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Rehabilitation of Petroleum Wells as Borehole Heat Exchangers to Provide Heat for District Heating Networks in Small Towns or Villages: Case Study in Magallanes Basin, Chilean Patagonia

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ABSTRACT

As the Chilean National Oil Company (ENAP) has been exploiting oil and gas in Magallanes basin for more than six decades, 40% of the wells are no longer hydrocarbon producers. Therefore, the aim of this work is to assess the rehabilitation of oil and gas wells as Deep Borehole Heat Exchangers (DBHE) to supply the heating demand. Analytical calculation of heat transfer within the DBHE and with the surrounding rock are carried out to estimate the thermal energy and temperature levels output. For this work, the assessment is carried out for the 2,821 m depth Chulengo 1 well, which is next to village of Punta Delgada. Corrected Bottom Hole Temperature in well is 122 ˚C. The results indicate that rehabilitation of the Chulengo 1 well as a DBHE, can provide about ~82 kW_{th}, which than supply the heating demand of 18 houses of 75 m^2. A district network is considered for heating the houses due to its wide range of long-lasting advantages. Regarding the assessment results and the significative percentage of no longer hydrocarbon producer wells, there are promising conditions for the development DBHE rehabilitating abandoned oil and gas wells with a low exploration risk and a high probability of success.

1. INTRODUCTION

The cities and towns of the Magallanes region have the highest thermal energy consumption of Chile (Ortega, 2017). For more than six decades heating has been provided by oil and gas reserves available in the region. Because of the decrease in oil and gas reserves, more than 40% of the wells are no longer hydrocarbon producers. The above, along with the global context of energy transition to clean and renewable resources for heating (SUBDERE, 2012) encourage to rehabilitate abandoned oil and gas wells to provide geothermal heating.

In this work the potential of rehabilitation an abandoned oil and gas wells as a Deep Borehole Heat Exchangers (DBHE) for heating purposes is assessed. The DBHE rehabilitation considers coupling a geothermal heat source with a district network, due to its excellent compatibility and wide range of positive impacts (IRENA, 2017). To estimate the output temperature levels and feasible installed capacity an analytical tool is applied to one case of study. For this work, village of Punta Delgada (north of Magallanes region) is the case of study, because is very close to several oil and gas wells (Figure 1).

The methodological approach comprises analytical calculation of heat transfer between the DBHE and the surrounding rock and the heat transfer within the DBHE (Davis and Michaelides, 2009). To consider the geothermal gradient, the well is discretized into segments and the temperature of the circulating working fluid inside the DBHE is calculated (downward and upward). The above, considering thermal connection between adjacent segments. For the case of study, the Chulengo 1well is considered, which is next to the area of interest and that according to the records of ENAP is no longer oil and gas producer. For calculations several input data are taken from the successful implementation of the 2,786 m depth DBHE, which supplies the heat to a district heating network in Prenzlau, northern Germany (NGB).

Due to the strikingly similar geological setting of the different sites of interest in the Magallanes basin (Biddle et al., 1986; González et al. 1998; Schwarz et al., 2011) the assessment can be replicated in other sites with similar energy needs. The results obtained and the favourable conditions for deep geothermal energy development encourage to carry out more detailed analytical or numerical analyses to quantify the geothermal resource assessment in the most promising locations.

2. GEOLOGICAL SETTING

As will be seen below, the stratigraphic sequence is very important to define the thermal properties of rocks that exchange heat with the Deep Borehole Heat Exchanger (DBHE). The Magallanes basin stratigraphic sequence is divided in two provinces regarding stratigraphy and deformation pattern: (1) the deformed province in the west, and (2) the platform province in the east (Natland et al., 1974). In this work, we focus on stratigraphy of the platform province, where most of the oil and gas wells were drilled. Therefore, is the province where a non-productive oil and gas well can be rehabilitated as a DBHE. For this work, village of Punta Delgada in the north of Magallanes region is the case of study, because is very close to several oil and gas wells. In particular the Chulengo 1 well is chosen because is no longer hydrocarbon producer (Figure 1).

