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Electromagnetic thermal stimulation of shale reservoirs for petroleum production

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ABSTRACT

Light hydrocarbons produced from unconventional tight shale reservoirs with matrix permeability in nano-Darcy range accounts for more than half of the petroleum production in the United States in the past several years. This has been enabled mainly by the drilling of long horizontal wells coupled with extensive hydraulic fracturing. A typical fracturing job for a horizontal well requires two to five million gallons of water which imposes significant challenges in many areas of the world that lack water resources. In addition, treatment and disposal of produced fracturing fluids can be expensive and may negatively impact the environment. Here we show a 'water-free' stimulation method to produce light hydrocarbons from the extremely tight reservoirs using electromagnetic (EM) waves to heat the formation and elevate pore-water pressure. We demonstrated in the laboratory that microwave heating pulverized shales and other tight rocks without confinement and generated extensive fractures within shales with 15 MPa isotropic confinement pressures. Our calculation indicates that for typical shale reservoirs pore-water pressure can increase to 90 MPa or higher that is sufficient to stimulate the formation for production with a less than 100 °C temperature increase of the reservoir. Using a simplified coupled model of EM heating and thermal diffusion, we estimated that with practically reasonable amount of power input the EM heating can stimulate a sufficiently large volume of tight reservoirs to produce light hydrocarbons.

1. Introduction

Light hydrocarbons in organic-rich shales were once considered impossible to produce commercially due to the nD permeability; but now contribute approximately 50% oil and 70% gas production in 2015 in the United States (U.S.EIA, 2016a; U.S.EIA, 2016b) and are becoming globally important, having benefited from the combination of horizontal drilling and hydraulic fracturing. The estimated world recoverable light hydrocarbon reserves from shales are estimated to be 418.9 BBL oil and 7576.6 TCF gas (U.S.EIA, 2015). Approximately 4.3 million barrels oil and 53 billion cubic feet of gas per day were produced from shales alone in the U.S. (U.S.EIA, 2016a; U.S.EIA, 2016b). However, the estimated ultimate recovery (EUR) factor is small: approximately 6% for shale oil and 25% for shale gas using hydraulic fracturing (U.S.EIA, 2015). Moreover, hydraulically fracturing one well typically requires 2 to 5 million gallons of water which can be difficult to obtain in many regions in the world. In addition, reprocessing recovered fracturing water can be expensive financially and environmentally. Thus, developing water-free or water-efficient fracturing techniques is highly desirable. Here we present an alternative 'water-free' method using electromagnetic (EM) wave to heat the rock and elevate the pore-water pressure to stimulate shale reservoirs or any other tight reservoirs (Chen et al., 2015). For this paper tight reservoir are defined to have matrix permeability typical for shales, i.e., nD scale.

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 induced cracks (Cooper and Simmons, 1977). The effect was quickly recognized to be useful for rock grinding (Walkiewicz et al., 1989) and mineral separation (Kingman et al., 1998). Microwave heating is 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, 1977). Specifically for oil shale, EM heating was proposed to retort kerogen into light hydrocarbon *in situ* so it can be produced. The physics behind the majority of

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these applications includes two aspects: differences in thermal adsorption ability and thermal expansion coefficient of minerals composing the subject rock. EM may heat some components of the formation more efficiently than others and the thermal expansion coefficients can differ quite significantly (Chen et al., 2015). Consequently, fractures are generated in the rocks when the temperature increases. While all the above applications have been based on the heterogeneous mineral responses to EM heating, here we investigate the pore-water pressure increase in tight rocks due to EM heating. This is a very different mechanism than the differential heating, strain inducing mechanism; the “trapped” pore water heating and commensurate pressure elevation is a very effective mechanism to break tight rock and is a potential alternative or complementary method to stimulate shale reservoirs for production.

The method utilizes the physical fact that in a tight rock when water is heated and its volume cannot significantly change because the shale matrix permeability is in the nD range (Luffel et al., 1993) and the pore water is effectively trapped, and, thus, the pore-water pressure increase rapidly. When the pore-water pressure becomes sufficiently high, the rock fails. Consequently, formation permeability increases to more efficiently recover light hydrocarbons from these tight reservoirs.

This paper details the physics of EM heating to stimulate shale and other tight reservoirs. First we estimate the pore-water pressure elevation in a tight rock using a simplified model where the water is quickly heated and the temperature rises rapidly. We then show experimental results of microwave stimulation of tight rocks under zero confinement and under approximately 15 MPa isotropic confinements. The experimental results verify the efficacy of stimulating tight rock reservoirs with EM heating. We then estimate the power requirement for EM to stimulate a tight reservoir: we evaluate the thermal diffusion at microscale to prove that local thermal equilibrium can be readily achieved. We then calculate EM heating in macroscale and show that a reasonable amount of EM power input can raise the temperature of sufficiently large volume of a tight reservoir for EM thermal stimulation.

