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Study of heat transfer by thermal expansion of connate water ahead of a steam chamber edge in the steam-assisted-gravity-drainage process

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HIGHLIGHTS

- Proposed a modeling of heat transfer by thermal expansion in SAGD.
- Proved the important convection heat transfer ahead a steam chamber in SAGD.
- Provided heat efficiency improvement methods in SAGD.

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ABSTRACT

Steam-Assisted Gravity Drainage (SAGD) has been the preferred thermal method for bitumen recovery from reservoirs in western Canada, such as Athabasca and Cold Lake. In SAGD, near the edge of a steam chamber, the viscosity of bitumen can be reduced by several orders of magnitude by the release of latent heat from injected steam. Consequently, the heated bitumen flows downwards to a horizontal production well, under the action of gravity. A critical control of oil production performance in SAGD is the heat transfer ahead of the steam chamber edge. It is commonly suggested that heat conduction is the only, or dominant, mechanism for heat to be transferred to the cold oil sands. Heat transfer through convection is neglected in classical models, such as in Butler's theory. Although a few mathematical studies have recently been performed to examine the role of convective heat transfer through condensate flow perpendicular or parallel to the steam chamber edge, the role of heat transfer by cold connate water thermal expansion in SAGD has been given little attention. In this study, an analytical model is derived for heat transfer induced by thermal expansion of the connate water, and the result is reasonably consistent with the numerical simulation results obtained by running CMG STARS. The relative roles of conduction and convection ahead of the steam chamber edge are re-examined. The results show that heat convection accounts for a much higher percentage of the total heat transfer than conduction. This study also suggests that parameters that have a close relationship with the thermal expansion of connate water, such as the steam injection temperature and connate water saturation, can affect the relative roles of conductive and convective heat transfer in SAGD. Based on this study, the heat transfer efficiency can be enhanced through improving convection induced by thermal expansion of connate water.

1. Introduction

Under native reservoir conditions, bitumen is too viscous to be moved by gravity. In order to lower bitumen's viscosity to a sufficiently low level so as to make it mobile, two methods are applicable: (1) increasing the bitumen temperature by steam injection; or (2) diluting the bitumen by light hydrocarbon component (solvent) dissolution [1]. To take advantage of high temperatures and gravity drainage, SAGD was proposed as an in-situ bitumen recovery method by Butler in 1982 [2]. Recently, SAGD has been commercially available and extensively operated for bitumen recovery; as of 2010, half of in-situ thermal heavy oil production in Alberta, Canada was through SAGD [3].

Typically, SAGD consists of a pair of horizontal wells drilled into a formation. The production well is located about 2 m above the base of a reservoir, with the injection well drilled parallel to, and about 5 m above, the producer [3–5]. Steam is introduced into the reservoir through the injection well, and a steam chamber is formed at the saturated steam temperature. Steam flows and condenses when it comes into contact with the cold oil sands at the steam chamber edge. The latent heat transfers to the surrounding

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formations and warms up the bitumen. Under the action of gravity, the heated oil and condensate flow downwards to the horizontal production well [6,7]. As the oil is removed, the pore space is occupied by the injected steam, which results in the advancing of the steam chamber [8].

A critical parameter in the oil production performance of SAGD is the extent of heating of the oil sands. The higher the heat flux into the oil sands, the greater the extent of oil viscosity reduction, and correspondingly the thicker the heated mobile oil layer near the steam chamber edge [9,10]. That is, a comprehensive understanding of heat transfer mechanisms and temperature distribution are necessary to optimize a SAGD operation, especially regarding heat efficiency optimization. In the classical analytical models of SAGD, as depicted schematically in Fig. 1, conduction is assumed to be the only heat transfer mechanism ahead of the steam chamber edge to mobilize bitumen [8,11–23]. In Edmund's analysis, for example, it is noted that the convective heat flux ahead of the steam chamber edge is close to zero, as the condensate flow streamline is nearly parallel to the isotherms [12]. Depending on the calculation of the enthalpy change, liquid flow near the steam chamber edge only delivers about 22% of the total energy transferred to the cold oil sands, which consists of about 18% carried by the condensate and about 4% carried by the oil. Conduction is the only way to account for the large remaining portion of heat transferred [12]. It is therefore concluded that, except for the areas in the very near vicinity of the production well or when there is live steam penetration, heat conduction is the dominant form of heat transfer ahead of the steam chamber edge in SAGD [13].

