

Investigation of Geothermal Power Generation on Abandoned Hydrocarbon Wells

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Abstract-- In Hungary there is a big opportunity to utilize geothermal resources. The oil industry has left many hydrocarbon wells abandoned, which could be prepared to produce geothermal energy. A feasible way to produce electricity if these wells are used as heat sources of an enhanced geothermal power generation system (EGS).

The average heat flux density in our country is significantly higher than the average value in the whole European continent. More than 3000 wells exist, thanks to the industrial and experimental drilling excavations. Removing these wells would be a significant cost for the oil companies. The aim of this work is the neglect or reallocation of the above mentioned extra cost by the installations of geothermal power plants.

This paper deals with the opportunities of geothermal power generation from a fictive 2200 meter depth oil well. Some construction changes were needed on the wells for the power generation. The bottom of the well has to be settled and another pipe is needed to fit in as a coaxial construction. This paper focuses on small-scale applications, so the possible use of organic Rankine-cycle (ORC) was considered, which enables the power generation from low temperature heat sources and operates also in lower power scales. The possibility of single and double loop ORC systems were investigated. In case of an ORC cycle with a double loop system the medium warmed up in the well while evaporating the working fluid of the ORC in the heat exchanger. In case of the single loop version, supercritical pressure was used to avoid the back streaming of working fluid caused by the density changing. The medium warmed up supercritically expands directly on the turbine. Due to the need of temperature difference in the heat exchanger the efficiency was lower in the first case. Based on our calculations with the single loop system a significantly higher efficiency can be achieved than with the double loop systems, therefore this solution was investigated more in details. Different working fluids were investigated. We pointed out the choosing aspects of the best medium. The optimization of certain parameters were also performed in order to achieve the best efficiency and thereby the best performance.

Finally the economic implications of the technically best solution were presented and some suggestions to short the payback time of the investment. The scaled model can provide near continuous output, making the technology a renewable, zero-carbon option for supplying baseload electricity generation.

Index Terms--EGS, Geothermal power generation, ORC, Abandoned hydrocarbon wells.

I. INTRODUCTION

Geothermal energy is the heat inside the Earth's reserves, which is fed by the decay heat of the long-lived radioactive elements in the earth's crust. Because of the extra-thin, 60-100 km lithosphere beneath the Pannonian Basin Hungary can be classified as a geothermal forefront in Europe. The average Hungarian geothermal gradient is around 50 °C / km. The geothermal gradient in the Great Plain and Southern Transdanubia is higher, the Little Plain and the mountainous areas is lower than the national average. In Hungary, in spite of the favorable conditions, the measured surface temperature rarely exceed 100 °C. [1]

The current economic environment enables cost efficient power generation only above 100 °C media temperatures. Many researches are being undertaken to ensure the exploitation of the geothermal resources for electricity production on lower temperature levels. The article summarizes the results of our work with the Mining Support Ltd. The underground processes of the system were calculated by the company and our task was to plan the surface system from the input data provided by the company.

A. Utilization of the abandoned hydrocarbon wells as EGS (Enhanced Geothermal System)

Our country is very well explored, which means that drilling exploration are the largest in the world (1 well / 5 km²). The number of the dry holes, drilled by the hydrocarbon industry in 66 years is approximately 3000. Figure 1. shows the spatial coverage of these holes.

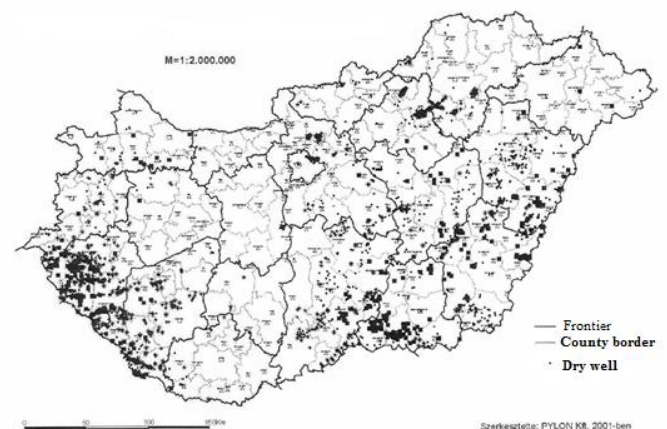


Fig. 1. The spatial distribution of Hungary's dry wells [2]

