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CO_2 as a Working Fluid for Generating Energy in Unused Hydrocarbon Wells

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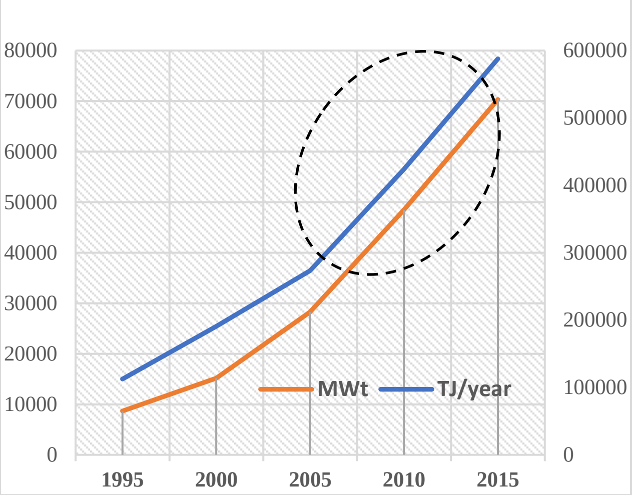
ABSTRACT

Hungary's good geothermal potential is well-known. Based on the 2016 Geothermal Atlas of Hungary, 1622 thermal wells produce hot water for direct heat utilization, and about 170 abandoned or temporarily closed hydrocarbon wells have been rated as very good geothermal sources. Hungary also has natural gas reservoirs with high CO_2 content, in some cases over 90%. The low critical pressure of CO_2 makes it ideal as a heat-bearing medium and working fluid in a geothermal system. This paper investigates how we could harvest these wells' geothermal potential using supercritical CO_2 as a working fluid. To this end, a thermodynamic calculation model has been developed to determine the heat transfer mechanism in the well.

1. INTRODUCTION

As can be recognized from official geothermal reports, ground-source heat pumps (GSHP) have the largest energy use and installed capacity worldwide, accounting for 49,898 MWt (70.95%) of installed capacity and 325,028 TJ/yr (55.30%) of annual energy use (Lund and Boyd, 2015). Although most of the installations are found in North American, Europe and China, the number of countries with GSHP installations increased from 26 in 2000, to 33 in 2005, to 43 in 2010, and to 48 in 2015. The equivalent number of installed 12 kW units (typical of USA and Western Europe homes) is approximately 4.16 million. This is a 51% increase over the number of installed units reported in 2010, and over three times the number of units reported in 2005.



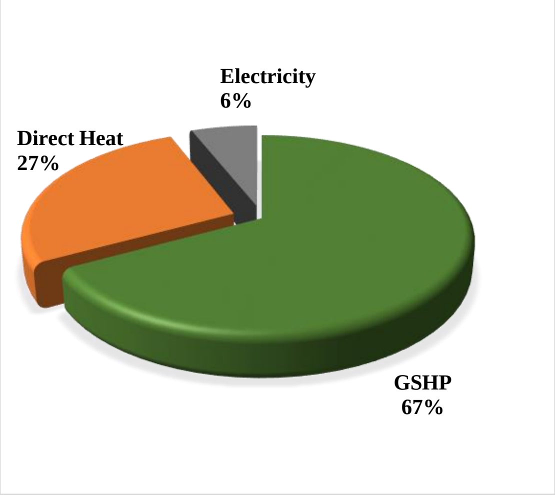


Figure 1: Worldwide geothermal direct-use 1995-2015

Figure 2: Share of installed capacity in Europe as of 2016

In Europe, last year's GSHP installation growth rate is even more impressive. The shallow geothermal (GSHP) proportion increased from the 63 % reported at EGC 2013 to 67 % as of EGC 2016. A capacity of at least 22,900 MWth was achieved by the end of 2015, distributed over more than 1.7 Million GSHP installations (Antics et al., 2016).

2. SHALLOW AND DEEP BORE-HOLE HEAT EXCHANGRS

The heat content of rocks near the surface is a huge geothermal energy resource. The borehole heat exchanger (BHE) is a device to extract such geothermal heat from shallow rocks, without geofluid production. The BHE is a heat exchanger installed inside a borehole, circulating any heat-bearing fluid. The borehole heat exchanger could be a double U tube or two coaxial pipes. In the borehole, the area around the pipes is backfilled with a material of high thermal conductivity. The energy supply of the BHE is transferred by conduction, a fairly inefficient means of attaining medium output temperature. The reasons for this inefficiency are: the relatively shallow depth of the BHE; the low heat transfer area; the low surrounding temperature; and the weak heat conductivity of the surrounding rock. The output temperature of the circulating fluid can however be increased to the required level through use of an electrical heat pump.

