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On the use of heat pipe principle for the exploitation of medium–low temperature geothermal resources

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HIGHLIGHTS

- Direct geothermal heat extraction systems for direct uses and power production.
- Utilization of shallow medium–low temperature geothermal reservoirs and aquifers.
- Heat Pipe and Closed Loop Thermosyphon principles for geothermal energy utilization.
- Review of Heat Pipe Turbine schemes from literature and discussion on design issues.
- Performance analysis of ORC systems combined with SBES heat extraction systems.

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ABSTRACT

In the direct use of geothermal energy without fluid extraction, heat transfer takes place with no alteration of the natural hydrogeological balance of the basin. An interesting solution both for thermal energy and power production could be the application of heat pipe principle, in particular the Closed Loop Two Phase Thermosyphons (CLTPT). In shallow or not much deep geothermal reservoirs with temperature below 100 °C, the two phase closed loop thermosyphon can transfer heat very efficiently. In this case the most important task is the enhancement of the heat transfer mechanism between the heat exchanger and the aquifer.

In the first part of the paper a review of particular applications connected to the geothermal heat pipe applications is proposed, then an analysis of the main technical elements regarding the geothermal aquifer exploitation through two phase thermosyphon systems are given. Some guidelines for power systems sizing are discussed and a proposal for the design of a single borehole heat extraction system with binary cycle utilization is provided.

1. Introduction

The utilization plants for low and medium temperature (70–100 °C) geothermal reservoirs based on geofluid extraction, like ORC plants have some inconveniences. The mass withdrawal from the aquifer can alter the natural balance of the basin, while over-exploitation causes temperature and pressure reduction during the lifetime of the plant [1]. The use of extraction pumps for the circulation of corrosive or chemically aggressive geothermal fluids leads to high installation and operation costs and short machinery useful life. Moreover a second well is usually necessary for reinjection, due to evident technical and environmental reasons. In the exploitation of the great geothermal reservoirs, in particular for power purposes, other important issues have to be considered, like for example micro-seismicity, waste water treatment and in a more significant way scaling, chemical deposition phenomena and corrosion [2].

These problems can be avoided using devices that only allow heat transfer with the aquifer, basing on the concept of the Single Borehole Extraction System (SBES), proposed in 1986 by Lockett [3]. For this application a secondary fluid (e.g. water or a low boiling point organic fluid) is needed and a downhole heat exchanger (DHE) is necessary. A DHE consists of a coil or a U-tube located in a well, in which the working (or secondary) fluid circulates (by natural convection). The use of DHE has been discussed extensively in literature both numerically and experimentally in a period of over 30 years. Some papers well summarize the various activities and problems related as for example Lund [4] and Carotenuto et al. [5].

Several types of downhole heat exchangers have been proposed in order to extract heat directly from shallow geothermal aquifers

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or ground: thermosyphon type heat pipe, concentric tube thermosyphon, downhole coaxial heat exchanger (DCHE), U-tube downhole heat exchanger, as well as others.

The main disadvantages of DHE systems respect to fluid extraction systems deal with the absence of heat flow induced into the aquifer by fluid extraction. The heat flow that can be extracted from the well is then tied only to the natural convection that occurs in the aquifer-well system. In case of low aquifer permeability, the convective transport can be particularly weak and the heat extraction can only reach limited values. However, even in favorable conditions, that is for permeability greater than about 10^{-4} m/s or 10^{-3} m/s, DHEs are suitable systems for moderate temperature geothermal applications (typically above 70 °C).

An alternative and more advantageous pathway with respect to DHE is the application of the heat pipe concept, both in the basic version and in the Closed Loop Two Phase Thermosyphon (CLTPT) configuration [6,7]. The principle of Geothermal heat pipe has been proposed in applications with some renewable energy sources and utilization of deep underground heat sources.

A particular case of Closed Loop Thermosyphon, named geothermal convector (GTC), for the heat extraction from geothermal aquifers was proposed and tested by Carotenuto et al. [8]. Rieberer [9] has carried out theoretical and experimental studies on ground-coupled heat pumps using carbon dioxide based thermosyphons.

The utilization of the thermosyphon concept for geothermal heat extraction avoids the need of a downhole pump. Downhole pumps have two different drawbacks: firstly, they have relatively short lifetimes as they operate in harsh conditions, and secondly it is less thermodynamically efficient to pump and pressurize the fluid and then exchange heat on the surface. Compared with the conventional systems based on the extraction of water, CLTPT permits to exchange heat at a constant temperature and it has also other advantages:

- it can be used even in dry geothermal areas (or characterized by very low fluid circulation);
- a loop type heat pipe can control the heat transfer rate by controlling the flow rate of the returning working liquid.

