Abandoned oil and gas wells exploitation by means of closed-loop geothermal systems: a review

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Abandoned oil and gas wells exploitation by means of closed-loop geothermal systems: a review

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In mature oilfields, decommissioned oil and gas wells with depths reaching approximately 5000-6000 metres represent good candidate structures for geothermal heat exploitation, as they can provide useful access to subsurface geothermal energy resources.
Comprehending the possibility to economically harness geothermal energy by means of co-axial WBHEs is bound to the main features of the physical model, applied to estimate the amount of heat that can be gained from the borehole.
Simultaneously, due to the continuous spatial variability of geological formations in oilfields, accurate and realistic estimates of the heat exchanger performances cannot be separated from a proper consideration of the thermophysical parameters of geological strata surrounding the hydrocarbon wells.
Keywords: *renewable energy, geothermal energy, sedimentary basin, abandoned oil and gas well, WBHE technology.*

Sfruttamento di pozzi di petrolio e gas abbandonati mediante sistemi geotermici a circuito chiuso: una review. *In giacimenti petroliferi esauriti, i pozzi di petrolio e gas dismessi con profondità che raggiungono circa 5000-6000 metri rappresentano strutture potenzialmente utili per lo sfruttamento del calore geotermico, in quanto possono fornire un accesso utile alle risorse di energia geotermica sotterranea.*
La comprensione della la possibilità di sfruttare economicamente l'energia geotermica mediante WBHE coassiali è vincolata alle caratteristiche principali del modello fisico, applicato per stimare la quantità di calore che può essere ricavata dal pozzo.
Allo stesso tempo, a causa della continua variabilità spaziale delle formazioni geologiche nei giacimenti petroliferi, stime accurate e realistiche delle prestazioni degli scambiatori di calore non possono essere applicate senza una corretta considerazione dei parametri termofisici degli strati geologici circostanti i pozzi di idrocarburi.
Parole chiave: *energia rinnovabile, energia geotermica, bacini sedimentari, pozzi di petrolio e gas abbandonati, tecnologia WBHE.*

1. Introduction

Both the 2030 UN Agenda for Sustainable Development and the 2015 Paris Agreement on Climate Change represent two fundamental contributions to guide the transition towards an economic model that aims, not only at profitability and profit, but primarily social progress and environmental protection.

"Responsible production and consumption" is one of 17 Global Goals that make up the 2030 Agenda for Sustainable Development: to achieve increased energy efficiency, all nations are required to urgently change the way they produce and consume goods as well as how they manage natural resources.

Notably, more progress must be made regarding the integration of renewable energy in end-use applications in buildings, transportation and industries. Public and private investments in energy must also increase, while a focus on regulatory frameworks and innovative business models is necessary to transform global energy systems (United Nations, 2019).

In this context, the primary aim of energy companies is to provide energy solutions that are increasingly sustainable and distant from those based on fossil fuel, through technological development and environmental values.

Geosciences has long been considered a promising solution to these issues while serving an important role in decarbonisation through the development of a range of options that can directly encourage the transition to sustainable energy sources, at urban and regional scales: power generation from renewable resources, heating and cooling buildings using geothermal energy, carbon capture and storage (CCS) and more ambitious technologies that limit negative emissions, such as bioenergy (BE) (Ringrose, 2017).

Among the various available energy resources, geothermal energy is a weather-independent, stable, environmentally friendly resource that represents one of the main future energy solutions that will have to be increasingly exploited for both power generation and direct use applications.

In particular, energy production based on the exploitation of deep geothermal energy resources derived from disused or abandoned oil and gas wells in oilfields across continents could represent a considerable future economic and environmental potential.

It could solve problems associated with suspended oil and gas wells near municipalities, thereby allowing us to hypothesise long-term scenarios for exploitation – even at the end of the hydrocarbon production cycle of wells – to the benefit of end users in the industrial, civil and agriculture districts.

Existing wellbores, surface facilities, useful geological and geophysical data empower potential geothermal projects in oilfield by reducing capital costs, minimising risks and significant inconveniences (Wang *et al.*, 2018; Liu *et al.*, 2018).

Considering the temperature ranges associated with deep oil and gas wells in hydrocarbon fields (65-150°C), energy companies have recently started to place greater effort in developing various strategies for harnessing this type of deep geothermal energy resource.

