Renewable Energy 123 (2018) 353–381

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Review

The wellbore heat exchangers: A technical review

C. Alimonti*, E. Soldo, D. Bocchetti, D. Berardi

University of Rome — DICMA, Via Eudossiana 18, 00184 Roma, Italy

ARTICLE INFO

Article history:
Received 7 September 2017
Received in revised form
12 January 2018
Accepted 11 February 2018
Available online 13 February 2018

Keywords:
Wellbore heat exchanger
Geothermal energy
Deep borehole heat exchanger
Heat transfer

ABSTRACT

The available literature on the WellBore Heat eXchangers (WBHX) has been analyzed giving prominence to three aspects. First, the heat transfer through the geothermal reservoir and between the formation and the well has been analyzed. Then, the design of the WBHX and the modelling of the heat exchange has been reviewed. Lastly, the analysis of the performance of the WBHX in the production of thermal and/or electrical energy has been focused. Regarding the modelling of the heat transfer in the reservoir and between the wellbore and the formation, the sensitivity studies in literature highlight as key parameter the residence time of the fluid into the device. At fixed flow rate the residence time of the fluid in the WBHX is function of the well diameter. From analyzed papers, it raises the need of the insulation of the upward pipe in order to avoid heat losses. The range of produced thermal power is 0.15÷2.5 MW and of electrical power is 0.25÷364 MW. The WBHX is a promising technology if and only if is applied in the more convenient geothermal assets. The continuous study of the possible designing solutions and the improvements to enhance heat transfer is fundamental to allow this technology ready to market.

Contents

1. Introduction

The customary method to extract energy from a geothermal system at medium or high enthalpy is the production of geothermal fluids using wells. When the temperature of the extracted brines is greater than 150 °C, they are used to produce electricity in flash or dry steam geothermal power plants. When the temperature is lower than 150 °C, direct uses or electricity production using a binary power plant are the possible applications. The brines have properties not suitable to the terrestrial ecosystems. Therefore, after the use and before to inject it back into the ground the geothermal fluids must be treated.

The extraction and reinjection of the brines entail some technical and environmental risks, also in the closed loop binary power plants: corrosion and scaling of pipes, groundwater pollution, land subsidence and induced seismicity. Therefore, the production of the brines involve high economic costs. The investment can become non-profitable in unconventional geothermal systems where there are fluids with characteristics requesting special techniques. The possibility of negative impacts on the environment and the risk of induced seismicity, however of low intensity, can cause a negative social response to the geothermal development in areas with a high urbanization or with a high natural seismicity.

* Corresponding author.
E-mail address: claudio.alimonti@uniroma1.it (C. Alimonti).

https://doi.org/10.1016/j.renene.2018.02.055
0960-1481/

Nomenclature

A	cross-section of heat transfer
c_p	specific heat capacity
D	diameter
Ei(x)	exponential integral function
f	friction factor
gradT	temperature gradient
h	convective heat transfer coefficient
H	height
k	heat transfer coefficient
l	characteristic length
L	length
Nu	Nusselt number
p	pressure
$\dot{Q}$	heat flow
q	volumetric flow rate
r	radius, radial distance
r_s	radius of thermal influence
S	heat exchange rate
t	time
T	temperature
T_0	formation initial temperature
u	specific internal energy
U	velocity (flow rate)
v	velocity of Darcy
V	volume
z	vertical distance

Greek

α	thermal diffusivity
ε	surface roughness
λ	thermal conductivity
ν	kinematic viscosity
ρ	density

Indexes

c	external casing
D	adimensional
down	downward
ei	infinite distance
f	fluid
g	ground
h	hydraulic
i	inner
in	inlet
ins	insulation
m	media
o	outer
out	outlet
s	soil
t	total
st	steel
up	upward
w	well, wellbore
ws	interface WBHX/soil

In the last decade, several studies have been focused on the possibility to produce geothermal energy from a medium enthalpy geothermal system without production of brines, using a deep borehole heat exchanger, as well as for the shallow geothermal applications. This WellBore Heat eXchanger (WBHX), according to Nalla et al. (2005) [1] definition, is made of two coaxial tubes inserted in the well (Fig. 1). In the external annulus is injected a heat carrier fluid (water or a low boiling point fluid) which is heated going deep; at the bottomhole the fluid enters in the internal tube and it flows up to the wellhead also helped by the difference in density between hot and cold fluid (thermosiphon effect). The extracted heat can be used to produce thermal power or electrical power with an Organic Rankine Cycle machine. The WBHX plant has the advantage of avoiding costs and consequences related to the extraction and reinjection of the geothermal fluids. The main weakness is the low efficiency in heat recovery respect to the conventional geothermal plants. The lower mass flow rate that circulates in the device and the heat exchange mainly by conduction cause a lower wellhead temperature and consequently a lesser heat flow.

The target of this review is to collect the available literature on the WBHX in order to analyze the strength and the weakness points that concern the use of the deep borehole heat exchangers. Sapinska-Sliwa et al. (2015) [2] have published a previous review on the deep borehole heat exchangers: the paper is a conceptual review, which collects the few WBHX installations in the world, with particular emphasis on the Carpathian region. Whereas the aim of the present paper is to give prominence to three key aspects. Firstly the simulation of the heat transfer through the geothermal reservoir and the heat exchange between the formation and the well; then, the design of the WBHX and the modelling of the heat exchange in the dual pipes system; lastly the analysis of the performance of the deep borehole heat exchangers in the production of thermal and/or electrical energy.

The analyzed papers are quite recent (2002–2016) and can be classified into four groups depending by the treated topic:

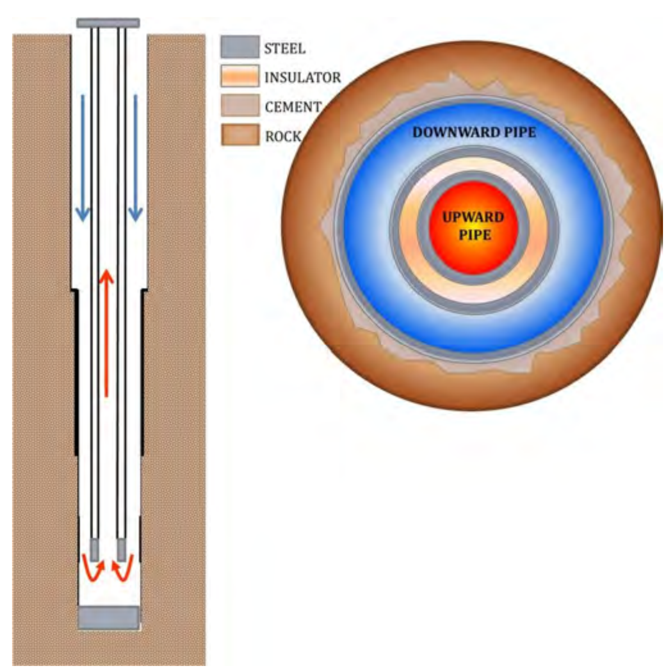


Fig. 1. WBHX (alimonti et al. 2016 [23]).

- articles with the target of the performance evaluation of the WBHX applied in real case studies ([3–7]) or in case of different design and reservoir ([1,8,9]);
- articles focused only on the heat transfer from the formation to the cylindrical wall of the wellbore ([10] [11] [12]);
- evaluation of the application of the WBHX to existing wells that have been abandoned, as for the depleted oil and gas wells ([13–25]), or the geological well studied by Ref. [26];
- Papers not focused on the deep borehole heat exchanger but that are interesting for the heat transfer model into the well and into the geothermal reservoir ([27]) or between the reservoir and the well ([28] [29]).

2. Modeling the WellBore heat eXchanger

2.1. The heat flow from the reservoir to the WBHX

This section describes the modelling of the heat exchange between the reservoir and the well in the analyzed papers. The model of the heat transfer through the reservoir and between the formation and the wellbore is a key issue to evaluate the heat flux extracted with a deep borehole heat exchanger. Furthermore, the unsteady state model of the heat exchange allows evaluating the evolution of the temperature near the borehole wall and therefore the productivity trend of the system.

Basic modeling is the combination of the Fourier's Law and the conservation of energy describing the distribution of the ground temperature during the heat extraction by a borehole heat exchanger. In a cylindrical geometry and in a homogeneous medium, the following relation expresses the governing equation:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T_r}{\partial r} = \frac{1}{\alpha}\frac{\partial T_r}{\partial t} \tag{1}$$

where $\alpha = \lambda/\rho c_p$ is the thermal diffusivity of the ground [$m^2\ s^{-1}$], λ is the thermal conductivity [$W\ m^{-1}\ K^{-1}$], c_p is the specific heat capacity [$J\ kg^{-1}\ K^{-1}$], ρ is the density [$kg\ m^{-3}$]. The heat transfer is purely conductive; the convection phenomenon due to the circulation of the fluids is neglected. The partial differential equation can be solved with numerical methods or with analytical solutions. Some authors use the analytical solution of Carslaw and Jaeger ([30]) to express the changing of the temperature in time and in radial direction respect to the axis of the well:

$$T(r,t) = T_0 + \frac{q}{4\pi\lambda}\int_{r^2/4\alpha t}^{\infty}\frac{e^{-u}}{u}du = T_0 + \frac{q}{4\pi\lambda}\left[-E_i\left(\frac{-r^2}{4\alpha t}\right)\right] \tag{2}$$

According to O'Sullivan et al ([31]). the use of numerical models in order to develop and manage the geothermal fields has become a standard practice since the 90's. The improvement in the hardware and software has produced increasingly powerful computers that can solve the complex systems of non-linear partial differential equations that describe the mass and energy transfer in geothermal reservoirs. The heat and mass transfer is a very complex phenomenon in a heterogeneous system like the geothermal one, in which phase changes can occur and several chemical species are present. The numerical simulation entails the discretization of the geothermal system into a grid of elements. O' Sullivan et al ([31]). indicates that the recent models have complex 3D structures with many elements (3000÷6000), but the dimension of the single element is still large: the typical horizontal dimension is 200 m and the typical vertical one is 100 m. The equations that describe the heat and mass transfer in the geothermal system are solved in the nodes of the grid, setting some boundary conditions at great distance from the axis of the well. Furthermore, considering the radial symmetry of the problem, it is common practice studying only the half of the system, starting by the axis of the well. The more widely used codes are STAR ([32]), TETRAD ([33]) e TOUGH2 ([34]) that can generate irregular meshes or grid.

The modern numerical simulators are able to model the heat transfer inside the reservoir; the main issue remains the coupling of the reservoir model with the model of the WBHX. Table 1 summarizes the solutions founded in the analyzed literature.

The WBHX are limited to two abandoned wells in Switzerland, at Weggis and at Weissbad. The papers of Kohl et al ([3] [4]). describe the performance of the plants and the numerical model of the heat transport in the rock and in the pipes.

The numerical simulation considers the changing of the heat content, the diffusion, the advection and the heat transfer. The used finite element code FRACTure [35] has the special feature of combining elements with different dimensions. Therefore, considering the axial-symmetrical geometry of the WBHX, this has been studied as a 1-D element surrounded by 2D elements. The finite elements mesh has been generated with WinFra, a semi-

Table 1
Reservoir and WBHX models.

Reference	Reservoir model	WBHX model	Coupling
Kohl et al. [4]	FRACTure	FRACTure	–
Nalla et al. [1]	TETRAD/GEOTEMP	TETRAD/GEOTEMP	–
Kujawa et al. [26]	Analytical model	Analytical model	Direct
Wang et al. [8]	AUTOUGH2	Numerical model	Iterative process
Davis and Michaelides [13]	–	Numerical model	–
Bu et al. [14]	Analytical model	Numerical model	Direct
Cheng et al. [15,16]	Analytical model	Analytical model	Direct
Cei et al. [10]	Tough2/Analitical model	–	–
Taleghani et al. [9]	Analytical model	–	–
Templeton et al. [17]	FlexPDE	FlexPDE	–
Akhmadullin and Tyagi [5]	–	Simulink	–
Feng et al. [6]	Cactus	Numerical model	Direct
Galoppi et al. [7]	Fluent	Numerical model (EES)	Iterative (Matlab)
Le Lous et al. [11]	Feflow	Feflow	Direct
Noorollahi et al. [18]	ANSYS	ANSYS	Iterative process
Noorollahi, Yousefi and Pourarshad [19]	ANSYS	ANSYS	Iterative process
Sliwa et al. [20]	BoHEx	BoHEx	Direct
Wight and Bennett [21]	–	Analytical model	
Alimonti and Soldo [22]	Analytical model	Numerical model	Direct

automated program. A link to common CAD programs established via the DXF-interface allows generating the geological structures and the technical ones. The entire mesh has a refinement around the pipe system especially in the lower part of the borehole and it is coarsened at vertical and horizontal distance from the well.

The hypothesis of homogenous properties of the soil has been used. The ground is a Molassic rock. The selected upper boundary condition corresponds to the annual mean temperature of the surface (9 °C). In the simulation of the WBHX at Weggis the surface heat flow has been used (73 W/m^{2}K), estimating the value by the temperature profile and the thermal properties of the ground. For the Weissbad plant, the basal heat flow (75 W/m^{2}K) has been taken from the geothermal map of the Switzerland. The authors defined some load-time functions in order to describe the transient evolution of selected parameters or boundary conditions.

The data collected during the operation of the Weggis plant and of the Weissbad plant (time, inlet temperature, outlet temperature, pumping power, frequency of the pump, flow rate) have been used to validate the simulation model.

The paper of Garcia- Gutierrez et al ([27]). does not concern the WBHX, but the study of the production from deep wells in the geothermal power plant of Cerro Prieto (Mexico). The article is interesting for the used method to simulate the heat transfer in the reservoir. The partial differential equation expressing the transient temperature distribution in the rock formation in cylindrical coordinates is solved using the finite difference techniques, having imposed the following boundary and initial conditions:

$$\mathrm{Tr} = (\mathrm{t}, \mathrm{r} = \mathrm{r_w}) = \mathrm{Ti}\ \mathrm{Tr} = (\mathrm{t}, \mathrm{r} = \infty) = \mathrm{Tg} \tag{3}$$

$$\mathrm{Tr} = (\mathrm{t} = 0, \mathrm{r}) = \mathrm{Tg} \tag{4}$$

where r_w is the wellbore radius, T_g is the undisturbed ground temperature evaluated as a function of depth, T_i is the temperature of the rock-fluid interface. T_i is estimated with the wellbore model, based on the conservation equations of mass, momentum and energy for steady state and homogeneous flow.

A 1-D mesh-centered grid composed of radial elements represents the reservoir; the equation of the temperature for each node has the following form:

$$A_j T_{j-1}^{n+1} + B_j T_j^{n+1} + C_j T_{j-1}^{n+1} = D_j \tag{5}$$

where A, B and C are the coefficients matrices, T^{n+1} is the solution vector, D is the constants vector. The matrix is solved with the Thomas algorithm ([36]). The system of equations of formation and well is solved using a fractional time step in each cell. The authors have validated the model comparing the results with the analytical solution of the heat transfer problem of Carslaw and Jaeger [30] and with the data measured in the geothermal field.

Kutasov [28] has developed a semi-analytical equation to evaluate the dimensionless temperature at the wall of an infinite long cylindrical heat source with a constant flow rate. In a second paper ([29]) the author has modified the equation to extend the calculation of the transient dimensionless temperature of an infinite long, variable rate, cylindrical heat source. Kutasov has validated his results using the values calculated by Chatas ([37]) of the dimensionless wall temperature over a range of values of dimensionless time. Chatas used the numerical integration to solve the integral form of the diffusivity equation for a distance equal to the radius of the well ($r = r_w$).

Nalla et al. [1] have conducted a sensitivity analysis of operating and design variables of the WBHX, using a numerical model. The authors used two different simulators: GEOTEMP ([38]) and TETRAD ([33]); they selected TETRAD because of some grid and computational problems of GEOTEMP. TETRAD is a 3-D multi-phase and multi-component simulator, which solves the energy and mass conservation equations.

The proposed model simulates the WBHX and the surrounding formation represented using a cylindrical computational grid. Each element of the grid has assigned parameters and properties. The thermal properties of the rock are constant. The hypothesis of impermeable rock was assumed; therefore, no-flow boundaries were assigned. Two boundary conditions have been imposed: basal heat flux at the bottom of the domain and surface heat loss at the top of the domain. Two heat transfer mechanisms have been considered: the conduction from the formation to the wellbore and the advection in the WBHX.

Kujawa et al. [26] have developed an analytical model based on the Fourier equation in order to evaluate the application of a WBHX in an existing well, Jachowka K-2. The following relations describe the unsteady heat transfer between the rock and the fluid flowing down in the annulus of a WBHX:

$$d\dot{Q}_{down} = k\left(T_s - T_f\right)dA \tag{6}$$

$$\frac{1}{k} \cong \frac{1}{h} + \frac{D_c}{2\lambda_s} ln \frac{4\sqrt{\alpha_s t}}{D_c} \tag{7}$$

The convective heat transfer is related to the Nusselt number (h = Nu λ/l) which has been evaluated with three different equations, depending on the flow regime. The Averin's equation has been used for the turbulent flow in the annulus; otherwise, for the laminar flow, the Nusselt number has been evaluated with the Sarma's equation.

The authors have considered the change over time of the heat flux into the formation surrounding the WBHX using the expression of the radius of influence of the well $r_s = 2\sqrt{\alpha_s t}$. The geothermal gradient is 25 °C/km and 7.03 °C is the surface temperature. The thermophysical properties of the soil are taken from Polgeotermia.

Wang et al. [8] have proposed the use of the deep borehole heat exchanger in an EGS reservoir. In order to study the potential of the plant the authors have developed a coupled model: a numerical model based on the conservation equations of mass, momentum and energy describes the heat transfer between formation and the WBHX and a second one inside the exchanger; the reservoir model has been implemented with AUTOUGH2 [39].

The following energy conservation equation describes the heat transfer between rock and the well:

$$\frac{\partial \rho_f V u}{\partial t} = -\lambda A \nabla T \tag{8}$$

The conduction is the only heat transfer mechanism neglecting the convection and the Joule-Thompson effect. A radial gridding has been used for the formation, with a logarithmic spacing. The logarithmic spacing has been used also for the time scale.

The reservoir model constructed with AUTOUGH2 is based on the EGS field of Soultz (France). A grid of 11 blocks with logarithmic spacing from 0.05 to 50 m represents the rock matrix; perpendicular to the formation grid, two parallel and independent fracture planes are represented: one has lower permeability but greater volume, the other one has high permeability but smaller volume. The fracture system is symmetric with the wellbore in the center; therefore, only one quarter of it has been studied using a 20 × 20 grid composed by 50 blocks with dimension 50 × 25 m. The thickness of the fracture zone is 0.5 m.

The geothermal gradient is 40 °C/km, the surface temperature is 20 °C and the initial pressure at the top of the reservoir (4000 m) is 400 bar.

The numerical model of Davis and Michaelides [13] is based on the conservation equations of mass, momentum and energy; no reservoir model has been developed. The heat transfer between the formation and the heat carrier fluid has been estimated as:

$$\dot{Q}_{down} = 2\pi rh\left(T_{ws}(z) - T_f\right)\triangle z \tag{9}$$

The convective heat transfer coefficient is calculated using the hydraulic diameter and the Dittus-Boelter relation for the Nusselt number.

Bu et al. [14] studied the geothermal energy production with deep borehole heat exchanger using abandoned oil and gas wells in China. They implemented in MATLAB the mathematical model based on the energy conservation equations and the flow resistance equation. The system is discretized using the following steps $\Delta t = 1800$ s, $\Delta r = 2$ m, $\Delta z = 10$ m.

Cheng et al. [15,16] have proposed the application of the WBHX in the abandoned oil wells in China also. They developed an analytical model, which includes the heat transfer equation, the fluid momentum equation and the fluid energy equation.

The radial heat flux from the rock to the interface wellbore/formation is based on the Ramey's [40] definition, therefore the transient formation heat transfer can be written as:

$$\frac{d\dot{Q}}{dz} = \frac{2\pi\lambda_s(T_{ei} - T_{ws})}{f(t)} \tag{10}$$

Cheng et al. [15,16] proposed an expression for the function *f(t)* that considers both the time and the heat capacity of the wellbore:

$$f(t) = \frac{16\omega^2}{\pi^2}\int\frac{1-\exp(-\tau_D u^2)}{u^3\Delta(u,\omega)}\,du \tag{11}$$

where τ_D is the adimensional time (α_s/r_{inj}^2); r_{inj} is the radius of the injection pipe; α_s is the thermal diffusivity of the rock; $\omega = (\rho c)_e/(\rho c)_w$ is the ratio of volumetric heat capacities of formation and wellbore; u is the dummy variable for the integration. The term $\Delta(u,\omega)$ depends on the zero-order and first-order Bessel function of the first kind and the zero-order and the first-order Bessel function of the second kind. The heat transfer between the formation and the fluid flowing downwards is expressed by the fluid energy equation in the following form:

$$2\pi r_{inj}h\left(T_{ws} - T_f\right) = \frac{d\dot{Q}}{dz} \tag{12}$$

Cei et al. [10] have studied the heat transfer from a pure conductive geothermal system to a U-tube loop device without fluid production. An analytic method and a numerical simulator have been used to evaluate the thermal profiles in the formation at different times and the outlet temperature of the working fluid. The analytic method is based on the Fourier's equation and the solution of Carslaw and Jaeger [30]. Two different cases have been simulated: uniform vertical temperature of 240 °C and constant heat rate equal to 500 kW; a variable heat rate supposing that the initial value is 500 kW and using the superposition effect.

