Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Integrated Approach for the Design of Geothermal Binary Power Plants

Dario Alfani[1], Paola Bombarda[1] and José Fuster Justiniano[2]

[1]Dipartimento di Energia, Politecnico di Milano, via Lambruschini 4, 20156 Milano, Italy

[2]Universidad Tecnica Federico Santa Maria, Avenida España 1680, Casilla 110-V, Valparaíso. Chile

paola.bombarda@polimi.it

Keywords: binary, orc, doublet, integrated approach

ABSTRACT

Geothermal binary power plants are generally designed and optimized considering only the surface equipment of the plant. The optimization process consists of selecting the most suitable working fluid for the power cycle together with optimum operating parameters, namely the cycle pressures and temperatures. However, it would be desirable to adopt a more comprehensive approach, which includes also the subsurface part of the geothermal power plant: such an approach, though often invoked, is not commonly adopted. In this paper, an open-source software, aimed at the calculation of the performance of a geothermal doublet, is coupled to a commercial software, typically employed for power plant design. Particular attention is given to the combined subsurface/surface calculation, and plant performance will be optimized starting from the reservoir conditions. Ascertained that the reservoir temperature is the most important design parameter for the whole installation, the paper aims at investigating the effect of the other subsurface features on the design point of the surface installations, so as to attain a fully optimized power plant and the highest available conversion efficiency. The simulation model will feature a geothermal doublet coupled to an ORC plant for the power generation; several parametric calculations will be conducted, considering different reservoir conditions and a selection of appropriate working fluids for the ORC. Results of simulations will be discussed with the aid of Second Law analysis, with the scope of pointing out the key outcome of the integrated design procedure.

1. INTRODUCTION

The importance of geothermal exploitation by means of binary plants will grow in the future, since the water – dominated resources are very abundant, and the intrinsic advantages of the binary technology will extend the range of application of this technology in the overlapping area with flash plants.

The simplest plant scheme for geothermal exploitation consists of a couple of wells, a producer well and an injection well, called “a doublet”, and a power plant, located at surface. The doublet allows the circulation of the geothermal fluid from the reservoir to surface and then back to reservoir, while the power plant is charged with the conversion of the thermal energy carried to the surface by the geothermal fluid into electric power. In order to have an acceptable mass flow rate for the economic exploitation of the reservoir, a downhole pump is generally adopted. A geothermal binary power plant consists of a closed power cycle; most commonly, a Rankine cycle adopting an organic fluid (ORC) as working fluid is selected. The cycle is typically designed and optimized considering only the surface equipment of the plant. The optimization process involves selecting the most suitable working fluid for the power cycle together with optimum operating parameters, namely the cycle pressures and temperatures. A copious literature exists regarding the optimization of the ORC plant (see for example Astolfi et al. (2014)). It would be nevertheless desirable to adopt a more comprehensive approach, which includes also the subsurface part of the geothermal power plant. A first attempt in this direction is due to Frick et al (2010), and also Blocher et al. (2010); further contributes were given by Franco and Vaccaro (2012) which underline the importance of a sustainable exploitation.

2. SIMULATION MODEL

The simulation of both surface and subsurface plants is very demanding and requires a deep expertise, and, at the moment, no general software is available for an overall simulation. Considering that developing an ad hoc software would require an enormous effort, it deemed reasonable to start the investigation by means of a cascaded use of existing software.

Several software exist for the subsurface calculation; in the framework of this paper, an open-source software, DoubletCalc v1.4.3 ((van Wees at al., 2012) and Mijnlieff et al. (2014)), which is aimed at evaluating the performance of a doublet in the context of a sedimentary reservoir, was selected as software for subsurface calculation. This software adopts a simplified methodology and includes a probabilistic calculation, and seems particularly promising for the application to binary plants.

For the surface performance evaluation, a commercial software, most widely adopted, Aspen Plus v10.0, was selected.

2.1 Model description

DoubletCalc considers the geothermal fluid as water with dissolved salts (NaCl equivalent), which has an effect on the geothermal fluid thermophysical properties: the viscosity and the heat capacity depend on temperature and salinity, while the density is a function of temperature, pressure and salinity of the geothermal fluid. The software sketch the geothermal fluid loop starting from a static condition in the reservoir aquifer, evaluating the flow through the reservoir, the production well, the heat exchanger at surface, the reinjection well, and finally again to the static condition. The loop is divided in a number of small segments and flow evaluation proceeds considering mass balance, momentum balance and energy balance for each segment. Steady flow condition is assumed, and non-adiabatic flow is evaluated through the wells; for further details see Mijnlieff et al. (2014).