The majority of works that have been carried out on existing abandoned petroleum wells have focused on open-loop systems designed to repurpose petroleum fields as geothermal reservoirs (Sanyal and Butler, 2010; Limpasurat *et al.*, 2011; Kharseh *et al.*, 2019).

However, open-loop technologies were found to be subject to some technical problems, including groundwater recession, corrosion and scaling problem (Nian and Cheng, 2018).

A further issue was represented by the re-injection of fluids. Due to the physicochemical properties being unsuitable for terrestrial ecosystems, geothermal fluids must be treated before re-injection underground. Since these operations require the drilling and maintenance of additional wells, the treatment and pumping of fluids often entailed higher economic costs related to potential geothermal projects.

However, an effective alternative was found in the use of closed-loop deep geothermal systems (using a closed circuit of pipes). Different from a conventional open-loop geothermal system, heat carrier fluids in closed-loop systems circulate inside of wellbore heat exchangers (WBHEs), while no ground fluids are extracted from surrounding rocks and working fluids are not in contact with the surrounding formation. Moreover, corrosion and scaling problems are also limited.

Due to their proven advantages, a large number of researches dealing with developing closed-loop system technologies has appeared in the literature (Kujawa *et al.*, 2005, 2006; Bu *et al.*, 2012, 2014; Cheng *et al.*, 2013, 2014; Wight and Bennett, 2015; Alimonti and Soldo, 2015, 2016).

However, despite some recent successful theoretical oilfield geothermal closed-loop system experiments worldwide (Liu *et al.*, 2018), certain challenges remain in the large-scale harnessing of geothermal resources in oilfields, including low levels of thermal energy recovery, low energy conversion efficiency, and especially the inadequate assessment of geothermal potential (Zarrouk and Moon, 2014; Wang *et al.*, 2016).

Furthermore, even if there is a great availability of geological and geophysical data relating to drilled rock formations that were acquired during the prospecting phases in oilfields, very few works comprehensively consider the influence of vertical and horizontal variations in geological parameters in heat exchange mechanisms.

The main aim of this paper is to provide a review of the advanced research developed for retrofitting abandoned oil and gas wells in sedimentary basins, highlighting the methodological potential and the limits of obtained evaluations from a geological perspective.

Firstly, we summarised the main features of the different types of closed-loop technologies available for harnessing geothermal energy resources from oilfields, primarily focusing our attention on coaxial WBHE technology.

Secondly, we analysed the thermal simulation methods and heat transfer models applied to describe the mechanisms of heat exchange in abandoned oil and gas wells. Finally, the limits in the extracted thermal energy estimations obtained by 1) assuming constant geological parameters, 2) neglecting the contribution of fluids circulating within the geological formations (forced convection phenomena) were underlined.

2. Geothermal energy systems in oil fields

Nearly existing drilled hydrocarbon wells are located in geological contexts associated with sedimentary basins. Sedimentary basins are areas of the earth's surface of tectonic origin that continuously subside and accept sediments transported by streams, oceans and atmospheric currents directly or biologically precipitated from seawater (Raffensperger and Vlassopoulos, 1999).

Over time, geological and geophysical exploration campaigns in such geological contexts have ascertained the coexistence of hydrocarbons and low to medium temperature geothermal energy resources, located in their deepest regions (Wang *et al.*, 2016).

Consequently, as a type of energy stored in subsurface geological formations and associated with hydrocarbons in sedimentary basins, geothermal energy must be extracted before final utilisation.

Especially in mature oilfields, decommissioned oil and gas wells with depths of approximately 5000-6000 metres represent good candidate structures for geothermal heat exploitation, thus providing useful access to subsurface energy resources.

2.1. Closed-loop geothermal energy systems: Wellbore heat exchangers (WBHEs)

In current practice, two main types of closed-loop systems have been tested for harnessing geothermal energy resources by taking advantage of disused boreholes in oilfields: U-tube and coaxial double-pipe WBHE technologies (Wang *et al.*, 2016, 2018).

In U-tube heat exchangers, fluid is pumped through one tube string and comes out of the other (Fig. 1). It is by this action of flowing through the well that the fluid in the U-tube can gain heat energy from the surrounding geological formations.

On the other hand, the coaxial heat exchanger is composed of two concentric pipes, as shown in Fig. 2.