The numerical model has been developed using TOUGH2, a numerical simulator for multi-dimensional and multiphase flows in porous and fractured media [41]. The simulation domain has a radius of 200 m and a vertical dimension of 3000 m; the grid is composed of 60 vertical layers and 12000 cells. The horizontal layers are divided into 206 cells with variable dimensions; the first two radial cells represent the well and the casing (radius = 0.05 m, thickness = 0.01 m). The geothermal gradient is linear (40 °C/km) and the ground temperature is 120 °C. The effect of the WBHX is simulated with the properties of the selected working fluid (water) (Table 2). The injection temperature is 80 °C and the hypothesis of perfect insulation of the internal tube is used.

In order to validate the analytical model a simulation with constant heat rate equal to 500 kW and uniform vertical temperature profile of 240 °C has been carried out: Fig. 2 shows the good fitting between the two models. The results demonstrate that the decrease of the formation temperature is concentrated in the first 10 years of operation, especially near the wellbore, and that the influence radius is about 20 m.

Taleghani [9] proposed an analytical model of the heat transfer from the formation to a system of fractures realized in the surrounding of the WBHX and filled with highly conductive material. The basis of the model is the equation of Carslaw and Jaeger [30] of the heat conduction into a porous media. The model is applied to three different cases: non-fractured well case, single double-wing fractures, single penny-shaped fracture.

The following relation is used to calculate the heat flux from the formation to the wellbore in case of non-fractured well case:

$$\dot{Q}_{down} = \int_t q\,dt = H\,\frac{8\lambda}{\pi}\int_0^\infty \frac{1-\exp(-\alpha u^2 t)}{\alpha u^3\left[Y_0^2(au)+J_0^2(au)\right]}du \tag{13}$$

Where J_0 and Y_0 are zero order Bessel functions of first and second kinds.

In the case of single double-wing fractures, the one-dimensional geometry of the diffusion equation is used to evaluate the heat flux from the rock to the fractures:

$$q = 4LH\lambda\frac{\partial T(0,t)}{\partial y} \tag{14}$$

where L is half of the length of the fracture and H is the opening of

Table 2
Parameters – TOUGH2 simulation ([10]).

Material	Density [kg/m^3]	Porosity [−]	Permeability [m^2]	Thermal conductivity [W/m °C]	Specific heat [J/m^3 °C]
Water	1000	0.99	1E-5	0.8	4180
Casing	7800	0.00	0	50.0	500
Rock	2600	0.00	0	2.5	2600

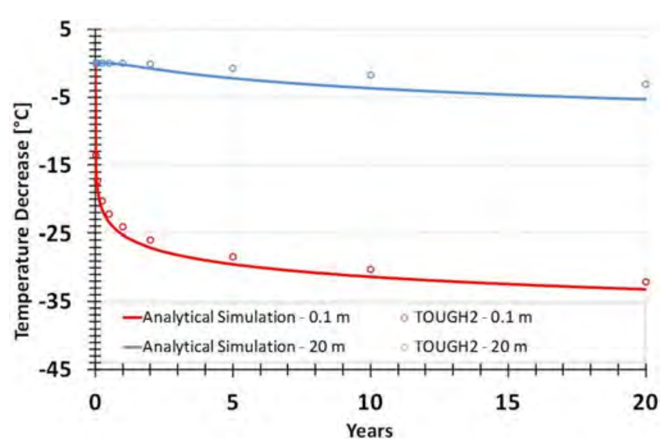


Fig. 2. Formation temperature decline, constant heat rate case ([10]).

the fracture.

In case of single penny-shaped fracture the two dimensional geometry is used. It is assumed that the thermal conductivity of the cemented fractures is higher than the rock one, that the formation is a homogenous porous medium fully saturated with a single-phase fluid, that the depth of the fracture allows to ignore any effect on the surface and that the fracture is uniformly filled with proppants. After a while, steady state conduction is reached and the temperature distribution is calculated with the following relation:

$$T(r,z) = \frac{2}{\pi}\arcsin\left[\frac{2a}{\sqrt{(r-a)^2+z^2}+\sqrt{(r+a)^2+z^2}}\right] \tag{15}$$

the cylindrical coordinates (r,θ,z) are used, a is the radius of the fracture.

The calculation of the heat flux into the fracture is carried out by finding the temperature gradient and applying the Fourier's law.

Templeton et al. [17] have used the software FlexPDE to develop the heat transfer model. The Fourier equation describing the heat conduction in the formation is inserted in the energy conservation equation together with two other terms: a term accounting for the effect of the groundwater flow and the fluid flowing in the WellBore Heat eXchanger; a term of the convective heat transfer inside the WBHX. The model domain is 40 m, equal to the radius of thermal influence. The radial symmetry of the heat exchanger allows simulating only half of the WBHX imposing a boundary condition of no flux on the left side of the model (the axis of the well). On the bottom and on the right side of the domain in order to reproduce the natural geothermal gradient a constant temperature condition applies: the values of the temperature are selected in according to the average ground temperature and the geothermal gradient of an abandoned oil well in the Persian Gulf.

Feng et al. [6] have used the computational toolkit Cactus to simulate the Camerina A, a low enthalpy geopressured reservoir located in Louisiana, where they proposed to apply a horizontal downhole heat exchanger. The simulation represents the WBHX as a linear heat sink. At each time step, Cactus calculates the reservoir temperature used as boundary condition of the downhole heat exchanger model.

Galoppi et al. [7] have developed a coupled model of the WBHX and the formation. The authors studied the application of a double-pipe heat exchanger in the area of Campi Flegrei (Italy). The reservoir is modeled as a 2D axial-symmetric geometry with cylindrical coordinates using the software FLUENT. The formation domain has the depth of 1520 m and the width of 50 m and it is divided into 364800 cells: 120 in horizontal direction and 3040 in vertical direction. The cells are quadrangular with variable size: 0.499 mm near the well and 1440 mm near the boundary of the formation. The heat transfer in the formation is conductive, the rock is homogeneous and the temperature at the top and the bottom is constant.

Le Lous et al. [11] concentrated their study on the simulation of the reservoir using the FEFLOW code to model the formation as a 3D element and the WBHX as a 1D element. The domain has dimensions 1000 m × 1000 m x 5500 m; the depth of the borehole heat exchanger is 5000 m. The Delunay mesh generator, included in FEFLOW, has been used for the discretization of the domain in triangular elements with smaller width near the well. Along the south and the north mesh borders of the first layer the fixed hydraulic head boundary condition (Dirichlet type) has been imposed. On the vertical faces and on the deepest layer the hypothesis of fixed flux has been used (Neumann type boundary condition). The surface temperature is set to 10 °C and it is constant outside the influence radius of the well. The geothermal gradient is 30 °C/km. The proposed model evaluates the heat transfer in the formation and the variation of the temperature at the external borehole wall. The heat extraction operated by the WBHX is modeled with a fluid injected with a temperature of 0 °C and a flow rate of 300 m^3d^{-1}. The authors do not developed the heat transfer model inside the deep borehole heat exchanger.

Alimonti and Soldo [22] have developed an analytical model, implemented in a C computation code, of the heat exchange in the WBHX. The model is based on an analytical solution of the heat transport equation into the rock. It is assumed that the heat transfer from the reservoir to the borehole wall happens only by conduction and between the wall and the working fluid by conduction and convection. The increasing of the radius of thermal influence in time has been calculated using the following relationship ([42] [43] [44]):

$$r_s = 2\sqrt{\alpha_s(t')} \tag{16}$$

The model includes fluid properties and geometrical characteristics. The following relation is used to estimate the heat flux transferred from the rock to the fluid in the downward pipe:

$$\dot{Q}_{down} = 2\pi r_w k_t \left(T_{ws}(z) - T_f\right)\triangle z \tag{17}$$

The convective heat transfer coefficient k_t is calculated using the definition of the Nusselt number and a form of Dittus-Boelter equation, having assumed turbulent flow inside tubes.

2.2. The heat flow through the WellBore heat eXchanger

In the following section the solutions adopted by the different authors in the modeling and design of the WBHX are reported. The simulation of the heat transfer inside the dual pipe system is the key point to evaluate the potential of the deep borehole heat exchangers and to optimize the design of the plant. The most common approach is to study the conservation equations of the mass, the momentum and the energy inside the downward pipe and upward pipe.

Only two WBHX have been realized, Weggis and Weissbad wells in Switzerland. The geometry of the installed WBHX in existing well is reported in Fig. 3 a and b ([4] [3]). The average geothermal gradient of the Weggis area is about 30 °C/km; the well has a depth of 2302 m and the temperature at the bottom of the well is 73 °C. The internal pipe is insulated until 1780 m of depth using a vacuum pump, which drops the pressure between the internal coaxial tubes to the value of 0.2 bars. The Weissbad well has a depth of 1200 m and a bottomhole temperature of 45 °C.

The heat carrier fluid is pure water for both of the plants; the flow rate is 10.5 m^3/h at Weissbad plant and 4.86 m^3/h at Weggis plant.

As previously mentioned the WBHX was simulated as a 1-D element using the FRACTure code. The model is able to calculate the effect of the changing of the diameters on the fluid velocity. The simulation distinguishes between the heat transfer concerning the insulated pipe or the non insulated pipe.

Using the measured inlet temperature as input value, the authors have set the geometry and the boundary conditions in order to fit the outlet temperature of the model to the measured data.

The authors have simulated the circulation and recovery periods demonstrating that the duration of the cycles does not affect the outlet temperature (Fig 4). The outlet temperature depends on the inlet temperature, the flow rate, the heat flux and the thermal

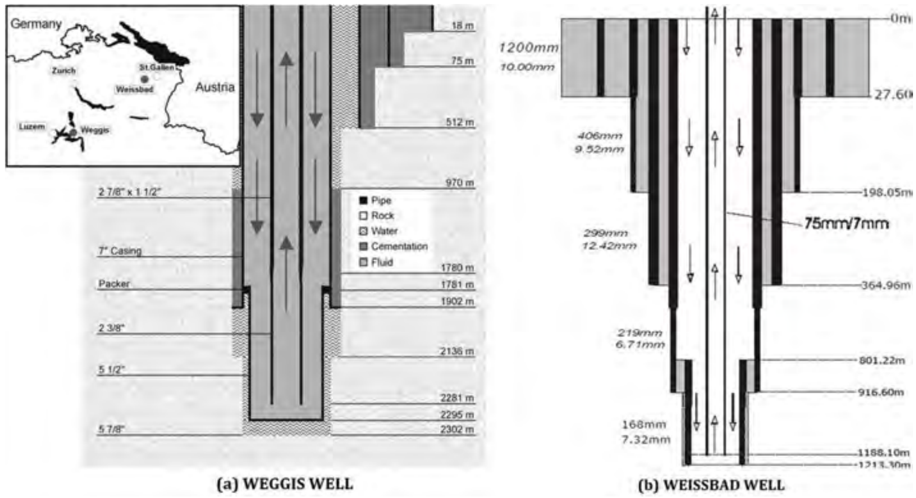


Fig. 3. Well completion of Weggis and Weissbad plants ([4] [3]).

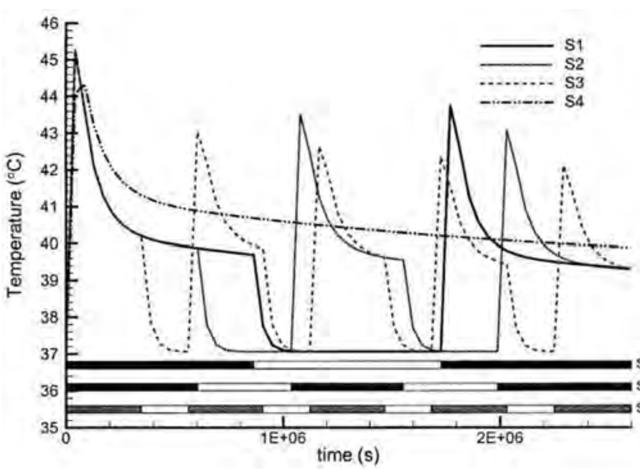


Fig. 4. Sensitivity analysis of operation conditions. The horizontal bars indicate the length and frequency of the S1–S3 runs, the circulation of S4 run is continuous ([4]).

conductivity of the material that surrounds the WBHX.

Nalla et al. [1] proposed a base case scenario for the first application of the numerical model of the WBHX and surrounding formation developed with TETRAD (Table 3).

The numerical model simulates with a cylindrical grid the most important elements of the WBHX plant: the tubing, the insulation, the casing and the cement. The well diameter is constant for the entire length. The pipes are made of steel, the magnesia is used for the insulation, and the well is cased and cemented until the depth of 762 m, leaving the rest of the wellbore as “an open hole”. As already mentioned in Section 2.1, the heat transfer in the WBHX is assumed to happen by advection, whereas the heat moves by conduction from the formation to the wellbore.

The working fluid, water, is Newtonian and under pressure in order to avoid evaporation. The model simulates the changing of the fluid density with the pressure and the temperature. The frictional pressure losses in the well are considered negligible.

Fig. 5 shows the design of the WBHX in the well Jachowka K-2, reported in Kujawa et al. [26] and used to evaluate the performance in extraction of geothermal energy. The authors named the device Field Exchanger.

The depth of the well is 3950 m and the bottomhole

Table 3
Base case description ([1]).

WELL GEOMETRY		PARAMETERS	
Tubing inner diameter	76.2 mm (3.0 in.)	Basal heat flux	0.1 W/m^2
Casing length	762 m	Geothermal gradient	57.8 °C/km
Tubing outer diameter	88.9 mm (3.5 in.)	Formation thermal conductivity	1.73 W/m °C
Insulation outer diameter	101.6 mm (4.0 in.)	Formation volumetric heat capacity	1810.7 kJ/m^{3}K
Casing inner diameter	228.6 mm (9.0 in.)	Insulation thermal conductivity	0.07 W/m °C
Casing outer diameter	244.475 mm (9.625 in.)	Insulation volumetric heat capacity	7608.4 kJ/m^{3}K
Wellbore diameter	311 mm (12.25 in.)	Tubing and casing thermal conductivity	44.83 W/m °C
Well depth	5593 m	Tubing and casing volumetric heat capacity	3836.93 kJ/m^{3}K
		Cement thermal conductivity	0.87 W/m °C
		Cement volumetric heat capacity	1260.80 kJ/m^{3}K
		Working fluid volumetric heat capacity	4186.8 kJ/m^{3}K
		Circulation rate	6.3 $\cdot 10^{-3}$ m^3/s
		Surface temperature	26.7 °C
		Temperature of injected fluid	26.7 °C
		Bottomhole temperature	350 °C

temperature is 105.8 °C. The heat transfer mechanisms regarding the fluid that is flowing up in the internal pipe are described by the multi-layer wall solution expressed by the following overall heat transfer coefficient:

$$\frac{1}{k} = D_0\left(\frac{1}{h_i D_i} + \sum_{i=1}^{n} \frac{1}{2\lambda_i} ln \frac{D_{i+1}}{D_i} + \frac{1}{h_o D_{n+1}}\right) \tag{18}$$

For the calculation in the internal tubing, where there is turbulent flux, the Nusselt number has been calculated with the Mikheev’s equation.

Wang et al. [8] have proposed a particular design of the WBHX

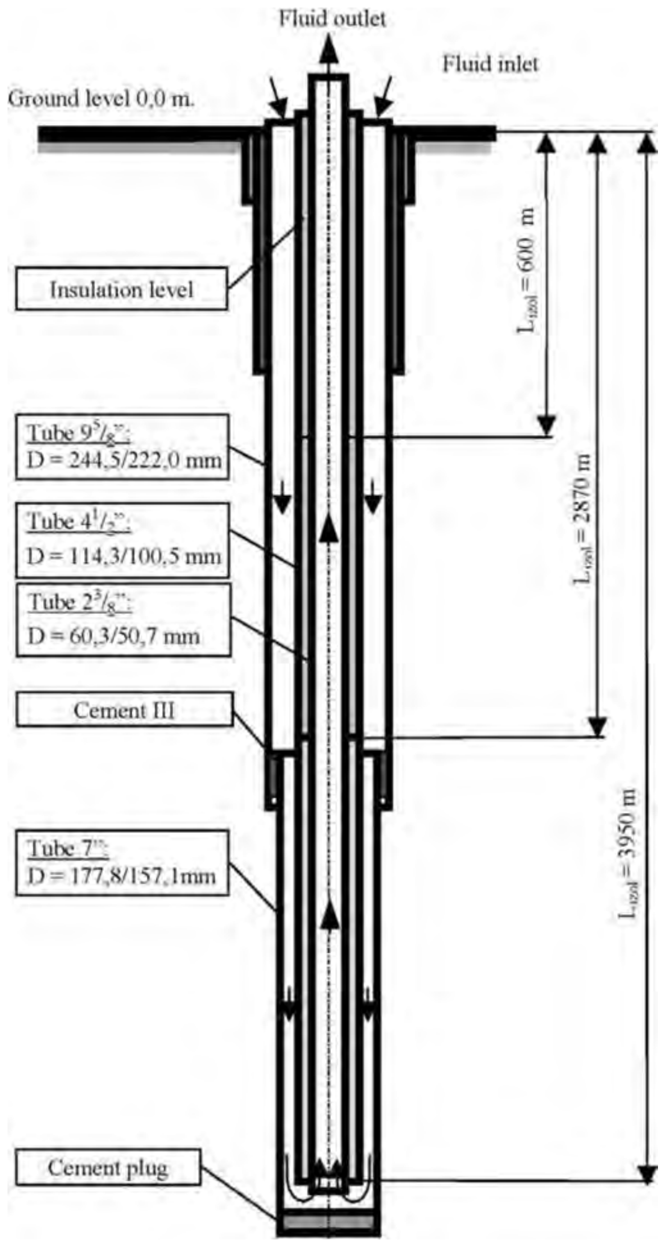


Fig. 5. The scheme of the field exchanger in the Jachowka-K2 well ([26]).

in order to apply it in an EGS, avoiding the depletion of the heat that occurs in this type of systems. The authors recommend fracturing the rock surrounding the WBHX, which is equipped with a second open annulus between the external casing and the radius of the borehole. Therefore, the connection between the reservoir and well brings additional heat to the WBHX thanks to the geothermal water that moves in the second annulus and in fractures, driven by free convection. A binary power plant connected to the deep borehole heat exchanger converts the thermal energy in electrical one.

The authors have built a numerical model based on conservation equations of mass, momentum and energy in order to simulate the heat transfer inside the WBHX. The following overall heat transfer coefficient has been adopted:

Table 4
Parameters of the base case proposed by Ref. [8].

Casing diameter	340 mm
Tubing Diameter	65 mm
Thickness Insulation	5 mm
Length	5000 m
Insulation material conductivity	0.05 W/m °C
Working fluid	Isopentane
Mass flowrate	2 kg/s
Surface temperature	20 °C
Geothermal gradient	40 °C/km
Formation volume heat capacity	900 kJ/m^3°C
Formation thermal conductivity	2 W/m °C
Formation density	2000 kg/m^3
Condenser temperature	320 K
Turbine efficiency	85%

$$\frac{1}{k_t} = \frac{r_o^2}{r_i^2}\frac{1}{h_i} + \frac{r_o}{\lambda_{st}} ln\frac{r_o}{r_i} + \frac{1}{h_o} \tag{19}$$

h_i is calculated with the relation $h_i = k_f/r_i\ 0.0395\ (Re)^{0.75}$ ([45]).

The finite difference method has been used to solve the system equations and the equations regarding the heat transfer between the well and the formation. The model has been validated using the results of Nalla et al. [1].

The numerical model has been coupled with the reservoir model constructed with AUTOUGH2 using an iterative approach. In fact, both of the models provide boundary conditions for the other one. Therefore, starting from a hypothetical value of the flow rate in the external annulus, the numerical model of the WBHX is used to calculate the pressure and the temperature at the bottom of the formation. These values are the input data of the AUTOUGH2 model which evaluates a new value for the flow rate in the annulus. This value is used to start again the procedure until there is convergence between the flow rate values calculated with the two models.

Table 4 reports the parameters of the base case of Wang et al. [8]; the authors have carried out a sensitivity study by modifying the design of the WBHX and the operating parameters.

Davis and Michaelides [13] have studied the possibility of use the WBHX in the depleted oil wells of Texas. The model of the WBHX is constituted by the conservation equations of mass, momentum and energy.

The friction factor has been calculated with the Haaland's equation [46]. The proposed plant is a WBHX connected to a binary power plant; the working fluid is isobutane. The selected well has a depth of 3000 m and a casing diameter of 12 inches. The geothermal gradient is linear; the thermo-physical parameters of the formation are taken from the RailRoad Commission of Texas. The polystyrene has been used for the internal insulation of the borehole heat exchanger.

