Influence of heterogeneity on heat transport simulations in shallow geothermal systems

Javier Rodrigo-Ilarri1, Max Reisinger2 & J. Jaime Gómez-Hernández1

1 *Grupo de Hidrogeología, Instituto de Ingeniería del Agua y Medio Ambiente (IIAMA), Universitat Politècnica de València (UPV), Camino de Vera s/n 46022, Valencia (Spain), jrodrigo@upv.es*

2 *REVITAL Integrative Naturraumplanung.* *A-9990 Nußdorf-Debant, Nußdorf* *71 (Austria)*

**Abstract.** The influence of parameter heterogeneity, such as permeability, porosity and thermal conductivity, on heat transport simulation is analyzed. A set of synthetic aquifer simulations considering different degrees of heterogeneity in the hydraulic conductivity, porosity and thermal conductivity fields were created by sequential Gaussian simulation techniques. Heterogeneity of the hydraulic conductivity showed to have a significant influence on the evaluation of a cold plume in a porous media. Higher variances in the hydraulic conductivity distributions cause an important rise in the variability of the simulated temperature fields and a considerable increasing of uncertainty in the simulated heat distribution in the aquifer system. Results show that model results are more sensitive to heterogeneity on permeability than on porosity or thermal conductivity.

**Keywords.** Stochastic simulation, heat transport, heterogeneity, permeability, porosity, thermal conductivity

**1 Introduction**

Shallow geothermal system use the energy stored in the first approximately 400 m under the earth surface (Llopis Trillo & López Jimeno, 2009). From about 10-20 m in depth, temperature is considered to be constant during the year. Deeper below the surface, temperatures increase according to the geothermal gradient (3°C for each 100 m of depth on average) (Sanner, 2001).

Due to low temperatures (10 °C to max. 30 °C) in the shallow zone the so called low enthalpy energy is obtained. Low enthalpy energy cannot be used directly and geothermal systems have to be applied to make use of it.

The most common system to extract heat from the underground is the Ground Source Heat Pump system (GSHP). A GSHP system extracts thermal energy from a cold zone to transport it to a warmer zone. The natural form of heat transport would be in the opposite direction (from warm to cold) according to the second law of thermodynamics. To invert the natural heat flow, it is necessary to supply the system with energy, normally with a compressor. In these systems for each kWh of electric energy used for the compressor, up to 4.5 kWh of thermal energy can be provided (Conde Lázaro & Ramos Millán, 2009). Another advantage of GSHP´s is the reversibility which allows to obtain heating and cooling with the same system.

Natural groundwater or collectors installed in the underground in which a fluid circulates are used as heat sources. In the first case the natural groundwater is used directly, it is pumped up with a well and transported to the heat exchanger. After extracting energy it is re-injected to the ground. These systems are called Open Loop Systems.

In the second case a fluid circulates through the collectors which are installed in the underground. The fluid is heated up on his way in the collectors and transports the energy to the GSHP system. This type of systems are called Closed Loop Systems (Llopis Trillo & López Jimeno, 2009).

**2 Scope and objectives**

Different investigations on heat transport in the subsurface have been made so far, most of them assuming homogenous aquifer conditions. Kupfersberger (2009) developed a 2D numerical groundwater model to simulate the impact of groundwater heat pumps on groundwater temperature in the Leibnitzer Feld aquifer, Austria. He validated the simulated results comparing them to field site measurements. A 3D density-dependent groundwater flow and thermal transport model was developed and validated using the results of the thermal injection experiment by Molson (1992).

The effect of heterogeneity on heat transport simulation was the object of several investigations over the last few years. Ferguson (2007) presented a study on the topic, using stochastic modeling on two aquifers with low and high degrees of heterogeneity. He concluded that there is considerable uncertainty in the distribution of heat associated with injection of warm water into an aquifer. Bridger and Allen (2010) developed a model to evaluate the influence of aquifer heterogeneity as result of geologic layering on heat transport and storage in an aquifer used for thermal energy storage. Bridger and Allen (2010) used FEFLOW to create a three-dimensional groundwater flow and heat transport model. All these investigations considered only the heterogeneity of the permeability, porosity and thermal conductivities were assumed to be constant.

The present work has been made in order to get more information about heat transport modeling in aquifer systems. Based on the results obtained by Shuang (2009), further investigation on how heterogeneity affects heat transport simulation has been made. Synthetic aquifers with different grades of heterogeneity were created using SGeMS (Remy, 2009).

A set of heat transport simulations were performed using MT3DMS (Zheng & Wang, 1999) as heat transport code.

To evaluate the importance of heterogeneity in permeability as well as heterogeneity in porosity and thermal conductivity, different simulations with homogeneous and heterogeneous parameters were made and compared to each other.

Therefore, the main objectives of this work are:

* To analyse the influence of heterogeneous distributions of permeability on heat transport simulations in shallow geothermal systems.
* To analyse the influence of heterogeneous distributions of porosity, bulk density and thermal conductivity on heat transport simulations in shallow geothermal systems.

Mean values of permeability and porosity, injection rates, initial temperature distributions as well as the model dimensions and well layout were taken from Shuang (2009).

**3 Heat transport modeling using MT3DMS**

MT3DMS code (Zheng and Wang, 1999) was originally written to simulate solute transport. The comparison of the solute transport equation (Eq. 1) and the heat transport equation (Eq. 2) shows the similarities of these two processes. Table 1 shows the nomenclature used hereafter.

|  |  |
| --- | --- |
|  | (Eq. 1) |

|  |  |
| --- | --- |
|  | (Eq. 2) |

*Table 1: Nomenclature*

|  |  |  |
| --- | --- | --- |
| Parameter | Unit | Description |
| *C* | [kg m-3] | Dissolved mass concentration |
| *cs* | [J kg-1 K-1] | Specific heat capacity solid |
| *Cs* | [kg m-3] | Concentration sources and sinks |
| *Dm* | [m2 s-1] | Coefficient of molecular diffusion |
| *F* | [m] | Depth of the water table |
| *H* | [m] | Thickness of the aquifer |
| *k* | [m s-1] | Hydraulic conductivity |
| *Kd* | m3 kg-1 | Distribution coefficient |
| *n* | [-] | Effective porosity |
| *Q* | [m3 s-1] | Water injection rate |
| *qh* | [W m-3] | Heat injection or extraction |
| *qs* | [m3 s-1 m-3] | Flow rate of sources and sinks solute transport |
| *R* | [-] | Retardation factor |
| *t* | [s] | Simulated time periode |
| *T0* | [K] | Initial temperature |
| *Tf* | [K] | Temperature of the water |
| *Tin* | [K] | Temperature of the injected water |
| *Ts* | [K] | Temperature of the solid |
| *va* | [m s-1] | Seepage velocity |
| *αh* | [m] | Horizontal transverse dispersivity coefficient |
| *αv* | [m] | Vertical transverse dispersivity coefficient |
| *αL* | [m] | Longitudinal dispersivity coefficient |
| *αs* | [m] | Dispersivity coefficient |
| *γ* | [-] | Unit weight of the fluid |
| *λ* | [W m-1 K-1] | Thermal conductivity |
| *λe* | [W m-1 K-1] | Overall thermal conductivity of the saturated aquifer |
| *λf* | [W m-1 K-1] | Thermal conductivity of the fluid |
| *λs* | [W m-1 K-1] | Thermal conductivity of the solid |
| *λu* | [W m-1 K-1] | Thermal conductivity of the unsaturated soil |
| *μ* | [kg s-1 m-1] | Viscosity of the fluid |
| *νs* | [m s-1] | Velocity |
| *ρb* | [kg m-3] | Bulk density |
| *ρece* | [Jm-3K-1] | Volumetric heat capacity of the saturated aquifer |
| *ρf* | [kg m-3] | Density of water |
| *ρfcf* | [Jm-3K-1] | Volumetric heat capacity of the fluid |
| *ρs* | [kg m-3] | Density of the solid |
| *ρscs* | [Jm-3K-1] | Volumetric heat capacity of the solid |
| *σ2* | [-] | Variance |

MT3DMS was verified for heat transport by Mendez Hecht (2008) and Molina Giraldo (2008). Therefore, MT3DMS can be used for the simulation of heat transport with some adaptations on the equation coefficients. Further information about heat transport modeling with MT3DMS can be found in other studies such as Molina (2009). In order to perform heat transport modeling, the following adaptations of the original mass transport parameters were performed:

Heat exchange between solid and liquid phase:

|  |  |
| --- | --- |
|  | (Eq. 3) |

Heat exchange between solid and liquid phase is implemented in MT3DMS in the chemical reactions package. The type of sorption has to be set to linear isotherm sorption. The input parameters required by MT3DMS to calculate the retardation factor are the bulk density *ρb* and the distribution coefficient *Kd*.