Circulating working fluid is injected into an outer pipe (injection pipe), flows down to the lower part of the exchanger and is gradually warmed up by acquiring heat from the rocks. After the fluid reaches the bottom hole of the well, it flows upwards through an installed pipe with an inferior diameter that acts as the inner pipe (extraction pipe).

Both the outer wall of the inner pipe and the outer pipe are thermally insulated, while the bottom hole is sealed.

Heat exchange occurs both on the outside wall of the exchanger (between the geological formation and the fluid flowing through the injection pipe) and between the fluid in the injection pipe and the fluid flowing through the extraction pipe.

Compared to U-tube heat exchangers, coaxial heat exchangers have the advantages of a higher surface area and volume of the working fluid, through which heat exchange occurs. As a result, under the same injection rate conditions (q), fluid flow velocity in the coaxial pipe system together with the hydraulic pressure required for fluid circulation could be lower, thereby resulting in a lower pumping energy consumption.

Additionally, since the outer pipe (casing) is already present, the retrofitting of a double-pipe heat exchanger to an abandoned well also requires significantly reduced construction times compared to adapting a U-tube heat exchanger.

Finally, the coaxial geometry of a double-pipe heat exchanger has the advantage of reducing the thermal resistance between the circulating fluid and the wellbore.

For these different listed advantages of coaxial pipe geometry, many authors have recently started to shift their attention to the use of coaxial WBHEs, in attempts to develop increasingly accurate thermal simulation methods and heat transfer models.

3. Coaxial wellbore heat exchanger

3.1. Energy balance equations

The energy balance equation of the fluid in the outer pipe (injection pipe) of a coaxial WBHE can be expressed as the following equation (Eq. 1):

$$\frac{\partial\left((\rho c)_f A_0 T_{fo}\right)}{\partial \tau}+\frac{\partial\left((\rho c)_f A_0 v_f T_{fo}\right)}{\partial z}=-\frac{dQ}{dz}+\frac{dQ_{i0}}{dz} \quad (1)$$

where A_0 and v_f are the outer pipe area and fluid velocity, respectively, T_{fo} is the fluid temperature in

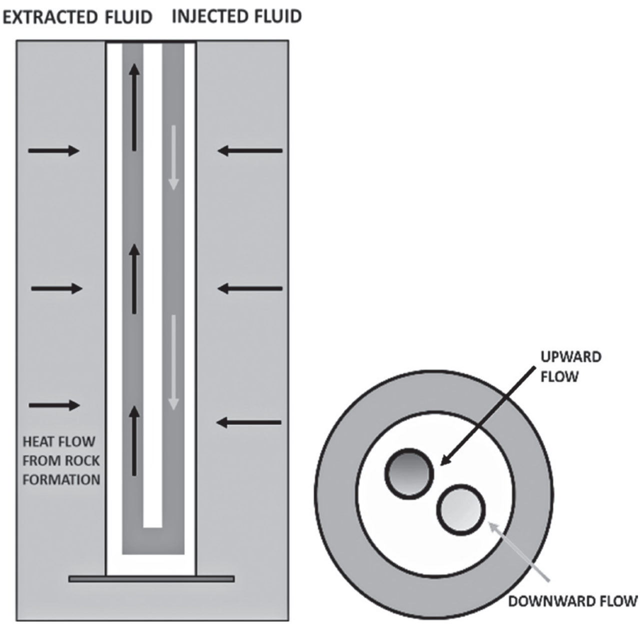

Fig. 1. Schematic representation of a U-tube WBHE.
Rappresentazione schematica di uno scambiatore di calore a U.

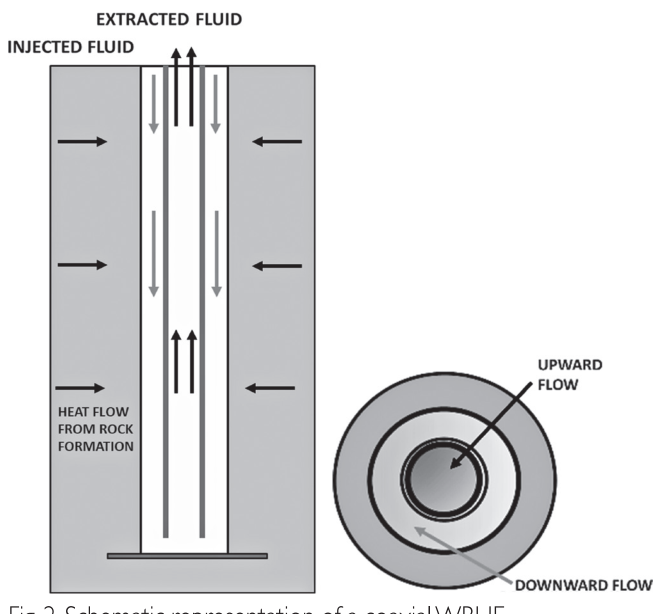

Fig. 2. Schematic representation of a coaxial WBHE.
Rappresentazione schematica di uno scambiatore di calore di tipo coassiale.