Bu et al. [14] have evaluated the utilization of the depleted oil and gas wells also. They proposed to convert the extracted heat into electrical power via a "flash-steam" plant and to use the waste-water into a district heating plant. Following are reported the equations of energy conservation in the extraction tube and in the injection annulus, respectively:

$$\frac{\partial T_r}{\partial t} + \frac{\partial U T_r}{\partial z} = -S_{c,i} = -\frac{k_t(T_i - T_c)}{\rho A_r c_{p,f}} \tag{20}$$

$$\frac{\partial T_r}{\partial t} + \frac{\partial U T_r}{\partial z} = S_{c,i} + S_{ws,c} = \frac{k_t(T_i - T_c)}{\rho A_i c_{p,f}} + \frac{h_c 2\pi r_c (T_{ws} - T_c)}{\rho A_c c_{p,f}} \quad (21)$$

The total heat transfer coefficient is:

$$k_t = \left[\frac{\pi}{\frac{1}{2h_i r_i} + \frac{1}{2\lambda_s} ln\left(\frac{r_o}{r_i}\right) + \frac{1}{2h_o r_o}} \right] \quad (22)$$

The convective coefficients have been calculated using the Dittus-Boelter formula for the evaluation of the Nusselt number in case of turbulent flow. The flow resistance equation, or pressure loss equation, completed the WBHX.

In order to solve the system of equations the authors have given initial and boundary conditions. The initial conditions are constant velocity of the fluid ($0.01 < V_{in} < 0.06$ m/s), injection temperature of 30 °C, ground temperature of 15 °C, linear geothermal gradient. The influence radius of the well equal to 200 m is the boundary condition. Bu et al. [14] validated their model using the results of Kujawa et al. [26].

The analytical model proposed by Cheng et al. [15,16] is composed by the momentum equation and the energy equation. The friction loss gradient is calculated using the hydraulic diameter d_h and the friction factor is expressed by the Haaland's equation [46].

The hypothesis of perfect insulation of the internal tubing has been used; therefore, no heat exchange occurs between the fluid flowing downwards and the fluid flowing upwards. The heat flow acquired by the injected fluid is equal to the radial heat flow from the rock to the external wall of the WBHX.

Cheng et al. [15,16] have proposed to convert the produced thermal power into electrical one using an Organic Rankin Cycle. The ORC working fluid circulates directly into the WBHX. Table 5 reports the parameters of the base case.

The work of Cei et al. [10] has omitted the modeling of the deep borehole heat exchanger and the heat transfer phenomena into the double pipe. The authors have evaluated the outlet temperature of the working fluid in the WBHX using an analytical model and the numerical simulator TOUGH2.

Taleghani [9] proposed to improve the performance of the WellBore Heat eXchanger using the fracturing of the rock. The fractures are filled with a high conductivity material (cements or proppants) in order to increase the heat transfer between the formation and the WBHX. The improved design can be applied to the vertical wells and to horizontal wells, thus increasing surface contact area. The author did not report any geometrical data of the system (depth, casings diameters, and dimension of the fractures) and no model of the heat transfer inside the exchanger has been developed.

Templeton et al. [17] have developed a coupled WBHX-reservoir with the finite elements software FlexPDE. The authors have proposed the conversion of an abandoned oil well in the Persian Gulf into a geothermal well using a deep borehole heat exchanger with constant diameters of the casings. The formation properties are assumed homogeneous and they have the typical values of the sedimentary rocks in which the hydrocarbon reservoirs occur. The working fluid is water. Table 6 shows the base case parameters.

The design of the WBHX proposed by Templeton et al. [17] includes the insulation of the external casing until the depth at which the formation temperature equals the temperature of heat carrier fluid; this precaution avoids the heat loss from the down flowing water in the annulus to the rock.

The authors have proposed two scenarios. A constant inlet temperature scenario has been used to carry out a sensitivity analysis of the performance of the WBHX changing the inlet temperature, the mass flow rate, the length of the external insulation, the thermal conductivity of the ground, the geothermal gradient, and the vertical groundwater flow. In the second scenario, the produced power is constant whereas the inlet temperature of the

Table 5
Parameters of the base case study ([15]).

Depth	6000	m
External radius of injection well	0.14	m
Internal radius of injection well	0.125	m
External radius of recovery well	0.06	m
Internal radius of recovery well	0.05	m
Inlet pressure of fluid	2	MPa
Surface Temperature of formation	288.15	K
Temperature gradient	0.040	K/m
Formation thermal conductivity	1.8	W/mK
Formation volumetric heat capacity	$2.3 \cdot 10^6$	J/m^{3}K

Table 6
Parameters of the case study ([17]).

Geometrical characteristics		
External radius of injection well	0.098	m
Internal radius of injection well	0.075	m
External radius of recovery well	0.04	m
Internal radius of recovery well	0.02	m
Thickness of the insulation	0.02	m
FORMATION PROPERTIES		
Temperature gradient	0.03	°C/m
Formation density	2200	kg/m^3
Formation thermal conductivity	2	W/mK
Formation specific heat	1000	J/kgK
THERMAL PROPERTIES		
Water inlet temperature	70	°C
Water density	1000	kg/m^3
Water thermal conductivity	0.608	W/mK
Water specific heat	4200	J/kgK
Insulation density	1.225	kg/m^3
Insulation thermal conductivity	0.025	W/mK
Insulation specific heat	1010	J/kgK

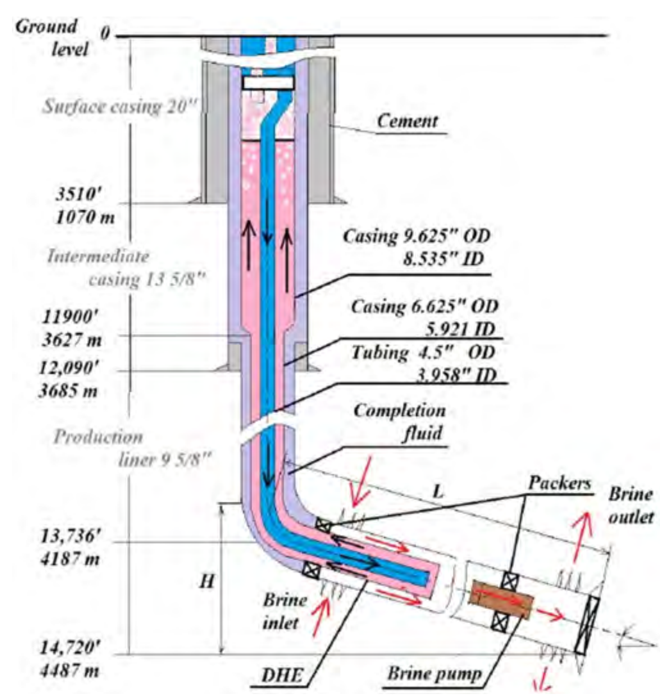


Fig. 6. Downhole heat exchanger proposed by Ref. [5].

fluid has been modified in order to have a constant difference between the outlet temperature and the inlet temperature. The authors have evaluated only the thermal power production for both scenarios.

Fig. 6 shows the schematic design of the downhole heat exchanger (DHE) developed by Akhmadullin and Tyagi [5] for a low enthalpy geopressured reservoir. All the elements that compose the plant are commercially available parts in the petroleum industry and the casing design was performed. The authors propose to enhance the efficiency of a DHE forcing the convective phenomena. The DHE is provided of a horizontal offset with an external annulus where the brine enters and transfers the heat to the working fluid in the internal annulus. Therefore, the working fluid is injected through a pump into the internal tubing and it flows upward into the internal annulus, unlike all the design solutions in this review.

The plant is equipped with two pumps: an external one that pumps the working fluid towards the tubing and a brine pump installed into the horizontal section in order to pump the brine from the formation into the annulus and then back into the reservoir. The reinjection distance must avoid the thermal breakthrough. The DHE is connected to an ORC plant in order to produce electrical energy. Akhmadullin and Tyagi [5] have studied the application of the DHE into Camerina A reservoir, located in Louisiana (USA).

The heat transfer into the DHE has been studied with the software Simulink. The model is the mathematical solution defined by Feng [47] and based on the equation of the energy balance in porous and isotropic medium.

Feng et al. [6] have deepened the study of the DHE for horizontal wells proposing two different configurations. In the configuration G (Fig. 7) the geofluid enters in the internal tubing through a crossover at the top of the horizontal section; the working fluid enters in the external annulus (II) and acquires heat from the reservoir in contact with the casing and the cement (conductive heat transfer). At the end of the DHE the working fluid diverts the direction and enters into the annulus I, it flows upward and acquires heat from the brine in the internal tubing (conductive and convective heat transfer). The external wall of the Annulus I is insulated to avoid heat losses between the flow paths of the working fluid.

In the configuration W (Fig. 8) the working fluid enters in the internal tubing and when it revers the direction and flows upward in the internal annulus (I), it acquires heat from the geofluid which is pumped into the external annulus (II). The external wall of the tubing is insulated in order to avoid the heat losses from the working fluid flowing upward.

The authors developed the model of the heat exchange inside the DHE assuming steady state condition inside the reservoir, perfect insulation of the casing I (configuration G) and the tubing (configuration W), constant material thermal properties and reservoir temperature.

Galoppi et al. [7] have developed a 1-D model of the WBHX based on the conservation equations of mass, energy and momentum. In order to apply the model, the authors have divided the double-pipe heat exchanger into a finite number of subportions (Fig. 9). The hypothesis of radial heat flux and no heat exchange between two consecutive volumes is used.

The heat flow terms in the energy equations are calculated as follows:

$$Q_{in} = \frac{T_s - \frac{(T_{OUT,in} + T_{OUT,out})}{2}}{R_{down} + R_p} \tag{23}$$

$$Q_{out} = \frac{\frac{(T_{IN,in} + T_{IN,out})}{2} - \frac{(T_{OUT,in} + T_{OUT,out})}{2}}{R_{up} + R_{ins} + R_{down}} \tag{24}$$

where T_s is the rock temperature, R_{up} and R_{down} are the thermal resistance of the ascending fluid and descending fluid respectively, R_c and is the thermal resistance of the external casing, R_{ins} is the thermal resistance of the insulation. In order to calculate the convective coefficient contained in the thermal resistance terms the Chilton-Colburn formulation for turbulent flow has been adopted to calculate the Nusselt number ($Nu = 0.125\ f\ Re\ Pr^{1/3}$).

The model of the WBHX is coupled with the 2-D formation model through the rock temperature, which is the starting point of the simulation. Then the 1-D model calculates the fluid temperature and the heat transfer coefficient, which become the boundary conditions of the formation model. The 2-D model runs and evaluates the new rock temperature, which is used in the 1-D model.

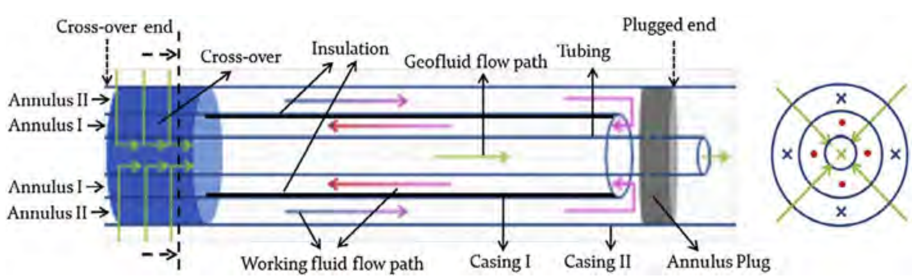


Fig. 7. Downhole heat exchanger: configuration G ([6]).

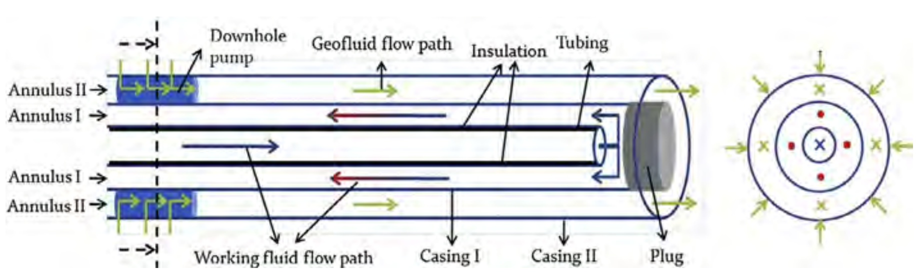


Fig. 8. Downhole heat exchanger: configuration W ([6]).

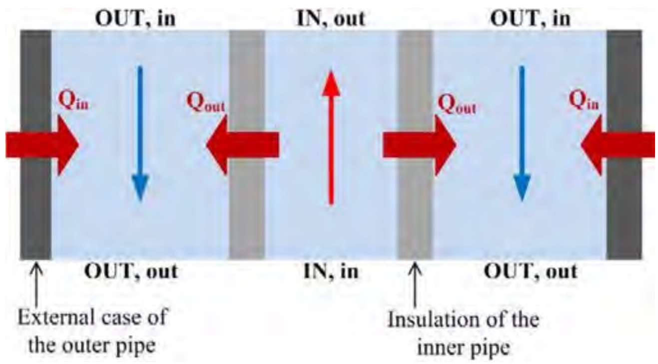


Fig. 9. Sub-portion of the wellbore heat exchanger ([7]).

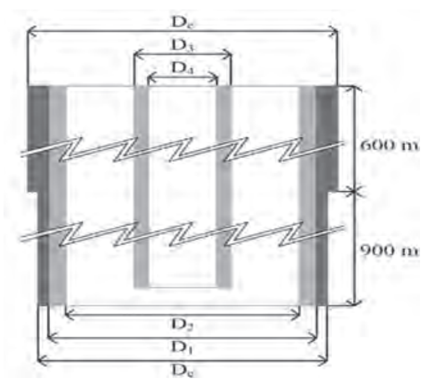


Fig. 10. Geometrical scheme proposed by Ref. [7].

Table 7
Geometrical and thermal properties ([7]).

Geometrical characteristics		
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
Lengths	1500	m
FORMATION PROPERTIES		
Rock density	2100	Kg/m^3
Rock thermal conductivity	0.85	W/mk
Rock specific heat	750	J/kgK
Bottomhole temperature	300	°C
THERMAL PROPERTIES		
Isobutane inlet temperature	53.5	°C
Casing thermal conductivity	60.5	W/mK
Insulation thermal conductivity	0.027	W/mK
Cement thermal conductivity	2	W/mK

The coupling of the models and the passage of data between them has been made developing a MATLAB routine.

The authors studied the application of the double-pipe heat exchanger in the area of Campi Flegrei (Italy); Fig. 10 and Table 7 resumes the geometrical and thermal properties of the proposed plant and of the formation. The working fluid is isobutane. The authors have not specified the insulation characteristics of the inner pipe.

The ANSYS Design Modeler has been used by Noorollahi et al. [18] and by Noorollahi, Yousefi and Pourarshad [19] to create a 3D model of the WBHX and of the surrounding formation (Fig. 11). The ANSYS Fluent Software has been used to study the heat transfer between the ground and the borehole and inside the WellBore Heat eXchanger. The software solves the system of continuity, momentum and energy equation.

Regarding the design of the WBHX, two different solutions have been proposed: a double pipe heat exchanger with constant diameters, and a double pipe heat exchanger with variable diameters (Fig. 12, Table 8).

Sliwa et al. [20] used the computer numerical simulator BoHEx to evaluate the applicability of the WBHX into the R-1 gas well. The proposed model solves the equations of mass conservation, Navier-Stokes and heat transfer in the borehole heat exchanger. This system of equations is coupled with the equation of the heat transfer between the formation and the borehole wall.

Wight and Bennett [21] have used an analytical model based on the overall heat transfer coefficient and the equation of fluid temperature in the WBHX, function of the geothermal gradient and the depth:

$$T = (T_g + gradT\, z \sin\theta) + (T_i - T_g)\exp\left(-z/a\right) - \left(gradT\, a \sin\theta\left[1 - \exp\left(-z/a\right)\right]\right) \quad (25)$$

where a is the relaxation distance calculated as:

$$\dot{m}c_p / k_t \pi d \quad (26)$$

$$\frac{1}{k_t} = \frac{dx}{\lambda} \quad (27)$$

Using the previous relations, the authors have estimated the mass flow rate ($\dot{m}$) that must be circulated in the borehole heat exchanger, in order to have an outlet fluid temperature (T) of 130 °C, typical in the binary power plants. The Darcy-Weisbach equation has been used together with the Colebrook equation of the friction coefficient in order to calculate the head losses during the circulation of the fluid:

$$\Delta p_{loss} = f\left(\frac{2z}{D}\right)\left(\frac{v^2}{2g}\right) \quad (28)$$

$$\frac{1}{\sqrt{f}} = -2log\left[\left(\frac{2.51}{Re\sqrt{f}}\right) + \left(\frac{\varepsilon/D}{3.72}\right)\right] \quad (29)$$

Alimonti and Soldo [22] have studied the possibility to use the WBHX to very deep oil well in Italy. The well is one of the 50 drilled wells of the Villafortuna Trecate oilfield, active since 1984. The depth of the reservoir is between 5800 and 6100 m, the temperature of the fluids is about 160 ÷ 170 °C, therefore the asset can be classified as a medium enthalpy geothermal resource. The Villafortuna-Trecate field is still producing but at present only 8 wells are in production. Fig. 13 illustrates the design of the WBHX proposed.

The model of the WBHX is based on the discretization of the well in a 1-D model. The following equation describes the heat flow in the upward pipe:

$$\dot{Q}_{up} = 2\pi r_o k_o \left(T_{f,up} - T_{f,down}\right)\Delta z \quad (30)$$

The overall heat transfer coefficient includes a conductive component through the composite pipe itself and by two convective components, one on the internal wall and one on the external wall of the WBHX:

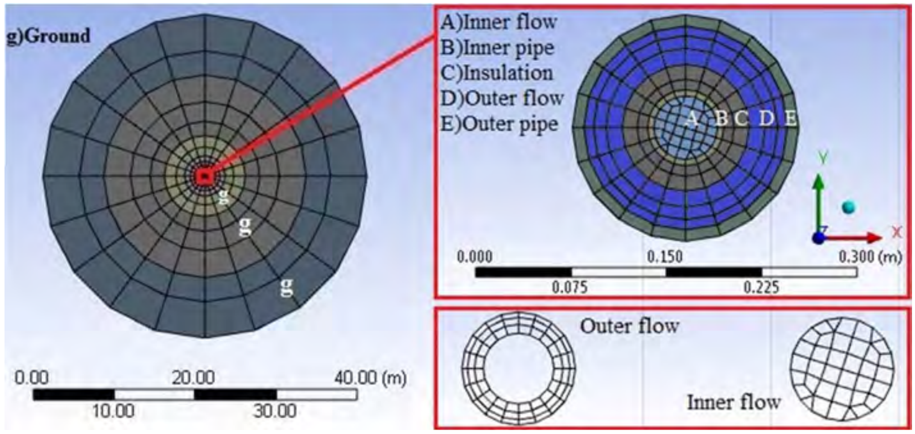


Fig. 11. Meshing geometry of the WBHX and the formation ([18]).

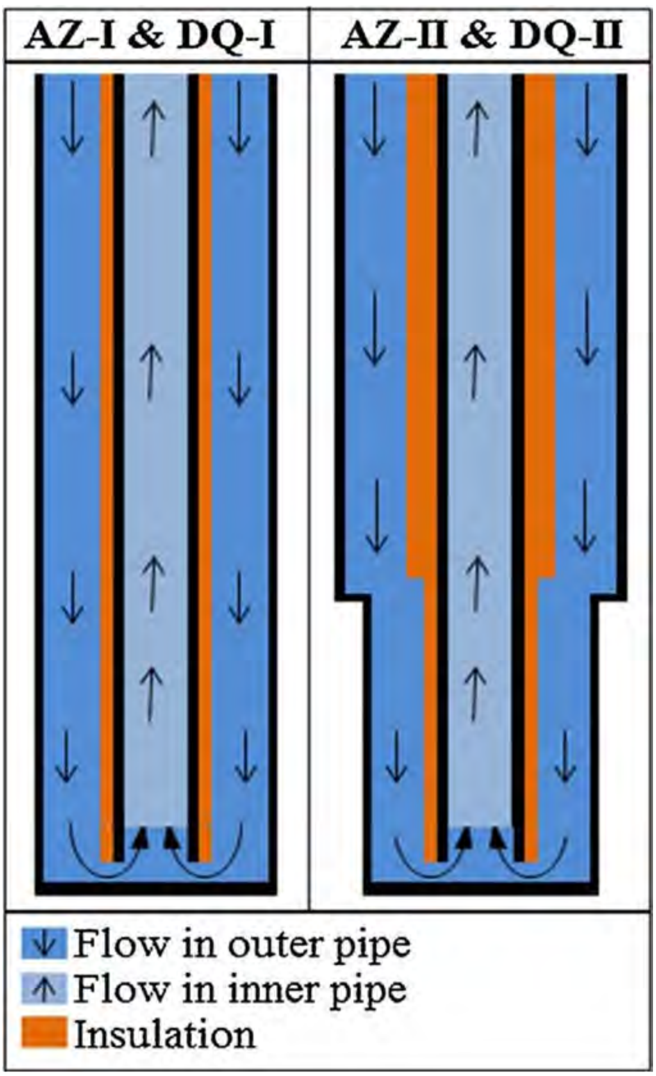


Fig. 12. The two design solutions proposed by Ref. [18].

$$\frac{1}{k_o} = \frac{r_o}{r_o + t} \cdot \frac{1}{h_i} + r_o \sum_{i=1}^{n} ln\left(\frac{r_{i+1}}{r_i}\right) \cdot \frac{1}{\lambda_i} + \frac{1}{h_o} \tag{31}$$

Table 8
Geometrical characteristics used by Ref. [18].

