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Geothermal Energy Exploitation of Campi Flegrei Using a Deep Borehole Heat Exchanger: the Coupling of the Borehole Model with a SHEMAT Reservoir Model

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ABSTRACT

Campi Flegrei area (Italy) is a caldera that hosts a hot and saline geothermal system with a geothermal gradient in the range 100 ÷170 °C/km. The site is well known in the geothermal sector but the geothermal exploitation of the area has never take off in the past, due to the competitive price of the oil. Nowadays, the negative social response to the activities of drilling and fluid extraction is the main barrier to the geothermal development. The possibility of producing geothermal energy without brine extraction, using a deep borehole heat exchanger, may be the key issue for the restart of geothermal projects in the Campi Flegrei area.

The feasibility evaluation of the deep borehole heat exchanger should include the study of the heat transfer inside the formation and of the temperature decline in the surrounding of the device. This is true especially in the case of Campi Flegrei area, where the geological and hydrological structure of the reservoir produces an advective transport in the first 2 kilometers, which may produce a recovery action with respect to the heat extracted from the ground.

The software Processing SHEMAT has been selected for the reservoir modeling, whereas the production of heat via heat exchangers has been simulated using a pure conductive semi-analytical model (Geopipe). The coupling between the two models has been made with an iterative approach. Then, the simulation has been carried out using only the semi-analytical model, which is able to evaluate the variation in time of the ground thermal resistance when the borehole heat exchanger is working. The aim of the authors is the comparison of the two approach in terms of sustainability of the heat extraction in time and the influence on ground temperature.

1. INTRODUCTION

Since 2000, several researches have been focused on the possibility to produce geothermal energy without brine extraction via deep borehole heat exchangers. Nalla et al. (2005) named this type of device, WellBore Heat eXchanger (WBHX) describing it as two coaxial tubes inserted into the well (Fig.1).

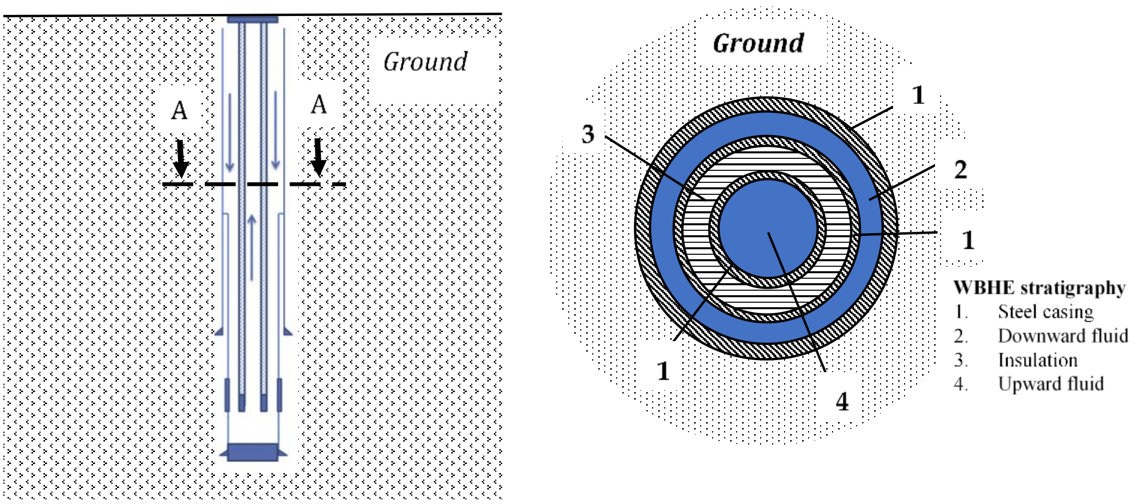


Figure 1: Vertical and axial sections of the WBHX.

The strength of this solution is the prevention of costs and consequences related to the extraction, handling, and reinjection of geothermal fluids. The low heat transfer effectiveness and the high pumping work, with respect to the conventional geothermal wells are the main weaknesses. Anyway, the WBHX could represent an opportunity for the exploitation of unconventional geothermal systems, in which the brine is absent or it requests expensive treatment techniques. Several authors evaluated and proposed the refitting of the depleted oil & gas wells in order to produce geothermal energy with the deep borehole heat exchanger. The extracted heat can be used for the production of thermal power or electricity with an Organic Rankine Cycle plant (Alimonti and Soldo, 2018).

Despite few field tests on the deep borehole heat exchanger have been carried out (Kohl et al., 2002), the evaluation of the performance of the WBHX is widely treated in literature. The authors have focused their analysis on the operational parameters, design characteristics, thermal properties of the formation and the heat carrier fluid. The results demonstrate that the most efficient heat carrier fluid is water and the most influencing parameter of heat extraction is the residence time of the fluid in the device, which is function of the flow rate and the diameters (Alimonti and Soldo, 2016). Kujawa et al. (2006) and Wang et al. (2009) demonstrated that the insulation of the internal pipe is necessary in order to avoid heat exchange losses. The temperature of the extracted fluid is directly proportional to the geothermal gradient, the thermal conductivity and the volumetric heat capacity of the ground according to Bu et al. (2012) and Templeton et al. (2014). The maximum wellhead temperature indicated in literature is of 150 °C, the estimated thermal power is in the range 0.15÷2.5 MW and the electricity in the range of 0.25÷364 kW. The thermal disturbance reaches a maximum distance of 20÷50 m (Bu et al.,2012).

