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Geomechanical aspects of reservoir thermal alteration: A literature review

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ABSTRACT

This paper reviews the impact of the geo-temperature alteration in applications relevant to coupled reservoir geomechanics. Some important geomechanical aspects of the reservoir thermal alteration are highlighted in operations such as drilling, waterflooding, hydraulic fracturing, thermal EOR, geothermal energy exploitation, CO_2 storage, and nuclear waste disposal. Additionally, this document presents a review of both, experimental and theoretical evidence, which allows anticipating that changes in temperature may have a significant effect not only on the production and development of hydrocarbon reservoirs, but also, on the environmental aspects involved in these operations. As could be reviewed, there are still several gaps in the literature regarding theoretical modeling and experimental studies, as well as, the lack of correlation between field observations with theoretical and experimental results.

1. Introduction

It is well known that most rocks experiment a volumetric strain under a temperature alteration, which can be an expansion or a contraction. This strain is proportional to the temperature change if the rock behaves within the elastic domain. Furthermore, if the rock is constrained, confining stresses will build up or decrease depending if the temperature is raised or reduced, respectively (Stephens and Voight, 1982). The theory of thermoelasticity predicts that thermal stresses alone can cause significant damage and yield in materials (Boley and Weiner, 1960; Nowacki, 1962). Therefore, since under reservoir conditions the rock around the wellbore is already subjected to loads such as pressure and stress accumulation; the thermal alteration is likely to induce important geomechanical phenomena not only on a near wellbore scale but also on a reservoir scale. The above may trigger effects such as crushing of the sand grains, fracturing, wellbore instability, shearing, fracture slip, rupture of the inter-granular mineral cohesion, and so on (Dusseault, 1993; Gupta and Civan, 1994; Wang and Dusseault, 2003). Each of these effects may contribute not only to the positive or negative stress-induced alteration of the flow capacity of the rock and subsequently the productivity of the well, but also, it may have implications for the reservoir management and environmental issues.

This paper provides an overview of the geomechanical aspects of the reservoir thermal alteration including theoretical, experimental, and field evidence. The motivation for doing this literature review is to conceive the geomechanical effect of thermal alteration on the hydrocarbon reservoirs, mainly because there is an enormous potential of recovering heavy oil reserves through thermal EOR operations, as well as, to visualize other applications where the alteration of the current geo-temperature may induce interesting geomechanical phenomena.

2. The thermal effect in the reservoir

Within the reservoir, high temperatures (T > 180 °C or 356 °F) may have a considerable influence on the behavior of the rock-fluid system (Shafiei and Dusseault, 2013). The main temperature effect on the reservoir is causing volumetric strain and, since the rock is constrained to a certain degree, inducing thermal stresses (Fig. 1); which may result in shear or tensile stressed zones around the borehole (Dusseault, 1993). The Young's modulus is of great influence on the generation of thermal stresses, the stiffer a material is, the bigger the thermal stresses induced (Stephens and Voight, 1982). Temperature changes can alter the reservoir porosity and permeability in different ways; if the confining pressure is high, heating the formation can reduce the permeability if the solid grains expand into the pore volume (Palciauskas and Domenico, 1982); otherwise, the permeability may be enhanced due to shear dilation or fracturing (Palciauskas and Domenico, 1982; Azad and Chalaturnyk, 2011). Cooling the formation during fluid injection can also improve the permeability by rock fracturing or fracture reactivation, which is a result of a reduction of the compressive stresses within the cooled region (Lee and Ghassemi, 2009).

Depending on the hydraulic diffusivity of the porous media, thermal

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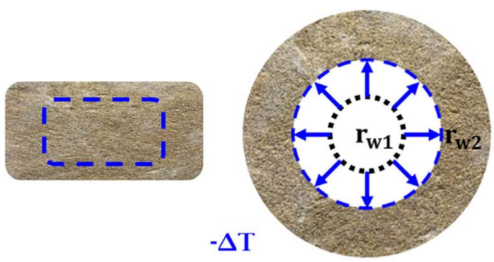
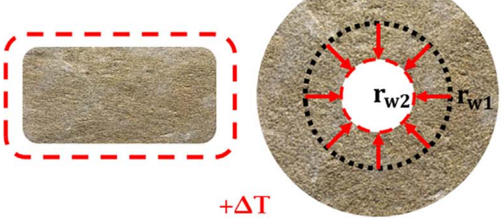
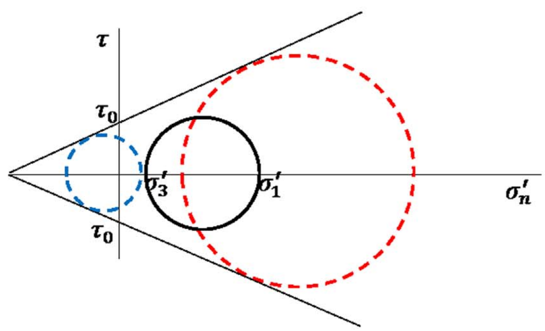


(a) Thermally induced shrinkage of a rock at room conditions (left) and a rock around the wellbore (right).



(b) Thermally induced expansion of a rock at room conditions (left) and a rock around the wellbore (right).



(c) Schematic of the thermally induced stress increase (red) and reduction (blue).

