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Evaluation of liquid aerosol transport through porous media

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ABSTRACT

Application of remediation methods in contaminated vadose zones has been hindered by an inability to effectively distribute liquid- or solid-phase amendments. Injection as aerosols in a carrier gas could be a viable method for achieving useful distributions of amendments in unsaturated materials. The objectives of this work were to characterize radial transport of aerosols in unsaturated porous media, and to develop capabilities for predicting results of aerosol injection scenarios at the field-scale. Transport processes were investigated by conducting lab-scale injection experiments with radial flow geometry, and predictive capabilities were obtained by developing and validating a numerical model for simulating coupled aerosol transport, deposition, and multi-phase flow in porous media. Soybean oil was transported more than 2 m through sand by injecting it as micron-scale aerosol droplets. Oil saturation in the sand increased with time to a maximum of 0.25, and decreased with radial distance in the experiments. The numerical analysis predicted the distribution of oil saturation with only minor calibration. The results indicated that evolution of oil saturation was controlled by aerosol deposition and subsequent flow of the liquid oil, and simulation requires including these two coupled processes. The calibrated model was used to evaluate field applications. The results suggest that amendments can be delivered to the vadose zone as aerosols, and that gas injection rate and aerosol particle size will be important controls on the process.

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1. Introduction

Remediation of contaminated vadose zones is often hindered by an inability to effectively distribute liquid- or solid-phase amendments. Many amendment-based approaches, such as bioremediation, chemical oxidation or reduction, and reactive barriers have been successful in saturated formations. However, the use of these remedial approaches in unsaturated materials has been limited because of the challenge of delivering the amendments.

Aerosol delivery is a promising approach for distributing amendments in contaminated vadose zones (Hall, 2013). The concept involves aerosolizing amendments, creating micron-scale liquid droplets suspended in a gas by Brownian motion and vortices in the carrier fluid. During injection into porous media the aerosol particles are transported along with the gas until they are deposited on the surfaces of soil grains. The process is continued until appropriate concentrations are achieved, ideally resulting in a radially and vertically broad distribution. Such a distribution could not be achieved by injecting pure liquid-phase solutions, which would flow preferentially downward in the vadose zone.

Transport and deposition behavior depends on the liquid used to create the aerosol (Hall, 2013). Injection of fresh water aerosols through vertical sand-filled columns caused water to accumulate only near the injection screen. Using the same injection rates, but creating aerosols from soybean oil had a much different effect. In this case, the liquid was transported along the entire 1.5-m-long column (Hall, 2013). Tests were also conducted using 200 g/L salt water (NaCl) as the

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aerosolized liquid. The water content only changed slightly when salt water was used and the water content was similar to when the aerosols were created using fresh water. However, salt content increased along the column even though liquid water was not transported (Hall, 2013). Apparently, this occurred because the water evaporated during transport, causing the salt to precipitate and be transported as a solid. In contrast, the soybean oil did not evaporate because it had a lower vapor pressure than water.

Results from column tests present some intriguing insights, but additional work is required to evaluate potential applications to remediation. The analysis of transport of liquid aerosols in unsaturated porous media has received little attention, so there is limited basis for quantitatively evaluating the experiments and scaling up to field settings. Addressing this shortcoming is the primary objective of the following paper. The approach to meeting this objective was to develop a quantitative model for aerosol transport and calibrate it using experimental data. Most field applications would likely involve injecting aerosols into wells where they would flow along radial flow paths, but previous investigations have focused on transport through cylindrical columns. As a result, a new set of experiments was conducted using a radial geometry to more closely match the pattern of flow expected in the field.

2. Methods

Experiments were conducted using a wedge-shaped apparatus filled with sand. Carrier gas and aerosols were injected at the central axis of the apparatus, they flowed radially outward through the sand, and exhausted out the periphery (Figs. 1 and 2). A numerical analysis was developed and used to investigate the effects of aerosol injection on resulting amendment distributions in porous media. The analysis simulated aerosol transport and deposition in a partially saturated system with mobile gas and liquid.

