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Effect of increased groundwater viscosity on the remedial performance of surfactant-enhanced air sparging

Jae-Kyeong Choi[a], Heonki Kim[a,*], Hobin Kwon[a], Michael D. Annable[b]

[a] Dept. of Environmental Sciences and Biotechnology, Hallym University, Chuncheon, Gangwon-do 24252, Republic of Korea
[b] Dept. of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611, USA

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ABSTRACT

The effect of groundwater viscosity control on the performance of surfactant-enhanced air sparging (SEAS) was investigated using 1- and 2-dimensional (1-D and 2-D) bench-scale physical models. The viscosity of groundwater was controlled by a thickener, sodium carboxymethylcellulose (SCMC), while an anionic surfactant, sodium dodecylbenzene sulfonate (SDBS), was used to control the surface tension of groundwater. When resident DI water was displaced with a SCMC solution (500 mg/L), a SDBS solution (200 mg/L), and a solution with both SCMC (500 mg/L) and SDBS (200 mg/L), the air saturation for sand-packed columns achieved by air sparging increased by 9.5%, 128%, and 154%, respectively, (compared to that of the DI water-saturated column). When the resident water contained SCMC, the minimum air pressure necessary for air sparging processes increased, which is considered to be responsible for the increased air saturation. The extent of the sparging influence zone achieved during the air sparging process using the 2-D model was also affected by viscosity control. Larger sparging influence zones (de-saturated zone due to air injection) were observed for the air sparging processes using the 2-D model initially saturated with high-viscosity solutions, than those without a thickener in the aqueous solution. The enhanced air saturations using SCMC for the 1-D air sparging experiment improved the degradative performance of gaseous oxidation agent (ozone) during air sparging, as measured by the disappearance of fluorescence (fluorescein sodium salt). Based on the experimental evidence generated in this study, the addition of a thickener in the aqueous solution prior to air sparging increased the degree of air saturation and the sparging influence zone, and enhanced the remedial potential of SEAS for contaminated aquifers.

1. Introduction

Groundwater air sparging (AS) has been used for the removal of volatile compounds from both NAPL and aqueous phases (Bass et al., 2000; USEPA, 2001; Zhou et al., 2013). The soil vapor extraction (SVE) process is often combined with an AS system to maximize the removal efficiency of the entire process (Kirtland and Aelion, 2000; Lee et al., 2014; Qin et al., 2013a). The remedial performance of the AS process applied at an NAPL-contaminated aquifer depends on a number of parameters (Burns and Zhang, 2001; Reddy and Adams, 1998). The chemical nature of the NAPL is critical for applying the AS process, since mass transfer from the condensed phase to the gaseous phase by volatilization (or vaporization) is the main mechanism of removal (Adams and Reddy, 2000; Chao et al., 1998; Johnson et al., 1993; Mohamed et al., 2007). The hydrogeology of the contaminant source zone, location, spread, and thickness of the NAPL plume are also of importance for designing the most efficient AS process for remediation (Di Julio and Drucker, 2002; McCray and Falta, 1997; Tomlinson et al., 2003; Waduge et al., 2004). Engineering modifications including intermittent, or pulsed, AS were effective for increasing the removal rate of NAPL constituents, compared to continuous air injection (Heron et al., 2002; Johnson et al., 1999; Neriah and Paster, 2016; Yang et al., 2005). The spacing of wells greatly affects the coverage of the AS process, and the size of the zone of influence (ZOI) (Rogers and Ong, 2000).

In recent studies, chemical modifications of resident groundwater prior to implementing the AS process dramatically increased mass removal performance (Kim and Annable, 2006; Zheng et al., 2010). Reduction of the groundwater surface tension using a surfactant decreases the air entry pressure of the media, resulting in higher air saturations when the AS process is implemented (Kim and Annable, 2006). Surface tension reduction will decrease the air entry pressure proportionately regardless of the physical nature of soil (e.g., porosity). However, in heterogeneous soils, the actual air saturation may vary spatially due to

* Corresponding author.
E-mail address: heonki@hallym.ac.kr (H. Kim).

