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Models for thermo-fluid dynamic phenomena in low enthalpy geothermal energy systems: A review

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A B S T R A C T

The need to address the global challenge of using clean energy, mitigating climatic changes and favoring sustainable development, has promoted the diffusion of new technologies for the use of renewable energy resources. Geothermal technologies can generate electricity and/or heating and cooling while producing very low levels Green House Gas (GHG) emissions and therefore play an important role in realizing these targets. In particular, low temperature applications have known a great development over the last years, thanks to the larger availability, compared to high temperature traditional ones, and to the increasing cooling demand that is also related to the global warming. A sustainable and profitable use of low enthalpy geothermal resources is strictly related to a correct analysis of ground thermal response to energy extraction/injection: in fact, sizing methodologies and optimization strategies are based on a balance of plant's energy demand and predictions of ground thermal variations due to these energy requirements. Therefore, an accurate mathematical modeling of thermo-dynamic behavior of the ground is fundamental for optimal design of geothermal plants for two reasons: it is the basis for the estimation of ground thermo-physical properties from the analysis of the Thermal Response Test, and it is essential in order to predict hour by hour (or short term) responses of the ground to continuously changing energy loads and therefore to estimate system energy consumption. Besides, there is a great interest in modeling thermo-fluid dynamic phenomena which occur in geothermal wells and geothermal heat exchangers as these can significantly affect the performance of the whole system.

In this work, the numerical models that are currently available for simulation of the thermo-fluid dynamic phenomena occurring in low enthalpy geothermal energy systems are analyzed, underlying the main differences and recent advances in modeling approaches.

Contents

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1. Introduction

Geothermal energy is the energy contained in the Earth's interior. The origin of this energy is linked with the internal structure of our planet and the corresponding complex physical processes that still occur in it. Practical uses of geothermal energy, for bathing, washing and cooking, date back to prehistory. The Etruscans, Romans, Greeks, Indians, Chinese, Mexicans and Japanese have all left evidence that they used hot waters in ancient times, when these waters were commonly thought to have healing properties [1]. According to Muffler and Cataldi [2], the term geothermal resources is usually referred to accessible geothermal reservoirs, characterized by the presence of a geothermal fluid; a small portion of these resources can be extracted economically and this portion is usually known as useful accessible resource base.

Geothermal resources are commonly classified on the basis of the reservoir temperature; Muffler and Cataldi [2] classify the reservoir as low, intermediate and high enthalpy when the fluid temperature is lower than 90 °C, between 90 °C and 150 °C, or higher than 150 °C, respectively. Other classifications are available in ref. [3–5], however in this work, the above classification is used. Nowadays, geothermal energy is widely employed both for electricity generation and direct applications such as greenhouse and space heating and geothermal heat pumps. An important part of the design process for a sustainable use of geothermal energy is the ability to predict the interaction between the reservoir and the heat exchange system used for transferring energy from and to the ground. Accurate modeling is fundamental for the development of this energy source, which is otherwise considered to be highly riskily. Moreover, the concomitance of high water content and high temperatures strongly influence the energy balance in the soil, as phase change may occur. Fig. 1 presents a classification of geothermal resources as a function of their temperature level and water mass flow rates available: as the large range of variability of these quantities between the different reservoirs, a correct characterization of geothermal system is fundamental for a correct modeling of the thermo-fluid behavior of it. This figure indicates also the complexity in modeling the geothermal system of the geothermal system: low permeability shallow formations present a low level of model complexity, supercritical systems are characterized by a very complex thermo-fluid behavior. For these complex systems, only very few models are available in scientific literature and all are characterized from a high uncertainty of input and output parameters, and from a low level of generality, but very specific [6].

This work, presents a review of the models available for modeling thermo-fluid-dynamic processes taking place in geothermal reservoirs used for low enthalpy applications. The need for alternative energy resources has given rise to the development of Ground-Source Heat Pump (GSHP) systems for space cooling and heating in residential and commercial buildings. GSHP systems use the ground as heat source/sink to provide space heating/cooling as well as domestic hot water.

GSHP technology compared to air-coupled heat pumps offers the main advantage of higher performance due to the ground temperature, which is lower than the external air for cooling and higher for heating, due to its temperature stability during the years. At a depth of few meters, in fact, ground temperature is almost constant, equal to the annual mean temperature of external air [7].

Despite these advantages, GSHP systems have not been widely used yet. This may be attributed to the high installation costs, large ground area requirement, and the lack of creditable prototype for systems design [7,8]. GHSPs include a wide variety of systems that may use groundwater, ground or surface water as heat sources or sinks [9]. These systems have been basically grouped into three categories [10]: (1) Surface Water Heat Pump (SWHP) systems, (2) Ground-Coupled Heat Pump (GCHP) systems and (3) Ground-Water Heat Pump (GCHP) systems. In a SWHP system, heat rejection/extraction is accomplished by the circulating working fluid through High-Density PolyEthylene (HDPE) pipes positioned at an adequate depth within a lake, pond, reservoir, or other suitable open channels. The major disadvantage of these systems is that the surface water temperature can be affected by weather condition.

This review focuses on mathematical modeling of thermal effects on the ground involved in geothermal energy use, SWHP systems will not be discussed further in the present study. A synthesis on simulation of alternative direct low enthalpy systems will be presented.

In order to give a general overview on the subject, only a brief summary of numerical models for medium and high enthalpy reservoirs will be presented here. A detailed and comprehensive review on the subject has been recently proposed by Franco and Vaccaro [6].

2. Low enthalpy applications: Ground-Source Heat Pumps (GSHP)

2.1. Ground-Coupled Heat Pump (GCHP) systems

In a GCHP system, heat is extracted from the ground and often re-injected via a closed loop, i.e. Ground Heat Exchanger (GHE), through which water or antifreeze fluids circulate. GHEs commonly used in GCHP systems typically consist of HDPE pipes which are installed in either vertical boreholes (called vertical GHE) or horizontal trenches (horizontal GHE). In horizontal GCHP systems, GHEs typically consist of a series of parallel pipe arrangements laid out in dug trenches approximately 1–2 m below the ground surface. The major disadvantage is that at their typical depths the ground temperature is more affected by the external air conditions. Another disadvantage is that the installation of horizontal systems needs larger surfaces than vertical ones.

In vertical GCHP systems, the GHE configurations may include tens or even hundreds of boreholes, each containing single or double U-tubes through which heat exchange fluid circulates. The borehole annulus is generally backfilled with special material (grout) that can prevent contamination of ground water.

In recent years, in order to reduce perforation costs and land area requirements, foundation piles have been used as GHEs. Pipes are buried in concrete piles, in configurations of single or multiple U-tubes or spiral coils. This last configuration has the advantage of