To perform the simulation, DoubletCalc needs as inputs the key reservoir parameters of the target location (e.g. reservoir depth and thickness, permeability, water salinity, etc.), the main operating features of the downhole pump (pump pressure difference and global efficiency), the details of the casing scheme and the design data of the surface heat exchanger. The data are collected under three different input sets: Aquifer properties, Doublet and pump properties, Well properties. Note that the possible presence of an injection pump should be simulated by correspondingly increasing the pressure difference of the downhole production pump.

Finally, yet importantly, the calculations performed by DoubletCalc are based on a stochastic (Monte Carlo) approach, which allows handling the effect of subsurface uncertainties. Consequently, output results consists of a set of three values: the percentile 90, 50 and 10 of the probabilistic distribution when output in table format is selected, or could consist of a stochastic plot, which represents the probabilistic distribution of the selected variable (e.g. the volumetric flow of the geothermal fluid). However, in the frame of this work, the results provided by DoubletCalc are used deterministically, selecting the mean statistical values, as input to the surface plant simulation code.

The heat exchanger at surface represent the junction point between the subsurface and surface calculation: actually, the subsurface software calculates the thermal power extracted, but, being the heat exchanger a component of the surface plant, this thermal power is evaluated also by the surface software.

The simulation model for the performance evaluation of the surface plant allows to build the plant scheme by adding single components; the evaluation proceeds considering mass and energy balances for each component. Again, steady flow condition is assumed. It is to underline that the selected process simulator allows to properly evaluating both geothermal fluid and working fluid thermodynamic properties, which are very important in order to fulfill a correct simulation of the plant performance. To run the simulation, Aspen needs as inputs some of the results of DoubletCalc calculation, namely the mass flow of geothermal fluid, and pressure and temperature at the primary heat exchanger inlet; moreover, the main design and operating features of all the plant components need to be specified.

A simplified representation of the simulated overall system is shown in Figure 1.

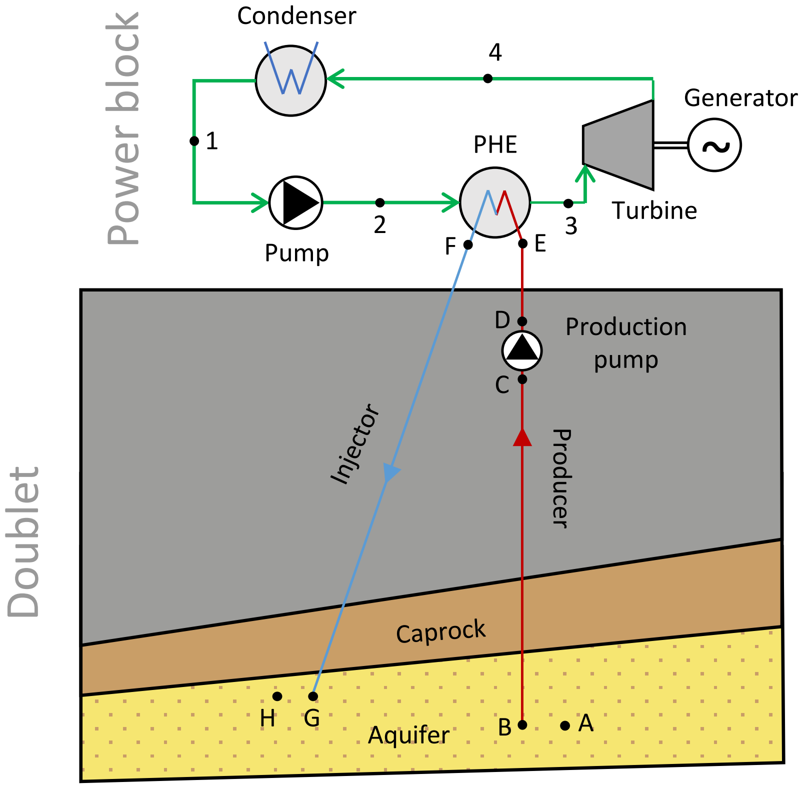

Figure 1: Overall scheme of the doublet and power plant simulated by the cascaded software

2.1.1 Performance evaluation parameters

The most relevant parameter for assessing the geothermal plant performance is the net plant power, given by:

$$P_{net} = P_{net,ORC} - P_{DHP} \quad (1)$$

where $P_{net,ORC}$ is the net power of the ORC plant, and P_{DHP} is the power consumption of the downhole pump. The net power of the ORC plant is given by:

$$P_{net,ORC} = P_{turbine} - P_{pump} - P_{auxiliary} \tag{2}$$

where $P_{net,ORC}$ is the net power of the ORC plant, and $P_{turbine}$ is the electric power generated by the turbine, and P_{pump} and $P_{auxiliary}$ are respectively the electric consumption of the working fluid pump and of the ORC plant auxiliaries, which main contribution is given by the cooling water circulation pump.