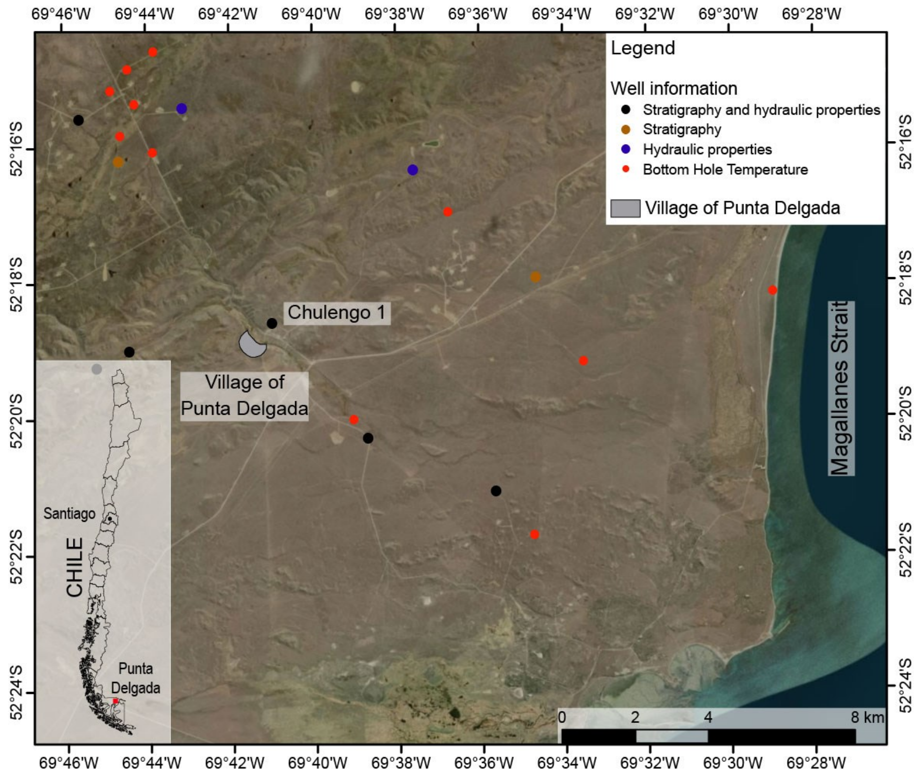

Figure 1: Location of the case of study for the assessment (village of Punta Delgada) and the distribution of oil and gas wells. Location and data set information of the wells are provided by the Chilean National Oil Company (ENAP).

The Magallanes basin is in the southernmost part of South America, between 47˚-55 ˚S latitude. The basin covers about 200,000 km^2 and has an NNW-SSE elongated geometry, with a maximum width of 370 km and length of 700 km (Biddle et al., 1986). The stratigraphic sequence is presented in the context of geological evolution and depositional environment. The nomenclature of geological units in the platform province is informal for most of the cases. The metamorphic basement of the stratigraphic sequence in the platform province is composed mainly of granodioritic Gneiss (Natland, 1974; Cunningham, 1995).

From Upper Triassic until Quaternary, the evolution of the Magallanes basin is divided into three stages, which control geological environment and consequently lithology of the stratigraphic sequences (Biddle et al., 1986). These stages and its related stratigraphic sequences are presented below:

2.1 Upper Triassic – Upper Jurassic: Tectonic extension and rifting

During the upper Triassic to lower Jurassic period, a tectonic extension started south of Gondwana, which triggered NNW – SSE graben and hemi-graben series. Afterwards, during the Middle Jurassic to Upper Jurassic period a rift was developed, which ended with the Gondwana breakup (Gust et al., 1985). In this context, the Tuff Series was deposited (Figure 2), which is composed of pyroclastic sequences, volcanic acid rocks, and sedimentary rocks interbedded (Thomas, 1949). This acid volcanism was triggered by the cortical crust fusion, due to its thinning in the rift stage (Prieto, 1993). The end of the rifting stage coincides with the *Green Rocks* Marginal Basin developing, which is characterized by passive boundaries and thermal subsidence (Katz, 1972; Dalziel, 1981).

