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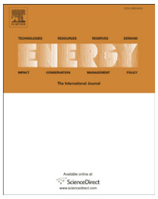

On the physics of cyclic steam stimulation

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A B S T R A C T

Steam fracturing as done during cyclic steam stimulation is an effective thermal process for initiating recovery from viscous oil reservoirs such as oil sands reservoirs found in Alberta, Canada and Liaohe, China. A key component of these processes is the ability to inject high temperature steam into the formation to fracture it which in turn raises its permeability and mobilizes the oil by lowering its viscosity. The dynamics of steam fracturing are not fully resolved especially how steam fingers into the reservoir and how its state changes as heat losses occur from the injected steam. The results of this study reveal that steam condensate, pressurized by the steam vapour upstream, fractures the formation. The results also show that dilation of the reservoir during steam injection relieves the pressure which in turn lowers the steam injection pressure below that of the case where no dilation occurs.

1. Introduction

Steam fracturing, as done in some cyclic steam stimulation operations, leads to not only reservoir rock failure by a reduction of the mean effective stress through an increase of the pore pressure but also heating of the reservoir via latent and sensible heat transfer to the reservoir rock. For viscous oil systems such as oil sands reservoirs, this improves the mobility of the oil by lowering the viscosity of the oil, reducing the interfacial tension which raises the oil's relative permeability, and enlarging the absolute permeability of the reservoir rock.

Cyclic steam stimulation operations are being conducted in several extra heavy oil reservoirs in the world including Alberta, Canada and Liaohe, China. The key differentiator of the Cyclic Steam Stimulation (CSS) operations in Cold Lake, Alberta, Canada and CSS operations in the Liaohe Oil Field in China is that in the Canadian Operation, steam is injected above the fracture pressure of the reservoir whereas in the Chinese operation, steam is injected below the fracture pressure. Both CSS operations, as shown and described in Ref. [1]; achieve reasonably low steam-to-oil ratios. However, steam fracturing operations require high pressure steam: for Cold Lake, the steam is generated at about 17 MPa and injected into the formation at between 11 and 13 MPa; the fracture pressure of the oil sands reservoir is equal to about 9.9 MPa ([3,6]). This represents a significant energy investment to generate this steam. In the Liaohe CSS operation, the steam is injected at roughly 9.5 MPa which is lower than the fracture pressure, estimated to be equal to about 13 MPa [13].

The literature contains few papers that discuss steam fracturing in CSS operations [2,3,5–7,10–12]. Most of the papers were based on the research and development activities of Imperial Oil's Cold Lake Project where high pressure and high temperature steam is injected into the formation above the fracture pressure of the formation.

Steam injectivity during Cyclic Steam Stimulation (CSS) can be achieved by injecting at pressure high enough to fail the formation mechanically, in other words, at high enough pressure to fracture the formation [10]. In terms of CSS operation, the literature reports that the most important recovery mechanism for early CSS is formation compaction [6,7]. During steam fracturing, the formation is dilated and as a consequence, it lifts the overburden. This is seen at the surface in the form of heave and in some CSS operations, the heave can be as high as 45 cm [2]. The second dominant drive mechanism is considered to be solution gas drive [6,7]. Solution gas drive occurs when the steam injection period has been completed and the system goes on production and since the low pressure point in the reservoir is the production well, solution gas comes out of solution in an annular region surrounding the wells as the pressure drops there. The solution gas expands in the direction of the pressure gradient which effectively drives fluids, including

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mobilized oil, to the production well. Although it does contribute to oil production, fluid thermal expansion and gravity drainage plays a relatively minor role in early stage. Later, after the steam chamber has grown to an appreciable size vertically, gravity drainage plays a greater role for moving mobilized oil to the production well.

The research documented here focuses on the physics of CSS by using refined thermal reservoir models to understand the basic physics of steam fracturing and transport into the reservoir and consequent heat transfer, oil mobilization, and movement to the production well. The model is based on the history-matched Liaohe oil field geological model described in Ref. [1]. Here, two single well locations (one with relatively poor reservoir properties and the other with relatively good reservoir characteristics) are used to analyze CSS recovery process dynamics. Based on the two wells, four submodels are constructed and evaluated to understand CSS with dilation and CSS without dilation. To model steam-induced dilation and fracturing, the quad model, developed by Ref. [2]; is used in this work. This model is capable of representing elastic dilation and recompaction as well as irreversible changes of the formation associated with fracturing when the pore pressure exceeds the fracture pressure and healing of the fracture when the pressure drops below a compaction pressure.