This work was supported in part by the Mining Support Ltd.
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The elimination of the abandoned wells represents a significant cost to the owners. However, if the well is located in an area where the geothermal gradient is sufficiently high, there should be examination for the utilization of wells for energetical goals. After the reconstruction, the wells can function as EGS (Enhanced Geothermal System), also known as HDR (Hot Dry Rock) system.

By conventional EGS in few kilometers depth, developed with a fracturing fissure functions as a heat exchanger. The surface water is injected into this fissure to pick the heat up. The circulation system is complemented by the supply and accent wells and surface recovery units.

In our case, there are no cracks in the rock, so the hydrocarbon wells are serving as a heat exchangers, and the heat transfer medium is not water, but carbon dioxide therefore the well must be hermetically closed in order to prevent fluid loss. The artificially developed geothermal systems use Rankine- or Kalina Cycle solutions for recovering heat power.

In Rankine cycle (ORC) heat transfer fluid heats and vaporizes the secondary fluid through the heat exchanger. The resultant vapor is expanded in a turbine. After condensation the fluid is returned to the beginning of the cycle. With well-chosen temperature of the fluid the poor efficiency of ORC can be increased. Kalina cycle can provide 40-70% better efficiency than the current systems. Here, the secondary fluid is a mixture of bicomponent water and ammonia. The increase in efficiency caused by the various evaporation temperature, which is not going to decrease the heat loss. The high costs of patent rights makes the investment too expensive, so the system was based on ORC surface circulation.

II. MODELING

A. Well model

In the course of our work, our task was to insert electricity production cycle to abandoned hydrocarbon wells. The model of the well based on geological research was made by Mining Support Ltd. Minor modifications were performed on the well. The bottom of the liner is closed without perforation and a production tube is placed coaxially inside. The well functions as a double-tube heat exchanger. The company's model was created with carbon dioxide heat transfer medium, due to the low price and because with this media both the single-loop and double-loop system are viable. The liquid carbon dioxide is injected into the outer ring. The fluid goes down to the bottom while heats up, then turns back on the bottom into the producer tube and comes up to the surface in supercritical state. Figure 2 shows the process. The company has a model that can calculate the established thermodynamic parameters of the working fluid on wellhead from the injection pressure and mass flow. The tender information package contains the well parameters and properties of the rocks in which the well is located.

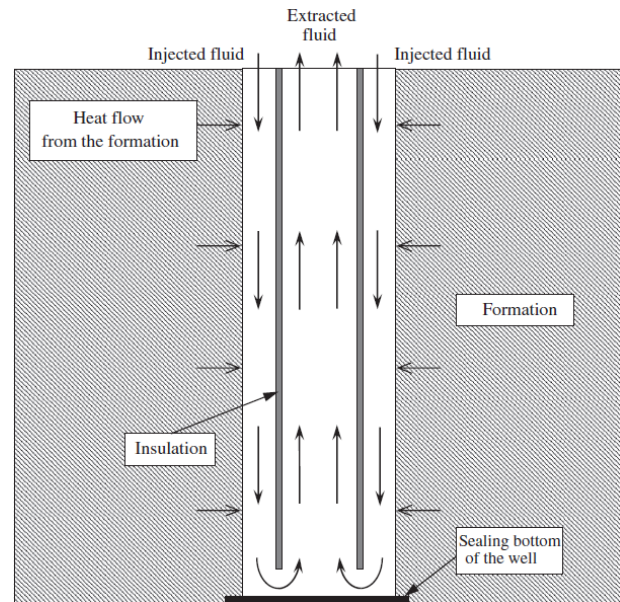


Fig. 2. The design of the fountain [3]