2.2 Lower Cretaceous: Thermal subsidence

The thermal subsidence, which started in the Lower Cretaceous period, produced a large marine transgression that deposited hundreds of meters of clastic marine sedimentary rocks overlying the Tuff Series (Biddle et al., 1986). The Springhill Formation is at the base of the marine sedimentary sequence and overlies the Tuff Series or metamorphic basement in unconformity contact (Thomas, 1949). The Springhill Formation represents a transgressive succession composed of fluvial, coastal plain, estuarine and open marine siliciclastic deposits (Biddle et al., 1986).

Five stratigraphic sequences overlie the Springhill Formation from bottom to top: Strata with Favrella steinmanni, Shale with Ftanitas strata set, Margas Formation, Greenish grey Shale strata set, and Sandy shale strata set (Natland, 1974). These sequences were deposited in shallow to deep marine platform environments and are composed of shale, mudstone, siltstone, marges and limestone (Mordojovic, 1951; Cecioni, 1955).

2.3 Upper Cretaceous - Miocene: Foreland

During Upper Cretaceous, a compressive tectonic setting was developed west of the Magallanes basin. This compressive setting stopped the thermal subsidence, triggered the Magallanes fold and thrust belt developed in the west, and the Magallanes foreland basin in the east (Biddle et al., 1986). The main source of sediments came from the uplifted terrains of the Magallanes fold and thrust belt (Natland et al., 1974).

The marine stratigraphic sequence, deposited in the foreland basin tectonic setting from Upper Cretaceous to Miocene, is composed of four sequences from bottom to top: Glauconitic Zone strata set, Bahía Inútil group, Claly Sandstone strata set and Brush Lake Formation (Natland et al., 1974). These sequences were deposited in shallow to intermediate depth marine platform environments and are mainly composed of sandstone, shale and mudstone (Mordojovic, 1951; Brawick, 1955; Cañón, 1968).

On top of the sequence of sedimentary rock, the Miocene Fílaret Formation marks a transition from marine to continental environment. The Fílaret Formation is composed of sandstone, shale, and carbon layers (Cortés, 1963). On top of the sedimentary stratigraphic sequence is the volcanic Upper Miocene – Lower Pliocene Palomares Fomation (Natland et al., 1974). Finally, Pleistocene glacial sediments cover most of the Magallanes basin (Natland et al., 1974).

