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Geomechanics for the thermal stimulation of heavy oil reservoirs --- Canadian experience

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Abstract

This paper will cover both caprock integrity and reservoir deformation, drawing from our years of experience in working with the heavy oil/oilsands industry in Alberta, Canada. Theoretical principles are described, analytical derivations made and field examples given, all to help illustrate the fundamentals and summarize the learnings in proactive utilization of geomechanics to enhance the reservoir performance and proactive consideration of geomechanics to ensure the caprock integrity. Topics include dilation tendency and fracturing behaviour in the oilsands, major geomechanical work components for the caprock integrity analysis/design, mini-frac tests and nonlinear coupled thermo-hydro-mechanical processes.

Introduction

Canada plays an important role in the global energy industry and the oilsands resource in Alberta, Canada is an increasingly important component to this energy supply. It has recently over-taken the conventional crude in the total production output. Oil sands can be classified as an extra heavy oil reservoir primarily made up of a mixture of sand, water and bitumen. Bitumen is an extremely heavy oil with a viscosity reaching up to 10^6 cp at in-situ reservoir temperatures and therefore must be liquefied via steaming before it can be produced. According to the Alberta government, using currently available technology and under the current economic conditions, there are 170.4 billion barrels of recoverable oil in the oil sands deposits of Northern Alberta. Moreover, there are 315 billion barrels of potentially recoverable oil.

Approximately 80% of the oil sands are recoverable through in-situ production with only 20% recoverable by mining. A variety of commercial in-situ production methods are currently available, including: (1). Primary recovery where sands and heavy oil are produced together; (2). Conventional enhanced oil recovery methods such as water flood or polymer flood; (3). Cyclic steam stimulation (CSS); (4). Steam assisted gravity drainage (SAGD). Recovery factors for CSS and SAGD are the highest and therefore, they are the most common in-situ bitumen/heavy oil recovery processes in the industry. They are also the focus in the current paper.

Both CSS and SAGD inject steam into the reservoir, heating the bitumen and reducing its viscosity enabling it to flow freely. CSS injects the steam at a high pressure, usually around the original reservoir fracture pressure. These periods of high pressure steam injection are followed by production cycles on the same wells when no steam is injected. SAGD injects the steam at a lower pressure but the steam injection is continuous and a growing steam chamber is formed in the reservoir. While reservoir engineering focuses mainly on the fluid phase, an issue that was often overlooked is the inevitably altered structure of the rock matrix caused by the steam injection. The overburden rock can be impacted as well. Therefore, deformation and potential failure of rock materials, which falls into the domain of geomechanics, becomes an important subject.

In CSS and SAGD, two primary geomechanical issues need to be addressed: reservoir deformation and caprock integrity. Nowadays, the industry proactively utilizes geomechanics to enhance the thermal operation. One primary example is to create a fracture in the oilsands reservoir so that hydraulic conduits are formed. These conduits then serve as staging areas for the controlled injection of steam in the reservoir. Timing the stimulation of properly spaced hydraulic fractures allows for more efficient oil recovery. In this case, geomechanics can create profits for the industry and is highly sought after. On the other hand, the industry is obligated to ensure safe caprock integrity. In these situations, geomechanics may appear to be a undesired burden. However, maintaining an intact caprock is far more important than immediate reservoir performance. As one senior geologist said, the hydrocarbon is an important resource, but we have a far more important resource for mankind --- clean groundwater supply (Personal communication, 2008). Fortunately, the industry has taken a proactive stance and the government enforces a vigilant work program on the caprock integrity issue. The following description presents further examples to illustrate the above points.

Two major objectives are planned for this paper: to present the theoretical and practical evidences to support the importance of geomechanics and to introduce the optimum work flow for studying geomechanical issues. First, a brief introduction on the reservoir geology sets the stage to understand the unique geomechanical properties and in-situ conditions in the oilsands. Then, an overview is given about deformation and fracturing behaviour in the oilsands. Subsequently, attention turns to the caprock integrity, explaining the geomechanical work program needed. The next two sections are relevant to both reservoir and caprock: operational and quality-control considerations for mini-frac tests and nonlinear thermo-hydro-mechanical coupling. A summary and discussion is given at the end.