Conductive heat transport:

|  |  |
| --- | --- |
|  | (Eq. 4) |

The conductive heat transport is implemented in MT3DMS in the dispersion package. The dispersivity coefficient *αh* can be introduced without adaptations. However, the molecular diffusion coefficient *Dm* for heat conduction has to be calculated. Previous computations of bulk density (*ρb*) and thermal conductivity for the saturated aquifer (λ*e*) are also required.

|  |  |
| --- | --- |
|  | (Eq. 5) |
|  | (Eq. 6) |

Convective heat transport:

To simulate convective heat transport the advection package of MT3DMS has to be activated. MT3DMS provides different solution schemes for the advection term. In this study, simulations using different solution schemes were made. The results and the simulation time were compared to evaluate the most efficient solution method. The most satisfying results were made with the Hybrid MOC/MMOC (HMOC) solution scheme.

Sources and sinks

*The sources and sinks term is introduced in the well package of MODFLOW and MT3DMS.* Temperature [°K] is treated like a concentration [kg/m3] the recharge rate is constant [kg/m3]

|  |  |
| --- | --- |
|  | (Eq. 7) |

**4 Model setup and input parameters**

The model layout and dimensions were assumed considering the field site data of the Esseling site (Shuang, 2009). It consists of a grid with 100x100 cells (1m x 1m x 1m) and 40 layers. The same layout as Shuang (2009) was chosen to compare results. Following Rasouli (2008), the aquifer is assumed to be confined. The left and the right boundary of the model are considered as constant head boundaries. The upper and lower boundary and the bottom of the model are no-flow boundaries. All other cells are assigned as active flow cells.

Flow simulations were performed assuming a hydraulic gradienti=0.02. Prescribed constant heads are 45 [m] on the left boundary and 43 [m] on the right boundary. Horizontal and the vertical hydraulic conductivities were set equal to make the aquifer isotropic.

The injection well is located in cell (30,50) from layer 10 to layer 15 of the model. The total injection rate was divided and assigned to each layer. The recharge was assumed to be constant over 360 days. The total simulation time was divided into 12 stress periods and a steady state simulation was performed. As the definition of the boundary conditions is required, a constant temperature value was assigned to the left hand boundary of the model. All other cells are active temperature cells. The advection term of the heat transport equation was solved with the Hybrid MOC/MMOC (HMOC) solution scheme as it runs faster than the Ultimate TVD scheme and it is free of numerical dispersion (Zheng & Wang, 1999). The type of sorption in the chemical reaction package was set to linear isotherm sorption. No first order reaction was simulated.

Table 2 summarizes the flow and heat transport model input parameters that were considered to be known throughout the simulation process.

*Table 2: Fixed flow and heat transport model input parameters*

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Symbol | Value | Unit |
| Total recharge rate | *Q* | 1.84E-4 | [m3s-1] |
| Pumping rate |  | 3.05E-5 | [m3s-1] |
| Initial temperature | *To* | 283.15 | [K] |
| Longitudinal dispersivity | *αL* | 0.5 | [m] |
| Horizontal transverse dispersivity | *αh* | 0.05 | [m] |
| Vertical transverse dispersivity | *αv* | 0.05 | [m] |
| Effective molecular diffusion coefficient | *Dm* | 1.838E-6 | [m2s-1] |
| Bulk density | *ρb* | 1961 | [kgm-3] |
| Distribution coefficient | *Kd* | 1.983E-4 | [m3kg-1] |
| Temperature injected water | *Tin* | 278.15 | [K] |
| Retardation factor | *R* | 2.5 |  |
| Density of the solid | *ρs* | 2.65 | [kgm-3] |
| Solid specific heat capacity | *cs* | 830 | [Jkg-1K-1] |
| Solid volumetric heat capacity | *ρscs* | 2200000 | [Jm-3K-1] |
| Water volumetric heat capacity | *ρfcf* | 4185000 | [Jm-3K-1] |
| Saturated aquifer volumetric heat capacity | *ρece* | 2716000 | [Jm-3K-1] |
| Solid thermal conductivity | *λs* | 3 | [Wm-1K-1] |
| Water thermal conductivity | *λf* | 0.6 | [Wm-1K-1] |
| Saturated aquifer thermal conductivity | *λe* | 2 | [Wm-1K-1] |

**5 Results and discussion**

The stochastic simulation of the hydraulic conductivity fields was realized with the Stanford Geostatistical Modeling Software (SGeMS). The sequential Gaussian simulation algorithm was used. Based on the set of hard data and a target histogram, 10 synthetic conductivity fields were created for the scenarios shown in Table 3. Scenarios 1 to 3 correspond to heterogeneous permeability distributions and constant n and λ values and Scenarios 4 to 6 correspond to heterogeneous permeability distributions and heterogeneous n and λ values.

Table 3: Overview of the simulated scenarios

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Scenario | σ2logK | Mean logK | Nr. simulations | Description |
| 0 | 0 | -3.86 | 1 | K homogeneous |
| 1 | 0.1 | -3.86 | 10 | k heterogeneous / n, λ constant |
| 2 | 0.5 | -3.86 | 10 | k heterogeneous / n, λ constant |
| 3 | 1 | -3.86 | 10 | k heterogeneous / n, λ constant |
| 4 | 0.1 | -3.86 | 10 | k, n, ρb, λ heterogeneous |
| 5 | 0.5 | -3.86 | 10 | k, n, ρb, λ heterogeneous |
| 6 | 1 | -3.86 | 10 | k, n, ρb, λ heterogeneous |

Figure 1 shows the logk histogram and the conductivity field view of the first simulated field (Simulation #0) for Scenario 3 (σ2logk =1).

Figure 2 shows the heat transport model results and the position of the heat plume after 360 days of injection for realizations #0 of Scenarios 0, 1, 2, and 3.

Results show heterogeneity has an important effect on the shape of the temperature plume, which decrease both in length and width when heterogeneity increases.