B. Model of the system on the surface

For the calculations the solver called FluidProp was used. It is able to determine the thermophysical properties of numerous fluids with thermodynamic functions. The Cycle Tempo program was used for the validation of the calculation results, which also uses FluidProp. FluidProp is able to perform calculation based on many different equations. StanMix was used in our model, which counts with the iPRSV state equation (modification of the Peng-Robinson-Stryjek-Vera equation). This equation is one of the best, in the description of behavior of non-ideal gases and fluids. [4] [5] The minimum allowable temperature difference in the evaporator, condenser and regenerator was chosen to 5 °C. For the turbine and pump efficiency 75% was considered, for the generator 95%. These values are relatively low. In practice machines with better efficiencies are also available, but our model does not calculate with the pressure drop in the condenser, regenerator and pipes (except the well), heat losses and the energy demand for cooling (pump and fans), therefore the use of lower efficiency lead to more realistic results. The maximum mass flow rate in the geothermal well was 20 kg/s. Based on the calculation of Mining Support Ltd. our model calculates constant 75 °C outlet temperature, because the change of the mass flow has only a slight influence on the exit temperature, therefore this effect was neglected.

The thermal power of the well is constant, so the electric power is determined by the efficiency, so the goal is to achieve the highest possible efficiency.

III. DUAL-LOOP ORC SYSTEM

At first a dual-loop ORC system was examined, where the CO₂ leaving the well is directly lead to a heat exchanger to evaporate the working fluid of an ORC system. A schematic of the organic Rankine-cycle can be seen on the Fig. 3.

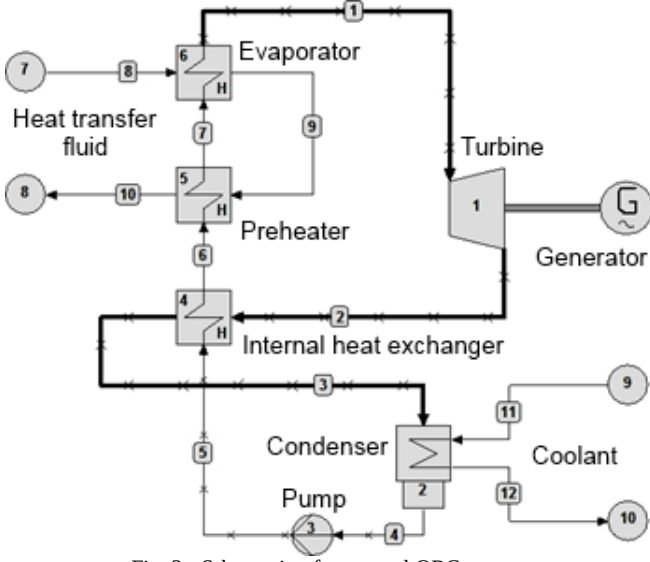


Fig. 3. Schematic of a general ORC system

The CO₂ has to be cooled down under 31 °C to return into liquid state, which is an important condition for the proper operation of the well. The main apparatus of the cycle is the preheater and evaporator heat exchanger, where the heat of the CO₂ is transferred to the ORC's working fluid. The minimal temperature difference between the two medium occurs in the starting point of the evaporation, therefore a higher share of the preheating stage in the total heat transfer leads to a lower CO₂ outlet temperature. Assuming a given evaporation temperature this share is higher in a case of a working fluid with lower critical temperature, therefore two different working fluid was considered with low critical data: R125 (pentafluoroethane) and R32 (difluoromethane). Superheating of the working fluid was also assumed to 70 °C corresponding the 5 °C minimum temperature difference, since this significantly improves the cycle efficiency. Fig. 4. shows the T-Q diagram of the heat exchanger, where the blue curve stands for the CO₂ medium and the red one for the working fluid.

