Evaluation of geothermal energy production using a WellBore Heat eXchanger in the reservoirs of Campi Flegrei and Ischia Island

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ABSTRACT

The volcanic district of Campania (Italy) is an area with a remarkable geothermal potential, especially in the areas of the Vesuvio, Campi Flegrei and Ischia Island. However, in the Campania region it is very difficult to obtain the community support for geothermal projects because the population is scared by of possible induced seismic and volcanic phenomena related to the plant activities.

A good compromise between the social acceptance and the geothermal energy exploitation can be the extraction of heat without the production of geothermal fluids by using a heat exchanger inside the well, the WellBore Heat eXchanger (WBHX). The aim of this work is the evaluation of the performance of the wellbore heat exchanger in the reservoir of Campi Flegrei and Ischia Island.

1. INTRODUCTION

In the volcanic district of Campania several researches between 1939 and 1943 and between 1977 and 1985 have been conducted. More than one hundred wells have been drilled, reaching the maximum depth of 3046 m. These investigations have confirmed the presence of high geothermal gradients in the areas of Campi Flegrei and Ischia.

Currently, some pilot projects of binary power plants in these areas have been proposed to the Ministry of Economical Development. However, a positive social acceptance of geothermal exploitation projects is important these days. In the Campania region it is very difficult to obtain the community support for geothermal projects because the population is scared of possible induced seismic and volcanic phenomena during the extraction and reinjection activities.

To find a good compromise between the social acceptance and the geothermal energy exploitation, the extraction of heat without the production of geothermal fluids can be a valid option. This can be achieved by using a heat exchange device inside the well, the wellbore heat exchanger (WBHX). This type of plant is a closed loop, where a heat carrier fluid circulates inside the well without direct contact to the reservoir brines.

Starting from the literature data, the geothermal energy production using the WBHX in the area of Campi Flegrei and in the south-west sector of the Ischia Island was evaluated. For this purpose a numerical simulator was used, which implements an analytical model of the heat exchange between the WBHX and the geothermal reservoir. The results of the simulations recommend a different application of the extracted heat for each area.

2. STUDY AREA

2.1 Campi Flegrei area

The Campi Flegrei area has a typical horseshoe shape and it is located in the north-western border of the Napoli gulf; the area is a caldera with 12 km diameter with its centre in the Pozzuoli bay. From the regional geographic point of view, the phlegrean area is located inside the tectonic structure named graben, which is a wide coastal plain between the Tirreno and the Appennini (pleistocene-holocene period). According to Orsi et al. (1996), the formation of the caldera is formed by two high energetic eruptive events: the eruption of the Campanian Ignimbrite (39.000 years ago) and of the Neapolitan Yellow Tuff (15000 years ago) (Armienti et al., 1983; Lirer et al. 1987; Rosi & Sbrana, 1987; De Vivo et al., 2001; Deino et al. 2004).

The dynamism of Campi Flegrei is characterized by the bradyseism: rises and drops of the ground which has occurred over centuries and has left clear traces. The most intense seismic period in the last 50 years, has occurred between 1982 and 1984; during which a ground subsidence of of 2 m was observed.. The magnitude of the phlegrean earthquakes is generally lower than 1.0, with a maximum magnitude of 4.0 in the period 1982-84. The majority of the seismic events are located at a depth of 2-3 km and are not detected by the population but only by the instruments.

According to Zollo et al. (2008), the conceptual model of the geothermal reservoir of the Campi Flegrei can be represented by a deep magmatic source (8-10 km), with a thickness of about 1 km and a diameter equal to that of the caldera and an heat flux of $6{\cdot}10^{12}$ Jm^{-2} per area. This primary source provides heat for the layers above. At a depth greater than 3-4 km the fluids circulate very slowly, therefore the heat transport is conduction dominated. In the shallow layers (0-2 km) an advective transport takes place because of the high permeability due to the fracture system. This also allows the fluid transfer to the surface.

Several wells have been drilled in the area of Campi Flegrei since the 40’s by the companies SAFE, AGIP and ENEL (Figure 1).

Three aquifers have been identified in the underground: the first aquifer is located at a depth between 500 and 1000 meters with 20% of vapour and temperatures in the range of 100 ÷ 130 °C; the second aquifer is located at a depth between 1800 and 2000 meters with 40% of vapour and an average temperature of 300°C; the third and deepest aquifer is located between 2500 and 2700 meters depth and is most likely a vapour dominated system.

Figure 1: Campi Flegrei caldera. The dotted line indicates the limit of the caldera. White circles represent the location of shallow wells drilled since 1939; red circles represent the deep wells drilled during the AGIP-ENEL Joint Venture until 1980 (Carlino et al., 2012).

