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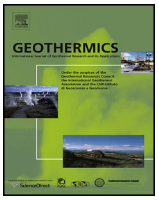

Free thermal convection in heterogeneous porous media

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ABSTRACT

This study investigates free thermal convection in heterogeneous porous media and its dependency on grid discretization. Heterogeneous hydraulic conductivity fields are described with a geostatistical approach. Numerical experiments are carried out with the heterogeneous thermal Elder problem. Results are evaluated qualitatively and quantitatively. Key results show that (1) grid convergence for thermal variable-density flow simulations in heterogeneous porous media can be achieved, (2) the degree and structure of a heterogeneous hydraulic conductivity field significantly affect thermal convective flow patterns, (3) steady-state heat distribution depends on the hydraulic conductivity field rather than on thermal conductivity, (4) more variant log hydraulic conductivity fields result in an increase of the heat flux, of the heat stored, and of the upwelling length of thermal plume fingers, (5) an increase in the horizontal correlation length of the log hydraulic conductivity field leads to an increase of the heat stored and the upwelling length, but it does not affect the heat flux, and (6) an increase in the mean of the log hydraulic conductivity field leads to an increase of the heat flux, of the heat stored, and of the upwelling length.

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1. Introduction

Spatial variations in solute concentration, temperature, and fluid pressure cause fluid density variations, which can potentially lead to variable-density flow. Variable-density flow is a key process in many natural phenomena and engineering applications (Diersch and Kolditz, 2002). Variable-density flow has received considerable attention in groundwater hydrology and geothermal reservoir engineering, where fluid temperature differences can be significant (e.g., Cheng, 1978; Graf, 2009; Graf and Therrien, 2009; Goldstein et al., 2010; Grant and Bixley, 2011; Nield and Bejan, 2013).

Free thermal convection (hereinafter referred to as thermal convection or thermal variable-density flow) is purely driven by spatial variations of fluid temperature in the absence of a hydraulic gradient. Thermal convection is one of the main physical phenomena of variable-density flow, for example in geothermal reservoirs. Thermal convection is therefore of particular interest in geothermal engineering, especially in geothermal energy extraction because thermal convection transfers a greater amount of energy than conduction alone (Barbier, 2002). Geothermal energy is considered as an economical, renewable source of energy, and the demand for geothermal energy is predicted to increase (Fridleifsson, 2003). It is therefore important to understand thermal convection in homogeneous and heterogeneous porous media.

In homogeneous porous media, where both permeability and thermal conductivity of the porous medium are uniform, thermal convection has been extensively studied and is reasonably well understood. The criterion for the onset of thermal convection with different boundary conditions has been mathematically investigated by Horton and Rogers (1945), and Lapwood (1948). Wooding (1957) gave a finite difference solution for steady-state thermal convection in two-dimensional (2D) porous media. Elder (1967) conducted both a laboratory experiment with a Hele-Shaw cell in aqueous media and a numerical study of transient thermal convection in 2D porous media. Holst and Aziz (1972) derived a numerical solution of transient thermal convection in three-dimensional (3D) porous media. Holst and Aziz (1972) found that the convective motions in three dimensions transfers a larger amount of heat than in two dimensions depending on the spatial dimensions and on the Rayleigh number of the problem. Kassoy and Zebib (1975) investigated the effect of viscosity variations on the onset of thermal convection, while Horne and O'Sullivan (1978) investigated the effect of both viscosity variations and the effect of thermal expansion coefficient on convective flow patterns. Graf and Boufadel

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(2011) numerically studied the effect of viscosity variations, capillarity and grid spacing on thermal convection. Graf and Boufadel (2011) concluded that (1) viscosity variations significantly affect convective flow patterns under both saturated and variably saturated flow conditions, (2) capillarity must be accounted for under variably saturated flow conditions with low soil moisture, and (3) grid spacing strongly affects convective flow patterns and grid convergence is very difficult to achieve. Cooper et al. (2014) conducted an experimental study of transient thermal convection in a 2D porous medium, which was filled with spherical glass beads, to compare experimentally obtained length and time scales of plume development to theory. Exhaustive reviews of related studies can be found in Diersch and Kolditz (2002), Goldstein et al. (2010), and Nield and Bejan (2013).

In heterogeneous porous media, where both hydraulic conductivity (or permeability) and thermal conductivity of the porous medium may vary, thermal convection has been studied in different types of heterogeneity. For examples, Gheorghitza (1961) and Mckibbin and O'Sullivan (1980) focused on the criterion for the onset of thermal convection in multi-horizontal layers with different permeabilities and uniform thermal conductivities. Mckibbin and Tyvand (1982) studied thermal convection in multi-horizontal layers with different permeabilities and thermal conductivities by using an equivalent homogeneous anisotropic porous medium for the permeability and thermal conductivity fields. Mckibbin and Tyvand (1982) found that the equivalent homogeneous anisotropic representation of the multi-layered system is capable of modeling large-scale convection, which occurs throughout all layers. However, convective motions may only occur in layers with higher permeability or thermal conductivity (Mckibbin and O'Sullivan, 1980; Mckibbin and Tyvand, 1982). McKibbin (1986) investigated the onset of thermal convection, the convective flow patterns, and the spatial distribution of the surface heat flux in multi-vertical layers with different permeabilities and thermal conductivities, finding that they are strongly controlled by the permeability and thermal conductivity contrasts between layers. Nield and Kuznetsov (2007a) studied the effect of both horizontal and vertical heterogeneity (in terms of both hydraulic conductivity and thermal conductivity) on the onset of thermal convection. Nield and Kuznetsov (2007a) focused on the case of weak heterogeneity, where hydraulic conductivity and thermal conductivity both vary by a factor smaller than 3. Other notable studies and their results related to thermal convection in heterogeneous porous media are McKibbin and Tyvand (1983), Nield and Kuznetsov (2007b,c), Nield and Bejan (2013). While the heterogeneity in all of the above-mentioned studies was represented deterministically, other studies showed that heterogeneity in natural aquifers is more realistically being represented using geostatistical approaches (e.g., Boggs et al., 1990; Freeze, 1975; Gupta et al., 2006; Sudicky, 1986).

