Numerical simulation of geothermal resources: a critical overlook

Maurizio Vaccaro[1,2], Paolo Conti[1,2]

[1] Unione Geotermica Italiana (UGI)

[2] University of Pisa - Dipartimento di Ingegneria dell'Energia, dei Sistemi, del Territorio e delle Costruzioni (DESTEC, Department of Energy, Systems, Land and Construction Engineering)

largo Lucio Lazzarino 1, 56122, Pisa (PI), Italy

mauriziovaccaro@hotmail.it

Keywords: Numerical simulation of geothermal resources, Modelling of Geothermal Systems, Reservoir Engineering, Shallow Geothermal Systems.

ABSTRACT

The numerical simulation is a challenging part of the study of the geothermal resources. In this paper some of the main problems, criticalities and issues related to both simulation of reservoirs and ground thermal analysis are treated. Numerical simulation is successfully applied in several scientific fields and to solve a great number of engineering problems. Several applications in geothermal energy are possible, like reservoir engineering, ground heat exchange for HVAC (Heating, Ventilation and Air Conditioning) applications, environmental impact, hydrogeology.

An interdisciplinary approach is necessary to pursue an aware and reliable utilization of the numerical models, due to the great complexity of the geothermal phenomenon. The different backgrounds involved are Numerical Analysis, Earth Sciences, Energy Engineering, Geochemistry. In this paper the authors discuss about the numerical simulation of the resource (generally considered): large spatial scale (reservoir engineering) and small spatial scale (shallow systems) examples are both illustrated. Particular attention is paid on these aspects: thermophysical parameters, boundary conditions, physical equations of the model, potential assessment, coupling of the "plant-reservoir" system. All of them are important to elaborate a critical and engineering point of view. For example, physical hypothesis and assumptions about the system are two of the main criticalities in the application of numerical approach; they have to be clear and reliable and their consequences should be known before the simulation is set up. The principle "trash in, trash out" should be known since the accuracy level of the input data is not always dealt as a problem, but it has a great influence on the results.

The industry and market operators sometimes look at numerical models in a wrong way. Models should be related to the decisions about the utilization plant (heat/power) size. If the sustainability of a utilization project is seen from a global point of view, in which Environment, Economy, Technology are merged, the numerical models can be seen as the synthetic instrument to elaborate industrial strategies in relation to the resource durability. A discussion about when and why numerical models should be successfully implemented is carried on, also taking into account case studies and practical examples.

1. INTRODUCTION

Numerical simulation is a fundamental and strongly interacting instrument for plant design. Different approaches to the numerical simulation of geothermal reservoirs operation are here considered, with reference to some case studies of geothermal fields and ground. The perspectives of numerical simulation of geothermal reservoirs as support to the design and sizing of geothermal plants are outlined.

Numerical simulation of geothermal reservoirs allows to understand the hydrogeological behaviour and heat transport into the reservoir. The simulation process substantially deals with the numerical resolution of mass, momentum and energy conservation equations (depending on the complexity of physical model adopted). For example, in simple shallow systems models only Fourier Law (heat conduction) is often adopted, under homogenous media hypothesis. Some thermal problems can be treated both in an analytical or numerical way. Porous and fractured media models are instead considered in more complex and in larger spatial scale (reservoir engineering) simulations.

Some general and macroscopic aspects of the discussion about the application of numerical simulation to the geothermal energy study are here listed:

- equations which describe the phenomena considered (circulation, energy/mass transport),
- estimation of the main thermophysical parameters;
- Boundary Conditions (BC);
- geothermal potential assessment;
- coupling of the different models of the "geothermal system", power/thermal utilization and reservoir.

In general the problem of the potential assessment is strongly interdisciplinary. The process which brings to the evaluation of the appropriate plant parameters and sustainability assessment involves at least three backgrounds, as shown in Fig. 1.

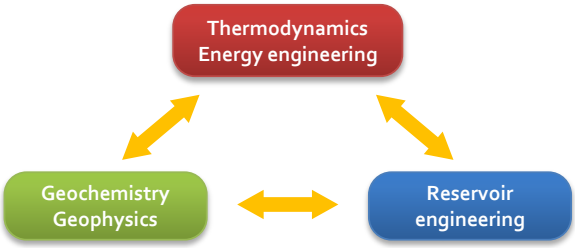

Figure 1: Conceptual scheme of the interdisciplinary approach proposed.

One can consider that this concept is known or basic, but its implementation in a real project development is not easy. In industry, for example a lot of players only consider the geological/geophysical aspects to be important, forgetting the environmental impact and in particular the power plant efficiency variations. It can happen that Economic issues turn to be prevalent. In the case of ORC plants diffusion, often only one of the background is prevalent. Binary power plants are considered to be economic, low-impacting on the environment, but this is true only if the size and the mass flow rate extracted/reinjected are appropriate to the reservoir considered. Similar observations can be made regarding HVAC applications. Key factors are similar to the case of large reservoirs (previously listed in this introduction). The main types of BCs refer to heat pumps devices or heat transfer performance of GHE (Ground Heat Exchangers). It could happen that a very accurate numerical model is coupled with a rough description of heat flux between HVAC system and the ground. The underestimation of the influence of thermal diffusivity value of the soil is another typical element of weakness. The hydrogeological equilibrium must be considered in case of aquifer exploitation. In those cases the environmental impact is not easy to be evaluated, and also the regulations are lacking or not up-to-date.

2. NUMERICAL SIMULATION APPLIED TO GEOTHERMAL ENERGY UTILIZATION

The numerical simulation of geothermal reservoirs is a field under development. It can be used with different aims, both for the design or for monitoring (O'Sullivan et al. 2001, Franco and Vaccaro 2012). Numerical models have been developed also for the analysis and the prediction of GHE performance (Yang et al. 2010). Physical and numerical studies are available and are the base of implementation of both commercial and academic (or open) softwares (Diersch and Kolditz 1998, Kolditz et al. 1998).

