Advances in Water Resources 71 (2014) 65–80

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Impact of fracture network geometry on free convective flow patterns

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ARTICLE INFO

Article history:
Received 30 January 2014
Received in revised form 30 May 2014
Accepted 1 June 2014
Available online 11 June 2014

Keywords:
Groundwater
Fractures
Rayleigh number
Density-driven flow
HydroGeoSphere
Numerical modeling

ABSTRACT

The effect of fracture network geometry on free convection in fractured rock is studied using numerical simulations. We examine the structural properties of fracture networks that control the onset and strength of free convection and the patterns of density-dependent flow. Applicability of the equivalent porous medium approach (EPM) is also tested, and recommendations are given, for which situations the EPM approach is valid. To date, the structural properties of fracture networks that determine free convective flow are examined only in few, predominantly simplified regular fracture networks. We consider fracture networks containing continuous, discontinuous, orthogonal and/or inclined discrete fractures embedded in a low-permeability rock matrix. The results indicate that bulk permeability is not adequate to infer the occurrence and magnitude of free convection in fractured rock. Fracture networks can inhibit or promote convection depending on the fracture network geometry. Continuous fracture circuits are the crucial geometrical feature of fracture networks, because large continuous fracture circuits with a large vertical extent promote convection. The likelihood of continuous fracture circuits and thus of free convection increases with increasing fracture density and fracture length, but individual fracture locations may result in great deviances in strength of convection between statistically equivalent fracture networks such that prediction remains subject to large uncertainty.

1. Introduction

Density-driven flow is an efficient mechanism for solute transport in unstable hydrogeological systems, especially if head gradients as a driving force for groundwater movement are absent. In the absence of a hydraulic gradient, potentially unstable flow situations may exist where water of high density overlies water of low density [1,2]. Depending on aquifer and fluid properties, potentially unstable flow situations can either induce density-driven free convection, or can be dissipated by molecular diffusion [2,3]. If free convection occurs, solutes penetrate faster and further into an aquifer than by diffusion alone [4]. In that case, convection cells may form, and the associated flow pattern depends on the prevailing concentration (or temperature) gradient, and on hydrogeological aquifer properties [3,5,6]. Review papers of Diersch and Kolditz [1] and Simmons [7] discuss the widespread importance of free-convective, density-driven flow in porous media. Convective patterns in homogeneous porous media and fractured rock are likely to be different, because fractures represent preferential pathways for water flow [8].

Density-dependent flow phenomena in homogeneous unfractured porous media have been studied for almost a century. In the early 20th century, Lord Rayleigh [9] derived mathematical formulations on the correlation of the physical properties of a homogeneous porous medium, the magnitude of thermally induced density variations and the onset of free convection. Rayleigh [9] introduced the Rayleigh number, which compares buoyancy that promotes free convection with diffusion that dissipates free convection. The Rayleigh number can be used to predict whether a system is purely diffusive and stable, or whether it is unstable and free convection will occur. The Rayleigh criterion has been applied to a variety of two-dimensional scenarios in laboratory experiments [10], and numerical simulations (e.g. [3,5,10,11]).

Horton and Rogers [5], and independently Lapwood [3] applied the Rayleigh criterion to a free-convection problem in a layer of saturated porous medium. In this scenario, convection is found, when the critical Rayleigh number of $4\pi^2$ is exceeded [12]. The scenario was later called the Horton–Rogers–Lapwood problem (HRL problem) and was adopted by Weatherill et al. [6] for a benchmark test. This benchmark test provides solutions for two-dimensional convective patterns and transport efficiency in homogeneous porous media in finite, infinite and inclined boxes. The work of Weatherill et al. [6] was extended to a three-dimensional

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http://dx.doi.org/10.1016/j.advwatres.2014.06.001
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benchmark test by Voss et al. [13] showing the existence of convective modes that depend on box inclination, aspect ratio and Rayleigh number. Leijnse and Oostrom [14] found that multiple steady-state convective patterns are possible for the HRL problem if the Rayleigh number exceeds a value of $6.25\pi^2 \approx 61.7$.

The Elder [10] experiment investigated thermal convective patterns in a Hele-Shaw cell. A modified haline version of the Elder problem has been used frequently for benchmarking (e.g. [15–18]). It was found that multiple steady-state solutions with different convective patterns exist for the Elder problem. Depending on numerical scheme and grid resolution used to simulate the Elder problem, one of those solutions is forced (e.g. [1,16,17,19]). Van Reeuwijk et al. [17] used a pseudospectral approach to clearly define the multiple steady-state solutions. While the HRL problem and the Elder problem apply to convective flow in homogeneous porous media, Diersch and Kolditz [1], and Simmons et al. [20] emphasized that convective flow patterns in heterogeneous and fractured porous media are not yet fully understood.

Schincariol and Schwartz [21] experimentally examined mixed convection in layered and lenticular porous media and showed that local permeability variations impact convective flow patterns. Permeability differences of less than half an order of magnitude can affect convective patterns of dense plumes and lead to accumulation of mass along material interfaces in mixed convective systems.

