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Feasibility study of a geothermal power plant with a double-pipe heat exchanger

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Abstract

The technologies currently in use for the power production in the geothermal field are sometimes affected by two crucial problems: the environmental impact and the drilling costs. The first issue is related to the techniques adopted to increase the heat exchange (as artificial subsoil fracturing) or to the use of aquifers which contain pollutants that are not properly disposed or confined. The drilling costs are high because two wells are generally necessary to operate properly the power plant. An interesting solution could be the adoption of a double-pipe heat exchanger that consists in two concentric pipes placed in a single well. This setup allows the operation of the plant in a closed loop configuration with no mass exchange between the subsoil and the surface. A coupled approach based on a 1D model for the pipe and a 2D axisymmetric model for the surrounding rocks was developed in this study to investigate the actual capability of a double-pipe system in different operating conditions.

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Keywords: double-pipe; medium enthalpy; combined model 1D-2D; transient analysis; radius of influence

1. Introduction

Nowadays the geothermal resources exploited for energy applications are mainly at high temperature (300 – 400°C in a depth range of 1500 – 4000 m depending on the zone). Extraction wells, usually, intrude into aquifers and operate

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Nomenclature

Latin letters

A	Area [m^2]
cp	Specific heat coefficient [J/kgK]
D	Diameter [m]
f	Friction factor
g	Gravitational constant [m/s^2]
h	Enthalpy [kJ/kg]
HTC	Convective heat transfer coefficient [W/m^2K]
k	Constant
L_y	Control volume length [m]
m	Mass flow rate [kg/s]
Nu	Nusselt number
Pr	Prandtl number
p	Pressure [Pa]
Q	Heat flow [W]
R	Thermal resistance [K/W]
Re	Reynolds number
T	Temperature [K]
t	Time [s]
w	Velocity [m/s]
X	Depth [m]

Greek letters

λ	Thermal conductivity [W/mK]
ρ	Density [kg/m^3]
η	Efficiency

Subscripts

a	Fluid in upward direction
c	Cement
d	Fluid in downward direction
des	Design condition
f	Fluid
h	Hydraulic
i	Insulation
IN	Inner pipe
in	Inlet
off	Off-design condition
OUT	Outer pipe
out	Outlet
p	Pipe
r	Rock

with a mixture of vapor and water in different percentages. The most common systems exploited at the time are the hydrothermal systems. They are traditionally classified as water or vapor dominated depending on their reservoir composition. The extracted geothermal fluid (steam or water and steam) has a chemical content that is highly dependent on the rocks of each reservoir. The environmental impact of these systems consists mainly in pollution of air and water bodies since they re-inject the working fluid after the use (some systems work even in open loop by discharging the exhaust steam in atmosphere).

The high temperature resources are not equally distributed throughout the world and those already known are already exploited with a direct expansion in a steam turbine or in single (or dual) flashing plants. The focus of current research interest is moving towards the medium-low temperatures in the range of 120-150°C. Organic binary geothermal systems are usually used for the exploitation of these resources. An accurate analysis of the subsoil conditions in terms of temperature gradient and composition is needed in order to choose the adequate organic fluid for each plant [1]-[5].

Since the aquifers are not equally present in the world, the latest technology applied for the medium-low temperature is the Hot Dry Rock (HDR) technology, part of the Enhanced Geothermal Systems (EGS). These systems are employed in presence of a hot subsoil where a natural mixture of vapor and water is not available and are based on the artificial fracturing of the subsoil at high depth (above 5000 m) in order to improve the thermal heat exchange [6]-[10]. Water is circulated down the injection well and through the HDR reservoir, which acts as a heat exchanger. The fluid then returns to the surface through the production well, and thus transfers the heat to the surface as steam or hot water. These systems allow the exploitation of the geothermal energy where the aquifers are not present but they show some limitations: the high environmental impact due in particular to the man-made fracturing and the limited regulation control [7]-[9].

Recent studies have investigated the possibility of exploiting the geothermal gradient by using a borehole heat exchanger to produce vapor (with water or an organic fluid) for power generation (electrical or thermal). This solution leads to a lower environmental impact thanks to a closed loop and reduction of costs (only one well is needed).

Many efforts were devoted in investigating this technology in high depth applications by using 1D models mainly. Several researchers investigated the exploitation of abandoned oil wells by using water or isobutane as working fluids.