2. Experiments

2.1. Samples and preparation

Microwaving tests were performed on one tight Tennessee sandstone and more than 30 outcrop shale plugs from Mancos, Marcellus, and Eagle Ford. Saturation of the dry Tennessee sandstone sample was achieved by first vacuuming the plug for more than 40 h and then imbibing 2% KCl solution under vacuum condition. The shale plugs were either tested as received or placed in the solution for 5 h before the microwaving experiment. All shale plugs were cylindrical with 2.54 cm diameter and 2.54 cm length. The diameter of the Tennessee sandstone plug was 2.0 cm.

2.2. Water content determination

Water content was measured using low field NMR (2 MHz or 13 MHz) by comparing the measured NMR signal from a 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).

2.3. Microwaving

Destructive microwaving tests were performed with a common household microwave (Hamilton Beach Household Microwave, Model P100N30AP_F4). The maximum microwave exposure time was set to be 45 s. The microwaving experiment was immediately terminated when the audible rock failure was detected. For experiments at zero confining pressure, samples were placed in a thick-walled glass bottle to contain the broken pieces. A small hole was drilled in the bottle cap to avoid pressure build-up within the bottle when the sample was heated. For experiments with confinement pressure, a hole drilled in the back-wall of the microwave allowed a tube to extend outside the microwave which was connected with an external pressure regulator and valves to a high-pressure nitrogen cylinder. The sample chamber was pressurized by the nitrogen gas to provide an isotropic confinement to the tested sample. When the nitrogen gas pressure in the sample chamber reached 13.8 MPa which took less than 30 s, the valve to the pressure gas cylinder was instantly closed and the microwave was turned on to start the experiment. Microwave heating of the test sample also increased the temperature of the nitrogen gas in the chamber; as the results, the confinement pressure from the nitrogen gas increased as well. Therefore, 13.8 MPa is considered as the minimum confinement pressure the tested samples were subjected to.

2.4. In situ temperature measurement

Temperature measurement were made on samples inside an Anton Paar Manowave 300. Fiber optic sensors (FISO Technologies Inc.) were inserted into small diameter (1 mm) drilled holes in the sample. A layer of Nano Diamond Thermal Compound (Formula 7, Antec, Inc.) was painted onto the sensor to provide good thermal contact between the sensor and the rock for rapid and accurate temperature measurement. The sample was then irradiated in an Anton Paar microwave for specified time at various power levels. The fiber sensor was feed through the exhaust tube of the microwave to a computer for data logging.

3. Result

3.1. Pore-water pressure elevation with temperature increase in tight rocks

The pore-water pressure increase by heating is calculated based on a model that water is contained in the pores of nm to µm size within an impermeable rock matrix. The rock matrix is assumed to be elastically linear, as illustrated in Fig. 1a. The perturbations to the *in situ* stress field by the water-filled pores, however, are localized to within three to

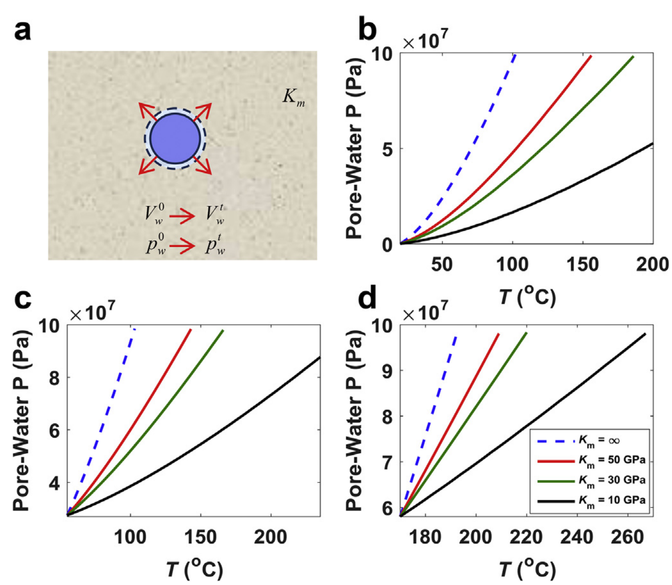

Fig. 1. Temperature dependent pore-water pressure elevation in a tight rock. a, illustration of a water filled pore in a rock matrix that allows the water to slightly expand when heated from the solid sphere to the dashed sphere. **b,c,d,** dependence of pore-water pressure on temperature for different rock bulk moduli at different initial conditions: **b,** $p_w{}^0 = 1.01 \times 10^5$ Pa, $T_w{}^0 = 20$ °C, laboratory condition; **c,** $p_w{}^0 = 2.75 \times 10^7$ Pa, $T_w{}^0 = 55$ °C, approximately corresponding to Marcellus reservoir; **d,** $p_w{}^0 = 5.80 \times 10^7$ Pa, $T_w{}^0 = 170$ °C, approximately corresponding to Haynesville reservoir.