Regarding the modeling of the heat transfer into the reservoir and between it and the WBHX, the most accurate method entails the application of the conservation equation of mass, momentum and energy in the wellbore and in the formation. A common approach is the development of a model (analytical, semi-analytical, or numerical) for the exchanger, which is then coupled to a reservoir model, developed with a numerical simulator (i.e. TOUGH2, SHEMAT, FEFLOW) (Alimonti et al., 2018). A more recent approach is the use of Multiphysics software that allow to model either the reservoir and the WBHX. In this case, the coupling is direct and simultaneous. Mottaghy and Dijkshoorn (2012) have highlighted that simultaneous simulation of the WBHX and the reservoir requires a great computational time. This time is drastically reduced, without losing accuracy, coupling the reservoir numerical model with a semi-analytical finite difference formulation for the WBHX. The authors have also demonstrated the positive effect of the groundwater flow on the performance of a 100 m depth borehole heat exchanger.

The target of this paper is the modeling of the use of a WBHX in the volcanic area of Campi Flegrei (Italy). In this paper, we propose a coupled model of the geothermal reservoir and the deep borehole heat exchanger. The reservoir model has been built using the SHEMAT software, developed by Aachen University (Clauser, 2003). The software is able to simulate the production of brines through wells, but not the production of heat via heat exchangers. The conductive heat transfer in the deep borehole heat exchanger has been simulated using a pure conductive semi-analytical approach, which is based on thermal resistances and the Fourier equation. The coupling between the two models has been made with an iterative approach, using the ground temperature in contact with wellbore walls and the heat production. Then, the simulation has been carried out using only the semi-analytical model, which is able to evaluate the variation in time of the thermal resistance of the ground when the deep borehole heat exchanger is working.

The target is to identify the differences of the results in terms of thermal disturbance of the ground and to understand if, in presence of high temperature convective structures in the ground, the use of a pure conductive model may be a too precautionary condition.

2. THE CASE STUDY: CAMPI FLEGREI VOLCANIC DISTRICT

The Campi Flegrei area is a horse shape caldera of 12 km located in the N-W limit of the Napoli gulf, Italy (Fig. 2). The area is part of the Neapolitan volcanoes district, which includes also Ischia Island and Somma-Vesuvius volcano.

This large area was famous since Roman times for the thermal manifestations (hot springs, fumaroles, gas emissions) and it was used for thermal baths. Between 1930 and 1980 the volcanic district has been studied with exploration campaigns by energy companies (SAFEN, ENEL, AGIP) and scientific researches, but the industrial exploitation of the geothermal resources to produce electricity have never take off, because of the low cost of oil price and the lack of interest for renewable energies in 80's. 117 wells have been drilled in the area (26 in Campi Flegrei) reaching the maximum depth of 3046 m. The investigations have demonstrated that fluids with temperatures > 100°C (Fig.3) are present at relative shallow depths in the area of Campi Flegrei (Carlino et al., 2012).

A hot and saline geothermal system with a high geothermal gradient (100÷170 °C/km) is present in the subsoil of Campi Flegrei. A small magma sill has been inferred at the depth lower than 3-4 km (Berrino et al., 1984; Woo and Kilburn, 2010), the greatest magmatic source seems to be located at the depth of 8-10 km, with a thickness of almost 1 km and a diameter equal to that of the caldera (Zollo, 2008). At a depth greater than 3-4 km the fluids circulate very slow and the heat is transferred due to conduction. In the shallower layers (0-2 km) an advective transport takes place, because of the high permeability due to the fracturing system. According to Carlino (2018), the research investigations on the volcanic district of Campania have demonstrated the essential contribution of fluid advection to reach the thermal state of shallow crust in the area. Different authors (Chiodini et al. 2003 and 2012; Troiano et al. 2011; Petrillo 2013) have simulated the hydrothermal system of Campi Flegrei, demonstrating that the bradyseism of the area can be explained by fluid injection at the bottom of shallow layers (3-4 km).

In this paper, the application of the deep borehole heat exchanger has been evaluated in the area of Mofete, which presents higher temperatures, according to the measured data of AGIP campaign reported in Fig.3. Using the estimation method of Muffler and Cataldi (1978), Carlino et al. (2012) calculated that the total heat energy stored in the Mofete geothermal reservoir is equal to 1.08 $\times 10^{17}$J, while the recoverable energy is equal to 3.7 GWy.

Figure 2: Campi Flegrei caldera (Carlino et al., 2012).

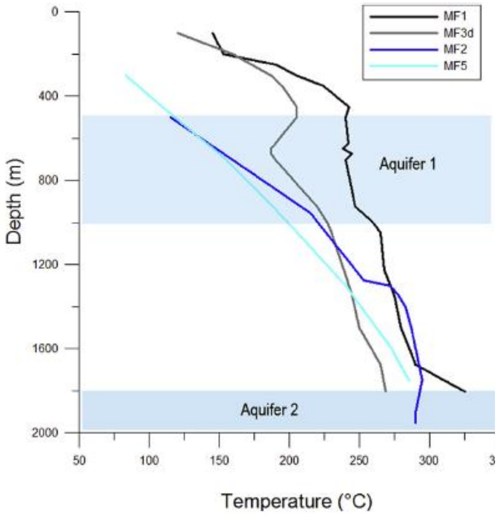


Figure 3: Campi Flegrei temperature profiles (Carlino et al., 2016).

3. METHODS

3.1 The WellBore Heat eXchanger model: Geopipe simulator

The heat transfer in the WBHX and between it and the ground is evaluated using a semi-analytical approach based on thermal resistances shown in Fig.4. An analytical solution of the Fourier equation of the heat transport is used in modeling the heat transfer into the ground source, which is assumed as a purely-conductive medium. The thermal resistance of the soil between the external well casing surface and the undisturbed ground (R_s) accounts for the actual radius of thermal influence due to the undergoing heat extraction. It is evaluated with the following relation:

$$R_s = \frac{1}{2\pi\lambda_s} \ln\left(\frac{2\sqrt{\alpha_s t}}{r_{o,1}}\right) \quad (1)$$

R_a is the thermal resistance between the downward fluid and the undisturbed ground temperature, R_b is the thermal resistance between the downward fluid and the upward fluid.