2.1. Apparatus and aerosol supply system

The experimental apparatus was a wedge-shaped box with inside dimensions of 7.6 cm in height and 2.16 m in radius, with a 36° angle between the sides (Figs. 1 and 2). The interior of the apparatus was lined with a 0.3-cm-thick PVC sheet, and silicone caulk was used to seal the seams. A sheet of 0.6-cm-thick, closed-cell rubber foam on the underside of the lid was used to seal contacts with the sidewalls and terminal screen, and also prevented voids from forming on the upper surface of the fill sand. Fine wire-mesh screens were mounted at radial distances of 16 cm and 2.16 m to hold the sand in place while allowing air and aerosols to flow (Fig. 2).

An aerosol supply system used air injected into jet aerosolizers. We experimented with the design of jet aerosolizers and the ones used for the experiments were created by drilling two 0.76-mm-diameter holes in rectangular, aluminum blocks with dimensions of approximately 5 cm × 5 cm × 1.25 cm (details in Hall, 2013). One through-going hole was intersected by a transverse hole. Gas was injected into the through-going hole, whereas liquid was injected into the transverse hole. A 3-mm-deep, cone-shaped hole was created on the outlet end to create a venturi that gradually expanded the flow. Two aerosolizers were used during testing, each sandwiched between 3/4-inch NPT steel flanges (aerosolizer housings) (Fig. 1).

An air compressor was used to supply pressurized gas to the inlet side of the aerosolizers. The pressure to the aerosolizer was regulated and the gas flow rate was monitored with variable-area flow meters (Fig. 1). Peristaltic pumps were used to control the liquid flow rates to the aerosolizers. The aerosols flowed from the aerosolizer housing into 3-ft.-long sections of a 2-inch PVC pipe that were mounted at 45-degree angles (Fig. 1). Aerosols flowed downward through this section and then upward where the two pipes merged causing the larger droplets of liquid to settle out in the liquid reservoir (Fig. 1). The terminus of the

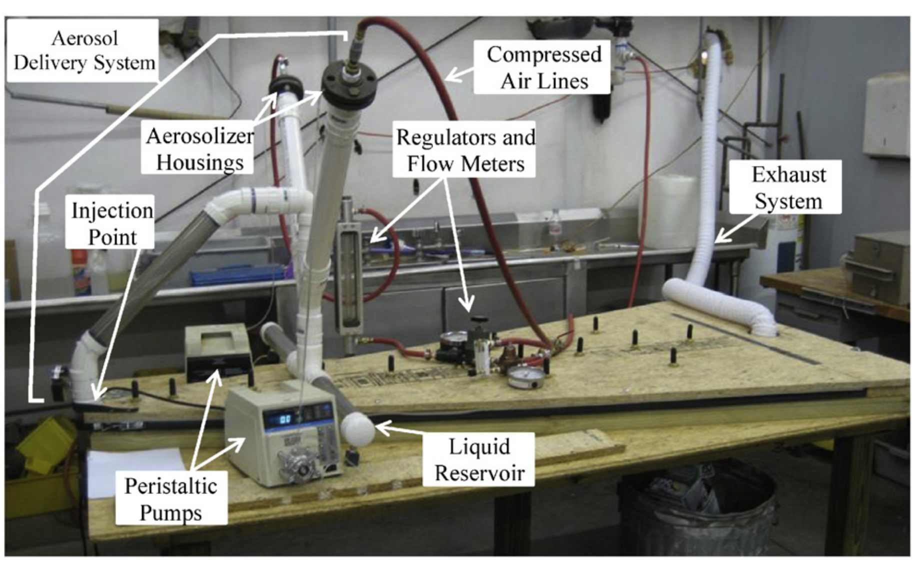

Fig. 1. Apparatus used for experiments with the lid and aerosol delivery system in place.

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