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Hot water flushing for immiscible displacement of a viscous NAPL

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Abstract

Thermal remediation techniques, such as hot water flooding, are emerging technologies that have been proposed for the removal of nonaqueous phase liquids (NAPLs) from the subsurface. In this study a combined laboratory and modeling investigation was conducted to determine if hot water flooding techniques would improve NAPL mass removal compared to ambient temperature water flushing. Two experiments were conducted in a bench scale two-dimensional sandbox (55 cm × 45 cm × 1.3 cm) and NAPL saturations were quantified using a light transmission apparatus. In these immiscible displacement experiments the aqueous phase, at 22 °C and 50 °C, displaced a zone with initial NAPL saturations on the order of 85%. The interfacial tension and viscosity of the selected light NAPL, Voltesso 35, are strongly temperature-dependent. Experimental results suggest that hot water flooding reduced the size of the high NAPL saturation zone, in comparison to the cold water flood, and yielded greater NAPL mass recovery (75% NAPL removal vs. 64%). Hot water flooding did not, however, result in lower residual NAPL saturations. A numerical simulator was modified to include simultaneous flow of water and organic phases, energy transport, temperature and pressure. Model predictions of mass removal and NAPL saturation profiles compared well with observed behavior. A sensitivity analysis indicates that the utility of hot water flooding improves with the increasing temperature dependence of NAPL hydraulic properties.

Keywords: Hot water flooding; Viscous NAPL; Numerical model; Multiphase flow; Heterogeneity

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1. Introduction

The remediation of nonaqueous phase liquid (NAPL)-contaminated aquifers remains a significant challenge despite over two decades of active research and development. Considerable advances in our understanding of the phenomena governing the migration and entrapment of NAPLs in the subsurface have been made and a number of innovative remediation technologies have been developed (e.g. Johnson et al., 2004; She and Sleep, 1999; Ramsburg and Pennell, 2002). The decision to remediate contaminated aquifers, however, is a source of considerable debate due to difficulties in achieving drinking water standards in contaminated aquifers at the completion of remedial activities (Sale and McWhorter, 2001; Rao and Jawitz, 2003; NSF, 2004). Due to difficulties in achieving desired cleanup goals the development of innovative remediation strategies is ongoing.

Many NAPL recovery strategies were first developed in the petroleum industry and later adapted for the remediation of NAPL-contaminated sites (e.g. surfactant flushing and thermal recovery techniques). Hot water flooding, a thermal recovery technique for enhanced petroleum production, has received relatively little laboratory study in the contaminant hydrology community but has been applied at various field sites (Fulton et al., 1991; EPA, 1993; Davis, 1995; EPA, 2000). At these field sites significant quantities of NAPL were recovered. However, free phase mobile NAPL was still present at each site following significant hot water flushing. In one-dimensional horizontal column experiments, Davis (1995) found that hot water flooding of NAPL (a viscous oil and creosote)-saturated sands enhanced NAPL removal by as much as 33%.

In the petroleum industry a number of studies have examined hot water flooding for the recovery of petroleum (e.g. Dokla, 1981; Willman et al., 1961; Edmondson, 1965; Fournier, 1965; Goodyear et al., 1996; Okasha et al., 1998). In many of the one-dimensional column experiments the initial rate of NAPL recovery is independent of temperature but more NAPL is ultimately recovered at elevated system temperatures (Willman et al., 1961; Edmondson, 1965; Dokla, 1981; Okasha et al., 1998). In these experimental studies oil recovery varied widely for the different NAPLs studied. Numerical modeling studies also suggest that hot water flooding will reduce the amount of residual petroleum in reservoirs (Fournier, 1965; Goodyear et al., 1996). These numerical studies assumed density and viscosity temperature dependencies but neglected temperature effects on interfacial properties. Although interfacial phenomena are commonly neglected in petroleum reservoir simulators, there is significant experimental evidence that these phenomena are important with regards to the determination of residual petroleum saturations following hot water flooding (e.g. Edmondson, 1965; Dokla, 1981).

Hot water flooding techniques exploit the temperature dependence of fluid properties, such as density, viscosity and interfacial tension, for improved NAPL removal efficiencies. The impact of these properties on NAPL recovery can be assessed by examining the constitutive relationships that govern multiphase flow. The soil matrix is often idealized as a bundle of capillary tubes of varying diameter. Capillary pressure in a cylindrical capillary tube is determined using the Young–Laplace equation (Adamson and Gast, 1997):

$$P_c = \frac{2\gamma_{ow}\cos\theta}{R} \tag{1}$$

where γ_{ow} is the interfacial tension between water and NAPL, θ is the contact angle measured through the water phase and R is the radius of the capillary tube. The Young–Laplace equation suggests that capillary pressure varies linearly with interfacial tension and $\cos\theta$. Sleep and Ma (1997) measured the temperature dependence of NAPL/water interfacial tension utilizing Voltesso 35 as the representative LNAPL (light nonaqueous phase liquid) (Fig. 1). In their system