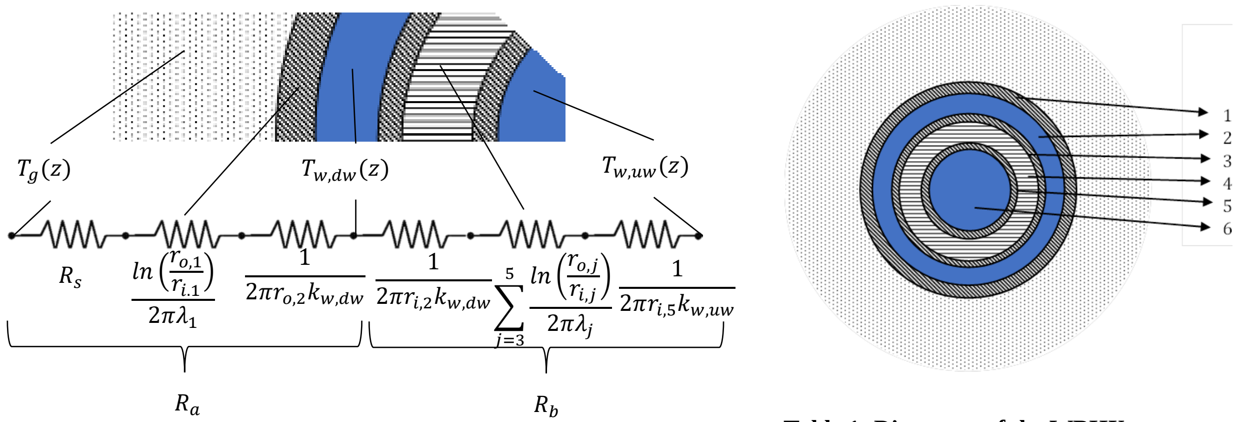


Table 1: Diameters of the WBHX.

1	9 5/8 inch	OD 244.4 mm	ID 226.6 mm
3	7 inch	OD 177.80 mm	ID 150.36 mm
5	3 ½ inch	OD 88.90 mm	ID 77.92 mm

Figure 4: Thermal resistances of the WBHX model and design.

The conductive thermal resistance of the well strata is evaluated through the classical heat transfer theory for cylindrical geometries. $h_{w,dw}$ and $h_{w,uw}$ are the convection coefficient within the annulus and in the upward pipe respectively. The classical Dittus-Boelter equation has been used to calculate all the convective coefficients, adopting the same convection coefficient on the outer and inner surface because the flow is fully developed turbulent (Lavine et al. 2001). Both Nusselt and Reynolds numbers can be evaluated considering a hydraulic diameter D_h.

The energy balance of the WBHX is expressed by the following relation:

$$\dot{Q}_{WBHX} = \dot{m}_w c_w \left(T_{w,uw} - T_{w,dw}\right) \tag{2}$$

where $\dot{Q}_{WBHX}$ is the total heat exchanged by the working fluid with the ground. The outlet temperature of the fluid $T_{w,uw}$ and the fluid temperature profile along the WBHX is evaluated through the following set of equations:

$$\begin{cases} \dot{m}_w c_w \frac{dT_{w,dw}}{dz}(z) = \frac{T_s(z)-T_{w,dw}(z)}{R_a} - \frac{T_{w,dw}(z)-T_{w,uw}(z)}{R_b} \\ -\dot{m}_w c_w \frac{dT_{w,uw}}{dz}(z) = \frac{T_{w,dw}(z)-T_{w,uw}(z)}{R_b} \end{cases} \tag{3}$$

with the following boundary conditions:

$$T_{w,dw}(L=0) = T_{in} \qquad T_{w,dw}(L) = T_{w,up}(L) \tag{4}$$

The set of differential equation is been solved numerically to find the outlet temperature $T_{out} = T_{w,uw}(0)$ as a function of the mass flow rate, $\dot{m}_w$, and the inlet temperature.

The thermo-physical parameters of the soil and the materials used as input data in Geopipe simulator are reported in Table 2 and 3. The surrounding rock has been modeled considering 5 different layers whose properties are taken by Carlino et al. (2016), Troise et al. (2001), Troiano et al (2011), Petrillo et al. (2013). The ground temperature at the depth z = 0 is assumed equal to 35 °C. The WellBore Heat eXchanger has assumed composed by steel casings and the air is the proposed material as insulator between the external annulus and the internal pipe.

Table 2: Thermo-physical properties of the soil.

Layer/Zone	Depth Range (m)	Δz (m)	Geothermal gradient (°C/100m)	Thermal conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kg K)
1	0-500	50	15.0	2.1	1800	1000
2	500-100	50	15.0	2.1	2100	1000
3	1000-140	50	15.0	2.1	2400	1000
4	1400-1800	50	15.0	2.1	2400	1000
5	1800-2000	50	15.0	2.1	2400	1000

Table 3: Thermal conductivity of steal casings and air.

Material	Value (W/mK)
Air	0.026
Steel	50

The Table 4 illustrates the input and output parameters of the simulation with Geopipe. The water is the selected working fluid according to the results in literature. The flow rate has been set to the value of 20 m^3/h in order to maximize the thermal power and the outlet temperature using very low energy to circulate the fluid.

Table 4: Input and output operating parameters of the simulation with Geopipe.

Input Parameter	Value
Circulating fluid	Water
Flow rate, $\dot{m}_{f,w}$	20 m^3/h
Inlet pressure	2.5 MPa
Inlet temperature T_{in}	40 °C
R_a	0.34 mK/W
R_b	3.22 mK/W

3.2 Reservoir simulation: SHEMAT software

The SHEMAT software is been selected in order to model the Campi Flegrei reservoir. The acronym SHEMAT means **S**imulator for **HE**at and **MA**ss **T**ransport, it is a general-purpose reactive transport simulation code, it is easy-to-use and adapt for a wide variety of thermal and hydrogeological problems in two or three dimensions (Clauser, 2003).