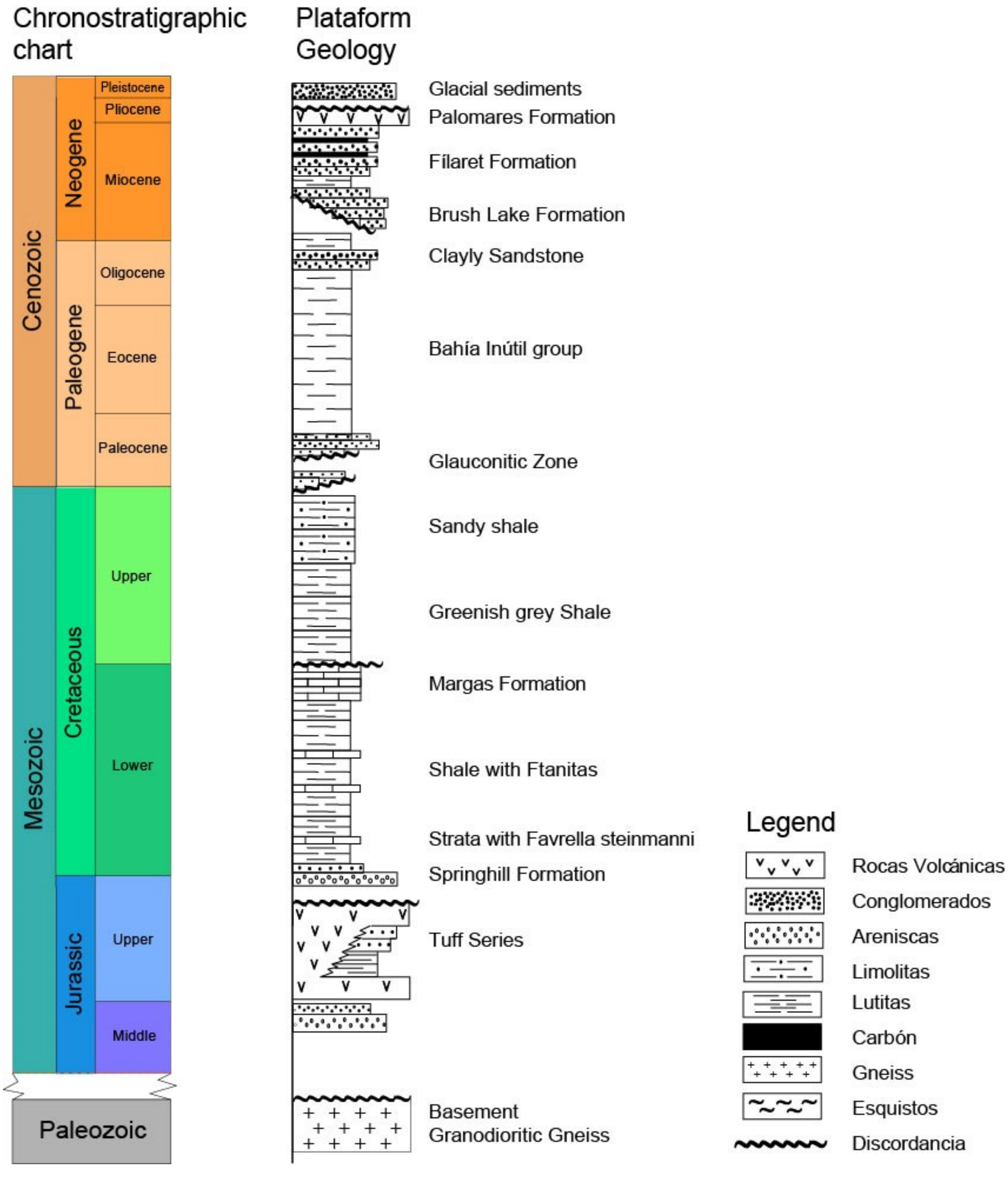

Figure 2: Sedimentary sequence in the platform province of Magallanes basin. The figure is modified from Mella (2001).

3. METHODOLOGY

The methodology comprises the use of an analytical tool to determine the installed thermal power and the temperature levels that can be achieved by rehabilitating an abandoned well as a Deep Borehole Heat Exchanger (DBHE). Therefore, the main features of the DBHE in terms of heat exchange are presented. Subsequently, the analytic tool is presented that is used in a case study (village of Punta Delgada), which has high favorability to implement an initiative such as the proposed one. The input data and assumptions are presented to show the scope and limitations of the assessment.

An important part of the input data and assumptions come from the successful implementation of the 2,786 m depth DBHE, which supplies the heat to a district heating network in Prenzlau, Northern Germany Basin (NGB). The system is managed and operated by the municipal energy supplier of the city of Prenzlau (Stadtwerke Prenzlau) and provides the heating to 1,400 m^2 of apartments for a retiree building complex.

3.1 Deep Borehole Heat Exchanger

The heat transfer in the Deep Borehole Heat Exchanger (DBHE) is similar to the shallow borehole heat exchanger (Florides and Kalogirou, 2007). There is a working fluid circulating within a closed system down to 800 to 3,000 m depth. The surrounding rock transfers the heat to the circulating fluid inside the DBHE by conduction through the heat exchanger casing. In case of DBHE, coaxial configuration is preferred, which traduces to one straight pipe inside the deep well. The working fluid goes down and heat up by the annular space of the DBHE and rises up through the insulated inner pipe Figure 3. For details in the heat transfer within the DBHE and with the surrounding rock see section 3.2.