Davis et al. [11] made the assumption that the system was working with a fixed temperature on the boundary of the pipe thus neglecting in the calculation of the heat exchange any transient effect and the thermal resistance of the rocks and the cement. Kujawa et al. [12] estimated the radius where the temperature of the rocks is undisturbed by using Charnyi's correlation [13]-[14] which expresses the radius of influence as a function of the time elapsed from the start of the heat exchange. Bu et al. [15] and Cheng et al. [16] focused their research to the analytical estimation of the transient time to have a more accurate calculation of the system performance. In particular, the study of Cheng et al. demonstrated that the stabilized time can be shortened by either the increase of the subsoil thermal conductivity or the decrease of the fluid inlet velocity. In their study, the system was close to the stability after 300 days of operation. Both Bu et al. [15] and Cheng et al. [16] estimated an electrical production by using an organic Rankine cycle associated with the double-pipe of 50 kW and 150 kW respectively. In all these studies, the presence of the cement between the pipe and the rocks was neglected.

These studies investigated the double-pipe technology by using 1D approaches that make the convergence of the model faster and more flexible. Obviously, 3D models are more accurate, but require computational resources that depend on the length of the borehole. For this reason their application was limited to low depth applications, such as the ground heat exchangers (GHEs). Some examples are the studies by Khalajzadeh et al. [17] and Li et al. [18] which examined the performance of a 50 m long vertical U-tube by utilizing a 3D model with the software FLUENT. Zanchini et al. [19] examined the performance of 100 m long coaxial borehole heat exchanger by modifying the values of the thermal properties of the subsoil and the mass flow. The simulations were carried out by means of a 2D axisymmetric unsteady model developed with COMSOL. Mottaghy et al. [20] presented a finite difference approach for modeling multiple borehole heat exchangers by using SHEMAT as flow transport code. This approach was based on the fact that the preferential direction of the heat flux was radial. In order to avoid a very fine radial discretization, the horizontal heat transfer was modeled by thermal resistances, whereas finite differences were used in vertical direction.

The purpose of this study was to estimate the feasibility of a medium enthalpy geothermal power plant equipped with a long double-pipe heat exchanger. With this goal in mind, a model to study the transient heat transfer between the subsoil and the pipe in all directions was developed. The investigation was carried out by coupling a monodimensional and a two-dimensional axisymmetric approaches to investigate the heat exchange in the double-pipe and through the subsoil, respectively. This study allowed the estimation of the temperature around the pipe from the initial condition to the steady state. Conversely to previous studies, in this analysis several issues as the presence of the cement around the pipe, the transient behavior of the heat exchange and the temperature distribution in the whole subsoil were considered for a high deep double-pipe. This investigation leads to a reliable estimation of the capabilities of such system.

2. Case study

A double-pipe heat exchanger consists of two concentric pipes: the fluid flows down in the external one absorbing heat from the rocks, reaches the maximum temperature at the bottom of the well and ascends into the internal pipe, which is insulated to prevent thermal losses.

After an extensive review of the geothermal areas where this technology could be applied, Mofete (NA) in Campi Flegrei, Italy, was chosen as a case study. Thanks to its favorable temperature gradient and to the interest in the development of a pilot plant, the place was already characterized and the temperature profile was known (the existing wells have a bottom temperature above the 300° C within 2000 m) [21].

In Fig. 1a the measured geothermal gradient up to 3000 m of depth in the Campi Flegrei area is shown. In this study the data of the MF1 well was used thanks to its favorable temperature distribution. By considering a thermal conductivity of the soil equal to 0.85 W/mK and a high porosity of the rocks, up to 50%, the value of the heat flow was estimated at 160 mW/m^2 [22].

For the purpose of the study, a 1500 m long double-pipe was considered. The dimensions and characteristics of the pipe were chosen according to the drilling standards (Table 1). A sketch of the double-pipe is shown in Fig. 1b. The diameters D_1 and D_2 are a trade-off between structural rigidity and thermal resistance. The diameters D_3 and D_4 are a trade-off between a proper insulation and a limited reduction of the passage section.

Table 1. Geometrical parameters and properties of the materials.

Quantity	Value	Unit
External diameter of the outer pipe (D_1)	0.406	m
Internal diameter of the outer pipe (D_2)	0.394	m
External diameter of the inner pipe (D_3)	0.229	m
Internal diameter of the inner pipe (D_4)	0.216	m
Cement diameter up to 600 m (D_c)	0.584	m
Cement diameter up to 1500 m (D_c)	0.445	m
External case thermal conductivity	60.5	W/mK
Insulation thermal conductivity	0.027	W/mK
Cement thermal conductivity	2	W/mK
Cement density	2500	kg/m^3
Cement specific heat coefficient	1400	J/kgK
Soil thermal conductivity	0.85	W/mK
Soil density	2100	kg/m^3
Soil specific heat coefficient	750	J/kgK

