A comparison between energy conversion systems for a power plant in Campi Flegrei geothermal district based on a WellBore Heat eXchanger

Alimonti Claudio[1], Soldo Elena[1], Berardi Davide[1], Bocchetti Donato[1]

[1] La Sapienza, University of Rome, Via Eudossiana 18 – 00184 Roma

claudio.alimonti@uniroma1.it

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ABSTRACT

One of the more complex issues in the geothermal plants is the re-injection of the fluids. This operation has multiple goals but it entail high economic costs. A possible alternative is the use of an indirect system to extract heat, the WellBore Heat eXchanger (WBHX). This kind of well completion allows to extract heat using an heat carrier fluid circulating in a closed loop, therefore it could be a solution to extract heat from unconventional geothermal systems, such as magmatic reservoirs like Campi Flegrei (Italy). The main weakness of the WBHX is a low heat recovery efficiency respect to a conventional geothermal technology. In order to maximize the conversion of the thermal energy into electricity, the paper is focused on the comparison of two different systems: an ORC power plant and a Stirling motor.

1. INTRODUCTION

One of the more complex issues in the geothermal plants is the re-injection of the fluids. This operation has multiple goals like the recharge of the geothermal reservoir, the balance of the underground pressure, the removal of the geothermal fluids not suitable to the terrestrial ecosystems, the compensation of surface subsidence due to the production activities.

Re-injection operations entail high economic costs because it’s required the drilling and maintenance of additional wells, the treatment and the pumping of the fluids. There are also some risks: the injected cold water could interfere with the hot waters of the production level, the geothermal brine could pollute the groundwater, the risk of corrosion and scaling in surface pipelines and in the re-injection wells, the induced seismicity phenomena.

A possible alternative is the use of an indirect system to extract heat, the WellBore Heat eXchanger (WBHX). This kind of well completion allows to extract heat using an heat carrier fluid circulating in a closed loop, therefore it could be a solution to extract heat from unconventional geothermal systems, such as magmatic reservoirs like Campi Flegrei (Italy). In fact, in the Campania region the geothermal projects do not get a positive social acceptance because the population is scared that the activities of a binary plant could induce phenomena of seismicity and volcanism. Furthermore in the magmatic systems the geothermal brines have particular physical and chemical characteristics, thus the extraction of such fluids involves significant technical problems and high economic costs that can make non-profitable the investment.

The main weakness of the WBHX is a low heat recovery efficiency respect to a conventional geothermal technology. This is due to the lower mass flow rate and to the indirect exchange of heat which causes a lower wellhead temperature. Therefore this paper is focused on the selection of the more efficient system to maximize the conversion of the thermal power into the electrical one.

The WBHX was implemented in the area of Campi Flegrei and, in order to maximize the electrical production, two different conversion systems have been compared: an ORC power plant and a Stirling motor.

2. CAMPI FLEGREI AREA

The Campi Flegrei area is located in the volcanic district of the Campania region, where there are three active volcanoes: Campi Flegrei, Ischia and Vesuvio (Carlino et al., 2012). This district is characterized by the presence of hot fluids even at shallow depth and by an high heat flux. The area was famous since the Roman Age for the thermal baths.

The Campi Flegrei area has a typical horseshoe shape and is located in the north-west limit of the Napoli gulf; the area is a caldera of 12 km with the centre in the Pozzuoli bay (Fig. 1). From the regional geologic point of view, the flegrean area is located inside a tectonic structure which forms a wide coastal plain between the Tirreno and the Appennini (pleistocene-holocene period). According to Orsi et al. (1996) the formation of the caldera is due to two high energy eruptive events: the eruption of the Campanian Ignimbrite (39.000 years ago) and of the Neapolitan Yellow Tuff (15000 years ago) (Armienti et al., 1983;

Lirer et al. 1987; Rosi and Sbrana, 1983; De Vivo et al., 2001; Deino et al. 2004).

