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The influence of the injection temperature on the recovery efficiency of high temperature aquifer thermal energy storage: Comment on Jeon et al., 2015

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1. Introduction

Recently, an article by Jeon et al. (2015) [1] was published in this journal on the recovery efficiency of high temperature aquifer thermal energy storage (HT-ATES) systems in which twenty such systems were numerically simulated. The output of these simulations served as a basis for constructing a meta-model with which the recovery efficiency could be estimated without the need for full numerical simulation. In turn, this meta-model was then used for a sensitivity analysis that ranked the input parameters based on their relative influence on the recovery efficiency. We thank the authors of this article for clearly showing the potential value of such a systematic approach in the field of HT-ATES and underground thermal energy storage systems in general.

In Schout et al. (2014) [2] a similar study was presented that also covered the recovery efficiency of HT-ATES systems, focusing on the development of a method for making 1st order estimates of the recovery efficiency within a range of conditions typically encountered in the sedimentary aquifers of the Netherlands. In contrast to Jeon et al., the results of Schout et al. are fully based on numerical simulations. Comparing their results with the results in Schout et al., Jeon et al. noted a striking difference in the relative sensitivity of the recovery efficiency to some of the analysed parameters. Most notably, while Schout et al. concluded that the injection temperature is an important factor for the recovery efficiency, Jeon concluded that its sensitivity to the injection temperature was virtually zero, and that it is solely sensitive to the aquifer permeability and the injection volume. This difference is especially relevant for case 1 in Jeon et al., since it concerns the same base case and similar parameter variation when compared to Schout et al. In this letter we argue that the sensitivity of the recovery efficiency to the injection temperature must have been underestimated by Jeon et al. by taking a closer look at the physical processes that lead to heat losses in the subsurface, and ultimately determine the recovery efficiency.

2. Heat losses in aquifer thermal energy storage systems

Energy losses in HT-ATES systems (thermal energy stored in the aquifer that is not retrieved during production) are caused by four processes. As outlined in Doughty et al. (1982) [3] they are thermal conduction, dispersion, regional groundwater flow and density-driven flow. In both the works being discussed, regional groundwater flow is assumed to be low and therefore its influence on the recovery efficiency negligible. Of the three remaining processes, both thermal conduction as well as density driven flow are driven by a temperature gradient, while dispersion can be considered independent of the water temperature and is therefore not considered in this discussion.

Heat losses in the aquifer resulting from thermal conduction are linearly proportional to the injection temperature: if the injection temperature is doubled and all other parameters are kept the same, heat losses through thermal conduction may be expected to double

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as well. Hence the injection temperature is not relevant in terms of its influence on the recovery efficiency through thermal conduction: the percentage of heat lost by thermal conduction is not temperature dependent [4].

However, according to our findings, heat losses due to density driven flow are nonlinear and can greatly influence the recovery efficiency. That density driven flow can have a profound and nonlinear effect was also shown by means of a field experiment and subsequent numerical simulation conducted by Buscheck et al. (1983) [5]. Density driven flow occurs as a result of the difference in density between the ambient and injected water and results in tilting of the thermal front between the stored and ambient water. The viscosity of the ambient and injected water also affects the tilting rate of the thermal front. Both density and viscosity have a nonlinear relationship with temperature (see Fig. 1). Fig. 2 (adapted from Ward et al., 2007) [6] shows a schematization of such tilting, which affects the recovery efficiency because part of the injected hot water moves away from the well screen and is only partly retrieved during the subsequent production cycle (assuming equal volumes of injected and produced water).

An analytical solution (Eq. (1)) for the rate at which tilting of the thermal front occurs was proposed by Hellström et al. (1988) [7].

$$t_0 = \frac{H}{\sqrt{k^h \cdot k^v}} \cdot \frac{C_a}{C_w} \cdot \frac{\pi^2(\mu_0 + \mu_1)}{32G(\rho_0 - \rho_1)g} \tag{1}$$

where t_0 is the characteristic tilting time (s), H is the thickness of the aquifer (m), k^h and k^v are the horizontal and vertical aquifer permeabilities (m^2), C_a and C_w are the volumetric heat capacities of the aquifer and of water (J/m^3K), μ_0 and μ_1 are the viscosities of the ambient and the injected water, respectively (kg/ms), ρ_0 and ρ_1 are the densities of the ambient and the injected water, respectively (kg/m^3), G is Catalan's constant (0.915 …) and g is the gravitational constant (9.81 m/s^2). The characteristic tilting time is the amount of time it takes for an initially vertical thermal front to reach a 60° angle with the horizontal, assuming a horizontally infinite aquifer.