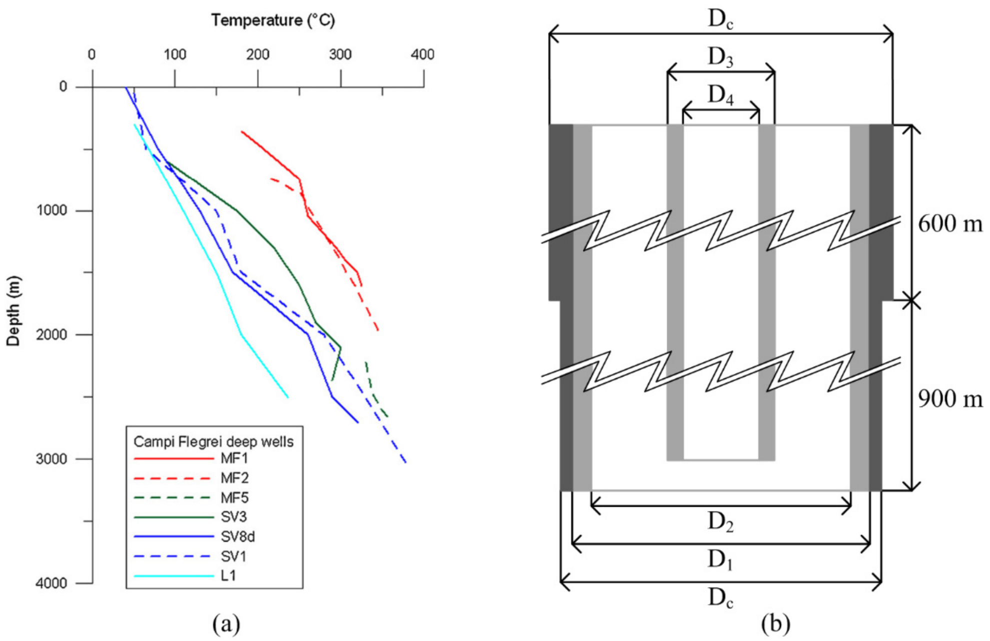

Fig. 1. (a) Temperature profiles measured during the drilling of the deepest wells at Campi Flegrei [21]; (b) scheme of the double-pipe.

As in many similar applications, isobutane was chosen as the organic working fluid. In all the simulations the same fluid inlet conditions of 35 bar and 53.5°C were considered.

3. Development of the model

A coupling between a 1D model and a 2D axisymmetric model was conceived to describe the trends of the heat exchange in the pipe and in the subsoil, respectively. A fully 3D approach would have increased the computational time without leading to an actual increase of the accuracy of the results. The coupling was realized by using the output of each calculation as a boundary condition of the other. In particular, the pipe wall temperature was used to estimate the heat flow coefficient and the fluid temperature within the pipe. These quantities were used in the 2D axisymmetric approach to estimate the subsoil temperature and the wall temperature in the next time step. The procedure allowed the description of the transitory condition in which the double-pipe operate from the initial condition to the steady state.

3.1. 1D model

The exchanger model was developed by using EES (Engineering Equation Solver). To perform the calculation, the double-pipe was divided into a finite number of sub-portions where the analysis was developed subsequently. The thermal flux was considered propagating only in the radial direction whereas the heat exchanged between two consecutive volumes was neglected. In each volume the continuity, energy and momentum equations were solved iteratively (Fig. 2).

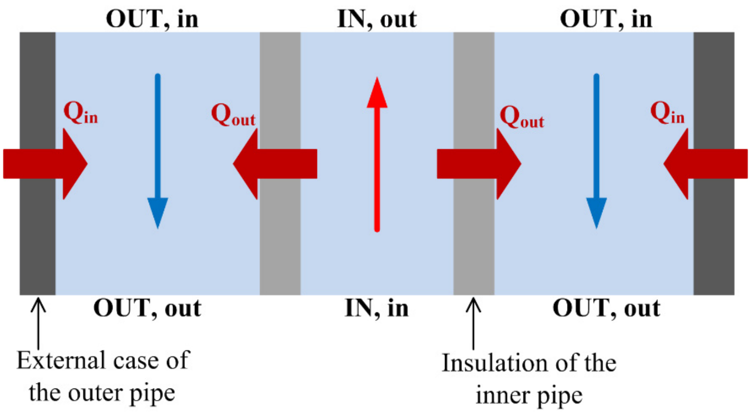

Fig. 2. Schematic of a calculation volume.