Higher output temperature can be attained by the so called deep borehole heat exchangers (DBHE), which are used in dry boreholes or abandoned wells. In such cases the well depth is the same as for thermal water or hydrocarbon wells, the heat transfer area is larger, the temperature of the surrounding rock is higher, and the heat conductivity of the deep compacted rocks is also higher than in shallower subsurface regions. Naturally, a DBHE has a lower thermal power capacity than similar thermal water wells (Horne (1980), Armstead (1983), Morita et. al. (1985, 2005)).

It has been a while since energy and geothermal experts took an interest in making use of the world's many abandoned hydrocarbon wells. The question of how to transform them into DBHEs has been addressed by numerous research and conference publications: Claesson, J. and Eskilson, P. (1988), Rybach (1995), G. Hellström et al. (1997), T. Kohl et al. (2002), A. Toth A. and E. Bobok (2008, 2016) have all dealt with this topic. By contrast, surprisingly few (except for Rybach, 1995) have looked into DBHE use as a practical matter. It is well known that most of a geothermal project's investment cost is expended in well exploration and drilling, which makes up about 60-70% of the development budget. An abandoned or temporary closed well nonetheless represents a high value, which should be utilized. Furthermore, DBHEs are an environmentally friendly way to increase geothermal energy production.

The simplified model of a BHE is shown in Figure 3. The casing is closed at the bottom without any perforations. The working fluid, usually water, flows downward through the annulus between the coaxial casing and tubing. Since the adjacent rock is warmer than the circulating water, the water temperature increases in the direction of the flow. An axisymmetric thermal inhomogeneity is developed around the well together with radial heat conduction towards the well. This is the heat supply of the system. The warmed-up water flows upward through the tubing while its temperature slightly decreases, this depending mainly on the heat conduction coefficient of the tubing. The system is analogous to a countercurrent heat exchanger. The main difference is the increasing adjacent rock temperature distribution with depth. Thus the familiar methods for design of heat exchangers are not sufficient for this case.

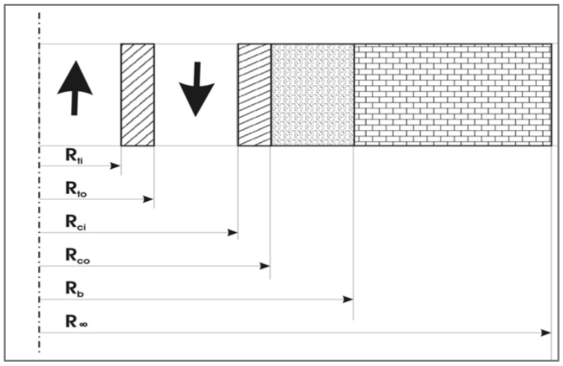


Figure 3: Schematic drawing of a BHE

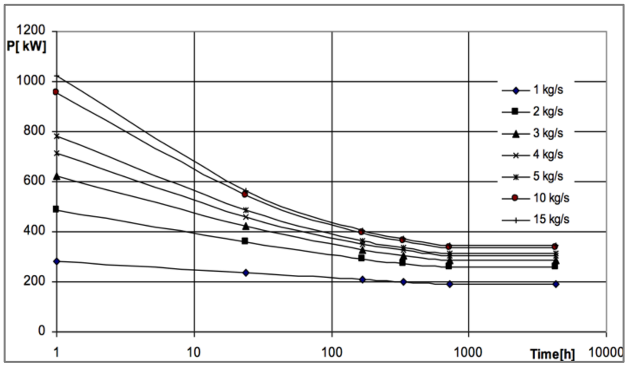


Figure 4: Extracted thermal power vs. time (Toth, 2008)

The temperature distribution for both the annulus and the tubing along the depth is determined on the basis of the surrounding rock temperature. One must then take into consideration the parameters influencing the temperature distribution and the thermal power of the system. Let's take an example for the temperature distribution of a closed-loop well. We will assume the depth of the well is 2000 m, the casing is 7", and the tubing is 4 ½". The tubing is a steel pipe with polypropylene heat insulation. The geothermal gradient is 0.05 ^{o}C/m, the heat conductivity of the polypropylene is 0.2 W/m^{o}C. The average heat conductivity of the rock is 2.5 W/m^{o}C. Calculating on the basis of different mass flow rates of 5, 10 and 15 kg/s., it can be recognized that the bottomhole temperature depends strongly on the mass flow rate.

The influence of the mass flow rate and the operational time on the thermal power of the system can be seen in Figure 4. The thermal power is plotted against the production time. For small mass flow rates the effect time is very small. For higher flow rates the change over time is important.

The DBHE's major disadvantage is the relatively low temperature of the outflowing water and the relatively low thermal power. This is due to the small heat transfer area and the low heat conductivity of the rocks. For this reason only small-scale operations can be based on this clean technology, even when applying heat pumps as well. During the initial period of the operation both the temperature and the power has a higher value, but they tend to a lower equilibrium value.