Parameters	AZ-I	AZ-II	DQ-I	DQ-II
Inner pipe (inch)	2 3/8	2 7/8	2 3/8	3 1/2
Outer pipe (inch)	5 ¾	7 and 5 ¾	6	6 and 8 1/8
Insulation thickness (inch)	0.4	0.4 and 0.6	0.4	0.4 and 0.6

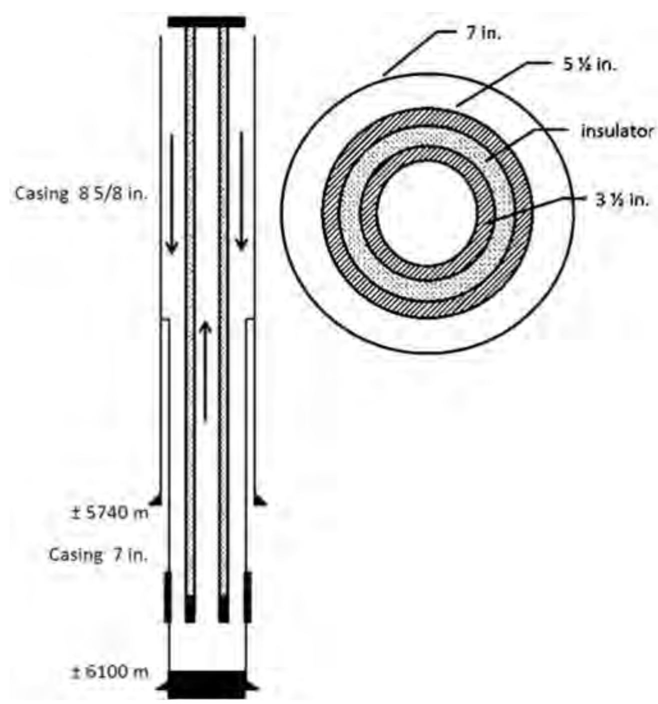


Fig. 13. Proposed design ([22]).

The coefficient of convective heat transfer h_o to the inner wall is calculated using the Dittus-Boelter equation of the Nusselt number, as well as the coefficient of convective heat transfer h_i to the outer wall. The calculation of the pressure losses in the thermo-hydraulic circuit has been included in the model in order to evaluate the required pumping power to ensure circulation.

Kędzierski et al. [12] have deepened the aspect of the influence of the pressure and temperature on thermo-physical properties of the working fluid circulating in the WBHX. The authors developed a method, called internal functions method, in order to estimate the correct value of the heat transfer coefficient of water at the borehole surface, depending on the depth.

3. Performances of the wbhx

The performance of the deep borehole heat exchangers, in terms of produced energy and efficiency of the system, reveals a high heterogeneity due to the different thermal properties of the soils. Not only but also to the use of different technological solutions (type of heat carrier fluid, flow rate, insulation of the pipes, final use of the extracted heat, depth of the WBHX, circulation of WBHX fluid into a binary power plant or use of an intermediate exchanger).

Kohl et al. [3] refer about the data on the WBHX plant installed at Weissbad in two unpublished reports. The few available data are the temperatures of the outlet fluid between 1996 and 1998. The authors indicate that the wellbore heat exchanger produced a fluid with a temperature much lower than expected, about 10 °C on yearly average; the minimum temperature was 9 °C and the maximum one was 14 °C.

The WBHX installed in the Weggis well has been used to provide heating and domestic hot water for multiple-family dwellings. Kohl et al. [4] report that the heat pump of the system worked for 10 h/year because of the high outlet temperature of the fluid: the monthly mean measured temperature was between 40 °C and 45 °C. The plant has produced 112 MWh during the heating season 1994/95, 238 MWh in 1995/96 and 223 MWh in 1996/97. The pumping power was respectively of 17, 22 and 20 kW. The produced thermal power was between 20 and 40 kW but the numerical simulations have demonstrated that the WBHX may produce a maximum power of 250 kW. Rybach and Hopkirk [48] as the maximum performance of the deep borehole heat exchangers have indicated this value also.

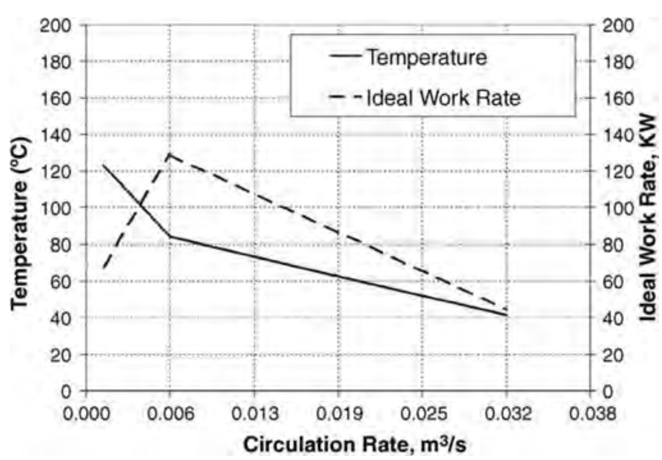


Fig. 14. Effect of the changing of the circulation rate on the operation of the WBHX ([1]).

Nalla et al. [1] have carried out a sensitivity analysis, changing the operating parameters, the design of the WBHX and the thermal properties of the formation in order to investigate their effects on the performance of the WBHX and to identify a best case scenario.

The results of the analysis highlighted that the key parameter of the performance of the WBHX is the residence time of the working fluid, related to the flow rate. The authors evaluated the ideal work and they observed an optimum value of the flow rate that maximizes the ideal work (Fig. 14).

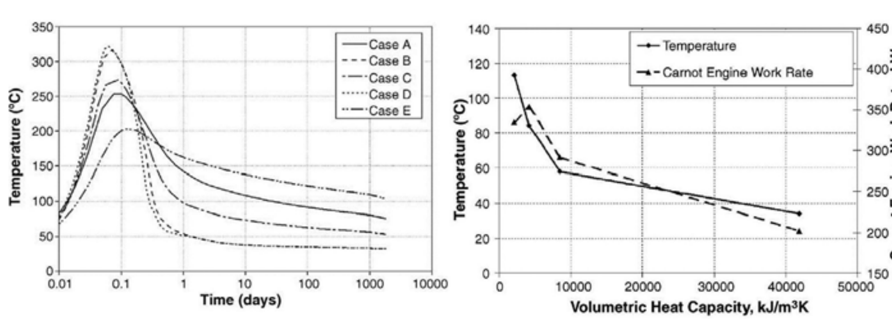
At fixed flow rate, the enlargement of the well diameter causes an increasing of the time residence in the WBHX. Anyway, the effect on the outlet temperature of the fluid is too limited to justify the increasing of the completion costs. The use of different cased and cemented lengths (1524 m, 3048 m, and 4572 m) does not influence significantly the outlet temperature. The simulations demonstrated the fundamental role of the insulation in order to avoid the heat losses and the consequent cooling of the working fluid. Anyway, the use of a perfect insulator did not improve the performance of the WBHX, demonstrating that the insulation with magnesia is sufficient.

The authors studied the influence of the working fluid properties using 5 different cases: the results are shown in Fig. 15. The lower values of outlet temperature and ideal work are obtained for higher values of volumetric heat capacity (ρc_P) (Case B and D); the B and D cases have the same trend of temperature, demonstrating that the heat transfer is driven by the volumetric heat capacity and not by the density nor the specific heat independently. The Case A simulates the pure water; the C and E cases use the thermal properties of water but with a double density and a half density respectively. The water (Case A) is the best heat carrier fluid, considering the values of outlet fluid, the ideal work and the low cost.

The increase of the basal heat flux, at fixed bottomhole temperature, produces a decreasing of outlet temperature of the fluid. This phenomenon occurs because, in order to obtain the same bottomhole temperature, the well depth decreases and so the residence time of the fluid.

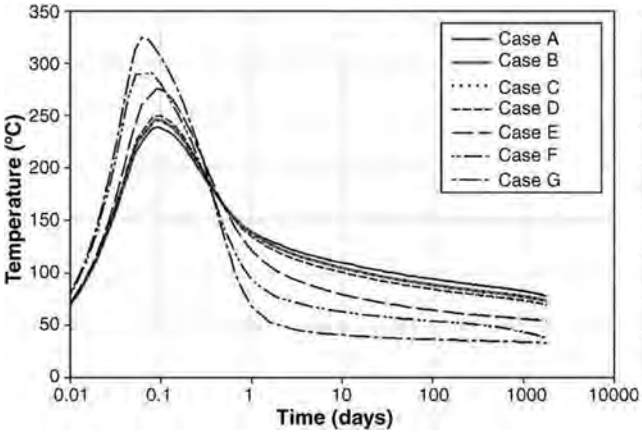
The effect of the variation of the rock thermal properties has been studied simulating different formation types (Fig. 16). The effluent fluid temperature varies directly with the thermal conductivity and the volumetric heat capacity because the heat transfer is directly proportional to the thermal conductivity and inversely proportional to the square root of the thermal diffusivity.

Starting from the results obtained with the sensitivity analysis, the authors proposed a best-case scenario for the application of the WBHX (Table 9): the outlet temperature in the pseudo state



Cases	ρ (kg/m³)	c_p (kJ/kg°C)	ρc_p (kg/m³ K)
A	1000	4.187	4187
B	1000	41.87	41,870
C	2000	4.187	8374
D	2000	20.93	41,870
E	500	4.187	2093

Fig. 15. Influence of the thermal properties of the working fluid on the operation of the WBHX ([1]).



Cases	λ (kg/m³)	ρc$_p$ (kg/m³ K)	α (m²/s)	λ/α$^{0.5}$ (Js$^{0.5}$/m² °C)
A	1.89	1876	1.01 x 10^{-6}	1881
B	1.56	1878	8.33 x 10^{-7}	1709
C	1.57	1811	8.68 x 10^{-7}	1685
D	1.41	1576	8.92 x 10^{-7}	1493
E	0.69	1469	4.69 x 10^{-7}	1008
F	0.60	188.3	3.18 x 10^{-6}	336
G	0.16	181.1	8.6 x 10^{-7}	173

Fig. 16. Outlet temperature VS time for different formations ([1]).

Table 9
Best CASE description ([1]).

WELL GEOMETRY		**PARAMETERS**	
Tubing inner diameter	76.2 mm (3.0 in.)	Basal heat flux	0.1 W/m^2
Tubing outer diameter	88.9 mm (3.5 in.)	Formation thermal conductivity	1.89 W/m°C
Insulation outer diameter	101.6 mm (4.0 in.)	Formation volumetric heat capacity	1875.7 kJ/m^{3}K
Casing inner diameter	578.0 mm (22.75 in.)	Insulation thermal conductivity	0.07 W/m°C
Casing outer diameter	593.7 mm (23.375 in.)	Working fluid volumetric heat capacity	4187 kJ/m^{3}K
Wellbore diameter	660.4 mm (26.0 in.)	Insulation thermal conductivity	0.07 W/m°C
Well depth	5593 m	Circulation rate	6.3×10^{-3} m^3/s
RESULTS		Surface temperature	26.7 °C
Outlet temperature	98 °C	Bottomhole temperature	350 °C
Ideal work	198 kW		
Electrical power	50 kW		

condition is 98 °C and the ideal work is 198 kW. Anyway, the electrical power evaluated with the performance of existing energy conversion plants is less than 50 kW; therefore, the authors indicate the direct use as the suitable application of the WBHX.

Table 10 reports the results obtained by Kujawa et al. [26]: the authors have carried out a sensitivity analysis changing the flow rate, the fluid inlet temperature and the condition of insulation of the internal tube. The heat carrier fluid is water and the simulation time is 1 year. The results show that the performance of the deep borehole heat exchangers is strongly influenced by the flow rate and the fluid inlet temperature. The selection of higher values of flow rate produces higher values of thermal power but the fluid temperature is lower. The best insulation condition is with the use of air for the entire length of the well. The analysis demonstrated the feasibility of the use of the well Jachowka K-2 in order to produce geothermal energy when the flow rate is 2 and 10 m^3/h, even though the thermal power values are not calculated net of the pumping energy request. Nevertheless, the authors suggest that fluid outlet temperature is too low for electricity use.

The sensitivity analysis carried out by Wang et al. [8] has concerned the insulation of the internal tubing, the diameters of the well and of the tubing, the flow rate, the connection with the fractures, the thermosiphon effect.

The results demonstrated that the insulation of the tubing is necessary in order to avoid the heat losses in upward fluid flow (Fig. 17 a,b). Fig. 18 a shows an optimum point of the flow rate which guarantees the maximum ideal work. The connection with the fractures produces a significant increase of the thermal power (Fig. 18 b).

The sensitivity study of the design has highlighted that the thermal power is directly proportional to the casing diameter (Fig. 19 a) and inversely proportional to the tubing diameter (Fig. 19 b).

The authors demonstrated that the use of a choke valve at the bottom of the WBHX, in order to reduce the pressure and facilitate the pressurization of the fluid, entails a higher outlet temperature (Fig. 20 a). Regarding the produced power of the system and the sustainability in time, the simulations show constant values of the thermal and electrical power for 30 years, although the conversion efficiency is low (about 14%) (Fig. 20 b).

Davis and Michaelides [13] evaluated the net electrical power at different values of the bottomhole temperature, injection pressure and injection velocity of the working fluid and tubing diameter. The results are very promising.

Fig. 21 shows that the insulation with polystyrene is sufficient to avoid a considerable decrease of the temperature of the fluid

Table 10
Results ([26]).

V	T_{inj}	Air gap (L = 3950 m)			Polyurethane foam (L = 600 m)			Air gap (L = 2870 m)		
m^3/h	°C	T_{out}	Q	Q	T_{out}	Q	Q	T_{out}	Q	Q
		°C	kW	MWh/y	°C	kW	MWh/y	°C	kW	MWh/y
2	15	86.41	162.05	1365	19.97	11.34	96	74.44	134.12	1130
10	15	67.28	598.24	5040	19.06	46.43	391	54.60	449.87	3790
20	15	49.90	802.55	6761	19.25	97.20	819	43.07	640.99	5400
30	15	40.88	895.20	7541	19.43	152.15	1282	37.01	757.32	6380

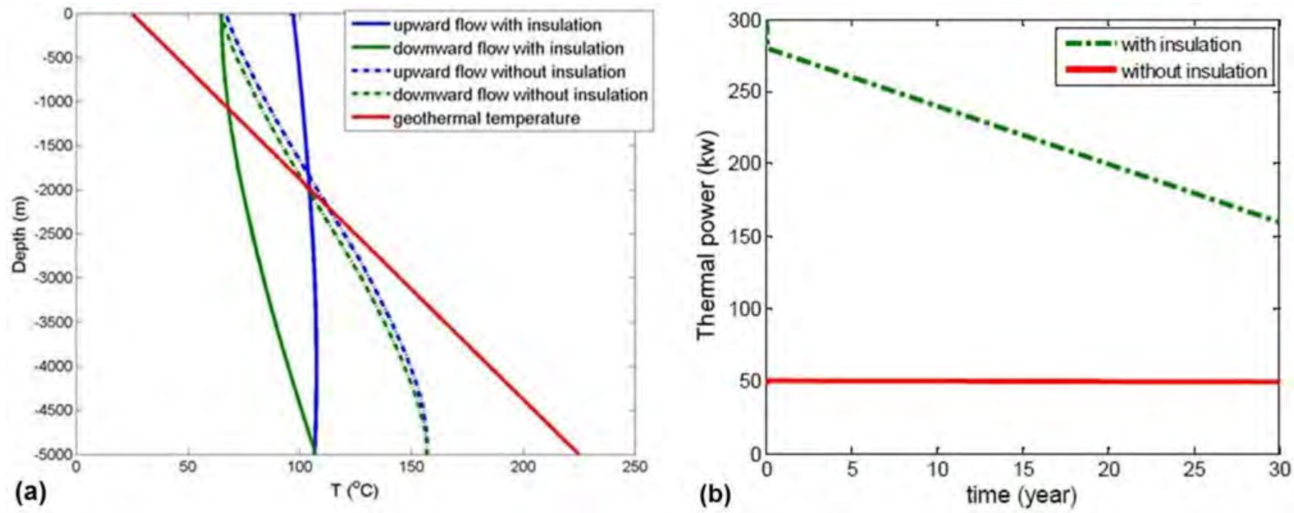


Fig. 17. Effect of the insulation on the outlet temperature and the thermal power ([8]).

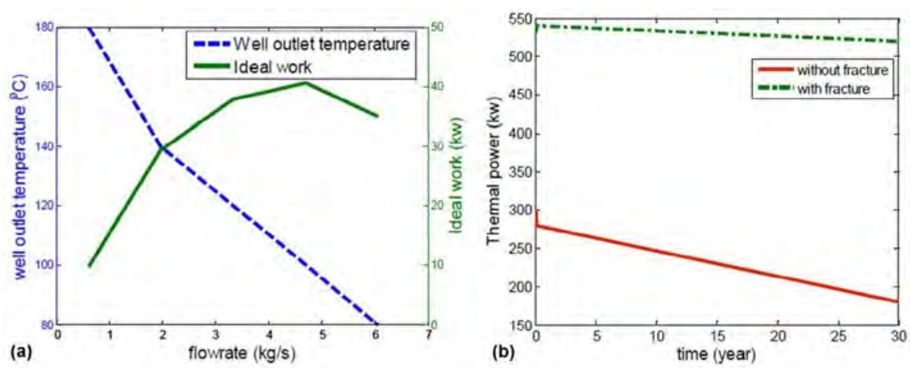


Fig. 18. Effect of the flow rate (a) and of the fracturing (b) ([8]).

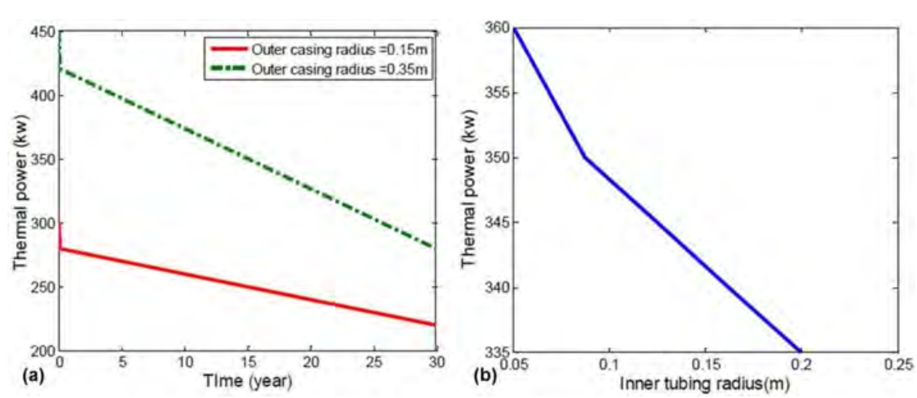


Fig. 19. Effect of the diameters modification on the thermal power ([8]).

flowing upward; the net power is directly proportional to the bottomhole temperature and it is constant for injection pressure of about 20÷40 bar.

Fig. 22 reports the optimization of the WBHX design: at fixed injection velocity of 2 m/s and a bottomhole temperature of 450 K (~177 °C) the maximum electrical power is obtained using an internal tubing with a radius of 3.5 inch. Nevertheless, increasing the injection velocity until the value of 3.5 m/s and using a tubing radius of 4 inch, the results indicate that it is possible to produce about 3.4 MW. Table 11 summarizes the main parameters of the best-case scenario.

The performance analysis carried out by Bu et al. [14] focused on the geothermal gradients and the flow rate into the WBHX (Fig. 23).

The simulation results after 2 months of operation confirm the key aspect of the flow rate, and therefore of the residence time of the fluid in the WBHX. The increase of the flow rate causes a drop of the outlet temperature, independently by the geothermal gradient. The thermal power grows with the flow rate, but the

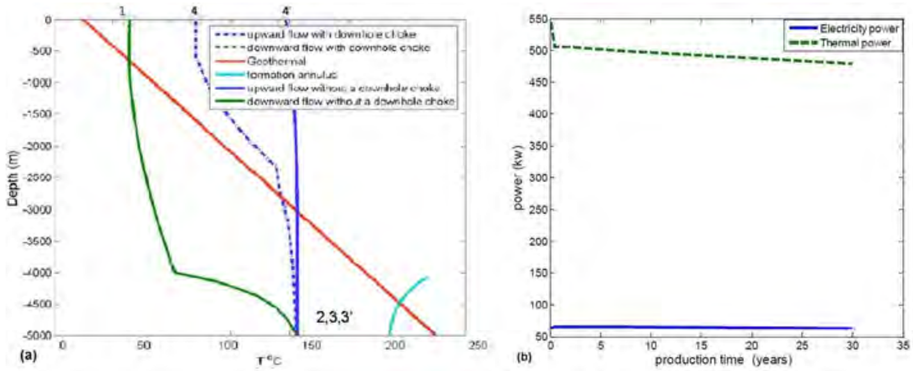


Fig. 20. Effect of the choke valve (a) and power production VS time (b) ([8]).

