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Numerical Modelling of Deep Geothermal Exchanger and Its Application for the Litoměřice Site, Czech Republic

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ABSTRACT

The use of geothermal energy in the Czech Republic is still at its very beginning. To accelerate the progress of geothermal energy in the Czech Republic, the RINGEN project has been established. Among seven project partners, our team from the Technical University in Liberec (TUL) provides the software solution for the estimation of the deep geothermal exchanger behavior.

A coupled thermos-hydraulic numerical model has been implemented in software Flow123d (developed in TUL; Březina, 2019), alongside the COMSOL Multiphysics software, serving as a benchmark (Comsol, 2019). The geometry of the fracture network, which constitutes the deep geothermal exchanger, is stochastically generated by our own script in tPython language. The algorithm uses the conventional Poisson process with conditions of 1) a network connectivity and 2) a correction of the defect cases (e.g. small intersections or close parallel fractures).

The contribution shows scenarios of various site geological structure and geothermal exchanger set ups. Using the current knowledge of the (probable) geologic properties at the Litoměřice site, the model results have been used as quantitative estimations of the exchanger output and working life. Both regional and local variants of the model will be considered, first on a coarse scale, including the wide surroundings of the exchanger and second on a more detailed scale of the exchanger, providing the range of results for different stochastically generated fracture networks. The results are interpreted with an aim to determine (predict) a long-term sustainability of the energy mining based on proposed working regime designs.

1. INTRODUCTION

At this moment, there is no geothermal power plant in the Czech Republic, either in operation or under construction. Geological conditions in the Czech Republic are suitable only for HDR systems, which are very demanding both technologically and economically (but with a perspective or returns as the technologies will probably be attainable in the next 10-20 years). This work is a part of the RINGEN project (Research INfrastructure for Geothermal ENergy; www.rin-gen.cz), which is focused on creating professional background for the research into effective utilization of deep geothermal energy. The infrastructure mainly comprises the building of a highly specialized geothermal centre at the Litoměřice site, which will concentrate key equipment, technologies and background for research teams of 7 project partners: 3 universities, 3 institutes of the Czech Academy of Science, and the Czech Geological Survey.

1.1 Numerical Modeling

Among other activities in this project, such as the use of technological and geo-scientific disciplines or monitoring methods, the mathematical (numerical) modeling plays an important role. As all the geological data and information are widely uncertain before the final drilling, results of numerical models can help with making estimations or predictions (for the output of the geothermal heat exchanger, its sustainability etc.). The character of the numerical model can bridge the data uncertainties by computing various scenarios for various (or perturbed) input data.

A numerical model is a complex folder of many particular segments such as all available input data, technical limitations, selected physical processes and their mathematical description, implementation, solving and (last but not least) proper evaluation of the results (Figure 1). Though the numerical modelling is regularly used in the area of HDR systems, it should be adapted to particular in-situ conditions. This contribution summarizes the collection of current modeling/computational resources and computational results for selected tasks related to the proposed testing HDR system at the Litoměřice area. A coupled thermo-hydraulic numerical model is implemented in the groundwater flow simulator software Flow123d (developed in TUL), with a stochastically generated fracture network. The commercial software COMSOL Multiphysics (Comsol, 2019) served as a benchmark. These are the first steps of the process of making more complex computational features for a practical use in the geothermal energy sector in the Czech Republic.

2. LITOMĚŘICE SITE

The Litoměřice area (Figure 2 left) represents one of the best sites for probing geothermal technologies and the only place within the Czech Republic holding permission for an exceptional earth crust examination. These key assumptions enable the drilling of deep geothermal boreholes down to 4 to 5 km and likely create a geothermal heat exchanger to achieve clean energy from the drilled depth. Litoměřice city and its representatives support the sustainable energy strategy. On their path to become a low-emission city, the geothermal project RINGEN stands as one of the most important milestones.

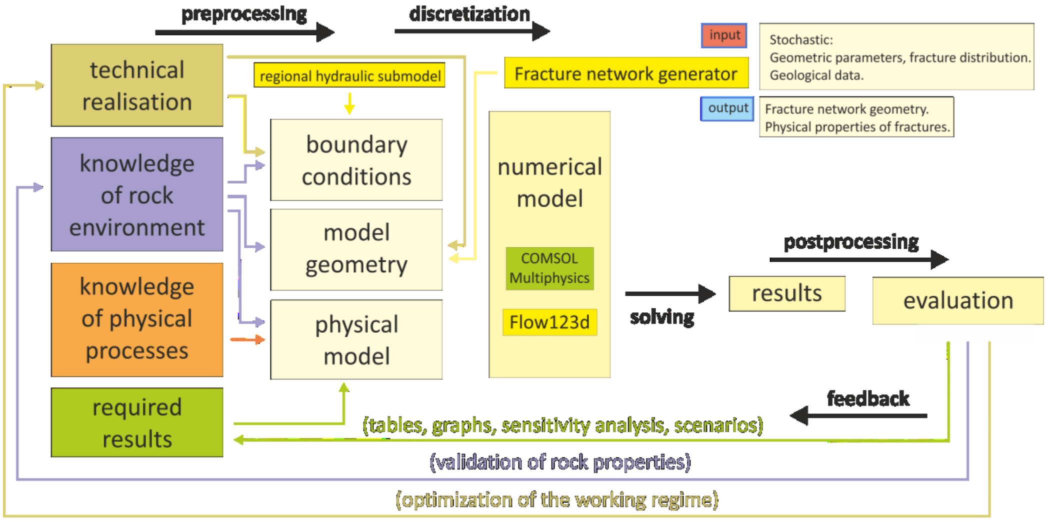

Figure 1: Extensively conceived structure of the numerical model. Dark yellow boxes indicate our implementations.

