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Temperature Plume Migration in Aquifers: The necessary first step to geochemical evaluation of thermally-mobilized constituents

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Summary

Evaluation of the spatial and temporal evolution of a thermal plume is the first step to understanding the potential for environmental impact from thermally-mobilized constituents. The importance of considering the effects of density and viscosity when estimating the groundwater flow direction is shown in this study. The primary source of uncertainty with respect to heat transport is shown to be the characterization of the Darcy flux and the groundwater flow direction which is usually estimated from manual water levels or pressures from pressure transducers. When these measurements are taken in a thermally impacted area, the groundwater flow direction can be misleading due to the dependency of water density on temperature. This can be especially important in sites with low hydraulic gradients. Correcting a density profile at monitoring wells on a thermal well pad is an important step in getting the equivalent freshwater hydraulic head. Simple calculations and analytical models can then be used to assess the upper bound transport distance of a thermal plume. However, these approaches may be overly conservative because they neglect heat losses to confining aquitards and, in the case of relatively shallow aquifers, heat loss at the ground surface. On the other hand, building complex 3D numerical models for each site would be expensive and time consuming. To provide quick and accurate predictions of the spatial and temporal evolution of thermal plumes in a confined aquifer, a study was undertaken using 3D numerical modelling. The model was used to assess thermal plume transport through time as affected by variables such as groundwater flow velocity, aquifer thickness, and aquifer depth. A total of 1,300 numerical simulations were performed and are summarized for use by hydrogeologists for rapid estimation of thermal plume transport distance under a variety of hydrogeologic conditions typical of confined aquifers in the oil sands that are penetrated by thermal wells. It is crucial that practitioners understand how dynamic the flow system is in proximity to thermal wells. If the temperature dependent (and time variable) effect to viscosity are not accounted for, unnecessary cost can be incurred when attempting to delineate a thermal plume, or manage liabilities.

Introduction

Steam-assisted gravity drainage (SAGD) and cyclic steam stimulation (CSS) rely on the injection of steam into the reservoir to recover bitumen. Heat transfer from thermal wells to aquifers results in groundwater heating and mobilization of otherwise immobile constituents such as arsenic. Additionally, water density and dynamic viscosity decrease due to the increased temperature. Geochemical evaluation of thermally-mobilized constituents in aquifers should not be completed before understanding the spatial and temporal extent of temperature plumes.

Theory and Methods

Governing Equations

Heat transfer in porous media occurs by conduction through water and soil solids, and by mechanical dispersion and forced convection as heat is carried by moving groundwater. The convection-dispersion equation can be expressed as follows (Stauffer et al. 2013):

$$\frac{\partial T}{\partial t}+\nabla\cdot(\mathbf{v}_T T)-\nabla\cdot\left[\mathbf{D}\nabla T\right]=0 \tag{1}$$

in which T denotes temperature (°C), $\mathbf{v}_T$ is the effective heat transport velocity and **D** is the dispersion tensor. The effective heat transport velocity is related to specific discharge (Darcy velocity) **q** as follows:

$$\mathbf{v}_T=\mathbf{q}\left(\frac{C_w}{C_m}\right); \tag{2}$$

$$\mathbf{D}=\frac{\lambda_m}{C_m}+\alpha\,\mathrm{v}_T \tag{3}$$

where C_m and C_w are the volumetric heat capacities of the bulk porous medium and water (J/m3/°C), respectively, λ_m denotes the bulk thermal conductivity (W/m/°C) and α the thermal dispersivity. Water properties such as water density ρ_w (kg/m^3) and dynamic water viscosity μ_w (Pa·s) are temperature dependent. The temperature dependence of density and viscosity of water directly affects hydraulic conductivity as follows (Bear 1972):

$$K(T)=\frac{kg\rho_w(T)}{\mu_w(T)} \tag{4}$$

where k (m^2) is the permeability tensor of the porous medium and g is the gravitational acceleration (m/s^2). Figure 1 shows that water viscosity drops by almost an order of magnitude as its temperature is increased from near 0°C to 100°C. Water density does not vary significantly over the first 20°C above zero with its maximum water density close to 4°C. By contrast, the water density has dropped to almost 955 kg/m^3 at 100°C. Figure 2 shows the effect temperature has on hydraulic conductivity where the normalized hydraulic conductivity at 4°C is unity. It can be seen that the hydraulic conductivity increases by a factor of 5 as the temperature is increased from near 0°C to 100°C.