2.1.2 Second law analysis

Useful information for the evaluation of the plant performance can be given by the second law analysis. The second law efficiency is commonly be calculated either as “brute force” exergy efficiency or functional exergy efficiency (see Di Pippo, 2004):

$$\eta_{II,\text{"brute force"}} = \frac{net\ plant\ power}{exergy\ rate\ supplied\ by\ the\ geothermal\ fluid} = \frac{\dot{P}_{net}}{\dot{m}[h-h_0-T_o(s-s_0)]} \tag{3}$$

where ṁ is the mass flow, h is the enthalpy, s is the entropy, and with reference to ambient conditions (T_0, p_0, s_0).

$$\eta_{II,\,Functional} = \frac{net\ plant\ power}{exergy\ rate\ expended} = \frac{\dot{P}_{net}}{\Delta\dot{E}} = \frac{\dot{P}_{net}}{\dot{m}[e_{in} - e_{out}]} \tag{4}$$

Usually the previous equations are applied to power plant only; in the present work, the functional efficiency is selected, and the analysis is extended to the doublet, considering the exergies respectively at aquifer production point A and reinjection point G, with reference to Figure 1. This implies that the formulation for exergy has to be rewritten considering the gravitational term $g(z - z_0)$ (being z the height), i.e.

$$e = \dot{m}[h - h_0 - T_o(s - s_0) + g(z - z_0)] \tag{2}$$

since the depth change from reservoir condition to surface must be taken in account. The kinetic term $\frac{v^2-v_0^2}{2}$, which is commonly dropped, can still be neglected, since only liquid flow is concerned. See Moran and Shapiro (2006) for further details of flow exergy.

2.1.3 Reference case and basic assumptions

The Altheim project is one of the first geothermal binary plants in Europe, and was selected as a reference case for this work. It exploits a doublet, producing hot water from the Austrian part of the Molasse Basin, at around 2300 [m] depth; the salt content in the geothermal fluid is very little, and thermodynamic properties of the geothermal fluid are therefore very similar to the ones of water. The project started in 1989, with the main goal of supplying hot water for the district heating, and some years later the project was expanded implementing an electrical submersible pump in the production well and adding a 1 MW ORC plant for electricity generation (Pernecker and Uhlig, 2001). Several paper were published reporting the design and operating data of the Altheim plant; however, as matter of fact, published data are not always consistent, and make difficult a proper selection of the data needed for the cascaded simulations.

The most important parameters used for the simulations with DoubletCalc are reported in Table 1; for all other not reported values, the default values of DoubletCalc were adopted. Also, the number of sections of equal length in which the well is divided during the simulation was assumed equal to 50 (default value of DoubletCalc). For this reference case, the output values from DoubletCalc at percentile 50 were used as input for the subsequent plant performance calculation.

Table 1 Basic assumptions for the performance evaluation of the reference case.

		Reference
Aquifer properties		
Hydraulic conductivity (m/s)	2.75 x 10^{-5}	ENGINE report
Permeability (mD))	812	calculated
Aquifer gross thickness (m)	280	ENGINE report
Aquifer top at producer m TVD)	2305	ENGINE report
Aquifer top at injector m TVD)	2165	ENGINE report
Water salinity (ppm)	negligible	ENGINE report
Surface temperature (°C)	11	assumed
Geothermal gradient (°C/m)	0.038	Cociancig (2014)
Doublet properties		

Temperature at heat exchanger outlet (°C)	70	Cociancig (2014)
Distance between wells at aquifer level (m)	1700	ENGINE report
Production pump depth (m)	290	Pernecker, Uhlig (2001)
Pump global efficiency	0.75	Assumed
Pump pressure difference (bar)	11.5	Estimated
Well properties		
Producer penetration angle (deg)	0	Cociancig (2014)
Injector penetration angle (deg)	60	Cociancig (2014)
Producer casing (inch)	9 5/8; 7	Cociancig (2014)
Injector casing (inch)	9 5/8; 7	Cociancig (2014)
ORC plant		
Geothermal fluid mass flow (kg/s)	From DoubletCalc	
Geothermal fluid temperature at power plant inlet	From DoubletCalc	
Geothermal fluid temperature at power plant outlet	70°C	Pernecker, Uhlig (2001)
Cooling medium	Water	Pernecker, Uhlig (2001)
Cooling water mass flow (kg/s)	340	Pernecker, Uhlig (2001)
Cooling water inlet temperature (°C)	10	Pernecker, Uhlig (2001)
Cooling loop pressure drop (bar)	2.5	assumed
ORC working fluid[1]	Fluorocarbon	Pernecker, Uhlig (2001)
Net electric power (kW)	1000	Pernecker, Uhlig (2001)
Turbine isoentropic efficiency	0.85	assumed
Pump	0.75	assumed
ΔTmin Primary Heat Exchanger (°C)	5	assumed
ΔTmin condenser (°C)	3	assumed