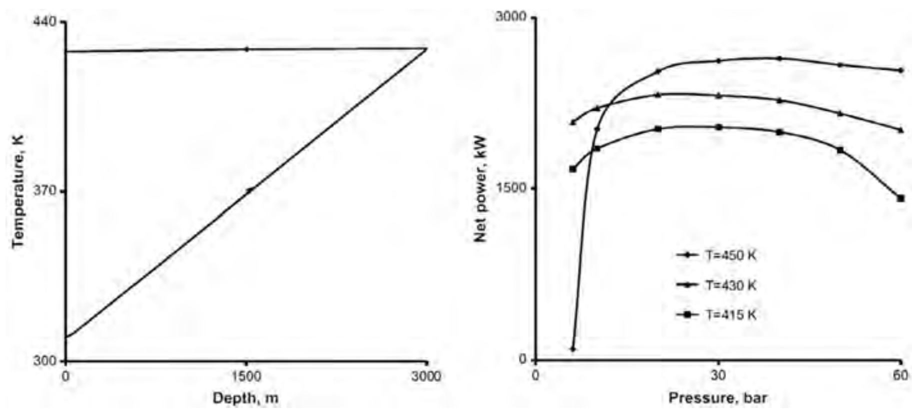


Fig. 21. Evaluation of the efficency of polystirene and of the net power for different bottomhole temperature and injection pressure ([13]).

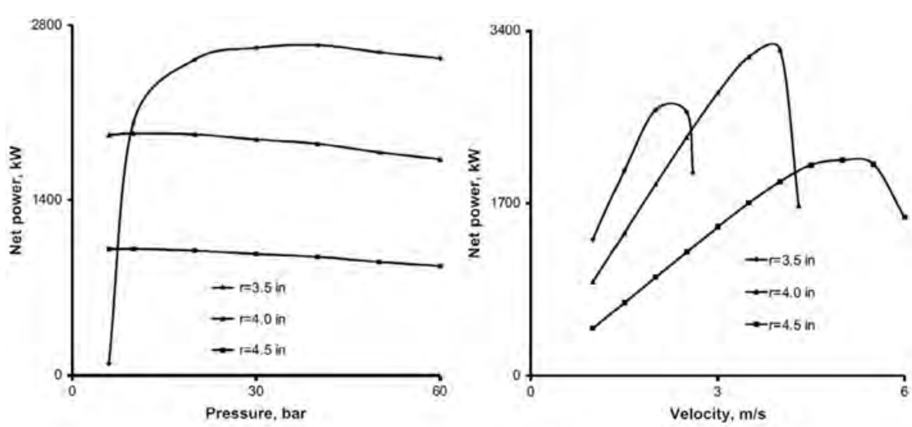


Fig. 22. Study of the net power for different tubing diameters and injection velocity ([13]).

Table 11
Best case ([13]).

Casing diameter	12″
Tubing Diameter	4″
Thickness Insulation	1″
Length	3000 m
Bottomhole temperature	450 K
Insulation material conductivity (polystyrene)	0.027 W/m°C
Working fluid	Isobutane
Injection velocity of isobutene	3.5 m/s
Injection temperature of isobutene	310 K
Turbine efficiency	85%
Net power	**3.4 MWe**

request of energy for pumping increases too. Therefore, there is an optimum value of flow rate (0.03 m/s) maximizing the net power. In Table 12 are reported the main parameters and the results of the best case.

Bu et al. [14] have demonstrated that the geothermal energy production can last at least for 10 years, without significant loss of performance (Table 13).

The impact of the heat extraction on the ground temperature in time and space has been studied (Fig. 24). The geothermal gradient and the fluid velocity are fixed ($T_g = 45$ °C/km and $V_{in} = 0.03$ m/s respectively). The results of the simulations indicate that the operation of the WBHX causes a decrease of the temperature near

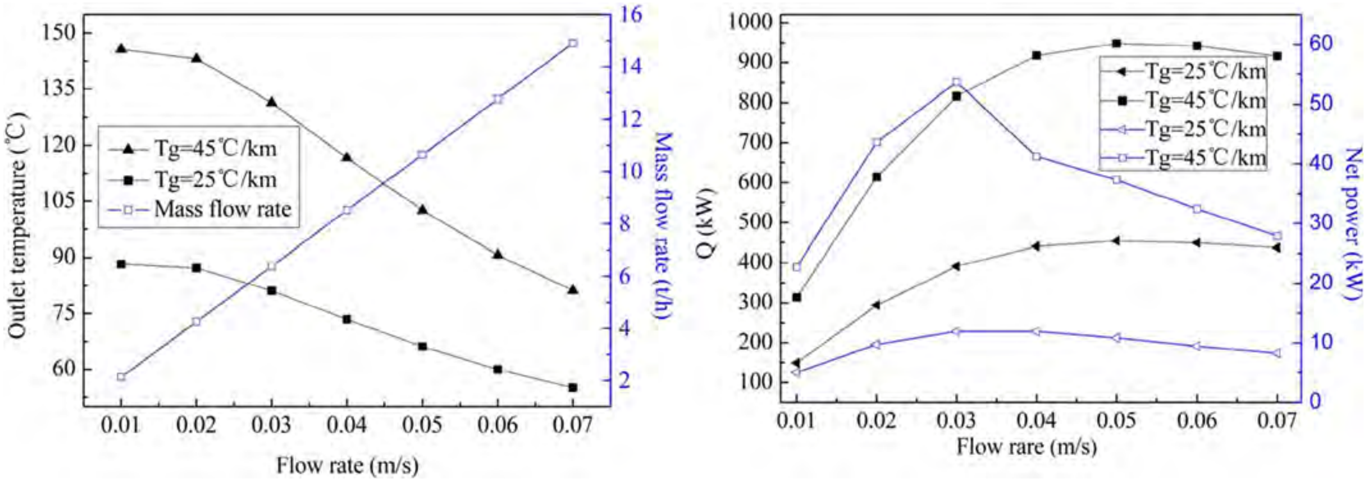


Fig. 23. Outlet temperature VS flow rate - power VS flow rate ([14]).

Table 12
Best case parameters ([14]).

Length	4000 m
Tubing Diameter	0.1 m
Casing Diameter 1 (Length = 2500)	0.34/0.3 m
Casing Diameter 2 (Length = 1500)	0.33/0.3 m
Insulation thickness	0.01 m
Geothermal gradient	45 °C/km
Insulation material conductivity	0.027 W/m°C
Working fluid	Water
Injection velocity	0.03 m/s
Injection temperature	30 °C
Outlet temperature	**129.88 °C**
Thermal power	**815.76 kW**
Net power	**53.70 kWe**

Table 13
WBHX parameters for different life time (v = 0.03 m/s) ([14]).

Time [year]	T_{out} [C°]	P_{net} [kW]	Q [kW]
1	129.88	52.26	802.14
5	128.50	50.96	790.18
10	127.92	50.42	785.17

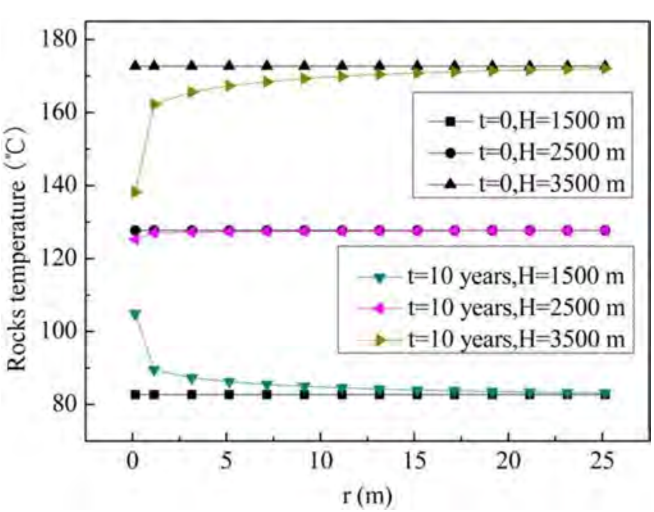


Fig. 24. Evolution of the formation temperature in time and space ([14]).

the well (~1.5 m) in the deepest layer (3500 m), no impact in the intermediate layer (2500 m) and an increase of the ground temperature in the shallow layer (1500 m). This phenomenon is due to the temperature of the working fluid that is higher than the formation temperature in the shallow layer, therefore the heat moves from the fluid to the rock. On the contrary, in the deep layer, the fluid is colder than the formation and it acquires heat from the rock. Considering that the thermal disturbance has a radius of 20 m, the authors indicate a minimum distance of 40 m between the wells.

Fig. 25 shows the results of the sensitivity analysis of Cheng et al. [15]. They have changed the formation thermal conductivity and volumetric heat capacity of the rock, geothermal gradient and fluid velocity. They have studied the effect on the outlet temperature and the time necessary to reach a steady state condition. The selected working fluid was isobutane (R600a).

The thermal properties of the formation (Fig. 25 a and b) have a limited effect on the outlet temperature of the working fluid and on the stabilization time. Instead, the performance of the WBHX strongly depend on the fluid velocity and by the geothermal gradient. The fluid temperature is inversely proportional to the injection velocity (Fig. 25 c) or rather it is directly proportional to the residence time into the WBHX. The higher geothermal gradient, the higher the temperature of the fluid at the bottomhole (Fig. 25 d).

After 400 days of operation, the steady state condition is reached and the outlet temperature of the working fluid is about 127 °C (400 K).

Fig. 26 shows the results obtained using the data reported in Table 5 (Chap 2). The outlet temperature and pressure are inversely proportional to the velocity of the working fluid (Fig. 26 a), therefore even if the heat flow increases with the flow rate (Fig. 26 b), there is an optimal velocity (0.2 m/s) which produces the maximum net electrical power (154 kWe).

Cheng et al. (2014) [16] have deepened the sensitivity analysis. Considering an operating time of 300 days, the authors have evaluated different working fluids in order to find the more suitable for the WBHX application; they also simulated different depths of the borehole heat exchanger and two values of geothermal gradients. The results are reported in Figs. 27–29: the net power produced is directly proportional to the well depth and the geothermal gradient. The higher values of net power are obtained with R134a and R245fa.

Following are reported the results of Cei et al. [10]. Fig. 30 shows the decrease of the outlet fluid temperature in time evaluated with

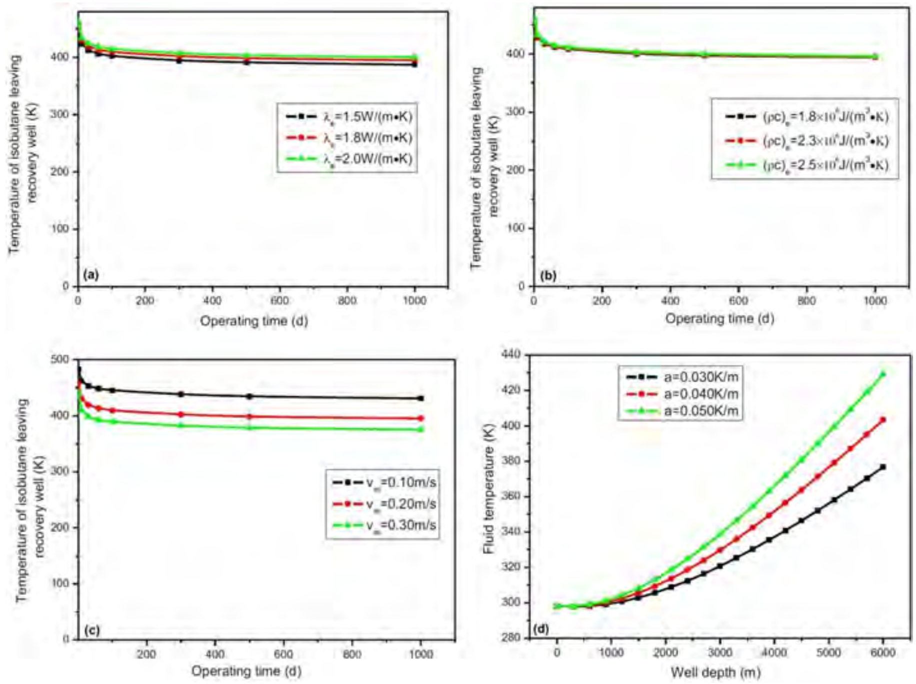


Fig. 25. Sensitivity study [15].

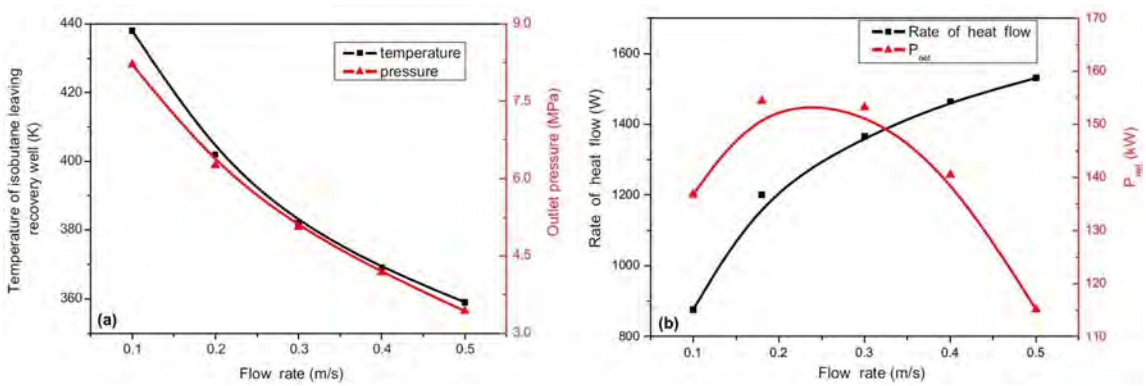


Fig. 26. Temperature and pressure VS flow rate (a); heat flux and electrical power VS flow rate (b) [15].

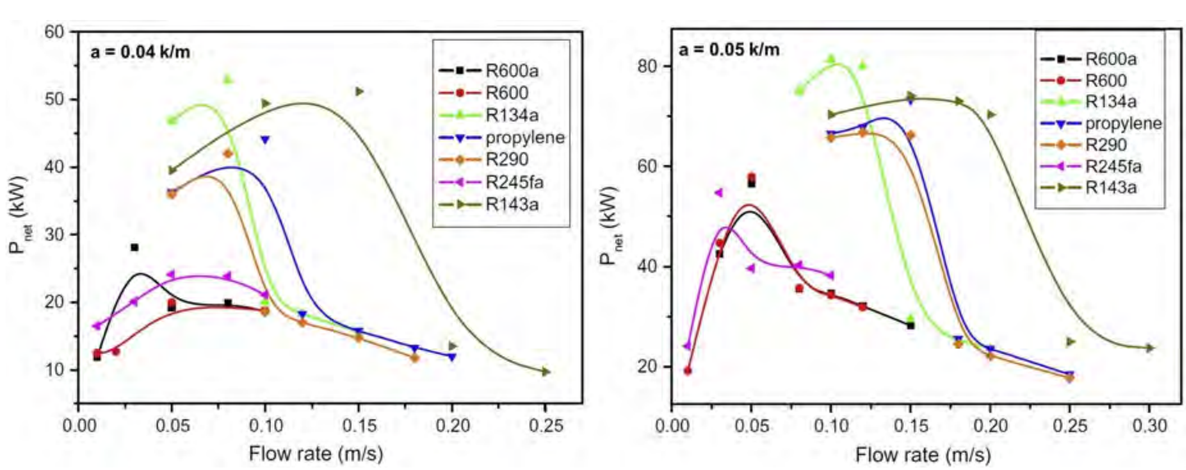


Fig. 27. Net power produced; well depth = 4000 m [16].

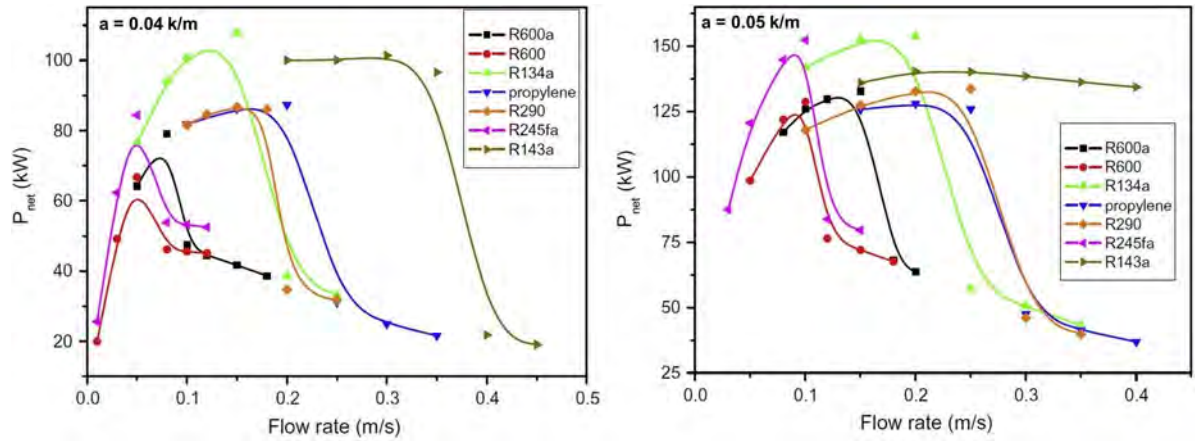


Fig. 28. Net power produced; well depth = 5000 m [16].

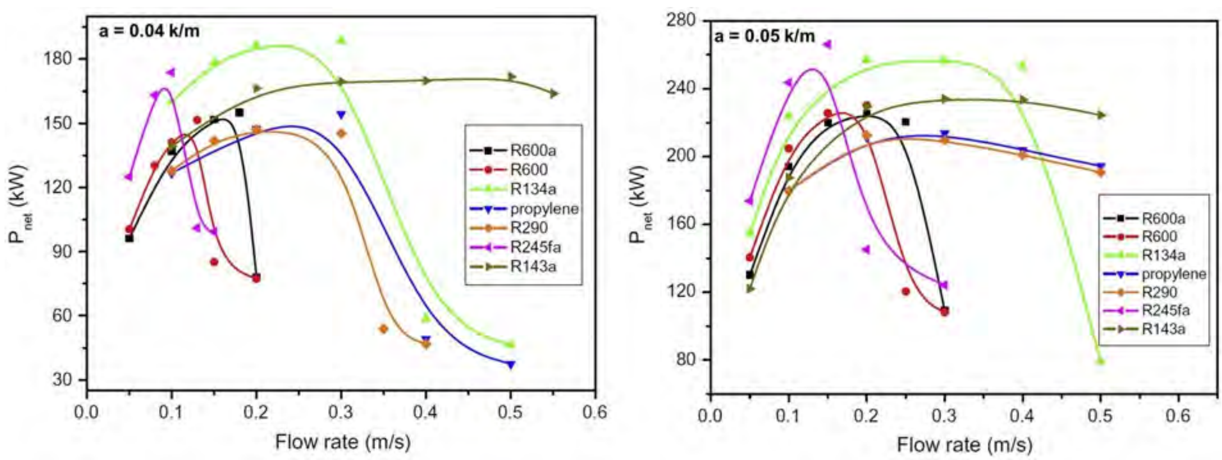


Fig. 29. Net power produced; well depth = 6000 m [16].

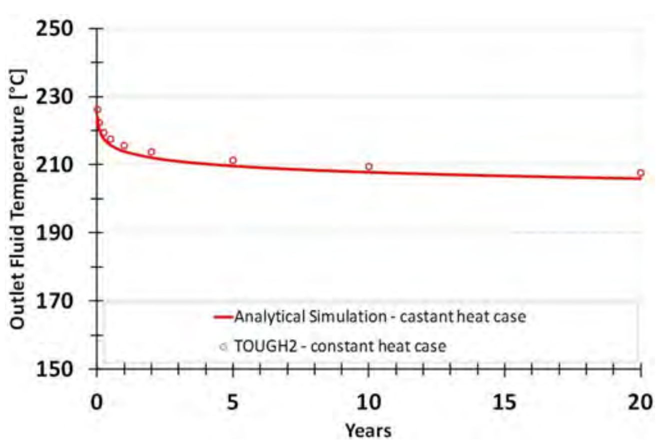


Fig. 30. Fluid temperature decline in time, constant heat rate case ([10]).

an analytical model and the numerical simulator TOUGH2: the drop of the temperature is less than 20 °C and it is concentrated in the first 2 years of operation, then a steady state condition is attained. The hypothesis of constant heat rate equal to 500 kW is used; the graph shows a good fitting between the results of the two models.

Fig. 31 a and b report the results of the numerical simulations considering a variable heat rate with a starting value of 500 kW. The maximum value of the gross electrical power (35 kW) is obtained for a flow rate equal to 4 kg/s (Fig. 31 a), then it decrease to 25 kW after 5 years of operation of the WBHX. Fig. 31 b highlights the performance of the system depending on the selected flow rate, and so on the residence time of the fluid in the well. The value of 4 kg/s remains the optimum one. Even if the thermal power grows with the flow rate, when the flow rate exceeds the value of 10 kg/s the outlet temperature is equal to the injection temperature (~80 °C).

Fig. 32 shows the effect of the fracturing in the surrounding of the WBHX proposed by Taleghani [9]. The green line presents the results when no fracture is induced in the formation, the red line and the blue line represent the heat extracted in case of double-wings fracture and penny-shaped fracture respectively; the author reports that the values of extracted power after 30 years are: 76 kW, 254 kW and 647.7 kW.