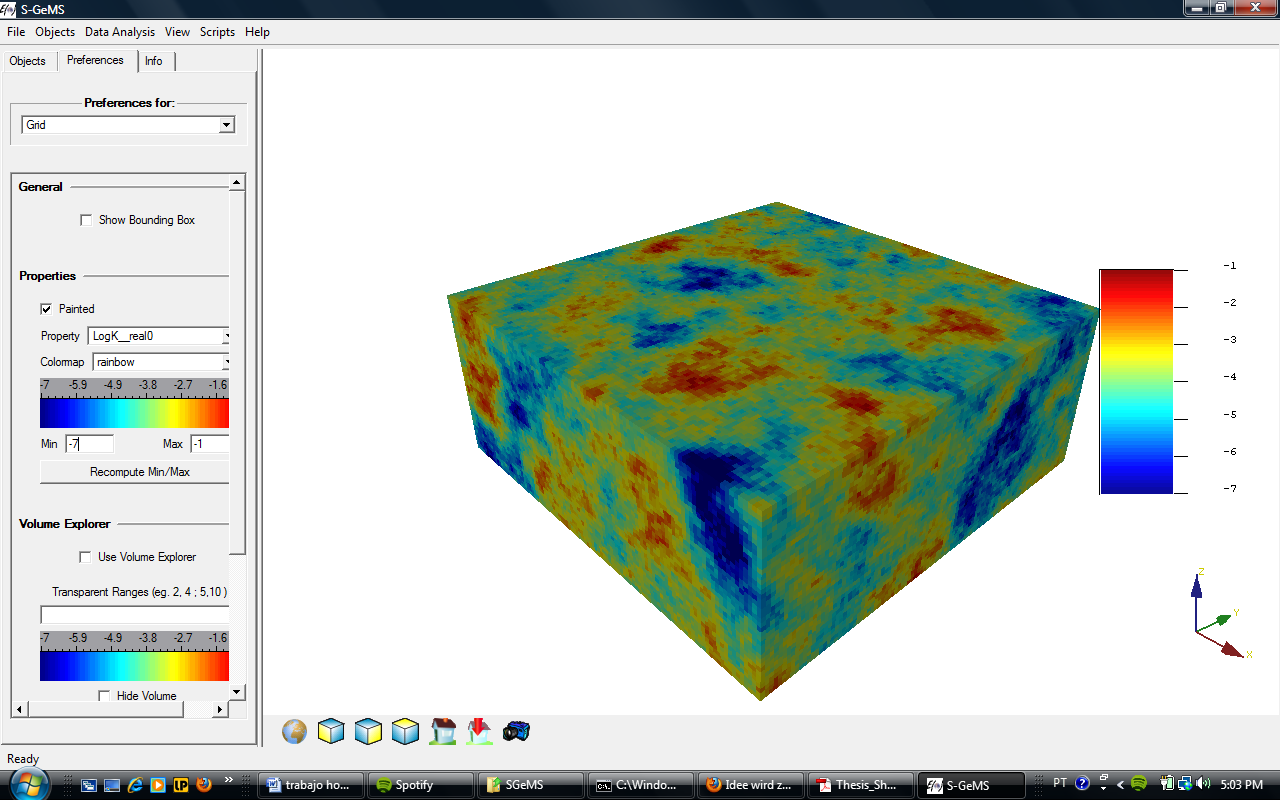
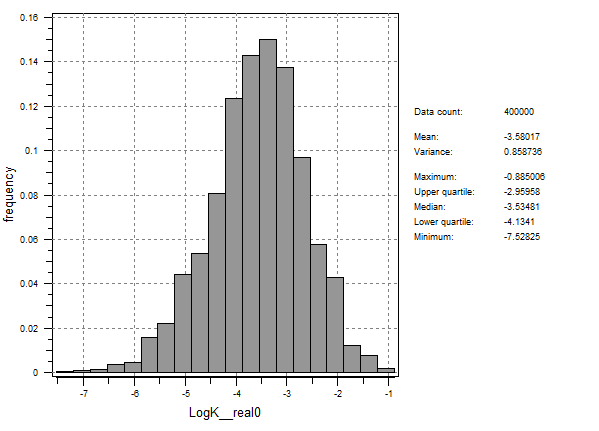