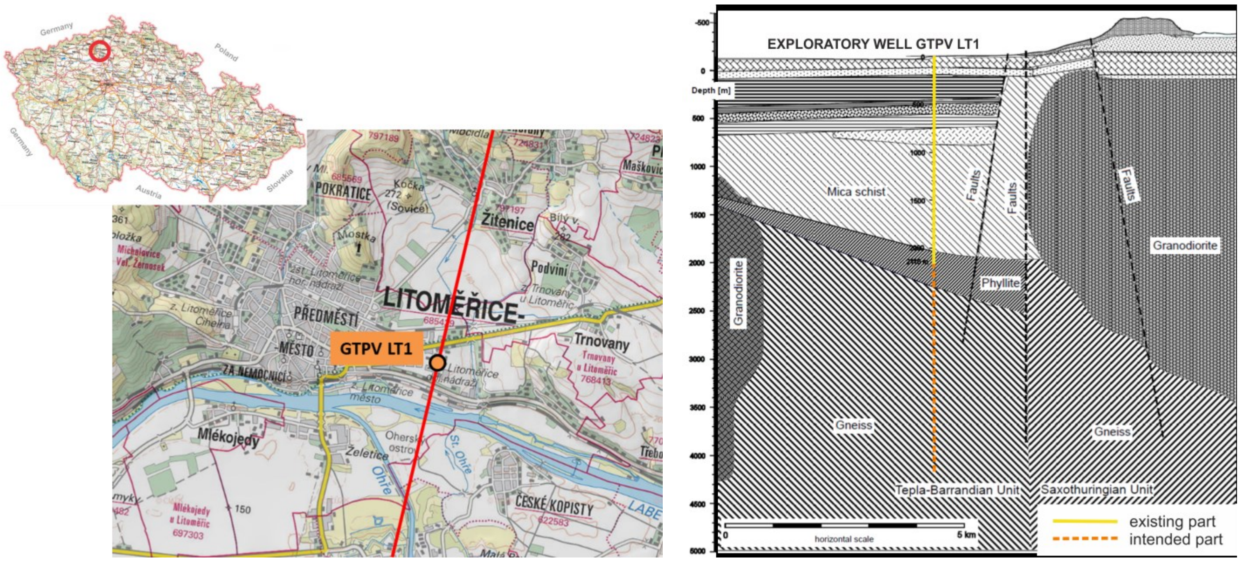

Figure 2: Litoměřice site with the position of the exploratory well PVG LT-1 (on the left; map from Czech National Geoportal, 2019). The red line corresponds to the direction of the likely vertical geological profile (on the right, adapted from Čápová, 2013).

2.1 Geological Situation

Information about the rock massif at the subject area was partly provided by the existing exploratory well PVGT LT-1. Its depth (2100 m) is insufficient for a practical geothermal use, but it (together with low depths analysis) confirmed the deep rock interface in the depth about 2000 m, where mica schist rocks are replaced by phyllite rocks. Adding this information to estimates from large-scale geological models (made by noninvasive methods; Mlčoch and Konopásek, 2010), we can assume a compact massif at the depth of 4-5 km with two possibilities of the rock structure: (1) phyllite rock progresses to subject depths, (2) a gneiss rock (so called Bílina block) pushed from NW below the phyllite layer. The latter is more probable, being indirectly confirmed by the results of a 2D temperature models in Šafanda et al. (2007) or Čápová (2013). The likely geological profile at Litoměřice area is visualized in Figure 2 on the right. The used rock properties are listed in Table 1.

Table 1: Estimated rock properties in Litoměřice area.

	density	porosity	permeability	thermal conductivity	heat capacity
gneiss	2.66 $g.cm^{-3}$	2.6 %	10^{-17} m^2	3.1 $W.m^{-1}.K^{-1}$	900 $J.kg^{-1}.K^{-1}$

2.2 Thermal Conditions

Initial temperature distribution around the proposed geothermal exchanger has been estimated from the values measured in the exploratory well PVG LT-1, in the combination with results of the temperature model, published in Šafanda et al. (2007). The thermal conditions in objective depths are listed in Table 2.