The continuity equation can be expressed as (Eq. 1 and 2):

$$\rho_{OUT,in} w_{OUT,in} A_{OUT} = \rho_{OUT,out} w_{OUT,out} A_{OUT} \tag{1}$$

$$\rho_{IN,in} w_{IN,in} A_{IN} = \rho_{IN,out} w_{IN,out} A_{IN} \tag{2}$$

where ρ is the density of the fluid, w the velocity and A is the passage area in the two concentric pipes.

The energy equation has two different contributes. In the external pipe, where the fluid flows down, the heat balance is described by Eq. 3 while in the internal pipe where the fluid flows up by Eq. 4.

$$m_{OUT,in} \Delta h_{OUT} = Q_{in} + Q_{out} \tag{3}$$

$$m_{IN,in} \Delta h_{IN} = Q_{out} \tag{4}$$

where Q_{in} and Q_{out} are the heat exchanged and:

$$\Delta h_{OUT} = cp_{OUT} (T_{OUT,out} - T_{OUT,in}) \tag{5}$$

$$\Delta h_{IN} = cp_{IN} (T_{IN,in} - T_{IN,out}) \tag{6}$$

where *cp* was calculated by using a mean value of *p* and *T* between the inlet and the outlet of each sub-portion. Q_{in} and Q_{out} are:

$$Q_{in} = \frac{T_r - \dfrac{(T_{OUT,in} + T_{OUT,out})}{2}}{R_d + R_p} \tag{7}$$

$$Q_{out} = \frac{\dfrac{(T_{IN,in} + T_{IN,out})}{2} - \dfrac{(T_{OUT,in} + T_{OUT,out})}{2}}{R_a + R_i + R_d} \tag{8}$$

where the terms R_d, R_p, R_a and R_i represent the thermal resistances of the fluid descending in the outer pipe, of the outer pipe (stainless steel), of the fluid ascending in the inner pipe and of the insulation of the inner pipe, respectively. The temperature of the rocks is imposed step by step along the whole heat exchanger by considering the 2D axisimmetric calculation. As for the thermal resistances of the fluid, the convective heat transfer coefficient is calculated from Nusselt number as shown in Eq. 9.

$$HTC = \frac{Nu * \lambda}{D_h} \tag{9}$$

$$Nu = 0.125 f \,\mathrm{Re}(\mathrm{Pr})^{\frac{1}{3}} \tag{10}$$

$$f = 0.184(\mathrm{Re})^{-0.2} \tag{11}$$

where λ is the thermal conductivity of the fluid provided by the internal software library, *Nu* is estimated from the Chilton-Colburn formulation for turbulent flow in a pipe as shown in Eq. 10 and *f* is the friction factor for a low roughness pipe [23]. These correlations are applied in both the inner and the outer pipe. The hydrauilic diameter D_h of the downward flow is given by the difference of the two diameters according to [23], while for the upward flow it is simply the inner diameter.

The momentum equation for the geometry proposed is (Eq. 12):

$$\begin{aligned} & p_{OUT,in} + \frac{1}{2}\rho_{OUT,in} w_{OUT,in}{}^2 + \rho_{OUT,in} g X_{OUT,in} = \\ & = p_{OUT,out} + \frac{1}{2}\rho_{OUT,out} w_{OUT,out}{}^2 + \rho_{OUT,out} g X_{OUT,out} + \frac{1}{2} f \rho_{OUT,out} w_{OUT,out}{}^2 \frac{L_y}{D_h} \end{aligned} \tag{12}$$

where *p* is the static pressure of the working fluid and *X* is the depth where the pressure is calculated. The last term represents the distributed pressure losses along the pipe. Eq. 12 is written for the outer pipe, but the same equation can be considered to the inner pipe.

The accuracy of the model increases with the number of the control volumes. Since EES shows a limit on the number of the variables to be processed, in this study the double-pipe was divided in 120 control volumes each one corresponding to 12.5 m.

3.2. 2D axisymmetric model

The heat exchange through the surrounding rock was modeled with a 2D axisymmetric approach by using FLUENT as calculation code with a cylindrical coordinate system. Only conductive heat transfer was assumed through the surrounding rocks (Eq. 13) that were considered as a homogenous region without heat volumetric sources and relative motions (Fourier's equation). Due to the high aspect ratio of the geometry, the double precision solver was used [24]. The second order upwind differencing scheme was used to estimate the energy equation despite a greater calculation time.

