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Preliminary study of improving reservoir quality of tight gas sands in the near wellbore region by microwave heating

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ABSTRACT

The formation damages, such as water blocking and clay swelling, in tight gas reservoir have been recognized as severe problems impairing gas production. To remedy these damages, formation heat treatment (FHT) was taken as one of the effective measures by some researchers. In this paper, the effects of microwave heating on the petrophysical properties of sandstone samples has been investigated. A modified commercial microwave oven was used to heat the core plugs and aluminum tubes were used to accommodate tight sandstone samples in order to confine them and reduce their contact with air. After microwave heating, any alterations in the porosity, permeability, texture, structure, mineralogy, and pore size distribution of tight sandstones were investigated by a series of lab experiments.

By subjecting tight sandstone samples to microwave, the surface temperature of sandstone can be elevated to approximately 400 °C or more. The intense heat is effective in changing the structure, texture and mineralogy of the sandstone. The shrinkage or decomposition of minerals, which are shown by XRD analysis, and generation of micro-fractures created more spaces in the samples. By employing Automated Permeameter, porosity and permeability are found increased after heating. Nuclear Magnetic Resonance (NMR) and CT numbers of all samples after microwave heating indicate the increase of porosity as well. Moreover, the NMR T_2 distribution reveals the smaller pores diminished, so the incremental porosity of short NMR T_2 decreased. Micro-fractures generated between grains or in grains due to decomposition of some cement minerals and clay shrinkage, so the amplitude of long NMR T_2 increased. The fractures are visible both in X-ray CT images and in Scanning Electronic Microscopy (SEM) images. By comparing with NMR T_2 distribution data, it is found that the presence of micro-fractures accounts for the increased population of pores with T_2 larger than 10 ms.

The numerical simulation of microwave heating in the borehole indicates that the microwave heating is effective to raise the temperature of reservoir rock to approximately 900 °C within 1 day and to remove the water within a distance of 25 cm from the borehole wall. The efficiency of microwave heating can be further improved by optimizing the downhole microwave device.

1. Introduction

As one of the unconventional resources, tight gas is produced from the reservoir with low porosity and permeability. Suitable well stimulation method needs to be performed in such reservoir in order to produce gas in an economical rate (Holditch, 2006). In addition to its poor reservoir quality, the formation damage, which is defined as the impairment of reservoir quality and production, is another crucial problem as well. Due to the intrinsic small pore size in tight gas reservoir and thus the high capillary pressure, the production of tight gas well is susceptible to formation damages such as water blocking and clay swelling. Water blocking refers to the blockage of the pores by the increased water saturation in the near wellbore area due to mud-filtrate invasion. Water blockage will result in reduction of the gas production because of the reduction of relative permeability to gas. Clay swelling is the problem caused by the sensitivity of some clay minerals to fluid salinity. For example, the smectite expands significantly when it is in contact with incompatible fluids in the formation. Clay swelling can impede the gas from flowing through the pore throat leading to the reduction of gas flow rate. With the purpose to eliminate such formation damages, some measures have been investigated by

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several researchers. Their studies provide very valuable information and experiences, although they have more or less disadvantages regarding time efficiency, cost efficiency and environmental friendliness. However, among them, the thermal methods, especially the microwave heating or high frequency electromagnetic heating, are believed to treat formation damage effectively with the least compromise to the abovementioned disadvantages.

The term, Formation Heat Treatment (FHT) was firstly brought out by (Jamaluddin et al., 1995). They applied intense heat, in the form of electrical heater, to the near wellbore area in order to evaporate the moisture phase, to dehydrate, degrade or decompose clay minerals and to create micro-fractures. The thermal shock affects the lattice structure of almost all clay minerals and the degree of changes in the clay lattices depends on the temperature level (Jamaluddin et al., 1998).

The high temperature is the most important factor in the technique of FHT due to the temperature sensitivity of minerals composed of sedimentary rocks. The impact of temperature on clay minerals has been studied by many researchers (Atomic Energy of Canada Limited Research Company, 1990; Grim and Bradley, 1940; Hajpál and Török, 2004; Hoekstra, 1976; Jamaluddin et al., 1998; Li et al., 2006; Mubiayi, 2013; McGill et al., 1995; Sanmiguel et al., 2001; Wu et al., 2011). Table 1 lists the temperature effects on clay minerals.