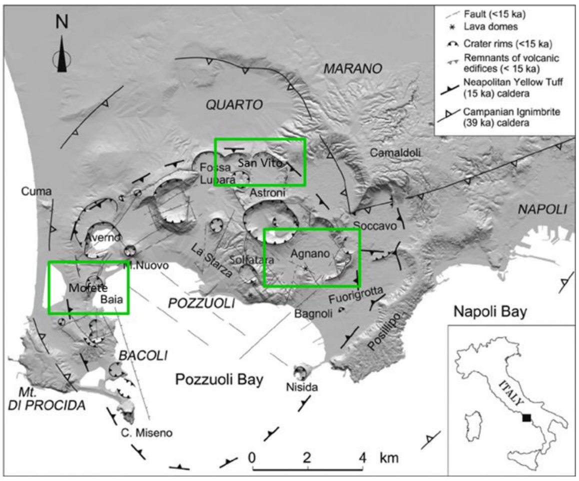

Figure 1: Campi Flegrei caldera (modified picture from Costa et al. 2009).

Using the results of many studies conducted on the area and the new stratigraphic data, Di Vito et al. (1999) gave a detailed reconstruction of the volcanic and deformative history of Campi Flegrei.

The most ancient rocks are only exposed along the cliff which edges the Campi Flegrei area. These rocks constitute the igneous cupolas of Punta Marmolite and of Cuma, the pyroclastic deposits of the Tuff of Torre Franco and the Tuff of Monte Grillo. In a mine at north-east of the Quarto plain the pyroclastic deposits alternating with paleo-soils, of at least ten different eruptions, are visible.

Pyroclastic deposits of the same age have been discovered during drilling operations at Poggioreale, Capodimonte, Ponti Rossi, Chiaiano e Secondigliano.

The Campanian Ignimbrite is the most scattered pyroclastic deposit of the Campanian region; it has covered an area of almost 30000 km^2. At present only the fifteenth part of the ancient volume is present, due to the erosion process and the layering of more recent sediments. A visible characteristic of this soil is the changing of colour, often gradually, from the grey to yellow caused by hydrothermal phenomena. The typical grey facies of the Ignimbrite is made of pumices and lithic fragments with variable dimension in a cineritic matrix, which is the 90% of the total volume. In the yellow facies there is a secondary zeolitization.

The Neapolitan Yellow Tuff is an extended deposit of pyroclastics yellow and grey, in a structure variable from layering to massive, made up of pumice, lava and tuffaceous fragments in a cineritic matrix, with a variable composition from trachytic to phonolitic, probably the result of a zoned magma chamber (De Gennaro et al., 2000).

The dynamism of Campi Flegrei is characterized by the bradisism: a slow movement of lowering and rising of the ground which have occurred over the centuries and have leaved clear traces. The seismicity of the area seems to be related to the lowering phases of the caldera, during these periods no seismic event is detected. The most seismic period in the last 50 years, has occurred between 1982 and 1984; during this period a lowering of the ground of 2 meters has been produced. The magnitude of the flegrean earthquakes is generally lower than 1.0, with a maximum magnitude of 4.0 in the period 1982-84. The majority of the events are located at the depth of 2-3 km and they are not sensed by the population but only by the instruments.

According to Zollo et al. (2008) the conceptual model of the geothermal reservoir of the Campi Flegrei can be represented by a deep magmatic source (8-10 km), with a thickness of almost 1 km and a diameter equal to that of the caldera and an heat content per area of $6{\cdot}1012\ Jm^{-2}$. This primary source provides the heat for the above layers. At the depth greater of 3-4 km the fluids circulate very slowly therefore the heat transport is for conduction. In the shallow layers (0-2 km) an advective transport takes place because of the high permeability due to fractures.

The most interesting areas form the geothermal production point of view are Mofete, San Vito and Agnano which are indicated in Fig 1. These areas have been investigated since the 40’s by companies. SAFE, AGIP and ENEL have drilled several wells with a maximum depth of 3 km.

In the Mofete area using the data obtained in previous surveys conducted in the area, three aquifers have been identified. A first aquifer is at the basis of the Neapolitan Yellow Tuff, between 500 and 1000 meters with 20% of vapour and temperatures in the range 100 ÷ 130 °C; a second aquifer is in the zone of the calcium silicate and aluminum at the depth between 1800 and 2000 meters (40% of vapour and a medium temperature of 300°C); the deepest aquifer level is between 2500 and 2700 meters and it is probably a vapour dominated system. The medium geothermal gradient the Mofete area is almost 180°C/km.