From this it can be recognized that there exists an upper limit to the flow rate, beyond which the equilibrium thermal power cannot be increased. This thermal power determines the sustainability of the system. Heat conduction toward the well cannot carry more heat than this upper limit. Heat conductivity of the adjacent rock mass restricts the exploitable thermal power usable by mean of a single closed-loop geothermal well. The sustainable power production of such a system can be determined if one knows how deep the well is, how well its tubing is insulated, what the local geothermal gradient is, and what the material properties are in the rocks around the well.

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3. DBHE COMBINED WITH HEAT PUMPS USING CO_2 WORKING FLUID

Standard heat pump systems can usually produce an output temperature of 55-60 °C. Less commonly, high-temperature (80-90°C) heat pumps can be designed for heat recovery, for such heat sources as: waste heat from the cooling circuits used in energy generation or production plants; and water or wastewater (8-35°C). It is a significant innovation to employ high-pressure heat pump systems, which use CO_2 as a working fluid application, for the purpose of recovering heat from low-temperature waste heat flows.

The concept of using high pressure (supercritical) CO_2 instead of water as a heat transmission fluid has often been proposed (Wetenhall et al, 2014, Toth-Bobok, 2013). As has been noted elsewhere, CO_2 has certain thermophysical and chemical properties that could make it attractive as a heat transfer medium.

In Table 1, some different working-fluid critical properties are summarized: temperature, pressure and density. One of the main reasons for selecting these fluids is to guarantee a supercritical condition at the Ultimate Heat Sink (UHS) temperature: The fluid state at the compressor inlet should be supercritical to minimize the work required of the compressor (L. Coco-Enrıquez eta l, 2017).

Name	Symbol	Critical Temp. (°C)	Critical Press. (MPa)	Critical Density (kg/m^3)
Water	H_2O	373.9	22.06	322.0
Carbon dioxide	CO_2	30.9	7.38	467.6
Methane	CH_4	-82.6	4.59	162.6
Ethane	C_2H_6	32.2	4.87	206.2
Nitrogen	N_2	-146.9	3.39	313.3

Table 1: Comparing the critical properties of some working fluids

Using supercritical CO_2 has certain concrete benefits:

- CO_2 critical pressure is one third that of water, which makes operating conditions more economical;
- Co_2 is a stable, inert fluid at the operating temperature ranges under consideration for the power cycles,
- Co_2 is an abundant fluid in nature, inexpensive, non-toxic and causing minimal environmental impact in low quantities,
- Co_2 is very compressible and expandable,
- Co_2 is cheap and may earn its users credit for storing a greenhouse gas.

A significant amount of energy (5-10MW_t) can be created if there are hundreds of bore-holes close together, so that they can form an interconnected network (Wetenhall, B. et al, 2014). Unfortunately, the DBHEs in closed CH wells are usually 1-2 km apart from each other, making it hard to connect them into a bigger system.

The heat source for large-scale CO_2 working fluid systems has traditionally been the waste water from power plants, industrial wastewater technology, or even communal wastewater (Coquelet C. et al. 2017).

The use of direct DBHEs hasn't really caught on (Kohl, T., et al, 2002) because it is very expensive to drill a deep well (>2000m) which might not even attain temperatures higher than 60 °C (140K). No abandoned or closed hydrocarbon well can be economical if it does not produce temperatures above 100°C. Using supercritical CO_2 as a working fluid, however, can yield temperatures up to 140-150°C (284-302K), which can be accomplished with the equipment. The systems Temperature – Entropy diagram is shown in Figure 5.

Here we can see how it is possible to get temperatures higher than 100 °C from a DBHE, using recirculated supercritical CO_2 working fluid. The surface compressor operates the thermodynamic cycle. The working fluid is CO_2.