Table 2: Estimated thermal conditions in Litoměřice area.

temperature gradient [$K.m^{-1}$]	0.024		
extrapolated heat flux [$mW.m^{-2}$]	72		
temperature [°C]	depth = 1800 m	depth = 5000 m	
	56.5	phyllite: 140 (± 8)	gneiss: 146 (± 7)

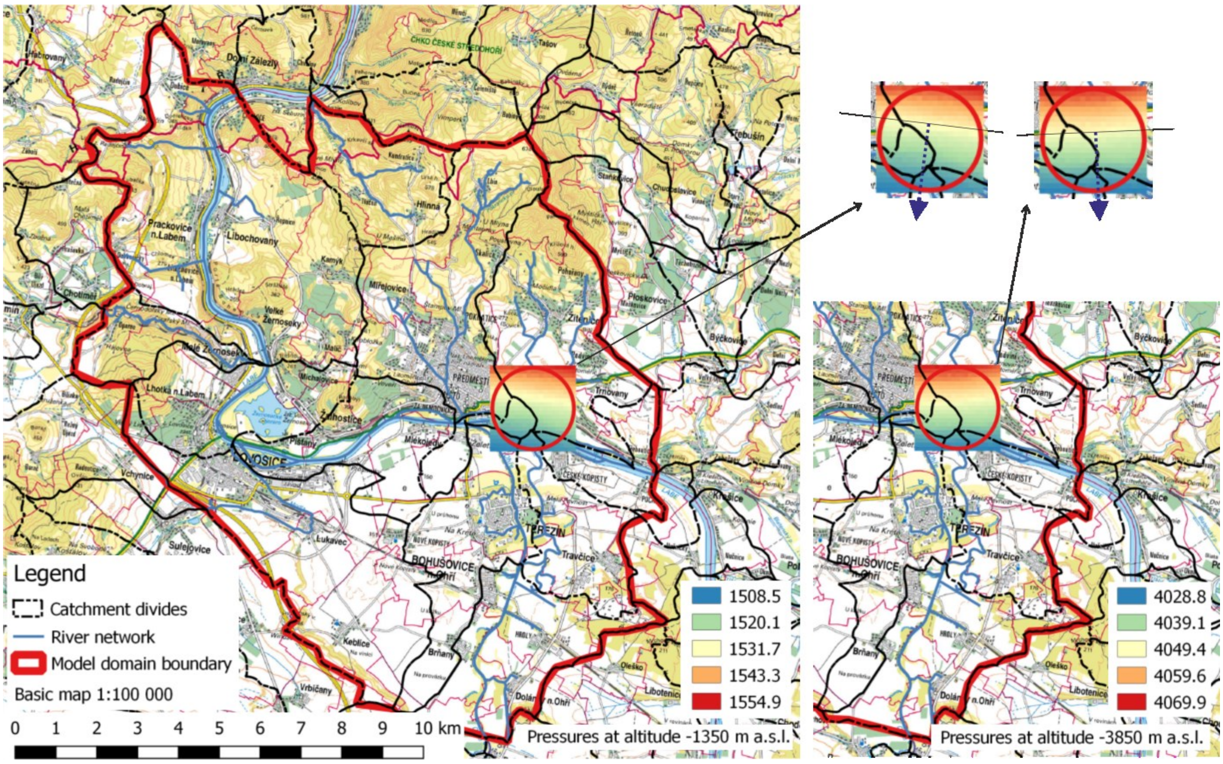

Figure 3: Pressure distribution [mH2O] in the area 2x2 km around the exploratory well PVG LT-1. Left: at the altitude of -1350 m a.s.l. Right: at the altitude of -3850 m a.s.l. Maps adapted from State Administration of Land Surveying and Cadastre (2019).

2.2 Hydraulic Conditions

Pressure distribution at the subject area has been estimated at two altitudes by the additional regional hydraulic model (not described here in detail). Selected altitudes -1350 m a.s.l. and -3850 m a.s.l. correspond roughly to depths 1500 m and 5000 m (with real landscape considered). Following inputs have been used:

- the map of watershed divides of order 4 (from TGM Water Research institute, 2019),
- the map of stream network of the Czech Republic (from TGM Water Research institute, 2019),
- landscape morphology data (from Czech Office for Surveying, Mapping and Cadastre, 2019),
- precipitation distribution (from Krásný et al., 1982).

The area of the modeled domain was 153.4 km^2, with the base at -5000 m a.s.l. Its horizontal shape was determined by 14 watershed divides of order 4, covering the surroundings of the well PVG LT-1 (see Figure 3), with assumed homogeneous Neumann boundary condition on the walls. Remaining inputs determined boundary conditions on the surface, which were of two types: 1) prescribed flux through the infiltration part of the surface, 2) zero pressure head for the drainage part of the surface. The domain was vertically divided into four hydraulically homogeneous layers (0/-100/-1350/-3850/-5000 m a.s.l.).

The hydraulic model was implemented in the software Flow123d, with the hydraulic conductivity values calibrated with the software UCODE (Poeter and Hill, 2019). The results of the hydraulic model are illustrated in Figure 3. The pressure gradient has the S-N direction for both observed altitudes and is approximately equal to 0.02 mH2O.m^{-1}. If we assume the cross section area of the geothermal exchanger equal to 50 m x 250 m and its hydraulic conductivity between 10^{-4} and 10^{-6} m.s^{-1}, this means that flow through the exchanger varies from 0.25 to 25 l.s^{-1}. Assuming an unfaulted rock outside the exchanger, we can predict an insignificant regional water outflow throughout its operation. This can obviously change for the case of the faulted/fractured rock.