SHEMAT uses a Finite Difference method (FD) to solve the system of partial difference equations of energy conservation and mass conservation. The energy conservation equation is used to study the heat transfer in the porous medium, which is described by the following relation:

$$\left(\frac{\partial T}{\partial t}\right)\left(\phi\rho_f c_f + (1-\phi)\rho_s c_s\right) - H - \nabla\cdot\left(\underline{\lambda}\nabla T\right) + \nabla\cdot\left(\rho_f c_f \boldsymbol{v} T\right) = 0 \qquad (5)$$

where $\underline{\lambda}$ is the thermal conductivity tensor of the material.

The equation of the fluid flow is derived by the combination of Darcy law for porous medium and the mass conservation equation:

$$\left(\frac{\partial h_0}{\partial t}\right) - \nabla\cdot\left[\frac{\rho_f g \boldsymbol{k}}{\mu}\left(\nabla h_0 + \rho_s \nabla z\right)\right] - W = 0 \qquad (6)$$

SHEMAT solves the heat and mass conservation equations on a Cartesian 2-D or 3-D grid with coordinates x,y,z or on a 2-D vertical cylindrically grid with radius (r) and depth (z) coordinates.

In order to model the Campi Flegrei reservoir, a vertical cross sections model is been built using a grid cells mesh. Each grid cell is 50 m X 50 m. The Fig. 5 illustrates the model, the total dimensions and the used convention for Cartesian axes. The Table 5 summarizes the composition of the grid in the three dimensional plains. The papers of Carlino et al. (2016) (Fig.6) and Troise et al. (2001) (Fig. 7) have been used to select the appropriate dimension of the model of Campi Flegrei reservoir.

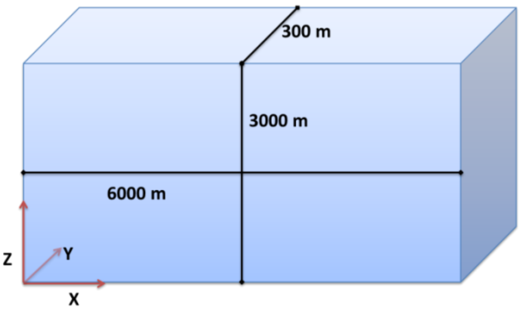


Table 5: Grid composition

Plain	Rows	Columns
X-Z	60	120
X-Y	6	120
Z-Y	60	6

Figure 5: Dimensions of Campi Flegrei domain.

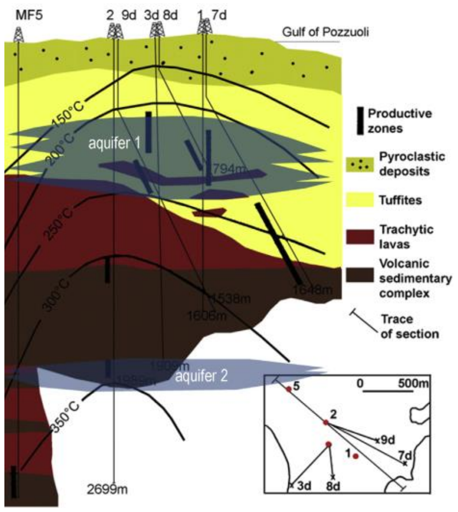


Figure 6: Conceptual model of Campi Flegrei reservoir (Carlino et al., 2016).

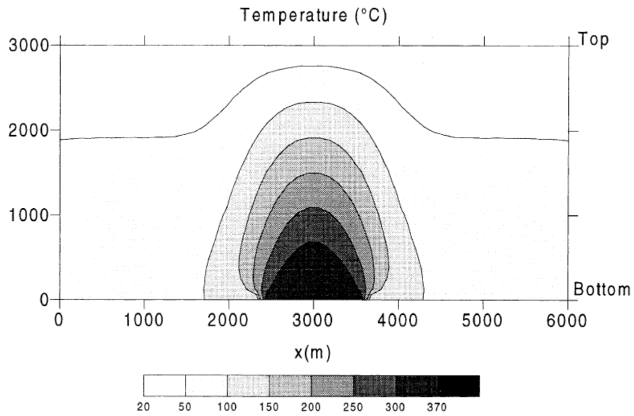


Figure 7: 2D Campi Flegrei model by Troise et al. (2001).

The software allows to select different properties zones, which correspond to the layers of the ground with specific thermal, physical and chemical properties assigned. 6 properties zone have been selected setting the properties reported in Table 6 and derived by Carlino et al. (2016) and Troise et al (2001). The hypothesis of parallel homogenous isotropic layers is been used.

Table 6: Properties zone of Campi flegrei model.

Layer/Zone	Depth Range (m)	Porosity	Permeability (m^2)	Thermal conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)
1	0-500	0.3	10^{-15}	2.1	1800	1000
2	500-1000 (aquifer)	0.3	10^{-14}	2.1	2100	1000
3	1000-1400	0.3	10^{-18}	2.1	2400	1000
4	1400-1800	0.3	10^{-17}	2.1	2400	1000
5	1800-2000 (aquifer)	0.3	10^{-15}	2.1	2400	1000
6	2000-3000	0.3	10^{-18}	2.1	2400	1000

Regarding the simulation type, SHEMAT software is able to simulate fluid flow, heat transfer, species transport and chemical reactions. Considering the scope of the research, only the heat transfer and the groundwater flow have been simulated. The simulation is in transient condition, composed by 31 periods for a total simulation time of 88450 years.

