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Possible applications of ground coupled heat pumps in high geothermal gradient zones

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ABSTRACT

Geothermal energy is increasingly being used to heat and cool buildings. However its use has been slow to catch on due to the high installation costs of the most common Borehole Heat Exchangers (BHE), which constitute the major cost item of an air geothermal conditioning system. In areas where the shallow subsoil temperature is higher than normal (geothermal basins), the average temperature of the carrier water in the BHE is higher than in systems located in areas with a normal geothermal gradient, thus improving heat pump Coefficient Of Performance (COP). This paper investigates a range of solutions that use geoexchange systems coupled with BHE in anomalous geothermal zones. This study evaluates a residential building's heating system when it is directly coupled with BHEs and compares the results with a range of thermal plant solutions. In Northern Italy, as in many other parts of the world, there are places where the ground's thermal conditions are anomalous, with temperatures reaching around 35–85 °C, instead of normal values of about 13–15 °C. The energy of the building was analyzed by means of the TRNSYS, coupled with the CaRM model—designed by the authors—which provides detailed thermal behaviour readings for Ground Heat Exchangers (GHE).

1. Introduction

Ground Coupled Heat Pumps (GCHP) have been increasingly used in the last decade around Europe, and companies producing heat pumps, or drilling wells and boreholes, are devoting more time and energy to this field. GCHP systems can be used in a wide range of applications, from small residential buildings to large-scale commercial ones, and are considered to be one of the most highly efficient heating and cooling technologies. The core of the system is the Ground Heat Exchanger (GHE), which comes in a range of models and comprises a closed loop of buried pipes. The GHE may be a simple pipe system buried in the ground; it may also comprise a horizontal network or, more commonly, vertically drilled boreholes filled with double U (or single U) pipe and grout (i.e. Borehole Heat Exchangers [BHE]) [1]. These systems, when coupled with heat pumps, ensure far greater energy efficiency than air-source systems. However, they are rarely used because of their high initial installation costs.

Ground temperatures usually vary from 7 °C to 20 °C, depending on outdoor mean annual air temperature. Geothermal areas are therefore a highly promising field of application, as subsoil temperatures can reach 35–85 °C. When low-temperature geothermal energy is employed (known as low-enthalpy use) the ground normally performs as an energy source, energy sink or storage device [2–4]. For the purposes of this study, the ground will be considered only as an energy source due to the high mean temperature level of the subsoil. Accordingly, the GCHP systems in geothermal areas must be used in heating mode only.

A number of European regions are well known as low temperature (i.e. liquid dominated) shallow geothermal sites [5], and many of them are home to famous tourist destinations. In a wide variety of cases, however, it might be difficult to heat houses directly with water and indirectly with open circuit water-to-water heat pumps due to local regulations and restrictions. Nevertheless, even if the ground reaches mean temperatures of about 25–30 °C, its energy can be exploited through the use of vertical closed loop heat exchangers in GCHP, which, if properly designed and installed, do not damage the groundwater.

Low-temperature geothermal energy has recently attracted more attention because it can be used in geographical areas that are not typically associated with it. Its appeal includes, but is not

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Nomenclature

a	diffusivity (m^2/s)
Fo	Fourier's number (at/r^2) (–)
k	slope of the curve (–)
q	specific heat flow per unit length (W/m)
r	radius (m)
R_b	borehole thermal resistance (m K/W)
t	time (s)
T_b	borehole wall temperature (°C)
T_f	fluid temperature (°C)
T_0	undisturbed ground temperature (°C)
γ	Euler's constant (–)
λ_{ground}	ground thermal conductivity (W/m K)
RppA	thermal resistance between adjacent tubes (m K/W)
RppB	thermal resistance between opposite tubes (m K/W)
Rp0	thermal resistance between tubes and borehole wall (m K/W)

limited to, its stable, base-load energy output, low environmental impact and high renewability [6].

The north-east Italian town of Abano Terme, which sits in the Euganean Geothermal Basin, is one potentially attractive site for the expansion of geothermal resource utilization due to the area's high ground temperatures [7].

The thermal properties of the water in the Abano Terme area were known to the ancient Romans, but they were only marketed on a larger scale at the beginning of the 20th century, reaching their peak in the 1960s, when artesian wells stopped the natural outflow of thermal water and pumps were used to extract thermal water from the sandy aquifers in the alluvial cover. However, as this water was not injected back into the aquifers, the extraction rate overtook the recharge rate, causing subsidence, which reached a rate of 2 cm/y, and damaged some buildings and infrastructure [8].

