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# Analytic Investigation of Convection During Conduction Heating of a Heavy-Oil Reservoir

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## Abstract

*The assumption of constant temperature is often valid for the operation and analysis of most conventional oil reservoirs; however the average behaviour of reservoirs exposed to thermal flooding is non-isothermal. In addition to being non-isothermal, heated reservoirs are characterised by non-uniform temperature distribution. Where the heating mechanism is conduction, most analyses ignore convection (including natural convection) in the overall heat balance. However, the induced temperature gradient affects fluid properties (especially viscosity and density) and their spatial distribution.*

*In this paper, possible buoyancy-induced natural convection is investigated by simulating one-dimensional vertical temperature profiles of a semi-infinite reservoir column, fully saturated with undersaturated heavy oil, subjected to conduction heating from the bottom. Using a realistic temperature dependence of the density and viscosity of typical Athabasca bitumen, vertical distributions of in-situ oil density, velocity and Nusselt number consistent with the induced temperature gradient are established. The simulation results indicate that at any time, oil density increases vertically away from the heat source, a condition that is gravitationally unstable, with a potential for fluid-redistribution, triggering convection. In this study, the magnitude of a Nusselt number is used as a proxy for the relative importance of natural convection. Although it is shown that free convection can be important, its significance depends on the duration of heating as well as rock and fluid properties. Consequently, we argue that the convective heat-transfer, in addition to temperature and time-dependent variations of oil density and viscosity, should be considered in realistic models of thermal recovery of heavy oil, even if the heating philosophy is "apparently" conduction.*

## Introduction

Thermal processes are the most successful methods for commercial recovery of heavy oil and bitumen. While the analyses of non-thermal processes focus on mass and momentum balances, heat transfer introduces additional complexity to thermal recovery. Although dependent on the rock and fluid characteristics, heat transfer rate, as against drainage rate, is often the controlling mechanism in thermal recovery of initially immobile oil (Al-Rabaani *et al.*, 2008). However, despite the large effort undertaken, conflicting results from different analytic, numerical or experimental investigations and field performances indicate the poor understanding of the physics of the process (Albahlani and Babadagli, 2008; Sasaki *et al.*, 2002; Robertson, 1998).

Conduction heating is perhaps the simplest form of thermal recovery. In man-made conduction heating, a heating medium (e.g. steam) is injected continuously into a highly permeable section or fracture (natural or artificial) within the reservoir, and the adjacent oil zone heated by vertical and horizontal thermal conduction. Commercial applications of this technique for oil recovery are available (Doscher *et al.*, 1964), and its use as a surveillance tool for analysing field observations has been reported (Closmann, 1984; Neuman, 1984; Closmann and Smith, 1983). Although the heating medium is not intended to flow into the oil zone, where this happens e.g. through steam channelling, the average behaviour has been analysed as effective conduction, ignoring convection (Satter, 1967). In other cases, the moving-conduction theory has been used to approximate a seemingly thermal convection process (Akin, 2005; Butler, 1994; Reis, 1992; Butler, 1987; Butler, 1985).

In the Steam-Assisted Gravity-Drainage (SAGD) process, a steam chamber forms and expands as steam flows continuously to the perimeter of the chamber where it condenses and heats the surrounding oil (Butler, 1994). The heated oil and condensate drain continuously to the producer below the injector. The upward growth of the chamber is characterised by