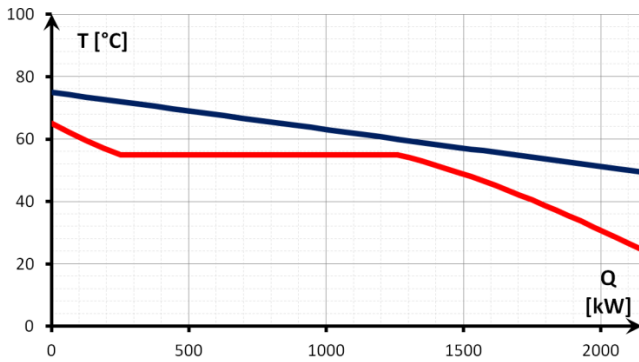


Fig. 4. T-Q diagram of the evaporator with R125 working fluid

Several different evaporation temperatures were examined, and the result are summarized in the Table 1. T_{evap} stands for the evaporation temperature, η_{ORC} is the cycle efficiency, $T_{\text{CO}_2, \text{out}}$ is the outlet temperature of the CO₂ from the heat exchanger and η_{heat} is the heat utilization ratio. When the CO₂

outlet temperature is above 30 °C an external cooling is needed to bring it into liquid state and pump it back to the well. The heat utilization ratio expresses that what proportion of the total heat rejected by the CO₂ while cooled from 75 °C to 30 °C is transferred to the working fluid. The overall efficiency is the product of the ORC efficiency and the heat utilization ratio.

TABLE 1.
EFFICIENCIES OF A DUAL-LOOP ORC SYSTEM IN CASE OF DIFFERENT WORKING FLUIDS AND EVAPORATION TEMPERATURES

Working fluid	T_{evap} [°C]	η_{ORC} [%]	$T_{\text{CO}_2, \text{out}}$ [°C]	η_{heat} [%]	η_{overall} [%]
R125	60	6.33	54.69	45.18	2.86
	50	5.89	48.41	59.13	3.48
	40	4.62	43.80	69.37	3.20
R32	60	6.27	58.63	36.42	2.28
	50	5.67	48.94	57.95	3.29
	40	4.49	41.70	74.01	3.33

A higher evaporation temperature enables a better ORC efficiency, but causes a higher CO₂ outlet temperature and therefore a lower heat utilization ratio, which reduces the overall efficiency. The heat utilization ratio can be improved by choosing a lower evaporation temperature, but this reduces the ORC efficiency and causes similarly low overall efficiency.

Another case without the regenerator internal heat exchanger was also examined, which improved the heat utilization ratio, but reduced the cycle efficiency. As a result of the two opposing effect the overall efficiency remained almost the same, and while the application of a regenerator only increases the investment costs, its use is not recommended. Excluding the superheating also has the similar effect to both the heat utilization ratio and the cycle efficiency, therefore it does not affect the value of the overall efficiency. According the presented results a dual-loop ORC system cannot be able to reach a higher electrical efficiency under the specified conditions, therefore the possibility of a single-loop system was also examined.

IV. SINGLE-LOOP ORC SYSTEM

The direct use of carbon-dioxide also was investigated. In this case, the carbon-dioxide flows out the well and expands on the turbine. There is no transfer medium. Depending on the pressure level after the expansion flows the medium in the regenerator or straight into the condenser.

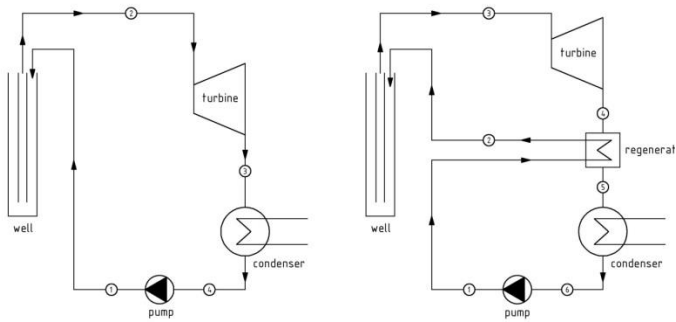


Fig. 5. Schematic diagram of single-loop ORC system. Left side without regenerator, right side with regenerator.

