

Response to the comments of Anonymous Referee #2

We would like to thank Referee #2 for the thoughtful comments. The following is our response.

1. What could make this paper interesting, but is not discussed, is a thorough evaluation of how the different transport rates for solutes and heat may affect macro-dispersion: Heat diffuses about 100 times faster than solutes while heat is advected, roughly speaking, at the Darcy velocity but solutes at the pore velocity (see, for example, the discussion of the thermal retardation factor in Bodvarson, 1972, *Geothermics*, Vol. 1). This behavior affects macro-dispersion: For example, Geiger & Emmanuel (Water Resources Research, 2010) showed that the concept of macro-dispersion can also break down for heat transport in heterogeneous fractured porous media, leading to "non-Fourier" transport (in analogy to non-Fickian transport) but this is less likely than for solute transport due to the different transport rates for heat and solute.

Reply

Thanks for the references.

(a) According to Geiger and Emmanuel (2010), in systems with a low degree of heterogeneity the heat transfer is Fourier-like, while in systems with a high degree of spatial variability in the flow fields, such as often occurs in fractured systems, thermal transport is expected to become anomalous like. As mentioned in the manuscript, the analyses in this study are limited to small perturbation in hydraulic properties, assuming that the standard deviation of the random log hydraulic conductivity fluctuations is smaller than unit (weak heterogeneity). The field-scale heat transport under this study can therefore be modeled by using macroscopic dispersive flux formalism (Gelhar and Axness, 1983).

(b) We have added the following statements on page 11 (Line 274):

“Based on the application of the Continuous Time Random Walk transport formalism to the fracture networks, Geiger and Emmanuel (2010) concluded that in systems with a low degree of heterogeneity, heat transfer is Fickian-like

(or Fourier-like). The implication is clear that in the flow fields with a low degree of heterogeneity an effective advection-dispersion equation containing the macrodispersion coefficients can be used to model the heat transport at the field scale, as adopted in the paper. However, in systems with a high degree of spatial variability in the flow fields, such as often occurs in fractured systems, the thermal transport is expected to become anomalous like (non-Fickian heat transport) (Geiger and Emmanuel, 2010).”

2. I am also missing a discussion of the range of validity of this analysis because, strictly speaking, heat transport is a non-linear problem as density and viscosity change with changing temperature, which again changes the advective velocity and dispersion tensor.

Reply

Thanks for the suggestion.

We have added the validity of the assumption of constant thermal properties on page 5 (Line 112):

“It has been concluded from the analytical model of cold water front movement in a geothermal reservoir by Stopa and Wojnarowski (2006) that the velocity of the thermal front found from the weak model solution differs from the velocity obtained under the assumption of constant thermal properties by about 1 to 14%, depending on the temperatures used for evaluation of the thermal properties. In addition, Lo Russo and Taddia (2010) mentioned that the density and viscosity variations with temperature can be considered negligible for systems in an unconfined aquifer with temperature changes below 10-15°K. On the other hand, the heat transport simulation should take account of the physical temperature dependencies of the thermal parameters for systems with higher temperature changes ($\gg 10^\circ \text{K}$).”

3. Its content, while correct and well presented, is simply not novel enough to warrant publication.

Reply

The Eulerian based spectral approach was used by Gelhar and Axness (1983) to quantify field-scale solute transport processes in heterogeneous porous media. Their work focused on the prediction of macrodispersion under the steady-state condition (i.e., asymptotic macrodispersion) in heterogeneous aquifers. Existing stochastic studies on the field-scale temporal dispersion have built on the Lagrangian methodology. To the best of our knowledge, the application of the Eulerian concept (namely, the methodology of Gelhar and Axness) to the investigation of the field-scale temporal solute/heat transport by groundwater flow has so far not been attempted. This paper presents the closed-form expression for the field-scale temporal heat advection which might be the first article to provide a theoretical basis for the analysis of field-scale heat transport processes. Because the body of literature on stochastic analysis of heat transport is rather limited, it is our hope that the present article may stimulate prosperous studies in this area in the future.

References

- Geiger, S. and Emmanuel, S.: Non-Fourier thermal transport in fractured geological media, *Water Resour. Res.*, 46(7), W07504, doi:10.1029/2009WR008671, 2010.
- Gelhar, L. W. and Axness, C. L.: Three-dimensional stochastic analysis of macrodispersion in aquifers, *Water Resour. Res.*, 19(1), 161-180, 1983.
- Lo Russo, S. and Taddia, G.: Advective heat transport in an unconfined aquifer induced by the field injection of an open-loop groundwater heat pump, *American Journal of Environmental Sciences*, 6(3): 253-259, 2010
- Stopa, J. and Wojnarowski, P.: Analytical model of cold water front movement in a geothermal reservoir, *Geothermics*, 35(1), 59-69, 2006.