In the case of large scale analysis for deep geothermal fields a long history of studies and applications exist (O'Sullivan et al. 2001). Numerical solution for partial differential equations describing transport phenomena is a key element, but the history of numerical applications to geothermal energy has not been linear. A lot of phenomena are involved, and an "integrated approach" has never been pursued by industrial players. Although the developments of numerical methods in simulation softwares reached a remarkable level (also thanks to computer technology evolution), the development of numerical modelling for this energy resource has not been enhanced in a proportional way. Several reasons can be evidenced. The first is connected to the most exploited kind of reservoirs (high enthalpy). The efficiency of flash plants or dry-steam expansion plants is not so much dependent on little variations of geofluid temperature or reinjection temperature. So the development of this industry, until 1970s-1980s, has been mainly dominated by investment costs driven decisions. When the development of the fields and their massive exploitation brought to impoverishment and plant damaging (scaling, corrosion), then a major attention to the resource characterization has raised. A second reason can be related to a lacking integration between energy and environmental engineering problems (thermodynamic efficiency, geofluid consumption) and geological-geophysical issues (field exploration, resource assessment, reservoir monitoring).

The simulation can be very important in order to modify the management strategy of the geothermal field. The model must be enriched including the database of historical data collected during exploration. The main goal is to improve the potential assessment, in order to evaluate the plant or thermal utilization main parameters. The main aims, as summarized from cases review are fundamentally history matching and forecast of production scenarios.

2.1 History matching

The history matching is usually done to check the reliability of a model and evaluate the sustainability level in retrospect. It involves the analysis of an exploitation strategy according to his historical data log until present time or during a particular time interval. This is done to evaluate how the resource has been used. The check of the numerical model in a "feedback loop" and the calibration can be pursued (in order to improve analysis of future scenarios). Some aspects cannot be implemented into a simulation in a proper way, without knowing them from the history (e.g. natural recharge, natural change of the pathways of circulation into the rock formations, losses of pressure for different reasons than the extraction).

2.2 Forecast of production scenarios

The response of the geothermal system to different utilization scenarios can be studied. A reliable model can be used to study how the durability of the resource changes depending on different extraction rates, reinjection temperature, wells siting, fractures (also induced). The design strategy can be based on the results of the model simulation. This is true for both power plants and thermal energy direct uses.

2.3 Methodological survey on purposes and technical issues: an interdisciplinary approach

The simulation has to follow two main directions:

1) the unperturbed (or undisturbed) natural state;
2) the utilization scenarios (during the exploitation).

This is the starting point for the following discussion about development and criticalities of reservoir and aquifers models. Techniques and strategies to conceive and correctly simulate a numerical model have been studied, and widely proposed (among others) by Ungemach et al. (2007) and Ungemach and Antics (2008). Some fundamental requirements have to be remarked, in relation with the design strategy:

- database of physical and geological data for the geothermal potential assessment;
- set of thermophysical parameters for the design and optimization of plants or utilizations (to elaborate exploitation scenarios).

The hydrogeological problem (the complete knowledge of the geological structures and of the circulation system) has to be connected with the engineering tasks of the design and optimization of the energy conversion system. Softwares are evolving very quickly, but a key factor is the quality and reliability of the data and thermophysical parameters processed. For example it is difficult to have precise values of effective porosity and permeability. Numerical simulation is very sensible to unrealistic data input.

The conceptual scheme for the realization and simulation of a model of a geothermal reservoir is represented in Fig. 2 (after Ungemach and Antics 2008).Different phases in the development of the model can be individuated. A "block-structure" is needed together with the dataset of the parameters which best fit what it is expected by the conceptual model. This first step model should reproduce:

- geological structure of the reservoir,
- geometrical features of wells and fractures,
- Hydraulic, Thermal, Mechanic and Chemical conditions (HTMC).

In a multidisciplinary working team it happens that who is in charge of the simulation is not totally aware of the conceptual model of the field. It is necessarily a work of a team in which different geothermal backgrounds and experiences are shared. An important step of "interpretation" and appropriate data collection is needed, in order to elaborate the conceptual model (Huenges 2010). The numerical model has to be consistent at least with the hypothesis collected in the conceptual scheme. Each geothermal field in the world is different for structure, stratigraphy, temperature, pathways of circulation of fluids, number of reservoirs, chemical properties of fluid and rocks, origin of the thermal anomaly, hydrothermal alteration involved. All these elements should be clear already in the conceptual model elaboration. The model is then reviewed through calibration and refinement. It has to be clear that it is an iterative process, in which the parameters and boundary conditions should be adjusted according to the conceptual and physical model previously elaborated and to the uncertainty level of the input data. Thermophysical properties vary with siting, depth, hydrothermal alteration. Their value can be adjusted and the mesh can be refined, basing on the data from geophysics exploration, geological maps, natural manifestations, wells temperature profile, in order to fix the parameters and to achieve an acceptable reliability level.

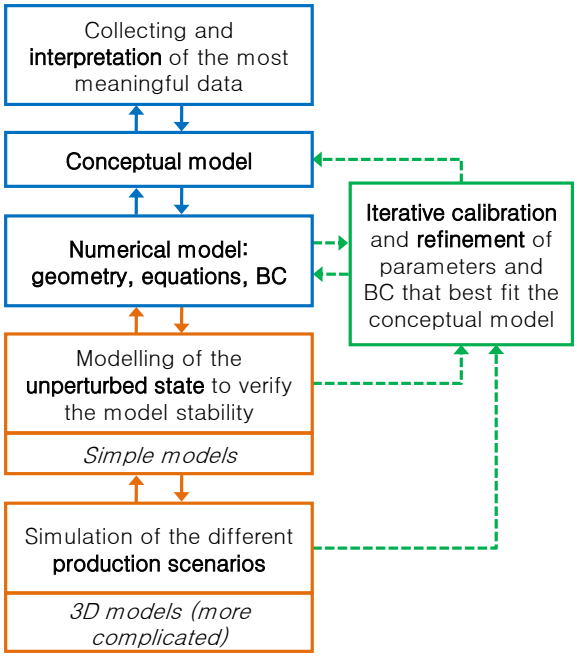

Figure 2: Conceptual scheme for the realization and simulation of a model of a geothermal reservoir.