Table 2 Output values calculated by the cascaded run of DoubletCalc and Aspen

	Calculated values	Design values (*Reference* Pernecker and Uhlig)
Mass flow (kg/s)	87.14	81.7
Temperature at power plant inlet (°C)	102.6	106
Temperature at power plant outlet (°C)	70	70
Pressure at power plant inlet, (bar)	10.7	unknown
Downhole pump power consumption (kW)	146.4	unknown
Net ORC plant power	1008	1000
Net geothermal plant power	861.6	unknown

[1] A fluorocarbon was initially selected as working fluid for the ORC plant, but it was soon substituted with Solkatherm. Model validation relies on the initial working fluid. For further details see Bombarda and Gaia (2006).

As a first comment, it can be seen that the cascaded run of the two simulation codes allows a reasonable simulation of the plant performance.

3. PLANT DESIGN AND OPTIMIZATION

The optimization process of an overall geothermal plant is a very complicated problem: in the following sections, we shall try to discuss the problem considering that a standard design is assumed for the wells, and therefore the choice of the well casings is out of the scope of this paper. The main purpose of this work is to investigate whether and in which range of the reservoir parameters the optimization of doublet and plant operating parameters need to be conducted simultaneously.

3.1 Main issues

The plant optimization should consider both the net electric power generated and the economic return of the investment. However, regardless of the economic optimization, it is important to discuss the mechanism, which maximizes the net power: this will be dealt with in the following paragraphs, based on Equation 1. The consumption of downhole pump P_{DHP} is calculated as:

$$P_{DHP} = \frac{\dot{V} \cdot \Delta p}{\eta_{DHP}} \quad (3)$$

where $\dot{V}$ is the geothermal fluid volumetric flow rate, Δp is the pressure difference of the pump, (i.e. the pressure difference needed to circulate the geothermal fluid in the doublet loop), and η_{DHP} is the global efficiency of the downhole pump, considering also the electro-mechanical losses. Note that this power consumption increases more than linearly with the geothermal flow rate, because the Δp term includes the friction term, which depends on the flow rate of geothermal fluid. On the other side, the electric power produced by ORC power plant roughly increases linearly with the geothermal fluid flow rate: therefore, an optimum flow rate, which maximizes the geothermal net plant power, should exist. The optimization of the overall geothermal plant was performed assuming the site data of the Altheim reference case; a further sensitivity analysis was conducted considering decreasing reservoir permeabilities. The basic assumptions, already presented, in Table 1 were maintained for the optimization process, except for the ORC working fluid.

3.1.1 ORC plant optimization

The selection of ORC working fluid is a design choice of paramount importance. It must allow a high cycle efficiency, but it is essential to investigate also other aspects like the component sizing (firstly the turbine design), the compatibility with plant material together with safety and environmental compliance. Usually pure working fluids are selected as working fluid in ORC plants, mainly refrigerants and hydrocarbons in the frame of geothermal exploitation. The choice of the working fluid depends on the fluid critical temperature, which should possibly be somewhat lower than the temperature of the geothermal source, on the molar complexity and molar mass; further information can be found in (Astolfi et al., 2014). In concert with the working fluid, the thermodynamic cycle configuration must be selected: in the context of this work, the selection of a simple saturated cycle is appropriate.

A preliminary analysis was conducted by Fuster (2019), fixing the geothermal fluid flow at the design value of the Altheim plant, and evaluating the performance of several working fluids (common hydrocarbon and refrigerants). An innovative fluid, the HFO-1234ze(E), was also considered among the selected working fluids, due to the fact that the European Regulation on fluorinated greenhouse gases allows the adoption of HFO fluids, and this fluid could be used in the future without restrictions. For every working fluid, the cycle was optimized by selecting the evaporation temperature, which allows the highest cycle net power (an example of this optimization procedure is shown in Figure 2). Fuster showed that similar results are obtainable with all the working fluids, but at substantially different evaporation pressures; the HFO-1234ze(E) implies the highest evaporation pressure (this would also entail an expensive sizing for the plant components, due to high-pressure requirement). Nevertheless, the HFO-1234ze(E) was selected as working fluid for further analysis. Note that, in Figure 2, the reinjection temperature is also shown: it is evident that the optimum pressure corresponds to a low value of this temperature; if, either due to following geothermal fluid utilization or due to scaling risk, a limit is binding, the operating evaporation pressure should be moved to a higher value, in order to respect the constraint. For example, in the case of the Altheim plant, the limit is set to 70°C because of cascaded utilization of the geothermal fluid. For the considered case, the second law functional efficiency (Equation 4) results 37.57%; the various terms of exergy losses are shown in Figure 3.

