The Effect of Ground Source Heat Pumps on Biodegradation Kinetics and Contaminant Transport

Iman Roohidehkordi, Magdalena M. Krol

Department of Civil Engineering, Lassonde School of Engineering, York University, Canada

Geothermal or ground source heat pumps (GSHPs) are among the growing renewable energy technologies used for heating and cooling of buildings. However, little work has been done to investigate their geo-environmental effects within the subsurface, especially in contaminated environments. This research uses FEFLOW software, to simulate heat and mass transport of a vertical closed-loop GSHP system. Transient flow and heat transport results for a multiple borehole system are presented for a hypothetical building located in Toronto, Canada, and shows long-term effects on subsurface temperature. Moreover, the impact of heat exchanged with the subsurface on biodegradation kinetics is examined in a contaminant transport simulation, to evaluate the possibility of utilizing this heat as a remediation strategy. The results revealed that temperature changes caused by GSHP operation can significantly enhance biodegradation of hydrocarbon contaminants. For instance, elevated subsurface temperature resulted in 96% reduction in benzene concentration, after one year of GSHP simulated operation for an office building located in Toronto, Canada.

Introduction

Geothermal or ground source heat pumps (GSHPs) are among the top growing renewable energy technologies used for heating and cooling of buildings [1].

A GSHP is a device that uses a ground loop to absorb energy from the subsurface and transfer it to a building by applying external work with a compressor, thus keeping the warmer space heated. Alternatively, this cycle can be reversed allowing for heat to be absorbed from the building and subsequently injected to the subsurface. A common scheme to exchange heat with the subsurface is through vertical pipes called borehole heat exchangers (BHEs).

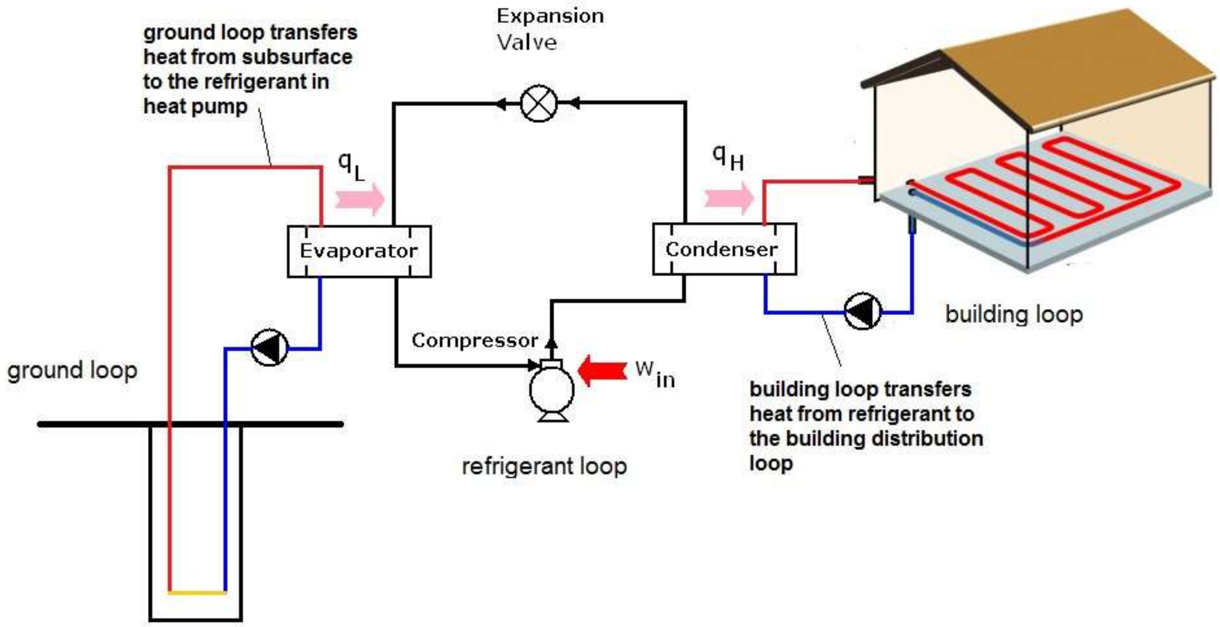

Fig. 1. Schematic diagram of a GSHP used for space heating

Operation of GSHPs can disturb ground temperatures in the vicinity of the boreholes and temperature isolines around the boreholes, called thermal plumes, can be formed [2, 3]. For unbalanced load scenarios, the situation greatly intensifies and a long-lasting thermally affected zone (TAZ) might form downstream of groundwater flow, which can interfere with other boreholes and cause system efficiency loss. Moreover, long-term environmental effects such as chemical or biological impacts associated with subsurface temperature changes might arise. Typically, adverse effects such as water quality have been the focus of other researches [4, 5]. However, a rise in subsurface temperature could be more favorable for certain microorganisms responsible for contaminant biodegradation and therefore might enhance the bioremediation process. With many brownfield sites worldwide requiring cleanup (around 30,000 in Canada [6], 450,000 in United States [7], and 3,000,000 across Europe [8]), rejected heat from geothermal heat pumps could be utilized as a thermal remediation strategy to remove contaminants that are susceptible to heat treatments (e.g. petroleum hydrocarbons or volatile organic compounds).

This study describes how heat, contaminant transport, and groundwater flow was simulated for a multiple BHE system using FEFLOW software, based on a 3-storey building located in Toronto, Canada. The impact of thermal plume development, resulting from GSHP operation, on benzene (as a common brownfield contaminant) was investigated through temperature-dependent biodegradation kinetics.

Background

To model a geothermal heating system, both analytical [9, 10, 11] and numerical [12, 13, 14] approaches have been considered to solve transport equations within the subsurface, with numerical models being usually preferred for scenarios that have complex geometries, ground heterogeneity, and borehole thermal interactions [15]. Numerical simulations are typically done using well- known commercial software packages like FEFLOW [3, 12, 13, 16], or COMSOL Multiphysics and SEAWAT [17, 18]. These studies established the impact of design parameters like borehole arrangement and spacing, location and climate, and thermal load profile as well as hydrogeological factors like groundwater flux, hydraulic and thermal conductivities, and so forth.