A first model of the unperturbed state is the result of the attempts here described. It should be run for a long simulation time interval, in order to verify the model stability and convergence. In case of strong uncertainty about both the heat transport phenomena and geophysical data, simple 2D models (or lumped parameters models) could be firstly run.

Exploitation and energy utilization scenarios can be then run starting from the unperturbed state simulation as initial conditions. The renewability assessment and durability of the resource can be then evaluated. In particular, temperature and pressure should be kept stable into the reservoir as much as possible. If chemical properties and saturation curve of the specific geofluid mixture are known, scaling and chemical deposition phenomena can be also introduced in the calculations, in a multi-physics simulation environment. This could complicate in a sensible way the model, and it is possible only when the awareness about the specific geothermal field is high and if the numerical stability of the model is not affected. The numerical model must be reliable in order to be used as a prediction of the real reservoir. For example the results of pressure tests and

interference tests can be previously simulated in order to understand the appropriate permeability and porosity values.

It is evident that some of the geophysical and general result are not directly necessary or relevant for the plant design the plant, but at least the potential and the first attempt extraction rate should be calculated. The results of the simulation should show in particular the migration of the cold front to the production zone during time and the depletion of the resource with respect to the exploitation scenario. The results of a good simulation model allow to design and correctly size the power plant, taking into account the sustainability of the whole system.

3. BRIEF BACKGROUND ABOUT NUMERICAL MODELING

3.1 Remarks on reservoir simulation

The basic calculations executed by the softwares for numerical simulation substantially deal with the resolution of the flow into porous and fractured media. Equations of conservation of mass, momentum, energy, concentration of pollutant or chemicals dissolved are treated and numerically solved. According to the Darcy's Law, the volumetric flow rate is proportional to the slope $i=\Delta h/L$ (being Δh the piezometric head difference ad L the length of the aquifer considered). It is also proportional to the hydraulic conductivity K, which is related to the permeability k according to the equation

$$K = k\frac{\rho g}{\mu} \qquad [1]$$

where ρ and μ are respectively the density and the viscosity of the fluid, while g is the gravity acceleration. The variations of the kinetic head could also be neglected in these cases. In case of anisotropy an hydraulic conductivity tensor $\vec{K}$ can be defined, to take into account the preferential flow spatial direction. Darcy's Law is currently used if the hypothesis of local thermal equilibrium can be considered to be satisfied.

From an historical point of view, the studies about transport in reservoirs or aquifers were born in the field of mining engineering and applied thermodynamics. The task is to understand the response of a porous or fractured system when a hydraulic gradient is applied. Anyway the application of some experimental concepts to the geothermal fields is not a trivial task. The hypothesis and the real situation of the field should be compared very carefully. An example is the application of average properties to rock formation in which anisotropy or local variation could be present. Porosity varies also with pressure and depth, it is important to understand which assumption have to be done when assigning an average value of such properties to an extended rock body with an unknown field of fractures. Fractures are particularly difficult to reproduce in a numerical model. In fact their accurate description is important if their spatial extension is comparable to the rock formation mass and volume, otherwise average properties can be considered. Fundamental differences between the flow in porous and coherent media respect to fractured media flow must be taken into account (Rybach and Muffler 1981). In the most common reservoir simulation codes, like for example TOUGH2, it is possible to define different models for the relative permeability as a function of the liquid saturation in the mixture geothermal fluid (Pruess et al. 1999).

Appropriate Boundary Conditions (BC) have to be assigned to the model. The BC kind are similar when considering flow or heat transport. Typically 1st kind BC (Dirichlet BC) for thermal and flow problems deal with the assignment of, respectively, the local temperature and the hydraulic head (or pressure value). Also 2nd kind BC (Neumann BC) can be used, when fluid flux or heat flux must be assigned. There exist also 3rd kind BC (e.g. for convective BC) and 4th kind BC (implementing Dirac δ function for wells conditions) in the most used codes. The thermal boundary conditions can usually represent: heat flow from the bottom, fixed temperature at bottom/top or intermediate layers, adiabatic conditions. Concerning the conservation of mass flow rate, the boundary conditions are used to reproduce: natural manifestations; natural recharge; lateral or regional flows; wells withdrawal/reinjection in the aquifers; hydraulic head. Initial conditions represent the status of a system for which a transitory simulation has to be run. They can be assigned as thermal gradient, pressure distribution, hydraulic head levels (of rivers or aquifers).

The materials characterization should by site-dependent in order to obtain reliable and physically consistent results (particularly for 3D models). The mesh refinement is fundamental to improve the analysis and optimize the computational tasks (concentrating for example thickening the mesh in the wells area or along the faults). Different techniques can be adopted for the modelling of the faults, but once more the data input accuracy (upflow/downflow, fluid rate, permeability, thermal anomaly) has to be very high to achieve reliable results.

The integration of all the interdisciplinary inputs and procedures is the most challenging and crucial part of a modelling process. An important issue of this process deals with the quality of information and data flowing through the different steps. It is an iterative process, continuously changing and improving, as the information flow goes both ways (Antics 2001). A good and reliable model is often object of discussion and reinterpretation.

3.2 Remarks on shallow systems modelling

The expression "Geothermal Shallow System" usually indicates some specific components of GSHPs, responsible for the coupling of geothermal reservoir and heat pump device. They are divided into: ground-

coupled (GCHP), groundwater (GWHP), and surface-water (SWHP) (ASHRAE 2011). The latter is not considered in this work. Even for the shallow system modelling (small spatial scale), the constitutive equations are Fourier and Darcy Law; they are used together or separately according to different cases:

1. *Fourier's Law* is used for ground heat exchanger modelling, when the assumption of soil as a pure conduction media can be adopted;
2. *Fourier's Law and Darcy's Law* are used for ground heat exchanger, when groundwater flow effects are considered (*"Porous Media theory"*);
3. *Darcy's Law*: is used for GWHPs to model the behaviour of aquifers and producing wells.

