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Assessing SAGD Response due to Plastic Deformations

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Summary

Deformations of oil sands are usually triggered in SAGD process because high pressure and temperature steam is continuously injected into the reservoir. Laboratory experiments on Alberta oil sands showed that stress induced plastic deformation can significantly increase the porosity, absolute permeability and water relative permeability of oil sands, which will enhance oil production and steam chamber growth in SAGD process. Realizing the importance of plastic deformations in SAGD performance, some of the current reservoir simulator, e.g. CMG, have already started to consider the impact of geomechanics simultaneously with flow simulation. However, due to the complexity of plastic behavior and its significant influence on flow properties, current reservoir simulators still cannot correctly model the interactions of flow and geomechanics in SAGD process due to plastic deformation induced by thermal expansion.

Sequentially coupled reservoir-geomechanical simulation is used to analyze the impact of plastic deformations on SAGD response by use of an in-house coupling platform. The permeability enhancement in steam chamber caused by thermal expansion can be correctly modeled during SAGD process. The oil production, steam chamber growth and surface heave are significantly enhanced by plastic deformations as the simulation results demonstrate. The caprock integrity also deserve more attention as steam might channel through the shear planes caused by plastic deformations.

Introduction

In conventional oil recovery, geomechanics has already been applied routinely in problems such as borehole stability, hydraulic fracturing and subsidence. In SAGD process, the geomechanics plays a more important role because of significantly elevated temperature and pressure in steam chamber. The stress-strain behavior of oil sands in Athabasca McMurray formation and Cold Lake Clearwater Formation were studied extensively, and it has been confirmed that the stress-strain response of oil sands is stress path dependent. The first predominant stress path is the reduction in mean effective stress due to pore pressure increase. It causes unloading of the sand grains and reservoir matrix under isotropic in situ stress state. However, for an anisotropic in situ stress state, where horizontal stresses are higher than vertical stresses like UTF site, the pore pressure change might potentially generate shear deformations in the reservoir. The second stress path is the large increases in horizontal stress due to thermal expansion of sand grains, reservoir matrix and pore fluid. The combination of effective mean stress, shear stress and thermal expansion create a complex net change in reservoir pore volume and permeability.

A series of lab experiments have been conducted to characterize the stress induced deformations and their impact on porosity, absolute permeability and relative water permeability change of the Athabasca Mcmurray Formation oil sands under different boundary conditions. Oldakowski demonstrated that absolute permeability change is a function of pore volume change and is independent of the stress path which the specimen has followed to undergo this volume change after isotropic unloading and triaxial shear tests on Athabasca oil sands. However, the change of pore volume is strongly related to stress paths. The absolute permeability increase varies from 13% to 70% for an average increase of 1.4% volume change in isotropic unloading. The absolute permeability changes from 46% decrease for a specimen contracting by 2% to 42% increase for a specimen dilating by 2.6% during triaxial shear tests.

During the isotropic unloading, it is observed that water relative permeability can have 500% increase with only 1.6% volume increase. The water relative permeability increases by three orders of magnitude because of 6% volume change caused by shear dilation. As oil sands samples are easily disturbed during sampling process, Touhidi-Baghini conducted experimental studies on permeability variation during shear process by use of outcrop of bitumen free McMurray Formation sandstone. For a dilative volumetric strain of 2%, vertical absolute permeability increased 40% and horizontal permeability increased 20%, which further confirms that shear dilatancy significantly improves absolute permeability. From previous experimental results, Li concluded that isotropic stress and shear stress are two major geomechanical responses affecting absolute permeability and relative permeability of water in SAGD process. The isotropic unloading occurs near the chamber front where effective stresses drops dramatically due to pore pressure change. The shear dilatancy can be predominantly found around the interface between the drained and partially drained zone. Particularly, the oil sand permeability increases dramatically after shear failure.

Evidence of shear planes in oil sands can be found in laboratory shear tests and field observations. Samieh and Wong investigated deformation of Athabasca oil sands at low effective stresses (50 kpa to 750 kpa) in triaxial compression tests. From sequence of computer-aided tomography (CAT) scan slices through the core, it can be observed the light areas indicating lower-density shear planes with higher porosity and absolute permeability. According to the heat transfer field observation of SAGD process by Birrell and Ito, high porosity and permeability shear planes formed ahead of steam chamber allows hot fluids to enter the cold oil sands formation. The repetitive ovals in temperature changes from thermocouples away from injector and producer wells indicate that existing shear plane is being reactivated or new shear planes are being created. Collins proposed that the optimum injection pressure during well-pair startup should be sufficiently high to trigger shear failure in oil sands between the injector and producer wells to accelerate interwell heating by convective heat flux. However, as the steam chamber rises close to caprock, the injection pressure should be gradually reduced but kept within 500 kPa of the fracture pressure. For cold regions of reservoir in front of the growing chamber, the increase in absolute permeability of 30% to 50% may occur which would be a remarkable enhancement for flow in oil sands reservoir. Given that the SAGD production rate is proportional to the square root of permeability according to Butler's theory, geomechanical enhancement of overall performance is significant in SAGD process. It has been widely accepted that only by including the interaction of flow and geomechanical behavior can we achieve a more complete understanding of the SAGD process. However, current commercial reservoir simulators cannot correctly model the interactions between flow and geomechanical behavior with updating porosity and permeability based on dynamic temperature and pressure in SAGD process. The coupling technique can appear in various forms: fully coupled, iterative coupled, explicit coupled and loosely coupled approach. The details of different coupling schemes are explained in Tran et al and Kim et al. In this paper, sequentially coupled simulation is selected due to its good combination with accuracy and computational efficiency.