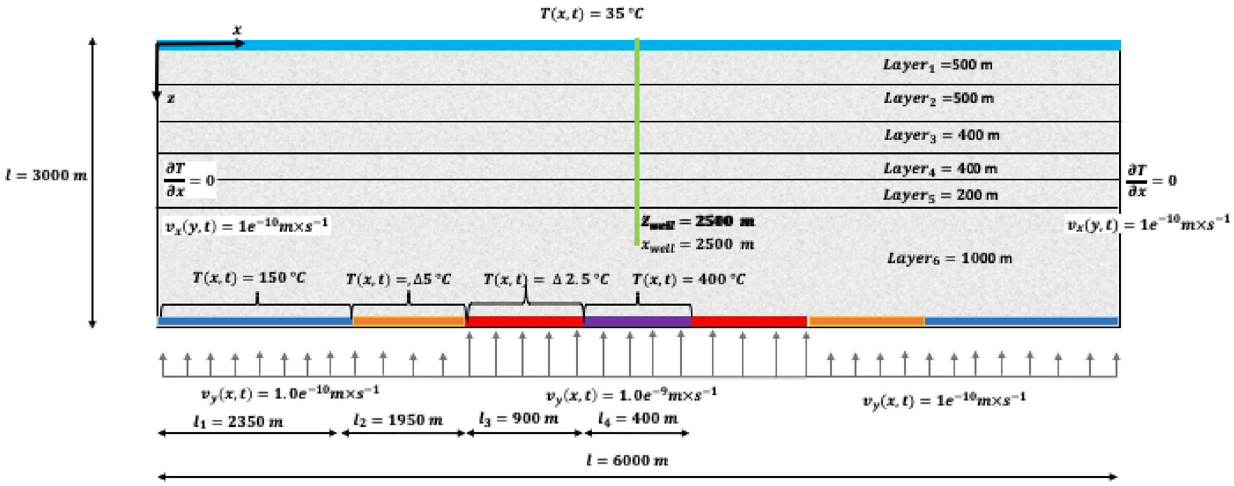


Figure 8: Boundary conditions imposed at the domain of Campi Flegrei.

A specific flow boundary condition has been set for the cells of the 4 external borders, whereas the internal cells are active. According to the conclusions obtained by Chiodini et al. (2003, 2012), Troiano et al. (2011) and Petrillo et al. (2013), a flux from the bottom to the top of the model (10^{-9} m/s in the center cells and 10^{-10} m/s in the rest of the cell) has been imposed. Furthermore, a flux from left to right has been hypothesized and set to 10^{-10} m/s. Regarding the thermal boundary conditions, the temperature has been fixed at the top and the bottom of the model, leaving the other cells active: in this way, the software calculates the temperature field at the end of the simulation time. No fluid heat production or constant heat flow have been imposed. The Figure 8 summarizes all imposed boundary conditions.

3.3 The coupling of Geopipe and SHEMAT software

The coupling of the heat transfer in the WellBore Heat eXchanger and in the reservoir has been carried out using two parameters: the ground temperature and the heat production. The SHEMAT software runs and produces a temperature pattern in every cell of the domain. The ground temperature at the interface of the WBHX is used as input in Geopipe simulator, which produces as output the heat acquired from the surrounding ground after 1 hour of operation. These values are introduced as input in the reservoir model in order to investigate the effect of thermal disturbance on the ground in time. The flowchart reported in Figure 9 illustrates the workflow of the process: the procedure is repeated changing the simulation time (t*) in SHEMAT. The simulation time of GEOPIPE remains fixed (1 hour), whereas the input ground temperature (SHEMAT output) varies with the time.

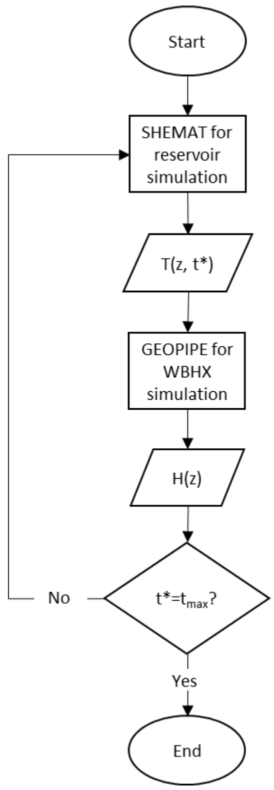


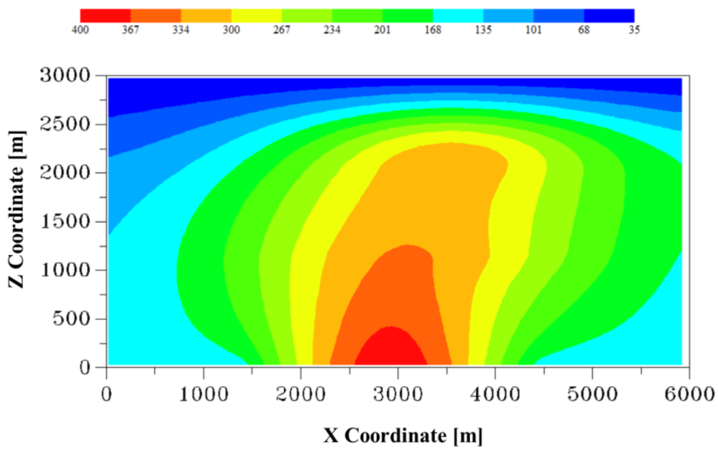
Figure 9: Workflow of the two models coupling.

The selected simulation times are 1 month, 6 months, 1 year, 5 years, 10 years, 25 years, 50 years.

4. RESULTS

In this section the results obtained with SHEMAT software coupled with Geopipe simulator are discussed and then compared with the results obtained using only Geopipe simulator.