Nield and Simmons [22] investigated the onset of free convection in heterogeneous porous media using the Rayleigh number for homogeneous porous media. By averaging over a set of the heterogeneous parameters, Nield and Simmons [22] showed that the Rayleigh number can give good estimates in case of weak heterogeneity. A new indicator for the onset of free convection in strongly heterogeneous media was proposed, assuming that a system is unstable if instability can be found in any part of the domain.

McKibbin and O'Sullivan [23] examined the effect of homogeneous horizontal layers with different permeabilities on free convection. It was found that, with increasing number of layers, the convective pattern resembles that of an anisotropic, homogeneous equivalent medium. McKibbin and Tyvand [24,25] further developed the approach of McKibbin and O'Sullivan [23] to an extreme case of heterogeneity by diminishing the thickness of every other horizontal layer to the thickness (aperture) of fractures and by implicating strong permeability contrasts. The thin horizontal layers were either assigned a very low permeability [24], or a very high permeability [25] compared to the interjacent thick layers. Results suggest that the influence on convective patterns becomes larger with increasing permeability contrasts between layers. The critical Rayleigh number (where convection started) was altered by the presence of highly permeable horizontal zones representing fractures, depending on the permeability contrast and the number of fractures. The introduction of horizontal fractures into a previously homogeneous and purely diffusive setting tended to hinder convection, especially for high permeability contrasts.

Graf and Therrien [26] provided a free convective flow problem with a high-density solute source at the top of the domain and a single continuous 45° inclined fracture embedded in a low-permeability rock matrix. Convection cells formed in the adjacent rock matrix along the fracture and migrated downwards as the solutes penetrated into the fracture. Graf and Therrien [27] later extended their study to a single non-planar fracture embedded in a three-dimensional porous rock matrix and found that free convection and fingering within the fracture may occur. The convection cells that formed in the fracture at early stages eventually merged when the fingers coalesced. In the adjacent rock matrix, only upward flow of freshwater was observed.

Yang et al. [28] solved coupled heat and flow equations for discretely fractured porous media using a finite element scheme. That approach was applied to a free convective flow problem in porous media containing a single continuous vertical fracture as well as a set of uniformly spaced, continuous vertical and/or horizontal fractures. Yang et al. [28] showed that convective patterns and strength of convection are governed by the fracture locations. Interconnected fractures induce free convection even if the porous medium they are embedded in is impermeable. Multiple horizontal fractures tend to stretch convection cells horizontally while multiple vertical fractures compress convection cells horizontally. By comparing flow patters in fractured porous media with flow in homogeneous anisotropic media, Yang et al. [28] showed that convective patterns are similar if the bulk horizontal and vertical permeability of the fractured-porous medium is equal to the horizontal and vertical permeability of the equivalent homogeneous anisotropic medium. While Yang et al. [28] significantly contributed to our understanding of thermally induced convective flow in uniformly spaced fractures, it still remains unclear how fracture networks of irregular geometry and variable fracture aperture will influence the flow pattern of haline free convection. In a subsequent study, Yang [29] showed that it is possible to reproduce thermohaline flow along fractures and faults in the McArthur Basin in northern Australia with the discrete fracture approach, and it was found that basin-scale density-driven flow may be a good explanation for the formation of the rich ore deposits found in the basin.

Shikaze et al. [8] investigated plume migration in a regularly fractured porous medium with orthogonal continuous fractures, and found that fracture spacing is an important criterion to determine flow patterns. In systems with only vertical fractures, non-uniform fracture spacing lead to the formation of irregularly shaped convection cells. In the absence of an external head gradient, downwelling of saltwater in some fractures, and upwelling of freshwater in other fractures was found. The introduction of continuous uniformly spaced vertical and horizontal fractures with constant fracture aperture led to complex convective patterns if free convection was the dominant flow process. Shikaze et al. [8] concluded that more complex fracture network geometries may impede the prediction of free convective patterns and of mass transfer rates, and that the role of fracture network complexity is still unknown.

Graf and Therrien [30] studied density-dependent flow and transport in fracture networks with orthogonal continuous and inclined discontinuous fractures embedded in a porous rock matrix, and found that stability of horizontal fluid layers ("layer stability") is sensitive to matrix and fracture permeability, matrix porosity and diffusivity. Plume migration in irregular inclined fracture networks is highly sensitive to the number of fractures which are connected to the dense solute source. Graf and Therrien [30] considered only three realizations of a single combination of fracture length and fracture density. Thus, conclusions were limited to those specific geometrical features of the fracture networks.

Simmons et al. [31] investigated possible modes of free convection in fractured low-permeability porous media. A comparison of critical Rayleigh numbers and common ranges of natural fractured media properties led to the conclusion that convection within the fracture parallel to the fracture plane occurs for even very small density differences. Convection along fractures surrounding an impermeable rock matrix block is likely as well, while convection normal to the fracture plane requires large density differences and is hence unlikely. Therefore, not considering free convection in fracture networks may lead to a substantial underestimation of the probability of free convection. Simmons et al. [31] concluded that studying all three modes of free convection demands a full three-dimensional modeling approach. As this is very demanding in terms of computational power, a model with fractures being