$$\frac{\delta}{\delta t}(\rho h) = \nabla(\lambda \nabla T) \tag{13}$$

The computational domain is rectangular-shaped and the dimensions are 50 m for the horizontal side and 1520 m for the vertical side. These values have been proven to be sufficient to avoid the influence of boundaries on the results. Thanks to the regularity of the geometry, the quadrangular shape of the cells have been chosen. Due to the very low thermal gradient along the depth (0.183°C/m), the height of the cells can be greater than that adopted in a typical problem of heat transfer. After performing a mesh sensitivity a grid with 364˙800 cells, 3040 along the depth (50 cm high) and 120 cells along the radial direction was adopted. The temperature gradient in the special domain decreases gradually from the outside pipe surfaces to the far field. Therefore, the cell size changes from 0.499 mm close to the tube to 1440 mm at the external boundary. A further increase of the number of cells led only to an increase of the calculation time without an improving of the accuracy. The time step in the transient simulation was 1/10th of the whole period of transient analysis. A sensitivity analysis showed that an increase of the number of calculation steps did not lead to an increase of the accuracy.

3.3. Coupling between 1D and 2D models

Starting from the initial subsoil temperature distribution, the 1D model was adopted to estimate the fluid operating condition in each volume along the pipe. The resulting convective heat transfer coefficients and fluid temperatures were considered as boundary condition in the 2D axisymmetric approach where a transitory analysis was performed for a given period of time. Once the calculation was concluded, the new subsoil temperature distribution was used in the 1D model (Fig. 3a).

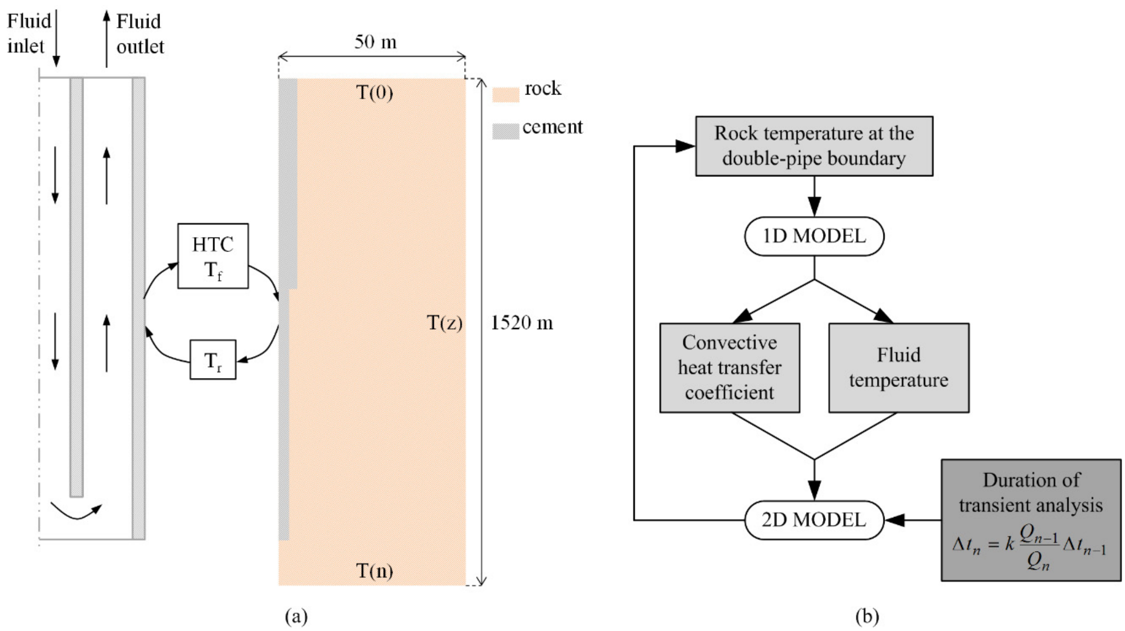

Fig. 3. (a) Definition of the boundary conditions; (b) complete scheme of the coupling.

A MATLAB routine was developed to couple the two models and manage the passage of data between them. As external boundary condition, the local temperature distribution with the depth was applied to the subsoil. At the top and the bottom of the domain, constant values of temperature were set up. In Fig. 3b the complete scheme of the coupling is shown.