3. Influence of the injection temperature on the recovery efficiency

In Fig. 3 the characteristic tilting time is plotted versus temperature for a range of temperatures that are typical for HT-ATES applications and for four different sets of k^h and k^v, assuming an

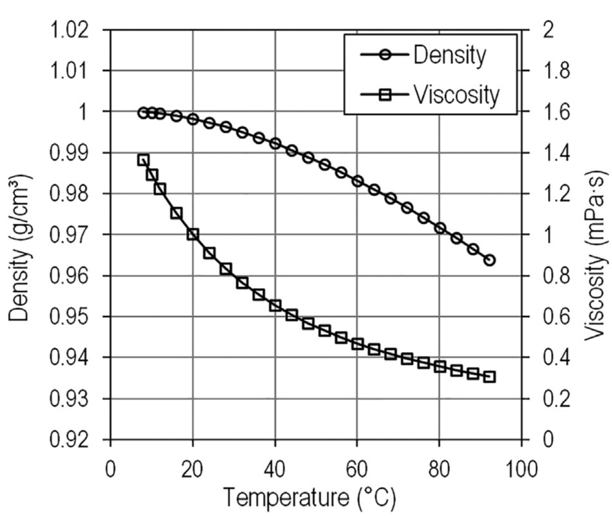

Fig. 1. Relationship between temperature and the density and viscosity of fresh water.

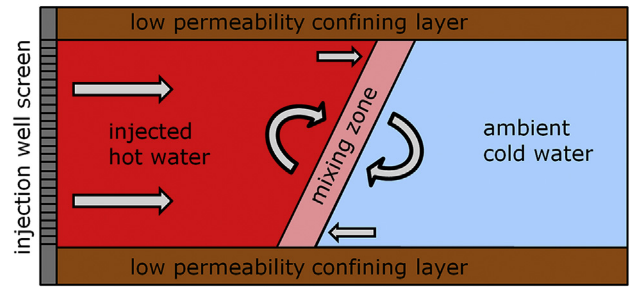

Fig. 2. Buoyancy driven tilting of an initially vertical thermal front. Arrows depict the velocity field with on the left hand side the advective flow caused by injection and the density driven rotation of the thermal front in the centre. Figure adapted from Ward et al. (2007) [6].

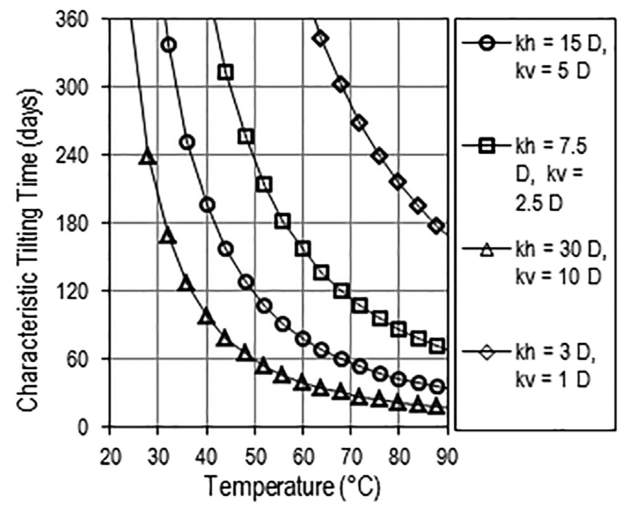

Fig. 3. Influence of temperature on the characteristic tilting time (time for an initially vertical thermal front to reach 60°) for four different combinations of aquifer permeabilities.

ambient groundwater temperature of 12 °C, H = 21 (m) and C_a = 3284 (J/m^3K). It becomes evident that, given certain permeability values, the characteristic tilting time can decrease by nearly an order of magnitude within the range of temperatures considered for HT-ATES systems.