The examples are drawn mostly from our own experience although some literatures are also cited for the further support. For decades, geomechanics has been promoted for the in-situ oil sands development in Alberta. Excellent work has taken place in both industry and academia. Initially, it was driven by the need to determine the optimal placing for steam injection. Then, the caprock integrity issue came into play as large-scale commercial production began and unforeseen stresses were placed on reservoirs and their caprocks. The literature to be introduced below is not extensive. Other publications of equal importance exist but are not referenced here as the objective of this paper can be achieved through limited citation.

A general description on the reservoir geology

The following description about the regional and reservoir geology, although brief, is warranted in order to explain the unique geomechanical properties possessed by the oilsands. It will also help appreciate the unique opportunities and challenges met in the in-situ oilsands developments. Most of the following summaries are based on a government publication by Flach (1984).

The oilsands reservoir rocks in Alberta were deposited during the Cretaceous period in the upper and lower Mannville Formation. There are three major oil sand areas in Alberta, namely Athabasca, Cold Lake and Peace River. The Athabasca oil sands area is the largest deposit and holds the most reserve. Most of the recent industrial activities are concentrated in this area and thus, more relevant details are presented below:

(1) The bitumen-bearing formation in the Athabasca area is called McMurray. It is a sequence of uncemented sands and shale that were accumulated in incised valleys on a pre-Cretaceous unconformity. From its bottom upwards, the McMurray deposits were formed in a fluvial environment initially. Such an environment then gave way to estuarine and finally transgressed by a marginal-marine environment. This relatively energetic depositional environment gives rise to a reservoir that is heterogeneous both vertically and laterally. For example, the presence of shale stringers or inclined heterolithic stratification (IHS) in most reservoirs can stop the steam chamber from rising and prevent the bitumen reserve above from being heated and produced.

(2) The Clearwater Formation, a layer of marine shale and sandstone, constitutes the regional caprock to the underlying McMurray reservoirs. Its thickness varies from a few meters to tens of meters. More Cretaceous deposits are also formed above the Clearwater. But their presence and thickness vary greatly across the region. The Cretaceous deposits may be absent in some areas due to the paleo-topography and more importantly to the glacial movement in Quaternary period. The McMurray formation overlies unconformably on carbonate rocks of Devonian age, including limestone and calcareous shale.

(3) The hydrocarbon source, migration and trapping mechanisms for the oilsands reservoir are not well understood. It is generally believed that microbial processes caused the extra heavy and highly viscous bitumen currently present in the reservoirs. The bitumen viscosity at the reservoir temperatures is of million-order centi-poses. The water phase exists in the reservoirs generally as a film around the sand grains. It is thus immobile or initial mobile water saturation is small. Thus, the initial water injectivity is very small if without rock deformation and failure.

(4) In addition, little energy is stored in the reservoirs. It is generally held that McMurray formation is under-pressured although the concept of pore pressure is less clear in such a fluid phase made of highly viscous bitumen and connate water. Therefore, in its virgin state there is essentially no drive mechanism to produce the bitumen from the formations. For the drive, reservoir production relies on the gravity in SAGD or compaction of the dilated sands in CSS. The dilation is induced during the injection cycles.

(5) Note that in all the areas, a continental glacial ice sheet as thick as 2 to 3 kilometers was present during the Quaternary period (e.g., Clark, 1980). This is equivalent to a minimum of 20 to 30 MPa of vertical overburden weight exerted on the Cretaceous deposits. The impact of such glaciation and its subsequent deglaciation on the mechanical properties of both reservoir sands and caprock shales is far-reaching. For example, the Cretaceous materials are all over-consolidated in the geomechanical terms. Strain-weakening and post-peak dilation behaviour dominates under low confining pressures. The glaciation also caused the diagenetic process that altered the grain-grain contacts in the oil sands from the initial tangential to the interpenetrative types currently observed. To a certain degree, pressure solution and crystal overgrowth also occurred in the sands. As will be shown later, such a unique grain-grain contact structure renders the oilsands with a significant dilation tendency that reservoir recovery if used properly.