3. NUMERICAL MODEL

3.1 Model Processes

The main factors in decision making of building the HDR system are its proposed energy output and sustainability. The reasonable approach to the energy output estimation can be made by the coupled thermo-hydraulic model, which is described by 1) the heat conduction equation and 2) the Darcy flow and continuity equations for both porous media and fractures (if they are included into the model). From the thermal-output-estimation point of view, it appears sufficient to substitute a HDR system by the bounded area made of highly permeable porous media. However, the combined porous media/fracture network model can provide e.g. information about the pressure or water flow-rate distributions and how they are influenced by the eventual changes of fracture properties in time.

Our model does not count for induced mechanical processes in the fractures or in the massif. In the RINGEN project, the modelling of coupled hydro-mechanical processes is in development simultaneously with other activities. Some results and experience notes on this field is a subject of the paper by Březina et al. (2019).

3.2 Geometry

The modeled area should be large enough to have boundaries, which are thermally unaffected by the exchanger. However, geometry that is too large increases computational demands. Two types of geometries of the deep geothermal exchanger with different scales were made with the use of available geological information:

1) Large-scale model geometries with different horizontal diameters from 2, 3 and 4 km (further called the "regional model", Figure 5 on the left), covering the whole vertical profile up to the surface. The exchanger is simplified to the bounded volume of a rock with a high hydraulic conductivity. The large-scale model serves primarily for the estimation of the thermally unaffected boundary for the small-scale model.
2) Small-scale model geometry with the diameter of 2 km (further called the "local model") with the exchanger composed of a discrete fracture network (DFN). The algorithm, generating the DFN, is briefly described in the paragraph 3.4.

The HDR configuration contains one injection well and one production well for both scales, with the distance between them 100 m. Both wells are represented by 2 m long interacting parts (Figure 5 right), with an added layer of a highly permeable rock with the same hydraulic conductivity as the average of fracture values (which improves the computational stability while its effect on the results is in the order of several percent).

3.3 Boundary and Initial Conditions

Thermal boundary and initial conditions appear from proposed in-situ values (see Table 2). The initial vertical temperature distribution is then determined by the relation $T(-5000 + h) = 146 - 0.024h$, where h is the relative vertical distance to the level of -5000 m. This initial temperature distribution also stands as Dirichlet boundary condition for the lateral sides of the modelled domain. The heat flux of 72 $mW.m^{-2}$ is prescribed on the bottom side of the modelled domain. The open boundary is prescribed for the upper side.

Initial distribution of the pressure head is determined by the results of the regional hydraulic model (see paragraph 2.2). For the lateral sides of the modelled domain, Dirichlet boundary conditions are defined. Boundary conditions for injection and production wells are of two types. On the injection well surface, either 1) the pressure (injection pressure + initial pressure head) or 2) the boundary flux is prescribed (either constant or time-modulated – see paragraph 4.2.1). On the production well surface, the constant pressure equal to initial pressure head is prescribed.

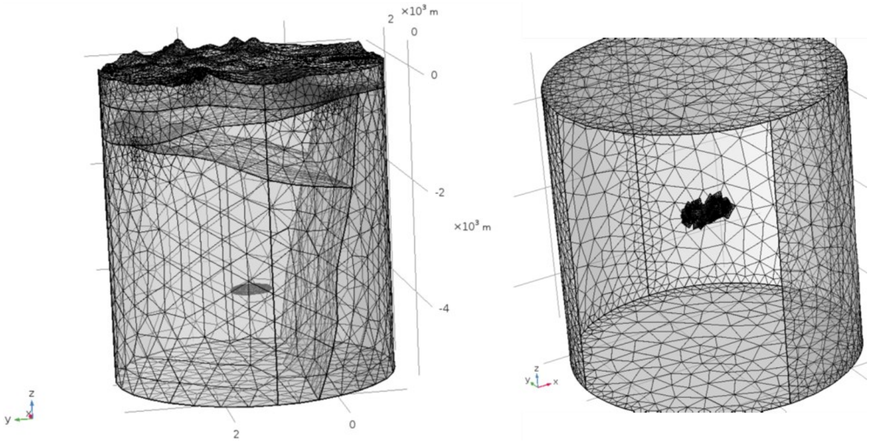

Figure 4: Discretized geometries. On the left – regional model covering the surroundings about 4 km. On the right – local model with a fracture network.

