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Density-driven convection in an inhomogeneous geothermal reservoir

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ABSTRACT

Present study is motivated by problems of admixture transport in geothermal systems. Numerical simulations of stochastic haline convection in an inhomogeneous domain consisting of a homogeneous isotropic porous medium divided by a horizontal layer at different porosity and permeability are performed. Convection is driven by more dense brine near the upper boundary which is fed by a dissolved admixture diffusing from the boundary. An influence of interior layer on convective flows and mass transfer in all domain is investigated. As obtained, dynamic behavior of fluid in the layer is forced or natural mode of convection depending on properties of this layer. There is the intermediate case when forced convection arisen initially is transformed into natural convection with time. In this case, the layer can order convective flows above itself so that the roughly periodic structure of "brine balls" is formed.

1. Introduction

The problem of admixture transport in groundwater saturating soils and rocks has a fundamental importance for alternative power engineering, ecology, environmental management and other human activities. In many cases, transport of dissolved admixture in the Earth is caused by the temperature and salinity gradients leading, in the gravity field, to a growth of instability and development of natural convection [1,2]. In deep aquifers, salinity gradients can be formed by a salt deposit nearby or by brine flows carrying dissolved admixture. There are several geological reasons inducing temperature inhomogeneities such as magmatic heat sources, chemical reactions or geothermal gradient which is resulted from the temperature increase within the Earth in the direction to the hot Core and available all over the place [3]. Normally, the geothermal gradient is about 20–30 K per each kilometer. Estimations exhibit that, in real geological conditions, convective motions of concentrated brine due to the geothermal gradient may be appreciably less than due to the salinity gradient [4]. In these conditions, thermal convection can be disregarded and only haline convection be taken into consideration.

Haline or, as is called also, density-driven convection is widely discussed in the context of carbon capture and sequestration technology, wherein liquid carbon dioxide is injected into geological formations to store it underground [5]. Diffusion of carbon dioxide and its dissolution in saline aquifers leads to a local increase in the brine dense and development of downward convective motions (see [6–13] and references herein). Similar problems on convection are actual in respect to exploiting underground geothermal systems which use deep heat of Earth and are alternative renewable energy sources [14,15]. If there is a salt supply near a geothermal reservoir, haline convection can develop and enhance an admixture transport into hot water to be extracted.

There are quite a lot of publications on numerical study of density-driven convection in rocks arisen from a horizontal unstable denser layer of brain. In these works, they investigate nonlinear convective regimes in a comparison with a linear stability analysis [6], an influence of the Rayleigh number on the intensity of transient convection in an initial stage [7], effects of random fluctuations of porosity and permeability on the onset of convection [8], mass transfer quantities based on model experiments and on comparable numerical simulation [10], convective regimes from onset to shutdown in anisotropic media having different values of horizontal and vertical permeability [11], an interplay with forced [16] or thermal modes of convection [12], and a complicated case including geochemical reactions [13].

One of key factors defining parameters of convective flows and mass transfer is the structure of solid matrix containing a liquid

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Nomenclature

A	aspect ratio, $= L/H$ [–]
c	concentration (mass fraction) of admixture, $= \rho_c/\rho$ [–]
c^{sat}	solubility (mass fraction of admixture in a saturated solution), $= \rho_c^{sat}/\rho^{sat}$ [–]
D	coefficient of diffusion in a porous medium [$\mathrm{m^2\,s^{-1}}$]
D_c	coefficient of molecular diffusion for a free solution [$\mathrm{m^2\,s^{-1}}$]
$\mathbf{e}$	unit vector in the direction of gravity acceleration, =(0, −1) [–]
g	module of gravity acceleration [$\mathrm{m\,s^{-2}}$]
H	height of porous domain [m]
h_d	distance from the upper boundary of domain to interior porous layer [m]
h_l	width of interior porous layer [m]
h_p	depth of admixture penetration [m]
k	permeability [$\mathrm{m^2}$]
L	length of porous domain [m]
M	dimensionless total admixture mass per the unit horizontal length [–]
M_0	dimensionless total admixture mass per the unit horizontal length due to diffusive mass transfer [–]
$\mathbf{n}$	unit vector normal to boundary, [–]
P	pressure [Pa]
R_m	relative admixture mass, $= M/M_0$ [–]
Rd	Rayleigh-Darcy number [–]
S	dimensionless density [–]
t	time, except Sections 2.3 and 4.3 [s], [d]; dimensionless time, in Sections 2.3 and 4.3 [–]
Δt	numerical time step [–]
$\mathbf{U} = (U_x,\ U_y)$	vector of filtration velocity $= \phi\mathbf{W}$ [$\mathrm{m\,s^{-1}}$]
$\mathbf{u} = (u_x,\ u_y)$	vector of dimensionless filtration velocity, $= \phi\mathbf{w}$ [–]
$\mathbf{W} = (W_x,\ W_y)$	vector of fluid velocity [$\mathrm{m\,s^{-1}}$]
$\mathbf{w} = (w_x,\ w_y)$	vector of dimensionless fluid velocity [–]
$\lvert\mathbf{W}\rvert_{\max}$	maximal module of fluid velocity [$\mathrm{m\,s^{-1}}$], [$\mathrm{mm\,d^{-1}}$]
$\lvert\mathbf{w}\rvert_{\max}$	maximal module of dimensionless fluid velocity [–]
x	horizontal coordinate, except Section 2.3 [m]; dimensionless horizontal coordinate, in Section 2.3 [–]
Δx	numerical space step in the x-direction [–]
y	vertical coordinate, except Sections 2.3 and 4.3 [m]; dimensionless vertical coordinate, in Sections 2.3 and 4.3 [–]
Δy_1	maximal numerical space step in the y-direction [–]
Δy_m	minimal numerical space step in the y-direction [–]