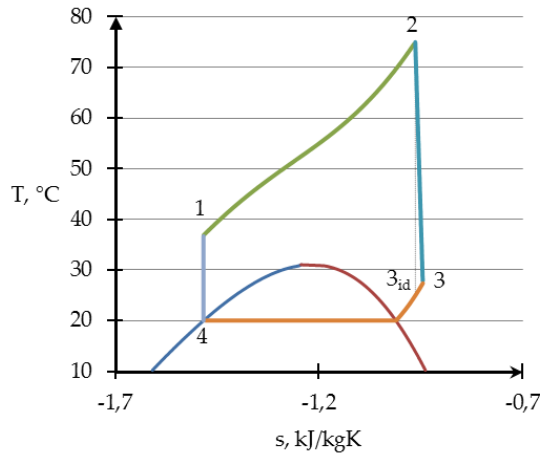


Fig. 6. T-s diagram without regenerator (115 bar, 75 °C)

Fig. 6. shows the T-s diagram without regenerator at 20 °C condenser temperature, 115 bar wellhead pressure and 75 °C wellhead temperatures.

After the condensation the liquified carbon dioxide is pumped back into the well (Fig. 5). The pressure drop in the well is supposed 20 bar.

The effects of the changes of wellhead pressure are shown on Fig. 7. and Fig. 8.

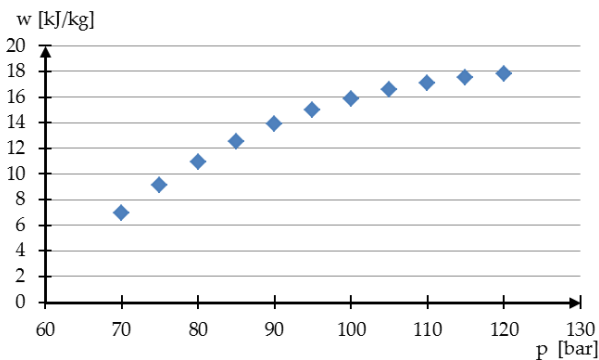


Fig. 7. The effect of pressure change on specific work

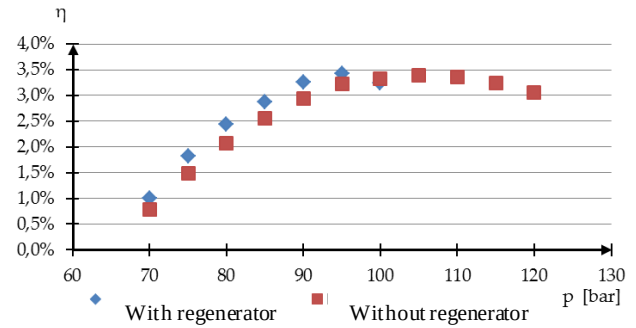


Fig. 8. The effect of pressure change on the efficiency

Fig. 7. shows that with the increase of the pressure the recovered work increment becomes increasingly smaller. Fig. 8. shows that the efficiency has a maximum depending on pressure and which is different with regenerator (75 bar), and without regenerator (105 bar).

It can also be seen on Fig. 8. that by using regenerator increases the efficiency, but it also has a limit, which is around 95 bar. In addition the temperature after the turbine is lower than after the pump, the direction of heat transfer is reversed. The Bošnjaković factor of the regenerator was taken into account in the calculation with value of $\Phi=0.9$ in the calculation.

The summer operation is critical. The condensation of the carbon-dioxide definitely needs a cooling below the critical point (31.06 °C) with a ΔT temperature difference which is necessary to the heat exchange. The allowed warming of the coolant agent for $\Delta T=6$ °C and the minimum temperature gap for the above mentioned $\Delta T=5$ °C recorded indicates that the system does not work with coolant agent which temperature is above 20 °C.

In summer it often happens that the temperature of natural waters and especially the air rises above 20 °C. Most of the wells are such areas, where water shortage is, so the most appropriate design is the air-cooled condenser. The condensation temperature depends on the air quantity and the surface of the condenser.

