Sets of stress path as a strategy to study efficiently the geomechanical trending behavior in CSS projects

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Abstract. Thermal recovery techniques such as CSS (Cyclic Steam Stimulation) induce significant changes in the stress path at the reservoir formation due to the induced thermal stresses in the wellbore and surrounding area. The understanding of phenomena regarding these stress paths is crucial to ensure safe operation and optimization of well productivity. Therefore, stress path analysis in CSS entails a challenge related to the number of focal points throughout the reservoir in which the stress paths should be studied. The reduction on the number of focal points is an advantageous step to ensure the appropriate analysis in extensive reservoirs with multiple sands and layers with different geomechanical and yield parameters. In the proposed grouping strategy, temperature and pore pressure are found to be key variables when determining the sets of stress paths with a common phenomenological trending behavior. In the current case study located in Middle Magdalena Valley basin, this grouping strategy allows a comprehensive analysis of 3 sets of stress paths strategically located on the borehole wall, inside and outside the steam front with the aid of numerical simulation software (CMG). Considering that stress paths usually represent a single focal point behavior within the reservoir, once this grouping strategy is implemented, an analysis of the whole reservoir is simultaneously performed during CSS.

1. Introduction
Thermal recovery techniques are part of the production strategies implemented in heavy oil reservoirs. These reservoirs contain oil with high viscosity and density at reservoir conditions whose mobility is extremely low. A strategy to address this issue is increasing reservoir temperature to reduce residual oil saturation through mechanisms such as viscosity oil reduction, rock wettability changes, and gas solution drive. Thermal recovery techniques, in which steam injection is employed as a source of heat, are the most used for the exploitation of heavy oil fields. They are Cyclic Steam Stimulation (CSS), steam flooding and Steam Assisted Gravity Drainage (SAGD) [1].

CSS is a steam thermal recovery technique that requires less logistics for its execution since it is applied in a single well that performs the role of injector and producer well at different stages. The main objective of CSS is to heat as much of the reservoir as possible, guaranteeing the decrease in the viscosity of the crude oil in the reservoir. CSS considers three stages per cycle: injection, soak and production. During the first stage, a volume of hot steam (400-600 °F) is injected for a period of 1 to 4 weeks, after which the well is shut in and allowed to soak. The soaking period lasts for a few days and it aims to
ensure high temperature proper distribution towards the well surroundings. The last stage, the production period, can last a few months [2].

1.1. Induced thermal stresses
Understanding thermal and pore pressure induced stress changes during thermal processes such as CSS allows to consider the stress distribution and plastic behavior in the heated zone. From the thermoporoelastic theory, it is well known that changes in temperature may create either strain or stress depending on the boundary conditions. Thus, Hooke’s law, includes the thermal expansion as in equation (1) where the term in bold from equation (1) expresses the impact of the temperature changes in the total rock strain [3]:

\[ \varepsilon_i = \frac{1}{E} \left[ \Delta \sigma_i' + v(\Delta \sigma_j' + \Delta \sigma_k') \right] + \beta \Delta T \]

(1)

It is possible to deduce that a heated reservoir has an increase in stresses. This phenomenon impacts directly into the lateral equilibrium if assume that the surrounding strata are cooler than the reservoir. This temperature difference, which creates a stress difference, induces a shearing phenomenon as shown in figure 1. In thermal processes two mechanisms are predominant (figure 2): i) thermal expansion and, ii) the dilation caused by the induced shearing stress. Thermal dilation occurs because the heating process leads to an increase of the tangential stress meanwhile the radial stress decreases and a strong volumetric strain takes place [4].

1.2. Stress path
Stress path is a way of representing the different stress states to which a point in the reservoir has been subjected; it is usually done graphically in the space p'-q, where p’ is the mean effective stress and q is the differential stress. Changes in the state of stresses in the reservoir are due to any operation that alters the initial state of the reservoir. For instance, the drilling of the well, the production of hydrocarbons or the injection of fluids in the reservoir.