Besides the degradation or decomposition of the clay minerals, the high temperature caused the evaporation of all the free water and partial clay bound water in the pore spaces, which increased the effective permeability to gas. The thermally induced stress in the heated zone may exceeds the yield strength of the grains and cements and creates inter-grain and intra-grain fractures (Jamaluddin et al., 1998). The well test indicated that the near wellbore region dehydrated at 382 °C, and the permeability of studied zone increased to 700% after heating. However, heating the sandstones to temperature of 700 °C will cause the irreversible changes of clay minerals' structures (Jamaluddin et al., 1999). The study on gas-phase combustion in porous media is another method for FHT. By using this technique, the reservoir can be heated to over 600 °C leading to the permanent reservoir quality improvement. Li et al. (2006) conducted microwave heating, a novel formation heat treatment technique, on tight sandstone samples and claimed that in microwave active region the energy from the expansion of gas and vaporization and expansion of liquid in the pore spaces can force the trapped fluid to move towards open spaces. The thermal expansive stress can produce a well-interconnected micro-fractures zone that facilitates the flow of moisture vapor and, ultimately gas.

The application of microwave heating in oil and gas industry is not new, it has been utilized in the production of heavy oil due to its efficiency in heating (Abernethy, 1976; Wacker et al., 2011; Carrizales, 2010; Liu and Zhao, 2012). The high frequency electromagnetic wave penetrates the reservoir and heats up reservoir rocks and interstitial fluids within its penetration depth effectively and efficiently. In terms of reservoir with moisture content, the microwave will be almost completely absorbed within a short penetration depth. However, as the water saturation decreased, the penetration depth of microwave can be extended further (Vermeulen and Chute, 1983).

Nevertheless, the application of microwave heating in removing formation damage and enhancing reservoir quality is still challenging. In this paper, the petrophysical and petrographic properties of sandstone samples before and after the treatment of microwave heating in the lab were investigated using multiple experimental techniques. This preliminary study is trying to contribute to the concepts of formation heat treatment by investigating the feasibility of microwave heating in formation heat treatment and providing comprehensive studies of sandstone samples.

2. Methods and experiments

Microwave heating is the method to elevate the temperature of the target object by utilizing high frequency electromagnetic wave ranging from 300 MHz to 3 GHz. The most common frequency band for microwave processing is 915 MHz and 2450 MHz. Two processes are involved in the interaction of microwave and sandstone: polarization, which is the short-range charge displacement, and conduction, which is the long-range charge transport. At low electromagnetic wave frequencies, the ionic conduction losses overwhelm the polarization while the opposite at higher frequencies (Clark and Sutton, 1996). The dielectric losses are decided by both the properties of microwave radiation, such as frequency and power level, and the properties of porous medium, such as the porosity, water saturation and mineralogy.

The propagation of electromagnetic wave was described by the Maxwell's equations:

Gauss's law

$$\nabla \cdot E = \rho/\varepsilon_0 \tag{1}$$

Gauss's law for magnetism

Table 1
Effect of temperature on clay minerals (After Carroll, 1970).

Mineral	Temperature, 1 h	Effect
Kaolinite, well-crystallized	575–625 °C	Replacement by amorphous meta-kaolin; no diffraction pattern
Kaolinite, disordered	550–562 °C	Similar to kaolinite
Dickite	665–700 °C	Similar to kaolinite
Mica, well-crystallized	700 °C	Shows gradual loss in weight, but does not break down below 700 °C; (001) spacing remain in diffractograms below 700 °C and up to 1000 °C
Illite, and clay micas	125–250 °C	Loss of hydroscopic water
	350–550 °C	Reverts to mica structures
	700 °C	Similar to mica
Glauconite	58–650 °C	Loss of interlayer water; reverts to mica structure
Biotite	700 °C	Phlogopite is similar to muscovite Biotite shows breakdown 700–1000 °C
Montmorillonite Group	300 °C	Original 15 Å spacing disappears; 9 Å spacing develops
Chlorite Group	600–800 °C	Show gradual weight loss, but no structural change
Mg-chlorite	650 °C	14 Å spacing is intensified; (004) at 3.54 not affected
Fe-chlorite	500 °C	14 Å spacing less intense and may become broad and diffuse
Mixed-layer clays	<600 °C	Varies with kinds of minerals present and amount of each