TABLE 2.
PERFORMANCES (105 BAR, 75 °C AT THE WELL HEAD, 20 KG/S CO₂)

Case	Electric power (kW)	Dissipated heat power in the condenser (kW)	Introduced heat power (kW)	Efficiency
regenerator	60.6	3277.6	3338.2	3.43%
without regenerator	112.0	3159.1	3304.0	3.39%

The performance of the cases with highest efficiency are shown in Table 2. The efficiency is very low in both cases.

V. FURTHER ANALYSIS OF MEDIA

According to our calculations, in case of carbon dioxide it is not economically feasible to build the power plant, therefore other working fluids were also examined. The selection is based on the critical point of the working fluid. It have to be lower than the wellhead temperature. On this basis we

examined the possibility of using R125, R22 and propane (Table 3.).

TABLE 3.
CRITICAL FEATURES OF WORKING FLUIDS

Material	Critical temperature [°C]	Critical pressure [bar]
Carbon-dioxide	31.04	73.8
R125	66.25	36.3
R22	96.05	49.8
Propane	96.67	42.5

To the usability of the well can be assured only with supercritical state change. At subcritical pressure the phase change causes a sudden change in the density, which is resulting steam bubbles and back flowing. According to the Table 3. and Table 4. is the chloro-difluoromethane (R22) is not appropriate, because the wellhead temperature is lower than the critical temperature. The necessary data for the calculation are provided by the Mining Support Ltd. (Table 6.).

TABLE 4.
MINING SUPPORT LTD. CALCULATIONS

Working fluid	m [kg/s]	T _{out} [°C]	Expected thermal power [MW _{th}]	Expected phase state
R22	4	85	2.19	wet steam
	10	80	5.49	wet steam
	15	78	8.04	wet steam
Propane	4	86	3.04	wet steam
	10	92	7.74	wet steam
	15	100	11	wet steam / dry steam
R125	4	90	2.15	dry steam
	10	92	5.5	dry steam
	15	92	7.9	dry steam

A. Propane

We carried out an examination of changing of the efficiency as a function of pressure (Fig. 9.).

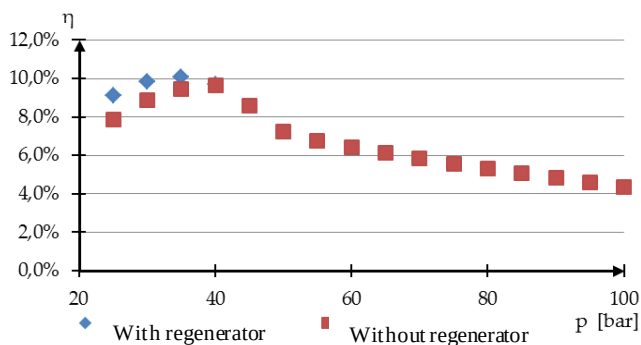


Fig. 9. Efficiency as a function of the pressure ($T_{\text{wellhead}}=100\text{ °C}$ and $T_{\text{cond}}=20\text{ °C}$)

It can be seen that at lower pressure the efficiency with

regenerator is higher, however this is not feasible, because it is below the critical pressure. The maximum efficiency without regenerator (9.47%) is about the critical pressure (42.5 bar). The T-s diagram of this case shows Fig. 10.

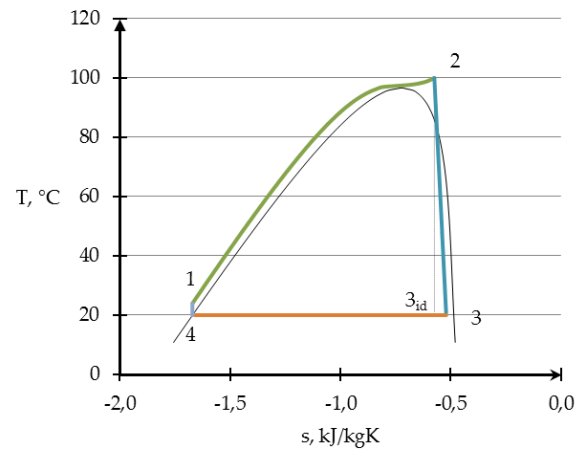


Fig. 10. T-s diagram of maximum efficiency ($p=42.5\text{ bar}$, $T_{\text{wellhead}}=100\text{ °C}$ and $T_{\text{cond}}=20\text{ °C}$)

This case is technologically difficult to achieve despite the high efficiency, because most of the expansion of the working fluid is in the wet field. It is also a disadvantage that the propane is highly flammable and explosive.