To simulate the stress state evolution and elasto-plasticity performance of the reservoir during CSS, Drucker-Prager model is chosen because of its simplicity that represents a yield surface (Fs) in a p’-q stress space as given by the equation (2), (3) and (4). Plastic deformation occurs when the stress path shifts to the yield surface [5].

\[ Fs = q - p' \tan \beta - d = 0 \]

(2)

\[ q = \sigma'_1 - \sigma'_3 \]

(3)

\[ p' = \frac{1}{3}(\sigma'_1 + \sigma'_2 + \sigma'_3) \]

(4)

where \( \beta \) represents the angle of the yield surface, \( d \) is the q-intercept of the yield surface and \( \sigma'_1, \sigma'_2, \sigma'_3 \) corresponds to the changes in the stress state. Touhidi-Baghini [7] and Chalaturnyk & Li [6]
propose a clear simplification of this stress path into experimental testing procedures through triaxial tests where two possible behaviors of stress path can occur during the steam injection within the reservoir, the first one due to the effect of increasing pore pressure and the second one as the response of increasing the temperature. Both effects are represented in figure 3 in the p'-q space for two possible reservoir depths. Considering anisotropic horizontal stress condition, an increase in pore pressure reduces the effective stress in the same proportion in any direction, which is represented by a horizontal line. Thermal expansion generates an increase in horizontal stress which causes both the mean stress and the differential stress to increase together. This tendency is due to an increase in horizontal stress, while the vertical stress remains relatively constant. The aforementioned behavior applies to shallow reservoirs, but in deeper reservoirs the vertical stress might increase due to confinement.

![Stress path in the reservoir during thermal recovery](image)

**Figure 3.** Stress path in the reservoir during thermal recovery [7].

2. Methodology
The analysis of stress path allows understanding the representation of the evolving effective stress behavior during the different stages of CSS. Induced thermal stresses and pore pressure changes are the main cause of the stress evolution which should be properly simulated in order to proactively safeguard the integrity of the formation and assess the stress-strain and failure mechanisms.

The main focus here is to study the stress path trending behavior of oil sands and the influence of the CSS process over it, in terms of the temperature and pressure disturbance patterns. The approach to develop it follows two steps: numerical simulation using a commercial thermal simulator (CMG-Stars) and the analysis of p'-q plots of stress path at strategic points in the reservoir to recognize potential localization of plastic shearing zones.

2.1. Case Study
Input data for the selected case study is compiled from information of a heavy oil field located in Middle Magdalena Valley basin, in Colombia which has undergone thermal recovery processes such as CSS (Cyclic Steam Stimulation). It is characterized by having two groups of sands, Zone A and Zone B, whose depth ranges from 1375 to 2403 ft with oil sands and interbedded shale layers. The case study reservoir properties include porosity of 0.22-0.25, permeability from 594-1402 mD with kh/kv= 0.3, viscosity of 4107 cP at reservoir conditions and API gravity of 11.5-12.5 °API. Regarding geomechanical features, rock cohesion value is 1500 psi with a friction angle of 30° and Young modulus of 2.5E6 psi. Horizontal stresses anisotropy and strike-slip stress regime is also incorporated in the model.

Concerning the operational variables, the steam injection rate is fixed at 1150 BWE/d, the steam temperature and steam quality are 520°F and 0.75, respectively. Numerical simulation case study uses a representative radial model of 40 x 8 x 69 (figure 4) where the grid-block size in the “r” direction varies from 0.06 to 29 ft and the vertical interval of the reservoir perforated is 414.84 ft. The number of days for each one of the stages of a cycle of CSS are 13 days for injection, 5 for soaking and 400 days for production. The considerations for the case study are based on a multiphase flow and single-well model defined by an upper, lower and lateral non-flow external boundary. Drucker-Prager failure criterion is implemented as well as the iteratively geomechanical coupling option of CMG.
2.2. Preliminary focal points

When selecting the preliminary strategic points to assess the evolution of the stress path during CSS, it is relevant to focus on the interest of evaluating shear stresses responsible of the volume change associated with the growth of steam-front and the understanding of the impact of the thermal expansion and variation of pore pressure in the plastic response of the reservoir [8].