Tab. 1. Coaxial WBHE: Geometric parameters.
Scambiatore di calore di tipo coassiale: e parametri geometrici.

Coaxial wellbore heat exchanger – Geometric parameters	Symbol	Unit of measure
Outer pipe area	A_0	[m^2]
Inner pipe area	A_i	[m^2]
Radius of outside wellbore	r_w	[mm]
External radius of the external casing	r_c	[mm]
Internal radius of the external casing	r_i	[mm]
Radius of the internal casing	r_0	[mm]
Thicknesses of the pipe exchanger	d	[mm]
Depth	z	[m]

the outer pipe, dQ/dz is the heat extraction from formation at unit of well depth (Wm^{-1}).

Although insulation is used to prevent heat loss from the inner pipe fluid, heat is partly transferred between the two pipes: dQ_{io}/dz represents the heat flux from the inner pipe to the outer pipe.

Therefore, the energy equation for the inner pipe can be given as (Eq. 2):

$$\frac{\partial\left((\rho c)_f A_i T_{fi}\right)}{\partial \tau}+\frac{\partial\left((\rho c)_f A_i v_f T_{fi}\right)}{\partial z}= =-\frac{dQ_{i0}}{dz} \quad (2)$$

By assuming steady heat transfer and constant heat flux in wellbore components (insulation, casing, cement), the heat extraction from formation dQ/dz can be assumed equal to the heat flux through the outside surface of the wellbore (interface of wellbore/rock formation) to the injected fluid (Hasan and Kabir, 1991; Nian and Cheng, 2018) (Eq. 3):

$$\frac{dQ}{dz}=2\pi r_w k_w (T_{f0}-T_w)= =(T_{f0}-T_w)/R_w \quad (3)$$

where k_w is the heat transfer coefficient between outer pipe fluid and wellbore exterior, R_w is the resistance between the outer pipe and surrounding rocks.

At the well bottom, the heated fluid is forced to enter and flow through the internal pipe of the coaxial WBHE. Going up to the wellhead, heat transfer occurs only through the wall of the internal pipe. Thus, dQ_{i0}/dz is determined by considering the temperature difference between the outer pipe and inner pipe fluids, together with the estimated thermal resistance insulation value (Eq. 4):

$$\frac{dQ_{i0}}{dz}=2\pi r_0 k_{i0}(T_{fi}-T_{f0})= =(T_{fi}-T_{f0})/R_{i0} \quad (4)$$

where k_{i0} is the heat transfer coefficient between the outer pipe and inner pipe and R_{i0} is the thermal resistance between the outer pipe and inner pipe.

3.2 Coefficient of heat exchange between outer pipe fluid and the wellbore exterior

Starting from an analysis of the energy balance equation of the fluid in the outer pipe (injection pipe) of a coaxial WBHE, a careful estimate of the parameter k_w is fundamental to properly evaluate the quantity of heat exchanged between the outer pipe fluid and drilled geological formations.

For a coaxial WBHE, the heat exchange coefficient (injection pipe) can be correctly expressed as the sum of heat transfer components in terms of thermal resistance values (R_w) (Eq. 5) (Nian and Cheng, 2018).

$$R_w = R_s + R_a + R_c \quad (5)$$

where R_s is the thermal resistance due to heat transfer by conduction in the rock and is a function of time, R_a is the thermal resistance due to the heat transfer by convection into the pipe and R_c is the thermal resistance due to the heat transfer by conduction through the casings of the well.

In the evaluation of total thermal resistance, the conductive term prevails; consequently, thermal exchange is directly proportional to the convective transfer coefficient.

Conductive thermal resistance (R_s) can be expressed as follows (Eq. 6):

$$R_s=\frac{1}{2\lambda_s} In \frac{2\sqrt{a_s t}}{r_w} \quad (6)$$

where λ_s is the thermal conductivity of the rock and α_s is the thermal diffusivity of the rock.

