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Impact of Thermal Pore Pressure on the Caprock Integrity during the SAGD Operation

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Abstract

Thermal stimulations of reservoirs cause significant amount of thermal energy stored subsurface and pore pressure altered from its original in-situ state. Such thermal and hydraulic disturbances inevitably stress and deform the rock formations including the reservoir and its overlying caprock, making the caprock integrity an important issue. This paper discusses the importance of thermally induced pore pressure for caprock integrity during a SAGD process. Relevant laboratory and field observations are presented to demonstrate its real existence, and then, numerical simulations are used to illustrate the major influencing material parameters and their evolving importance in space and time with respect to the steam chamber development. Finally, discussions are given about importance of the thermal pore pressure on the caprock integrity.

Introduction

In general, even at the pore scale, the thermal expansion coefficient of pore fluids is larger than that of solid rock matrix by about an order (Baldi, Hueckel et al. 1988). When porous rock materials are heated, pore fluid expands more than the rock matrix. If this excess of pore fluid expansion cannot dissipate in time, the fluid pressure in the pores will increase. Pore pressure induced by this process is called thermal pore pressure in this paper as well as in many publications in the literature (Baldi, Hueckel et al. 1988; Burghignoli, Desideri et al. 2000; Cekerevac and Laloui 2004). In SAGD operations, steam is injected into the oilsands reservoirs. The thermal energy inevitably heats the caprock shales and thermal pore pressure is likely generated. In general, pore pressure increase does not benefit mechanical integrity. Therefore, the impact of thermal pore pressure on the caprock integrity should be an important subject. Unfortunately, to authors' knowledge, little work is dedicated to this topic. A major objective of the present paper is to shed some light on this topic.

In the following description, evidence on the existence of thermal pore pressure and its physical mechanism are first presented. These include published analytical works, laboratory evidence and recent field observations. After concluding that the thermal pore pressure is real and must be considered, the present paper goes on to lay out the governing equations on the thermal pore pressure mechanism and conduct some sensitivity analyses on important effecting parameters, all of which is done within the context of the caprock integrity. Finally, the thermal pore pressure mechanism is discussed in a SAGD operation for its impact on the caprock integrity. A discussion and conclusion section ends the presentation.

Thermal Pore Pressure Mechanism

This section is not meant to give an exhaustive review on published works about the thermal pore pressure. Instead, some papers are cited below about the existence of thermal pore pressure. As described above, thermal pore pressure is generated when excess of the pore fluid expansion cannot dissipate in time. Such dissipation depends on the effective fluid mobility, *m*, as below:

$$m = \frac{k_a k_r}{\mu} \qquad (1)$$

where k_a is the absolute permeability of the porous rock, k_r is the relative permeability of the fluid and μ is the fluid viscosity. In bitumen-saturated oilsands, the fluid viscosity is initially very high. As a result, the effective fluid mobility is small and thermal pore pressure can be generated when the oilsands is heated. The thermally induced pore pressure was analytically studied by Butler (Butler 1986). He used a decoupled fluid and thermal transport solution to study the effect of effective permeability, steam temperature and bitumen viscosity on the induced thermal pore pressure. In his study, the thermal pore pressure can rise to the level that can fracture the reservoir sands even though the steam injection pressure is below the fracturing level. Such thermal pore pressure in oilsands was studied in geomechanical triaxial tests on the oilsands under high temperatures when the pore fluid was constrained from dissipating away (Agar, Morgenstern et al. 1986). As a result, the undrained thermal expansion coefficient is much larger than the drained thermal expansion coefficient. In the latter, the pore fluid is allowed to dissipate fully.