Another aspect of GSHP operation is its environmental impacts. Owing to the sensitivity of microbiological activity to temperature, biodegradation of the organic pollutants in groundwater is significantly dependent upon aquifer temperature changes [19]. The favorable impact of elevated temperatures on biodegradation of organic contaminants has been studied by several researchers in the past decades [20-23]. However, elevated temperatures might also lead to unexpected transport of the contaminants due to emergence of strong buoyant flows even with moderate temperatures arising from thermal treatments like electrical resistance heating (ERH) [24, 25]. Moreover, applying heat to the subsurface might result in bubble formation and mobilization of volatile compounds which in turn can lead to movement and eventual collapse of bubbles when reaching cooler zones, thus spreading the contamination, especially when high temperatures are applied [26]. Lastly, cyclic heating and cooling process during operation of a GSHP might lead to different biodegradation results from studies that focus on the heating-only scenarios when bioremediation is achieved by constant elevated temperatures unlike actual seasonal operation of a GSHP system [27]. Therefore, the applicability of GSHPs for enhanced bioremediation with cyclic heating and cooling loads which in turn leads to cyclic temperature rise and drop within the subsurface is the focus of this research.

Biodegradation kinetics

In this study, FEFLOW was used for simulation of a GSHP with a multiple borehole heat exchanger. In order to include biodegradation, Monod (Michaelis-Menten) kinetics is used in the model which can be described by the following equation [28]:

$$\frac{dS}{dt} = -\frac{\mu}{y} B \frac{S}{S + Ks}$$

where μ is maximum specific growth rate (1/h), S is substrate concentration (mg/L), y is biomass yield, B is biomass concentration and Ks is half saturation constant. To couple the temperature effect, Topiwala-Sinclair model presented in the following equation is implemented [20]:

$$\mu = A.e^{-Ea/RT} + B.e^{-E\ \ /RT}$$

where A and B are exponential factors (1/h), and Ea and Eb are the activation energy (kJ/mol) for cell growth and thermal denaturation, respectively. R is universal gas constant and T is temperature (K). Therefore, the maximum specific growth rate is the temperature-dependent biodegradation parameter which is applied in the mass transport simulation.

To achieve a comprehensive understanding of the effectiveness of utilizing GSHPs to enhance bioremediation, the worst-case scenario is defined based on the lowest biodegradation velocity at the reported temperature from the literature for P. putida microorganism [29]. By assuming the rate of biodegradation is zero at 0°C and optimal growth temperature as 34°C [20], the Topiwala-Sinclair model is calibrated for the desired temperature range:

$$\mu = 2.8 * 10^{28}.e^{-20\quad .3/T} + 6.63 * 10^{180}.e^{-128939.1/T}$$

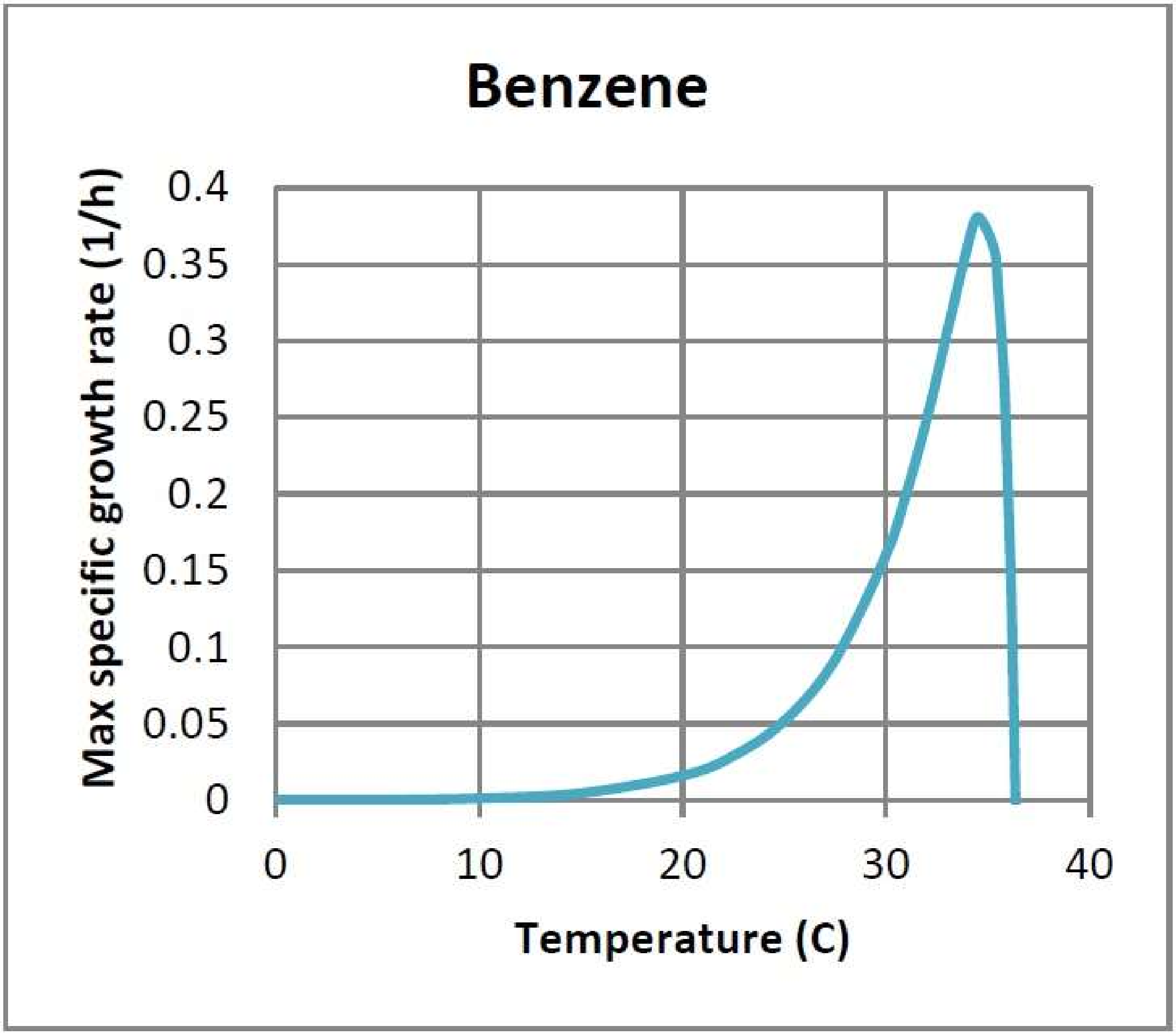

Fig. 2. Temperature-dependent maximum specific growth rate of P. putida strain grown on benzene using the Topiwala-Sinclair model

Model description

The case study used is a 3-story office building with 5,120 ft^2 total floor area located in Toronto, Canada using a model previously developed and tested [3]. Based on building specifications [30] and average Toronto outdoor air temperatures, building heating and cooling demands are calculated based on the heat loss and CLTD/CLF/SCL method proposed by ASHRAE [31]. Building heating and cooling monthly demands were then converted to a ground thermal load resulting in the following profile:

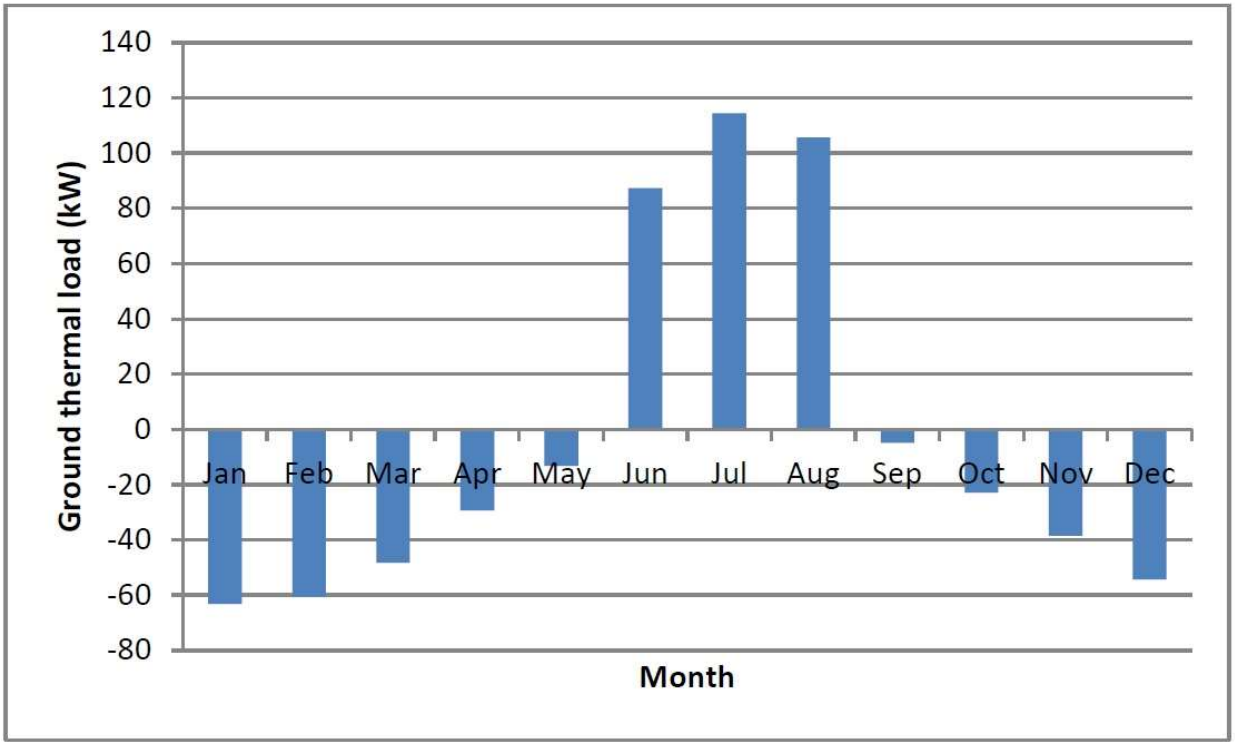

Fig. 3. Ground thermal load for the present case study

Based on the peak cooling load in July and assuming a 150 m borehole depth and average specific heat extraction rate of 50 W/m [28], 18 required boreholes is calculated which are arranged in a 6x3 configuration with 10 m spacing (Fig. 4).