In Eq. 6, the relationship $2\sqrt{a_s t}$ represents the time-dependent radius of the thermal influence of the well (r_s).

Convective thermal resistance R_a is determined by the following equation (Eq. 7):

$$R_a=\frac{1}{2r_c h_f} \quad (7)$$

where r_c is the external radius of the external casing, h_f is the convective heat transfer coefficient, usually calculated by the Nusselt number (Nu) and by a form of Dittus-Boelter equation, assuming turbulent flow inside tubes (Reynolds number ≥ 10^4) (Eqs. 8, 9):

$$h_f=\frac{Nu\lambda_f}{2r_c} \quad (8)$$

$$Nu = 0.023Re^{0.8}\,Pr^{0.4} \quad (9)$$

where $\Pr = \dfrac{\rho c_f \mu}{\lambda_f}$ and $\mathrm{Re} = \dfrac{\rho v_f 2r_c}{\mu}$

Finally, the thermal resistance to heat conduction through the casings of the well is determined as follows (Eq. 10):

$$R_c = \sum_{i=1}^{n} R_{\lambda i} = \frac{1}{2}\sum_{i=1}^{n}\frac{1}{\lambda_i} In\frac{r_{c,i+1}}{r_{c,i}} \quad (10)$$

where λ_i is the thermal conductivity of the rock in correspondence of the different casings of the well.

Generally, due to the high thermal conductivity of the steel piping, the total thermal resistance of the casing can be negligible compared to rock thermal resistance.

As a result, the heat exchange coefficient k_w can be correctly determined as follows (Charnyi 1948, 1953) (Eq. 11):

$$\frac{1}{k_w} = \frac{2r_c}{2\lambda_s} In\frac{4\sqrt{a_s t}}{2r_w} + \frac{1}{h_f} \quad (11)$$

3.3 Coefficient of the heat exchange between the outer pipe fluid and the inner pipe

Different from injection pipe, the total heat flux in the upward pipe (extraction pipe) is formed by 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 WBHE.

Consequently, the total heat exchange coefficient k_{i0} for the extraction pipe can be calculated as follows (Eq. 12):

$$\frac{1}{k_{i0}} = \frac{r_0}{r_{0+d}}\frac{1}{h_i} + r_0\sum_{i=1}^{n}\frac{1}{\lambda_i} In\left(\frac{r_{i+1}}{r_i}\right) + \frac{1}{h_0} \quad (12)$$

where r_0 is the radius of the inner pipe, d is the thicknesses of the pipe exchanger, h_0 and h_i are the coefficients of convective heat transfer to the inner and outer wall, respectively, and λ_i is the thermal conductivity of the pipe material (air and steel).

4. Current methodological developments

The works carried out by Kujawa *et al.* (2005, 2006) represent the pioneering researches for the evaluation of the possibility to retrofit abandoned oil and gas wells for geothermal energy exploitation, utilising a coaxial WBHE.

In their studies, they proposed a 2870-m-long coaxial WBHE for a Jacho′wka K-2 well with an external casing constituted by a column of steel pipes with diameters of 244.5/222.0 mm and a new column of pipes with diameters of 60.3/50.7 mm, located concentrically inside the exchanger.

Due to their starting assumptions of a steady state and a constant temperature at the interface of wellbore/formation, they considered a simplified heat exchange model in which the heat flux penetrating from the external fluid is equal to the heat flux conducted through the multilayer cylindrical barrier and to the heat flux penetrating the internal fluid.

In detail, they started from the formula of linear density of the heat flux transferring from one medium reported in Eq. 3 and estimated the overall heat transfer coefficient between the outer pipe fluid and wellbore outside (k_w) by using equations provided by Charnyi 1948, 1953 (Eq. 11) and Dyad'kin and Gendler, 1985 (Eqs. 13, 14):

$$k_w = \frac{k'_w}{1 + Bi\ ln\left(1+\sqrt{\gamma F0}\right)} \quad (13)$$

$$\frac{1}{k'_w} = \frac{1}{h_f} + \frac{D_1}{2}\sum_{i=1}^{n}\frac{1}{\lambda_i}\ln\frac{D_{i+1}}{D_i} \quad (14)$$

where $Bi = \dfrac{h_f r_c}{\lambda_s}$ is the Biot number, $Fo = \dfrac{a_s t}{r_c^2}$ is the Fourier number and γ is the parameter depending on the Biot number (if $Bi > 30$, $\gamma = \pi$. In other cases, $\gamma = 2$).