The critical point of this model was the choice of the period of each transient simulation. The value is a compromise between the accuracy of the transient behavior and the calculation time. Since after the initial steps the heat fluxes progressively decrease and the boundary conditions become more constant, the period of analysis can be progressively increased. With this goal in mind, a relation that couples the duration of the transient analysis with the inverse of the heat exchanged during the previous and current analysis was chosen (Eq. 14):

$$\Delta t_n = k \frac{Q_{n-1}}{Q_n} \Delta t_{n-1} \tag{14}$$

where Q_{n-1} and Q_n are the heat exchange at the previous and the current analysis respectively, and k is a constant.
The constant k was introduced to accelerate the calculation and to reduce the computational time. The lower is its value the greater is the calculation accuracy and the computational costs. Calculations after 1 day of the system operation with different values of k were carried out. In Fig. 4 the differences of the heat exchanged and the number of analyses for achieving this instant time (refereed to the values calculated with the lower value of k analyzed in this study equal to 1.005) are shown. In this study the value of k equal to 1.01 was chosen as a trade-off between the accuracy and the velocity of the calculation.

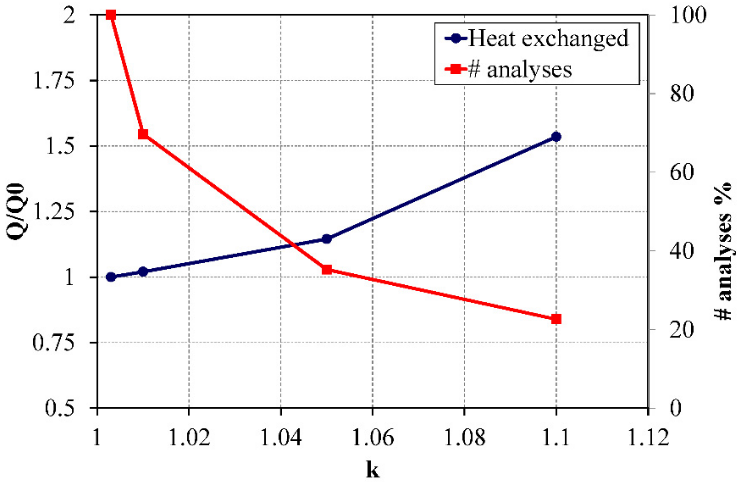

Fig. 4. Heat exchanged and number of analyses after the first day with different values of k.

4. Analysis of the results

The first analysis carried out was the estimation of the thermodynamic properties of the fluid in the exchanger during the operation. The results are presented in terms of fluid temperature and pressure along the pipe after 32, 128, 256 and 365 days with a mass flow rate of 1 kg/s. During the transient time the working fluid reaches different conditions because the temperature of the rocks in contact with the tube changes during the operation. In Fig. 5a the fluid temperature trends along the pipe are shown. In the descending way, the temperature increases rapidly up to the maximum value reached at the bottom of the pipe. The temperature in the ascending way decreases gradually because of the low heat transfer rate due to the presence of the insulation on the intern tube. The different fluid temperatures are due to the decrease of the surrounding rocks temperature during the transient time.

As shown in Fig. 5b, the pressure along the pipe increases in the vertical direction because of the contribution of the hydrostatic head. The values reached at the bottom become higher during the operation due to the reduction of the temperature that means an increase of the density. It is worth noticing that the position of the phase transition, where the curve shows a significant step, moves toward the output section during the operation.

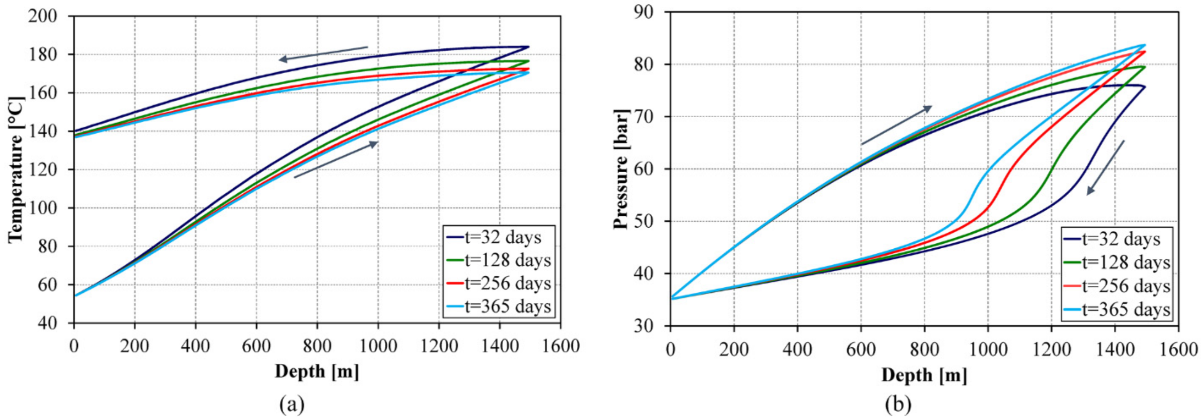

Fig. 5. Temperature (a) and pressure (b) profile in the double-pipe for transient times equal to 32, 128, 256 and 365 days.