Fig. 4 shows the relation between the characteristic tilting time and the recovery efficiency for 78 numerically simulated HT-ATES scenarios (data from Schout et al., 2014) [2]. When the characteristic tilting time is more than 100 days, the recovery efficiency is above 70% in all but one of the simulated scenarios. Apparently, the impact of density driven flow on the recovery efficiency is limited in that case. As can be seen in Fig. 3, large values of the characteristic tilting time are associated with low permeability values and/or low storage temperatures. This means that the impact of density driven flow on the recovery efficiency is limited for aquifers with a low permeability and/or for low storage temperatures. Since low permeability aquifers tend not to be feasible from an economical point of view (as more wells are necessary) and it does not concern storage of low temperatures, the characteristic tilting time for HT-ATES systems is usually below 100 days.

Fig. 4 also shows that the lowest values for the recovery efficiency are found for small values of the characteristic tilting time. Apparently, the characteristic tilting time is an important factor for the recovery efficiency when it is below 100 days. Small values of

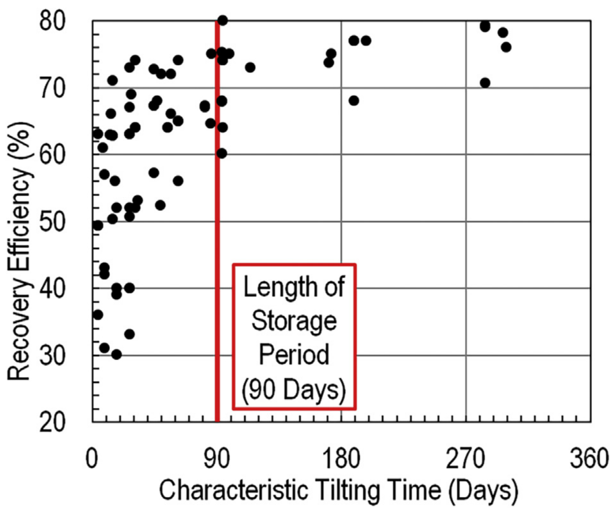

Fig. 4. Correlation between the characteristic tilting time and the recovery efficiency of 78 numerically simulated HT-ATES scenarios (data from Schout et al.).

the characteristic tilting time are associated with higher permeability values (needed for economically feasible aquifer thermal energy storage projects) and/or high storage temperatures. This means that in practice density driven flow is usually relevant for the recovery efficiency of HT-ATES systems. Hence, we doubt the suggestion by Jeon that the recovery efficiency is only sensitive to the aquifer permeability and the injection volume. According to our findings, the injection temperature is also an important parameter for the recovery efficiency of HT-ATES systems. This finding was acknowledged in the modelling study by van Lopik et al. (2016) [4], who investigated the potential for compensating the density difference by increasing the salinity of the injected water. In a variation on their base case scenario, they obtained a 13% increase in the recovery efficiency of their modelled system when decreasing the injection temperature from 80 to 60 °C.

It has to be noted that Fig. 4 also shows that a small value for the characteristic tilting time does not always result in a low recovery efficiency. This can be explained by the fact that other aspects, like the storage volume and the aquifer thickness are also relevant for the recovery efficiency, but have no influence on the characteristic tilting time. For instance: the impact of some tilting of the thermal front is much smaller when a large volume is stored in a thin aquifer (Drijver et al., 2012) [8].

4. Conclusions

In 2014 an article from Schout et al. [2] conclude that the injection temperature is one of the key parameters for the recovery efficiency of HT-ATES systems. In the October 2015 issue of this journal Jeon et al. conclude that, for the same base case and for similar parameter variations (case 1 in their article), the recovery efficiency of HT-ATES systems is not sensitive to the injection temperature. Here we argue that it is unlikely the recovery efficiency is insensitive to the injection temperature.

A higher injection temperature causes differences in density and viscosity between the injected and ambient water. As a result the injected hot water is forced upward in the storage aquifer. In the upper part of the aquifer the hot water flows away from the well and in the lower part of the aquifer, relatively cool water is much closer to the well. When the well switches to production and the amount that is produced is equal to the amount that was injected, relatively cold water will be produced from the bottom part of the aquifer and part of the hot water in the upper part of the aquifer (that has flown away from the well) will not be recovered. Since the degree of buoyancy flow depends on the temperature difference between the injected and ambient groundwater, these heat losses will increase with increasing injection temperature.

By using a numerically obtained dataset from a previous study (Schout et al., 2014), data from field experiments (Buscheck et al., 1983) and an analytical solution proposed by Hellstrom et al. (1988) we showed that the injection temperature has a significant and negative effect on the recovery efficiency.

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