in principle, can be used for subsurface fracturing applications. Calculation results in Fig. 5 show that pore-water pressure can easily increase a few thousand psi by raising the water temperature a few dozen degrees. Eq. (12) shows that the build-up rate of pore-water pressure is proportional to bulk modulus of the matrix. Therefore, the pressure elevates faster in hard rock and possibly in deeper reservoirs. Therefore, microwave or electromagnetic (EM) wave heating might be an efficient fracturing technology. Some advantages of the proposed EM technology over the widely used hydraulic fracturing are:

1. Foremost, microwave or electromagnetic (EM) wave heating is a "water-free" technology. This is significant for regions that are rich in tight reservoirs but lack water resource.
2. If EM heating can pulverize the tight rock in the subsurface with any resemblance to the laboratory experiments, a majority of the light hydrocarbons bound in the nanoporous rock system will be released.
3. EM heating avoids formation damage caused by fracturing fluid imbibition into shales during hydraulic fracturing.
4. It does not require any chemicals. In addition, controlling the size of stimulation zone with EM is relatively easy to implement, by setting the EM wavelength and energy density.
5. The EM technology should also work in deep reservoir and hard rocks.

In the subsurface, use of EM heating to fracture tight rocks requires much higher pore pressures than in the laboratory to overcome the overburden. This can be achieved by raise the water temperature higher.

7. Conclusion

We propose that EM heating method can be used to fracture tight reservoir as a water-free fracturing technology for light hydrocarbon production. It is based on the fact that when the temperature of water in a confined space, e.g., within a tight rock, increases, water expands and consequently the pressure within water-filed pores quickly elevates to the point where it exceeds the rock's tensile strength to break the rock. The feasibility of the proposed method has been successfully demonstrated under laboratory conditions. We believe that with further development, the proposed method could be a very attractive alternative to the hydraulic fracturing in many practical applications.

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We also use the related concept to estimate tight rock tensile strength by heating water to elevate pore pressure. The tensile strength equals the water pore pressure when the rock fails. We have shown that this method can be used on simple rocks such as tight sandstone. Application of this method on shale is more complicated due to the complex mineral composition and further development is needed. Microwaving tight rocks pulverizes them in the laboratory.

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