By performing calculations for selected volume flow rates of injection fluid (water) flowing through the heat exchanger (2, 10, 20 and 30 m^3h^{-1}) and temperatures respectively equal to 10, 15, 20, and 25°C, the authors demonstrated the practical significance of reusing the existing well for only two injection flow rate values: 2 and 10 m^3h^{-1}, with associated temperatures at the extracted fluid of 65°C and 47°C, respectively.

Furthermore, Bu *et al.* (2012, 2014) began to consider heat transfer from geological formations as being associated to two-dimensional heat conduction phenomena by replacing the assumption of constant temperature at the interface of wellbore/formation in Kujawa *et al.* (2005, 2006) and Davis and Michaelides (2009).

Through analysing abandoned wells that were 4000 m deep with an associated geothermal gradient of 25 °C/km and 45°C/km, Bu *et al.* (2012, 2014) discretised energy balance equations for coaxial WBHE using the finite volume method and solving it using the tri-diagonal matrix algorithm (TDMA) (Tao, 2001).

Although they considered the heat transfers from geological formations as transient in their study, a finite boundary was set for surrounding rocks with the assumption that rock temperature became constant at a radius of surrounding rocks over 200 m.

For their elaborations, the diameter of the injection well on the top part was fixed to 340/300 mm with a length of 2500 m, while the bottom diameter was 330/300 mm with a length of 1500 m. The inner diameter of the extraction well was 100 mm.

The results of Bu *et al.* (2012, 2014) works were fundamental to understanding how the amount of geothermal energy that can be extracted from abandoned oil and gas wells significantly depends on the injection fluid flow rates and on the recorded regional geothermal gradient.

For a selected geothermal gradient of 45 °C/km, they estimated net power output for the analysed single well of 53.70 kWe with an outlet temperature is 129.88 °C. The optimal flow velocity of the fluid at which they attained the maximum net power was 0.03 ms^{-1}, while the maximum value of heat from rocks was acquired at a flow rate of 0.05 ms^{-1}.

Different from Bu *et al.* (2012, 2014), Cheng *et al.* (2013, 2014) examined the effects of formation heat transfer with an infinite boundary and conducted a theoretical analysis of geothermal power generation from abandoned wells using isobutane as the working fluid. In their study, they started from Ramey's (1962) definition of radial heat flow from the formation at the heat exchanger/formation interface and introduced a novel transient heat conduction function f(t), as follows (Eq. 15):

$$\frac{dQ}{dz}=\frac{2\pi\lambda_s\left(T-T_w\right)}{f(t)} \qquad (15)$$

where T is the formation temperature at an infinite distance from the well axis, T_w is the heat exchanger/formation interface temperature and λ_s is the thermal conductivity of the rock formation.

Different from the traditional f(t) introduced by Ramey (1962) that only considered the effect of time, the novel transient heat conduction function obtained by Cheng *et al.* (2011, 2012) allowed the consideration of the effect of time and heat capacity of the wellbore on heat extraction from formation (Eq. 16):

$$f(t)=\frac{16\omega^2}{\pi^2}\int_0^{\infty}\frac{1-\exp\left(-t_D u^2\right)}{u^3\Delta(u,\omega)}du \qquad (16)$$

where $t_D=\frac{\alpha_s t}{r_i^2}$ is defined as dimensionless time, r_i is the inner radius of the injection well, α_s is the thermal diffusivity of the formation, ω is the ratio of the formation heat capacity and the wellbore heat capacity, u is the variable for integration and the function $\Delta(u, \omega)$ is associated to the following relation (Eq. 17):

$$\Delta(u,\omega)=[uY_0(u)-\omega Y_1(u)]^2+[uJ_0(u)-\omega J_1(u)]^2 \qquad (17)$$

where J_0 and J_1 are the zero-order Bessel function of the first kind and the first-order Bessel function of the first kind, respectively. Y_0 and Y_1 are the zero-order Bessel function of the second kind and the first-order Bessel function of the second kind, respectively.

The results of their studies, which were performed on an abandoned well with a depth of 6000 m, clearly showed for the first time how geothermal power generation is strongly influenced by the formation of heat transfer mechanisms.