The Figure 10 shows the temperature pattern for Campi Flegrei domain in the 2D plain X-Z. The results indicate that the model is able to represent the presence of the small magma sill at depth lower than 3-4 km and the propagation towards the surface of the thermal perturbation due to the injection of hot fluids at the bottom of the domain. The comparison with the results obtained by Carlino et al. (2016) (Fig.6) and Troise et al. (2001) (Fig. 7) confirms the accuracy of the model. The Figure 11 reports the temperature values along the depth for the central cells (x = 3000 m); the trend is similar to the curve of Mofete 1 well reported in Fig.3.



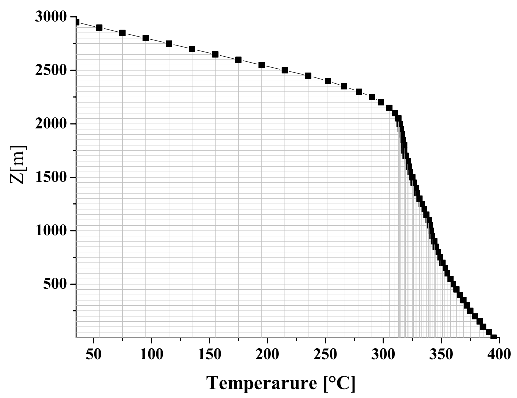


Figure 11: Temperature profile in the center of Campi Flegrei domain x=3000 m.

Figure 10: 2D Temperature pattern for Campi Flegrei domain.

The Figure 12 depicts the temperature profiles in the plain Y-Z for the layer 1, 60 and 120 and in the plain X-Y for the layer 1, 30 and 60. The results confirm the presence of the heat source at the base of the domain, resulting in a temperature that reaches the value of 400 °C in the center, and the thermal disturbance propagated by the injected fluid at the base of the domain. The Figure 13 shows the Z velocity in the plain X-Z: the values are 10^{-5} m/day, quite similar to the results of Petrillo et al. (2013). The velocity and the temperature patterns indicate the presence of a prevailing central plume, with convective cells distributed in different areas of the domain. All the results reported in Figures 10, 11, 12 and 13 are referring to the steady state condition, before the WBHX starts to operate.

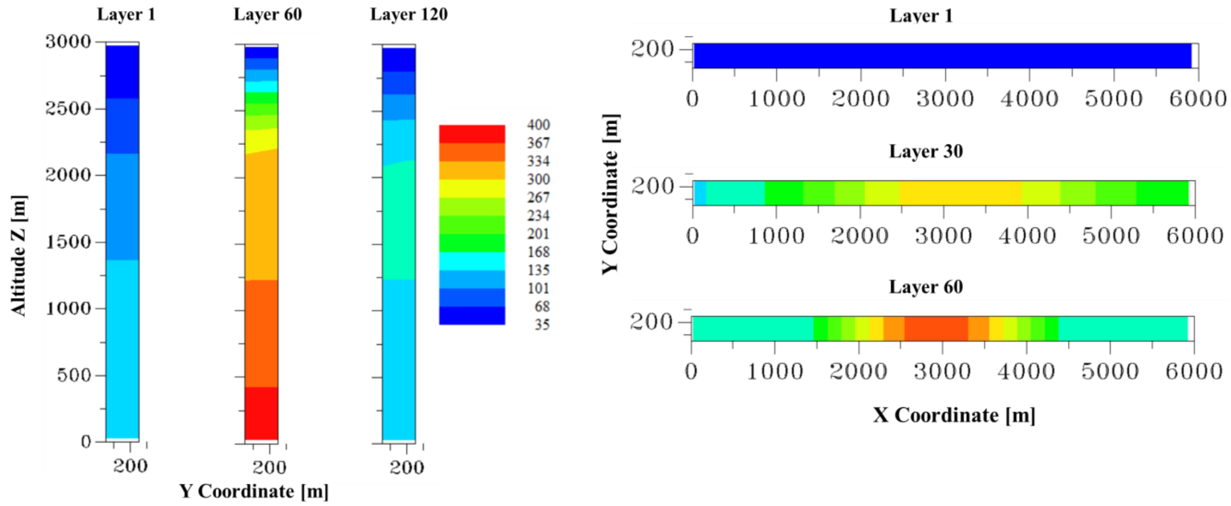


Figure 12: Temperature profiles in the plain Y-Z and X-Y.

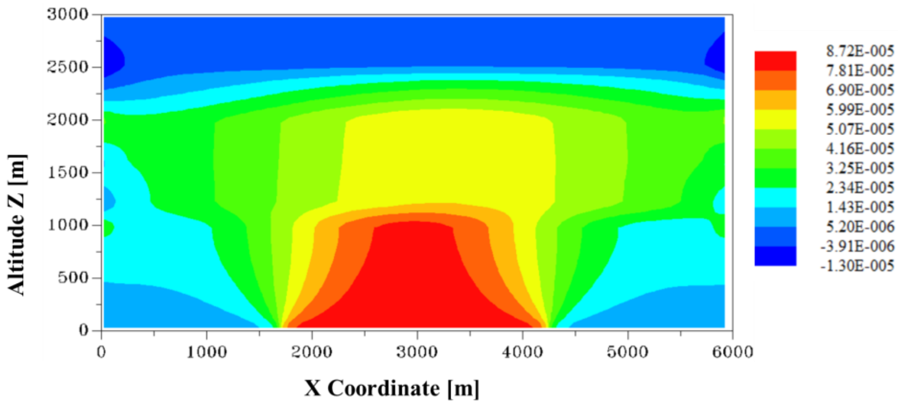
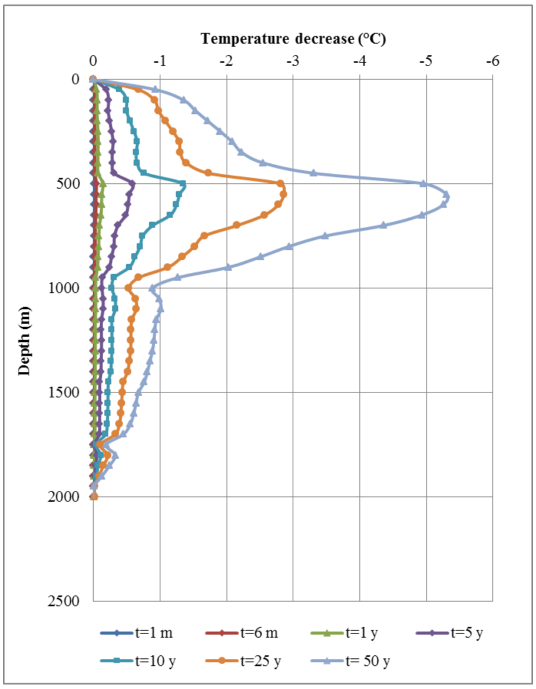