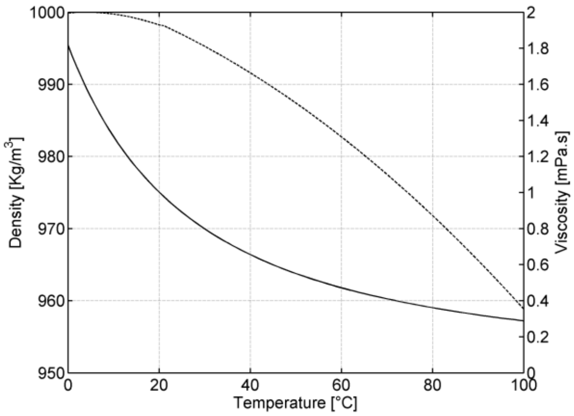

Figure 1. Water viscosity (solid line) and water density (dashed line) as a function of temperature

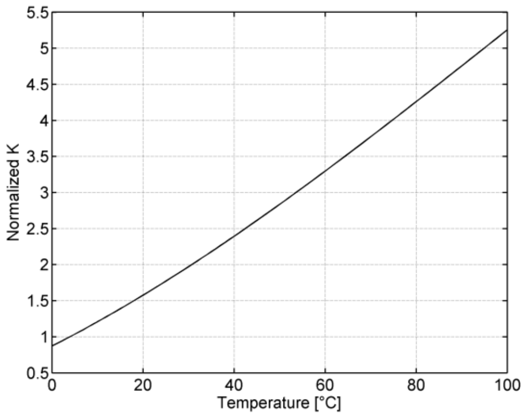

Figure 2. Normalized hydraulic conductivity as a function of temperaute

Field Observations

Steaming temperatures during SAGD and CSS operations can reach up to 270°C in the tubing. As a result, groundwater temperatures near the thermal wells are usually higher than 100°C. Even though gas phase might occur near the thermal wells in shallow aquifers, the radius of possible water flashing into steam around the wells is small compared to the scale of the thermal plumes. Thermal plume migration in aquifers is limited by heat losses due to transverse conduction in the aquifer and vertical conduction into the overlying and underlying sediments. Figure 3 shows the vertical thermal profile and the computed density profile for a monitoring well completed in shallow sand-gravel aquifer. The temperature near the water surface is 15°C which is related to a high atmospheric temperature during the time of the measurements.

Groundwater temperatures increase up to 27°C in the screened interval. Loss of thermal energy to the surface from a heated aquifer is evidenced from the temperature gradient between the aquifer and the ground surface. The vertical temperature profile shown in Figure 3 was captured by lowering a series of 25 sensors, equally spaced apart (8.0 m spacing), to the total depth at the base of a groundwater monitoring well. The vertical water density profiles are integrated from the surface of the water column to the mid-point of the well screen to estimate average water column density. The thermal effects also result in a decrease of the dynamic viscosity within the aquifer near the pad, which increases the hydraulic conductivity in the vicinity of the temperature plume. This creates a zone of convergent flow on the upgradient side of the plume, a flattening of the gradient in the area of the temperature plume, and heating and divergent flow on the downgradient edge. Hydraulic heads near the well pad are distorted into an hourglass shape by the effect of having decreased water viscosity in the area of heating (Figure 4).