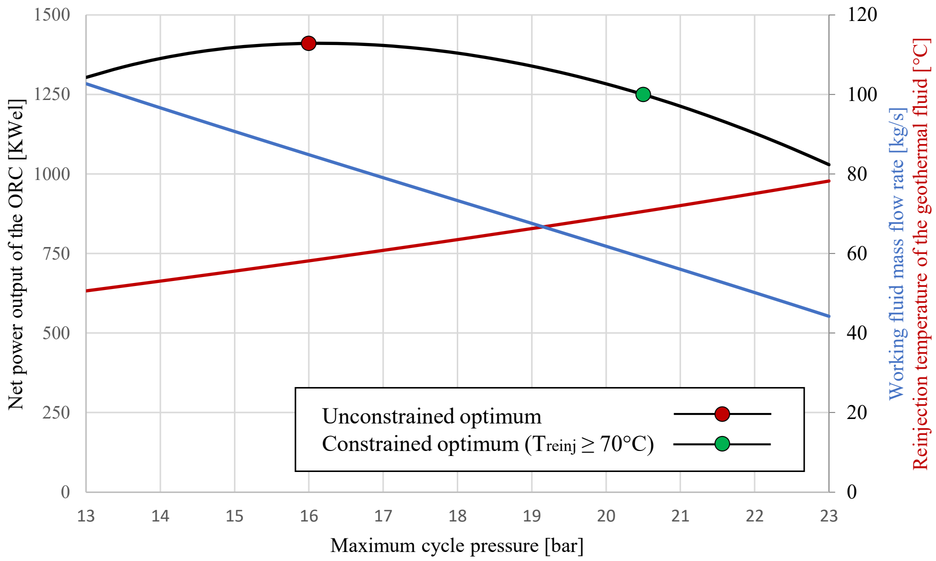

Figure 2: Optimization of the cycle evaporation pressure for a selected HFO working fluid.

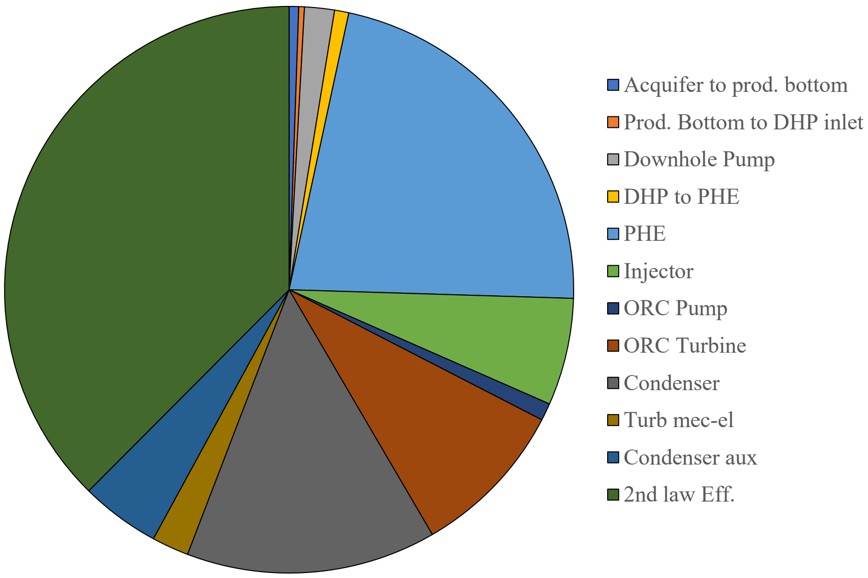

Figure 3: Overall second law analysis for the optimized case.

<u>3.1.2 Overall geothermal plant optimization</u>

The downhole pump is a key component for the plant operating, since acting on this component allows changing the geothermal flow rate in the doublet. Actually, no reference is made in DoubletCalc to a specific downhole pump, but, modifying the pressure difference across the pump it is possible to simulate the operating of the pump in an extended range of conditions for the considered doublet. The geothermal plant operating was investigated by changing the pressure difference of the downhole pump with respect to the design value; at the same time, the ORC cycle was optimized for every geothermal flow rate. Increasing the geothermal fluid flow rate produces a minimal change in the conditions of the geothermal fluid at ORC primary heat exchanger, but, being the cooling water conditions at condenser inlet fixed, this anyway slightly moves the optimum evaporation pressure.

