EKSPLOATACIJA GEOTERMALNE ENERGIJE – PRIMENA MODELIRANJA

GEOTHERMAL ENERGY EXPLOITATION – APPLICATION OF MODELING

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Geotermalna energija je toplota ispod površine zemlje ili jednostavno energija dobijena od unutrašnje toplote zemlje. Ovi podzemni rezervoari pare i tople vode mogu se koristiti za proizvodnju električne energije ili za direktno zagrevanje i hlađenje zgrada. Iako je model podzemnih voda je matematički, obično računarski prikaz sistema podzemnih voda. Iako je model podzemnih voda pojednostavljenje daleko složenije stvarnosti, ipak predstavlja koristan alat za istraživanje problema podzemnih voda i dostojno uporište za donošenje odluka u upravljanju podzemnim vodama. Modeli nude uvid u ponašanje sistema podzemnih voda. Model koji realno reprodukuje prethodno ponašanje u stanju je da sa određenim stepenom pouzdanosti predvidi niz reakcija na izmenjene buduće uslove povezane sa klimatskim promenama, promenama u korištenju zemljišta ili u eksploataciji podzemnih voda. U modeliranju podzemnih voda koriste se brojni softveri koji se odnose na različite fenomene ili njihovu kombinaciju, a među njima su najznačajniji COMSOL Multiphysics, Heat and Solute Transport Program (HST3D), Modular Three-Dimensional Multispecies Transport Model (MT3DMS), Visual MODFLOW i SEAWAT, kao i TOUGH2.

Ključne reči: *geotermalna energija; hidrodinamičko modeliranje; softveri*

Geothermal energy is the heat that comes from the subsurface of the earth or simply power received from the eearth’s internal heat. These underground reservoirs of steam and hot water can be used to generate electricity or to heat and cool buildings directly. A groundwater model is a mathematical, usually computer-based representation of a groundwater flow system. Although groundwater model is a simplification of a more complex reality, it is still a useful tool for investigating groundwater problems and a worthy stronghold for decision-making in groundwater management. Models offer insight on how a groundwater system behaves. A model that realistically reproduces past behavior is able to predict with a degree of confidence a range of responses to changed future conditions related to climatic variations, changes in land use or in groundwater extraction. In groundwater modeling, numerous softwares are used referring to various phenomena or their combination, and the most important are COMSOL Multiphysics, Heat and Solute Transport Program (HST3D), Modular Three-Dimensional Multispecies Transport Model (MT3DMS), Visual MODFLOW and SEAWAT as well as TOUGH2.

Key words: *geothermal energy; hydrodynamic modeling; software*

1 Geothermal energy

Geothermal energy is an inexhaustible source of energy. This form of energy is available almost everywhere; it is stored as heat in the soil, rocks, and fluids below the surface of the solid earth. Geothermal energy can be applied in electricity generation, process heating, and space heating. The use of geothermal energy has become attractive due to savings of fossil fuels and relatively low CO_2 emissions.

In order to produce geothermal- generated electricity, wells are drilled very deep, sometimes about 1.5 kilometers, into underground reservoirs to reach the steam and hot water, which can afterwards be used to drive turbines connected to electricity generators. The first geothermally generated electricity was produced in Italy, in 1904 and during the last decades its usage is in constant

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and fast development. According to the International Renewable Energy Agency (IRENA), geothermal energy has grown steadily from around 10 GW worldwide in 2010 to 13.3 GW in 2018 [1,2].

2 Groundwater modeling

A geological formation containing water is called an aquifer. Data on the level and movement of water through the aquifer are systematized into a model that can be used to predict underground flow.

Groundwater modeling is of exceptional/ special importance for assessing the recovery of geothermal resources.

In addition, groundwater modeling is used for:

• Planning of the exploitation of groundwater carried out by wells and captages, with modeling results enabling the efficiency of wells to be predicted;

• Soil remediation based on modeling that provides information on the propagation and interaction of pollution necessary for its planning;

• Planning for the exploitation of coastal aquifers near the shores of the sea, whereby modeling prevents saltwater intrusion;

• Drainage in mining, where modeling provides data on the optimal placement and operation mode of pumps [3].