Mcmurray formation, which is the major pay zone of Athabasca oil sand area, is well known for its complex geological heterogeneity. To capture detailed interaction of flow and geomechanical heterogeneity effect, heterogeneous high-resolution geo-cellular models are generated for MacKay river oil sands area based on public data for future research in coupled flow and geomechanical simulation. CMG STARS and Itasca FLAC3D are used to compute the flow and geomechanical behavior, respectively. An in-house coupling platform is used to transfer all the information between these two commercial software. Well Pattern C including 6 well pairs are chosen as the selected case study to show the impact of plastic deformations on both flow and geomechanical behavior.

Theory and/or Method

The Reservoir Geomechanical Research Group in University of Alberta developed a coupling platform to deal with SAGD process because geomechanics plays an important role in SAGD response. STARS (© CMG) and FLAC3D (© Itasca) are sequentially coupled to update porosity and permeability in reservoir simulations in selected time steps. For each coupled step, the outputs of pore pressure and temperature from CMG are passed to FLAC3D. Because the geomechanical properties, e.g. Young's Modulus, friction angle, dilation angle…, are also a function of confining stress, FLAC3D first updates the geomechanical properties and then obtain the updated stress and strain until the whole geomechanical model reaches equilibrium. The updated stress and strain are then inputted in the customized porosity and permeability update function to obtain the updated porosity and permeability for flow simulations in STARS. This sequentially coupled routine is applied only for selected user defined coupling steps for different scale of model. By using coupled reservoir-geomechanical simulations, the correct boundary condition and strain-softening model can be selected in FLAC3D to model the plastic deformation for each grid block. The user defined porosity and permeability update function for different rock types give flexibility to model the dramatical increase of permeability for only a small amount of plastic strain. Fine-scale geological model is generated by SKUA-GOCAD from the public log and core data in GeoScout, which will be inputs for coupled simulation to analyze the geomechanical impact on SAGD process.

Examples

Three comparing cases for Well Pattern C are generated to research on the impact of plastic deformation in SAGD performance. The first case is uncoupled flow simulation which only runs in CMG. The second one only considers elastic deformations and the permeability update function. The third one includes both elastic and plastic deformations and it clearly shows that the permeability has a dramatical change when plastic deformation occurs. The source of permeability difference between elastic and elasto-plastic case only comes from the plastic volumetric strain output by geomechanical model in FLAC3D. For this case, the maximum volumetric plastic strain is 2.66% which locates in the center of steam chamber in well pair 1. However, even this small change of volumetric strain tends to increase the absolute permeability by 3 times in steam chamber.

The simulation continues for 2000 days and the distributions of temperature at 2000 days are plotted in Figure 1. From top to bottom, the first case is uncoupled simulation. The second case is when only elastic deformations is included in coupled simulation. Because the permeability enhancement is not significant because of elastic deformations, the shape of steam chamber almost has no difference compared to uncoupled simulation. For the third case, which consider both elastic and plastic deformations, the steam chamber has a significant difference compared to the uncoupled simulation. The steam chamber is much larger for well pair 1 where no significant shale barriers exist. The chamber shape for well pair 2 has a larger difference compared to uncoupled simulation where shale barrier clearly hinders the propagation of the steam chamber. The major reason is that plastic deformations enhances the permeability at chamber front because of shearing process. Thus, the production rate become faster given the same injection pressure and reservoir condition.