3. THE WELLBORE HEAT EXCHANGER AND ENERGY CONVERSION SYSTEMS

The target to increase the geothermal power plant in Italy can be sustained by the adoption of new technology and the use of non-conventional resources. The proposal to use the WellBore Heat eXchanger combined with an energy conversion plan allows to attain this goal. In this work has been evaluated the Stirling motor as an alternative to more conventional ORC plant.

3.1 The WBHX

The WellBore Heat eXchanger device is a deep borehole heat exchanger (Fig.1). The well bottom is closed and a coaxial tube is inserted into the well; in the WBHX an heat carrier fluid circulates and acquires heat from the surrounding rock.

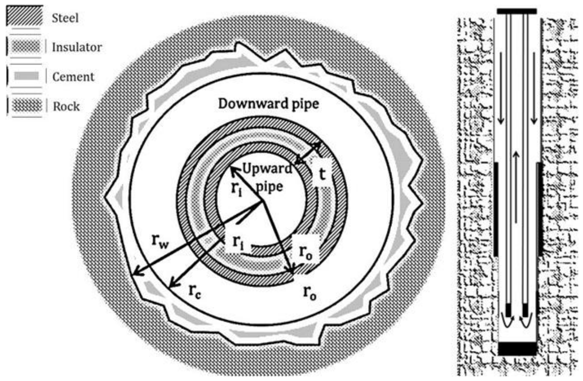

Figure 2: The WellBore Heat eXchanger.

Several researchers have analyzed the feasibility of the WBHX, the operative parameters and the use of the different heat carrier fluids (Nalla et al., 2005; Kujawa et al., 2006; Zhang, 2008; Davis and Michaelides, 2009; Bu et al., 2012; Cheng et al., 2013; Cheng et al., 2014; Templeton et al., 2014; Alimonti and Soldo, 2016).

In the proposed solution (Alimonti et al., 2016) the water has been selected as the best heat carrier fluid, thanks to its volumetric heat capacity, which is higher than those of the fluids generally used as working fluids. The water circulates in the annular space between the well casing and the external shell and, flowing downward, the fluid acquires the heat. At the bottomwell the water flows into the inner pipe thanks to the thermo-siphon effect and it goes back on the wellhead naturally therefore the electricity is not request to pump upward the fluid. The space between the two pipes is filled with insulating material.

The feasibility of the WBHX has been studied using a numerical model of the heat transfer phenomena in the exchanger and a thermodynamic model of the ORC.

In the implemented model the heat transfer into the rock happens by conduction; no convection takes place. In the downward pipe the heat moves by conduction from the reservoir to the external casing of the WBHX, that is separated from the rock wall by a layer of cement. The convection takes place between the casing and the water in the borehole heat exchanger. In the upward pipe the heat exchange occurs by conduction through the composite pipe and by convection one on the internal wall and one on the external wall of the WBHX (for further details see Alimonti et al., 2016).

3.2 ORC plant model

Fig 3 shows the schematic of the ORC plant. The black lines indicate the water circuit through the WBHX, the green lines indicate the working fluid circuit in the ORC plant.

The heated water exiting from the deep borehole heat exchanger, flows through the ORC heat exchanger (E) and transfers the heat to the working fluid. Then the water passes in the preheater and then is re-injected in the WBHX by means of the auxiliary pump P.

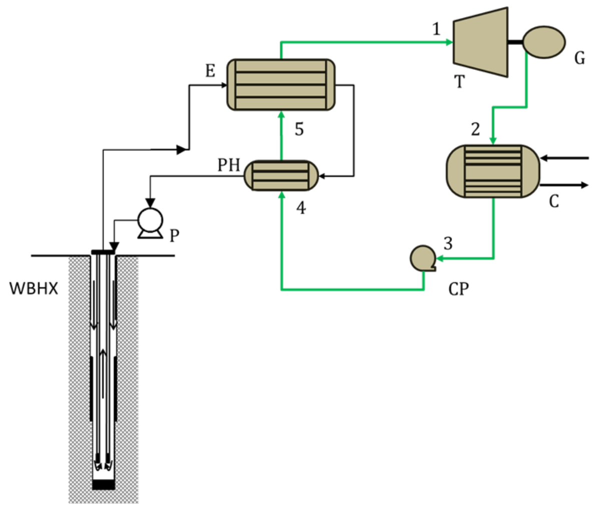

Figure 3: Schematic of the Organic Rankin Cycle power plant and WBHX implementation.