The simulation results are shown in Figure 4: it is evident that, if the downhole pump pressure difference is increased, also the mass flow rate increases, and therefore both the required pump power and ORC net power increase. For the present case, a maximum is hardly to see in the net plant power curve.

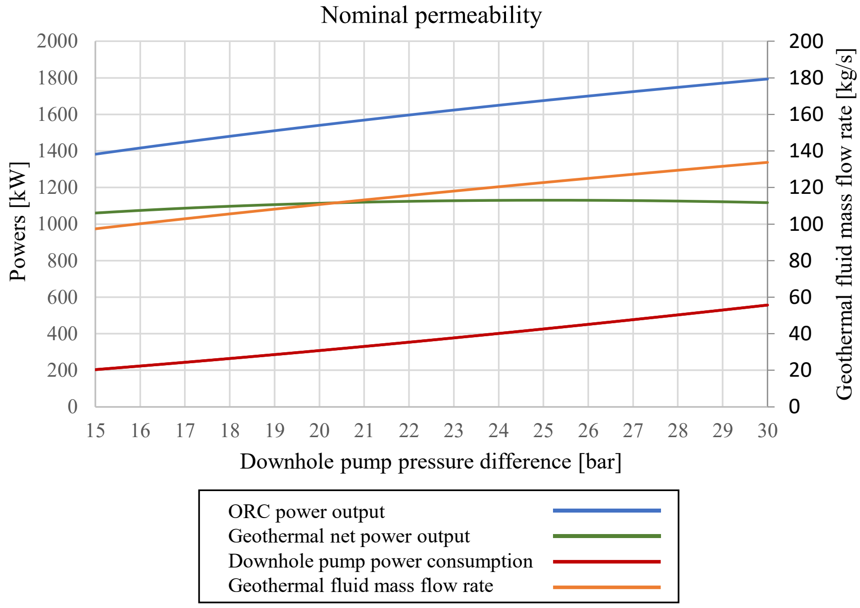

Figure 4: Optimization of the geothermal flow rate for the reference case with permeability 812mD; the pressure difference of the downhole pump is 11.5 bar (outside the axis limit).

3.2 Sensitivity analysis

It is well known that reservoir properties are estimated with an extent of uncertainty. It is therefore useful to conduct a sensitivity analysis, investigating the possible shift of the optimum operating conditions in case the permeability does not match the expected value.

3.2.1 Geothermal plant performance at different flow rates and decreasing permeability

The following graphs in Figure 5a and Figure 5b summarize the analysis conducted by decreasing the reservoir permeability, all parameters being constant. It is expected that, if the drawdown pressure drop increases, because of the lower permeability, a higher pressure difference of the downhole pump will be required. The graphs show the overall plant behavior as a function of the pressure difference of the downhole pump, and it is possible to notice that an optimal value is present depending on the permeability.

When the permeability is half of the design value, the situation is similar to base case, though of course the downhole pump consumption increases. When the permeability is decreased even more with respect to the base case, an optimum flow rate of geothermal fluid can be appreciated: this is evident when the permeability reaches 0,1 of the nominal value

The analysis conducted shows that, if the permeability has not the expected value, the design operating point of overall the plant, considering even the doublet and the downhole pump (and not solely the ORC, as it is commonly done) should be checked and possibly modified in order to achieve the maximum attainable power output.

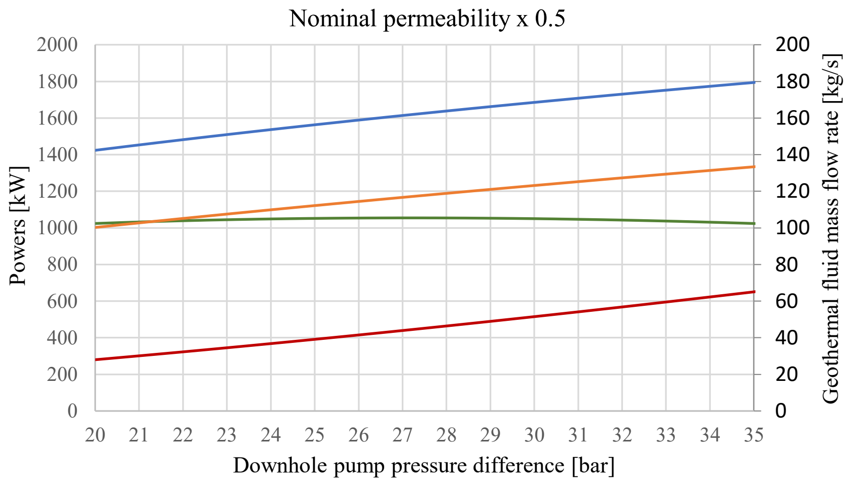

Figure 5a: Optimization of the geothermal flow rate for the 0.5 times the nominal permeability.