• Flood protection, where modeling provides data on the required reduction of groundwater levels.

• In geotechnics, where modeling allows the prediction of soil subsidence due to groundwater exploitation.

• In irrigation - since almost 90% of water consumption goes to irrigation [4], modeling helps to use it more efficiently.

• Modeling of underground stream in oil and natural gas exploitation.

3 Hydrodynamic model- term, elements and application

Generally, models represent conceptual descriptions or approximate presentations of particular physical systems, and in hydrogeology an approximation of the hydrogeological environment. Their basic functions are based on the simulation of the processes in the hydrogeological system, as well as the state of the hydrogeological system during time.

Mathematical modeling of groundwater regime is a basic modern tool in engineering problem solving in this field.

In these models, the physical system and the processes in it are approximately described by mathematical equations. In doing so, processes are represented by equations, physical properties by constants or coefficients in equations, and criteria of the state or potential by variable units.

The mathematical equations used to describe the model are based on the simplifications of the hydrogeological system, which is related to:

- groundwater flow;
- direction of the aquifer stream;
- geometry of the aquifer;
- heterogeneity and anisotropy of the present lithological members;
- mechanisms of matter transport and associated chemical reactions;
- interaction of matter transported with groundwater and minerals of porous medium.

Mathematical models can describe groundwater movements and the processes that accompany this movement (transport of heat, matter and filtration deformation), so it is more correct to use the term hydrodynamic models.

The hydrodynamic stream flow model for aquifer waters is a solution of a system of partial differential equations expressing the state and conditions of filtration of the aquifer waters and/ or associated processes in a porous medium. Mathematical or numerical models are the basic form of hydrodynamic models.

Elements of the hydrodynamic model are: characteristics of the hydrogeological environment (geometry of the outcrop, filtration characteristics of the porous medium, hydrodynamic state of the aquifer stream, elements of the balance of aquifer waters, etc.), boundary and initial conditions and mathematical apparatus.

The use of the model makes it easy to perform the extensive hydrodynamic calculations now performed by the software, enables the simulation of processes in the hydrogeological system and the forecasting of regimes and various accompanying processes for practically unlimited number of calculation schemes.

By making a hydrodynamic model it is possible to obtain spatial distribution of values of hydrogeological parameters, arrangement of piezometer levels in the analyzed stream field, direction, intensity and distribution of velocity filtration vectors of the aquifer waters, to quantify elements of balance of aquifer waters, as well as to predict the development of certain hydrogeological and hydrodynamic processes over time for different boundary conditions of the hydrogeological system.

4 Software in hydrodynamic modeling

Mathematical model in hydrogeology simulates groundwater flows from hydrodynamic aspect, processes of migration of substances contained in water, physicochemical reactions in water, processes of interaction of water and porous environment, processes of heat exchange, etc. [5]. Therefore, depending on the purpose or process being simulated, the following differ:

• Groundwater filtration models,

• Models of matter transport in a porous environment,

• Heat transfer models i

• Soil deformation models.

Accordingly, there are software programs that cover these issues in the field of hydrogeology, mainly a combination of these phenomena.

The following softwares are used in hydrogeological modeling: AST/TWOW–3D; BASIN–2D; COMSOL–3D; FEFLO–2D, 3D; FRACHEM–3D; FRACture–3D; ROCKFLOW/GeoSys–3D; HEATFLOW–1D, 2D, 3D; HST–2D, 3D; HydroTherm–2D, 3D; HYDRUS-2D, 3D; MT3DMS; Visual MODFLOW; SEAWAT–3D; SHEMAT–3D; SUTRA–2D, 3D; THETA–3D; TOUGH–1D, 2D, 3D.

The most important softwares for modeling geothermal processes are: COMSOL Multiphysics, HST3D, MT3DMS, Visual MODFLOW and SEAWAT, as well as TOUGH2 [6].

4.1 COMSOL Multiphysics

COMSOL Multiphysics, or simply COMSOL, was created by Svante Littmarck and Farhad Saeidi from the Royal Institute of Technology (KTH) in Stockholm in July 1986.