The soil temperature changes continually during the transient time as shown in Fig. 6. Due to the heat transfer between the soil and the exchanger, the radius of influence, which indicates the radius where the temperature of the rocks is undisturbed, grows. Initially, the isotherms are parallel to the surface and bend near the heat exchanger. Afterward, the radius of influence increases until an equilibrium condition, when the heat flow absorbed by the double-pipe matches the heat flow coming from the surrounding rocks, is achieved. In the present study after 1 year the equilibrium condition is achieved corresponding to a 15 m long radius of influence. In the literature, the Charnyi's correlation is usually used to estimate the radius of influence in case of 1D modeling [13]-[14] as a function of the transient time. In this case, the correlation would have estimated a radius of influence of about 9 m, about 40% lower than that calculated with the proposed combined model.

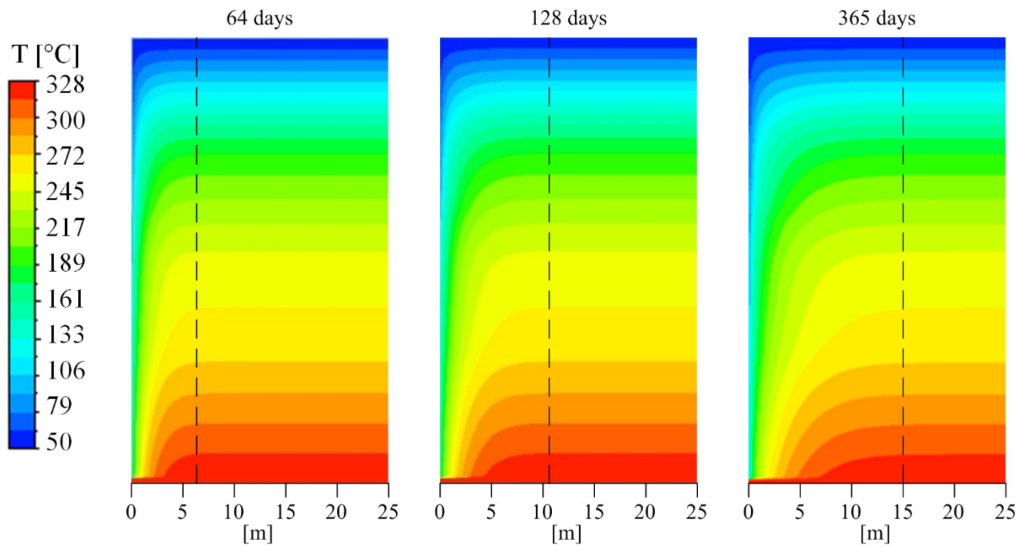

Fig. 6. Temperature field in the subsoil for transient time equal to 64, 128 and 365 days.

An important parameter investigated was the mass flow rate. This parameter plays a key role in the heat exchange between the subsoil and the double-pipe. Starting at the same initial condition, the higher is the mass flow rate, the greater is the flow velocity and the convective heat transfer coefficient. Fig. 7a shows the trend of the thermal fluxes with different mass flow rates flowing in the double-pipe. Even though in the first days they are strongly related, progressively the influence of mass flow rate decrease. This is due to a faster reduction of the subsoil temperature in case of greater fluid velocities. Furthermore, the mass flow rate values influence the fluid temperature reached during the transient time: the greater the mass flow rate the lower the temperature (Fig. 7b).