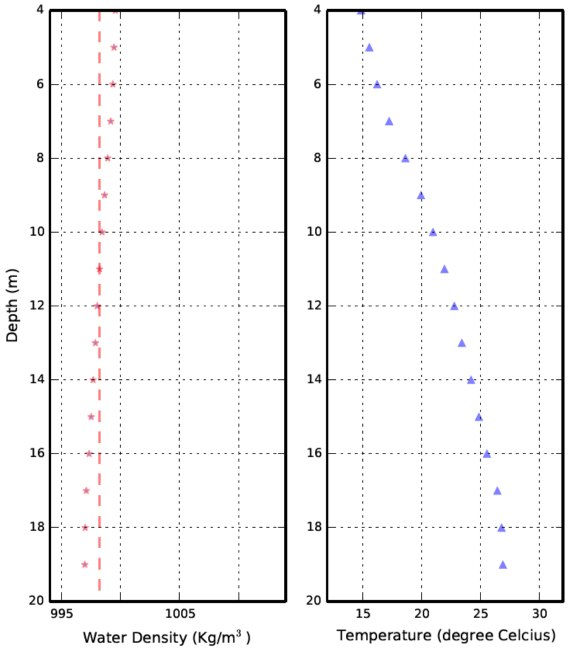

Figure 3. Temperature and density vertical profile

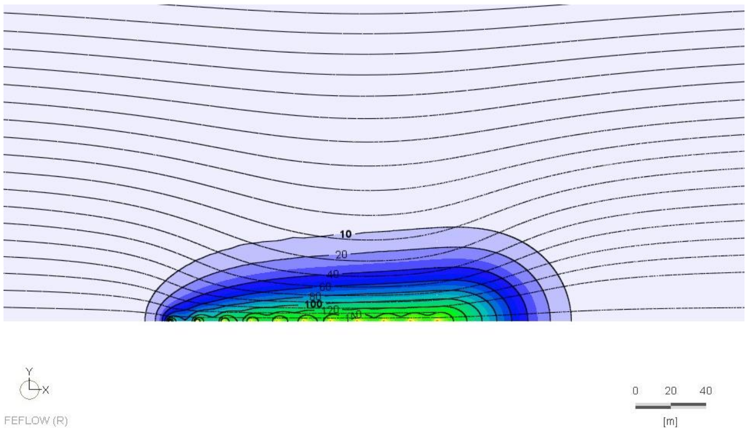

Figure 4. Effect of decreased water viscosity on hydraulic head

Numerical Modeling

A numerical modeling study (Matrix 2015) was carried out to examine the influence of factors such as groundwater velocity, aquifer thickness, and heat losses to the surface on thermal plume migration. The synthetic study area was centred on a hypothetical steam assisted gravity drainage (SAGD) operation project. Different conceptualizations of the model geometry were set up in order to explore the importance of different system elements. The aquifer thickness varied between 5 and 40 m and the distance from surface to the aquifer varied between 2.5 and 100 m. All of the hydrogeological units were assumed to be intersected by the vertical portion of a SAGD thermal well. Additionally, the number of wells and their orientation with respect to the groundwater flow velocity were also varied. The groundwater flow velocity varied between 0.1 and 25 m/year. Forward simulations were conducted under transient groundwater flow conditions and transient heat flow. The simulation time for each model was set to 10 years of ongoing steaming followed by 40 years of heat dissipation. The finite element code FEFLOW version 6.2 (DHI-Wasy GmbH 2014) was used to solve the groundwater flow and heat transport problem within a fully saturated porous media. Important insights gained by evaluating the model results include: 1) Faster groundwater velocities result in in thermal plumes with a short extent for the high temperature isotherm and an elongated low temperature isotherm; 2) Thermal plume transport distances are shorter in shallow aquifers. In other words, heat dissipation to the surface is more important for shallower aquifers. This effect seems to become negligible for aquifers greater than 30 m below the water table. The effects of temperature dependency of water density were not considered in the numerical model.