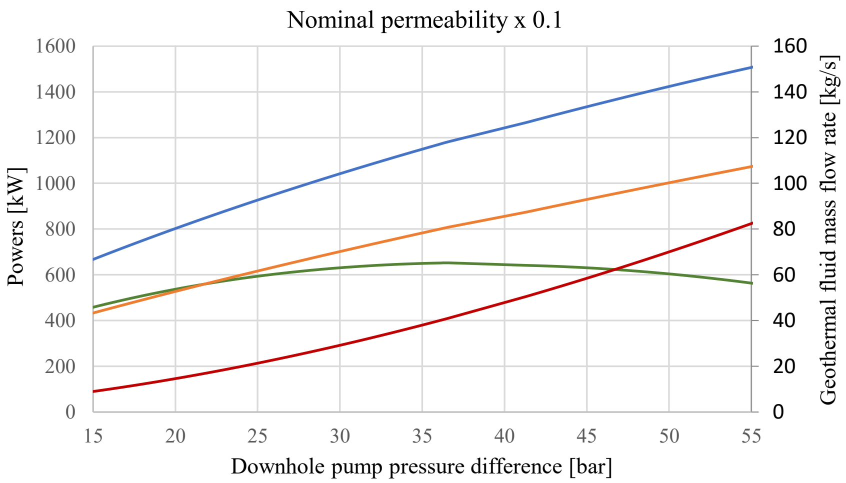

Figure 5b: Optimization of the geothermal flow rate for the 0.1 times the nominal permeability.

Finally, Figure 6 depicts the second law analysis comprehensive of doublet and ORC power block for the optimal value of downhole pump pressure difference at the three investigated permeability values.

It is possible to notice how the aquifer to production well bottom second law losses, mainly due to pressure losses in the aquifer, increase significantly as the permeability decreases. As a matter of fact, the pressure losses in the reservoir are directly related to the aquifer permeability and porosity and are inversely proportional.

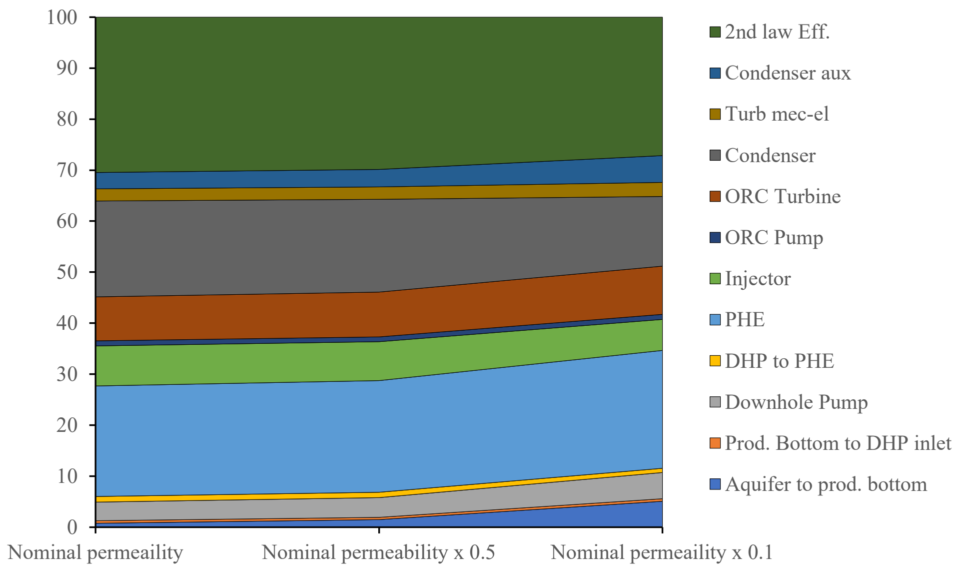

Figure 6: Second law analysis of the overall plant at different value of permeability. Note that the analysis is effectuated assuming the optimum geothermal mass flow rate, as evaluated from Figure 4, Figure 5a, Figure 5b.

3.2.2 Further comments

The analysis was conducted assuming a saturated simple cycle for the ORC: however, in case a more advanced cycle would be selected, as a recuperative cycle or a two pressure level cycle, the investigation would bring to a similar situation, but with an optimum flow rate somewhat higher, due to steeper trend of the ORC net power. Furthermore, with a higher performance cycle, the second efficiency would increase (and the exergy loss of the primary heat exchanger would most probably decrease, depending on cycle improvement).