Apart from points at the top and bottom of the reservoir and contacts between adjacent rocks which are usually related to the caprock integrity and shear failure [9], certain areas of interest stand out, such as pressurized areas near shale barriers as in interfaces that lead to shearing (stress concentration or collapse) [10]; the heated zone near wellbore in poorly consolidated sands with relevant changes in total lateral forces (temperature component) and effective forces (pressure component) and lastly, the zone of 10 m (32.8 ft) from the thermal front where the disturbance generated by the injection pressures is still latent [11]. Therefore, compiling the previous strategic points mentioned in literature and the obtained stress path plots in space p'-q, there is a preliminary list of 12 focal points at 0° (figure 5. (a)) which are duplicated when considering them at 90° of initial tangential stress.

According to figure 5, though the focal points change, stress paths represented by Zone A and B sand layers have a common pattern. It is attributed to their similar permeability value that allows the significant propagation of the temperature and pressure front. At the top of the reservoir, the shale overburden is slowly heated by conductive heating, represented by the differential stress poor increase (figure 5. (b)). Besides, the thermal expansion during injection increases the pore pressure, reducing the mean effective stress (p’) supported by the matrix. Once the soaking and production periods start, the low-pressure diffusivity of shales and cooling, increase the p’ and decrease the differential stress. On the other hand, at the borehole wall the increasing thermal expansion and horizontal stresses cause the differential (q) and mean effective stress (p’) to increase rapidly together as in figure 5. (c) where the temperature disturbance leads the stress path to assume an aggressive increment. Within the thermal front of the reservoir (figure 5. (d), (e), (f)), the coupled penetration of both the temperature and pressure disturbance facilitates the approximation of the stress path to the shear failure envelope due to the rock weakening and faster pore pressure diffusivity. The stress paths outside the thermal front as shown in figure 5. (g) and at the reservoir external boundary are less affected by the temperature compared to the heated zone in the vicinity of the well.

Assessing the stress path at 90° in the tangential direction, there are not many noticeable differences specially at the borehole wall and within the thermal front when assessing the global trend. However, the stress path peak value at the borehole wall in q is greater at 90° than 0°, opposite to p’ behavior (figure 5. (h), (i)). The anisotropic initial state of stresses does not greatly affect the stress path trending behavior according to the simulation results, it rather affects the peak stresses values.
Figure 5. Preliminary focal points for stress path analysis at 0° and 90°: a) location of main focal points in the proposed reservoir physical model, b) stress path plot at the top and bottom of the reservoir, c) stress path plot of the borehole wall (0°) for layer in Zone A and B, d) stress path plot at R/Re = 0.25 (0°) within the thermal front for layer in Zone A and B, e) stress path plot at R/Re = 0.05 (0°) within the thermal front for layer in Zone A and B, f) stress path plot at R/Re = 0.1 (0°) for layer in Zone A and B (transition zone), g) stress path plot at R/Re = 0.5 (0°) outwards the thermal front for layer in Zone A and B, h) stress path plot at the borehole wall (90°) for layer in Zone A and B and i) stress path plot at R/Re = 0.05 (0°) within the thermal front for layer in Zone A and B.
3. Results & Discussion