Originally known as FEMLAB, COMSOL is a software package for a variety of physical and engineering applications, especially for combined phenomena using the finite element method. These include a complete environment for modeling any physical phenomenon that can be described using ordinary or partial differential equations. It has become the industry standard for multi-physical effects modeling, research, design and development. It supports almost all platforms (for example Windows, Mac, Linux, Unix).

The COMSOL software package includes multiple modules organized into a single multiphysics simulation environment.

The following phenomena are covered by this software:

- fluid flow,
- heat transfer and
- transport of dissolved substance.

There are more than 20 COMSOL software modules. Some of them, significant for application in hydrogeology are:

- COMSOL Heat Transfer Module and
- COMSOL Subsurface Flow Module

The COMSOL software can model individual and coupled processes for different geological and ecological phenomena.

4.2 Heat and Solute Transport Program (HST3D)

The HST3D software (The Heat and Solute Transport Program) is suitable for simulating groundwater flow, which is accompanied by the transfer of heat and solution in saturated three-dimensional flow systems of variable density and viscosity. As such, this software, except for geothermal systems and heat storage in aquifers, is used to study waste injection into fresh or salted aquifers, the movement of pollutants within the aquifers, saltwater intrusion, storage of fresh water in salted aquifers, as well as for filling and recovering freshwater system.

4.3 Modular Three-Dimensional Multispecies Transport Model (MT3DMS)

The MT3DMS software is a modular three-dimensional model that is very suitable for modeling heat transport in closed geothermal structures. In addition, it is often used to simulate the transport of dissolved particles in hydrogeological systems and chemical reactions. Specifically, this software integrates five methods for solving matter of matter and heat transport, which covers a wide range of hydrogeological as well as heat transport problems. It can be adapted to the various specific systems under consideration [2].

4.4 Visual MODFLOW and SEAWAT

Visual MODFLOW software has included a newer version of the USGS SEAWAT that features temperature as a contaminant (in MT3DMS) and a new Viscosity package, which enables simulation of heat transport and fluctuation effects of fluid viscosity on groundwater movements.

Visual MODFLOW and SEAWAT are used in geothermal surveys to simulate the effect of heat pumps on groundwater temperature. In addition, these software are used to simulate heat and salinity transport in coastal areas and convection in deep aquifers, to collect fresh water in saline aquifers by simulating the effect of thrust and groundwater temperature on fluid viscosity, to simulate the circulation of aquifer waters in deep mines, geological platforms and basins, as well as for monitoring wastewater injected into deep wells and their impact on aquifers [7].

4.5 TOUGH2

TOUGH2 is software that is very much used in various fields. It was primarily intended for geothermal sources, but is used for a broader range of heat and moisture transfer problems as well as the drying of porous materials. It finds application in oil and gas engineering, environmental problems involving pollutants, and geological disposal of nuclear waste. A fluid and heat flow approach is used to describe these phenomena, which fully explains the motion of the gaseous and liquid phases, their heat transport as well as the phase transitions between liquid and vapor. TOUGH2 takes into account fluid flow in the liquid and gaseous phase that occurs under the influence of pressure, viscous and gravitational force [8].

5 Examples of process simulation in geothermal energy exploitation

5.1 Modeling using COMSOL Multiphysics software

COMSOL Multiphysics is a very good software for modeling geothermal processes. Over the last few decades, various techniques have been developed to obtain geothermal energy from distant underground levels.

Figure 1 shows methods for exploiting geothermal energy [9].