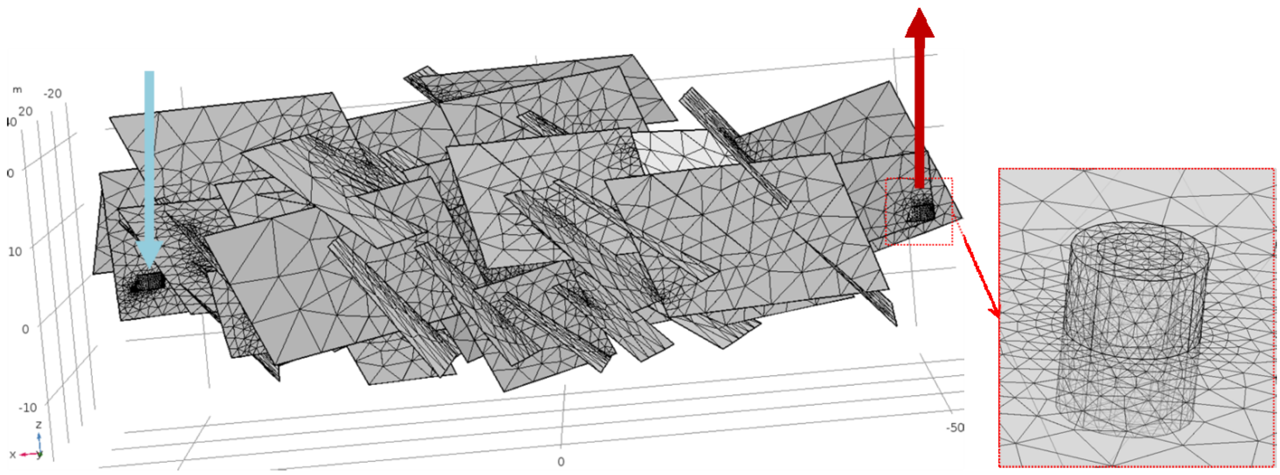

Figure 5: Discretized geometry of the fracture network with marked injection and production wells.

3.4 Stochastic Discrete Fracture Networks

Presumptions of DFN and their properties are obtained from geological information for the specific site, which are limited for the very low depths. The commonly used approach for generating a DFN is the use of stochastic methods, which expect basic information about the orientation, declination, dimension or the space distribution of the fractures. Hydraulic or mechanical properties can be specified in a similar way. Resulting DFN reflects the reality only in some measure, but series of results computed with different DFNs (constructed by the stochastic approach with various input parameters) can predicate the real situation. It should be mentioned, that we are actually lacking any relevant in-situ information about the fracture distribution or properties in object depths. This fact made the models with generated DFNs rather artificial, nonetheless from the future perspective it still provides some practical computational experience.

DFN, used in the small-scale model, was generated by the algorithm, implemented in the Python language. This algorithm uses the conventional Poisson process with added conditions of 1) the network connectivity and 2) the correction of the defect cases (e.g. small intersections or close parallel fractures). Stochastic models for the used (optional) parameters are adapted from Engelder (2004) and Fadakar (2014). These parameters are listed in Table 3. Output of the algorithm is a geometry file (*.stl) with a list of generated fractures and a text file with their physical properties.

The scheme of the fractured area is demonstrated in the left part of Figure 6. The area is defined by well coordinates, propagation angle and its range, divided by a given number of space intervals. The generating of fractures progresses successively in these intervals. Each new fracture has to intersect any existing fracture, otherwise it is substituted by another sample. Resulting fracture network can be considered as a certain approximation of fracture networks originated from a hydraulic fracturing. At the end, the algorithm checks for "defect" cases, which could (not necessarily) cause problems during discretization (see Figure 7), and corrects these cases in some measure (briefly: close (nearly) parallel fractures are merged, small overlaps or small fractures with very small intersections are deleted; the amount of "close", "small" or "nearly parallel" is optional indeed).

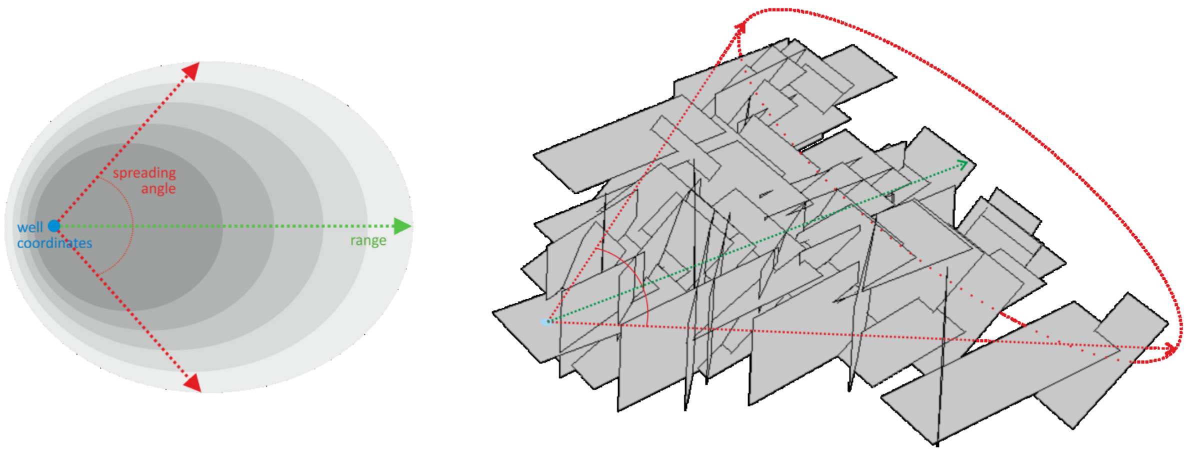

Figure 6: On the left – sequential propagation of generated fractures. On the right – an example of generated fracture network.