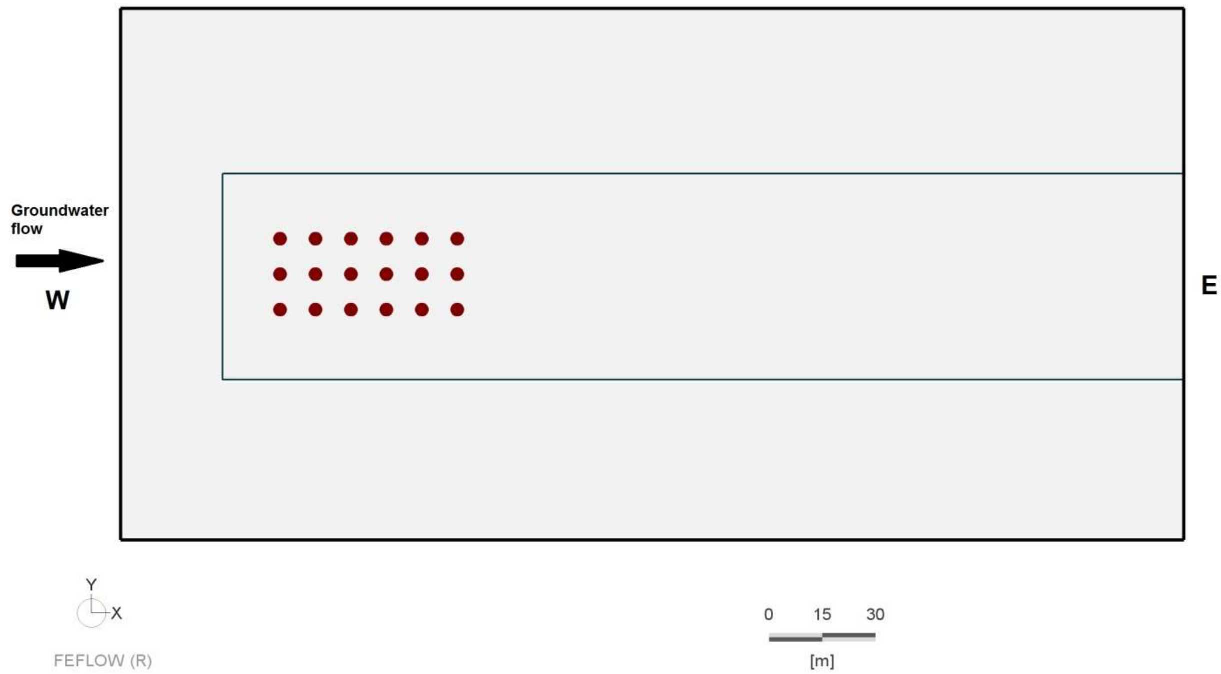

Fig. 4. The rectangular 6×3 layout used for the borehole arrangement

The model domain is taken to be 300 m by 150 m by 170 m, in the x, y, z (vertical) dimensions, respectively. The direction of groundwater flow is assumed to be from west to east at an initial Darcy velocity of 7.3×10^{-8} m/s and no flow boundary conditions are set at the north and south boundaries for a confined aquifer. The background subsurface temperature is set to 10°C while the top temperature boundary is set as variable and corresponds to the air temperature. The input power in boreholes is also variable according to monthly ground load values. The final 3D finite element model consists of 18 boreholes and 947,155 triangular prism elements (Fig. 5).

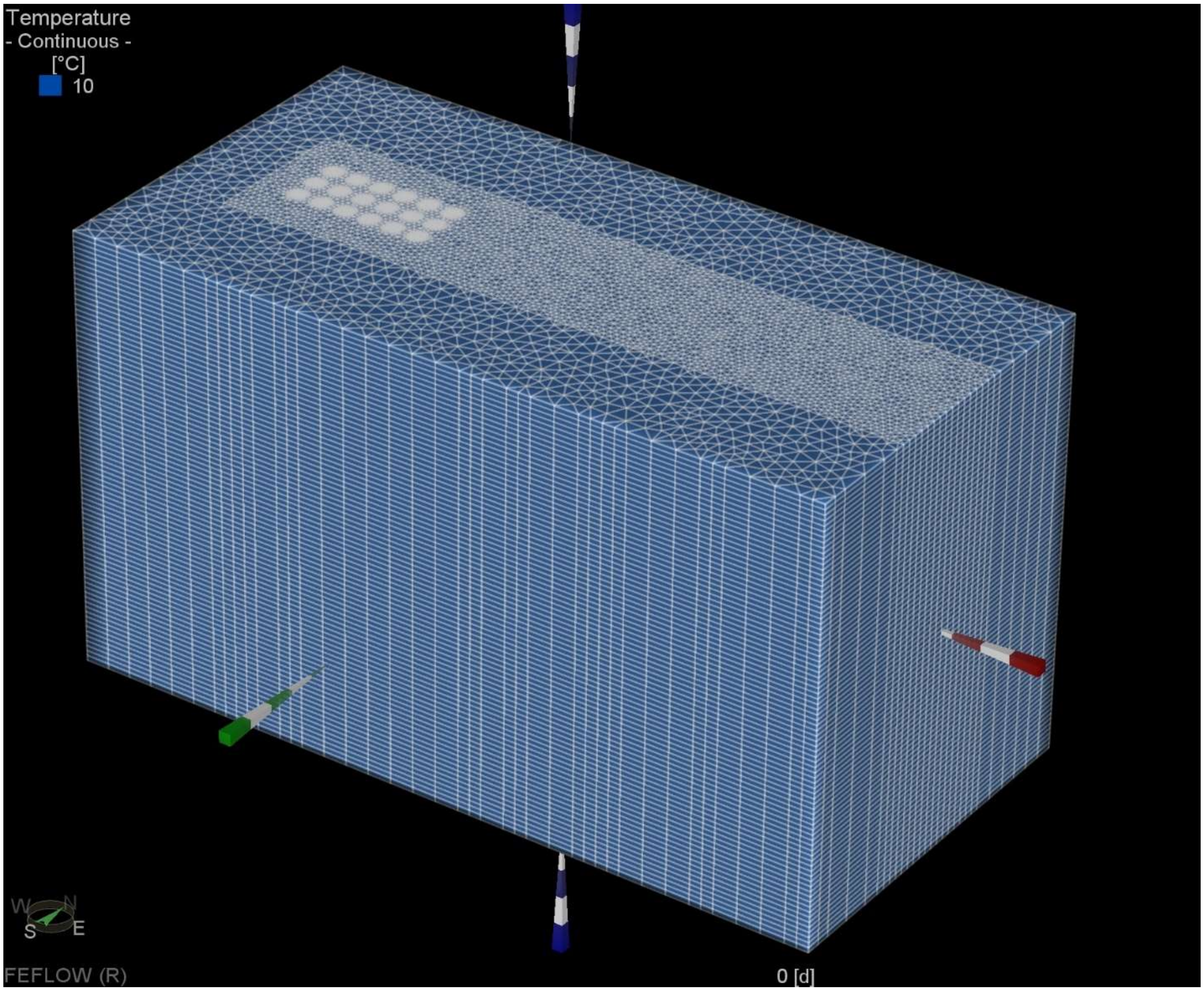

Fig. 5. Resulting 3D finite element model with 947k elements and 18 boreholes

Results

The developed FEFLOW model was run for 10 years in a transient flow, heat and contaminant transport simulation. The temperature distribution at the end of first and 10th year of operation at 30 mbgs shows the development of thermal plumes over time. Note that initial ground temperature was assumed as 10°C.