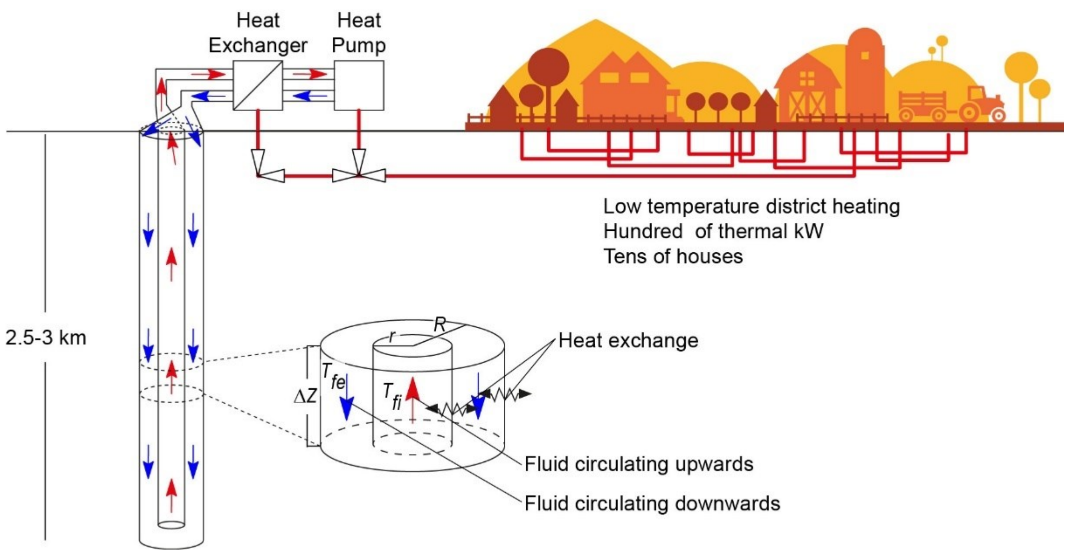

Figure 3: Deep Borehole Heat Exchanger (DBHE) scheme. The details in a section of the DBHE show the components involved in the heat transfer within the DBHE and with the surrounding rock.

The working fluid is pumped slowly downward through an annular space (5 – 65 m/min) to be heated during its way down to the bottom of the DBHE. Temperature difference between the inlet and outlet of the DBHE is can reach up to 15 °C (e.g. Agemar et al., 2014). In addition, if district heating network inlet temperature is required to be higher than the outlet temperature of the DBHE, an extra heat source is necessary to rise temperature levels (e.g. heat pump).

The DBHEs normally have capacities of few hundreds of kWth, which are much lower than open loop systems. This is due to the small extension of the heat transfer surface in contact to the surrounding rock, which corresponds to the heat exchanger outer casing surface. In contrast to open systems, there is no exploration risk in the case of DBHE. Due to the high investment, this geothermal utilization concept is particularly suitable in locations where abandoned oil or gas deep wells can be rehabilitated as DBHE.

3.2 Analytical calculation

In the following section the analytical calculation to assess the thermal installed capacity and output temperature of the DBHE are shown. For this work the Davis and Michaelides (2009) approach is used with minor modifications from Bergman et al. (2011). To simplify the explanation, the working fluid is called as the fluid, which is assumed as water. As mentioned earlier, the fluid goes down and heat up though the annular space of the DBHE and rises up through the insulated inner pipe. Therefore, there are two interfaces of heat exchange: (1) between the rock and the fluid circulating downwards, and between the fluid circulating downwards through the annular space and the same fluid circulating upwards through the inner pipe.

To calculate the heat exchange between the rock and the fluid circulating downwards $\dot{Q}$, the following equation is used:

$$\dot{Q} = 2\pi R \Delta Z \left(T_r - T_{fe}\right) U_{re} \quad [W] \tag{1}$$

Where R [m] is the outer pipe radius, ΔZ [m] the vertical length of the considered section, T_r [°C] and T_{fe} [°C] are the rock and fluid in the annular space temperatures, respectively, and U_{re} [W/m^{2}K] is the heat transfer coefficient between the rock and the outer section, which in turn is defined as (Bergman, et al., 2011):

$$U_{re} = \left(\frac{1}{h_e} + \frac{D_r}{k_r}\right)^{-1} \quad \left[\frac{W}{m^2K}\right] \tag{2}$$

Where k_r [W/mK] is the rock heat transfer coefficient, D_r [m] is the diameter beyond which the rock has a constant temperature, and h_e is the convective heat transfer coefficient in the outer edge of the annular zone:

$$h_e = 0.023 k_f \frac{{Re_e}^{0.8} Pr^{0.4}}{d_h} \quad \left[\frac{W}{m^2K}\right] \tag{3}$$

Where k_f [W/mK] is the heat transfer coefficient of the fluid, Re_e is the Reynolds number in the annular zone, P_r is the Prandtl number and d_h [m] the hydraulic diameter of the annular section:

$$d_h = 2(R - (r + t)) \quad [m] \tag{4}$$

Where r [m] is the inner pipe radius and t [m] is the width of the insulating layer.