In geostatistical approaches, the heterogeneity of aquifer is represented by random spatial functions, where the aquifer properties (hydraulic conductivity or permeability) are treated as random variables. Corresponding theory and examples can be found in the studies of Chilès and Delfiner (2012), Deutsch and Journel (1998), Gelhar (1986), Prasad and Simmons (2003), and Simmons et al. (2001). These studies showed that heterogeneous hydraulic conductivity (or permeability) fields can be characterized by the mean, variance, and horizontal and vertical correlation lengths of the log hydraulic conductivity or permeability field. In the remainder of this paper, "heterogeneity" refers to the hydraulic conductivity or the permeability field described by geostatistical approaches, while thermal properties are assumed to be homogeneous.

In recent years, a number of studies investigated mixed thermal convection in heterogeneous aquifers described with geostatistical approaches (Irvine et al., 2015). Ferguson (2007) found that there is a high degree of uncertainty in the isotherm distribution related to the injection of warm water in a heterogeneous permeability field, and that heterogeneity reduces the amount of energy recovered from the injected warm water at later time. Hidalgo et al. (2009) numerically investigated the effect of heterogeneous hydraulic conductivity fields on transverse heat dispersion where the energy was dissipated by a groundwater heat exchanger. Hidalgo et al. (2009) found that transverse heat dispersion is proportional to the variance and correlation length of the log hydraulic conductivity field. However, the variance of the log hydraulic conductivity field can be neglected in calculating the dissipated energy by the groundwater heat exchanger. Chang and Yeh (2012) conducted a theoretical study of field-scale heat advection in heterogeneous porous media. Their results showed that heterogeneity and correlation length of the log hydraulic conductivity field promote field-scale advective heat transport. All of the above studies, however, focused on mixed thermal convection, while purely free thermal convection has received little attention. An example of a study on free thermal convection in heterogeneous porous media was carried out by Nield et al. (2010), who focused on the onset of convection. In conclusion, a quantitative and qualitative study of free thermal convection in heterogeneous porous media has not yet been conducted.

Qualitative and quantitative studies on free haline convection in heterogeneous porous media based on geostatistical approaches exist. For example, Simmons et al. (2001) and Prasad and Simmons (2003) showed that (1) the degree and structure of heterogeneity strongly affect the onset of instabilities (e.g., plume fingers) as well as their subsequent development and/or decay, (2) the traditional Rayleigh number, which is based on the average permeability, is inadequate to predict the onset of instabilities, and (3) the assumption of homogeneity potentially leads to an underestimation of many important quantitative characteristics (e.g., solute flux, total solute mass, center of gravity of the plume, and penetration depth of fingers).

Physical mechanisms of heat transfer differ from those of solute transport (Irvine et al., 2015), where (1) heat is transferred by conduction through both solid and liquid phases, (2) heat can be stored in both solid and liquid phases, (3) thermal diffusivity is three to four orders of magnitude larger than molecular diffusion, and (4) the effects of temperature on fluid density and viscosity differ from those of solute. Therefore, the qualitative and quantitative characteristics of free thermal convection in heterogeneous porous media still remain unknown.

The understanding of thermal convection in heterogeneous porous media is further complicated by the difficulty in selecting the appropriate spatial discretization. This is not a particular problem of thermal convection but a common problem of variable-density flow simulations in both homogeneous and heterogeneous porous media. A typical example is the debate about the spatial discretization of the saline Elder problem (Voss and Souza, 1987) and of the thermal Elder problem (Graf and Boufadel, 2011; Oldenburg et al., 1995). In homogeneous porous media, spatial discretization of the saline Elder problem has been intensively investigated and controversially discussed (e.g., Diersch and Kolditz, 2002; Oltean and Bués, 2001; Prasad and Simmons, 2005). To date, there is no consensus about the unique solution as well as the appropriate grid discretization of the saline Elder problem. A unique solution only exists at low Rayleigh numbers (van Reeuwijk et al., 2009). Studying grid convergence of the thermal Elder problem also showed that grid convergence is very difficult to achieve (Graf and Boufadel, 2011), and that the unique solution is still unknown. In heterogeneous porous media, the effect of grid discretization on variable-density flow simulations is often assumed to be small without being verified (e.g., Prasad and Simmons, 2003), or does not come into question (e.g., Ferguson, 2007; Irvine et al., 2015; Simmons et al., 2001).

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