The results of the simulations of Templeton et al. [17] demonstrate that the insulation of the external casing of the WBHX until the depth where the formation temperature and the working fluid temperature are equal produces an increase of the outlet temperature of 4.4 °C, which represents an increase of the power of about 40%. Fig. 33 a and b reports the effect of the inlet temperature and the mass flow rate on the performance of the plant. The increase of the inlet temperature produces an increase of the outlet temperature, but the power decreases. As other authors have observed, there is an optimum value of the fluid mass flow rate, which

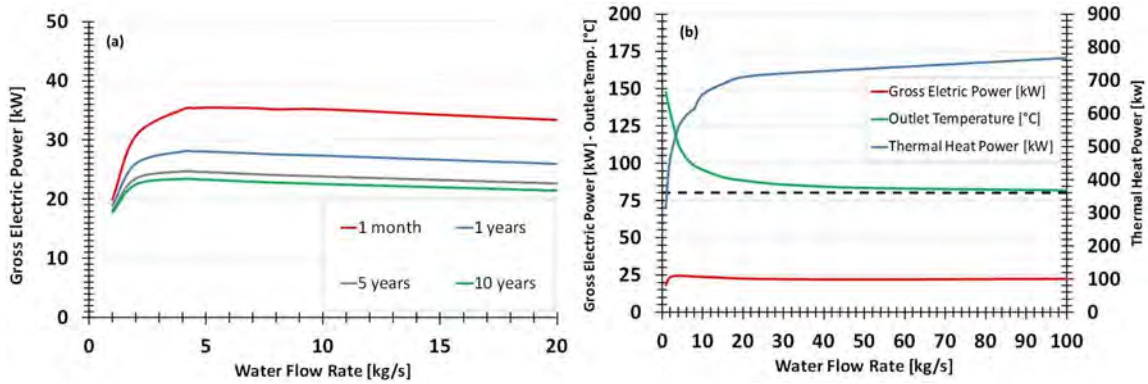


Fig. 31. Performance of the WBHX (a); numerical model, variable heat rate (b) ([10]).

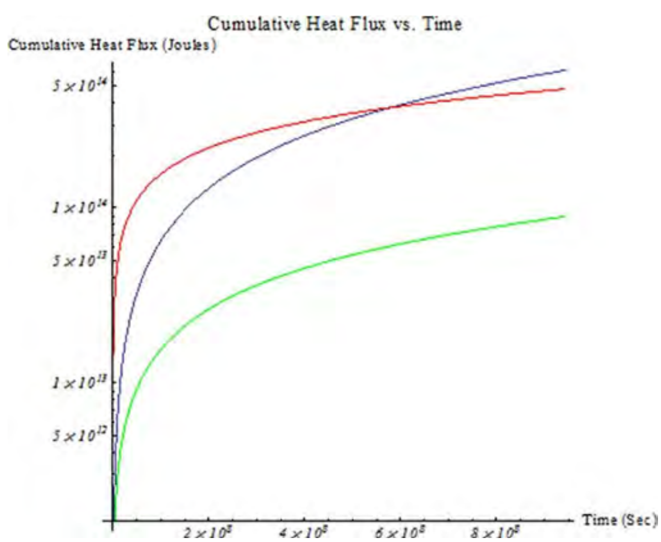


Fig. 32. Improvement of the heat extraction with the fracturing of the formation near the WBHX ([9]).

maximizes the outlet temperature. The optimal mass flow rate is 0.4 kg/s. Regarding the produced power, it is observed a fast increase for low values of the mass flow rate, and then a condition of plateau is reached.

The results of the sensitivity study demonstrate that the increasing of the ground thermal conductivity improves the performance of the system (Fig. 34 a), whereas the vertical groundwater flow cools the rock around the well therefore has a negative impact on the outlet temperature and the extracted power (Fig. 34 b).

The previous results are referred to a scenario with constant inlet temperature. Fig. 35 reports the results of the constant power scenario in time: the inlet temperature varies, keeping constant the difference between the outlet temperature and the inlet temperature. When a constant power of 200 kW is produced, the outlet temperature decreases from 80 °C to 60 °C in five years of operation. Therefore, the inlet temperature decreases from 50 °C to 20 °C.

Regarding the application of the deep borehole heat exchanger, considering the low values of produced power, the authors recommend the direct use and the heat pumps applications. Therefore, no conversion of the thermal power into electricity has been considered.

Following are reported the results of the performance analysis carried out by Akhmadullin and Tyagi [5]. The authors performed a thermodynamic analysis in order to find the more suitable working fluid for the proposed plant composed by a downhole heat exchanger and a horizontal offset. Table 14 reports results for the working fluids candidates: the n-Pentane is the most suitable fluid for this type of applications considering the high toxicity of toluene.

In Table 15 are reported the parameters of the case study. The outlet temperature of the working fluid is 118.7 °C when the length of the DHE is 304.8 m and the counter flow of the brine and the working fluid is adopted.

Feng et al. [6] have deepened the work of Akhmadullin and Tyagi [5] with a sensitivity study on the following aspects: the design of the DHE, the length, the working fluid mass flow rate, the brine mass flow rate, the reinjection distance and the dip angle.

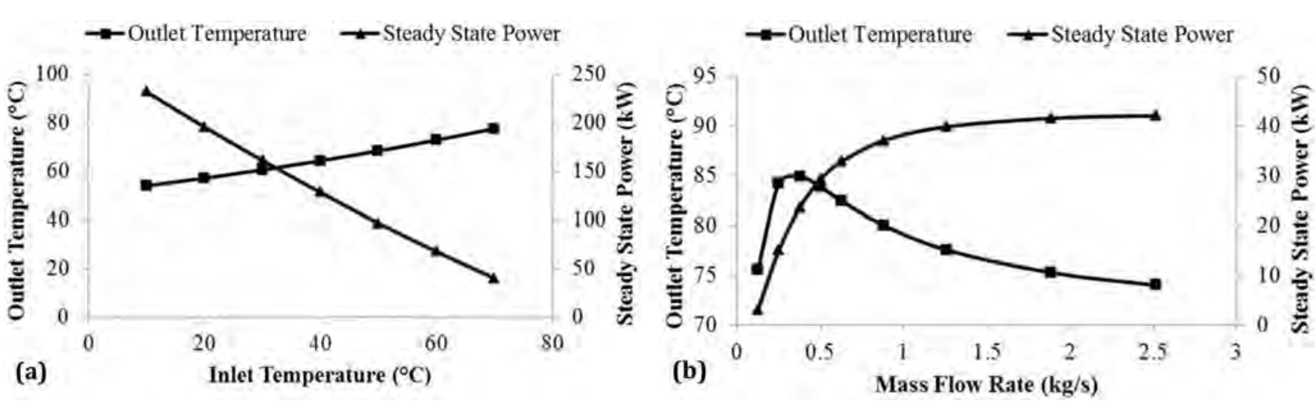


Fig. 33. Sensitivity study: Effect of the inlet temperature and the mass flow rate ([17]).

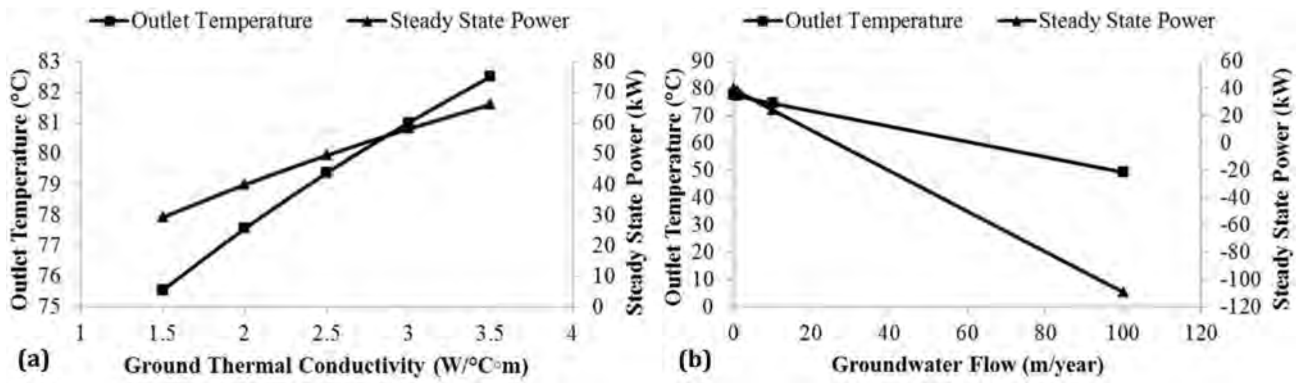


Fig. 34. Sensitivity study: Effect of the ground thermal conductivity and the vertical groundwater flow ([17]).

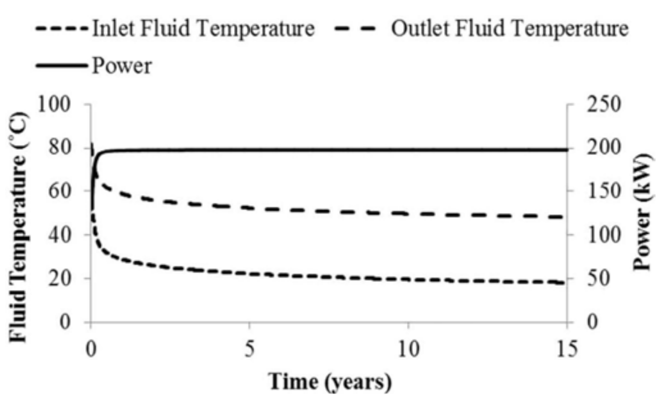


Fig. 35. Performance of the constant power scenario ([17]).

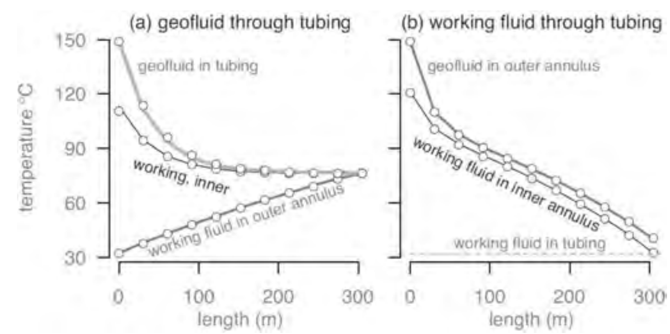


Fig. 36. Temperature of the fluids into the DHE; comparison between the configuration G (geofluid through tubing) and W (working fluid through tubing) ([6]).

Table 14
Results of the thermodynamic analysis [5].

Working fluid	Heat from reservoir (kW)	Thermal efficiency (%)	Turbine work (kW)	Electrical power (kW)
R134a	1070.67	12.56	134.47	99.64
R245ca	1239.72	14.56	181.46	146.63
Iso-Butane	1908.57	14.75	281.68	246.85
Toluene	2505.80	16.23	406.63	371.80
n-Pentane	2397.56	14.85	356.06	321.23

Table 15
Parameters of the case study [5].

Depth of the reservoir	4253÷4479	m
Temperature gradient until the top of the reservoir	23.04	°C/km
Temperature gradient into the reservoir	28.9	°C/km
Brine temperature at the bottomhole	126	°C
Surface temperature	30	°C
THERMAL PROPERTIES		
Formation thermal conductivity	1900	W/mK
Geofluid thermal conductivity	0.519	W/mK
Pipe thermal conductivity	45	W/mK
Cement thermal conductivity	0.580	W/mK
n-Pentane thermal conductivity	0.107	W/mK
Geofluid viscosity	0.00011	Pa•s
n-Pentane viscosity	0.00017	Pa•s
Geofluid specific heat	3.182	kJ/kgK
n-Pentane specific heat	2.736	kJ/kgK
Geofluid density	1000	kg/m^3
n-Pentane density	582	kg/m^3

Table 16
Base case parameters ([6]).

Rock density	2700 kg m^{-3}	**Reservoir properties**
Heat conductivity	1.9 Wm^{-1}K^{-1}	
Temperature	149 °C	
Length (baseline)	305 m	**DHE geometry**
Outer casing OD, ID	21.91, 19.37 cm	
Inner casing OD, ID	16.83, 15.36 cm	
Tubing OD, ID	12.70, 10.86 cm	
Heat conductivity	45 Wm^{-1}K^{-1}	
Density	582 kg m^{-3}	**Working fluid (n-butane) properties**
Heat conductivity	0.107 W m^{-1}K^{-1}	
Specific thermal capacity	2763 J kg^{-1}K-1	
Viscosity	1.7 × 10^{-4} Pa s	
Injection temperature	32 °C	
Mass flow rate	5.25 kg s^{-1}	
Density	1000 kg m^{-3}	**Geofluid (water) properties**
Heat conductivity	0.519 W m^{-1}K^{-1}	
Specific thermal capacity	3182 J kg^{-1}K-1	
Viscosity	1.1 × 10^{-4} Pa s	
Mass flow rate	2.34 kg s^{-1}	

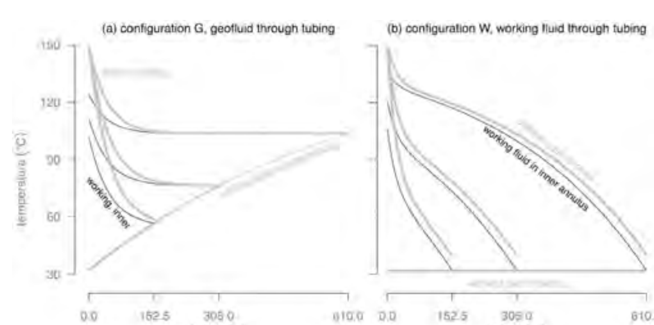


Fig. 37. Effect of the lenght on the fluids temperature ([6]).

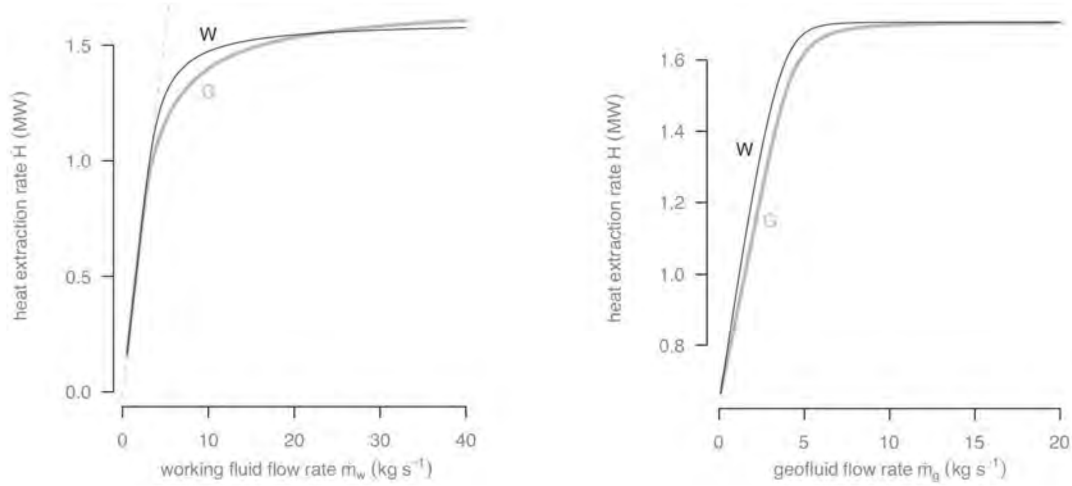


Fig. 38. Effect of the working fluid and the geofluid fluid mass flow rate on the heat extraction ([6]).

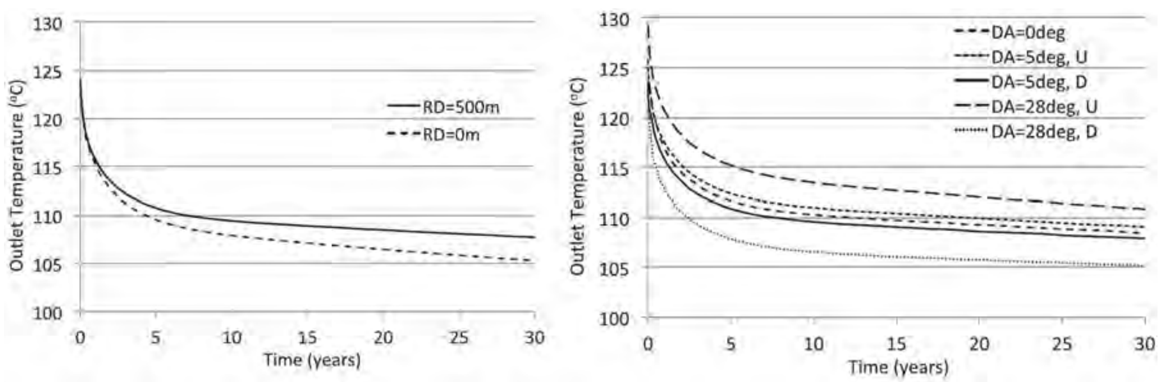


Fig. 39. Study of the effect of the reinjection distance (RD) and the dip angle (DA) on the outlet temperature of the working fluid ([6]).

Fig. 36 reports the comparison of the two proposed design. The configuration W, in which the working fluids is pumped in the internal tubing and the brine in the external annulus, produces and higher outlet temperature respect to the configuration G, in which the geofluid flows in the internal tubing and the working fluid circulates in the inner and outer annulus. Table 16 shows the base case parameters; the selected working fluid is n-butane.

The increase of the length influences directly the working fluid temperature, especially for the configuration W Fig. 37.

The heat extraction rate grows rapidly with the working fluid mass flow rate and with the geofluid mass flow rate (Fig. 38) and it reaches a plateau. The authors therefore have selected the configuration W guarantees the higher thermal power production.

Fig. 39 shows the influence of the reinjection distance and the dip angle in case of configuration W. The outlet temperature decrease in time is higher when the reinjection is carried out at 0 m from the bottom of the DHE. The authors have concluded that the reinjection at the distance of 500 m improves the sustainability of the production in time.

The authors have considered three values for the dip angle and two directions for the reinjection: the updip configuration (U) entails the reinjection at the head of the DHE; in the downdip configuration (D) the brine is reinjected at the bottom end of the DHE. The results of the simulations demonstrate that the higher

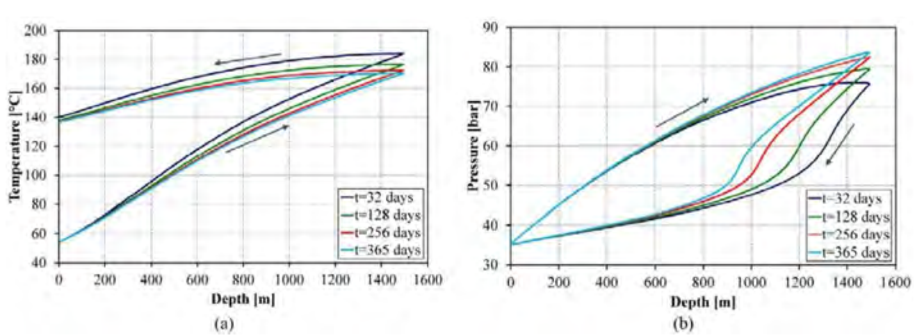


Fig. 40. Temperature profile (a) and pressure profile (b) in time ([7]).

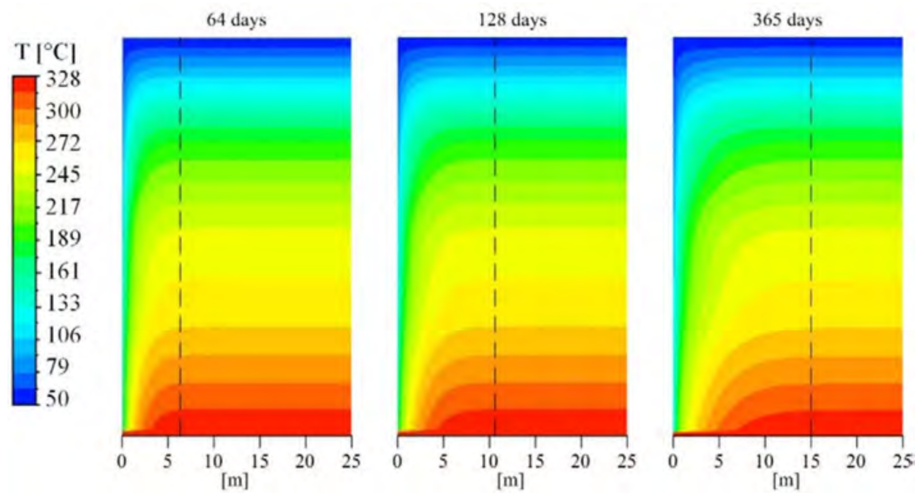


Fig. 41. Influence radius in time ([7]).

outlet temperature is obtained in case of updip configuration and a dip angle of 28°. Anyway, considering the complexity of transporting the cooled brine in the upward direction in contrast with the natural downward movement of a cold fluid, the authors discourage the use of the updip configuration. Therefore, the configuration with 0° of dip angle represents the more suitable one.

The power generation with the DHE has been evaluated using the thermodynamic analysis based on the equations of Yari [49] and the procedures of Di Pippo [50]. The net power is 357 kW.

In order to evaluate the application of the WBHX in the area of Campi Flegrei (Italy), Galoppi et al. [7] have studied the temperature and pressure profiles into the deep borehole heat exchanger in time (Fig. 40) and the effect of the heat extraction on the rock temperature (Fig. 41). An increase of the temperature and pressure arises in the downward flow phase whereas a decrease takes place in the upward pipe; the extraction of the heat causes a decrease of the formation temperature near the borehole wall and a progressive enlargement of the influence radius. After 1 year the influence radius is stabilized at 15 m.