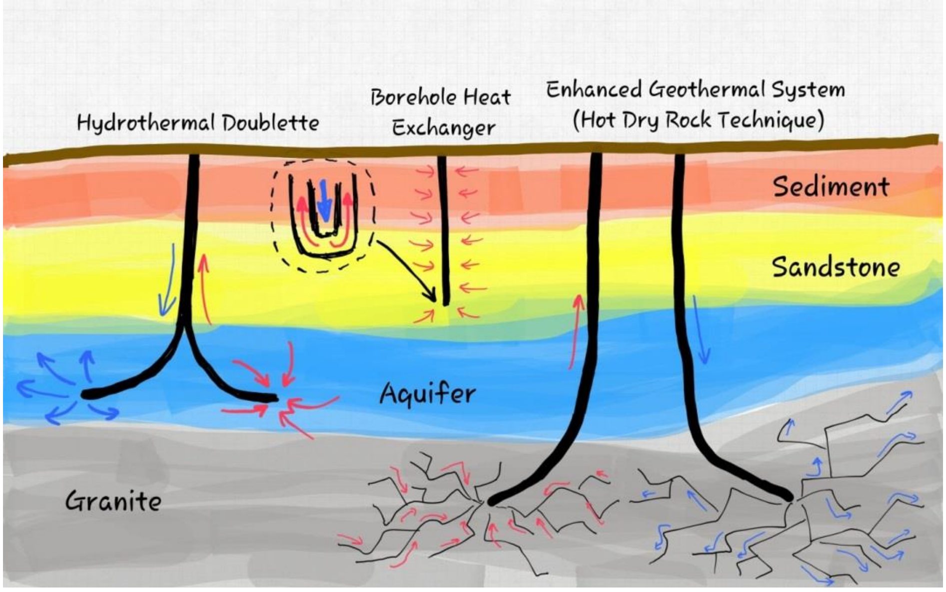

Figure 1. Geothermal energy exploitation methods [9].

Closed heat exchanger, so-called Borehole Heat Exchanger (BHE) is used as standard for shallow and medium deep drill holes. At BHE, fluid circulates through the pipes inside the drill hole, resulting in indirect heat exchange. The method has a limitation because the heat exchanger is closed with a limited effective heat exchange surface. This can be significantly accelerated by the exploitation of groundwater from the aquifers and by obtaining thermal energy by reinjecting the hot fluid away from the injection site using hydrothermal doublets. Enhanced Geothermal Systems (EGS) have been developed to exploit geothermal resources from non-porous hard rock. This is achieved by hyraulic breaking, or fracking. The hydraulic fracturing process involves pumping high pressure water into the desired layer to form new cracks and expand existing ones. The injected water can then flow through the cracks, heat up and be exploited in the second borehole [9].

Underground heat transfer occurs by convection, dispersion and conduction. It is necessary to know the thermal characteristics of geological layers in order to make simulations. However, unclear estimates are usually obtained from geological maps and samples. Convective heat transfer, whether naturally or artificially established through wells, can be one of the processes, even dominant.

Depending on the local geology, the subsurface flow regime may be accommodated in a fully or partially saturated porous medium, or may continue through cracks. Although the techniques for obtaining geothermal heat differ fundamentally, the COMSOL Subsurface Flow Module provides the necessary functions to simulate underground thermal processes.

The following example, given in Figure 2, is a series of three by three Borehole Heat Exchangers (BHE) at a depth of 135 meters in stratified rocky soil and serves to show some characteristics necessary for simulating geothermal processes. At a depth of 60-70 meters is an aquifer. The aquifer stream causes horizontal convective heat transfer. Due to the thermal interactions, the temperature of the middle BHE (green line) is lower than the other two. In the region of the aquifer, BHE further downstream from the other two (red line) has lower temperature than the other two due to heat exchange. To the right are the temp temperatures of the three wells in the middle of the row of heat exchangers. The tide temperatures of the three Borehole Heat Exchangers in the middle of the series are presented at the right. The model solves heat transfer around a shallow geothermal installation built into the surrounding geological complex. The complex is separated into parts, representing different geological layers with their specific properties. The thermal impact of seasonal changes in surface temperature is taken into account using the COMSOL Multiphisics ambient time base.