Heat transfer phenomena are at the base of GCHPs, while groundwater flow theory is at the base of GWHPs. These models have consistently shown the analogy of respective mathematical models. Historically, hydrologist drawn upon heat conductions transactions to develop their analysis of radial groundwater flows (Banks 2012). For this reason, similar consideration of those exposed in section 3.1 can be referred also to the numerical simulation ground heat exchangers.

Setting of thermophysical parameters

Only single average values of the properties are considered for the different layers (material) of the ground (particularly in simple models): thermal conductivity (W/mK), thermal diffusivity (m^2/s), hydraulic conductivity (m/s), porosity, water content, saturation. It is always recommended to investigate thermophysical parameters directly on the specific site, using appropriate techniques like the Thermal Response Test (TRT). Nevertheless, reference values from literature can be used in small projects (<20 kW by UNI 2012, or 30 kW by GEOTRAINET 2011), in order to preserve the economics and the quickness of decision process. However let us underline that handbooks and technical normative provide values for generic types of soil, in wide ranges. As a consequence, the parameter values can vary according both to the reference chosen, and according to the free interpretation of who is in charge of the simulate the model. A sensitivity analysis respect to thermal diffusivity value is shown in section 5.3.

Geometry modelling and boundary conditions

Usually, GHE simulation determine the temperature response of the ground around an exchanger, when a 2nd or a 3rd kind BC is imposed (heat flux and convective heat flux respectively). The overall temperature response of GHE fields at any time, with an arbitrary heat rejection/extraction sequence, is determined afterwards by means of spatial and temporal superimpositions. Not all the systems can be analyzed with this strategy: for example *"energy foundations"* (energy piles). Thermo-active ground structures are blunt bodies without a prevalent development dimension, so that they represent complete 3D problems. Energy foundations are positioned according to static considerations about the building, so their mutual distance is comparable with their diameter, making the spatial superposition difficult to apply. Finally, they are positioned close to the structure within a shallow ground portion where the temperature distribution is affected by weathering and by the presence of buildings. The quality of the results of numerical solutions is then dependent on the schematization of all these aspects.

3.3 Codes and softwares

Several softwares (both commercial or not) dedicated to the study and simulation of geothermal reservoir are now available. The most used are multipurpose softwares, with the possibility of simulation of different types of diffusion phenomena. Their applications are usually: geothermal reservoir engineering, nuclear waste disposal, contaminant transport, remediation, environmental assessment, saturated and unsaturated zone hydrology, mine dewatering studies, saltwater intrusion, groundwater age calculations, groundwater management and allocation.

Between the simulators for geothermal reservoirs, the following can be mentioned for diffusion: TOUGH2 (Earth Sciences Division, Lawrence Berkeley National Laboratory University of California), for the purposes of this work it has been used through the graphic interface (commercial software) Petrasim (Rockware – ThunderHead Engineering, PetraSim 5 User Manual, http://www.thunderheadeng.com/petrasim/); Feflow, DHI-WASY GmbH (DHI Group); SHEMAT and ECLIPSE (Schlumberger). In this codes a lot of the most known resolution algorithms (from numerical analysis and calculus) are implemented. In TOUGH2 (Pruess et al. 1999) an integral finite difference approach is adopted, while Feflow is a finite element code (the acronym means Finite Element subsurface FLOW system). Pre and post-processors are embedded in commercial softwares, so that data elaboration can be easily carried out.

Regarding the simulation of shallows system, the most known codes are: Earth Energy Designer 3.0 (BLOCON, www.buildingphysics.com), GLHEPRO 4.0 (School of Mechanical and Aerospace Engineering - Oklahoma State University, distributed by IGSHPA), and PILESIM2 (ISAAC of SUPSI). GHE models are also integrated into building simulation programs like TRNSYS (University of Wisconsin, http://sel.me.wisc.edu/trnsys/index.html), ENERGY PLUS 7.2 (US Department of Energy, http://apps1.eere.energy.gov/buildings/energyplus/), eQUEST-DOE 2.2 (http://www.doe2.com/equest/). These design tools are mainly based on the line-source model and Eskilson's approach, and duct ground storage model DST (Haberl and Do 2010).

Simulation codes are very useful tools for economics and time-savings of the design process, and also for technical feasibility. But the results provided by these software can be considered reliable only if geometric

configuration and BCs of the specific case analyzed are reliable.

4. LIMITATIONS AND CRITICALITIES OF NUMERICAL MODELS

Numerical simulation has some important limits (which are treated and discussed in this work):

- results strongly depends on the reliability and accuracy of the data;
- numerically stable models can be physically not consistent.

The first limit can be also expressed by the principle "trash in – trash out". It must be clear which is the physical-numerical problem to recourse numerical simulation for. One should evaluate if the numerical simulation is the more appropriate instrument to face a specific problem. Sometimes a problem can be simplified in a proper way to be solved according to calculus or numerical analysis without using dedicated softwares, in this case any differential equation solver could be used. Softwares for shallow systems often use pre-calculated solution for reference configurations. Therefore, to be aware of result quality, it is necessary to know the specific model implemented and the assumption (geometry an BC) from which that model derive. Reservoir model simulation has to be pursued only if it is the most suitable and appropriate way to elaborate a design strategy. "Lumped parameters" models can be very useful for some medium-low temperature fields, having not too much thick lithological layers. For particularly linear and simple problems they can be satisfactory, in spite of more sophisticated elaborations.

One possible risk is to start "asking too much" or "asking too bad information" to the numerical models, being them "too much" or "too less powerful". For example, starting from the same geological features of a field, a model can give different results depending on the resolution of the spatial distribution of the data. In this work some example are shown and discussed. Some typical problems due to incorrect initial characterization of the resource (particularly in case of power utilizations) can also be faced with an appropriate model simulation, they can deal with: oversizing of the plant (leading to excessive extraction); scaling (causing corrosion, productivity drop, diameter reduction); wrong reinjection strategy (losses of fluid or cooling of the reservoir).