The authors have simulated the use of different values of mass flow rate, demonstrating the direct proportionality between mass and outlet temperature and conversely an inverse proportion respect to the heat flux (Fig. 42). Therefore, the value of 1 kg/s has been used for the evaluation of the electrical power production with an ORC plant, obtaining a long-term power of 42 kW.

Le Lous et al. [11] carried out a sensitivity analysis in order to study the influence of the formation parameters, the borehole heat exchanger materials and operating settings on the performance of the WBHX and on the thermally affected area. Fig. 43 illustrates the parameters examined and the respective range of values. The black solid line represents the base scenario values; the white boxes are related to the reservoir parameters, the grey boxes are referred to the WBHX parameters. The working fluid is water.

The results demonstrate that the thermal performance of the WBHX is affected the most by the conductive components of the heat flow, therefore by the porosity, the thermal conductivities of the rocks and the grout and by the geothermal gradient. Furthermore, the thermal conductivity of the inner pipe and the discharge rate of the fluid strongly influence the specific heat extraction (Fig. 44).

The authors have concluded that the use of the deep borehole heat exchanger is feasible in order to produce thermal power; the potential power in their base-case scenario (Table 17) is 200 kW.

Noorollahi et al. [18] have studied the installation of the WBHX into two depleted oil wells in Iran: the AZ well and the DQ well, proposing two different design solutions for each well. The selected heat carrier fluid is water, injected in the WBHX at a temperature of 30 °C. The thermal power is converted into electrical power using a binary power plant; the organic working fluid is isobutane, which acquires heat from the water circulating in the WBHX. The main parameters of the simulation and the results are reported in Table 18, the variable diameters configuration guarantees higher values of outlet temperature and power production.

Fig. 45 a and b show the existence of an optimum value of the

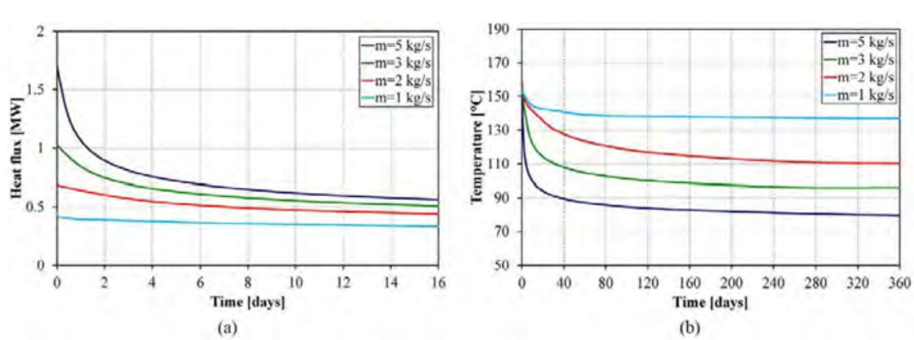


Fig. 42. Effect of the mass flow rate ([7]).

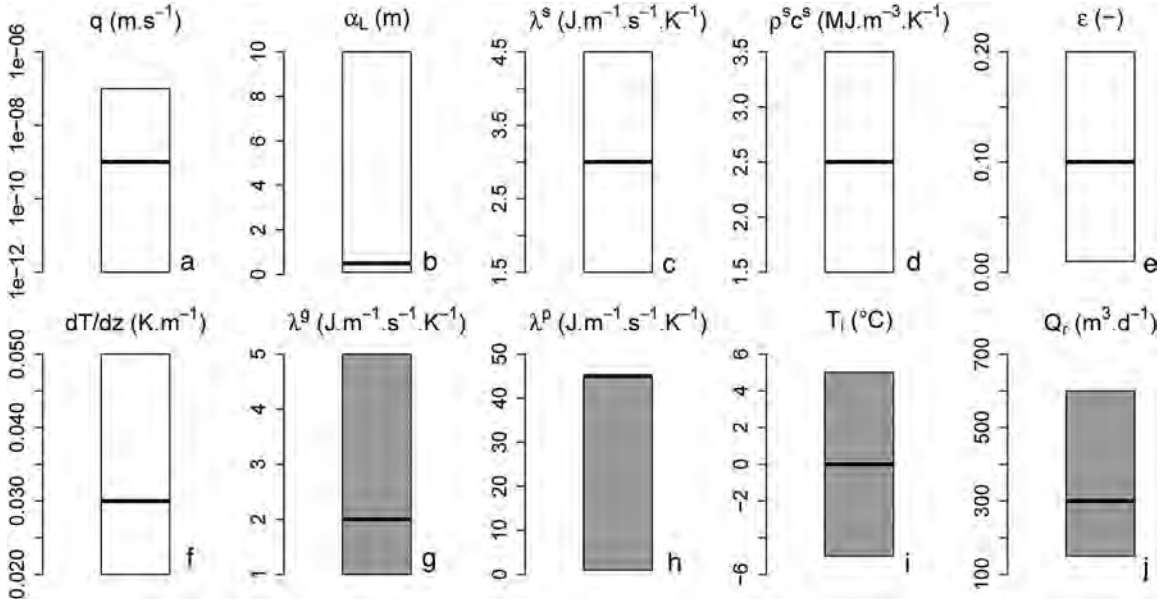


Fig. 43. Parameters examined in the sensitivity analysis of le lous et al [11].: (A) Groundwater flux, (B) Thermal dispersivity of the subsurface, (C) Thermal conductivity of solid, (D) volumetric heat capacity of solid, (E) porosity of the subsurface, (F) Geothermal gradient, (G) thermal conductivity of the grout, (H) Thermal conductivity of the inner pipe, (I) inlet temperature of the heat carrier fluid, (J) Discharge rate of the heat carrier fluid.

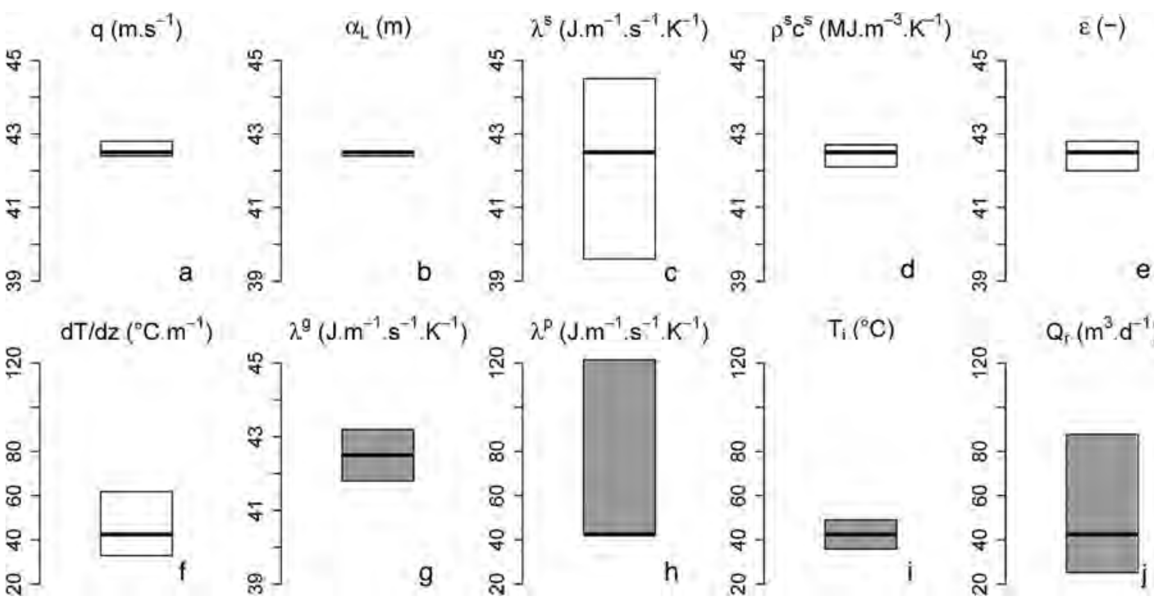


Fig. 44. Results of the sensitivity study in terms of specific heat extraction S (Wm^{-1}) ([11]).

Table 17
Base scenario ([11]).

Borehole diameter	0.3	m
Borehole depth	5000	m
Inlet pipe diameter (di)	0.235	m
Inlet pipe wall thickness (bi)	0.0111	m
Outlet pipe diameter (do)	0.0114	m
Outlet pipe wall thickness (bo)	0.0067	m
Water density	1000	kg/m3
Water viscosity	0.001307	kg/m s
Water heat capacity	4191	kJ/m3K
Water thermal conductivity	0.58	W/mK
Flow rate of water	300	m3/d
Inlet temperature	0	°C
Temperature gradient	30	°C/km

Table 18
Simulation data and results ([18]).

	AZ - I	AZ - II	DQ - I	DQ - II
Bottomhole Temperature (°C)	138.7	138.7	159.8	159.8
Depth (m)	3861	3861	4423	4423
Outlet Temperature (°C)	114.9	117.5	145.7	137.8
Flow rate (kg/s)	4.05	7.24	4.875	11.9
Thermal power (kW)	763	967	1106	1842
Net power (kW)	59.8	138	111.7	364

mass flow rate, as observed in previous papers.

Noorollahi, Yousefi and Pourarshad [19] have proposed the use of the thermal energy extracted from the DQ well in order to supply the Sugarcane Industry in Ahvaz.

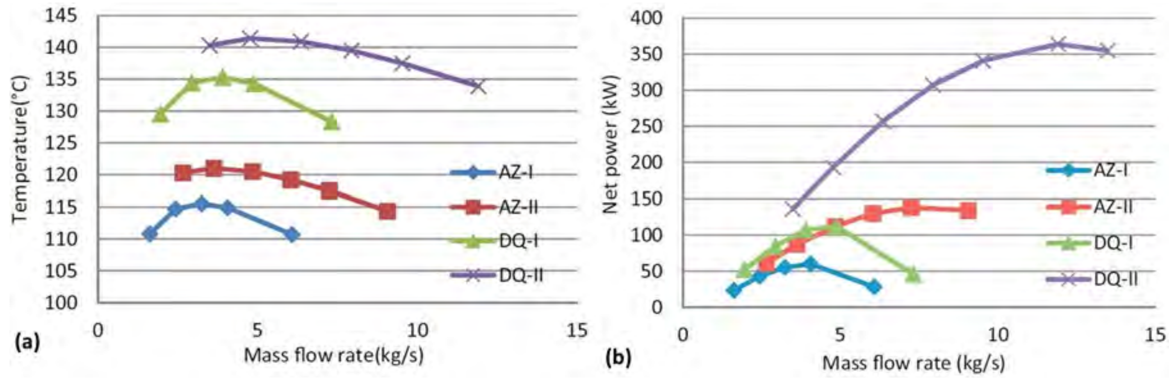


Fig. 45. Influence of the mass flow rate on the temperature (a) and the power (b) ([18]).

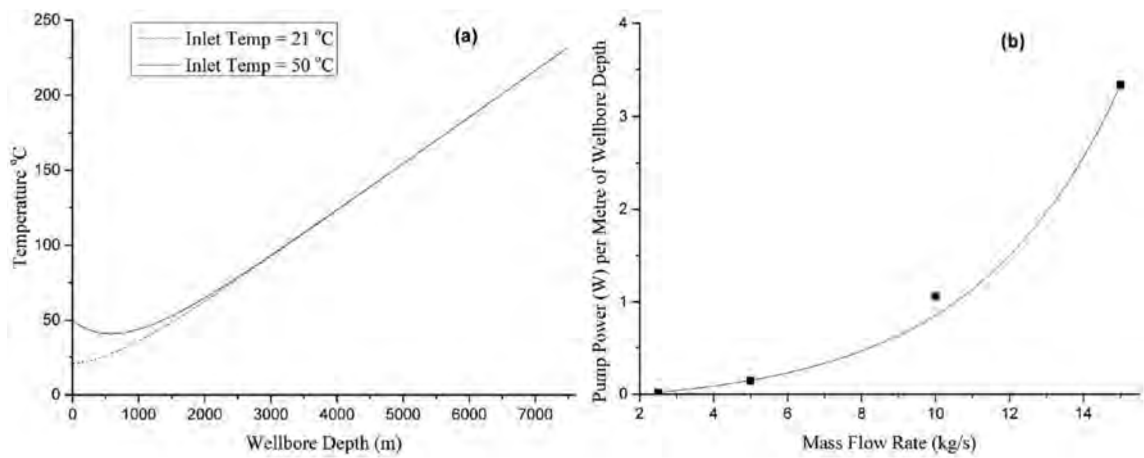


Fig. 46. Influence of the mass flow rate on the outlet temperature and the pumping power ([21]).

Table 19
Main data and results of the case study proposed by Ref. [21].

Casing diameter	9 5/8″
Depth (m)	4200
Outlet Temperature (°C)	130
Flow rate (kg/s)	2.5
Electrical power (kW)	109

Wight and Bennett [21] have studied the possibility of use the WBHX inside the depleted oil and gas fields in Texas, in order to produce electrical energy with binary power plants. The selected working fluid is water. The authors studied the influence of the mass flow rate on the fluid temperature and the pumping power (Fig. 46 a and b), concluding that the lower values of the flow rate guarantee the higher values of fluid temperature and the lower pumping power request too. Table 19 summarizes the main data and the results of the case study.

Alimonti and Soldo [22] have analyzed the possibility to implement the WBHX on the Villafortuna-Trecate oilfield (Italy). The research has been focused on the optimization of the WBHX to maximize the extracted heat. Therefore, a sensitivity study has been carried out on the following parameters: the heat carrier fluid, the design, the flow rate, the influence of the temperature on the fluid properties. The producible electricity using an Organic Ranking Cycle plant has been also evaluated. The proposed system is a plant with two steps of heat exchange: in the first step, the working fluid is circulated in the WellBore Heat eXchanger and it acquires heat from the rock; in the second step, the working fluid exchanges the heat with an organic fluid of the ORC machine. A thermodynamic model of the ORC plant has been realised in order to test different working fluids: the R-C318 has been selected for the

Table 20
Tested pipes diameters ([22]).

Dc_{ext} inch	Di_{ext} inch	Do_{ext} inch	Do_{int} mm	T_{bottom} °C	Thermal power kW	Pumping power kW	Net thermal power kW
7	5 ½	3 ½	77.9	136.29	921.05	27.74	893.31
6 5/8	5 ½	3 ½	77.9	121.40	915.07	66.63	848.44
9 5/8	5 ½	3 ½	77.9	143.80	997.79	7.96	989.82
10 5/8	5 ½	3 ½	77.9	145.66	1017.01	7.74	1009.27
7	5 ½	3 ½	69.8	136.29	921.07	30.60	890.47
7	5 ½	2 7/8	52.5	136.96	1002.17	44.40	957.77
7	5 ½	2 3/8	43.2	137.26	1038.64	63.49	975.15
7	5	3 ½	77.9	135.84	883.78	14.04	869.74

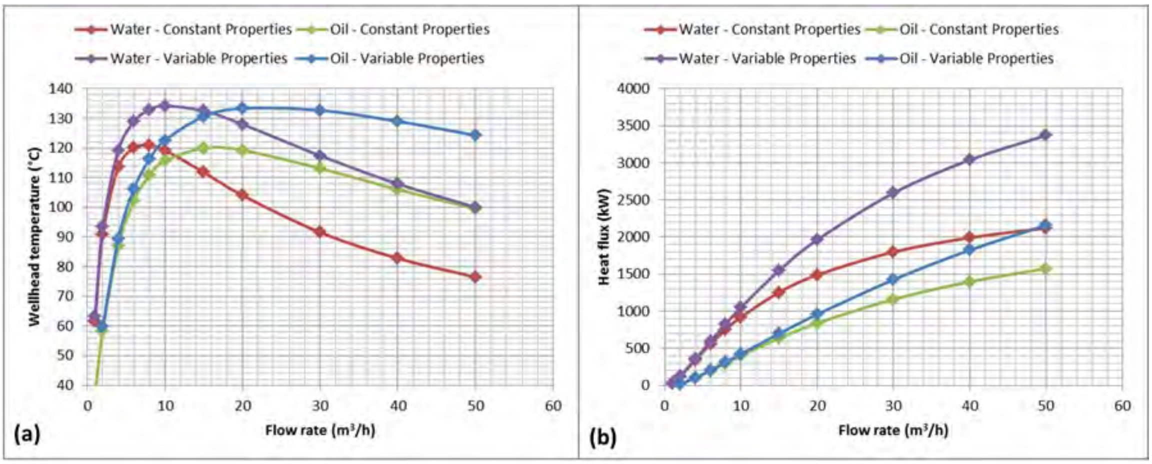


Fig. 47. Influence of the flow rate on the wellhead temperature (a) and the thermal power for different working fluids (b) ([22]).

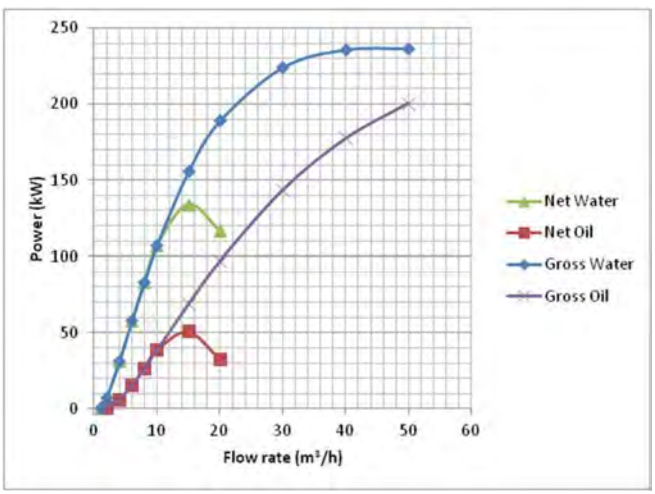


Fig. 48. Electrical power vs. flowrate - variable fluid properties ([22]).

Table 21
Optimum condition data and results ([22]).

Wellbore data	Depth	6000 m
	Thermal gradient	26 °C/km
	Bottom Temperature	170 °C
WBHX geometry	Length	6000 m
	Outer casing OD, ID	177.8, 150.37 mm
	Inner casing OD, ID	139.7, 121.4 mm
	Tubing OD, ID	88.9, 77.9 mm
	Thermal conductivity	50 $Wm^{-1}K^{-1}$
Working fluid WBHX (Water)	Density	1000 $kg\ m^{-3}$
	Thermal conductivity	0.67 $W\ m^{-1}K^{-1}$
	Specific thermal capacity	4186 $J\ kg^{-1}$K-1
	Viscosity	0.001 Pa s
	Injection temperature	40 °C
	Mass flow rate	15 m^{-3}/h
Working fluid ORC (R-C318)	Mass flow rate	4.33 $kg\ s^{-1}$
RESULTS	Wellhead temperature	132.5 °C
	Thermal power	1.5 MW
	Electrical Power	155.5 kW
	Pumping power	21.5 kW
	Net electrical power	134 kW

specific application.

Table 20 reports the tested pipes diameters: the selected configuration maximizes the heat flux and minimizes the pumping power request, thanks to the spontaneous circulation due to the thermo-siphon effect. The diameters of the pipes are constant; to insulate the internal and external casings for the entire length is used air.

Fig. 47 a and b show the importance of considering the changing of fluid properties due to the temperature increasing in the exchanger and the greater heat extraction obtained with the water respect to the diathermic oil. The produced thermal power increases with flow rate; otherwise, there is a specific value of the flow rate that guarantees the maximum outlet temperature (Fig. 47 b). The net electrical power also presents a maximum depending on the flow rate (Fig. 48).

Table 21 reports the data of the case study and the results: the calculations have been done considering a short time after the start-up of the plant; after 5 years, a pseudo state condition is reached and a reduction to a 45% of the initial power generation is attained. Nevertheless, the main increase of the thermal radius is in the first years, so the results after one year of exploitation can be considered representative of the potential size of the plant.

The authors have deepened the aspect of energy conversion systems comparing the ORC plant and a Stirling motor ([23]). Furthermore the possibility to install the WBHX in the areas of Campi Flegrei and Ischia Island has been evaluated ([24] [25]). Table 22 summarizes the main results.

The geothermal plant proposed by Ref. [51] is composed of a WBHX, in which the working fluid is water, and an ORC plant. The authors have optimized the parameters of the Organic Rankine Cycle using the WBHX model proposed by Ref. [13], the energy analysis, the exergy analysis, the economic analysis and the exergy-economic analysis. The results have demonstrated that the R-123 is the most appropriate organic fluid.

4. Discussion

In the previous sections, about 30 papers regarding the application of a WBHX and the modeling of the heat transfer into the reservoir and between it and the device have been analyzed. The most accurate model entails the application of the conservation equation of mass, momentum and energy in the wellbore and in

Table 22
Evaluation of WBHX implementation on different sites ([23] [24] [25]).