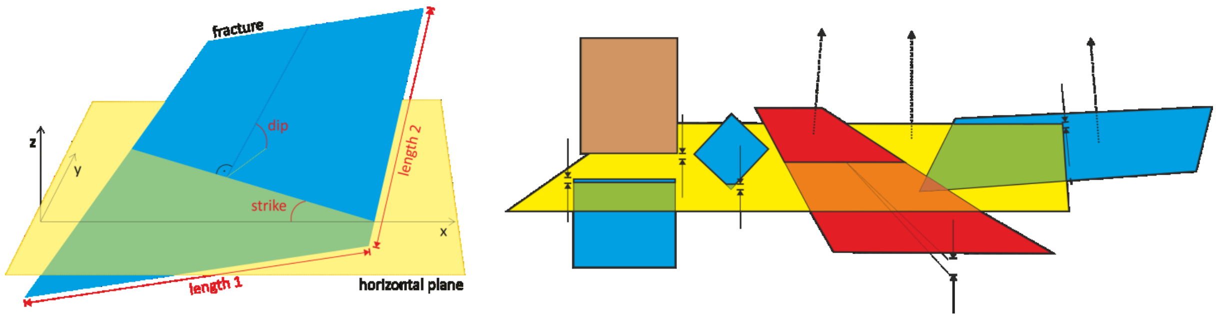

Figure 7: On the left – a meaning of fracture geometric properties. On the right – an illustration of "defect" cases – yellow (reference) fracture vs. the others (close fractures, fractures with very small intersections, close nearly parallel fractures).

Table 3: Used stochastic processes for various fracture characteristics.

fracture characteristic:	type of a stochastic process:
number of fractures in particular space interval	Poisson process
position (coordinates of the centre)	random sampling in particular space interval (acc. to selected distribution – uniform or normal)
strike	von Mises distribution
dip	
length	exponential distribution
aperture	normal distribution
hydraulic conductivity	determined from the aperture (cubic law)

3.5 Numerical Solution

The model has been implemented in software Flow123d and COMSOL Multiphysics. Discretized geometries, used in particular computation cases, were identical for both softwares. The discretized geometry of the regional model(s) had about 278 000 elements, the geometry of the local model had nearly 400 000 elements. The computational times were then tens of minutes for regional models, about 0.5-1 hour for the 30-year simulations with constant injection and several hours for cyclic injection (local models).

3.4.1 Flow 123d

Flow123d, developed in the Technical University in Liberec (Březina, 2019), is a simulator of underground water flow, solute and heat transport in fractured porous media. It supports computations on complex meshes consisting of simplicial elements of different dimensions. Therefore, it can combine continuum models and discrete fracture network models. Current version includes mixed-hybrid solver for steady and unsteady Darcy flow, finite volume model and discontinuous Galerkin model for solute transport of several substances and heat transfer. Using operator splitting, it supports models for various local processes including dual porosity, sorption, decays and simple reactions. Other methods are under an active development, such as XFEM method for modelling wells (1D-3D coupling) or methods for coupling of equations (Darcy flow) on non-conforming 2D-3D and 1D-2D meshes modeling preferential paths.

3.4.2 COMSOL Multiphysics

The COMSOL Multiphysics implementation of the same model used Heat Transfer in Porous Media and Darcy Flow (incl. Fracture Flow) modules. It has served as a benchmark to the results, obtained by the software Flow123D. It was also used as a preprocessor for the geometries.

4. RESULTS – CASE STUDIES

Results on two types of model geometry (regional and local) are presented. The quantities, presented in following graphs, are either the production temperatures (water temperature in the place of the product well) or the heat outputs.

4.1 Regional Model

The regional model geometry has been made in 3 versions, which differs in the horizontal diameter (2, 3, 4 kilometers). The injection flow rate was 23.5 ls^{-1}. The main goal was to presume the minimal size of the diameter for the small scale model, so that it does not significantly affect the results of production temperature (and the heat output). Figure 8 shows temperature profiles through the production well after 20 years (presented results are from the COMSOL software). The results differ in order of percentage for different versions, therefore the smallest diameter 2 km was stated as sufficient for the local model geometry. For the regional model, the exchanger had the shape of a thin block. Its proportions, especially its width, can affect the results significantly. Figure 9 shows the range of results for combinations of various widths (20-70 m) and heights (5-20 m) of the exchanger and various injection flow rates (the task geometry had diameter 2 km).

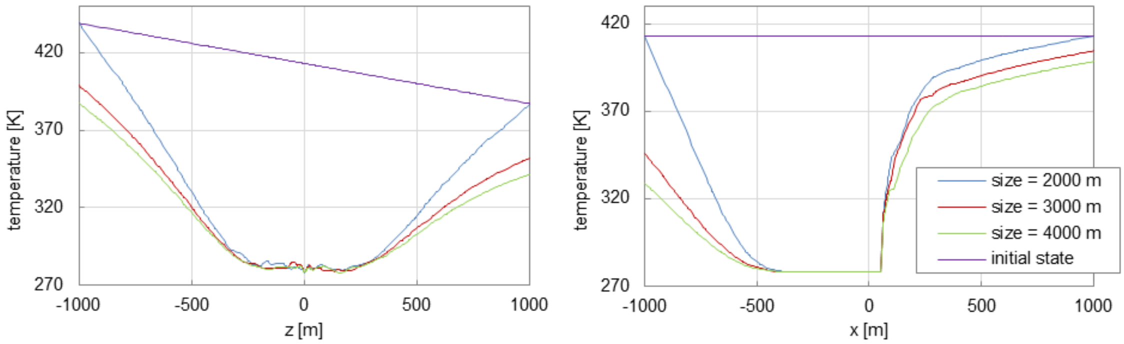

Figure 8: Vertical (left) and horizontal (right) temperature profile through the product well for various sizes of the regional model geometry (in time = 20 y).