In general, two systems are used in areas characterized by low enthalpy: open-loop and closed-loop. In open-loop systems, groundwater is the heat-carrier fluid and it enables heat to be exchanged directly with a heat pump or a heat exchanger. Water is extracted from a well and then either injected back into another well, or discharged at the surface. The same principle applies when hot groundwater is extracted for therapeutic purposes.

The alternative technique is to use closed-loop systems. A closed-loop system is generally not subject to bureaucratic issues related to mining concessions and does not cause subsidence.

This paper discusses an application that exploits low-enthalpy geothermal energy. The feasibility of installing a Borehole Heat Exchanger (BHE) in Abano Terme was analyzed and research was then conducted within the Euganean Geothermal Basin (Fig. 1) where thermal resources are exploited for multiple uses. The field covers a total surface area of about 40 km^2 and comprises four towns (Abano Terme, Montegrotto Terme, Battaglia Terme and Galzignano Terme) [9]. The word "Terme" means "Spa" and the area includes more than 130 establishments and 220 thermal pools. It is an important part of the region's economic, social and health sectors, employing over 5000 people directly and another 6000 in associated services.

In areas where the temperature is higher than usual, some critical aspects, such as materials and drilling methods, have to be taken into account. Furthermore, proper grouting materials for sealing have to be chosen to obtain good thermal contact between the pipe and ground, as have good hydraulic isolation between the different groundwater levels crossed by wells. Last but not least, pipes should be made of special materials due to high ground temperatures. Therefore, high-strength Peroxide Crosslinked Polyethylene (PE-Xa) is recommended, as it resists both standard circuit pressure and high temperatures.

The Euganean Geothermal Basin can be classified as a hydrothermal convection system, where the water is the dominant phase [10,11]. At present, about 250 wells are active and the total average extraction flow rate of thermal fluids is about 17 million m^3/year. These fluids are exclusively used for health purposes, as required by current legislation. The physical and chemical parameters of the Euganean area's thermal waters have been extensively analyzed, mainly with statistical methods. Temperatures range from 60 °C to 87 °C, and remain practically constant, confirming that the Basin has "a high-up flow rate". The total dissolved solids are 6 g/l with a primary presence of Cl and Na (70%) and a secondary one of SO_4, Ca, Mg, HCO_3 and SiO_2. 3H and carbon-14 measurements suggest a residence time of more than 60 years, but the most likely figure is a few thousand years. Analyses of oxygen isotopes show that the thermal waters are of meteoric origin and fall in an area up to 1500 m a.s.l. in the Pre-Alps [12]. Work [9] proposed a good example of the hydrothermal circuit, which explained the genesis and dynamics of Euganean fluids. Rainwater infiltrates the Pre-Alps and reaches depths of 3000–4000 m, is warmed up by the normal geothermal gradient, and circulates towards the South East, flowing through a complex of hills formed by the Lessini, Berici and Euganean Hills. The Permian crystalline-schist bed is the lower limit of the water circulation system and is conditioned by the structural shape of the region.

Fractures and faults in the structure of the Euganean Geothermal Basin lead to a rapid ascent of the fluids and to temperature homogenization, which is linked to the presence of convective motions. Other factors facilitate upwards movement, such as the side of the system being sealed with low permeability sediments and the hydraulic load being generated by cold groundwater seepage from the surface of the Euganean Hills [10,11].

The main aquifer is formed by Red Scaglia and Jurassic limestone, but the others, which are located in the alluvial quaternary sequence, are formed by sands interlayered with clay and silt. In this sequence, the deep waters mix with the surface waters, lowering salinities and temperatures. Until late last century, Abano Terme's spa-resort waters originated from springs or lakes. Later, they were pumped from wells that drained the quaternary aquifers. Later still, the extraction of sand, along with the formation of subsidence, led to the wells being deepened so that water could be drawn directly from the fractured rock [13,14].

2. Case study

GCHP systems use the ground or the groundwater flow as a heat source-sink to provide space heating and cooling and are generally more energy efficient than heat pumps that use outdoor air as a heat source-sink [15]. As aforementioned, in zones affected by thermal anomalies the use of heat pumps was especially investigated in terms of direct use of groundwater flow [16] in heating mode. This paper estimates the energy requirement of different building heating systems coupled with GCHP and BHE (i.e. closed loop system) in ground with an anomalous temperature gradient.

Research was divided into two parts. The first involved the definition of a building model and the subsequent calculation of heating loads during the year. Ground and BHE properties were then investigated to estimate thermal exchange capacity. A Thermal Response Test (TRT) [17–20] was performed to calculate ground properties in the study area with one BHE at a depth of about 125 m.