The working fluid in the ORC plant reaches the boiling point in the preheater PH (5) and then the condition of saturated vapor in the evaporator E (1). The saturated vapor is sent to the turbine T where the expansion takes place: the thermal energy is converted into kinetic energy and then in electricity by the generator G. Exiting from the turbine (2) the working fluid is condensed (C) (3) and then it is pumped (CP) to the preheater (4) (Fig. 4).

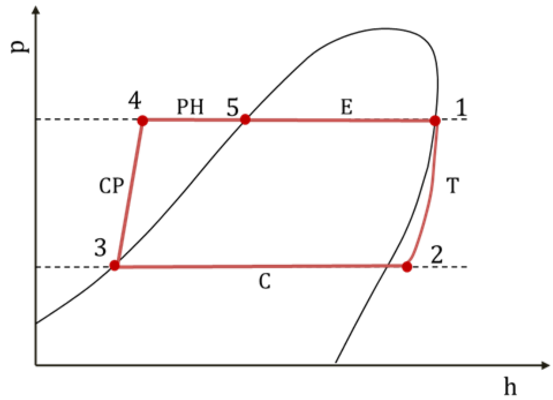

Figure 4: Pressure-enthalpy diagram for a binary plant.

Knowing the mass flow rate m_b and the outlet (T_a) and inlet (T_c) temperature of the WBHX, the mass flow rate of the working fluid m_{wf} can be calculated using the following equation:

$$m_{wf} = m_b\,[c_b\,(T_a - T_c)]\,/(h_1 - h_4) \qquad [1]$$

where h_1 is the enthalpy at the outlet of the evaporator and h_4 is the enthalpy at the inlet of the preheater.

Indicating with h_2 the enthalpy at the inlet of the condenser C, the electrical power available to the turbine T can been evaluated using the following equation:

$$W_t = m_{wf} (h_1 - h_2) \qquad [2]$$

The WBHX model calculates the temperature of the water at the wellhead T_a. The inlet temperature of water in the WBHX T_c of the water from the heat exchanger has been chosen in order to maximize the heat recovery from the wellbore. It is fixed at 40°C. The mass flow rate of the working fluid in the ORC plant is calculated according the temperature profile in the WBHX and fixing pinch point temperature around 5°C (Fig. 5).

The ratio of the net electrical power produced from the cycle W_{net} and the heat transfer rate in the heat exchanger unit Q_{ht} has been used to evaluate the thermal efficiency:

$$\eta_{th} = W_{net} / Q_{ht} = 1 - [(h_2 - h_3)/(h_1 - h_4)] \qquad [3]$$

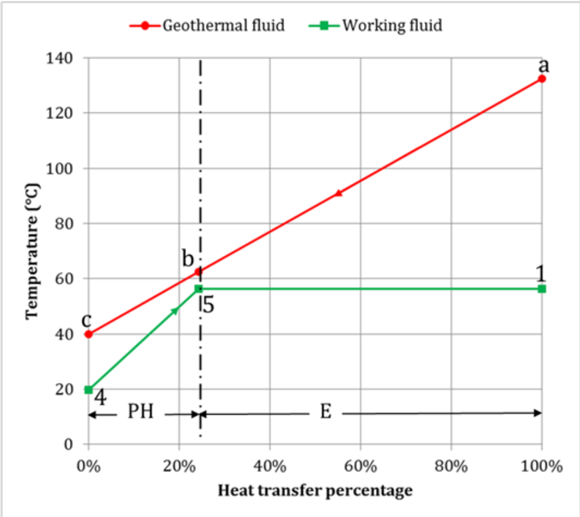

Figure 5: Temperature-heat transfer diagram for preheater (PH) and evaporator (E).