2. Reservoir simulation model

2.1. Reservoir and operation description

The Liaohe oil field's Block Du 84 operation is producing oil from the Guantao Formation which is located at a depth of between about 530 and 670 m. The sands in this formation are thick with average pay of about 90 m, average porosity equal to about 28%, and oil saturation averaging around 66%. The initial temperature of the reservoir is equal to 32 °C. The viscosity of the dead bitumen hosted in the reservoir is over 1 million cP. Similar to the Clearwater Formation in the Cold Lake deposit in Eastern Alberta, CSS is one of the major thermal recovery methods used in the Guantao Formation in the Liaohe Oil Field. However, an important difference between the operation strategy at Cold Lake to that at the Liaohe oil field is that sub fracture pressure injection is used in the Chinese reservoir.

Here, four models have been built to analyze CSS behaviour listed in Table 1. Fig. 1 displays the domains of both the rich and poor reservoir models. The poor and rich reservoir property cases were chosen from a geological model of the Liaohe Oil Field [1] at a well location representing the average behaviour of the CSS wells in the operation. A thermal reservoir simulation model, CMG STARS™ [4] was used in the research documented here. This simulator uses the finite volume method to solve the conservation of mass, energy balance, and gas-oil equilibrium behaviour (using a K-value formulation) in the context of Darcy flow of water, oil, and gas phases. The component material balance equation is given by:

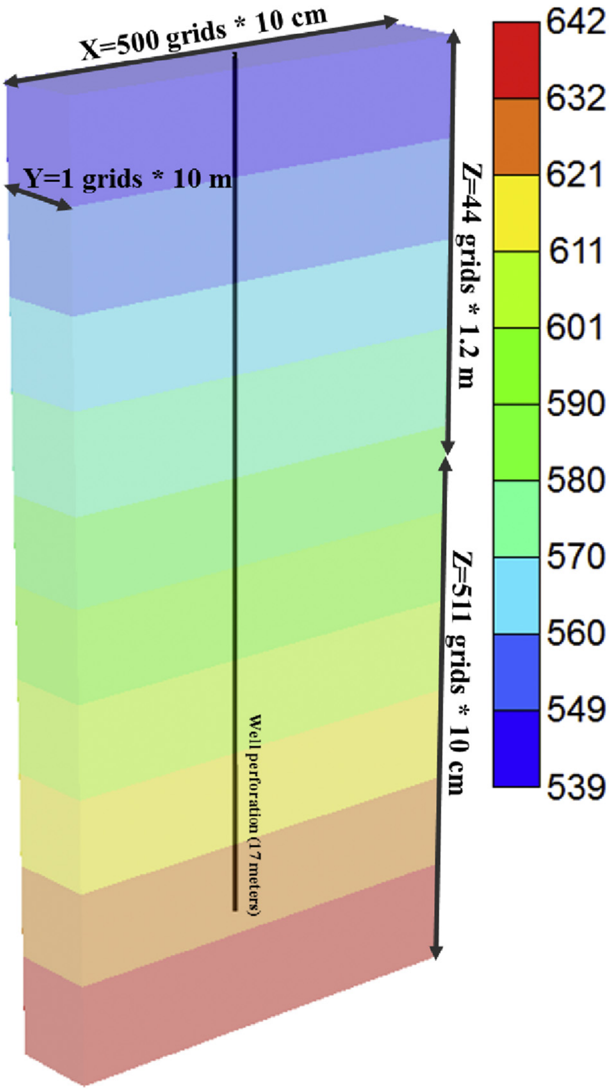

Fig. 1. Domain of both the rich and poor reservoir models.

$$\frac{\partial}{\partial t}\left[\phi\left(\frac{x_{wj}\rho_w S_w}{MW_w}+\frac{x_{oj}\rho_o S_o}{MW_o}+\frac{y_j\rho_g S_g}{MW_g}\right)\right]+\frac{\dot{m}_j-\dot{m}_{jr}}{MW_j}=\nabla\left[\frac{k_w\rho_w}{\mu_w}c_{wj}(\nabla P_w-\gamma_w\nabla z)+D_{wj}^{eff}\nabla\left(\frac{\rho_w x_{wj}}{MW_w}\right)+\frac{k_o\rho_o}{\mu_o}c_{oj}(\nabla P_o-\gamma_o\nabla z)+D_{oj}^{eff}\nabla\left(\frac{\rho_o x_{oj}}{MW_o}\right)\right.$$
$$\left.+\frac{k_g\rho_g}{\mu_g}c_{gj}\left(\nabla P_g-\gamma_g\nabla z\right)D_{gj}^{eff}\nabla\left(\frac{\rho_g x_j}{MW_g}\right)\right] \qquad (1)$$

Table 1
Average properties of rich and poor reservoir models.

	Porosity	Average porosity	Oil saturation	Average oil saturation	Permeability (mD)	Average Permeability (mD)
Heterogeneous Model with Rich Properties	0.15–0.47	0.35	0.27–0.89	0.75	500-8465	3250
Heterogeneous Model with Poor Properties	0.05–0.41	0.24	0.21–0.89	0.68	500-8194	1900