Advances in Water Resources 32 (2009) 315–328

Contents lists available at ScienceDirect

Advances in Water Resources

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

Gas tracer transport through a heterogeneous fracture zone under two phase flow conditions: Model development and parameter sensitivity

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A R T I C L E I N F O

Article history:
Received 17 March 2008
Received in revised form 26 September 2008
Accepted 3 October 2008
Available online 1 November 2008

Keywords:
Gas migration
Fracture
Gas tracer Test
Partitioning tracer
Multiphase conditions

A B S T R A C T

Large amounts of gas can result from anaerobic corrosion of metals and from chemical and biological degradation of organic substances in underground repositories for radioactive waste. Gas generation may lead to the formation of a gas phase bubble and to the migration of radioactive gaseous species. Transport occurs in, at least, in two forms: (1) gas bubble, migration is controlled by advection, dispersion and diffusion in the gas phase, and (2) within water pockets, the dissolved species migrate mainly by diffusion. We consider a two-dimensional system representing an isolated heterogeneous fractured zone. A dipole gas flow field is generated and gas tracers are injected. The delay in the breakthrough curves is studied. A simple method is used to solve the gas species transport equations in multiphase conditions. This method is based on a formal analogy between the equations of gas transport in a two phase system and the equations of solute tracer transport in water saturated systems. We perform a sensitivity analysis to quantify the relevance of the various transport mechanisms. We find that gas tracer migration is very sensitive to gas tracer solubility, which affects gas tracer transport of both mobile and immobile zones, and shows high sensitivity to diffusion in the gas phase, to heterogeneity and to gas pressure, but the largest sensitivity was observed with respect to injection borehole properties, i.e. borehole volume and water filled fraction.

1. Introduction

Little research has been devoted to the hydraulic characterisation of low permeability fractured media given the unsuitability of these media as a reliable source of groundwater. Nevertheless, a number of authors have studied these formations in the last 20 years because of the potential use of low permeability media for radioactive waste isolation. Several projects have been devised in an attempt to shed light on the processes that could occur in the whole repository system for long term waste disposal. In this context, gas can be produced during the post-operational phases of low and intermediate-level radioactive waste repositories through anaerobic degradation, accumulating in storage caverns [45]. If the rate of gas production at the source is sufficiently high, the resulting pressure build-up could have a negative effect on the barrier function of the rock and on the engineered barrier system (e.g. opening of existing fractures, generation of new fractures). In this situation, the gas phase migrates upwards through interconnected pores and fractures with the highest transmissivity. Shear zones might serve as primary conduits for gas migration away from the caverns through the geosphere. It goes without saying that an improved understanding of multiphase gas transport in fractures is of paramount importance for risk assessment of nuclear waste repositories.

According to the literature there are two main mechanisms for gas migration through fractured geological formations: (1) large scale fractured domains, where the movement of gas is assumed to be controlled by advection, described by Darcy's law and mainly driven by pressure gradients. Gascoyne and Wuschke [14] and Thunvik and Braester [36] among others developed simple models for gas migration that are useful in the absence of detailed information about the fractured media. They require only estimates of the bulk properties of the system. (2) The second mechanism is dominant in small scale domains, where the local transport is controlled by diffusion processes. Two models can be found in the literature to account for diffusive gas transport in porous media: (a) the Dusty Gas Model (DGM), which applies the kinetic theory of gases to the gaseous components in the porous media; (b) the advective–diffusive model based on a linear addition of advection calculated by Darcy's law and diffusion using Fick's law. Comparison of the two methods gives rise to discrepancies. Fick's law may overestimate gas diffusion fluxes, and its application to the porous media has been questioned [1,25,35,40]. Nevertheless, Webb and Pruess [41] compared ADM and DGM and found small differences between both methods for trace concentrations depending on gas pressure and temperature site conditions.

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doi:10.1016/j.advwatres.2008.10.008

Despite the large number of papers published on multiphase gas transport in porous or fractured media, few studies have addressed gas migration. The literature concentrates on two issues: (1) characterization of the multiphase flow parameters, such as the retention or relative permeability curves. In this case modelling data are derived from different sources, including numerical-synthetic experiments [10,18,32], laboratory measurements [6,13,26,30,43] and from site specific experiments [21,31]. (2) The second subject addresses numerical studies to simulate gas tracer migration in multiphase conditions through single fractures, applying common concepts in gas migration through porous media to a low permeability single fracture. Lunati and Kinzelbach [21] simulated gas injection dipole tests in a synthetic heterogeneous fracture to study the effects of the pore–volume–transmissivity correlation in a single fracture. They showed that the spatial gas distribution within the fracture depended on the relationship between the fracture pore volume and its transmissivity. However, these authors did not explore the role played by the different transport processes in their simulations. In this regard, a quantitative description of gas transport through single fractures has not yet been undertaken. One of the main difficulties with the simulation of two phase flow processes in fractured rock is the determination of effective mass exchange coefficients of the relevant components of the system. Mass exchange depends on the spatial distribution of water and gas along the water-conducting features and on the solubility and diffusivity of these components.