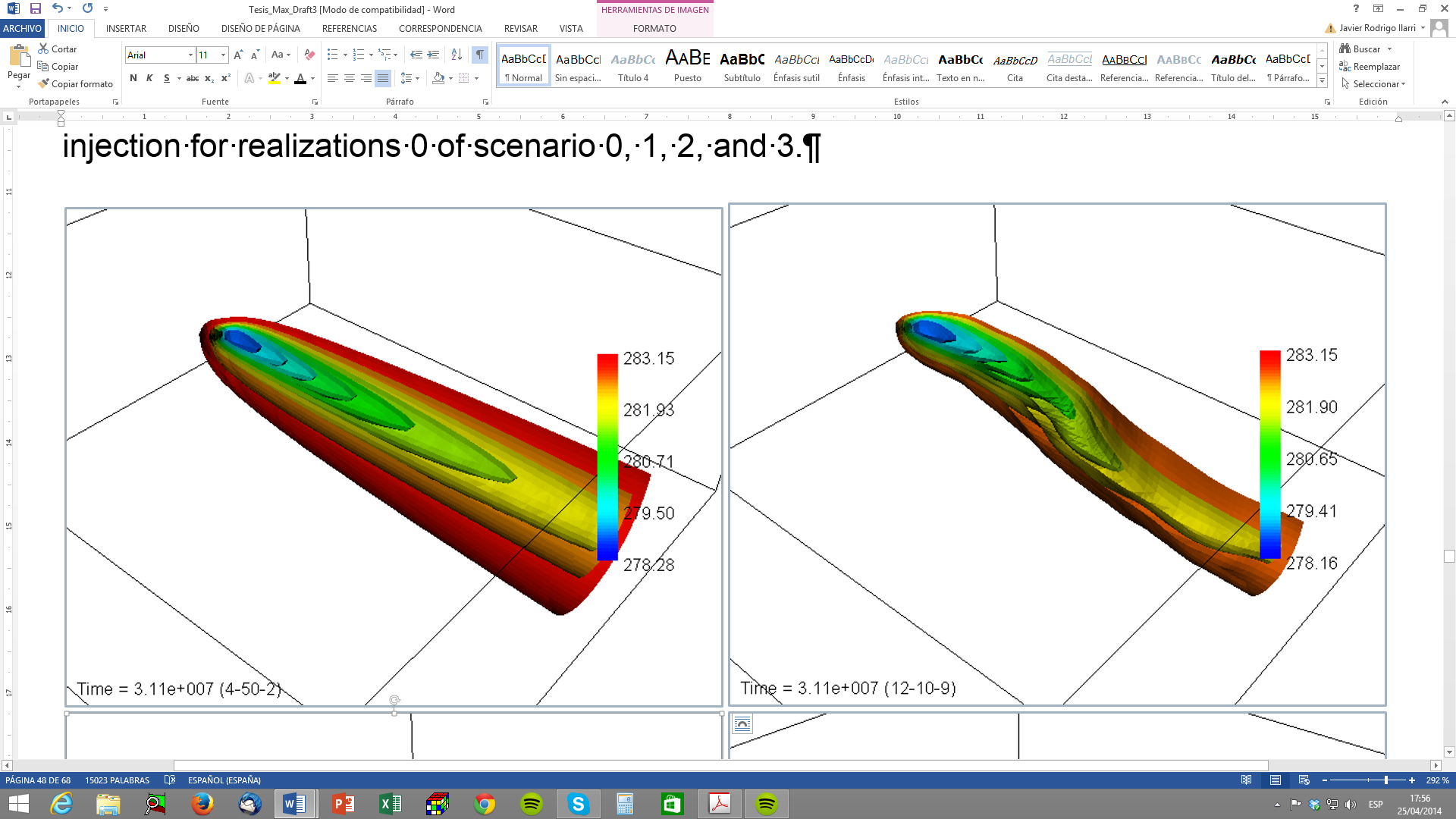
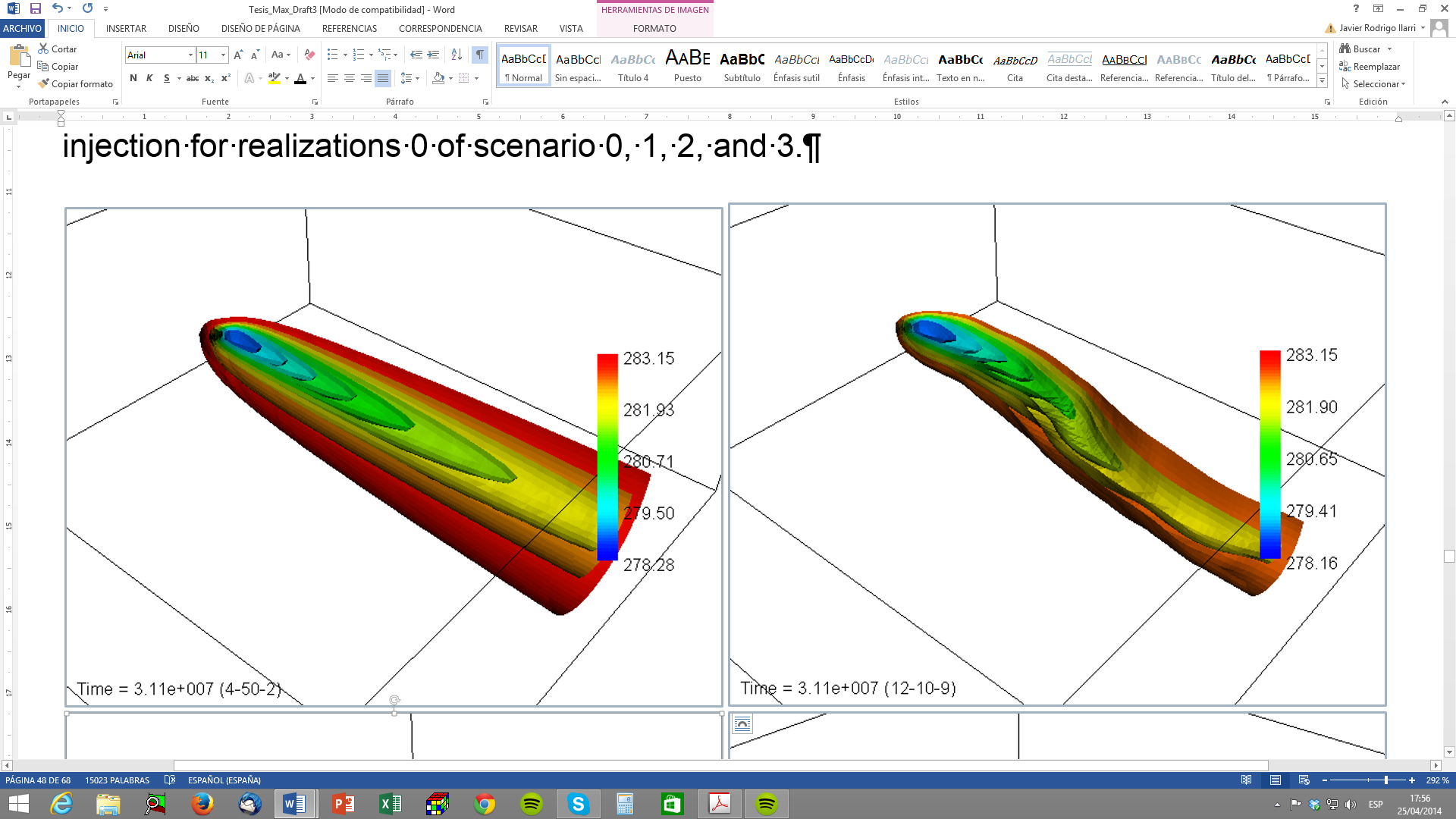