Greek symbols

α	salinity expansion coefficient, =0.815 [–]
κ	dimensionless permeability [–]
μ_s	dynamic viscosity
Π	dimensionless pressure [–]
ρ	density of solution [$\mathrm{kg\,m^{-3}}$]
ρ^{sat}	density of saturated solution [$\mathrm{kg\,m^{-3}}$]
ρ_c	density of dissolved admixture [$\mathrm{kg\,m^{-3}}$]
ρ_c^{sat}	density of dissolved admixture in a saturated solution [$\mathrm{kg\,m^{-3}}$]
ρ_0	density of pure water [$\mathrm{kg\,m^{-3}}$]
σ	dimensionless coefficient of diffusion [–]
τ	tortuosity factor [–]
ϕ	porosity [–]

Superscripts

$*$	upper boundary of domain

Subscripts

1	main porous medium, except Δy_1 in Section 4.3
2	interior porous layer
x	horizontal axis
y	vertical axis
th	threshold value

phase. In certain Earth's zones, a layered structure of crust has been formed under the high pressure during different geological events therefore a consideration of horizontal layered porous media is the way to approach real conditions. Investigators consider systems consisting of several separately homogeneous isotropic layers or anisotropic systems with continuous variations in porosity and permeability as an approach to multilayered porous media [17–20]. However, the data showing how a single interior porous layer at different porosity and permeability influences haline convection are not enough. There are only little results on this problem based on a simplified mathematical model and presenting some integral characteristics of initial stage of convection [4]. In the present paper, we continue investigations starting with [4].

The objective of our work is to study stochastic haline convection from the beginning to a developed stage in a porous domain containing a horizontal interior porous layer with lower porosity and permeability. Convection is driven by an unstable dense fluid layer near the top of domain, which is formed due to admixture diffusion from the upper boundary of this domain. The paper is organized as follows. In Section 2, we describe the problem under study and discuss the mathematical model suitable for solving this problem. In contrast to [4], we discuss how the permeability and coefficient of diffusion relate to the porosity and introduce appropriate relations into our description. The physical parameters of considered geothermal system based on reference data are put in Section 3. A brief report on the finite-difference numerical code designed for solving 2D problems is given in Section 4. We write also about tests and validation of the code. Local and integral numerical quantities characterizing flows and mass transfer are defined in this section as well. In Section 5, the report on numerical simulations of haline convection is given. We starts with a basic case corresponding to convection in a homogeneous domain with no interior layer. Next, the problem in a domain containing a horizontal layer at different properties is solved. We study how the layer properties influence selecting the mode of convection in the layer and convection characteristics in a domain as a whole. Effect of location of layer relative to the upper boundary and its width are discussed as well. We summarize our results and draw a conclusion in Section 6.

2. Theoretical background

2.1. Problem under study

A rectangular domain being a part of reservoir infinite in the horizontal direction is considered. The domain consists of homogeneous isotropic porous medium with uniform porosity and permeability (referred to a main medium) everywhere except an interior horizontal layer which is at different porosity and permeability. The interior layer is located at the distance h_d from the top and has the width h_l. Initially, the reservoir is filled with pure motionless water. The constant concentration of admixture is held at the upper boundary modeling an admixture source. No-flux conditions