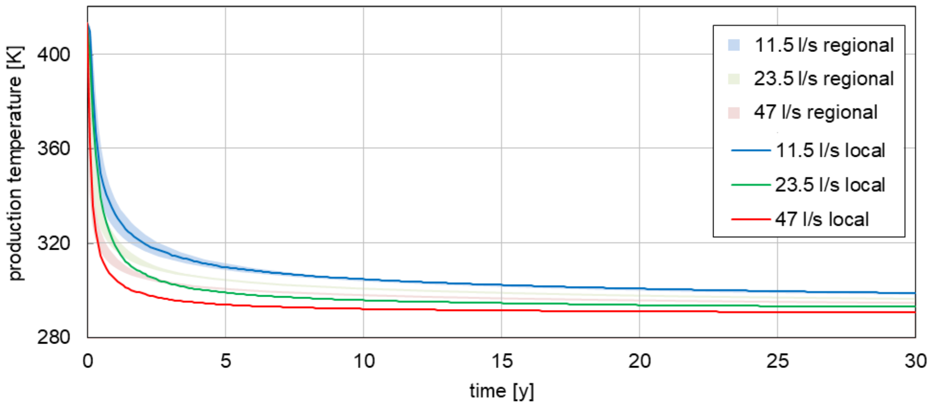

Figure 9: Time progress of the production temperature – a range of results (colour stripes) for the regional models in comparison with the local model (lines).

4.2 Local Model with Discrete Fracture Network

The local geometry was made with 4 different fracture networks. The results (production temperature and output) differ by less than 1% (it can be explained by the fact that the dimensions of networks were similar, the network was always connected and the inject boundary condition has been set via prescribed boundary flux). Thus the graphs below show the values belonging to one particular fracture network configuration. Higher variations (in order of 10 percent) were for the input pressures necessary to provide the required flux, as well as for the pressure space distribution. Other statistically evaluated results from a large number of stochastically generated DFN are discussed in Březina et al. (2019) in more detail (with the task being slightly different).

Computation on the local model was made with three variants of the injection flow rate: 11.5, 23.5 and 47 ls^{-1}. Figure 9 compares the production temperatures for the regional and local models. The difference in the results grows with increased injection flow rates. Higher production temperatures for the regional model can be explained by the simple character of the exchanger, with better and uniform warming of the water in porous media (a more accurate regional/local fitting or calibration was not an aim). Resulting values from Flow123d are slightly overestimated in comparison with COMSOL but preserve the development shape (Figure 10). An illustrative Figure 11 shows the temperature field distribution on the fracture network at two different time points.

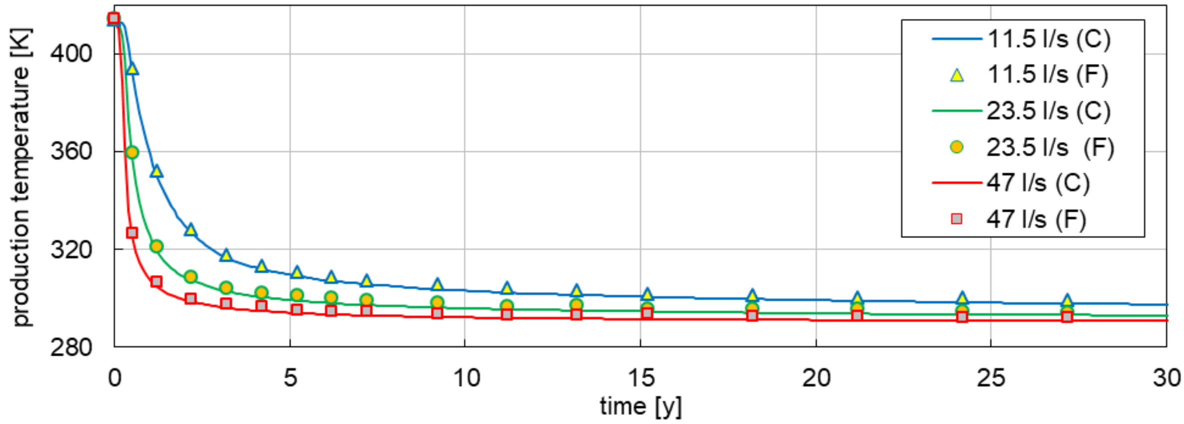

Figure 10: Time progress of the production temperature – a comparison between COMSOL Multiphysics (lines) and Flow123d (symbols).