Figure 1: Histogram and logk field – Simulation #0 Scenario 3 (σ2logk =1)

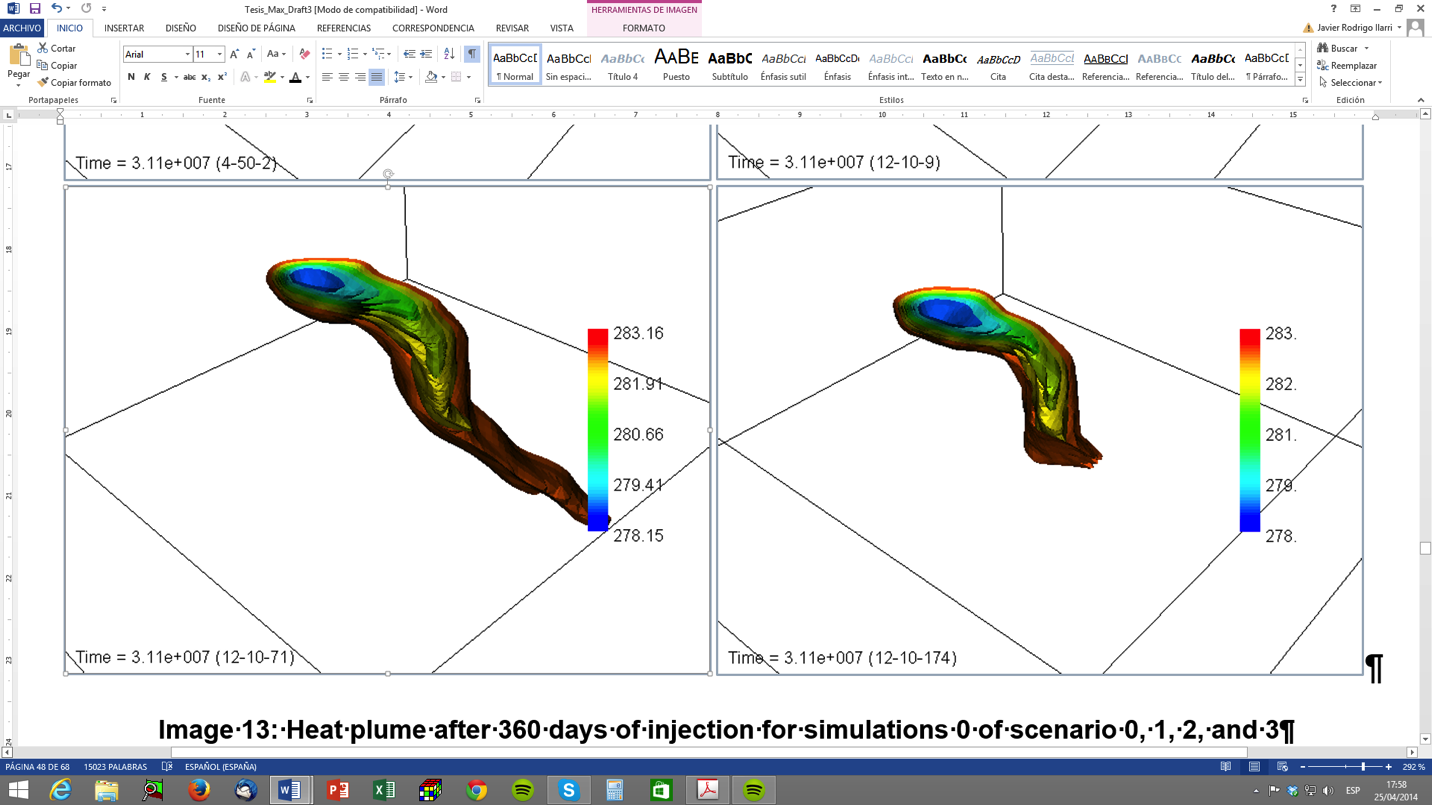
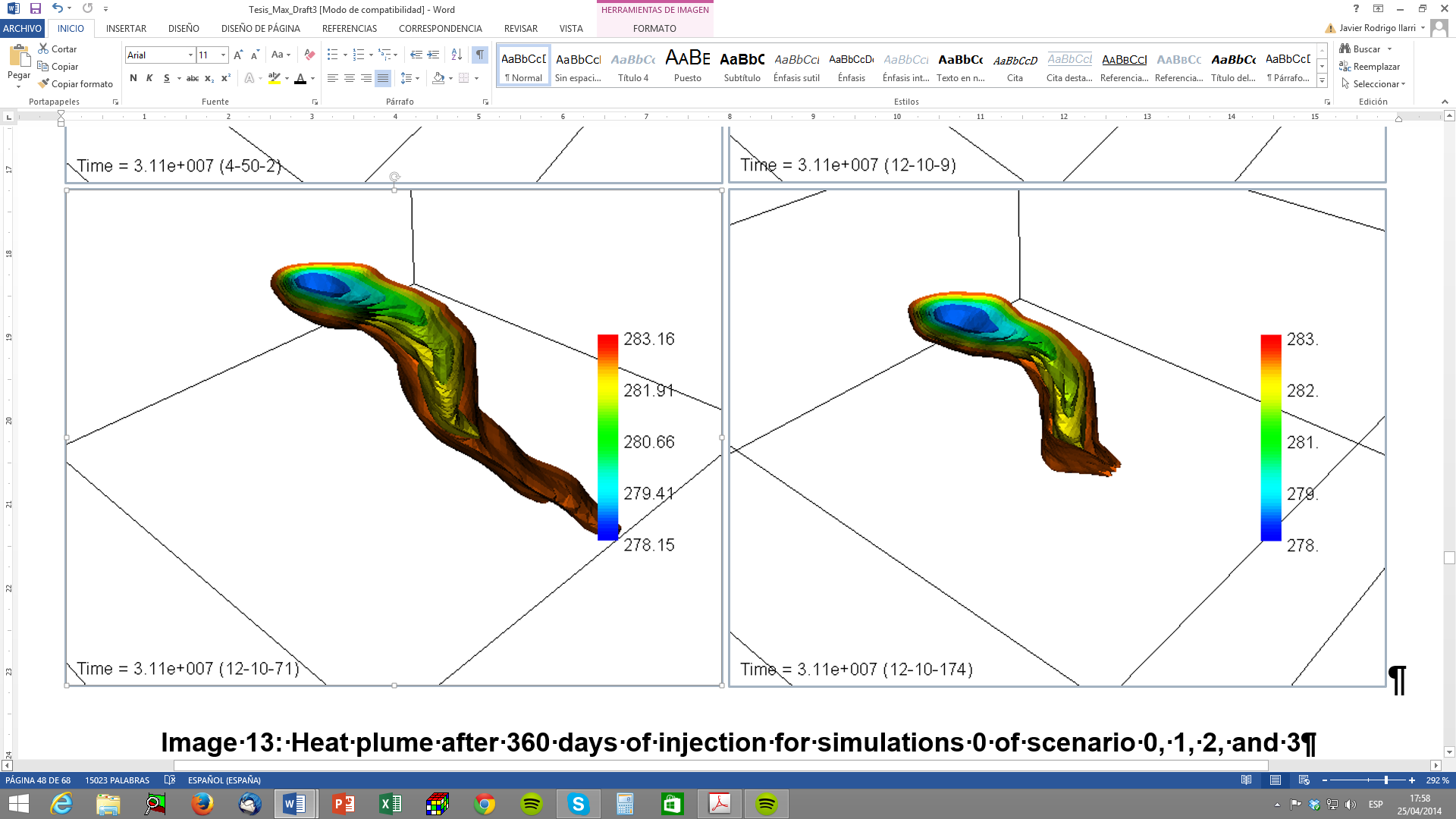
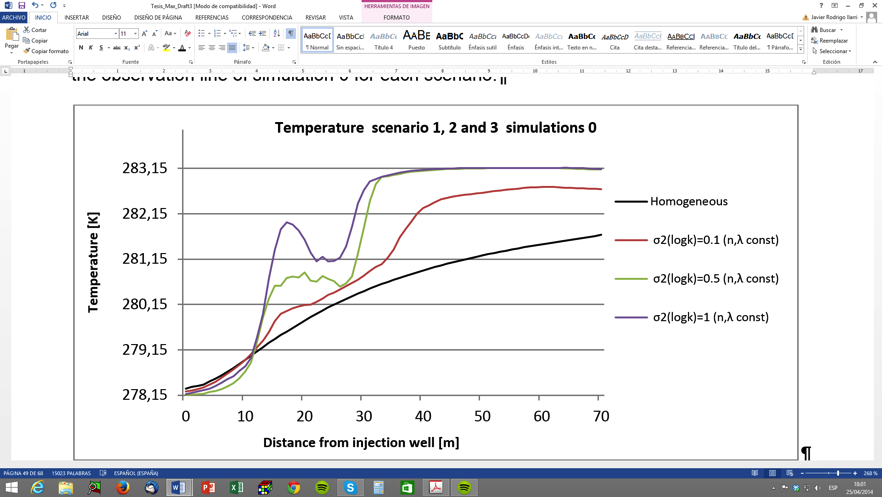
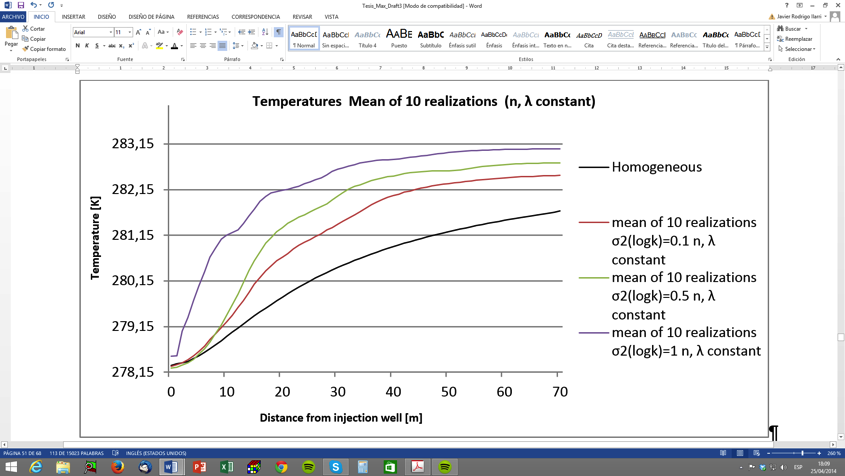
 

Figure 2: Heat plume after 360 days of injection for Simulations #0 of Scenarios 0, 1, 2, and 3