The aim of this work is to gain further insight into the processes affecting gas tracer dissolution/diffusion processes in shear zones, and to assess the relative importance of the various coefficients that are involved. To this end, numerical simulations of multiphase flow and gas transport are performed together with sensitivity analysis of the variables that govern the dissolution/diffusion processes is shear zones. The model simulates gas migration through a partially saturated heterogeneous fracture, and makes use of the formal analogy between gas transport in a two phase system equation and the solute tracer transport equation in water saturated systems.

2. Model development

Gas can be produced during the post-operational phases of low and intermediate-level radioactive waste repositories as a result of anaerobic degradation. Gas migrates from emplacement caverns mainly via geological discontinuities (e.g. shear zones). If the production rate is sufficiently high, gas displaces water from the fracture zone until a continuous gas phase (bubble) is formed. The gas bubble may then migrate displacing water from zones where entry pressure is small (i.e. zones of fracture). In areas where capillary pressure is too high to allow the gas to penetrate therefore, water is not displaced and the medium remains saturated.

The fracture conceptualisation for gas migration (Fig. 1) considers these two scenarios: (a) open fracture zones fully saturated with gas (mobile zone), notice that several open fractures may overlap, (b) fault gouge filled zones partially or fully saturated with water (immobile zone).

In order to simulate gas bubble conditions, a number of gas tracer injection tests (dipole configuration) were carried out in a granite fracture, at the Grimsel Test Site [12,38,39]. To this end, a steady state gas flow-field is established by injecting nitrogen at a constant rate into the injection borehole. After stationary flow conditions are achieved gas tracers are injected simultaneously, while keeping nitrogen as the main gas phase component.

The gas bubble, which is made up of a number of paths partially filled with gas, conducts most of the tracer from the injection to the extraction borehole. Advection, diffusion and dispersion in the gas phase are the transport mechanisms that must be considered in the bubble.

On the other hand, it is assumed that the entry pressure in the fault gouge is too high to allow the gas to enter. Water is not displaced, with the result that the water saturation degree remains constant and equal to one. In the development of the model, gas tracer mass transfer between the gas phase (mobile zone) and the liquid phase (immobile zone) is assumed to be locally instantaneous and governed by Henry's law. Experiments have shown that the assumption of local equilibrium for gas–liquid mass transfer is

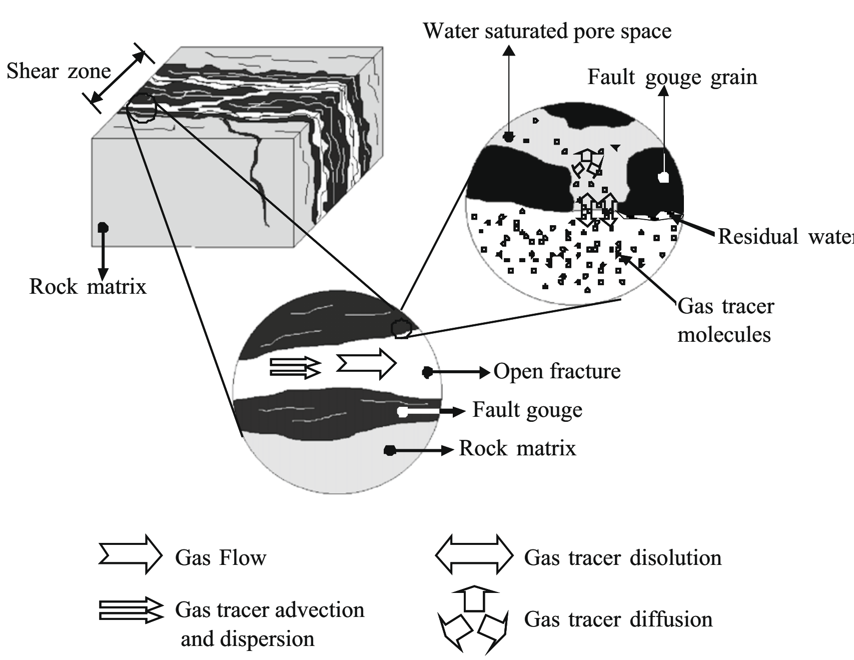

Fig. 1. Schematic description of gas transport in a shear zone. Gas tracer transport through the gas bubble is governed by advection and dispersion, whereas the main transport mechanism is diffusion in the fine grained water saturated porous medium.