Examples

Apparent Groundwater Flow Direction

A shallow sand-gravel aquifer of approximately 5 m thickness has been affected by thermal operations. Vertical temperature profiles such as the one shown in Figure 3 were measured in monitoring wells on and around the well pad. The average water column density was used to correct measured depth to water levels through the conversion to equivalent freshwater hydraulic heads at standard temperature. After correcting for density effects and accounting for the effect of increased hydraulic conductivity, the groundwater flow direction was reinterpreted to flow in a direction perpendicular to the flow direction interpreted in previous studies that used uncorrected manual water level measurements.

Thermal Assessment

Results provided by the numerical modeling study were used to estimate the potential temperature migration in the Ethel Lake Aquifer from a proposed SAGD operation. The aquifer is 5 m thick and is located 20 m below ground surface. Representative groundwater flux for this formation was calculated based on estimates of hydraulic conductivity estimates and observed hydraulic gradient. Predictions of the assessment are presented Figure 5. The predicted transport distances of the 6°C isotherm after 10 years of steaming from a SAGD well bore on the production well pad were estimated to range from 95 m (4.0 m/year Darcy flux) to 140 m (8.0 m/year Darcy flux). 40 years after steaming has ceased, the predicted transport distances of the 6°C isotherm were estimated to range from 140 m to 200 m depending on the groundwater flow velocity. Consequently, the effect of change in temperature is low beyond these distances downgradient from the production well pad. The predicted transport distances of the 30°C isotherms after 10 years of steaming were predicted to range from 50 m (4.0 m/year Darcy flux) to 70 m (8.0 m/year Darcy flux) downstream from the thermal well. 40 years after steaming has ceased, groundwater temperatures higher than 16°C are not present anymore. Consequently, arsenic release as a result of steam injection and bitumen production are anticipated to be localized and limited to the immediate vicinity of the steam injection and bitumen production wells on the production well pad.

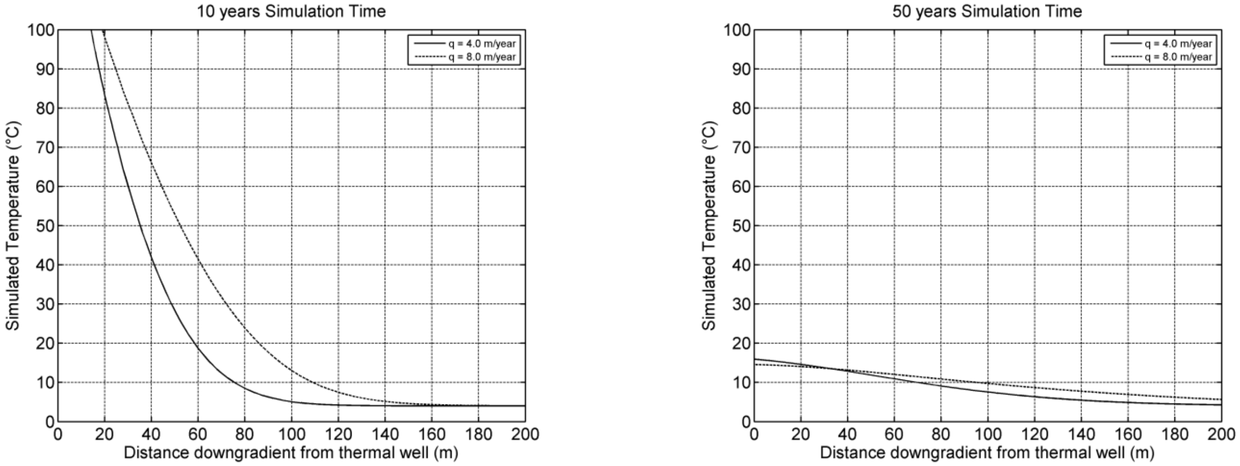

Figure 5. Simulated temperature over distance downgradient from the thermal well

Conclusions

Assessment of thermally-mobilized constituent is a necessary component of the risk management of thermal operations such as SAGD and CSS projects. The first step to evaluate such risks is to understand and delineate the groundwater flow direction and the spatial and temporal evolution of the thermal plumes. The use of proper tools and a knowledge of heat flow is crucial to make the best use of resources and to manage risks.

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