Figure 13: Z Velocity (m/day)

The Figure 14 and 15 show the results of the reservoir model coupled with the borehole heat exchanger model. The Figure 14 highlights the effect of heat extraction via the WBHX on the temperature of the surrounding ground: the most of the temperature decrease is in the second layer (500 – 1000 m) where an aquifer is present, whereas the temperature remains quite undisturbed in the last 1000 meters, where the slope of the geothermal gradient becomes sharper (Fig.11). According to the results, the heat extraction does not induce a thermal disturbance on the ground until the reach of 5 years of operation.

The Figure 15 shows that the heat production is constant in time and that the greater values of heat production are in correspondence of the shallow aquifer.



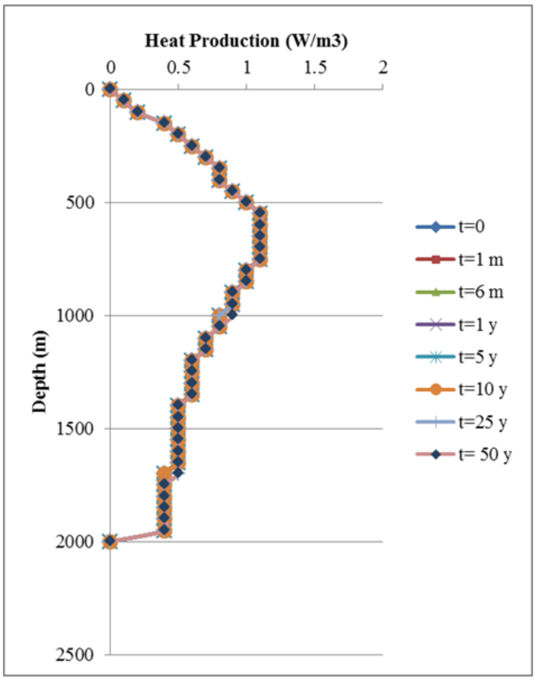


Figure 14: Decrease of the ground temperature at the interface of the borehole wall in time (SHEMAT output).

Figure 15: Heat extracted in time by the WBHX vs depth (Geopipe output).

The Figure 16 and 17 illustrate the results comparison of the two approaches: the reservoir-borehole model built with SHEMAT software coupled with Geopipe simulator and the use of a unique semi-analytical model (Geopipe). The main difference is that the use of a numerical simulator for the reservoir modeling allows representing all the geological structures, the presence of a magma sill in the underground, the conductive and the convective heat transfer in the ground. Otherwise, the Geopipe simulator is based on a pure conductive model. It estimates the ground thermal resistance in time without considering the effect of a possible thermal recovery due to high geothermal gradients or to a natural fluid injection in the ground. A pure conductive approach, fast and appropriate for the shallow probes, may be a too precautionary method in case of deep borehole heat exchangers as can be seen in Figure 16 and 17.

The outlet temperature of the water extracted from the WBHX (Fig. 16) seems to remain substantially stable in time, according to the SHEMAT-Geopipe simulation. The results obtained with Geopipe simulator indicated that the outlet temperature is subjected to remarkable decrease in the first year, passing from a value of 290 °C to 182 °C. In the next 49 years, the temperature decreases less then of 30 °C, demonstrating that after 1 years of operation a quasi-steady state condition is reached. The same trend has be observed for the estimated thermal power produced with the WBHX (Fig. 17): according to the SHEMAT-Geopipe simulation the WBHX may be able to produce 10 MW of thermal power without loosing a remarkable percentage of efficiency. Instead, the Geopipe simulator estimates a loss of 60% of the initial thermal power, already after 1 month of operation. In the next year, the thermal power decreases of others 750 kW, reaching the value of 3.3 MW. Then the establishment of a quasi-steady state condition guarantees that, in the next 49 years, the loss of thermal power is 700 kW.

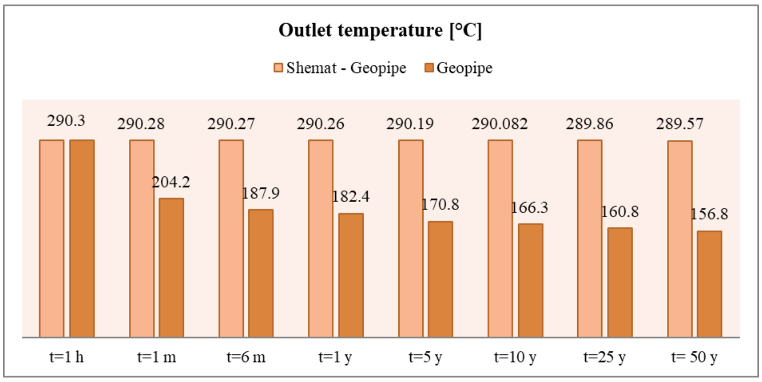


Figure 16: Variation of the outlet temperature in time.

