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An analysis of a mixed convection associated with thermal heating in contaminated porous media

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HIGHLIGHTS

- Subsurface buoyant flow occurring during thermal remediation is modeled.
- Buoyancy ratio is derived in terms of permeability, temperature, and gradient.
- Heated subsurface flow is grouped into 3 types, allowing for site characterization.
- Buoyant flow occurring under clay layers can lead to mass accumulation.
- Stagnation zone under clay layers can lead to mass transport into the clay layer.

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ABSTRACT

The occurrence of subsurface buoyant flow during thermal remediation was investigated using a two dimensional electro-thermal model (ETM). The model incorporated electrical current flow associated with electrical resistance heating, energy and mass transport, and density dependent water flow. The model was used to examine the effects of heating on sixteen subsurface scenarios with different applied groundwater fluxes and soil permeabilities. The results were analyzed in terms of the ratio of Rayleigh to thermal Peclet numbers (the buoyancy ratio). It was found that when the buoyancy number was greater than unity and the soil permeability greater than 10^{-12} m^2, buoyant flow and contaminant transport were significant. The effects of low permeability layers and electrode placement on heat and mass transport were also investigated. Heating under a clay layer led to flow stagnation zones resulting in the accumulation of contaminant mass and transport into the low permeability layer. The results of this study can be used to develop dimensionless number-based guidelines for site management during subsurface thermal activities.

1. Introduction

Thermal remediation is a common technology used in the groundwater sector to deal with organic pollutants such as dense non-aqueous phase liquids (DNAPLs) (Buettner and Daily, 1995; Sleep and Ma, 1997; She and Sleep, 1999; Sleep and McClure, 2001a; Heron et al., 2013). Thermal technologies include steam or hot water injection, thermal conduction heating, radio frequency heating (RFH), and electrical resistance heating (ERH). All these technologies increase the subsurface temperature, resulting in an increase in contaminant volatility. Unlike steam or hot water injection, ERH, RFH and thermal conduction heating can heat up the soil regardless of its stratigraphy. Due to these advantages as well as the ability to heat specific targeted locations in both saturated and unsaturated soils (Davis, 1997), ERH is the most widely used thermal remediation method in the United States (U.S. EPA, 2012). ERH has been used not only as the main remediation technology but also for aiding in remediation activities.

Operational ERH temperatures are typically around 100 °C and field experiments have shown that groundwater temperatures after thermal remediation remained between 45 °C and 75 °C for up to two years (Krauter et al., 1995). In addition, during thermal remediation, the temperature within and at the edge of the heated zone will vary substantially as will the temperature during pre-heat and cool down phases. This can lead to different flow regimes and under certain flow and heating conditions (which can be characterized by dimensionless numbers), buoyant flow may be induced that may potentially affect subsurface

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mass distribution (Krol et al., 2011a). For example, contaminants can become trapped under low permeability layers or mass can be transported to previously uncontaminated regions.

Subsurface water movement can be categorized into three main types of flow: buoyant flow, advective flow, and mixed flow. Buoyant flow is driven by a temperature or density gradient without external groundwater flow and is often referred to as density-driven flow. This type of flow is characterized by a circular movement of water. Advective flow is the movement of water resulting from a hydraulic gradient and therefore can also be referred to as forced flow. If both processes are occurring, the term mixed flow is used (Haajizadeh and Tien, 1984).

Buoyant flow has been studied extensively in the fields of fluid mechanics and heat transfer (Lapwood, 1948; Prats, 1966; Straus and Schubert, 1977; Prasad and Kulacki, 1984; Ingham and Pop, 1987; Fusegi et al., 1992; Das and Sahoo, 1999; Simmons et al., 2001; Mealey and Merkin, 2009; Nield et al., 2010). These studies determined that the strength of buoyant flow was dependent on the Rayleigh number. For a system heated from below, the onset of buoyant flow in porous media occurred at a Rayleigh number of $4\pi^2$.

Mixed flow literature has largely focused on bottom heated boundary conditions to describe geothermal phenomena such as volcanic debris or storage of nuclear wastes (Prasad et al., 1988). Since mixed flow includes advective flow through porous media, buoyancy was not only affected by the Rayleigh number (*Ra*) but also by the Peclet number (*Pe*) for heat transfer (Prasad et al., 1988; Lai et al., 1990; Prasad and Kulacki, 1984). The transition from buoyant to mixed flow resulted from either a decrease in *Ra* or an increase in *Pe*. If buoyant flow dominated, a multicellular and circular flow resulted near the heat source (Prasad et al., 1988; Lai and Kulacki, 1991). Alternatively, if *Pe* was above 10 and *Ra* was below 10 ($Ra/Pe < 1$), little or no buoyant flow was observed and the streamlines were dominated by advective flow (Prasad et al., 1988).