It is important to mention that the proposed stress path classification is influenced by the anisotropic initial stress state and the bottom displacement boundary condition of the model. Concerning this preliminary trending behavior of stress paths, the following 3 focal points are proposed: a) during injection at the borehole wall, there is a thermal expansion of the reservoir fluids and sand grains in the heated zone where the shear stress (q) and the mean effective stress (p') increase rapidly [12]; b) within the thermal front, the stress path evolves moving closer to the shear failure line. There is a combination of the effects of temperature and pressure where the stress path pattern is smoother and imitates the behavior of a curve with the shape of a “hat”; c) outwards the thermal front transition zone, the temperature effect has diminished, and the stress path emulates the shape of a quite short horizontal line where the pressure disturbance diffusivity is quicker and the changes are minimum. During production stage, the reservoir cools down and tries to return to the initial stress state with a relevant reduction of the mean effective stress (p') for all stress paths. In figure 6, the main temperature and pressure behaviour trends are represented in order to explain their correspondent influence on the stress path.

![Figure 6. Temperature and pressure profile at the end of each CSS stage.](image)

At the borehole wall in figure 7 section I, the injected steam induces thermal stresses due to the lateral boundaries imposed by the surroundings in terms of the reservoir as a closed unit and restricted bottom displacement; besides tangential (horizontal) and vertical stress increase whilst radial stress poorly changes which results in the increase of p’ and q. After pushing the stress path to a peak (figure 7 section II), the heat front propagation and convective behaviour stabilizes the temperature in the heated zone mitigating the differential stress. The increasing behavior of the tangential stress due to thermal expansion at the borehole wall and the decrease of vertical stress (figure 8) causes p’ and q drop, inducing certain tendency towards yielding as shown at the end of the injection stage stress path. During soak stage, which corresponds to section III in figure 7, conduction is dominant and there is a temperature and pressure drop, 30°F and 215 psi (figure 6) which is dependent of the rock-fluid thermal conductivity. Both components p’ and q decrease, as all effective stresses drop too. Lastly, during the production (figure 7 section IV) the reservoir cools to 151°F and produces at a constant value of 650 psi causing thermoporoelastic and pore pressure changes in the vicinity of the borehole wall to affect the stress path. All effective stresses have a greater drop compared to the previous stages (figure 8), and they return to the initial stress state. Both q and p’ are reduced due to the thermal expansion favored by the temperature differences as well as the increase in pressure that pushes the pore liquids towards non-saturated conditions (draw-down). However, after 60 days of production tangential effective stress turns negative and increases the differential stress (q) due to the temperature effect on the rock.
Within the reservoir thermal front, convection dominates [13]. During steam injection (figure 9 section I), temperature and pore pressure effects are combined by the thermoporoelastic effect with an increase in pore pressure (reduction of p’) and q relatively increases which is still sensitive to the temperature difference in the vicinity of the well; due to pressure and temperature antagonist stress path pattern, it results in a vertical line during the first time steps of the simulation at the injection stage. In figure 9 section II faster pore pressure disturbance propagation stimulates shear strain in the reservoir during injection and the stress state shifts closer to the failure envelope. As shown in figure 10 pressure reaches its maximum value of 958 psi after just one day of injection while temperature is slowly starting to increase. Pressure diffusivity is greater than the temperature diffusivity, facilitating volumetric expansion of the rock during that poroelastic behavior within the thermal front. In figure 9 section III an aggressive increment of all the effective stresses translates into a higher value of p’ and lower q due to the temperature diffusion that starts counterbalancing the pressure effect, making the stress path deviate from the failure line. Once the injector/producer well is shut in for soaking (figure 9 section IV), effective stresses have a smooth drop (figure 10) as well as the pore pressure and temperature which corresponds to the reduction on p’. Lastly, in the production stage (figure 9 section V) the stress path represents the pore pressure effect only as it turns to the left with decreasing mean effective stress due to the considerable pore pressure drop (figure 6) and unloading of the reservoir matrix.