Furthermore, they determined that the outlet temperature of working fluid tends to gradually decrease with increasing operating time, eventually approaching a steady state. The inlet velocity of isobutene in the injection well was also a binding parameter, as the heat obtained from abandoned well and fluid outlet temperature strongly decreased with increasing fluid inlet velocity.

Meanwhile, Templeton *et al.* (2014) also developed a two-dimensional cylindrical model by incorporating Fourier's three-dimensional diffusion law, two different terms describing the unsteady state heat transfer in the heat exchanger, the advective and conductive effects of the working fluid into the energy conservation equation, to generate a partial differential equation that properly describes the heat transfer mechanisms.

Comparing the results obtained from the proposed model with the ones reported in Kujawa *et al.* (2006) and Bu *et al.* (2012), they clearly showed that the use of a one-dimensional model tends to overestimate the performance of a coaxial WBHE.

More recently, Alimonti and Soldo (2016) also focused on the optimisation of a coaxial WBHE structure to maximise the heat extraction from an abandoned oil and gas well located in one of the largest European oil fields, the Villafortuna Trecate Oilfield. The main reservoir associated with this site was identified at between 5800 m and 6100 m depth with an available temperature of approximately 160-170 °C.

The same approach described by Kujawa *et al.* (2005, 2006) was proposed and implemented in a C-computation code for simulating formation heat conduction mechanisms (Eq. 6).

By fixing the sizing of the inner and outer tubes, as well as the final casing size as reported in Table 2 with an inlet temperature of the heat carrier fluid equal to 40 °C, they analysed variations in the

Table 2. WBHE tubes sizing in Alimonti and Soldo, 2016 – ID: internal diameter, OD: external diameter.
Dimensioni delle tubazioni dello scambiatore di tipo coassiale utilizzato da Alimonti e Soldo, 2016 – ID: diametro interno, OD: diametro esterno.

Tube sizing	ID (mm)	OD (mm)
3½ inches	77.9	88.9
5½ inches	121.4	139.7
Casing 7 inches	150.4	177.8

temperature of the extracted fluid as a function of different fluid flow rate values.

The results, performed by considering the properties of rocks to be uniform with depth (λ_s 2.5 $Wm^{-1}K$, ρ 2600 kgm^{-3} and pc_s 800 $Jm^{-3}K$) demonstrate how the fluid temperature reaches a maximum value of approximately 120 °C for an injection fluid flowrate of 10 m^3h^{-1}. Also, the increase in injection flowrate values tended to always cause a decrease in the recorded temperatures at the wellhead.

5. Discussion

Existing geological and geophysical studies conducted on sedimentary basins have confirmed the key role of the interaction of groundwater flow, mechanical deformation, mass transfer and heat transport processes in the formation processes of various economic resources (e.g., hydrocarbons and geothermal energy resources) (Bethke *et al.*, 1988).

Groundwater flow is involved in both the primary and secondary migration of oil and gas to the reservoirs (Wang *et al.*, 2016). Simultaneously, geothermal energy convection phenomena in the earth's crust have groundwater as the working fluid (Raffensperger and Vlassopoulos, 1999).

Conduction (thermal diffusion) favours heat flow processes, while the flow of pore water (advection) can simultaneously promote heat transport to the surface.

Different thermal conductivity values and other geological factors can also contribute to promoting spatial and temporal variations in temperature or heat flow patterns (Pfeiffer and Sharp, 1989).

Due to the geological complexity of sedimentary basins, correct estimates of geothermal potential that can be extracted from an abandoned hydrocarbon well cannot be performed without a proper analysis of the geological model, surrounding the analysed boreholes.

However, despite the great availability of geological and geophysical data relating to the drilled rock formations acquired during the prospecting phases in oilfields, very few works have comprehensively considered the influence of vertical and horizontal lithological variations within complexes, as well as the geological parameters in wellbore/rock formation in the heat exchange mechanisms.

Over time, authors have in fact primarily focused their attention on analysing the impacts on energy performance caused by changes in working fluid-related parameters such as initial temperature and injection flow rate values. Many other studies have also been conducted to identify the optimal design configurations for the selected WBHE.

In their elaborations, Kujawa *et al.* (2005, 2006), Bu *et al.* (2012, 2014) and Alimonti and Soldo (2016) fixed mean values of the different thermophysical parameters as weighted means: thermal conductivity of the rock, the volumetric heat capacity of the rock and rock density.