In case of shallow systems some factors affecting the results of a simulation can be: the mathematical methodology, the heat transfer to the ground, the fluid circulation model within the GHE and its configuration, the heat pump performance, the thermophysical properties of the ground, the influence of weathering, and the interference with close buildings or other artificial works (Yang et al. 2010).

5. EXAMPLES AND CASE STUDY

Some examples are illustrated and discussed in order to show and critically review the previously explained points. Both models about deep reservoirs and shallow aquifers utilizations are considered.

5.1 Momotombo reservoir (Nicaragua) "small scale" model

The first case analysed is the geothermal field of Momotombo in Nicaragua, for which a meaningful set of data is available from literature, mainly in Porras et al. (2007, and 2010). The aim of the simulation is to study different production scenarios. First of all an unperturbed state simulation has been carried out in order to define the steady state of the geothermal reservoir without fluid extraction. Then different production scenarios (production and reinjection rate, position of wells) can be simulated in order to prevent possible temperature and energy storage decline in the reservoir, and avoid cold fluid short-circuiting (from reinjection to production wells). In field production history let us consider a single flash unit (35 MW) from 1984 to 1988, two flash units (total 70 MW) from 1989 to 2001, then a binary cycle unit (7,5 MW until 2008). This simulation has been already been discussed by one of the authors (Franco and Vaccaro 2012), but here only a focus on the dependence of the results from variations in the thermophysical parameters and BC is carried on. The model is realised with TOUGH2 simulator (Pruess et al. 1999), using Petrasim (Rockware – Thunderhead Engineering).

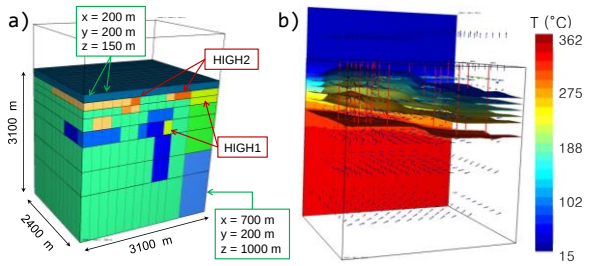

Figure 3: Momotombo model: (a) geometric features (most permeable materials are indicated, blocks with different sizes are pointed); (b) production scenario, temperatures (15 years).

Only the production/reinjection area of the model from literature is here simulated, its surface extension is 3,1 km x 2,4 km, with a vertical length of about 4 km (in the range between 950 m and -3000 m asl). It is divided into in 9 layers (Fig. 3a). The grid is built with 972 blocks (minimum size 200 m x 200 m, maximum size 600 m x 700 m). The total number of materials considered is 18. The most permeable layers have k = $1.0 \cdot 10^{-11}$ m^2, the porosity varies between 0.06 % and 0.25 % (at a depth interval between -150 m and -450 m). Atmospheric conditions are assigned on the surface. Natural recharges of fluid have also been taken into account. Surface natural manifestations have been considered, at a temperature of 185 °C. Initial conditions reproduce the natural pressure and temperature local gradients. The unperturbed state

simulation matches quite good with the original works in literature, the simulation time has been conventionally considered 10^6 years. In this work a focus on smaller temporal scale is considered. As already described in a previous work by one of the authors (Franco and Vaccaro 2012), some more severe scenarios (impacting on the resource durability) can be considered (respect to the historical ones), in order to understand the reservoir behaviour. A very intense scenario, in terms of production-extraction rates, is considered, with power plant size of 64 MW (to approach the total 77 MW from historical data), corresponding to an extraction rate of about 555 kg/s (simulation time of the scenario is 15 years). In Fig. 3b some results for this scenario are shown.

Respect to the more realistic case, let us consider the variations on the results when the permeability changes by only one order of magnitude. The *k* of the four more permeable materials has been increased by 10 times (scenario MAT1) and also decreased it by 10 times (MAT2), respect to the starting scenario (N1), see Table 1.

Table 1: Sensitivity analysis: permeability variations in the different scenarios (m^2).

Scenarios		Material name			
		HIGH1	HIGH2	POR11	POR12
N1	$k_{x,y}$	$2.6\cdot10^{-13}$	$5.0\cdot10^{-14}$	$6.0\cdot10^{-13}$	$2.6\cdot10^{-13}$
	k_z	$1.0\cdot10^{-11}$	$5.0\cdot10^{-15}$	$6.0\cdot10^{-12}$	$1.0\cdot10^{-11}$
MAT1	$k_{x,y}$	$2.6\cdot10^{-12}$	$5.0\cdot10^{-13}$	$6.0\cdot10^{-12}$	$2.6\cdot10^{-13}$
	k_z	$1.0\cdot10^{-10}$	$5.0\cdot10^{-14}$	$6.0\cdot10^{-11}$	$1.0\cdot10^{-11}$
MAT2	$k_{x,y}$	$2.6\cdot10^{-14}$	$5.0\cdot10^{-15}$	$6.0\cdot10^{-14}$	$2.6\cdot10^{-14}$
	k_z	$1.0\cdot10^{-12}$	$5.0\cdot10^{-16}$	$6.0\cdot10^{-13}$	$1.0\cdot10^{-12}$

Considering the wells MT27 and MT31 (assumed production rate is about 70 kg/s), some wide variations in the temperature decline can be observed respect to the N1 scenario, see Fig. 4 and Fig. 5. It can be observed that the gaps respect to the N1 scenario (at the beginning or at the end of the time interval) would lead to significant variations of the design parameters, and consequently to efficiency decline (and increase of the specific geofluid consumption). In Fig. 6 the horizontal sections of the model, with temperature distribution, after the 15 years simulation time, are shown.

Table 2: Sensitivity analysis: percentage temperature variation (stat-end simulation time).

	well MT27		well MT31	
MAT1	0 y	-2.30 %	0 y	-19.6 %
	15 y	17 %	15 y	-18.42 %
MAT2	0 y	-3.96 %	0 y	-0.4 %
	15 y	3.58 %	15 y	54.3 %

The permeability measurement and estimation are then fundamental. But in scientific or technical literature, uncertainty intervals for *k* values of one or more orders of magnitude are available. This example shows how important the reliability of the input data is for the scenarios forecast, in order to improve both plant performances and resource durability. The ΔT between the beginning and the end time of the interval does not allow a proper design of an efficient power system. Variations in the geofluid temperature (and maybe in deliverability) could cause a decline of η_I and η_{II} with time (and an increase of geofluid rate).