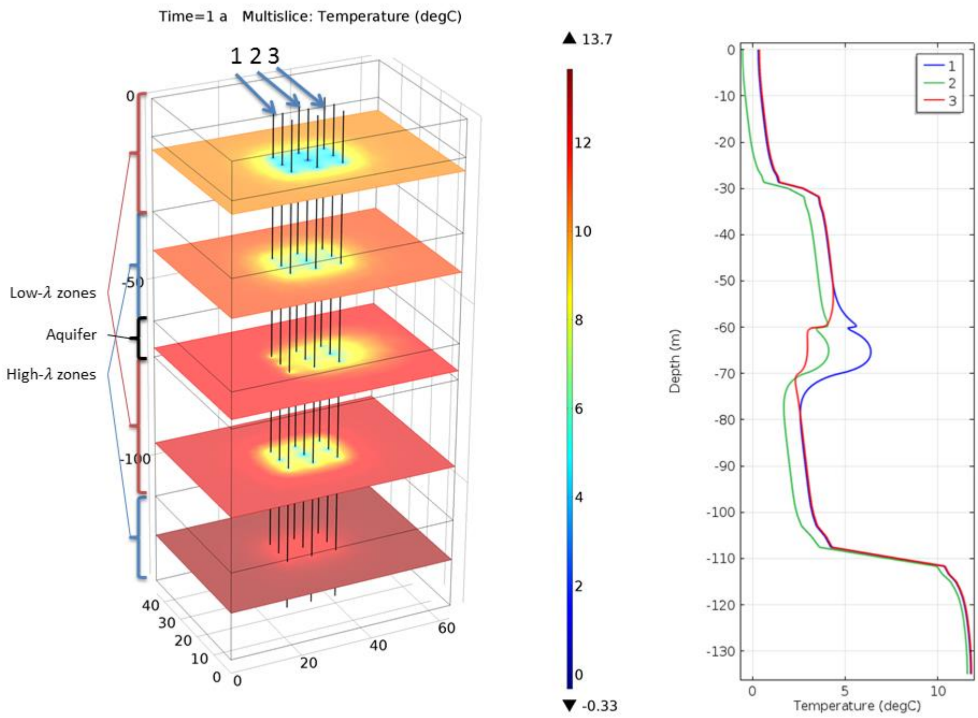

Figure 2. Model of three Borehole Heat Exchangers (BHE) [9].

Simulation is necessary to predict the long-term impact on BHE and to determine whether pipe freezing will be avoided. A direct way to model BHE quickly is to neglect the heating and heat transfer within the borehole and to establish appropriate boundary conditions for heat flux on the walls. Then the borehole becomes a local heat sink and heat spreads towards it. In case that more BHE is installed, there is a possibility of the heat exchanger interaction after a certain period. In particular, if there is an aquifer stream, the boreholes are thermally bonded. This thermal interaction can cause serious energy losses throughout the entire geothermal system. On the other hand, underground stream also increases the rate of thermal recovery. Reliable prediction is only possible if accurate geological data are available [9].

Figure 3 provides an example of the application of COMSOL Heat Transfer Module software for pipe design. This software allows heat transport modeling both in solid and liquid phases. It helps to analyze the effects of heating and cooling. The module provides the possibility to simulate and analyze convection, conduction and radiation while also considering structural mechanics, fluid dynamics, electromagnetism and chemical reactions [10].

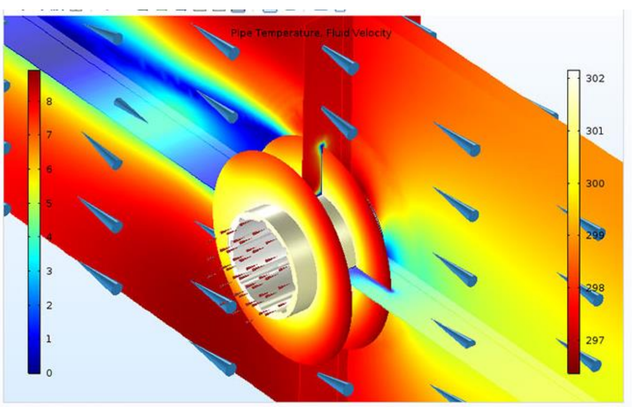

Figure 3. Application of COMSOL Heat Transfer Software Module for pipe design [10].

6 Conclusion

Hydrodynamic models have found important applications in the exploitation of geothermal energy and generally in hydrogeological research, which is almost impossible without them today.

Although these models are, by definition, a simplification of a more complex reality, they have proven to be useful tools in the exploration and use of geothermal energy thus providing valuable support in decision making related to the management of these resources.

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