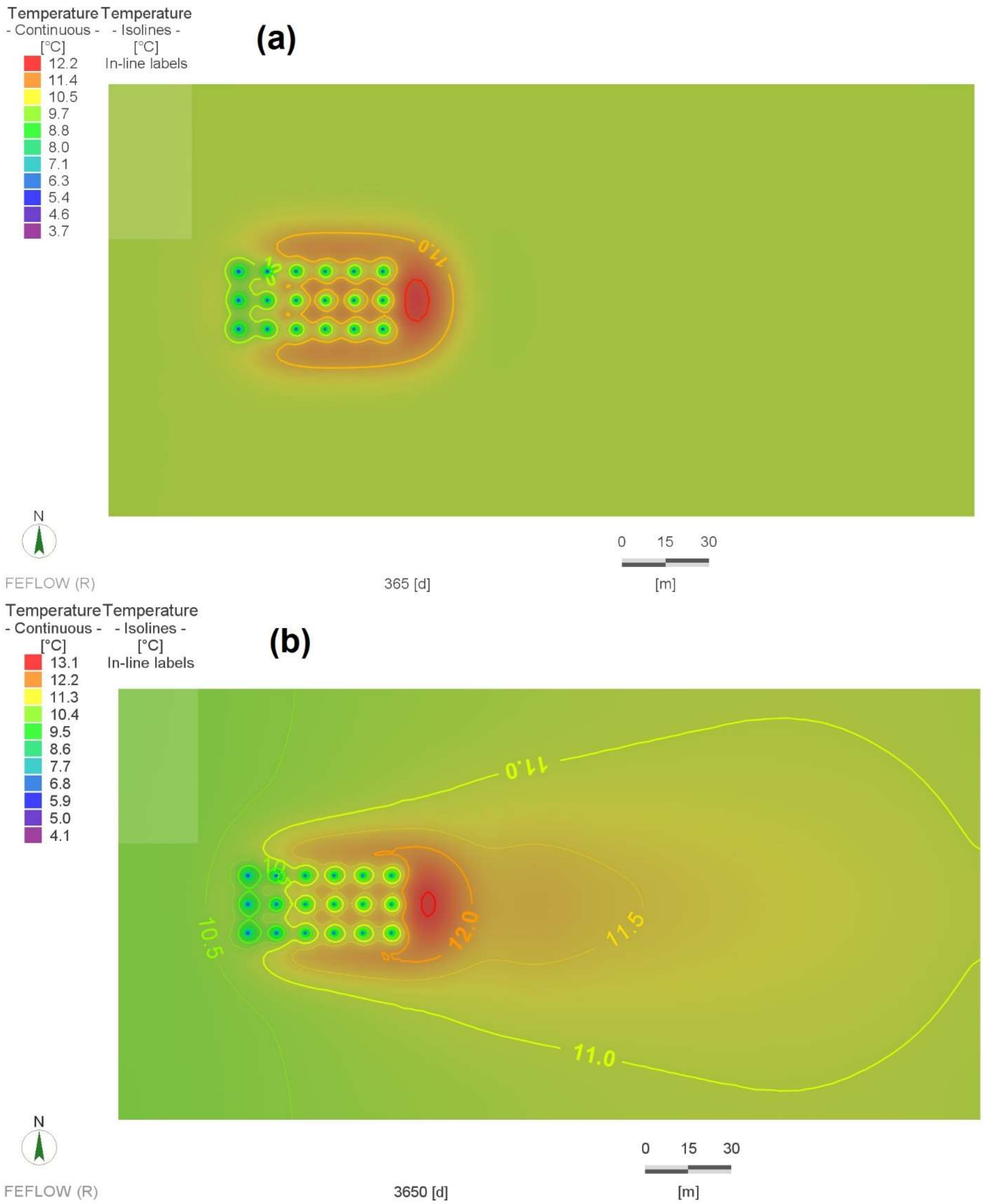

Fig. 6. Comparison of thermal plume development at 30 mbgs at the end of the (a) 1st and (b) 10th year of GSHP operation

Cross sectional view after 10 years of GSHP operation also shows the extent of TAZ.