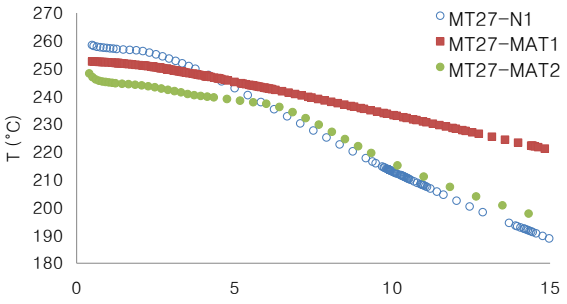

Figure 4: Well MT27 - MAT1: variations of the wells temperature.

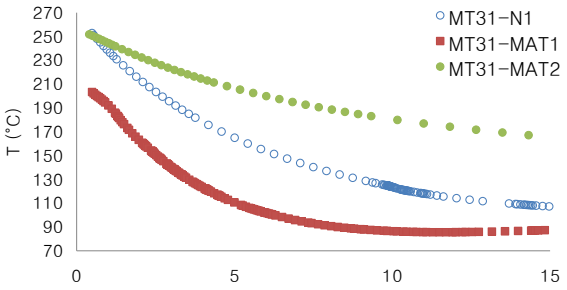

Figure 5: Well MT31 - MAT1: variations of the wells temperature.

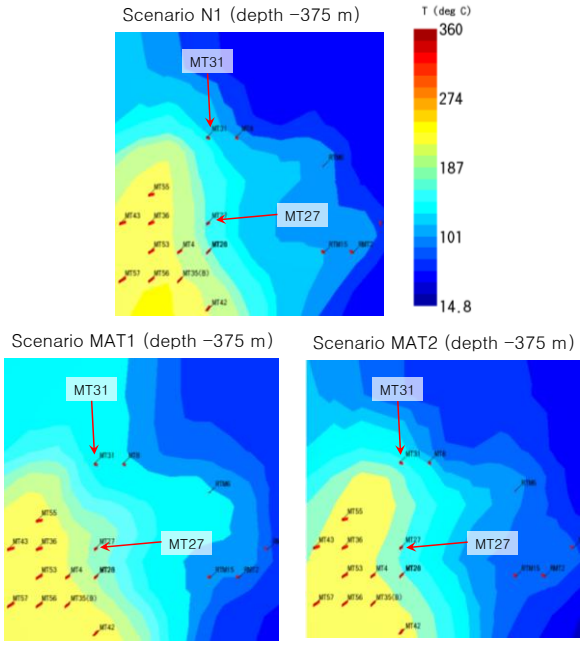

Figure 6: Temperature distribution, horizontal sections, wells MT27 and MT31, scenarios matching (Momotombo case study).

It is possible to observe (Table 2) that a considerable gap between the N1 temperature values and the other scenarios is obtained (up to 54.3 % after 15 years, MAT2, well MT31). In general the temperatures of

the MAT1 and MAT2 scenarios are lower at the beginning of the simulation interval. It is obvious that also the unperturbed state is modified when *k* changes.

5.1 Miravalles (Costa Rica) reservoir model

The Miravalles geothermal area has been widely studied and exploited (Parini et al. 1996, Vallejos-Ruiz 2010). In Haukwa et al. (1992) a numerical model of the reservoir is illustrated. Here only some outlines about the model are given, in order to show the differences in results matching between two mesh types. The sustainability level of the geothermal production is evaluated through a model of the reservoir, studying the resource response. The model parameters (rock properties, BC) are not completely available from literature, so that a calibration and integration phase have been done. The model will be object of future development and analysis in future works. The results, here only briefly described, are referred to the current state of development and these preliminary hypothesis.

The unperturbed state has been simulated, comparing the temperature distribution obtained with the literature data (simulation time of 10^6 years). Then also some production scenarios have been simulated. The model is realised with TOUGH2 simulator (Pruess et al. 1999), using Petrasim (Rockware – Thunderhead Engineering). In Fig. 7 the two mesh types (polygonal and quadrangular) are shown (different colours represent different rock materials). A matching between the simulation results (wells temperatures) (two mesh types respect to the literature) is shown, in order to underline the importance of the mesh (size and features) and refinement on the calculation (and interpolation of the results). Anyway this model is only qualitative.

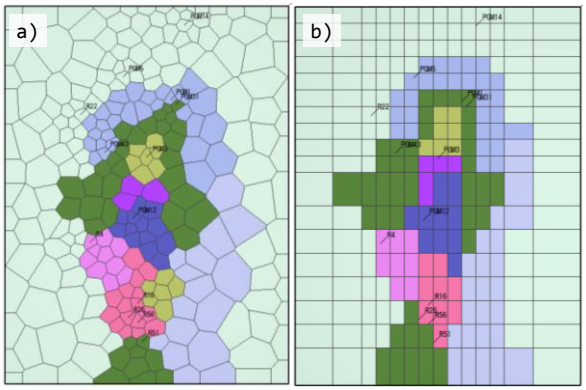

Figure 7: Miravalles geothermal reservoir model: polygonal (a) and quadrangular (b) mesh.

As the original model from literature has a polygonal mesh, in this study both a polygonal and a regular (quadrangular) mesh are compared. The model domain has an extension of 6x8 km^2, with a thickness of 1.6 km (from 100 m asl to -1500 m bsl). The calibration in this phase takes into account the 2D horizontal temperature distribution at -200 m asl available in Haukwa et al. (1992). In Fig. 8 the temperature distributions at -200 m with the different meshes are shown. A more realistic result in term of thermal gradient distribution is achieved with the quadrangular mesh.