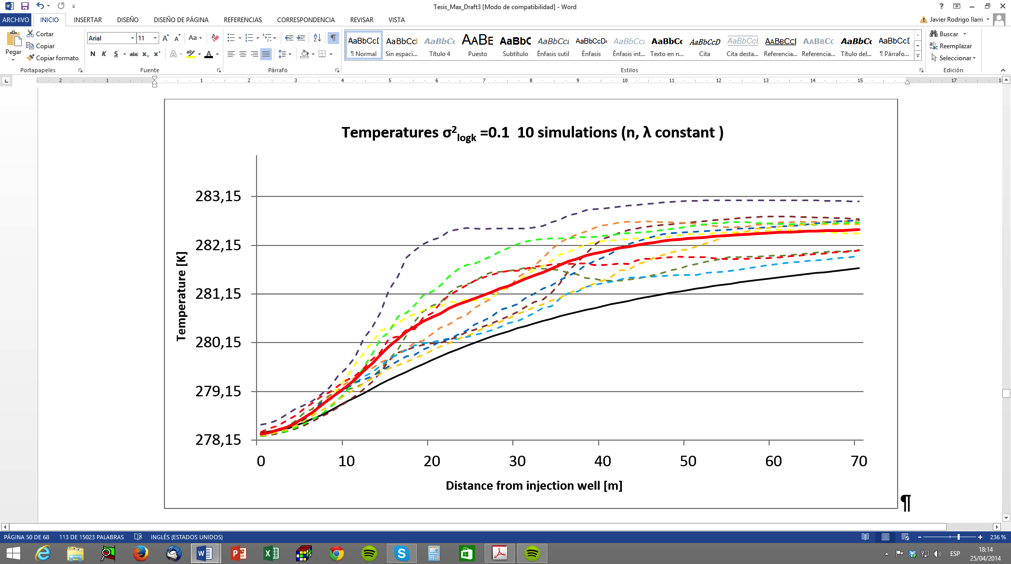
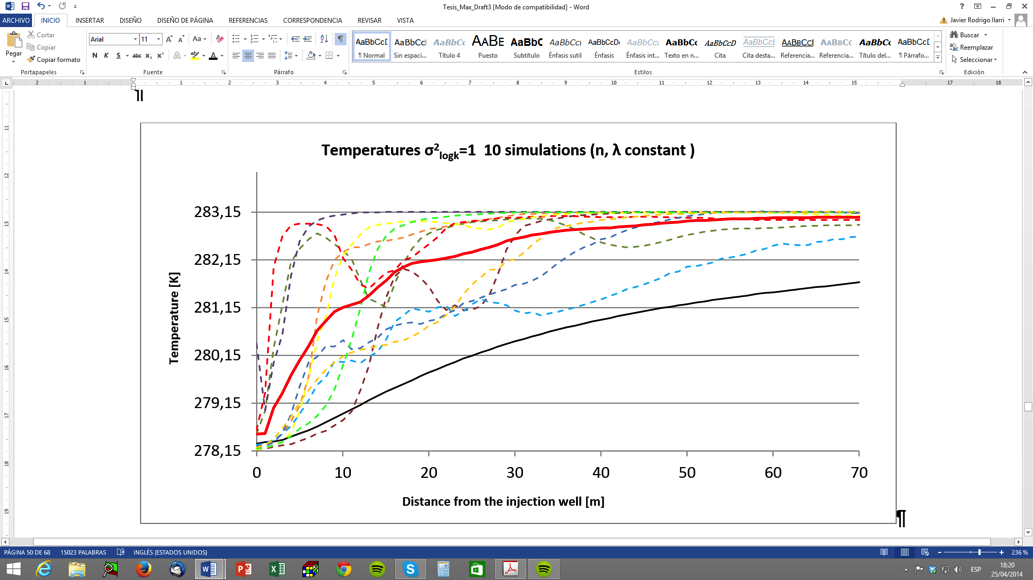
To demonstrate the influence of heterogenic hydraulic conductivity on the cold plume development, simulated temperatures along the observation line (from the injection well downstream, 12m depth) were plotted.

Figure 3 shows the temperatures along the observation line of simulation #0 for each scenario. The deviation of the cold plume in this model is mainly caused by predominating advective transport.

To visualize the differences between each of the simulations for a specific scenario Figure 4 show the results obtained for the 10 simulations of Scenario 1 (σ2logk =0.1) and Scenario 3 (σ2logk =1) (n, λ constant) together with their correspondant mean values.

*Figure 3:* Simulated temperatures along the observation line for simulation #0 of Scenarios 0, 1, 2 and 3 (n, λ constant) (left) and mean value of 10 realizations for each scenario (right)

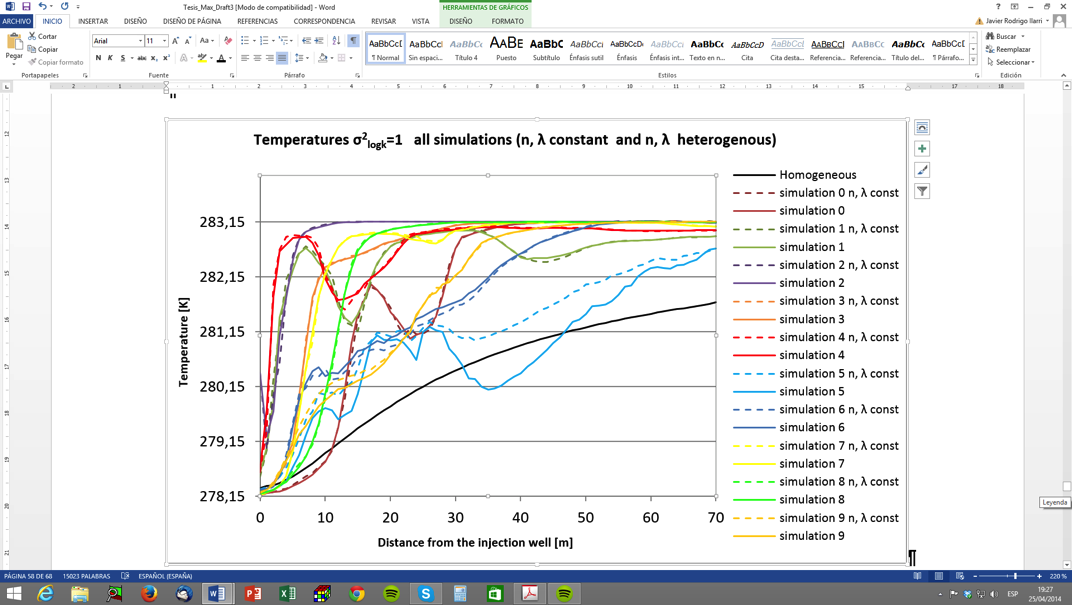
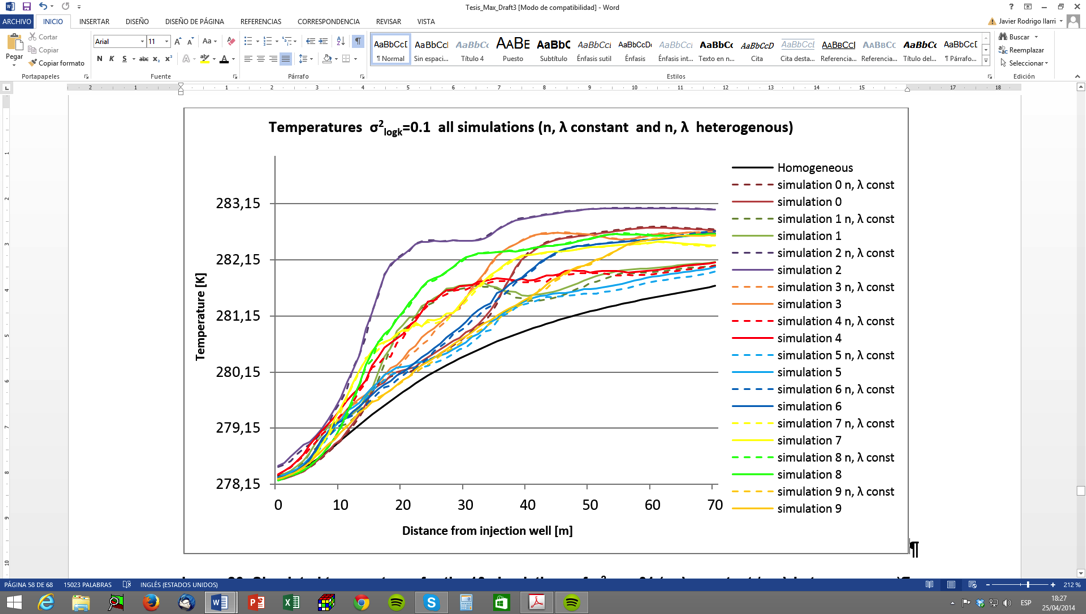
*Figure 4:* Temperatures on observation line for 10 realizations of scenarios 1 (left) and 3 (right)