Fig. 1. (a) A temperature drop makes a rock to shrink, the shrinkage of the rock around the wellbore causes the stress load to be reduced, which facilitates the hydraulic fracturing when performing an injection of cold fluid, this effect is schematized by the blue Mohr-Coulomb circle in (c). (b) An increase in temperature makes a rock to expand, the expansion of the rock around the wellbore causes the stress load to increase, if the rock can not expand freely. This effect is schematized by the red Mohr-Coulomb circle in (c).(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

expansion or contraction of the pore fluid may significantly affect the pore pressure response within the reservoir (Palciauskas and Domenico, 1982; Booker and Savvidou, 1984), which may induce inward or outward flows around the wellbore (Wang and Papamichos, 1994). This effect is known as thermal osmosis which is more important in low-permeability rocks (Yang et al., 2014). Pickens et al. (1987) demonstrate that thermal osmosis can affect the results of formation pressure and hydraulic conductivity tests, they also report a field case where a temperature change of 1 °C (1.8 °F) induces a pore pressure change of 145 psi (1 MPa). Temperature variations may also influence the brittle or ductile behavior of the rock, depending on factors such as the mineral and structural characteristics of the rock, the confining pressure, and the temperature range (Jaeger et al., 2007; Luo and Wang, 2011; Yu et al., 2015).

As regard to diffusion in a porous media, there is an analogous behavior between thermal stresses and the stresses due to fluid flow. Geertsma (1957) points out that the governing equations of both phenomena "turns out to be a Fourier-type equation if the fluid in the pores is a compressible liquid". Some authors have formulated equations using this analogy when lacking appropriate statements for the estimation of stress and displacement in a porous media (Lubinski, 1954; Seth and Gray, 1968; Norris, 1992). The propagation of the thermal front in the reservoir depends on the hydraulic and thermal diffusivity of the rock. Heat transport in the porous medium is mainly due to conduction and convection; convective heat flow predominates in rocks with high permeability, whereas conductive heat flow predominates in rocks with very low permeability (Hojka and Dusseault, 1992; Hou and Luo, 2011).

Unlike the influence of mechanical deformation on the pressure field, its effect on the temperature field is often ignored (Ohnishi and Kobayashi, 1993; Zimmerman, 2000). The response of the rock to the combined effects of stress, pressure, and temperature is studied under the theory of thermoporomechanics (e.g., thermoporoelasticity or thermoporoplasticity). Several authors have worked in the extension of Biot's theory to include the thermal effect (e.g. Schiffman, 1971; Brownell et al., 1977; Morland, 1978; Derski and Kowalski, 1979; Bear and Corapcioglu, 1981; Bowen, 1982; Palciauskas and Domenico, 1982; Noorishad et al., 1984; Booker and Savvidou, 1984, 1985). And some others have provide general formulations to include the theory of thermoporoelastoplasticity (e.g. Corapcioglu, 1983; Coussy, 1989; Hueckel and Borsetto, 1990; Coussy et al., 1991; Wang and Dusseault, 1995).

The response of the rock to the simultaneous alteration of the fields of stress, pressure, and temperature is referred as the thermo-hydro-mechanical effect (THM). As it will be seen in the next sections, the THM effect may modify the properties of the rock and induce a considerable alteration in the reservoir, such as uplift, stress reorientation, caprock impairment, fracturing, fracture reactivation, wellbore instabilities, and so on (Fig. 2).

3. Experimental evidence of the thermal effect

It is challenging to obtain definite conclusions from experimental results since these studies may be affected by different phenomena, on some occasions undetectable; such as changes in physicochemical properties of the fluid, rock-fluid interactions, changes in rock-matrix properties, and the inhomogeneities in the samples (Sanyal et al., 1973). It can be found in the literature experimental studies for different rock materials such as granite (Heuze, 1983), marble (de Bresser et al., 2005), carbonate (Amro and Benzagouta, 2009), basalt (Duclos and Paquet, 1991), shale (Johnston, 1987), chalk (Andreassen, 2011), and so on. To limit the scope of this review, the works presented in this section will be focused on isotropic samples of sandstone.

3.1. Effect of temperature on permeability

Several experimental studies have been performed with the aim of understanding the role of temperature on the permeability alteration of the rock. They are divided into flow-based and volumetric strain-based experiments. The results from the flow-based experiments are yet uncertain. Based on these tests, the different authors attribute the thermal alteration of permeability to several reasons, some of them are: (1) a mechanical response such as microstructural rearrangements in the rock matrix and changes in the pore structure (Greenberg, 1968; Afinogenov, 1969; Aktan and Farouq Ali, 1975; Arihara, 1974; Weinbrandt et al., 1975), (2) physicochemical reactions between the flowing fluid and the minerals within the rock (Afinogenov, 1969; Casse, 1974; Aruna, 1976; Udell and Lofy, 1989), (3) a superposition of different effects such as the decrease in porosity, changes in the tortuosity, variations in the resistivity factor, the electrokinetic effect, or clay reactions leading to migration and plugging by clay particles (Somerton and Mathur, 1976), (4) a mechanical or physicochemical effect which is intensified by the increasing confining pressure (Casse and Ramey, 1979), (5) converging flow in the core plugs (Sageev, 1980), (6) a plugging mechanism caused by the formation of colloidal ferric oxides or hydroxides derived from corrosion of the steel in the