B. R125

The critical temperature of pentafluoroethane is below the wellhead temperature, therefore the single-loop ORC is feasible. The optimal initial pressure can be determined by Fig. 11. The regenerator can not be used above 50 bar because of the turning of direction of the heat transfer.

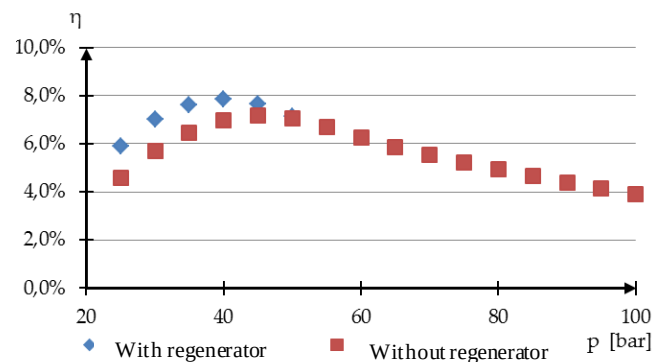


Fig. 11. Efficiency as a function of the pressure R125

The T-s diagram of the cycle with regenerator can be seen on Fig. 12.

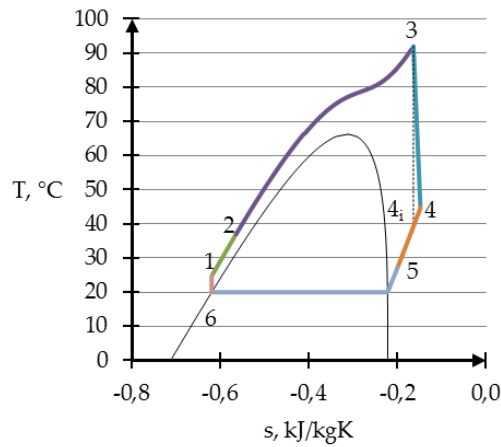


Fig. 12. T-s diagram of maximum efficiency, R125 medium with regenerator (p=40 bar, T_{wellhead}=92 °C and T_{cond}=20 °C)

The maximal efficiency with regenerator is 7.83% (40 bar initial pressure), while without regenerator is 7.17% (initial pressure 45 bar).

C. Comparison of working fluids

Table 5 show the efficiencies using different fluids

TABLE 5.

COMPARATIVE TABLE OF WORKING FLUIDS

Denomination	Reported efficiency [%]	Comment
Carbon dioxide with regenerator	3.98	Cheap working fluid, but poor efficiency
Without carbon dioxide regenerator	3.39	Cheap working fluid, but poor efficiency
R22	-	Too high critical temperature
Propane	9.47	The most of the expansion in the wet field
R125 with regenerator	8.44	The expansion in the superheated field
R125 without regenerator	7.17	The expansion in the superheated field

VI. ECONOMIC RATING

The feasibility of the small-scale geothermal power plant is mainly determined by its financial return. The financial evaluation of the project was based on the dynamic economic model, which takes the time value of the money into account while summing cash flows appearing in different periods. The assessment is based on the net present value (NPV), which is the sum of all discounted incoming and outgoing cash flows, and if its positive it means, that there is a return on the investment over the examined time. In case of the investigated power plant the main expenditure is the establishment cost in the first period, while the revenues are coming from the sold electricity:

$$NPV = \sum_{t=1}^n \frac{c_{E,t} \cdot E_t}{(1+r)^t} - C_0 \quad (6.1)$$

where NPV is the net present value [€], t is the number of a given period [-], n is the total number of periods, r is the discount rate [-], C₀ is the investment cost [€], c_{E,t} is the feed-in tariff of the electricity [€/kWh], and E_t is the power produces in the year t [kWh]. Assuming the same revenues in the different years, considering the NPV = 0 borderline case of return, (6.1) can be written in this easier form:

$$r \cdot \left(1 - \frac{1}{(1+r)^n}\right)^{-1} = \frac{c_E \cdot E}{C_0} \quad (6.2)$$