Besides conduction, heat transfer can also be achieved by convection, in which heat is delivered mostly by fluid flow. The assumption of only heat conduction occurring ahead of the steam chamber edge has been contested, because heat convection would be the dominant form of heat transfer under the substantial flow of condensate in the SAGD process, especially when the steam chamber pressure is significantly higher than the native reservoir pressure [24]. In addition, numerical simulation results have demonstrated that heat transfer by convection is greater than that by conduction [25]. With a given pressure difference between the steam chamber and the outer cold oil sands, a closed-form solution of heat convection can be formulated, and such formulation leads to the conclusion that convection is the dominant mechanism of heat transfer for reservoir locations where temperatures are above 225 °C, while conduction becomes the dominant mechanism where temperatures are below 125 °C [9]. Besides the convective heat flux through the condensate flowing perpendicular to the steam chamber edge, the inflow and outflow of the condensate along the steam chamber edge has also been studied to calculate heat transfer. Results show that this convective heat flux of the outflow contributes less than 10% of the conductive heat flux that is ahead of the steam chamber edge [10].

An additional possibility for how convection takes place is via steam fingering into the cold oil sands. However, it is commonly believed that fingering through bitumen is not significant, because steam condenses rapidly when flowing through low temperature bitumen [10]. Furthermore, the nonlinear behavior of compressibility, and a geomechanical analysis of oil sands in a SAGD operation, show that, under low pressure, heat transfer from the edge of a steam chamber to the outer oil sands depends mainly on conduction, because the mean stress remains unchanged by thermal stresses. Therefore, convection can only occur under high pressures and temperatures, where a pressure front is moving faster than a thermal front [26].

In the studies of heat transfer in a SAGD process, the behavior of convective heat transfer still remains unclear. In prior studies, heat convection is mostly focused on the result of condensate flow by pressure gradient resulting from the pressure difference between the steam chamber and the native oil sands. Simplified mathematical models for heat transfer for examining conductive and convective heat transfer mechanisms can be derived based on the assumptions of single phase flow and a given oil sands compressibility [10,23]. However, because of the quite low compressibility of oil sands, which is in the range of 0.4×10^{-6} to $0.6 \times 10^{-6}\ \text{kPa}^{-1}$ for Athabasca and 1.0×10^{-6} to $2.0 \times 10^{-6}\ \text{kPa}^{-1}$ for Cold Lake [27], the built up pressure gradient cannot provide sufficient potential for significant convective heat transfer to occur, leading to the conclusion that only heat conduction contributes significantly to the mechanism of heat transfer ahead of the steam chamber edge in SAGD [10,23]. Except for such analysis of convective heat transfer due to a pressure difference between the steam chamber and the native cold oil sands, there is a lack of understanding of the convective heat transfer by means of connate water flow induced by thermal expansion. In porous media, the excess fluid pressure created by fluid thermal expansion against a matrix is described as aquathermal pressuring, which has been discussed by many researchers [28,29]. In aquathermal pressuring, the fluid pressure increases significantly under elevated temperature once the fluid density reduces significantly [29]. Fig. 2 demonstrates the water density variance versus temperature [30]. For example, at 1.0 MPa, the water density decreases from 1,000.3 kg/m^3 to 887.1 kg/m^3 when temperature increases from 0 °C to 179 °C. Hence, the excess fluid pressure gradient, which results from the liquid volume expansion constrained by matrix, provides the potential for fluid flow [31]. In SAGD heat transfer analysis, when the connate water (which, as discussed above, can be expanded under elevated temperature conditions) is incorrectly assumed to have invariant density with respect to temperature and therefore to be stationary, it impairs the accuracy of simulating a thermal

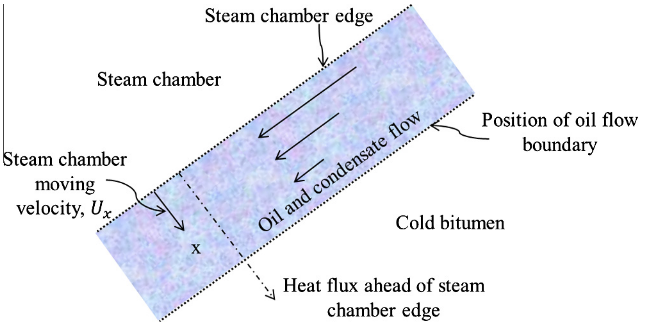

Fig. 1. Classical schematic of heat transfer from the edge of the steam chamber to the cold oil sands.

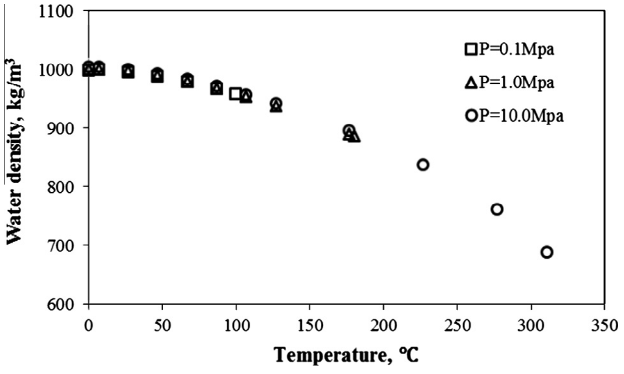

Fig. 2. Water density behavior under various temperatures [30].