Similar results were found experimentally. Lai and Kulacki (1991) observed that low groundwater flux values in a tank filled with porous media and heated from below, resulted in streamlines that were symmetrical about the heat source, and therefore representative of buoyant flow. As advective flow increased, the resulting flow and temperature fields were quite different from buoyant flow since the effect of advective flow became dominant and the symmetrical streamlines associated with buoyant flow disappeared (Lai and Kulacki, 1991).

Various studies have also been conducted on mixed flow with multiple heat sources (Lai et al., 1990), heated spheres (Andrew et al., 2003) and line sources (Kurdyumov and Linan, 2001). In addition, others have investigated buoyancy effects as a result of variable aquifer densities, either from CO_2 injection (Farajzadeh et al., 2007), salt intrusion (Dentz et al., 2006), or contamination (Schincariol et al., 1994; Schincariol et al., 1997). Mixed flow can also occur during subsurface thermal remediation, however no studies have examined this phenomenon nor the effects of mixed flow on mass transport.

This study investigates the effect of mixed flow on contaminant transport during thermal remediation. The spread of contaminants was examined with different subsurface geology (homogeneous and layered), remediation design (placement of electrodes) and temperature conditions (maximum subsurface temperature) to determine which parameters had the greatest impact on subsurface mass transport under non-isothermal conditions. Understanding the subsurface conditions that lead to buoyant flow, as well as, the effect of buoyant flow on contaminant transport, can aid in the design and application of subsurface thermal technologies.

2. Theory

2.1. Electro-thermal model

A two dimensional (2D) electro-thermal model (ETM) was used to simulate subsurface heating during ERH, as well as contaminant flow and transport (Krol et al., 2011a). ERH is applied to the subsurface using 3 or 6 phase heating where a series of electrodes are placed in the soil and connected to an AC voltage source (U.S. EPA, 1997; Vermeulen and McGee, 2000). The flow of current between electrodes generates heat and the increase in temperature facilitates the removal of contaminants (Looney and Falta, 2000; Boulding and Ginn, 2004).

ETM is a finite difference model that discretizes current, mass, flow, and energy equations spatially and temporally, using a backward difference, block-centered approach, while a fully implicit scheme is used for temporal discretization of these equations. ETM calculates several temperature-dependent properties such as water density and viscosity, and soil electrical conductivity. These properties are averaged between grid blocks using the harmonic mean value. The model was validated using several lab experiments and is fully described in Krol (2010) and Krol et al. (2011a).

To obtain the power generated by ERH, the current continuity equation was solved using phasor quantities for voltage to account for the AC voltage used by ERH (Hiebert et al., 1986; Hiebert et al., 1989; McGee and Vermeulen, 2007). The power dissipation (*U*) in the subsurface was determined using:

$$U = \sigma|\nabla V|^2 \tag{1}$$

where *V* is the voltage and σ is the bulk electrical conductivity. The power dissipated by ERH was then used in the energy transport equation:

$$\frac{\partial}{\partial t}[\rho_w \phi c_w T + (1-\phi)\rho_b c T] + c_w \rho_w \nabla \cdot \left[\vec{q} T\right] - K_H \nabla^2 T - U = 0 \tag{2}$$

where *T* is the temperature (°C), ρ_w is the density of water (kg/m^3), ϕ is soil porosity, ρ_b is the bulk density of the soil (kg/m^3), *c* is the heat capacity of the soil (J/kg °C), c_w is the heat capacity of water (J/kg °C), $\vec{q}$ is the Darcy velocity vector (m/s), and K_H is the bulk thermal conductivity (W/mK).

The flow of groundwater was modeled using the Darcy equation, taking into account changes in density and viscosity with temperature.

$$q = -\frac{k}{\mu}(\nabla P + \rho_w g \nabla z) \tag{3}$$

where *k* is the soil permeability (m^2), *g* is gravitational acceleration (m/s^2), *P* is the pressure (Pa), z is the elevation (m), and μ is the water viscosity (Pa·s). An iterative approach was employed to calculate water flow and energy transport since the equations are coupled through the temperature dependence of water properties. An absolute

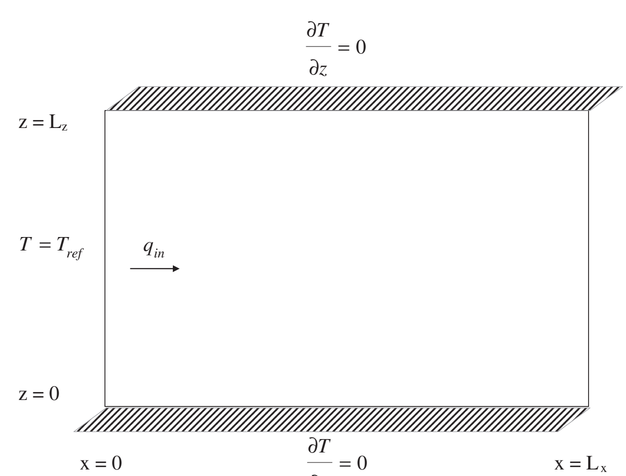

Fig. 1. Representation of the system being modeled.