The heat exchange between the inner and the outer pipe is modelled with the following equation:

$$\dot{Q} = 2\pi r \Delta Z (T_{fe} - T_{fi}) U_{ei} \quad [W] \tag{5}$$

Where T_{fi} [°C] is the temperature of the fluid in the inner section and U_{ei} [W/m^{2}K] is the global heat transfer coefficient between the outer annular zone and the inner section, which in turn is defined as:

$$U_{ei} = \left(\frac{r+t}{r} \times \frac{1}{h_i} + \frac{r+t}{r+t/_2} \times \frac{t}{k_a} + \frac{1}{h_e{}'}\right)^{-1} \quad [\frac{W}{m^2K}] \tag{6}$$

Where k_a is the heat transfer of the insulating layer, h_i the convective heat transfer coefficient in the inner section and $h_e{}'$ the convective heat transfer coefficient in the inner edge of the outer section:

$$h_i = 0.023k \frac{Re_i{}^{0.8} Pr^{0.4}}{2r} \quad \left[\frac{W}{m^2K}\right] \tag{7}$$

$$h_e{}' = 0.023k \frac{Re_e{}^{0.8} Pr^{0.4}}{2(r+t)} \quad \left[\frac{W}{m^2K}\right] \tag{8}$$

In order to convert heat to temperature, the following equation was employed:

$$T = \frac{\dot{Q}}{C_p \dot{m}} \quad [°C] \tag{9}$$

where C_p [J/kgK] is the specific heat of the fluid and $\dot{m}$ [kg/s] the flow rate.

The above equations are used considering 200 iterations on the way down and 200 iterations on the way up. In the first step, $T_{fe\ 0}$ is equal to the entrance temperature of the fluid, parameter that the user must provide. With the above, it is possible to calculate the heat transfer in the first stretch and consequently the resulting temperature of the fluid, $T_{fe\ 1}$, which is the entrance temperature for the second step and so on until the bottom of the well (200 iterations).

On the way up, temperature is calculated in a similar way. In the first step, T_{fe} and T_{fi} are equal in the zone where the fluid reverts its direction of flow at the bottom of the well. For the second step, T_{fi} is still the same but T_{fe} has the value of the one before last step going downwards. With the above, it is possible to assess T_{fe} for the next step, where T_{fi} has a temperature one stretch higher. Finally, temperature is calculated all the way up until the output of the well.

3.3 Input data and assumptions

The case of study considers the non-productive Chulengo 1 well, which is next to Village of Punta Delgada (Figure 1). Therefore, sedimentary sequence and BHT, besides well construction features are taken from Chulengo 1 well. The necessary parameters for analytical calculation of thermal power and temperature output, besides the chosen values are in Table 1. The description of these parameters and base for the chosen values are presented below. To determine the physical properties of the working fluid, it is assumed as water.

3.3.1 Entrance temperature of the fluid

The entrance temperature (inlet temperature) depends on the return temperature from the district heating network. Regarding the practical experience, in the above-mentioned district heating network coupled with a DBHE in Prenzlau, the entrance temperature of the fluid is 50 °C.

3.3.2 Inner radius

The inner radius is the radius of the concentric tube that is introduced into the oil and gas well. The ENAP reports, which include the inner tube for oil and gas extraction, record 2 7/8 inch. This diameter is exactly the same diameter of the inner tube of the successful implementation of a DBHE in Prenzlau. Therefore, 2 7/8 inch (0.07m) is chosen as the inner radius for this assessment.

3.3.3 Width of insulating layer

The width of insulating layer corresponds to the thickness of the concentric tube wall that is introduced into the well. There are several proposals for the width of the insulating layer. For instance, Bu et al. (2012) chose 1 [cm] for calculations, while Davis and Michaelides (2009) chose 2,54 [cm]. To avoid heat loses in the way up, a thicker insulating layer is preferred, i.e. 2.54 cm.