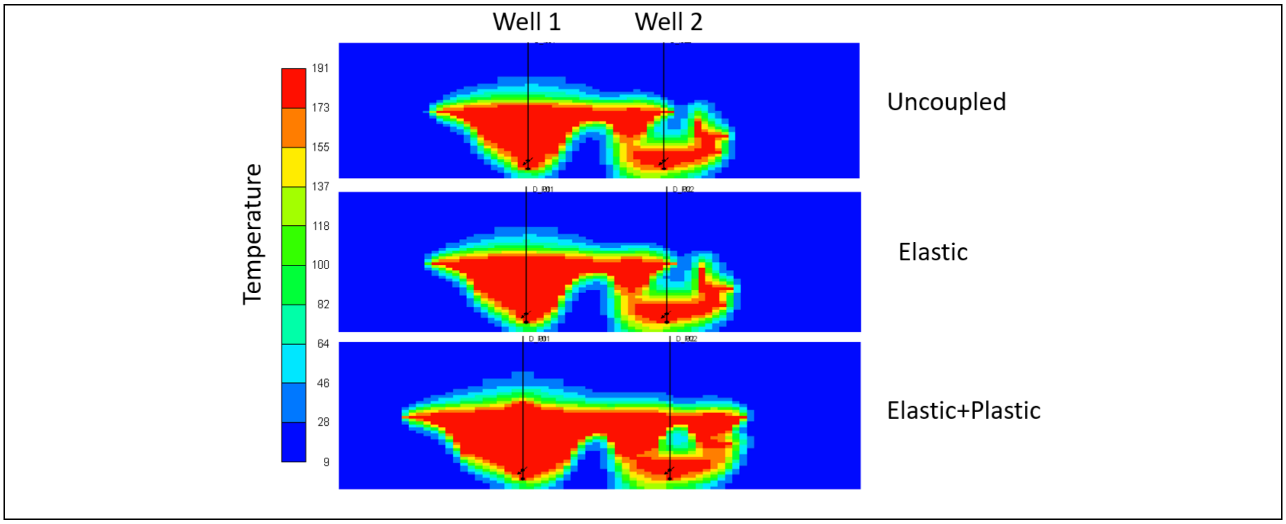

Figure 1: Temperature distributions at 2000 days of simulation. From top to bottom, they are uncoupled, elastic deformation included, and elastic & plastic deformations included cases.

The cumulative oil production for these three different cases are plotted in Figure 2 for well pair 1 and 2. The change of cumulative oil production is negligible when only elastic deformations is considered in coupled simulation. However, when plastic deformation is included, the cumulative oil production has a dramatical increase for both well pairs with and without shale barriers on the top of injector. The significant increase of well pair 1 is because the absolute permeability is greatly increase by plastic deformations in the reservoir. The sudden increase of oil production for well pair 2 is due to the shale barriers has failed so that the permeability in situ is greatly enhanced because flow can go through the generated shear planes. The coupled simulation which correctly models the permeability enhancement by plastic deformations has significant more oil production and well spread chamber compared to cases which only considers elastic deformations. For more accurate prediction of SAGD performance, plastic deformation is strongly recommended to be included in coupled reservoir-geomechanical simulation.

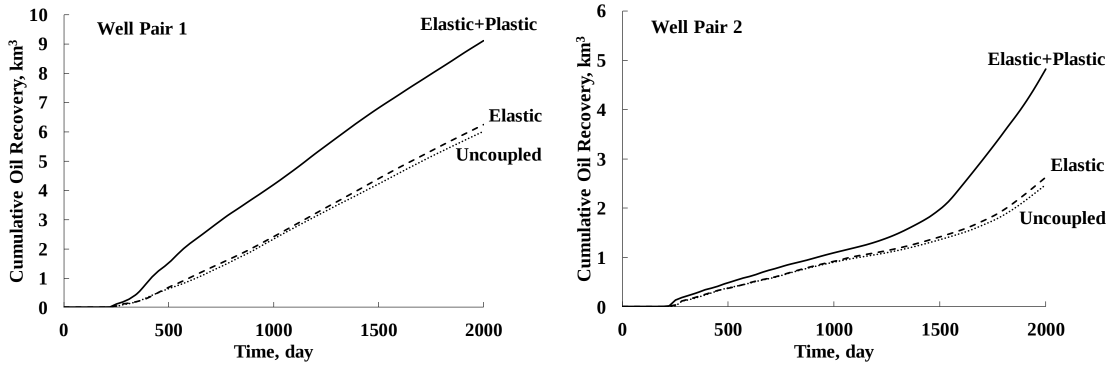

Figure 2: Cumulative production history for uncoupled, elastic deformation included, and elastic & plastic deformations included cases.

Conclusions

The SAGD performance is greatly affect by plastic deformation because porosity, absolute permeability and effective water relative permeability is a strong function of plastic volumetric strain. Field observations indicate that convection flow exists in shear planes of reservoir. Thus, the production and steam chamber growth can be enhanced by plastic deformation. Coupled reservoir-geomechanical simulation is proposed for accurate prediction of SAGD response when thermal expansion causes plastic deformation at chamber front. The oil production and steam chamber growth are significantly enhanced by plastic deformation as the simulation results demonstrates. To obtain a more accurate prediction of SAGD process, plastic deformations should be modeled carefully in coupled reservoir-geomechanical simulation.

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