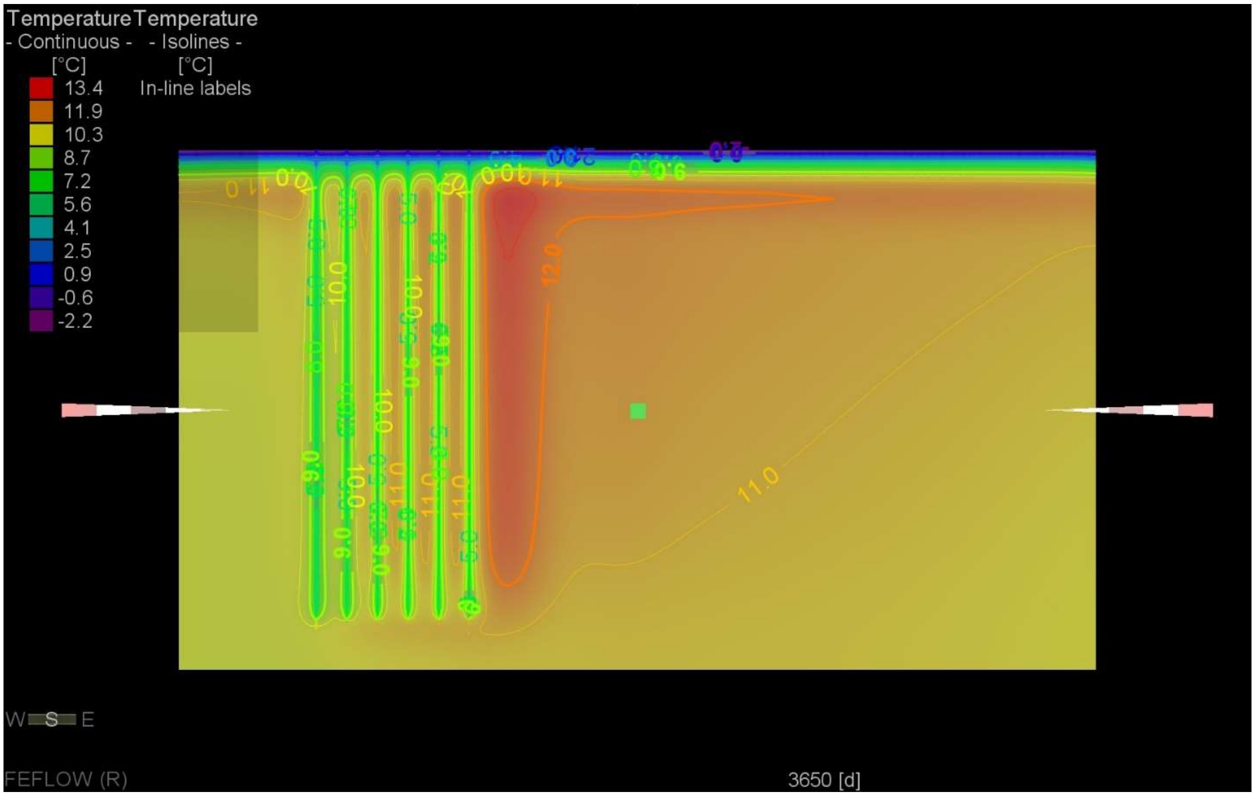

Fig. 7. Temperature distribution from the side-view in the mid-plane after 10 years

For the contaminant transport simulation, a spill was modeled with 100 mg/L initial concentration located at the depth of 28 to 32 mbgs, inside the borefield area:

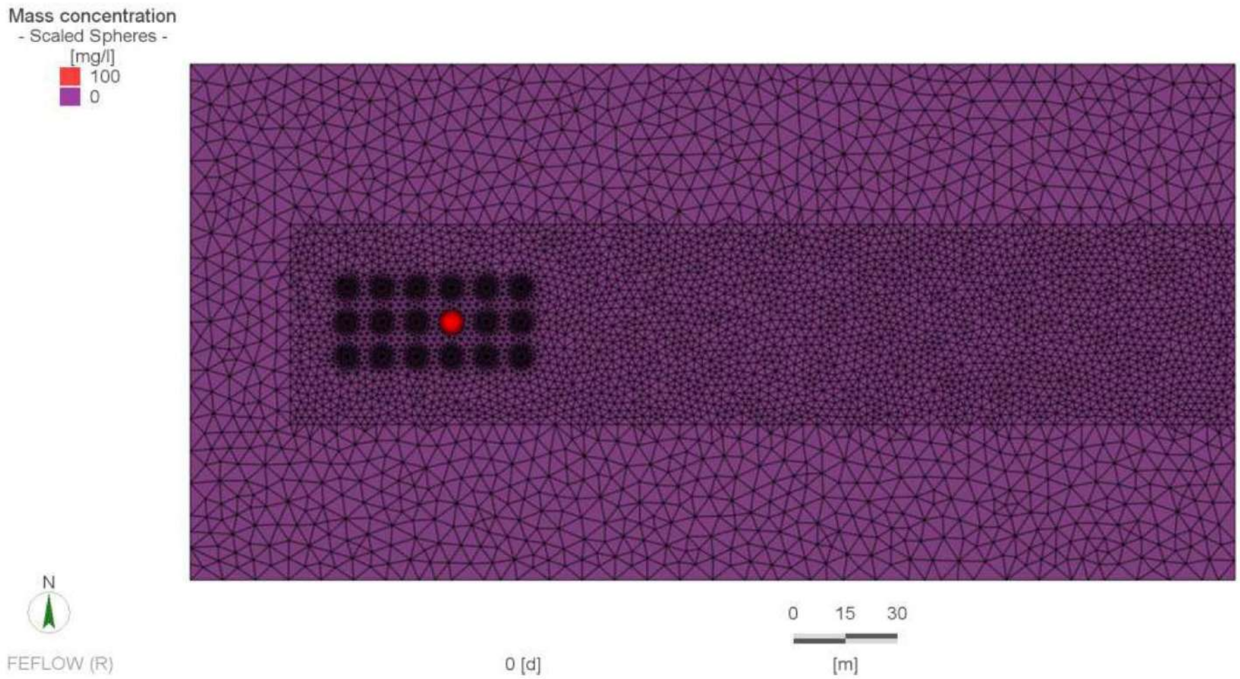

Fig. 8. Initial benzene concentration located at 28 to 32 mbgs depth

Based on the temperature distribution from the heat transport simulation, the monthly average subsurface temperature in the vicinity of the boreholes is derived and shown in Fig. 9.