Site	Depth	Gradient	Flow rate	Time	Thermal pow.	Electrical pow ORC	Electrical pow Stirling
Trecate	6 km	26 °C/km	20 m^3/h	10 h	1.3 MWth	121 kWe	152 kWe
Campi Flegrei	1.9 km	150-200 °C/km	20 m^3/h	1 year	2.5 MWth	260 kWe	450 kWe
Ischia	0.9 km	150-200 °C/km	20 m^3/h	1 year	0.75 MWth	–	

the formation. This approach allows the estimation of the influence radius of the well and the sustainability of the heat extraction, which are key issues for the feasibility of the WBHX. The system of equations can be solved with analytical or numerical methods, which require the discretization of the domain. In the analyzed papers the numerical simulators GEOTEMP, TOUGH2, FRACTURE, TETRAD, FEFLOW and FlexPDE have been used; the most used one is TOUGH2. The homogeneity of the rocks is the more common assumption for all models. Different approach for the boundary conditions are followed. The more used boundary condition are top and bottom temperatures. Sometimes, instead of temperature the heat flux is used, especially for the bottom boundary. The temperature gradient is also used to fix boundary temperature along the depth of reservoir.

In order to model the WBHX, different approaches have been followed. The more common is the development of a numerical model for the exchanger, which is then coupled to a reservoir model. The coupling could be direct or indirect, depending on the kind of models. 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. The limitations are related to the proper translation of the conceptual model into the software. From the analysis of the literature the influence radius of the exchanger is assumed to be in the range of 20–50 m.

The study of the performance of the WBHX and the influence of operational parameters, design characteristics, thermal properties of the formation and of the heat carrier fluid have been widely treated in literature.

The sensitivity analysis of Nalla et al. [1] demonstrated that at fixed flow rate the residence time of the fluid in the WBHX is function of the well diameter, increasing the outflow temperature. Nevertheless, the low increasing of the effluent temperature does not justify the considerable increasing of the well completion cost.

The diameters of the pipes have a secondary influence on the heat transfer: at fixed flow rate there is a direct proportionality between the casing diameter and the thermal power; on the contrary, the increasing of the internal tubing diameter produces a decreasing of the thermal power ([8]). The wellhead temperature of the heat carrier fluid is independent by the length of circulation and recovery periods ([4] [3]).

Therefore, to optimize the production from a WBHX is highly recommended to study the design defining the more appropriate well diameter and pipe diameter.

Several papers ([4] [1], [26] [8]) have shown that the insulation of the internal pipe is necessary in order to avoid heat exchange between the hot rising fluid and the colder fluid in the downward tube. Some authors have assumed that the insulation can be realized for the entire length of the well using the compressed air ([26] [22]) [4]. refer that the internal pipe of the WBHX applied at Weggis (Switzerland) has insulation for a limited length of the device using a vacuum pump. Nalla et al. [1] have proven that the magnesia is sufficient in order to insulate the internal pipes. Davis and Michaelides [13] adopted the polystyrene as insulation material.

Some improvements can be done developing new piping materials or using a filling material with high thermal insulation.

The performance of the WBHX is directly proportional to the geothermal gradient, the thermal conductivity and the volumetric heat capacity of the formation ([1] [14], [15] [17], [11] [18] [19]).

Concerning the working fluid, two different approaches have been followed: the circulation of a heat transfer fluid or in case of use of ORC plant the direct circulation of the low boiling point fluid. The water results to be the most efficient heat carrier fluid according to the results of [1] and [22]. The water has been considered also in the analysis of [26] [14], [10] [17], [11] [18], [19], [21]. In the two real applications of the WBHX in Switzerland, the working fluid was water [4] [8]. proposed the direct use of iso-pentane. Instead [13] [15], and [7] have selected the iso-butane. In a second paper [16], have evaluated different working fluids finding that the most suitable for the geothermal energy production with a binary plant are R134a and R245fa. The heat transfer is related to the volumetric heat capacity of the fluid as showed [1].

Some authors have studied different design solutions in order to increase the efficiency of the WBHX [17]. recommended the use of a high inlet temperature (70 °C) and the insulation of the external casing until the length at which the working fluid temperature equals to the rock temperature. In addition, the WBHX proposed by Ref. [1] has a limited cased and cemented length to increase the heat transfer efficiency [8]. have proposed a particular design of the WBHX. The rocks are fractured; a second open annulus between the external casing and the borehole, filled by connate fluids, increase the heat exchange to the WBHX thanks to the free convection. [9] suggested enhancing the heat extraction by fracturing the formation near the borehole and filling the fractures with high conductivity material; this solution can apply to the vertical wells and to horizontal wells having a larger contact area [5]. and [6] have studied a downhole heat exchanger with a horizontal section installed in the reservoir and equipped with an external annulus where the brine is pumped in order to transfer the heat to the working fluid, before being reinjected into the reservoir [18]. have compared the performance with a constant diameters completion and with a variable diameters completion, concluding that the performance of the WBHX is higher in case of variable diameters design. All these solution are increasing the efficiency of the heat exchange but also the investment costs. Thus, the evaluation of the performance increase compared to the costs is fundamental.

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. Although the evaluated thermal power is less than 1.5 MW, this possibility represents an interesting opportunity by an economic point of view, considering the high cost to drill new wells. According to the results of [14] and [10], after 10 years of operation of the WBHX the heat extraction produces a thermal interference only in the deepest layers and in the surrounding of the well (~20 m). According to [22], the power production reduces to a 45% of the initial value. Other authors suggested the application of the WBHX into EGS ([8]). This opportunity is quite interesting due to the highly reduction in investment cost due to the existence of the well. Conversely, the diameters of oil&gas wells are commonly lesser than those required for geothermal applications. This aspect could influence the possibility to use those wells.

Regarding the conversion systems of the thermal power into electricity, in most papers, the proposed solution is the ORC plant with the working fluid that circulates in the coaxial exchanger and

Table 23
Results comparison.

Paper	Real case	Simul. case	Working fluid	Depth [m]	Grad.T [°C/km]	T_{bw} [°C]	T_{in} [°C]	T_{out} [°C]	Q [m^3/h]	V [m/s]	Th power [kW]	El power [kW]
Kohl et al. [3] real case	X		Water	1213	NA	45	NA	10	10.8	–	NA	NA
Kohl et al. [4]	X		Water	2295	30	73	40	43	3.6	–	20÷40	NA
Nalla et al. [1]		X	Water	5593	57.8	350	26.7	84	22.68	–	NA	50
Kujawa et al. [26]		X	Water	3950	25	105.7	25	68.5	10	–	496	NA
Davis and Michaelides [14]		X	Isobutane	3000	54	177	50	177	NA	3.5	NA	**3000**
Wang et al. [8]		X	Isopentane	5000	40	220	50	140	11.69	–	500	70
Bu et al. [14]		X	Water	4000	45	190	30	129.8	0.848	0.03	815.7	53.7
Cheng et al. [15]		X	Isobutane	6000	40	130	27	130	0.509	0.2	1493	154
Cheng et al. [16]		X	R134a	6000	50	315	27	–	0.509	0.2	–	260
Cei et al. [10]		X	Water	3000	40	240	80	120	14.4	–	580	25
Taleghani [9]		X	–	–	–	–	–	–	–	–	647.7	–
Templeton et al. [17]		X	Water	NA	30	NA	30	60	1.4	–	200	NA
Akhmadullin and Tyagi [5]		X	n-Pentane	4366	29	126	37	118	28	–	2397.5	321.2
Feng et al. [6]		X	n-butane	–	28	–	–	–	–	–	–	357
Galoppi et al. [7]		X	Isobutane	1500	–	300	53.5	132.4	1434.2	–	400	42
Le Lous et al. [11]		X	Water	5000	30	160	0	5	12.5	–	200	–
Noorollahi et al. [18]		X	Water	4423	31.2	159.8	30	137.8	42.84	–	1842	364
Sliwa et al. [20]		X	Water	2340	28.28	73.18	3.8	18.9	9	–	150	–
Wight and Bennett [21]		X	Water	4200	31	151.2	50	130	9	–	–	109
Alimonti and Soldo [22]		X	Water	6000	26	170	40	132.5	15	–	1500	134
Alimonti et al. [24]		X	Water	1900	130	300	40	150	20	–	2500	260
Alimonti et al. [25]		X	Water	900	155	200	40	128	20	–	750	–

(The thermal power estimated by ref. [13] is reported in bold because it is much greater than the other thermal power data).

in the ORC plant. [18] [22], and [51] analyzed the use of a double fluid plant solution: the water circulates in the WBHX and heats the organic fluid circulating in the ORC plant by a heat exchanger [23]. evaluated also the use of a Stirling motor.

Table 23 summarizes the results of all consulted papers; it has been reported respectively: the case study, the working fluid, the depth, the geothermal gradient, the bottomhole temperature, the injection temperature of the working fluid, the outlet temperature of the working fluid, the flow rate, the velocity, the thermal power and the electrical power. The underlined values, not reported in the original paper, have been estimated for this review.

The analyzed papers are heterogeneous both for the thermal properties of the formation and of the heat carrier fluid, as well as for the operation condition of the WBHX. Therefore, also the results are heterogeneous. The outlet temperature varies between 5 °C and 177 °C and the inlet one between 0 °C and 80 °C. The range of produced thermal power is 150 kW÷2.5 MW and the rated electrical power is in the range 25 kW÷364 MW (excluding the result by Ref. [13]). Considering the low values of the estimated electrical power, some authors ([1] [26], [17] [11]) consider the direct use the most suitable application for the deep borehole heat exchangers.

5. Conclusions

The analysis of literature and the results obtained by the authors demonstrates the feasibility of the extraction of geothermal energy without brine production by means of the WBHX. The low efficiency in heat recovery respect to the conventional geothermal plants makes this solution not profitable for the hydrothermal systems. Anyway, considering the advantage of avoiding risks and costs related to the extraction and reinjection of the fluids, the WBHX may encourage a positive social response to geothermal plants and it could be an opportunity for the exploitation of conventional and unconventional geothermal systems. Therefore, a research to improve the performance and the applicability of the WBHX is worthwhile. In details, the aspects to be deepen are the heat carrier fluid, the pipes materials, the design and the conversion systems.

Regarding the heat carrier fluid, the evaluation of using nanoparticles in the heat carrier fluid is undergoing. The basic idea is the increase of the volumetric heat capacity of the pure fluid. First results, obtained based on available correlations, suggest a 1% increase of the heat exchange adding a 3% in volume of Aluminum oxide in water.

There is a lack of specific studies on materials that are made up the pipes of the WBHX. In order to improve the heat recovery of the device, the research should focus on the possibility to use for the internal pipe a material able to isolate it, reducing the heat losses during the recovery of heated fluid. Instead, the grouting material mainly affects the heat exchange with the formation. Therefore, improvements are needed more on the grouting materials than in materials constituting the external casing.

In order to overcome the limitation of conductive heat exchange, studies are aimed at introducing the possibility to have a convective component. Starting from the design solutions adopted by different authors and previously presented, may be proposed a new design in which natural convection takes place, maximizing the heat transfer and the electrical consumption is minimized.

Although some authors suggest the application of the deep borehole heat exchanger to produce thermal energy instead of electricity, the sector of energy conversion systems is in continuously growing and the use of the advanced ORC systems may be the next step.

The more important weakness point of the WBHX is the few real case applications. In fact, the few available data on the use of the WBHX into the wells of Weissbad and Weiss are not sufficient for a definitive evaluation. The other real cases of Aachen (RWTH-1 well) and in Hawaii (HGP-A well) are just a demonstration of the possibility to use this technology. The comparisons between modeling results and experiments are not always in agreement. Therefore, an effort should be made in order to obtain better results allowing to deploy proper designing methods.

A complete feasibility study of the use of the WBHX should include the study of the heat transfer inside the reservoir and of the temperature decline in the surrounding of the device in order to evaluate the time horizon of operation of a WBHX. Therefore, the coupling of the formation model and the WBHX model is highly recommended. This implementation is possible with some software (i.e. TOUGH2), or with a simple iterative process. The use of Multiphysics software is not recommended due to the complexity of the required modeling.

The well bore heat exchanger, or the deep borehole exchanger, is a promising technology if and only if is applied in the more convenient geothermal assets. The continuous study of the possible designing solutions and the improvements to enhance heat transfer is fundamental to allow this technology ready to market.

References

[1] G. Nalla, G.M. Shook, G.L. Mines, K.K. Bloomfield, Parametric sensitivity study of operating and design variables in wellbore heat exchangers, Geothermics 34 (2005) 330–346.
[2] A. Sapinska-Sliwa, M.A. Rosen, A. Gonet, T. Sliwa, Deep borehole heat exchangers – a conceptual review, in: Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19–25 April 2015.
[3] T. Kohl, M. Salton, L. Rybach, Data analysis of the deep borehole heat exchanger plant Weissbad (Switzerland), in: Proceedings World Geothermal Congress 2000, Kyushu - Tohoku, Japan, May 28-June 10, 2000.
[4] T. Kohl, R. Brenni, W. Eugster, System performance of a deep borehole heat exchanger, Geothermics 31 (2002) 687–708.
[5] I. Akhmadullin, M. Tyagi, Design and analysis of electric power production unit for low enthalpy geothermal reservoir applications, World Academy of Sci. Eng. Technol. Int. J. of Environ. Chem. Ecol. Geol. Geophys. Eng. 8 (6) (2014).
[6] Y. Feng, M. Tyagi, C.D. White, A downhole heat exchanger for horizontal wells in low-enthalpy geopressured geothermal brine reservoirs, Geothermics 53 (2015) 368–378.
[7] G. Galoppi, D. Biliotti, G. Ferrara, E.A. Carnevale, L. Ferrari, Feasibility study of a geothermal power plant witha double-pipe heat exchanger, Energy Proc. 81 (2015) 193–204.
[8] Z. Wang, M.W. McClure, R.N. Horne, A single-well EGS configuration using a thermosiphon, in: Proceedings of Thirty-fourth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 9-11, 2009.
[9] A.D. Taleghani, An improved closed-loop heat extraction method for geothermal resources, J. of Energy Resour. Technol. ASME 135 (4) (2013), https://doi.org/10.1115/1.4023175.
[10] M. Cei, R. Bertani, A. Fiorentini, P. Romagnoli, Evaluation of heat exchange in a geothermal well, in: Proceedings of European Geothermal Congress 2013, Pisa, Italy, 3-7 June 2013.
[11] M. Le Lous, F. Larroque, A. Dupuy, A. Moignard, Thermal performance of a deep borehole heat exchanger: insights from a synthetic coupled heat and flow model, Geothermics 57 (2015) 157–172.
[12] P. Kędzierski, Z. Nagórski, T. Niezgoda, Determination of local values of heat transfer coefficient in geothermal models with internal function method, Renew. Energy 92 (2016) 506–516.
[13] A.P. Davis, E.E. Michaelides, Geothermal power production from abandoned oil wells, Energy 34 (2009) 866–872.
[14] X. Bu, W. Ma, H. Li, Geothermal energy production utilizing abandoned oil and gas wells, Renew. Energy 41 (2012) 80–85.
[15] W.L. Cheng, T.T. Li, Y.L. Nian, C.L. Wang, Studies on geothermal power generation using abandoned oil wells, Energy 59 (2013) 248–254.
[16] W.L. Cheng, T.T. Li, Y.L. Nian, K. Xie, Evaluation of working fluids for geothermal power generation from abandoned oil wells, Appl. Energy 118 (2014) 238–245.
[17] J.D. Templeton, S.A. Ghoreishi-Madiseh, F. Hassani, M.J. Al-Khawaja, Abandoned petroleum wells as sustainable sources of geothermal, Energy 70 (2014) 366–373.
[18] Y. Noorollahi, M. Pourarshad, S. Jalilinasrabady, H. Yousefi, Numerical simulation of power production from abandoned oil wells in Ahwaz oil field in southern Iran, Geothermics 55 (2015) 16–23.
[19] Y. Noorollahi, H. Yousefi, M. Pourarshad, Three dimensional modeling of heat extraction from abandoned oil well for application in Sugarcane industry in Ahvaz– southern Iran, in: Proceedings World Geothermal Congress 2015, Melbourne, Australia, April 2015, pp. 19–25.
[20] T. Sliwa, A. Gonet, A. Sapinska-Sliwa, D. Knez, Z. Jezuit, Applicability of borehole R-1 as BHE for heating of a gas well, in: Proceedings World Geothermal Congress 2015, Melbourne, Australia, April 2015, pp. 19–25.
[21] N.M. Wight, N.S. Bennett, Geothermal energy from abandoned oil and gas wells using water in combination with a closed wellbore, Appl. Therm. Energy 89 (2015) 908–915.
[22] C. Alimonti, E. Soldo, Study of geothermal power generation from a very deep oil well with a wellbore heat exchanger, Renew. Energy 86 (2016) 292–301.
[23] C. Alimonti, D. Berardi, D. Bocchetti, E. Soldo, Coupling of energy conversion systems and WellBore Heat eXchanger in a depleted oil well, Geotherm. Energy 4 (2016) 11, https://doi.org/10.1186/s40517-016-0053-9.
[24] C. Alimonti, E. Soldo, D. Bocchetti, D. Berardi, A matrix method to select the more suitable extraction technology for the Campi Flegrei geothermal area (Italy), in: European Geothermal Congress 2016, Strasbourg, September 2016, pp. 19–23.
[25] C. Alimonti, E. Soldo, D. Bocchetti, D. Berardi, Evaluation of geothermal energy production using a WellBore heat eXchanger in the reservoirs of Campi Flegrei and Ischia Island, in: European Geothermal Congress 2016, Strasbourg, September 2016, pp. 19–23 (Poster session).
[26] T. Kujawa, W. Nowak, A.A. Stachel, Utilization of existing deep geological wells for acquisitions of geothermal energy, Energy 31 (2006) 650–664.
[27] A. Garcia-Gutierrez, G. Espinosa-Paredes, I. Hernandez-Ramirez, Study on the flow production characteristics of deep geothermal wells, Geothermics 31 (2002) 141–167.
[28] I.M. Kutasov, Dimensionless temperature at the wall of an infinite long cylindrical source with a constant heat flow rate, Geothermics 32 (2003) 63–68.
[29] I.M. Kutasov, Dimensionless temperature at the wall of an infinite long, variable rate, cylindrical heat source, Geothermics 36 (2007) 223–229.
[30] X. Carslaw and Jaeger: Chapter, The Use of Sources and Sinks in Cases of Variable Temperature 258-262 in: Conduction of Heat in Solids, second ed., 1959.
[31] M.J. O'Sullivan, K. Pruess, M.J. Lippmann, State of the art of geothermal reservoir simulation, Geothermics 30 (2001) 395–429.
[32] J.W. Pritchett, STAR: a geothermal reservoir simulation system, in: Proceedings World Geothermal Congress '95, Florence, 18–31 May 1995, pp. 2959–2963.
[33] P.K.W. Vinsome, G.M. Shook, Multi-purpose simulation, J. of Petroleum Sci. Eng. 9 (1) (1991) 29–38.
[34] K. Pruess, C. Oldenburg, G. Moridis, An overview of TOUGH2, Version 2.0, in: Proceedings of the TOUGH Workshop '98, Berkeley, California, 1998, pp. 307–314.
[35] T. Kohl, R.J. Hopkirk, "FRACTure" a simulation code for forced fluid flow and transport in fractured porous rock, Geothermics 24 (3) (1995) 345–359.
[36] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, McGraw-Hill, New York, USA, 1980.
[37] J. Lee, Well testing, SPE Monogr. Ser. (1982) 106–107.
[38] L.A. Mondy, L.E. Duda, Advanced Wellbore Thermal Simulator GEOTEMP2 User Manual, 1984 (Sandia report).
[39] M.J. O'Sullivan, AUTOUGH2 Notes, Department of Engineering Science, University of Auckland, 2000.
[40] H. Ramey Jr., Wellbore heat transmission, J. of Petroleum Technol. 14 (1962) 427–435.
[41] K. Pruess, G. Oldenburg Moridis, TOUGH2 User's Guide, Version 2.0, Earth Sciences Division, Lawrence Berkley National Laboratory, University of California, 1999.
[42] E.B. Chekalyuk, Thermodynamics of the Oil-bearing Bed ((Termodinamika Neftjanogo Plasta)) [in Russian], NEDRA, Moscow, 1965.
[43] G.A. Cheremenskii, Geothermy ((Geotermia)) [in Russian], NEDRA, Leningrad, 1972.
[44] D.P. Hart, R. Couvillon, Earth Coupled Heat Transfer, American Water Well Association, 1986.
[45] J.P. Holman, "Heat Transfer," Second Edition, McGraw-Hill, New York, 1968.
[46] S.E. Haaland, Simple and explicit formulas for the friction factor in turbulent pipe flow, J. of Fluids Eng. 105 (1983) 89–90.
[47] Y. Feng, Numerical Study of Downhole Heat Exchanger Concept in Geothermal Energy Extraction from Saturated and Fractured Reservoirs, PhD Dissertation, LSU, 2012.
[48] L. Rybach, R.J. Hopkirk, Shallow and deep borehole heat exchangers – achievements and prospects, in: Proc. World Geothermal Congress, Florence, Italy, 1995, pp. 2133–2138.
[49] M. Yari, Exergetic analysis of various types of geothermal power plants, Renew. Energy 35 (2010) 112–121.
[50] R. Di Pippo, Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact, Elsevier, Oxford, UK, 2008.
[51] H. Mokhtari, H. Hadiannasab, M. Mostafavi, A. Ahmadibeni, Determination of optimum geothermal Rankine cycle parameters utilizing coaxial heat exchanger, Energy 102 (2016) 260–275.