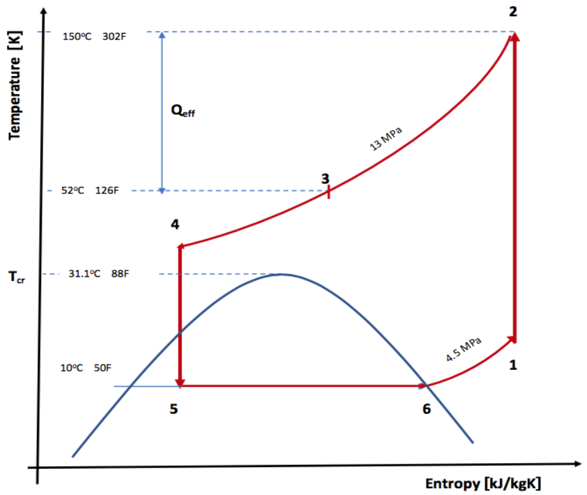

Figure 5: Temperature - Entropy diagram of the syste

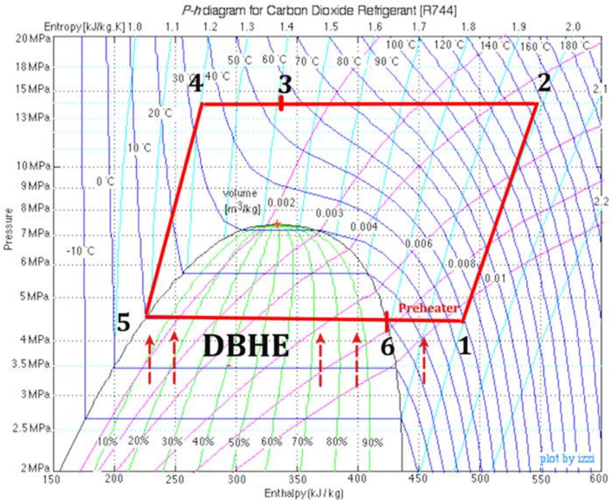

Figure 6: Pressure- Enthalpy diagram of the system

1-2: The compressor increases the pressure of CO_2 from 4.5MPa to 13MPa, while the CO_2 temperature increases from 27^{o}C (300K) to 150^{o}C (302K), and enters the supercritical phase.

2-3: After the compressor, the supercritical CO_2 goes through a heat exchanger which transfers the heat to a secondary working fluid. If the insignificant pressure loss is ignored, this can be considered an isobaric process. After this heat transfer, the resulting high temperature can be used for such direct heat applications as food canning, paper pulp processing, and sugar refining evaporation. It is also possible to generate electricity (100-200kW) with binary cycle, but its efficiency is rather low -- only 4-5 %. During this period the CO_2 is still in supercritical phase.

3-4: The supercritical CO_2, at 52^{o}C (126K) and 13 MPa, is cooled by a seconder heat exchanger which preheats the CO_2 that enters the compressor.

4-5: The pressure at the turbine decreases. This is an adiabatic expansion, during this period the CO_2 will be two-phase. At point 5 the CO_2 temperature is 10^{o}C (283K) and its pressure is 4.5MPa. At point 5 the CO_2 is in liquid and gas two-phase.

5-6: This two-phase CO_2 flows downward through the annulus between the coaxial casing and tubing. Since the adjacent rock around the well is warmer than the circulating CO_2, a radial conductive heat flux occurs. Because of this external heat source the two-phase CO_2 becomes a dry saturated vapor (6).

3. THE AMOUNTS OF ENTHALPY AT EACH STAGES

Work required to drive the compressor:	$W_{comp}=i_2-i_1$ =570-500 = 70 kJ/kg
Effective heat extracted from the system:	$Q_{eff}= i_2-i_3$ =570-330 = 254 kJ/kg
Internal heat for inverting the preheater:	$Q_{inv}= i_3-i_4$ =330-260 = 70 kJ/kg
CO_2 enthalpy reduction in the turbine:	$W_{turb}=i_4-i_5$=260-230=30kJ/kg
Maximum electrical energy that can be produced	
(5% of the total energy that enters the turbine)	We = 1.5 kj/kg
Heat from surrounding rock during the phase-change:	Q_{ph}= i6-i6=430-220=210kJ/kg
COP of the system:	COP=(Q_{ph}+Wt_{urb}/)W_{comp}==(210+30)/110=2.18

4. SUMMARY

This paper investigates how we could harvest these wells' geothermal potential using supercritical CO_2 as a working fluid. A temporarily closed hydrocarbon well is used as a deep borehole heat exchanger. The advantage of this system is that we could thereby broaden the spectrum of use required for high temperature technologies over 100^{o}C (200K). Electricity generation is also possible with a binary system, but its efficiency is rather modest. It can be justifiably said that this one-hole system is more suitable and efficient for direct-heat production than for electricity production. Several types of higher-heat (>100ºC) requirements can be satisfied, however, and where temperatures high enough for industrial applications are needed, this system would definitely be feasible. Starting at the top of the temperature range, these applications could include: hydrogen production; refrigeration; pulp and paper processing; and food dying and processing. These are only several of many possibilities. The weakness of the proposed production technology, using this closed-loop system, is that it produces only moderate thermal power and relatively low electric power. We could harvest significantly more energy with a system that uses a deep doublet, where the underground heat transfer area between the wells is an order of magnitude greater. An even more significant amount of energy (5-10MW_t) could be created if there are hundreds of bore-holes close together, so that they form an interconnected network. Unfortunately, the DBHEs in closed CH wells are usually 1-2 km apart from each other, making it hard to connect them into a bigger system.

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