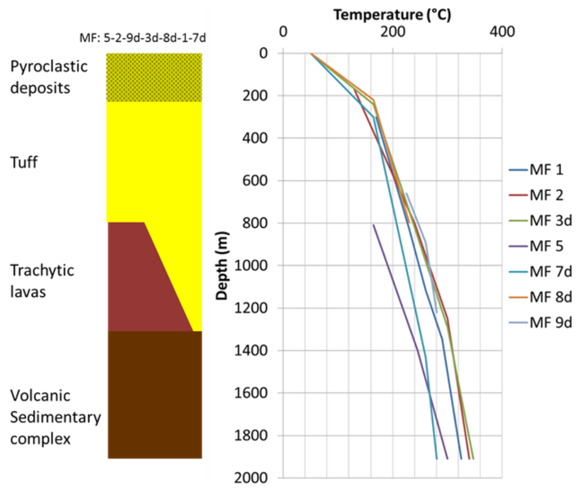

Figure 2: Simplified model of the underground and temperature gradients of Mofete area.

Using the results of Carlino et al. (2012), a simplified model of the underground and the geothermal gradients of Mofete have been built (Figure 2); the depth of 1900 m, corresponding to the maximum drilling depth, has been selected to evaluate the application of the WBHX. The trend of the geothermal gradients indicates that the reservoir is a liquid dominated system and that the heat exchange occurs by conductive phenomena.

Table 1 shows the physical and thermal properties of the geological formations.

Table 1: Physical and thermal properties of the geological formations.

Lythologhy	ρ kg/m^3	λ W/m K	c_p J/kg K
Pyroclastic deposits	1800	2.90	840
Tuff	1550	1.50	2000
Trachytic lavas	2500	2.90	840
Volcanic sediment. complex	1800	2.90	840

2.2 Ischia Island

Ischia Island is part of the Phlegrean islands, which is the emerged portion of a volcanic basin located in the north-western sector of the Gulf of Naples (Carlino et al., 2014). The surface of Ischia Island is about 42 km^2 and the maximum height is 787 m on the top of the Monte Epomeo, which is located in the central part of the island.

Ischia Island has a geothermal system probably due to a subjacent magmatic structure, whose top is located at a depth of approximately 2 km. Important superficial geothermal phenomena occur on the island, like fumaroles and hot spring.

Ischia is crossed by four fault systems (Vezzoli, 1988; Molin et al., 2003; Paoletti et al. 2009), which are responsible of the diffuse seismicity in the northern sector of the Island. The last and strongest seismic event occurred in 1883 (Carlino et al., 2014). At present, the seismicity is of low intensity and the earthquakes are located at shallow depth with several bradyseismic events (Paoletti et al. 2009).

The geothermal exploration of Ischia started in 1939 and stopped in 1954 in two different phases. Between 1939 and 1943, 84 wells have been drilled in the south-western sector (Fig. 3) (Forio and Serrara Fontana) and in the northern sector (Casamicciola) of the island; the maximum depth reached 100 meters. The second phase of exploration was conducted in the western and southern areas by Safen between 1951 and t1954. The drilling reached a depth of 1 km, which enabled a valuation of the geothermal gradients (Carlino et al., 2014).

The geothermal system of Ischia consists of two shallow reservoirs, which are geologically separated, and a third deeper reservoir. A shallow reservoir is located in the western sector of the island, close to the horst of Monte Epomeo, at a depth of 150 ÷ 500 m; the brine temperature is between 150 and 200 °C, the pressure is about 40 bar. The second shallow reservoir is in the eastern sector, located in the graben of Ischia and is characterized by a lower brine temperature. The deep reservoir has been hypothesized at a depth greater than 900 m with a brine temperature of 270 ÷ 300 °C and a pressure of 90 bar (Carlino et al., 2014; Di Napoli et al., 2011; Di Napoli et al., 2009; Chiodini et al., 2004).

The consequence of the high geothermal gradient and pressure in the island is that the water evaporates at the depth of 1 km and that the water in critical conditions (374°C, 22 MPa) may be found at the depth of 2 km.

Figure 3: Ischia Island. White circles represent the location of shallow wells; red circles represent the deep wells .

Using the information reported in Carlino et al., (2012), a simplified model of the underground of Maronti and Serrara Fontana has been built (Figure 4); in order to simulate the application of a deep borehole heat exchanger, a depth of 1000 m has been selected for all the wells. The geothermal gradients highlight that the reservoir is a steam dominated system and that the heat moves by convection.