The calculation was performed to determine the maximum acceptable value of the establishment cost, since this is the least predictable factor in the equations. The discount rate represents the time value of the money, and means the expected rate of return on the investment. According to the main economic principles the discount rate is equal to the rate of return on other investments with the same risk, and its value was assumed to 5% due to the currently low interest rates in Hungary.

The amount of the annual energy production can be calculated based on the nominal power and the capacity factor of the power plant. The geothermal power plant is able to run continuously, and due the low operating costs the constant operation is preferable also from an economic point of view. Considering the necessary maintenance works and potential outages a 90% capacity factor was used in the calculations. The maximal achievable power according to the previously described best solution was 212 kW, which enables about 1670 MWh annual electricity production.

The electricity produced in the geothermal power plant can be sold in the Hungarian feed-in tariff (FIT) system, which offers a guaranteed purchase price for a long time. The currently valid feed-in tariffs applied from 1st January 2015 can be seen in the Table 2. The average tariff is 10 c/kWh, which were calculated as an average of the different prices weighted with the length of the periods.

TABLE 6.

ELECTRICITY FEED-IN TARIFFS IN THE HUNGARIAN FIT SYSTEM [6]1

Electricity feed-binding price [c/kWh]			
Period	Peak	Valley	Deep Valley
Power plant producing 20 MW or less (excluding solar power)	11.6	10.4	4.2

The design lifetime of the power plant is 30 years, but the calculation was also carried out for shorter payback periods, since the majority of the investors have shorter return time expectations. Table 3 summarizes the maximum acceptable establishment costs with whom the investment pays off over the desired period.

¹ 310 Ft/€ exchange rate was considered in the currency conversion

TABLE 7.
MAXIMUM ACCEPTABLE INVESTMENT COST TO ACHIEVE THE DESIRED
PAYBACK

Desired payback period [years]	10	15	20	25	30
Acceptable investment cost [M €]	1.288	1.731	2.078	2.351	2.564

According to the size and nominal power of the designed power plant an establishment cost of about 2,5 million € is realistic, which leads to the return on the investment in the technical lifetimes of the system. Possible state or EU investment subsidies for the renewable power generation can significantly shorten the payback period, for example a 50% investment cost support rate could reduce the return time to less than 10 years.

The operation and maintenance costs of the power plant were neglected in the calculations, since these are not causing a significant error due to their quite low value. The possible changes in the economic environment were also ignored, while e.g. an increase of the electricity prices can considerably improve the return on the investment.

VII. SUMMARY

Our goal was to design a power generation system, which can utilize the abandoned hydrocarbon wells as enhanced geothermal system to produce electricity from the geothermal energy. Since most of the wells are away from residential area, which makes it uneconomic to transport the heat due to the high rate of heat loss, so the electricity production was the main goal.

We examined several system design and working fluid. We made detailed calculations on carbon dioxide working fluid in case of single- and double-loop systems. Result of the investigation it was found that the single-loop system is able to operate at higher efficiency, but with this working fluid, the investment is not recoverable in case of most economic scenario. In order to improve the competitiveness we investigated the system with other media like as propane, R22, R134a, R125.

The calculations showed that R125 is the best choice for working fluid. With R125 the power plant we designed is capable to 212 kW electric power in case of the well situated by the Mining Support Ltd. With 90% capacity factor the plant is able to produce about 1670 MWh of electricity. The power plant establishment cost is about 2,5 million €, which leads to the return on the investment around the technical lifetime of the system with the currently valid feed-in tariffs applied from 1st January 2015. With 50% investment cost support rate the payback period could be reduced to less than 10 years.

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