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Numerical simulation of geothermal reservoirs for the sustainable design of energy plants: A review

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ABSTRACT

Numerical simulation is a fundamental instrument for the elaboration and assessment of a strategic utilization of geothermal energy. It can be used for the evaluation of both the natural (unperturbed) state and the production scenarios. The motivation and important role of the numerical models are described here and deeply illustrated in the context of the geothermal energy exploitation. The mathematical–physical background is also briefly illustrated, together with all the practical problems of modeling and implementation. Particular attention must be paid to the boundary conditions and thermophysical parameters assignment and calibration. The reliability of the model must be accurately evaluated, in order to prevent common failures in design and running of the energy conversion units and wells. Several case studies are reviewed and discussed, and a final discussion is presented. The limits of the reservoir modeling and simulation are also outlined in a general methodological perspective of integrated analysis. The scenarios modeled and assessed can be then used as practical tools for the sizing and optimization of the power unit or direct heat utilization.

Contents

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1. Introduction

Geothermal energy is considered a strategic resource in many countries, even if its use appears to be often marginal in the national energy systems. Its continuous operating mode distinguishes geothermal energy from the other renewable sources, intermittent or stochastic. Majority of the geothermal sources worldwide are medium-low enthalpy type (water dominant, at temperature lower than 150 °C and pressure below 15 bars). Stefansson, [1] estimated that more than 70% of the geothermal resources available in the world are water dominated fields, at temperatures under 150 °C. The binary cycle technology with Organic Rankine Cycle (ORC) appears to be the most efficient and convenient solution for such a kind of resource [2]. Binary power plants are now objects of wide attention by energy markets, although their diffusion is still made difficult by a lacking technology standardization and due to the quite high specific costs [3,4]. The great variability of the resource characteristics worldwide is one of the possible reasons. The proper matching between the reservoir capability and the plants parameters (power size, extraction/reinjection rate) is a critical key point. In power plants using dry-steam (high enthalpy) geothermal resources, pressure and temperature reduction can be compensated by an increase of the mass flow rate. In case of binary plants, a variation of the resource properties (T_{geo}, p_{geo}) could also lead to a fast end of life of the plant. The first and most important activity to design a geothermal energy plant is an accurate investigation of the geothermal potential assessment, as well as the prediction of reservoir response at given industrial exploitation configurations. For these reasons, a multidisciplinary approach to the problem of exploitation of geothermal fields (in particular at medium-low temperature) is necessary. Thermal engineering, geochemistry, geophysics, and reservoir engineering are the fields involved in this technique (Fig. 1). The authors have diffusely discussed this topic in a recent paper [5].

Numerical simulation is a fundamental and strongly interacting instrument for plant design [6]. Different approaches are here considered with reference to several case studies of geothermal fields, which are reviewed and discussed. The perspectives of numerical simulation of geothermal reservoirs as support to the design and sizing of geothermal plants are also outlined. Simulation can be very important in order to define and progressively modify the management strategy of the geothermal field. Construction of the numerical model must be supported by a detailed knowledge of the spatial distribution of the properties of the reservoir: the accuracy in the definition of the dataset is fundamental for the construction of the model. The model is then enriched by including the database of historical data collected during exploration.

The results obtained depend a lot on the accuracy level of the input data. The model will be much more accurate if as much details as possible are known about the geological properties of the rocks (effective porosity, density, specific heat, permeability, thermal conductivity), thermophysical properties of the fluid (specific heat, density, thermal conductivity), fractures pattern and layout, natural recharge of fluid, geothermal boundary conditions.

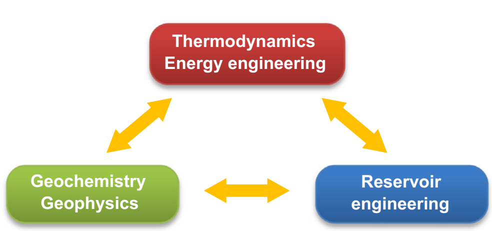

Fig. 1. The multidisciplinary approach proposed, with the connections between the three areas involved.

The numerical model of a geothermal reservoir is very important both for the definition of the geothermal potential assessment and of the reinjection strategy. The geothermal potential of a particular area means the definition of temperature (T_{geo}) and pressure (p_{geo}) of the geothermal fluid and also of the maximum mass flow rate (M_{geo}) that can be extracted maintaining the thermal properties of the reservoir and of the geofluid constant for a long time. Concerning the reinjection strategy, it is necessary to take into account the circulation model of the fluid in the regional area considered [7]. A general methodology for the reinjection technologies is not properly available in literature, the optimal strategy is in fact site-dependant, as the potential assessment itself. Interesting discussions on this particular topic are reported by Sigurðsson et al. [8], and recently by Kaya et al. [9].

The main task of potential assessment and sustainable plants design is the optimization and enhancement of the resource durability (Vaccaro [6]). Interesting contribution on the definition and evaluation of the sustainability and renewability of the geothermal energy uses are available in the recent paper by Hähnlein et al. [10], together with the paper by Axelsson [11]. Particularly in case of innovative geothermal utilizations (like for example EGS) the long-term consequences on the environment are not completely known yet. The same argument can be then referred to the renewability of the resource itself, which is directly dependent on the type and rate of utilization. The renewability (and sustainability) reference level can vary, as one can adjust the energy system size and extraction rate according to an acceptable durability level [11]. Also in case of direct heat utilization (e.g. district heating) some strategy remarks should be pointed out. In the recent paper by Fox et al. [12] the renewable capacity of deep systems is assessed and discussed in order to elaborate a rotating utilization strategy.

The numerical simulation of geothermal reservoirs is a well known topic and has already been an object of investigations and reviews (e.g. O'Sullivan [13]). Unfortunately, till now the use of numerical simulation has not faced any direct connection with the energy systems analysis. A proper prediction should deal with the changes of the different parameters in response to given mass flow rate extraction and reinjection (corresponding to the specific energy strategy). It is evident that a key role is assigned here to the numerical simulation of the reservoir, as compared to other reservoir engineering aspects (wells siting, fluid losses, tracer test). This ambitious task seems to be not of specific interest in most of the analyses carried out in the past, so the authors would like to review the recent developments in the field of numerical simulation of geothermal fields, focusing their attention on the particular use of such an important instrument for the sustainable design of geothermal plants.

2. Numerical simulation of geothermal reservoirs: strategic role for the design of geothermal plants

The numerical simulation of a geothermal reservoir is a well known field of research in the literature and it has already been an object of accurate review analysis and methodological overview [13–17].

Two main goals can be identified: history matching and forecast of future scenarios (consequent to the exploitation of the reservoir). History matching is usually done to check the reliability of a model and evaluate the sustainability level in retrospect. It is the analysis of an exploitation history according to the data log until present time or during a particular time interval. This also allows to check the numerical model in a