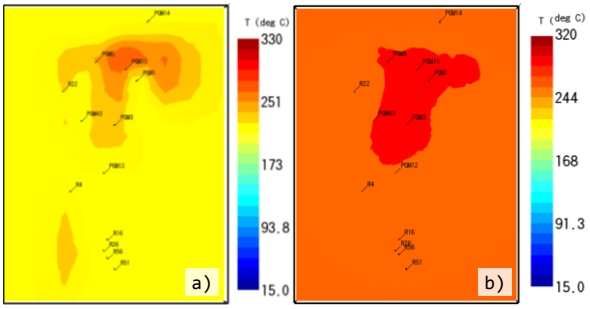

Figure 8: Miravalles case study: temperature distribution at -200 m asl with different meshes, (a) polygonal and (b) quadrangular.

Considering four extraction wells, let us now compare the gap between the temperature value measured (and given by literature for the pre-exploitation state) respect to the simulated value for the two mesh types. It is possible to see in Table 3 that (except for well no. 5) a substantial advantage is obtained with the regular quadrangular mesh. This is not a general law, anyway it is useful to understand the limitation and the approximation level of each model. Choosing a quadrangular mesh or a polygonal one is always the result of an approximation. Without a quantitative matching (e.g. wells data) it would be impossible to choose one of them only about literature or code performances. The self-consistence and coherence of a reservoir model should then be the first goal.

Table 3: Sensitivity analysis: percentage temperature variation (stat-end simulation time).

	Haukwa et al. (1992)	Polygonal mesh		Quadrangular mesh	
well no.	T (°C)	T (°C)	ΔT (%)	T (°C)	ΔT (%)
1	250	265	6.0 %	235	-6.0 %
3	240	265	10.4 %	241	0.4 %
5	230	276	20.0 %	276	20.0 %
12	235	265	12.8 %	241	2.6 %

5.3 Influence of thermophysical parameter

If the simulation is carried out without any actual data about the specific site, some values from the literature or technical standards must be used. A huge number of references can be consulted to estimate the thermophysical parameters. Table 4 shows some values of thermal conductivity (λ), volumetric capacity (ρc), and thermal diffusivity (α) provided by technical standards (UNI 2012, VDI 2000). The values can be also redouble when changing the reference. Thermal conductivity and thermal diffusivity are influenced by water content, dry density (composition), and frozen/unfrozen state (Farouki 1981, Fricke et al. 1992). The larger variations are due to water content. A simple example about the influence of thermal diffusivity value is here presented.

Table 4: Themophysical properties of common soils, recommended value is highlighted in brackets.

Type of soil	λ (W/mK)	ρc (10^6 J/m^{3}K)	α (10^{-7} m^2/s)
Dry sand	0.3–0.9 (0.4)	1.3–1.6	2.31–5.63 (2.76)
Water saturated sand	2.0–3.0 (2.4)	2.2–2.8	9.09–10.71 (9.6)
Dry clay	0.4–1.0 (0.5)	1.5–1.6	2.66–6.25 (3.23)
Water saturated clay	1.1–3.1 (1.8)	2.0–2.8	5.50–11.07 (7.5)
Dry gravel	0.4–0.9 (0.4)	1.3–1.6	3.08–5.63 (2.76)
Water saturated gravel	1.6–2.5 (1.8)	2.2–2.6	5.5–11.07 (7.5)

The thermal behaviour of a single borehole heat exchanger (BHE), buried in a pure-conductive homogenous media, is simulated. The heat flux profile shown in Fig. 9 (orange line) is imposed at BHE surface. Adiabatic BC is applied at the upper and lower boundary, while fixed temperature is imposed at infinite distance in radial direction. This example can be solved analytically (Carslaw and Jaeger 1959), in this work was obtained using COMSOL Multiphysics (finite element solver). It is useful to show the sensitivity with respect to the thermophysical parameters. Five values of thermal diffusivity (α) are considered (average value being $8.7 \cdot 10^{-7}$ m^2/s).

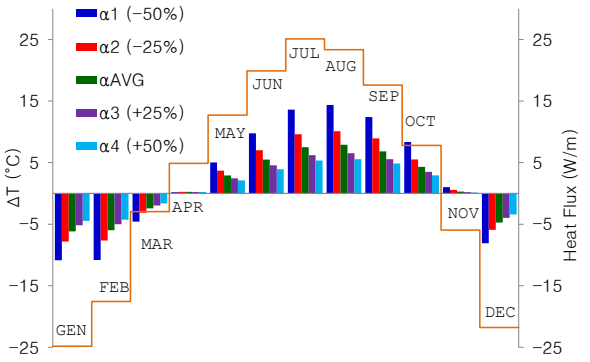

Figure 9: Temperature variation at borehole surface, depending on thermal diffusivity of the ground.

Table 5: Maximum temperature variation at borehole surface, depending on thermal diffusivity (α), average value is $8.7 \cdot 10^{-7}$ m^2/s.

$\Delta\alpha$ (%)	January		August	
	ΔT (K)	ΔT (%)	ΔT (K)	ΔT (%)
-50 %	-10.86	75.88%	14.36	81.84%
-25 %	-7.82	26.57%	10.11	28.00%
–	-6.17	–	7.90	–
+25 %	-5.17	-16.24%	6.52	-17.41%
+ 50%	-4.45	-27.88%	5.56	-29.53%

The sensitivity analysis is shown in Fig. 9 and Table 5. Temperature of BHE surface varies between -30% and +80% whit respect to average value. As it is well known, the external temperature of BHE determines the temperature of the fluid circulating in the system. This latter influences COP/EER value of the heat pump device, and consequently the feasibility.

6. CONCLUSIONS

Numerical simulation of geothermal resources is discussed, also by mean of examples. Models simulation is a powerful decision-making tool: it can provide useful indication about optimal sizing and sustainable management of geothermal utilization systems, both in large scale application (power generation), in direct use of hot aquifer, and in HVAC applications (Ground Source Heat Pump).

Nevertheless, the following issues have to be considered in order to obtain reliable results.