The use of heat pipe technology has also been proposed also for geothermal power production since the early 1990s [10–12]. An interest to the utilization of two phase thermosyphon is demonstrated in connection with development of Enhanced Geothermal Systems (EGS) for power purposes by Ziapour et al. [13] and Wang et al. [14]. Recently the use of Thermosyphon Loops has been proposed for heat extraction from the ground and for domestic space heating [15] and different applications. The advantage of heat pipe, using carbon dioxide as working fluid in conjunction with a ground source heat pump, is shown also by Ochsner in Ref. [16] and its use is prospected for moderate temperature aquifer with the working fluid in transcritical conditions (the critical temperature of CO_2 is only 31.1 °C).

Notwithstanding the scientific interest of the concept, commercial systems are not available today even if a meaningful research work has been carried out. Moreover the organic fluids that were used in most of the application are refrigerant (like R11), that are no longer acceptable, since they are banned.

In the present paper an analysis on the possible use of the CLTPT principle for the geothermal heat extraction from resources at temperatures below 100 °C is analyzed both in case of direct use and in case of power production from a binary cycle plant system based on CLTPT operating principle, with the aim of a complete knowledge for the development of such kind of system.

The paper is structured as follows: the next section describes the general aspects of the use of geothermal energy without liquid extraction, while Section 3 presents an analysis of geothermal energy systems that were experimentally investigated in the past both theoretically and experimentally. In Section 4 the approach used for the definition of the potential of an aquifer is presented. In Section 5 the use of a CLTPT system for power production (through a single borehole ORC plant) is illustrated. Section 6 reports a brief discussion, while conclusions are drawn in the last section.

2. Geothermal systems without fluid extraction

In geothermal heat utilization a balance between fluid/heat extraction and natural recharge has to be identified, in order to maintain the renewability of the source. Fig. 1 summarizes the main strategies and practices for geothermal resources utilization.

In the past years, an “open-cycle” layout with surface discharge and no fluid reinjection has been adopted. This clearly leads to geothermal resource impoverishment. Higher production rates can exceed the natural long-term recharge rate causing a resource depletion. For this reason in the majority of the utilization schemes the fluid reinjection is considered, to replenish the fluid content and to help sustaining or restoring reservoir pressure.

A completely different pathway is represented by the applications without fluid extraction: these systems can be used both for direct energy utilization and for power production (this second possibility is referred to experimental and not commercial solutions, as it is described in this paper). The absence of fluid extraction encounters the aim of geothermal sustainable utilization, also avoiding the drilling of a reinjection well. Furthermore problems related to the chemical properties of fluid extracted (scaling, corrosion) are avoided. Heat extraction from a geothermal reservoir or from the ground can occur by two methods: heat transfer from an aquifer and extraction of the heat from the rocks surrounding the well.

Let us schematize the process according to the first scheme that is of specific interest for the present paper. The scheme is based on the presence of an aquifer, in which different level and thermal conditions can be identified. The heat extraction from the aquifer is due to an auxiliary fluid that in general operates between two temperatures (T_{in} and T_{out}, with $T_{in} < T_{out}$). In case of a two phase system the two temperatures can be the same, but the quality of the fluid is different (Fig. 2).

If the heat exchanger becomes an evaporator, once heat extraction occurs and a convective flux in the water surrounding the evaporator is established, a portion of the water will be

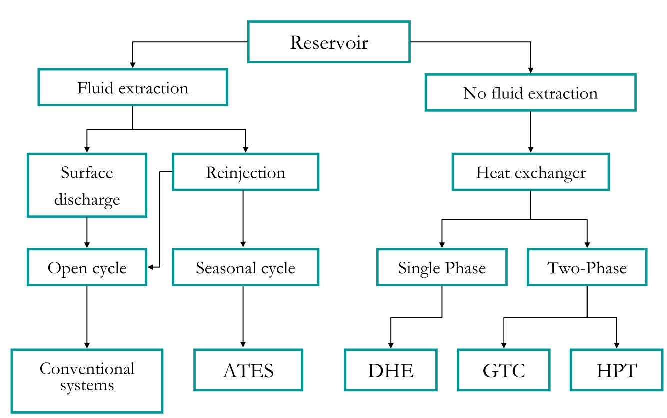

Fig. 1. Pathways for the use of geothermal energy.