4. CONCLUSIONS AND FUTURE WORK

The preliminary analysis conducted shows that the cascaded run of the two selected simulation codes is a powerful tool, and brings to a reasonable simulation of the plant performance, allowing an overall plant optimization. From the results it appears that, under a certain reservoir permeability, the flow rate of geothermal fluid should be optimized in order to extract the maximum power.

However, the collection of the input data required to run the two simulations is very demanding, above all for the data required by DoubletCalc, which are not easily found in the open literature, (unless maybe for some Dutch aquifers). The present analysis relies on the 50% probability results from DoubletCalc, but it would be interesting to adopt a more comprehensive approach, thus investigating the effect of the uncertainty of the subsurface parameters, which could be assumed when unknown.

The innovative working fluid selected for ORC plant in the frame of the optimization process, the HFO-1234ze(E), proved successful as far as thermodynamic performance is concerned.

Different version of the DoubletCalc software exist, and, while the present work is based on version v1.4.3, interesting future work could be conducted by means of subsequent versions, which can handle heterogeneous reservoirs, thus expanding the potential field of investigation to fractured reservoirs or enhanced geothermal systems. Moreover, the software version 2D enables the analysis of aquifer exploitation during its lifetime.

REFERENCES

AspenTech, Aspen Plus, (n.d.). http://www.aspentech.com/products/aspen-plus.aspx.

Astolfi, M., Romano, M.C., Bombarda, P., Macchi, E., Binary ORC (organic Rankine cycles) power plants for the exploitation of medium-low temperature geothermal sources - Part A: Thermodynamic optimization, *Energy* 66 (2014) 423-434

Blocher, G., Kranz, S., Zimmermann, G., Frick, S., Hassanzadegan, A. Moeck, I., Brandt, W. Saadat, A. and E. Huenges: Conceptual Model for Coupling Geothermal Power Plants with Deep Reservoirs, *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia (2010).

Bombarda, P. and Gaia, M.: "Geothermal binary plants utilising an innovative non-flammable, azeotropic mixture as working fluid," *Proceedings,* 28th NZ Geothermal Workshop, Auckland, New Zealand, (2006).

Cociancig B.: Altheim in Upper Austria – an example of cascaded geothermal energy use, *Proceedings,* WORKSHOP ON GEOTHERMAL ENERGY: Status and Future in the Peri-Adriatic Area, Veli Lošinj – (2014)

Di Pippo, R.: Second Law assessment of binary plants generating power from low-temperature geothermal fluids, *Geothermics* **33** (2004) 565–586

ENGINE Website: Lighthouse projects, Altheim, http://engine.brgm.fr/lighthouseProjects.asp

Frick, S., Kranz, S., Saadat, A.: Holistic Design Approach for Geothermal Binary Power Plants with optimized net electricity provision, *Proceedings,* World Geothermal Congress 2010, Bali, Indonesia (2010).

Franco, A., and Vaccaro, M.: An integrated “Reservoir-Plant” strategy for a sustainable and efficient use of geothermal resources, *Energy*, **37**, (2012), 299-310.

Fuster, J. “Simulation of a geothermal reservoir for the production of electricity using an ORC plant” Master Thesys, Politecnico di Milano (2019)

Mijnlieff, H.F., Obdam, A.N.M., van Wees, J.D.A.M., Pluymaekers, M.P.D. and J.G. Veldkamp: DoubletCalc 1.4 Manual, TNO report, (2014), TNO 2014 R11396, https://www.nlog.nl/en/tools

Moran M., and Shapiro H., Fundamentals of engineering thermodynamics: SI version, 5th ed., John Wiley & Sons Ltd, (2006)

Pernecker, G. and Uhlig, S.: Low enthalpy power generation with ORC-Turbogenerator: The Altheim Project, Upper Austria, *Proceedings,* International Summer School Conference: International Geothermal Days “Germany 2001”, (2001) https://pangea.stanford.edu/ERE/pdf/IGAstandard/ISS/2003Germany/III/6_1.per.pdf

REGULATION (EU) No 517/2014 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006

Van Wees, J.D., Kronimus., A., van Putten, M., Pluymaekers, M.P.D., Mijnlieff, H., van Hoof, P., Obdam, A., Kramers, L.: Geothermal aquifer performance assessment for direct heat production - Methodology and application to Rotliegend aquifers, *Nederlands Journal of Geosciences,* **91-4**, (2012), 651-665