In order to estimate the influence of heterogeneity of all parameters over the heat transport simulation results, a set of 10 new realizations for each one of the scenarios 4 to 6 were obtained. These scenarios consider heterogeneous distributions of permeability, porosity and thermal conductivity. There are some known empirical relationships between hydraulic conductivity and porosity such as those proposed by Kozeny (1927), Carman (1937), Carrier (2003), Schneider (2003), Regalado & Carpena (2004) and Mohnke (2008). In this work, the relation of Busch and Luckner (1993) was used, as it provides a simple linear relationship between hydraulic conductivity and porosity.

|  |  |
| --- | --- |
|  | (Eq. 8) |

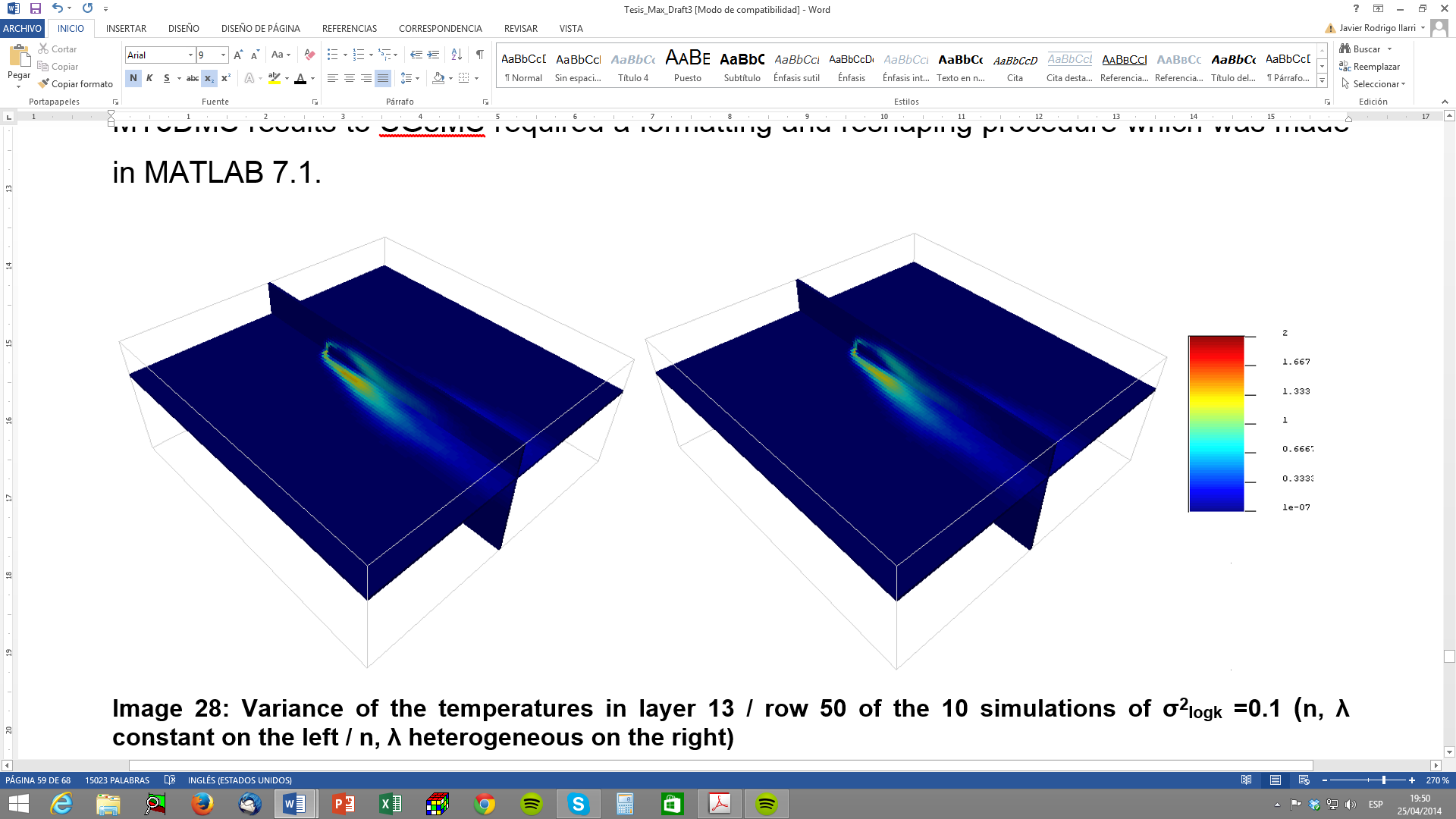
Following equations 5 and 6 these new porosity fields were afterwards used to compute every other needed parameter, like bulk density (*ρb*) and thermal conductivity (λ), and in a further step the effective molecular diffusion coefficient (*Dm*).

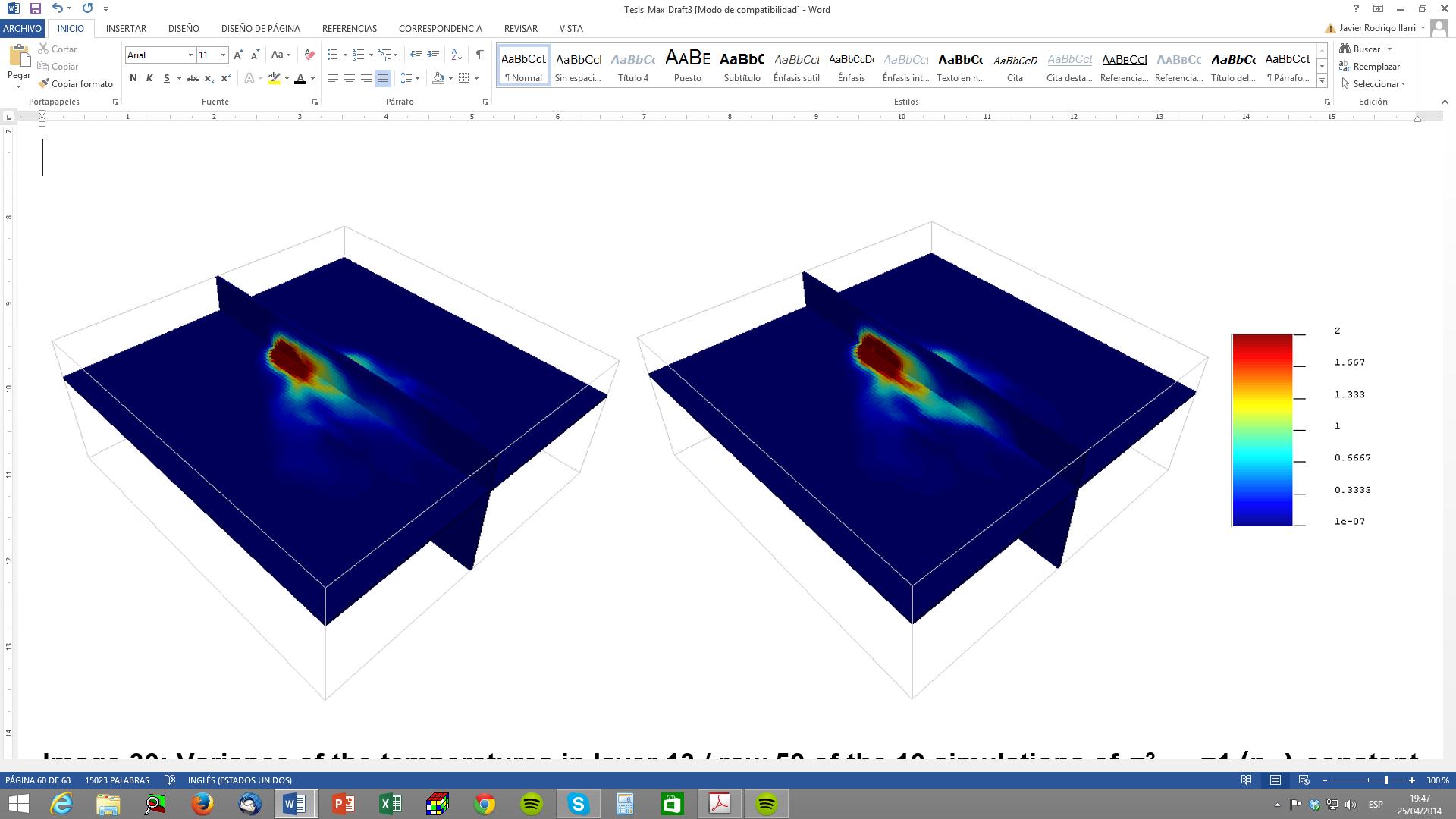
In order to summarize the results, figure 5 shows thesimulated temperatures along the observation line for 10 realizations of scenarios 1, 3, 4 and 6.