Thermally induced stresses and pore pressure coupling effect mitigates quickly once the stress state is located further from the injection well. Outwards the thermal front, during the injection the temperature tries to return to the reservoir condition and there is a significant pore pressure drop, even greater than the other radial distances (figure 6). In figure 12 the effective stresses remain almost constant during the injection, except when starting the soak stage. The temperature and pressure perturbation propagation is much slower, as observed in the stress path poor changes in figure 11. However, in figure 11 section III during production the effective stresses starts to increase a little which is reflected in p’ increase attributed to the depletion and compaction.
4. Conclusions
In brief, these 3 sets of stress path trending behaviour allow a more effective analysis process of the stresses behavior and lower post-processing time for the user who plots the stress path during each one of the stages of CSS. The strategic points at the borehole wall, within the thermal front and in the external zone are expected to represent global reservoir patterns where the reduction of the effective confining stress (increasing of pore pressure) and its interaction with thermal stresses during injection might shift stress state to scenarios of rock yield. Once the stress path moves further from the injection well, it shrinks, and the p’-q stresses values are reduced. On the other hand, the stress path behaviour seems to be restricted by the propagation of the pressure and temperature front during CSS. The temperature front stimulates a thermoporoelastic response of the rock accompanied by thermal expansion strain. The pressure front promotes a poroelastic response. The heat front mainly affects the stress state in the stimulated (near wellbore) zone.

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References

[1] Alvarez J and Han S 2013 Current overview of cyclic steam injection process Journal Petroleum Science Research 2 127.

[2] Torres-Hernandez C 2018 Modelamiento del perfil de temperatura dentro del yacimiento durante procesos de recobro térmico con inyección de vapor en yacimientos de crudo pesado, Master Thesis (Medellín: Universidad Nacional de Colombia) p 153.

[3] Dusseault M B 1993 SPE International Thermal Operations Symposium (Bakersfield: Society of Petroleum Engineers) p 11.

[4] Dusseault M B 2011 Geomechanical challenges in petroleum reservoir exploitation KSCE Journal of Civil Engineering 15 678.

[5] Drucker D C and Prager W 1952 Soil Mechanics and Plastic Analysis for Limit Design Quarterly of Applied Mathematics 10 165

[6] Chalaturnyk R J and Li P 2004 When is it important to consider geomechanics in SAGD operations? Journal Canadian. Petroleum Technology 43 9.

[7] Touhidi-Baghini A 1998 Absolute permeability of McMurray formation oil sands at low confining stresses, Ph.D Thesis (Edmonton: University of Alberta).

[8] Gong X, Wan R and Hadda N 2014 Finite element analysis of geomechanical failure during heat stimulation processes in heavy oil recovery Computer Methods and Recent Advances in Geomechanics (Kyoto: Taylor & Francis Group) p 472.

[9] Garipov T T, Voskov D V and Tchelepi H A 2015 SPE Canadian. Heavy Oil Technology Conference Rigorous coupling of geomechanics and thermal-compositional flow for SAGD and ES-SAGD operations (Calgary: Society of Petroleum Engineers) p 16.

[10] Pathak V, Tran D and Kumar A 2014 SPE Heavy Oil Conference Quantifying the uncertainty associated with caprock integrity during SAGD using coupled geomechanics thermal reservoir simulation (Calgary: Society of Petroleum Engineers) p 20.

[11] Dusseault J L and Collins P M 2010 Geomechanics effects in thermal processes for heavy-oil exploitations Heavy Oils: Reservoir charcaterization and production monitoring vol 13 ed S Chopra, L R Lines, D R Schmitt and M L Batzle (Tulsa: Society of Exploration Geophysicists) chapter 24 pp 287-291.

[12] Scott J D, Adhikary D and Proskin S A 1994 Volume and permeability changes associated with steam stimulation in an oil sand reservoir Journal. Canadian. Petroleum Technology 33 52.

[13] Romanov A and Hamouda A A 2011 SPE Asia Pacific Oil and Gas Conference Heavy oil recovery by steam injection, mapping of temperature distribution in light of heat transfer mechanisms (Jakarta: Society of Petroleum Engineers) p 13.