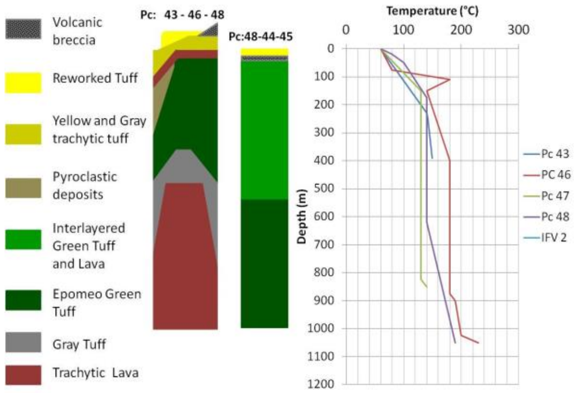

Figure 4: Simplified model of the underground and temperature gradients of Serra Fontana and Maronti.

The physical and thermal properties of the geological formations used for the simulations are shown in Table 2.

Table 2: Physical and thermal properties of the geological formations.

Lithologhy	ρ kg/m^3	λ W/m K	c_p J/kg K
Volcanic breccias	1800	2.90	840
Reworkered tuff	1550	1.50	2000
Yellow & gray trachytic tuff	1550	1.50	2000
Pyroclastic deposits	1800	2.90	840
Interlayered Green Tuff and Lava	2025	2.2	1420
Epomeo Green Tuff	1550	1.50	2000
Gray Tuff	1550	1.50	2000
Trachytic lava	2500	2.90	840

3. OPTIMIZATION DESIGN FOR THE WBHX

The WellBore Heat eXchanger device is a deep borehole heat exchanger (Fig.5). The well bottom is closed and a coaxial tube is inserted into the well; in the WBHX a heat carrier fluid circulates and acquires heat from the surrounding rock.

Several researchers have analyzed the feasibility of the WBHX, the operative parameters and the use of different heat carrier fluids (Kohl et al., 2002; Kujawa et al., 2006; Zhang, 2008; Davis and Michaelides, 2009; Bu et al., 2012; Cheng et al., 2013; Cheng et al., 2014; Templeton et al., 2014; Alimonti and Soldo, 2016).

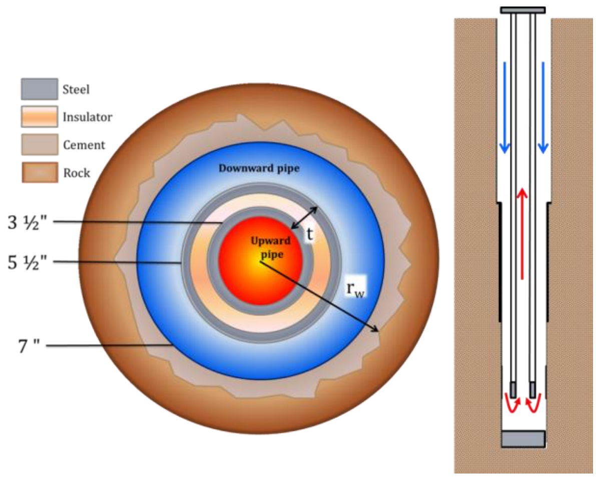

Figure 5: WBHX configuration.

In the proposed work (Alimonti and Soldo, 2016), the water has been selected as the best heat carrier fluid, because it has the higher volumetric heat capacity The water circulates in the annular space between the well casing and the external shell and, flowing downward, the fluid acquires the heat. At the well bottom the water flows into the inner pipe and, thanks to the thermosiphon effect, it goes back to the wellhead naturally. Therefore, no electrical energy is required to pump the fluid upward. The space between the two pipes is filled with insulating material.

The heat transfer phenomena between the hot rock and the water circulating in the WBHX take place by conduction and convection. Alimonti and Soldo (2016) proposed a WBHX model based on the analytical solution of the Fourier equation; the model has been implemented in a C computation code.

The geometric configuration of the exchanger, applied to Campi Flegrei and Ischia Island, is the result of 48 different configurations: the internal and external pipes have been changed, with a fixed flow rate of 10 m^3/h over a period of 183 days. The selected design is the one which gets the greater thermal power with the higher wellhead temperature and ensures the thermosiphon effect.

The internal and external diameters of the selected casings are reported in Table 3.

Table 3: Design of the WBHX in the Campi Flegrei area and Ischia Island.