*Figure 5:* Temperatures on observation line for 10 realizations of scenarios 1-4 (left) and 3-6 (right)

To quantify the uncertainty in the prediction of temperature distribution caused by heterogeneity of the parameters, the variance of the simulated temperature plumes for the 10 simulations was computed for all the scenarios. Figure 6 shows the temperature variances of the 10 simulations of scenarios 3 and 6.





*Figure 6:* Temperature variances (layer 13/ row 50) of scenarios 1-3 (left) and 4-6 (right)

When comparing results obtained between simulations of corresponding scenarios (scenarios 1 and 4 or scenarios 3 and 6) it has been found that the temperature differences are higher as heterogeneity increases. Some simulations made for scenario 3 (σ2logk=1) show temperature differences up to 1 °K.

Results show that an increasing variance of permeability causes increasing variance in the expected temperature distribution. Scenario 3 (σ2logk =1) shows considerably higher variances than scenario 1 (σ2logk =0.1). The highest variances have been found in the first 20 meters from the injection well. The changes in flow direction generate an uncertainty in the prediction of the temperature plume.

If hydraulic gradients were lower and consequently flow velocities decrease, the influence of dispersion would be higher and changes in thermal conductivity and porosity could have a major effect on the temperature distribution. Further simulations should be made using different hydraulic gradients to investigate the influence of heterogeneity in combination with the hydraulic gradient.

This shows that the effect of the heterogeneity of the porosity n and thermal conductivity λ can be important for heat transport simulation in highly heterogeneous systems. It is possible that, in combination with a low hydraulic gradient, high heterogeneity of the porosity n and thermal conductivity λ could cause a considerable increase in the uncertainty of the predictions of the temperature plume.

**6 Conclusions**

This work has been performed in order to analyse of the influence of parameter heterogeneity distributions on heat transport in shallow geothermal systems. Heterogeneous distributions of permeability, porosity, bulk density and thermal conductivity were considered on a set of simulations obtained by sequential Gaussian simulation techniques. Following conclusions can be taken:

* Heterogeneity in the hydraulic conductivity field causes significant changes in the hydraulic head distribution. This affects the flow velocity field which is used for heat transport simulation.
* Heterogeneity of hydraulic conductivity has a major influence on the shape and development of a temperature plume in a porous media. A high degree of variance in the logarithmic hydraulic conductivity distribution results in a rising variability of the simulated temperature fields and a considerable uncertainty in the prediction of the temperature distribution in an aquifer system. The calculated variances of the simulated temperature fields between are rising significantly with increasing degree of variance in the permeability field.
* Heterogeneity in permeability distribution causes changes in the shape and configuration of the temperature plume. The length and width of the plume decreased as the variance of the permeability increases.
* The zones of cold water seem to be more concentrated when the dispersion effect gets less important due to the higher flow velocities in the pore channels. This phenomenon is widely known as “channeling effect”.
* The heterogeneity of porosity and thermal conductivity seems to have less impact on modeling results than the heterogeneity of permeability. Low heterogeneity degrees in the porosity and thermal conductivity distribution do not cause important changes in shape and development of the simulated temperature plume. The calculated temperature variances in these scenarios are very small.
* However, in the most heterogeneous case (σ2logk=1) the calculated variance of the simulated temperatures increases significantly. This effect can be even more significant when the hydraulic gradient gets lower and consequently the flow velocities are lower too. In these cases, highly heterogeneous distributions of the porosity n and thermal conductivity λ could cause a considerable increase in the uncertainty of the predictions of the temperature plume.

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**References**

[1] Bridger, D. and Allen, D. (2010). Heat transport simulations in a heterogeneous aquifer used for aquifer thermal energy storage (ATES). Canadian Geotechnik Jounal , pp. 96-115.

[2] Busch, K.F. and Luckner, L. (1993). Geohydraulik Band 3 von Lehrbuch der Hydrogeologie. Gebr. Borntraeger.

[3] Carman, P. (1937). Fluid flow through a granular bed. Trans. Inst. Chem. Eng. , 150-167.

[4] Carrier, D. W. (2003). Good by Hazen; Hello Kozeny-Carman. Journal of Geotechnical and Geoenvironmental Engineering Vol. 129, 1054-1056.

[5] Conde Lázaro, E., & Ramos Millán, A. (2009). Guía Técnica de Bombas de Calor Geotérmicas. Madrid: Gráficas Arias Montano, S.A.

[6] Ferguson, G. (2007). Heterogeneity and Thermal Modeling of Ground Water. Ground Water , pp. 485-490.

[7] Kozeny, J. (1927). Über kappilare Leitung des Wassers im Boden. Wien: Hölder-Pichler-Tempsky, A.-G. [Abt.:] Akad. d. Wiss.,.

[8] Kupfersberger, H. (2009). Heat transfer modelling of the Leibnitzer Feld aquifer, Austria. Environ Earth Sci , pp. 561-571.

[9] Llopis Trillo, G. and López Gimeno, C. (2009). Guía Técnica de Sondeos Geotérmicos Superficiales. Madrid: Gráficas Arias Montano S.A.

[10] Mendez Hecht, J. (2008). Implementation and verification of the USGS solute transport code MT3DMS for groundwater heat transport modelling. Eberhard Karls Universität Tübingen.

[11] Mohnke, O. (2008). Pore size distributions and conductivities of rocks derived from Magnetic Resonance Sounding relaxation data using multi-exponential delay time inversion. Journal of Applied Geophysics, 66 , 73-81.

[12] Molina Giraldo, N. A. (2008). Verification of MT3DMS as heat transport code using analytical solutions. Eberhard Karls Universität Tübingen.

[13] Molson, J. W. (1992). Thermal energy storage in an unconfined aquifer: 1. Field Injection Experiment. Water Resources Research, Vol. 28-10, 2845-2856.

[14] Rasouli, P. (2008). Numerical Verification of Shallow Geothermal Models using FEFLOW. Eberhard Karls Universität Tübingen.

[15] Regalado, C. and Carpena, R. (2004). Esimating the saturated hydraulic conductivity in a spatially variable soil with different permeameters: a stochastic Kozeny-Carman relation. Soil and Tillage Research, 77, 189-202.

[16] Remy, N, Boucher, A. and Wu, J. (2009) Applied Geostatistics with SGeMS. A user’s guide. Cambridge University Press.

[17] Sanner, B. (2001). Shallow geothermal energy. Giessen, Germany: Justus-Liebig University.

[18] Schneider, J. H. (2003). New Least Squares Model Used For Development of Permeability-Porosity Correlation. Poteet Texas.

[19] Shuang, J. (2009). Geostatistical Modeling of Shallow Open Geothermal Systems. Eberhard Karls Universität Tübingen.

[20] Zheng, C. and Wang, P. P. (1999). MT3DMS Documentation and user guide. Washington: U.S. Army Corps of Engineers.