3.3 Stirling motor model

The Stirling motor is a regenerative closed cycle engine. The regenerator accumulates the heat from the working fluid that moves towards the cold part of the engine and then release it to the fluid that returns to the hot part of the engine, thus increasing the efficiency. The working fluid of the Stirling motor is a gas like air, nitrogen, helium or hydrogen. When a sufficient temperature difference between the hot cylinder and the cold cylinder is reached, a cyclic pulsation starts. Two pistons transform the cyclic pulsation into reciprocating motion. It is necessary to start the pulsation at the beginning, but it lasts as long as the temperature difference is maintained. There is no evaporator, condenser, feed water pump and numerous other associated elements of the ORC plant.

According to Kolin et al. (2000) when compared to the classic Clausius-Rankine cycle, mostly used in the present geothermal plants, Stirling cycle offers many theoretical and practical advantages. From thermodynamic point of view, Stirling cycle is equivalent to the optimal Carnot cycle, having the highest possible efficiency. The thermodynamic Stirling motor model follows the indications of Loyd Caleb C. (2009).

In Fig. 6 the pressure-volume diagram for the Stirling cycle is shown. The real cycle has a lower efficiency compared to the ideal cycle. The assumptions of an ideal Stirling cycle are the use of a perfect gas as a working fluid, absence of flow resistance, perfect regeneration, no conduction heat losses, isothermal expansion and compression, non-sinusoidal piston motion, absence of mechanical friction, dead space assumed to be zero.

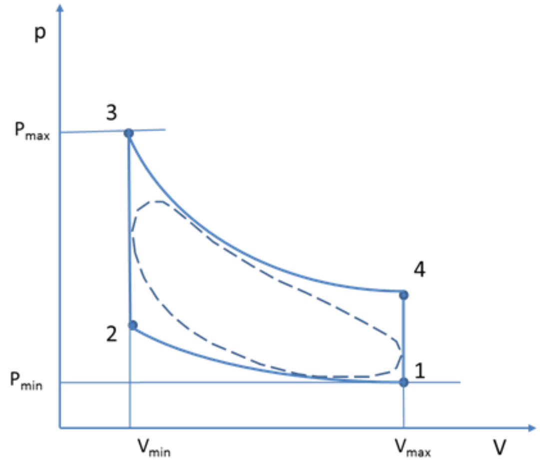

Figure 6: Pressure-volume diagram for a Stirling cycle (continuous line: ideal; broken line: real).

The amount of the net work per cycle can be evaluated as the sum of the work done during the gas compression stage (W_c) and the work done by the gas during the expansion stage (W_e):

$$W_{net} = W_c + W_e = nR(T_h - T_c) \ln (V_{max}/V_{min}) \qquad [4]$$

where:

n is the mole number of gas
R is the gas costant, equal to 8.314472 J/kg·mol
T_h is the hot source temperature
T_c is the cold sink temperature
V_{max} is the maximum volume
V_{min} is the minimum volume

Because in the ideal cycle the losses are absent, the produced work is equal at the supplied heat. Substituting inside the (17) the value of the net work and of the supplied heat, the efficiency of the ideal Stirling cycle can be calculated as:

$$\eta = (T_h - T_c) / T_h \qquad [5]$$

The ideal power is the product between the net work per cycle and the number of revolutions per minute:

$$EP = rpm \cdot W_{net} \qquad [6]$$

The reduction in power compared to the ideal cycle with no dead space can be evaluated with the empirical formula of the Schmidt Factor:

$$F_s = 0.74 - 0.68\,\delta \qquad [7]$$

where the dead space ratio δ is the ratio between the total dead space volume V_d and the total volume of the gas swept by the displacer V_{sw}:

$$\delta = V_d / V_{sw} \qquad [8]$$

The real power can be calculated with the following relation:

$$EP_{real} = EP \cdot F_s \qquad [9]$$

4. RESULTS

The deep borehole heat exchanger has been applied in the Campi Flegrei area assuming the stratigraphic and geothermal profile from the well Mofete 3d (MF3d), a well drilled during the survey done by ENEL-SAFE (1977 – 1985).