3.3.4 Flow rate

Regarding the experience in the functioning of the DBHE coupled with a district heating network in Prenzlau, the flow rate must not exceed 3-5 L/s, to avoid significant losses of energy in the fluid pumping due to dynamic friction. Therefore, to be conservative the value 3 L/s is chosen.

3.3.5 Average density of the fluid

The average density of the fluid is estimated by entering different, but possible values, iteratively in the analytical tool and modifying those values each turn it, the average water temperature is about 55 [°C]. For this temperature, the water density is 985.7 [kg/m^3].

Table 1: The input data for analytical calculation of thermal power and temperature output from the DHHE. The chosen values for each parameter are included.

Parameter	**value**	**Units**
Entrance temperature, T_i	50	˚C
Inner radius, r	0.07	m
Outer radius, R	0.122	m
Width of the insulating layer, t	0.0254	m
Flow rate, $\dot{m}$	3	Kg/s
Average density of the fluid, ρ	985.7	Kg/m^3
Average rock thermal conductivity, k_r	2.34	W/m·K
Average fluid thermal conductivity, k_f	0.645	W/m·K
Insulated layer thermal conductivity, T_r	0.027	W/m·K
Constant rock diameter, D_r	0.58	m
Average dynamic viscosity of the fluid, μ	0.0005039	Pa·s
Temperature of the rock, T_r	122	˚C
Depth of temperature measurement	2,819	m
Depth of the well	2,821	m
Average Prandtl number, P_r	3.3	
Specific capacity of the fluid	4,190	J/kg·K

3.3.6 Average rock thermal conductivity

Because of the different thermal conductivity for each lithologies (see section 2), is preferred to use an average thermal conductivity for the whole length of the well. This average conductivity is calculated as the weighted average of thermal conductivities of lithologies, which constitutes the stratigraphic sequence. For simplicity is considered the most relevant lithology in each geological unit (Table 2). The weighted average of thermal conductivities for the whole length of the well is 2.34 [K/m·K].

3.3.7 Average thermal conductivity of the fluid

To estimate the average thermal conductivity of the fluid, the same approach is used as to determine the average density of the fluid. The average thermal conductivity of water at 55 °C is 0.645 [W/m·K].

3.3.8 Thermal conductivity of the insulating layer

Polystyrene was chosen as the insulating material, which have a thermal conductivity of 0.027 [W/m·K].

3.3.9 Constant rock diameter

This parameter refers to the distance from the well at which the rock does not vary in temperature during the DBHE functioning, which in this case is 0,58 [m]. The value is estimated using the analytical tool to reproduce the functioning of the DBHE in Prenzlau.

3.3.10 Average dynamic viscosity of the fluid

To estimate the average thermal conductivity of the fluid, the same approach is used as to determine the average density of the fluid. The average dynamic viscosity of water at 55 °C is 0.0005039 [Pa·s].

3.3.11 Average Prandtl number

To estimate the average thermal conductivity of the fluid, the same approach is used as to determine the average density of the fluid. The average Prandtl number of water at 55 °C is 3.3.

3.3.12 Specific heat of the water

To estimate the average thermal conductivity of the fluid, the same approach is used as to determine the average density of the fluid. The average value is specific heat of water at 55 °C is 4,190 [J/kg·K].

Table 2: Average thermal conductivity and thickness for the stratigraphic sequence in villa of Punta Delgada. The reference well is Chulengo 1. Reference thermal conductivity of the rock are from Zoth and Haenel (1988).

Formation or informal unit	Thickness (m)	Lithology	Thermal conductivity (Wm/K)	Reference
Glacial sediments	100	Glacial sediments	1.49	Natland et al. (1974)
Palomares Fm.	300	Sandstone and siltstone	2.34	Natland et al. (1974)
Filaret Fm.	290	Sandstone, conglomerate sandstone and siltstone	2.47	Cortés (1963)
Brush Lake Fm.	640	Shale with sandstone and limestones interbedded	2.18	Barwick (1955)
Clayly Sandstones	200	Clayly sandstone with calcareous layers	2.47	Mordojovich (1951)
Bahía Inútil Group	150	Sandstone, siltstone and shale	2.06	Cañon (1968)
Glauconitic zone	190	Fine sandstone, siltstone and shale	2.47	Mordojovich (1951)
Sandy shales	100	Glauconitic siltstones	2.46	Mordojovich (1951)
Greenish grey shales	320	Siltstones with interbedded calcareous layers	2.46	Mordojovich (1951)
Margas Fm.	85	Marges with calcareous shales	2.46	Mordojovich (1951)
Shale with Ftanites	110	Siltstone	2.46	Mordojovich (1951)
Strata with Favrella steinmanni	250	Siltstones with interbedded limestone	2.46	Cecioni (1955)
Springhill Fm.	50	Quartz sandstone and conglomerates with interbedded shale	2.47	Thomas (1949)
Tuff series	36	Volcanic acid rocks interbedded with sedimentary layers	2.82	Thomas (1949)