7 Casing Diameter	150.3 mm
5 ½" Pipe - External Diameter	139.7 mm
5 ½" Pipe - Internal Diameter	121.4 mm
3 ½" Pipe - External Diameter	88.9 mm
3 ½" Pipe - Internal Diameter	77.9 mm
7 Casing Diameter	150.3 mm

4. EVALUATION OF THE WBHX PERFORMANCE IN THE STUDY AREAS

Following, the results of the application of the deep borehole heat exchanger in the study areas, are presented. Two different utilizations of the extracted heat have been suggested: in the area of Campi Flegrei, a geothermal electrical power plant is proposed, whereas for Ischia Island, the direct use of extracted thermal power is more beneficial.

4.1 Campi Flegrei area

The proposed plant for the Campi Flegrei area is the conversion of the thermal power into electricity, using an ORC plant. The electrical power has been calculated using the correlation provided in the MIT report (2006), obtained by regression of the data available from ORC plants that are active in the world:

$$E = TP \cdot \eta_{th} = TP \cdot (0.0935 \cdot T_i - 2.3266) \qquad [1]$$

where TP is the thermal power and Ti is the inlet temperature of the heat carrier fluid into the ORC plant.

The selection of the working flow rate is related to the potential produced electrical power (Fig. 6); after 10 hours of operation of the WBHX, the results of the simulations indicate that with a flow rate of 20 m^3/h, the maximum amount of electricity may be obtained.

Figure 7 shows, that in the first six months of application of the deep borehole heat exchanger a decrease of the wellhead temperature is observed.

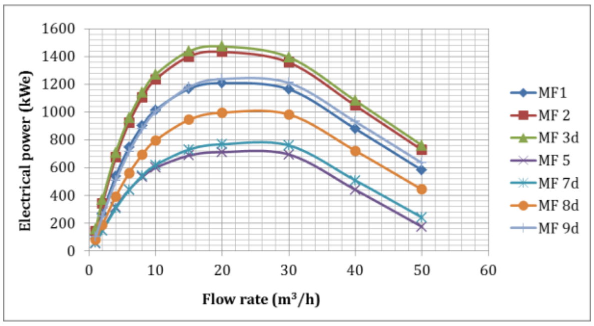

Figure 6: Electrical power versus flow rate after 10 hours of operation of WBHX.

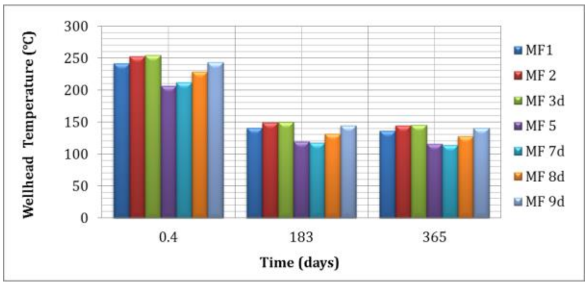

Figure 7: Wellhead fluid temperature in time (20 m3/h).

This phenomenon is due to a progressive enlargement of the influence area on the well, which takes place. After a period of six months, the system tends to approach a steady state condition. After one year of application of the WBHX the values of the wellhead temperature are between 114 °C (MF 7d) and 145 °C (MF 3d). The expected electricity production will be between 139 kWe and 267 kWe (Fig. 8).

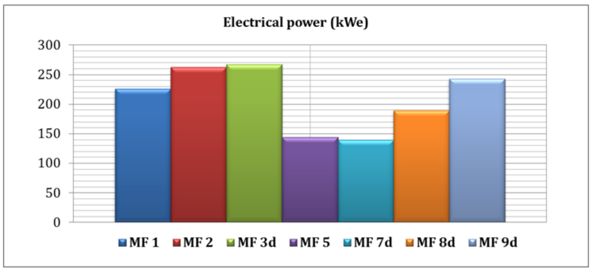

Figure 8: Electrical power versus flow rate after 10 hours of WBHX operation.

Table 4: WBHX-ORC power plant at Campi Flegrei.

Thermal power per well	2.3 MW
Wellhead temperature	150 °C
ORC efficiency	11%
Electrical power per well	250 kW
Number of wells	10
Power plant size	2.5 MWe ~ 22 GWh per year

The wells MF 3d and MF 2 are the ones that generate the highest values of electrical power (about 250 kWe). For the development of a 2.5 MWe geothermal power plant, the drilling of 10 wells in the area is recommended (Table 4). The average annual electrical need or a four-member family is 2.7 MWh. Therefore, the proposed plant may satisfy the electrical demand of approximately 8000 families.

4.2 Ischia Island

In Ischia Island, the conversion into electrical energy is not worthwhile and a district heating plant for civil or industrial use has been proposed.

To select the flow rate of water in the WBHX, the wellhead temperature (Fig. 9) and the produced thermal power (Fig. 10) have been taken into account.