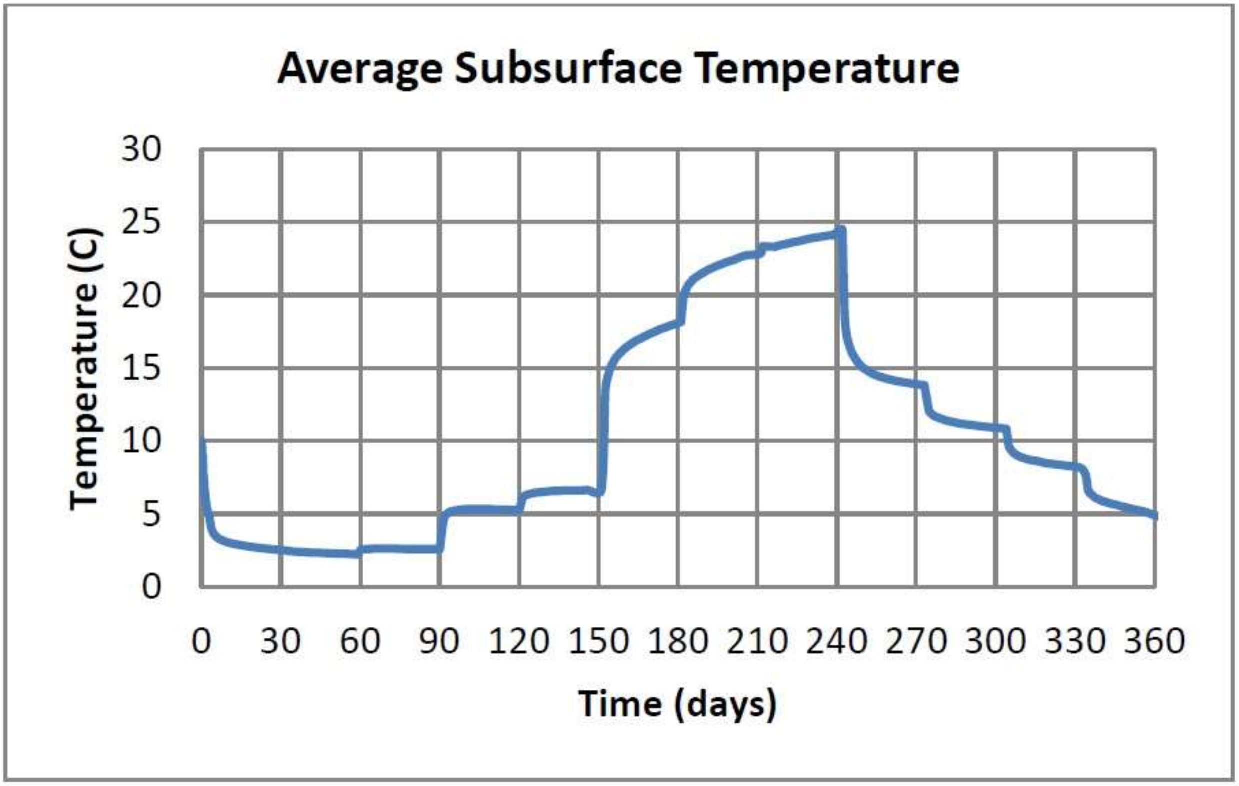

Fig. 9. Average subsurface temperature profile from heat transport simulations after one year of GSHP operation

Due to the limitations of FEFLOW, variable biodegradation kinetics could only be specified by time and not directly specified as a function of temperature. Therefore, the average subsurface temperature profile is used as the correlation between time and temperature (using Fig. 9), and a temperature-dependent Monod parameter (μ) is linked to temperature through a "time series" in FEFLOW. Fig. 10 depicts the comparison of the results for benzene concentration with variable biodegradation kinetics with the results when no GSHP is in operation and the temperature is therefore constant at 10°C. Comparison of the results reveals a remarkable mass concentration decline of 96% from 0.306 to 0.011 mg/L, when temperature-dependent biodegradation rates are included in the simulation.

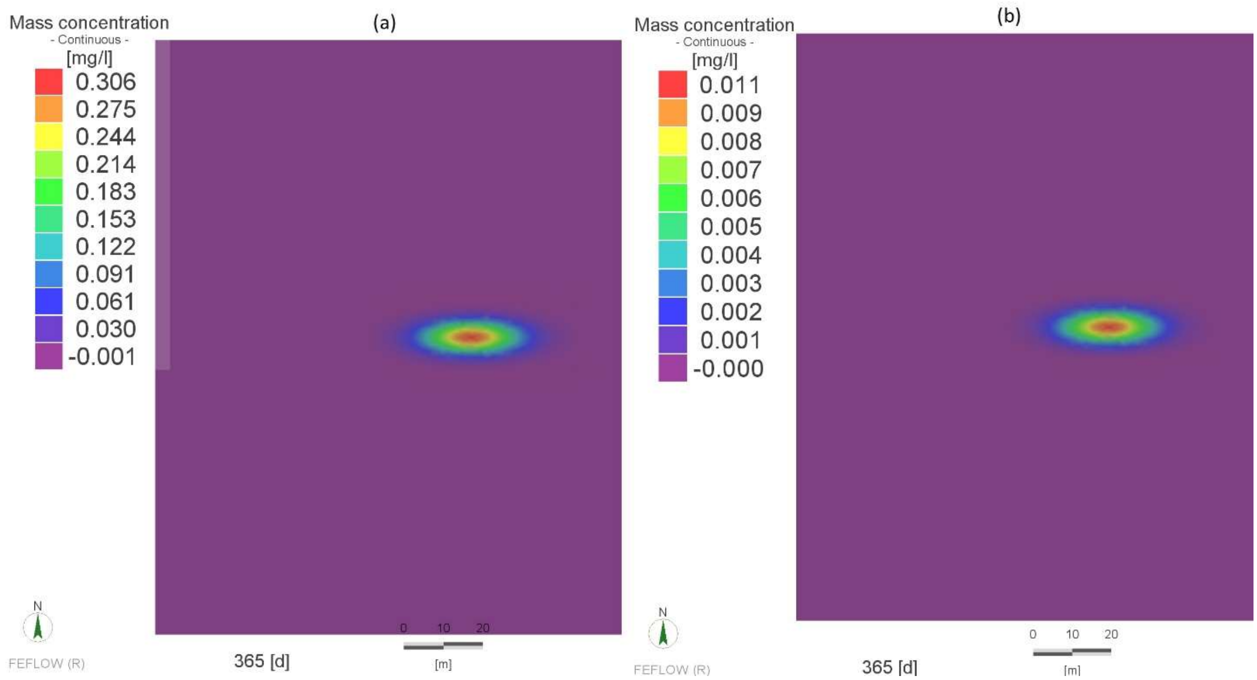

Fig. 10. Effect of GSHP on benzene concentration at 30 mbgs after one year for (a) no heating and (b) temperature-dependent biodegradation