4. RESULTS

Using the analytic tool described above (section 3.2), and with mentioned input data (section 3.3) the output temperature of the DBHE is 57 °C. The above means a temperature gain of 7 °C, which considering the caudal of 3 L/s is equivalent to 87.811 kW_{th}.

$$P = \dot{m} \cdot \rho \cdot c_p \cdot \Delta T \qquad (10)$$

Where, P is thermal power [kW_{th}], $\dot{m}$ is the mass flow circulating within the DBHE (kg/s), ρ is water density [kg/m^3], c_p is the specific heat capacity of water at constant pressure [4.183 J/kg·K], and ΔT is the difference between the inlet and outlet temperatures [7 ºC].

The heating installed capacity of a small 75 m^2 well-insulated house in Magallanes is about 6kW_{th} (Ortega, 2017). Regarding a simultaneity factor for heating purposes of 0.8 (EBP, 2018) it is possible to provide heating to 18 houses, which are equivalent to 1,350 m^2.

According to the geothermal experience in the city of Prenzlau, Germany, the oil and gas constructive features of the ENAP wells, and the calculated thermal power and temperature levels, there are promising conditions for the development of a sustainable Deep Borehole Heat Exchanger with a low exploration risk and a high probability of success in rehabilitating an abandoned oil and gas well. At the same time, it is important to consider the importance of provide heating to houses that are well insulated to work with low temperatures in the district network and manage the heat source efficiently.

5. DISCUSSION

The analytical tool used in this work is useful for rapid assessment of available energy and temperature levels in the case of a Deep Bore Hole Exchanger (DBHE) implementation. The analytical tool is simple and quick to use, but it is not an accurately estimation. Despite the good match with real cases, it is recommended numerical modelling for detailed sizing of geothermal installations in the case of a specific project.

Regarding the output temperature from the Deep Borehole Heat Exchanger (DBHE) is mandatory a district heating network, and heating devices in houses suitable for working with low temperature levels (~ 60˚C). It is also advisable, the houses are closer to each other othertoavoid heat loses because of hot water transportation. Low temperature heating networks are suitable for both low temperature geothermal systems and other renewable energies (IRENA, 2017).

In case of domestic hot water, it is necessary and additional heat source to reach temperature levels above 60 ˚C. For instance, in the case of the DBHE coupled with a district network operated by the municipal energy supplier of the city of Prenzlau (Stadtwerke Prenzlau), there is a heat pump to increase temperature levels for domestic hot water.

6. CONCLUSION

Considering that ~40% of the oil and gas wells are currently not producing in the Magallanes basin, besides the depth, bottom hole temperature, and constructive features of the oil and gas wells there is a great chance of success of rehabilitation of oil and gas wells as Deep Borehole Heat Exchangers (DBHE). The results shown that the rehabilitation of one abandoned well as a DBHE can supply the heating demand of few tens of houses.

The global experience suggests that geothermal energy must be coupled with district networks to efficiently, economically reasonably and sustainably provide heating. Currently the 4th generation of district heating systems work with lower temperatures as 60 ˚C (Schmidt et al., 2017), which is very similar to the output temperature of the DBHE.

The energy transition global context along with the almost depleted oil and gas reserves in the Magallanes basin create a unique and excellent opportunity for the transition from gas heating facilities to deep geothermal heating systems. The latter is aimed at reducing emissions, generating positive synergies in the urban context, increasing energy safety, reducing fossil fuel utilization and hence decarbonizing the energy sector and diversifying the energy mix.

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