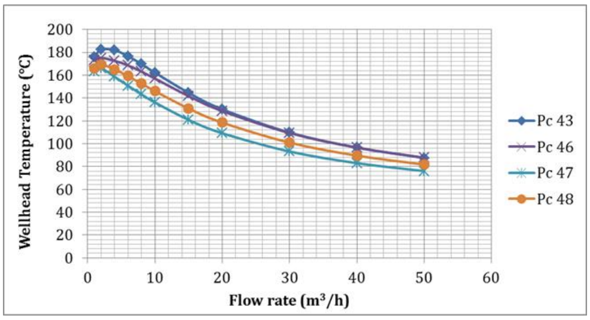

Figure 9: Wellhead fluid temperature versus flow rate after 10 hours of WBHX operation.

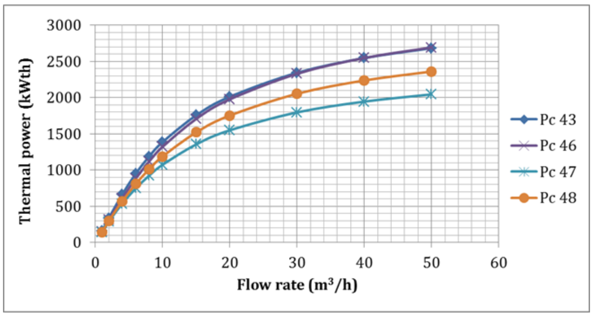

Figure 10: Thermal power versus flow rate after 10 hours of WBHX operation.

The thermal power increases with the flow rate, whilst the fluid temperature drops. Therefore, the value of 20 m^3/h has been chosen: after 10 hours of WBHX operation, the wellhead temperature is between 105 °C and 128 °C.

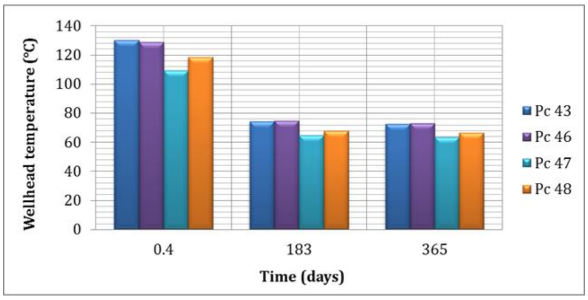

Figure 11: Wellhead fluid temperature over time (20 m3/h).

After one year of WBHX operation, the water temperature is between 63 °C and 73 °C (Fig. 11); these temperatures are still in the range of district heating applications.

The produced thermal power after one year is between 535 kWth and 740 kWth (Fig12).

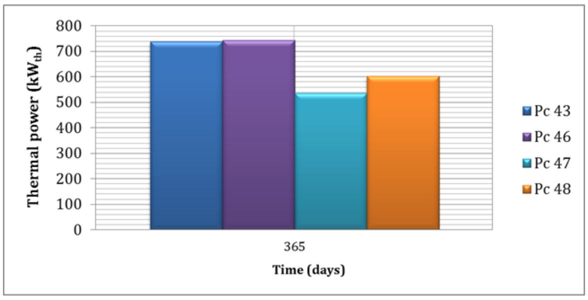

Figure 12: Wellhead fluid temperature over time (20 m3/h).

The highest values of thermal power are produced from the wells Pc 43 and Pc 46 (about 750 kW).

Considering a house of 75 m^2 with insufficient insulation, the request of thermal power is about 10 kW. The drilling of 10 wells in the area may satisfy the thermal demand of 750 apartments.

4. CONCLUSIONS

The aim of this work is to evaluate the application of the WBHX in the area of Campi Flegrei and in the south-western sector of the Ischia Island. The WellBore Heat eXchanger may be a good compromise between the social acceptance and the geothermal energy exploitation, as this device produces geothermal heat without production of brines.

The WBHX model is based on the analytical solution of the Fourier equation and implements a C computation code, has been used to simulate the thermal exchange between the rock and the wellbore heat exchanger.

The results of the simulations highlight that the application of a deep borehole heat exchanger in the study areas could be an interesting opportunity. Nevertheless, two different utilizations of the extracted heat have been proposed. In the area of Campi Flegrei, by combining the WBHX with an ORC machine in 10 wells, a 2.5 MWe power plant may be developed. In Ischia Island, the conversion into electrical energy is not worthwhile but the direct use of the extracted thermal power has been recommended. The thermal power of 10 wells in the area may satisfy the thermal demand of 750 apartments with an area of 75 m^2.

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