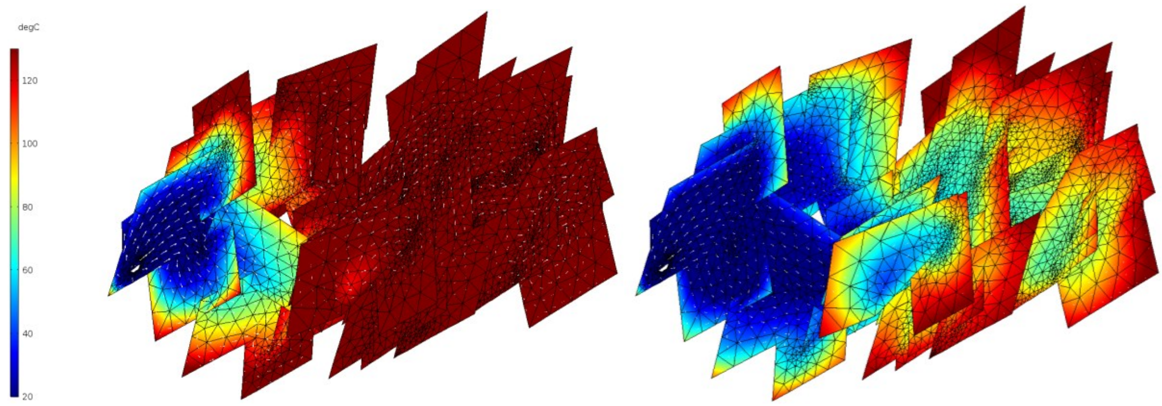

Figure 11: Temperature field distribution in t = 0.3 y (left) and t = 5 y (right). White arrows represent normalized flow velocity magnitudes and directions.

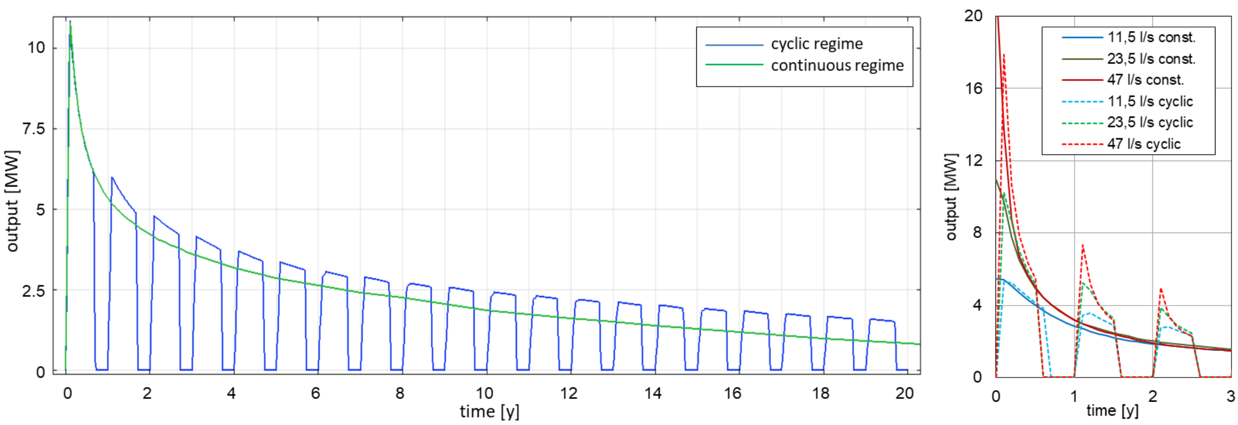

Figure 12: Time progress of the exchanger output – comparison between the continuous and the cyclic regime. Left – 20 year simulation for inject flow rate 23.5 ls^{-1}. Right – first three years for various inject rates.

4.2.1 Continuous vs. Cyclic Regime

In general, the sustainability of the exchanger can be significantly prolonged by properly selected seasonal intervals, mostly during the summer, when none or small output is required. The intervals allow warming-up of the exchanger proximal neighborhood from the more distant environment. A comparison between the continuous and cyclic regime is presented in Figure 12. The single yearlong cycle consisted of: 0.1-year long linear increase from zero to the maximal flow rate; 0.7-year long period of maximal flow rate; 0.3-year injection break (zero flow rate). The output difference in favor of the cyclic regime is growing in progressing time. It should be mentioned that the case study does not take into account processes which could occur during the intervals (e.g. a silting of fractures due to the chemical reactions).

4. CONCLUSION

For several problems mentioned above, we confirmed an applicability of the DFN/porous media concept in modeling HDR, together with a verification of the software Flow123d. From the basic thermal balance perspective, the regional porous media model is fully adequate. The discrete fracture network approach is though needed as an instrument of deeper insight into geothermal exchanger behavior, for eventual mechanically induced changes in the fracture properties (not included in the problem formulation at present).

Stochastic generator of DFN, preserving the network connectivity, has been briefly presented. Pure automatic stochastic DFN generation may decrease the quality of elements during discretization, therefore the calculations were made only on several post-processed networks.

The use of geothermal energy in the Czech Republic is in its very beginning phase. This work and its possible future improvement (e.g. an inclusion of mechanic processes) should help to improve the scientific and technical background for geothermal development in the Czech Republic. The model geometry is largely fit to its prospective usage at the Litoměřice area, where the first Czech HDR system is planned.

ACKNOWLEDGMENT

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