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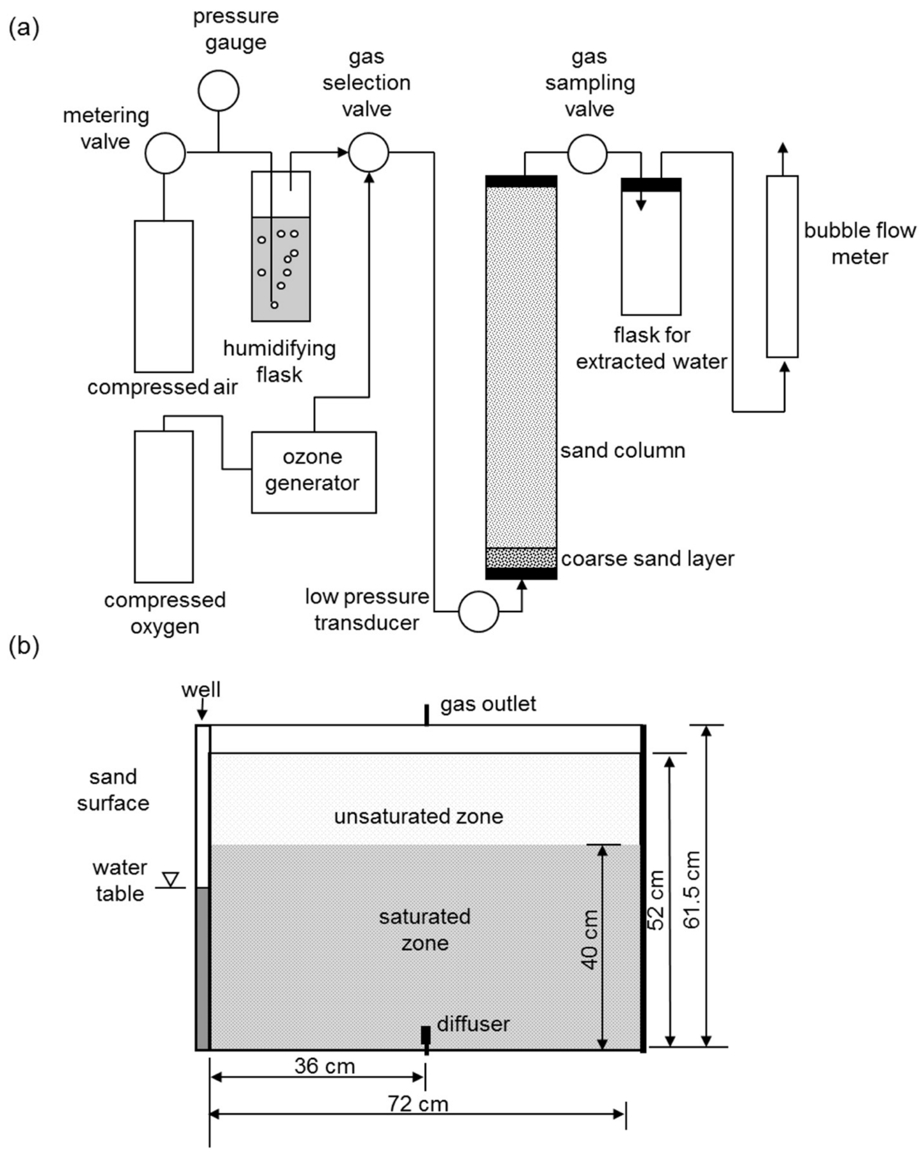

Fig. 1. Schematic diagram of experimental set up: (a) air sparging system with 1-D column installed, (b) dimensions of 2-D model with the heights of sand packing, saturated zone, and the water table.

differences in capillary pressure – water saturation relationships, even under steady sparging conditions (constant air pressure or air flow rate). When the resident water was replaced with a surfactant solution, the size of the sparging ZOI expanded (Kim et al., 2006; Qin et al., 2013a, 2013b, 2014). Surfactant-enhanced air sparging (SEAS), the AS process in which resident pore water is replaced by an aqueous surfactant solution, was evaluated for both VOCs dissolved in water, and NAPL (Kim and Annable, 2006; Kim et al., 2009; Lee et al., 2014). Due to the air rich conditions locally and the extended ZOI, SEAS performed better in recovering more mass of volatile contaminants when compared to the conventional AS process. SEAS also increased the dissolved oxygen level in the sparging ZOI (Qin et al., 2014). When ozone was used instead of air during the SEAS process, the rate of oxidative degradation of organic compound was increased, compared to the conventional ozone sparging process (Kim et al., 2013).

In the SEAS process, the surface tension of water is simply suppressed, so that the air entry pressure drops proportionately, and the water retention curve shifts toward lower capillary pressure, causing more air intrusion into smaller pores (Kim et al., 2006). With increased air saturation in the sparging ZOI, the contact area between the mobile air phase and the NAPL (or aqueous phase of VOC) increases. This enhances the overall mass transfer rate of VOCs across the air-NAPL (or air-water) interface, resulting in faster removal of VOCs from the aquifer.

The air saturation and the size of ZOI achieved by an AS process (including the SEAS process) become fixed when the sparging process is stabilized, or steady state is achieved. Air then flows at a constant rate, after the air introduced at the injection point breaks through the saturated region, and air flow circuits are established. During the transient state before a steady air flow condition is set, extra air pressure is required to push the air through the saturated zone. The minimum air pressure for the air intrusion through the saturated zone is the sum of hydrostatic pressure (P_h), capillary pressure (P_c), and pressure (P_v) necessary to overcome the resistance of water flow through the media. After the transient state, the air pressure will drop, and remain at lower level than observed during the transient state (Kim et al., 2015).

In this study, the effect of increased groundwater viscosity on the performance of the AS process was investigated. The changes in air pressure required for the AS process (including the SEAS process) as a function of groundwater viscosity were quantitatively evaluated, using a one-dimensional (1-D) sand-packed column. The relationship between air pressure change and air saturation achieved during the AS processes