- The modelling process of geothermal phenomena is complex, interdisciplinary approach is therefore necessary.
- Software represents (more or less) only solver tools for the physical equations used, Fourier Law and Darcy Law are the model most commonly implemented.
- Case study experience and history matching about existing and exploited fields is a fundamental background, and its diffusion should be enhanced.
- Thermophysical parameters, BCs, and meshing method strongly affect numerical simulation. Only a high accuracy level of the input data provides reliable results. According to the quality of information available, simplified models can be adopted.

It is clear that numerical simulation of geothermal reservoir is a key factor for the geothermal potential assessment and sustainable design of geothermal utilization devices. Anyway an “integrated” approach to the complexity of the geothermal phenomena is still lacking. Geothermal energy is a kind of particular renewable source, its use is sustainable only under particular conditions, which must be known (knowledge sharing) also to who is in charge of simulating the reservoir, explore the site and interpret the exploration data. Continuous matching with wells data and enhancement of the dataset available for each site are useful practical tools. The system to be considered and optimized is the “geothermal system” composed by the utilization equipment, the resource, the environment, and all the links between them, in terms of mass and energy transfer. An holistic and interdisciplinary perspective is needed for design and approach to geothermal energy.

REFERENCES

Antics, M.: Computer simulation of low enthalpy geothermal reservoirs, European Summer School on Geothermal Energy Applications, Oradea, Romania, *Text Book (Rosca, M. ed.)*, (2001), 77–92.

ASHRAE, Handbooks – HVAC applications (chapter 34), (2011).

Banks, D.: From Fourier to Darcy, from Carslaw to Theis: the analogies between the subsurface behavior of water and heat, *Italian Journal of Groundwater*, (2012), 9-18.

Carslaw, H. S., Jaeger J.C.: Conduction of heat in solids. *Clarendon*, Oxford, (1959).

Diersch, H.-J.G., Kolditz, O.: Coupled groundwater flow and transport: 2. Thermohaline and 3D convection systems, *Advances in Wafer Resources*, (1998), 401–425.

Farouki, O. T.: Thermal properties of soils, *Cold regions research and engineering lab Hanover NH*, USA, (1981).

Franco, A., Vaccaro, M.: An integrated "Reservoir-Plant" strategy for a sustainable and efficient use of geothermal resources, *Energy*, 37, (2012), 299–310.

Fricke, B. A. et al.: Soil thermal conductivity: effects of saturation and dry density. *Diss. University of Missouri-Kansas City*, 1992.

GEOTRAINET, Geotrainet training manual for designers of shallow geothermal systems, Project: IEE/07/581/S12.499061, *GEOTRAINET*, EFG, Brussels, (2011).

Haberl, J.S., Do, S.L.: A review of Ground coupled heat pump models used in whole-building completer simulation programs, *Proceedings of the 17th symposium for improving building systems in hot and humid climates*, (2010), Austin, Texas.

Haukwa, C., Bodvarsson, G.S., Lippmann, M.J., Mainieri, A.: Preliminary reservoir engineering studies of the Miravalles geothermal field, Costa Rica, *Proceedings 17th Workshop on Geothermal Reservoir Engineering (1992)*, Stanford, California (USA), SGP-TR-141.

Huenges, E. (editor), Geothermal Energy Systems. *WILEY-VCH*, (2010).

Kolditz, O., Ratke, R., Diersch, H.-J.G., Zielke, W.: Coupled groundwater flow and transport: 1. Verification of variable density flow and transport models, *Advances in water resources*, vol. 21, no. 1, (1998), 27–46.

O'Sullivan, M.J., Pruess, K., Lippmann, M.J.: State of the art of geothermal reservoir simulation, *Geothermics*, 30, (2001), 395–429.

Parini, M., Acuna, J.A., Laudiano, M., Reinjected water return at Miravalles geothermal reservoir, Costa Rica: Numerical modelling and observations, *Proceedings 21st Workshop on Geothermal Reservoir Engineering (1996)*, Stanford, California (USA), SGP-TR-151.

Porras, E.A., Tanaka, T., Fujii, H., Itoi, R., Numerical Modeling of the Momotombo Geothermal System, Nicaragua, *Geothermics*, 36, (2007), 304–329.

Porras, E.A., Bjornsson, G.: The Momotombo Reservoir Performance upon 27 Years of Exploitation, *Proceedings of the World Geothermal Congress*, Bali, Indonesia (2010), paper #0638.

Porras, E.A., Tanaka, T., Fujii, H., Itoi, R., Numerical Modeling of the Momotombo Geothermal System, Nicaragua, *Proceedings of the World Geothermal Congress*, Antalya, Turkey, (2010), paper #1139.

Pruess, K., Oldenburg, C., Moridis, G., *TOUGH2 User's Guide, Version 2.1*. Earth Sciences Division, Lawrence Berkeley National Laboratory University of California, Berkeley, California (USA), (1999, rev. 2012).

Rybach, L., Muffler, P. (Editors): Geothermal systems: Principles and Case Histories, *John Wiley and Sons*, (1981).

CTI/UNI 11466, Heat pump geothermal systems – Design and sizing requirements, Technical standard, *UNI*, Milano, (2012).

Ungemach P., Papachristou M., Antics M., Renewability versus Sustainability. A reservoir Management Approach, *Proceedings of the European Geothermal Congress*, Unterhaching, Germany, (2007), paper #216.

Ungemach, P., Antics, M.: Insight into Modern Geothermal Reservoir Management Practice, *Petroleum Engineering Summer School*, 2008.

Vallejos-Ruiz O., Update of a Lumped Parameter Model of the Miravalles Geothermal Field, Costa Rica, *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, (2010), paper #2226.

VDI, Thermische Nutzung des Untergrundes, *VDI 4640*, (2000).

Yang, H., Cui, P., Fang, Z.: Vertical-borehole ground-coupled heat pumps: A review of models and systems, *Applied Energy*, Volume 87, Issue 1, (2010), 16–27.

Acknowledgements (optional)

M. Vaccaro would like to acknowledge A. Orlandi (Bachelor Degree in Energy Engineering at the University of Pisa, 2011) for the help in the Momotombo "small scale" model simulation.