In water-saturated caprock shales, such as the Clearwater shales in north Alberta, the absolute permeability k_a is very low, normally in the hundreds of nano-Darcy range. As such, the effective water mobility is very low and thermally induced pore pressure can be generated if the shale rock is heated. Based on the coupled analytical solutions of a cylindrical constant heat source developed by Booker and Savvidou (Booker and Savvidou 1985), Wong et al. (Wong and Samieh 2000) studied the potential occurrence of tensile fracture in the heated Colorado shale during cyclic steam stimulations. The effects of thermally induced pore pressure on the wellbore stability was investigated by many authors (Li, Cui et al. 1999; Chen and Ewy 2004). Xu et al. (2011) studied the impact of thermally induced pore pressure on the mechanical strength of Clearwater caprock shales. They conducted high-temperature triaxial tests on the Clearwater shale at different heating rates and found that a fast heating rate may weaken or even break the caprock shales. This was believed to be caused by thermally induced pore pressure.

Recently, in a SAGD operation in north Alberta, thermal pore pressure was believed to be present in the Wabiskaw interval above the McMurray oilsands reservoir where the SAGD operation was ongoing. The Wabiskaw sands interval is saturated with bitumen. In one instance, during the drilling of a refill well into the steam chamber for extracting steamed oilsands cores, a high pressure of about 5 to 6MPa was encountered in the Wabiskaw interval. However, the McMurray oilsands reservoirs and its associated strata in the Athabasca oilsands area are greatly under-pressured. The SAGD operating pressure is around 3 MPa only. The high pore pressure that was encountered must have been induced. The thermal pore pressure mechanism is likely responsible. In fact, before the field observations were reported, geomechanical simulations considering the full thermo-hydro-mechanical coupling predicted a high pore pressure distribution in the Wabiskaw. The numerically-predicted pressure value is close to the field-observed. This is direct field evidence about the existence of thermal pore pressure.

In the Athabasca area, the caprock to the SAGD operation generally consists of the Clearwater shale. The shale has a low porosity in the range of 10% to 20% and its permeability is in the order of micro to nano-Darcy. Thus, despite its full water saturation, the effective water mobility is still very low. Thermal pore pressure is likely present when the Clearwater shale is heated during the SAGD operation. In high-temperature triaxial tests, the Clearwater shale samples must be heated appropriately slowly. Otherwise, the pore pressure inside the sample can be relatively high compared to the confining pressure which may weaken or even break the shale (Xu et al. 2011). As a result, the sample may fail abnormally. Figure 1 compares two different failure modes in the Clearwater shale under different drainage conditions when the samples were heated. One undrained sample, upon heating, was shattered into fragments by tensile fractures which were likely caused by the thermal pore pressure mechanism. The sample was Clearwater shale from around 400m deep. It was heated from room-temperature to 150 ºC in an undrained condition. After the heating, this sample has significantly lower mechanical peak strength (only one-third) than those of the samples with similar mineralogy and effective confining pressures but slowly heated in a drained condition. After the test, tensile fractures were clearly seen on the fast-heated sample while shear bands were seen on the other slowly-heated samples.

It can be concluded from the above description that the thermal pore pressure can be a significant mechanism affecting rock deformation and mechanical strength, thus compromising the caprock integrity. It is physically real, seen in both field and laboratory tests. Its effect is to increase pore pressure and is thus detrimental to maintaining the mechanical integrity. Hence, it is warranted to consider the thermal pore pressure mechanism in evaluating the caprock integrity during the SAGD operation. In the following, the thermal pore pressure is derived in the context of full thermo-hydro-mechanical (THM) coupling. The governing equations and constitutive models used to describe the thermo-hydro-mechanical behavior of caprock shales are presented and numerical sensitivity analysis cases are run to elaborate major influencing factors.

Governing equations and numerical simulation models

Mathematically, the thermal pore pressure is simulated in the context of coupled thermo-hydro-mechanical (THM) problems. Its governing equations consist of equilibrium equations for the solid deformation and mass and energy conservation equations for the heat and pore pressure diffusion. In computational geomechanics, many related research works have been developed, such as in geo-thermal reservoir development (Brownell, Garg et al. 1978), disposal geological formations (Booker and Savvidou 1985) and permafrost-structure interactions (Xu, Ab Corapcioglu developed a mathematical model for predicting the pore pressure, temperature and due to hot water injection into reservoir (Bear and Corapcioglu 1981). Application of variational principles and finite element