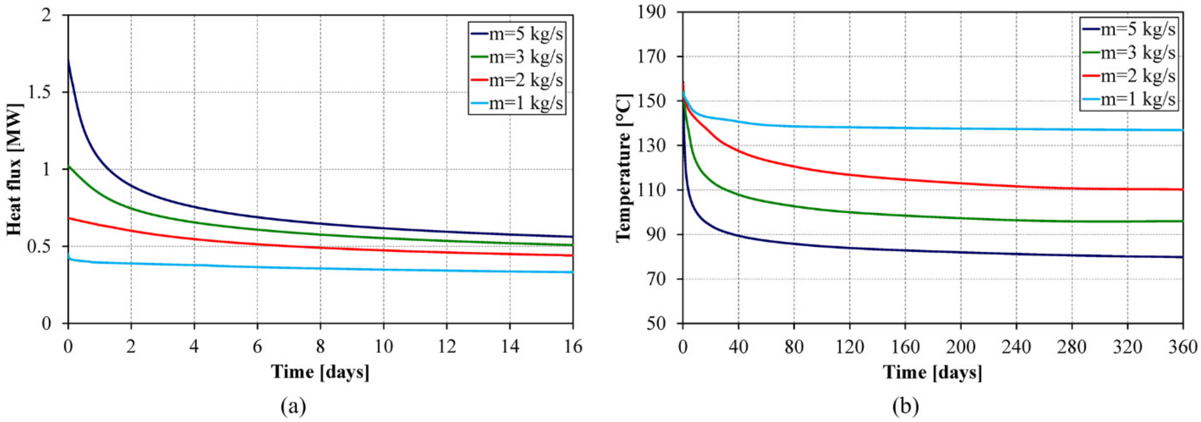

Fig. 7. Heat flow rate trend (a) and fluid output temperature (b) for different values of the mass flow rate.

For sake of completeness, the estimation of the power output of an ORC system coupled with the double-pipe was estimated. No back-up boiler was considered and the fluid from the double-pipe was directly sent to the expander inlet. A mass flow rate of 1 kg/s (isobutane) and a temperature as reported in Fig. 7b was considered. This mass flow rate is the only one that guarantees to have a temperature greater than the saturation temperature at 35 bar all year long. According to similar examples in the literature [16], no internal recovery between the condenser output and the double-pipe inlet was present. The condenser was supposed to work at 7 bar corresponding to 53.5°C. The power output was computed as the mass flow rate for the enthalpy variation on the expander. The expander isentropic efficiency was calculated according to Eq. 15 ([25]-[27]) where the design conditions are those of saturated vapor at 35 bar (132.4 °C) corresponding to a η_{des} of 0.85.

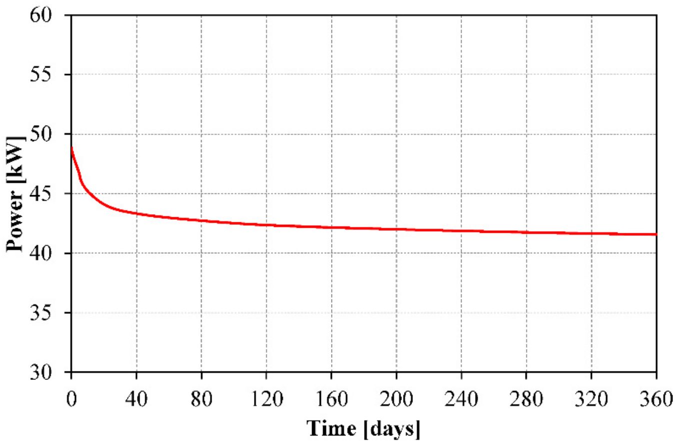

Fig. 8. Power trend with m=1 kg/s.

$$\eta = \eta_{des} \sin[0.5\pi(\frac{m_{off}\rho_{des}}{m_{des}\rho_{off}})^{0,1}] \quad (15)$$

In Fig. 8 the power produced by the plant during 1 year is shown. This result is in contrast with previous studies that, due to a not accurate modelling of the transient behavior of the system, showed overestimated power outputs for similar configurations.

5. Conclusions

A combined model was developed to study the heat transfer between a double-pipe heat exchanger and the subsoil in geothermal applications in order to evaluate the feasibility of this type of power plant. A 1D model was utilized for modeling the tube that was divided in control volumes and solved iteratively. A 2D axisymmetric model was developed to model the conductive heat transfer through the surrounding rocks and the structural cement. The transitory was reconstructed by simulating consecutive time steps in the 2D model where the boundary conditions, resulting from the 1D model, were kept constant. The duration of the time step was increased inversely to the heat flux. Campi Flegrei and, in particular the Mofete zone, was chosen as a case study since the subsoil temperature distribution was kwon from a previous experimental campaign and isobutane was chosen as the organic working fluid.

In order to validate the procedure, the behavior of the main parameters, such as the temperature and the pressure of the fluid and the radius of influence, was analyzed during the functioning. As expected, the mass flow rate has been one of most crucial parameter in the stability system. The greater the mass flow, the lower the output temperature of the fluid after a specific period. By reducing the mass flow rate from 5 kg/s to 1 kg/s, after 1 year the fluid output temperature increases of more than 50°C. The power produced by a typical organic Rankine cycle with a mass flow rate of 1 kg/s, which guarantees at regime a temperature greater than that of saturation, was studied. The long term power production turned out to be 42 kW that is far more reasonable than previous studies on similar plant operating in similar conditions. Furthermore, this study showed that the radius of influence calculated with a correlation present in the literature represents an underestimate of 40% in comparison to the value calculated in this study.

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