For better comparison, the breakthrough curves for these two cases of constant biodegradation and temperature-dependent biodegradation at a location 5 m far from benzene spill are plotted in Fig. 11, after a one-year period. The labels correlate with average ground temperatures. As seen in the graph, for the first 6 months (January to June) of geothermal operation, variable biodegradation assumption yields higher concentration of benzene which means less biodegradation is happening. This is due to the fact that during the first 5 months, ground temperature is less than 10°C since the GSHP is in heating mode, resulting in a lower biodegradation rate. During cooling mode, however, subsurface temperatures rise above 10°C and the biodegradation rate increases, leading to a substantial decline in concentration.

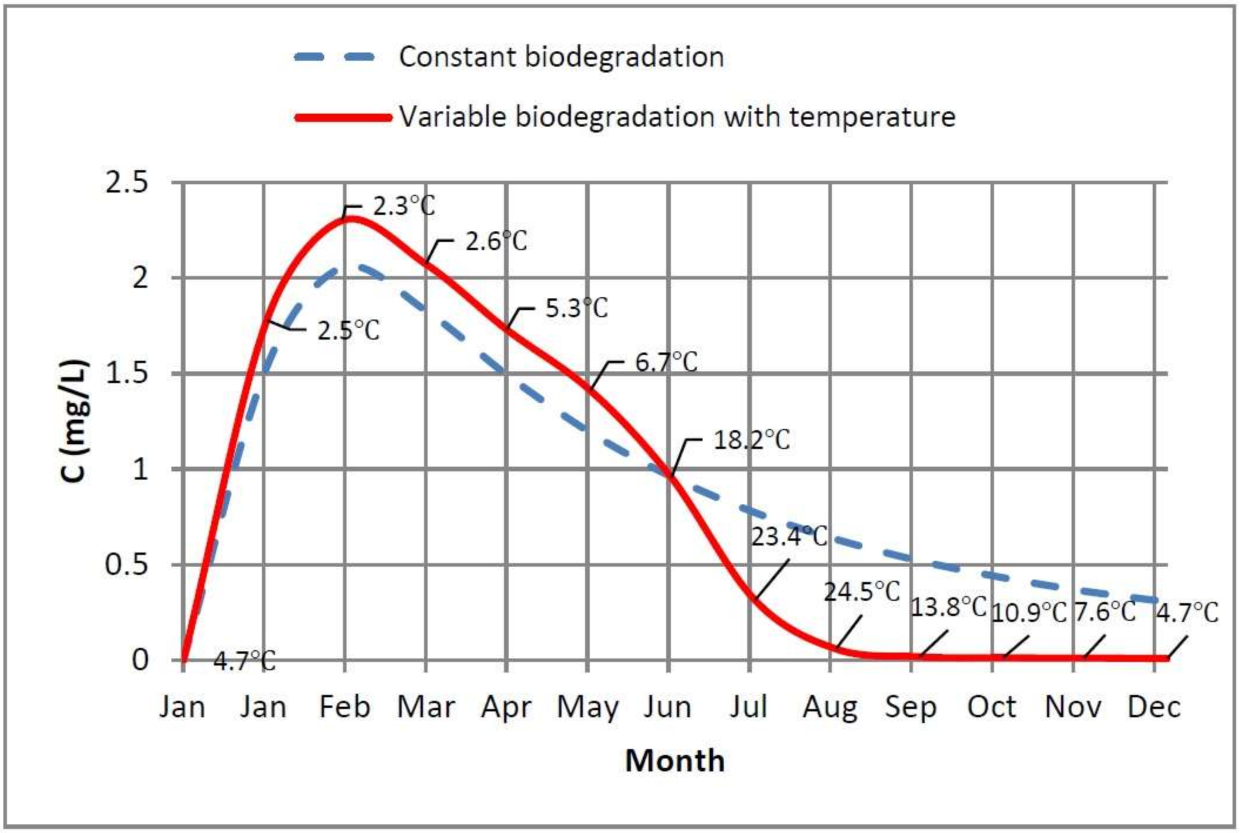

Fig. 11. Breakthrough curves with constant and variable biodegradation rates at 5 m horizontal distance from the benzene spill

Conclusion

In this research, subsurface flow, heat, and contaminant transport simulations in the presence of a geothermal heat pump system are performed. The result of contaminant transport simulations showed that even a cyclic subsurface temperature change in the range of 2 to 25°C could lead to a substantial increase in biodegradation rates compared to constant biodegradation at 10°C, when no geothermal heating is implemented. In a case study for a benzene spill and a GSHP designed for a 3-storey office building in Toronto, the favorable impact of GSHP operation for remediation purpose is demonstrated by a remarkable decline of 96% in benzene concentration, compared to the case with no geothermal heating. However, in this study, the average ground temperature in the vicinity of the boreholes is derived in each month, to calculate the corresponding biodegradation coefficients in FEFLOW. Although this approach paves the way to model variable biodegradation with time and temperature, it neglects the temperature changes associated with location. Thereby, it is only applicable to the contaminant source located close to the boreholes. Lastly, as the Monod equation is empirical and biodegradation parameters are strongly site-specific, more research is needed to obtain specific biodegradation rates for a certain microorganism and contaminants.

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