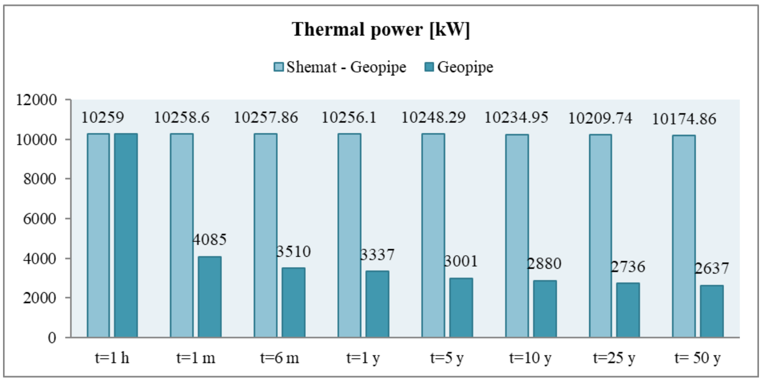


Figure 17: Variation of the thermal power in time.

5. CONCLUSIONS

In this paper the application of a deep borehole heat exchanger in the volcanic area of Campi Flegrei (Italy) has been evaluated. The site is well known in the geothermal sector for his high geothermal gradient and very high temperatures, even in the shallow layers. Anyway, the geothermal exploitation of the area has never take off in the past, due to the competitive price of the oil. Nowadays, the negative social response to the activities of drilling and fluid extraction is the main barrier to the geothermal development. The possibility of producing geothermal energy without brine extraction may be the key issue for the restart of geothermal projects in the Campi Flegrei area.

The main issue of the deep borehole heat exchanger is the low efficiency due to the heat extraction via conduction from the surrounding ground, which generates a thermal radius of influence. The common approach to the evaluation of this type of device ignores the effect of the geothermal reservoir, which may produce a recovery action with respect to the heat extracted. This could be the case of Campi Flegrei area, where the research investigations have demonstrated the presence of an advective transport in the first 2 kilometers and the presence of fluid injection at the depth of 3-4 km.

Therefore, two approaches have been used for the evaluation of the WBHX in the area of Campi Flegrei: the first one is a coupled reservoir-borehole model, the second one is a pure conductive semi-analytical model. The reservoir model has been built using the SHEMAT software. The coupling between the reservoir model and the borehole model has been made with an iterative approach, using the ground temperature in contact with the wellbore walls and the heat production. The second approach consists of the use of only the semi-analytical model, which is able to evaluate the variation in time of the thermal resistance of the ground.

The reservoir model, carried out with SHEMAT software, has a good agreement with the literature results, confirming the presence of a heat source at the base of the domain, a bottom temperature that reaches the value of 400 °C in the center, and the thermal disturbance propagated by the injected fluid at the base of the domain.

The comparison of the two simulation methods shows very different results. The SHEMAT-Geopipe model seems to indicate that the heat extraction via the WBHX does not affect remarkably the surrounding ground temperature, thanks to the recharge effect due to the natural heat flux in the reservoir of Campi Flegrei. The maximum temperature decrease is concentrated in the shallow aquifer, reaching the value of 5 °C after 50 years of exploitation. The heat production via WBHX remains unchanged in time, the temperature of the outlet fluid remains about 290 °C, and the plant may produce a thermal power of 10 MW for 50 years.

The results of the simulations carried out with Geopipe, which does not evaluate the recharge effect of the reservoir, show that, after 1 month of heat extraction with the WBHX, the outlet temperature decreases of 85 °C. Then the outlet temperature continues to drop, but more slowly, indicating that a quasi-steady state condition is established. This phenomenon is transmitted to the producible thermal power: after 1 month of source exploitation, a loss of 60% of the initial thermal power is observed. After 1 year of operation, the WBHX may produce 3.3 MW of thermal power, which decreases until the value of 2.6 MW after 50 years.

The big discrepancy between the results produced by the two different approaches, requests further investigation. On one side, it is undeniable that the use of a pure conductive model in the feasibility study of the deep borehole heat exchanger may exclude important phenomena, such as the recharge effect in case of high heat flux in the reservoir. On the other hand, the range of the discrepancy may be related to the procedure used to couple the reservoir model and the WBHX model, in particular the use of a very low heat production value and the size of the cells grid surrounding the borehole.

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NOMENCLATURE

a	thermal diffusivity	[m^2/s]
c	specific heat capacity	[J/kg K]
D_h	hydraulic diameter	[m]
g	gravitational acceleration	[m^2/s]
gradT	temperature gradient	[°C/100 m]
h	hydraulic potential, head	[m]
H	heat source/sink	[W/m^3]

k	convective heat transfer	[W/m^2 K]
k	permeability	[m^2]
L	total length of the well	[m]
$\dot{m}$	mass flow rate	[kg/s]
$\dot{Q}$	total thermal power	[W]
$\dot{q}$	heat flux	[W/m^2]
ρ	density	[kg/m^3]
R	thermal resistance	[mK/W]
r	radius	[mm]
T	temperature	[K or °C]
t	time	[s]
u	velocity	[m/s]
z,Z	depth	[m]
W	fluid source/sink	[m^3/s]

GREEK SYMBOLS

λ	thermal conductivity	[W/m K]
μ	dynamic viscosity	[Pa·s]
ρ	density	[kg/m^3]
φ	porosity	

SUBSCRIPTS, SUPERSCRIPTS

0	reference condition
dw	downward
f	fluid
i	inner
in	inlet
o	outer
out	outlet
s	soil property
up	upward
w	water
WBHX	WellBore Heat eXchanger