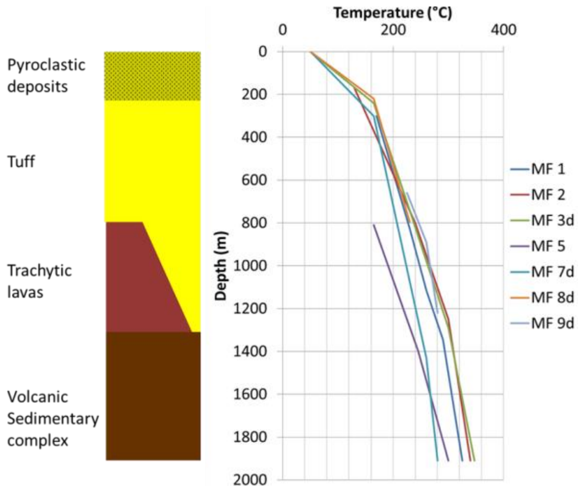

Figure 7: Stratigraphic and geothermal profile from the well Mofete 3d.

To evaluate the physical and thermal properties of the area (Tab. 1 and Tab. 2) the data presented in Carlino et al. (2012) have been used. The average geothermal gradient is almost 155 °C/km.

Table 1: Lithology and geothermal gradients of MF3d well.

Thick. (m)	Depth (m)	T (°C)	Lithology	GT (°C/100 m)
0	0	50	-	-
240	240	165	Pyroclastic deposits	47.92
500	740	230	Tuff	13
200	940	255	Tuff-Trachytic lava	12.5
390	1290	300	Trachytic lava	12.86

Based on numerical simulations, the configuration that ensures a greater efficiency in the heat extraction for the specific case study has been obtained (see Tab. 3).

Table 2: Physical and thermal properties MF3d well.

Lithology	ρ (kg/m^3)	λ (W/m K)	c_p (J/kg K)
Pyroclastic deposits	1800	2.90	840
Tuff	1550	1.50	2000
Tuff-Trachytic lava	2025	2.20	1420
Trachytic lava	2500	2.90	840

Table 3: WBHX design configuration.

Casing size	Outer diameter	Inner diameter
7”	177.8 mm	150.3 mm
5 ½”	139.7 mm	121.4 mm
3 ½”	88.9 mm	77.9 mm

The simulations highlight that, after a first period of decreasing of rock temperature at the WBHX wall, a pseudo steady state condition is reached. After six months a stabilised thermal power production of almost 2.5 MW per well may be expected. In Table 4 are reported the principal characteristics of the proposed plants.

Table 4: Summary of the energy conversion power plant.

Type of plant	**WBHX-ORC**	**WBHX-Stirling**
Nominal power	260 kWe	450 kWe
Well depth	1909 m	1909 m
Flow rate	20 m^3/h	20 m^3/h
Wellhead temperature	150 °C	150 °C
Reinjection temperature	40 °C	40 °C
Thermal power per well	2.5 MW	2.5 MW
Working fluid	RC318	air
η %	11.19 %	19.1 %

The main difference in energy conversion plants is due to the thermal efficiency of the Stirling motor that is greater than the ORC ones. This difference should also account the difference in modeling of the plants. Therefore, the Stirling motor could be a more energy efficient plant due to the lower energy consumption.

3. CONCLUSIONS

The production and re-injection of geothermal fluids in populated areas is becoming a key issue in public acceptance of new plants. Therefore, it is fundamental to find and propose technical alternatives in order to access geothermal resources otherwise not exploitable.

Being an important geothermal resource as well as an intense populated area, the area of Campi Flegrei has been identified for this purpose. The WBHX as the alternative technology to direct production of geothermal fluid has been selected. The evaluation of thermal potential for a single borehole of 1900 meters deep is 2.5 MW.

Combined with a wellbore heat exchanger, the evaluation of the more promising energy conversion technology in the geothermal field of the Campi Flegrei area has been performed. Two alternative technologies have been considered: ORC plant and Stirling motor. The ORC plant has been designed with the RC318 as working fluid. The nominal electrical power is 260 kW. The Striling motor has been designed for the same input condition of the ORC plant. The thermal efficiency is greater than ORC and allows to have a 450 kW of electrical power.

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