Also, in Kujawa *et al.* (2005, 2006) and Alimonti and Soldo (2016), since the applied modelling method of the influence radius depends only on a constant parameter of formations thermal diffusivity and time, it fails to account for thermal extraction amount from surrounding formation (Templeton *et al.*, 2014).

Notably, Cheng *et al.* (2013) were the first authors to analyse the influence of formation's thermal conductivity and formation's heat capacity values on the temperature variations of working fluid in an extraction well, by observing how the outlet temperature of the fluid increases with increasing formation's thermal conductivity. Simultaneously, the outlet temperature of working fluid leaving the recovery well also increases with the increasing formation heat capacity, for a fixed value of inlet flow rate and the thermal conductivity of formations.

Accurate estimates of the thermal potentials associated with decommissioned boreholes in oilfields necessarily require comprehensive studies in which thermodynamic analyses are combined with geological reconstruction works, at local and regional scales.

6. Conclusions

In mature oilfields, decommissioned oil and gas wells with depths reaching approximately 5000-6000 metres represent good candidate structures for geothermal heat exploitation, thus providing useful access to subsurface energy resources.

The coaxial wellbore heat exchanger currently represents a more effective technological solution to harness deep geothermal energy resources, if compared to U-tube WBHE.

Since the outer pipe (casing) is already present, the retrofitting of a coaxial WBHE to an abandoned well allows to significantly reduce the construction costs.

Comprehending the possibility to economically harness geothermal energy associated with deep abandoned boreholes by means of coaxial WBHE is strictly bound to the main features of the physical model, applied to estimate the amount of heat that can be gained from the well.

From an engineering perspective, the most influential parameters on the quantity of heat that can be exchanged in coaxial WBHE were represented by the inlet flow

Nomenclature.
Nomenclatura.

Parameter	Symbol	Unit of measure
Volumetric heat capacity of the fluid	ρc_f	[J m^{-3} K^{-1}]
Volumetric heat capacity of the rock	ρc_s	[J m^{-3} K^{-1}]
Density	ρ	[Kgm^{-3}]
Thermal conductivity of the fluid	λ_f	[W m^{-1} K^{-1}]
Thermal conductivity of the rock	λ_s	[W m^{-1} K^{-1}]
Heat conductivity of the porous media	λ_m	[W m^{-1} K^{-1}]
Heat conductivity of the pipe material	λ_i	[W m^{-1} K^{-1}]
Viscosity	μ	[kgm^{-1}s^{-1}]
Thermal diffusivity of the rock	α_s	[m s^{-1}]
Radius of thermal influence	r_s	[m]
Temperature of the rock	T	[°C]
Temperature at the interface of wellbore/formation	T_w	[°C]
Fluid temperature in the outer pipe	T_{fo}	[°C]
Fluid temperature in the inner pipe	T_{fi}	[°C]
Temperature of the environment at the inlet	T_{ei}	[°C]
Temperature of the environment at the surface	T_{es}	[°C]
Time	t	[h]
Flow rate	q	[m^{3}h^{-1}]
Fluid velocity	v_f	[ms^{-1}]
Heat transfer coefficient – outer pipe fluid and wellbore outside	k_w	[W m^{-2} K^{-1}]
Heat transfer coefficient – the outer pipe and inner pipe	k_{i0}	[W m^{-2} K^{-1}]
Convective heat transfer coefficient	h_f	[W m^{-2} K^{-1}]
Coefficient of convective heat transfer to the inner wall	h_0	[W m^{-2} K^{-1}]
Coefficient of convective heat transfer to the outer wall	h_i	[W m^{-2} K^{-1}]
Thermal resistance – outer pipe and surrounding rocks	R_w	[KmW^{-1}]
Thermal resistance – outer pipe and inner pipe	R_{i0}	[KmW^{-1}]

rate (q), the thermal conductivity of the selected heat carrier fluid (λ_f) and the thermal characteristics of the insulation materials.

Simultaneously, due to the continuous spatial variability of geological formations associated with deep oil and gas wells in oilfields, the thermophysical parameters of geological strata surrounding the well, as well as values of depth of strata and volume thickness, must be properly considered to achieve accurate and realistic estimates of heat exchanger performances.

Future works on the topic should be aimed at comprehensively include thermodynamic analyses and geological reconstruction models.

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