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Analytical method to evaluate the propagation time of injected water in aquifer by use GSHP system to solve environmentally conflictual aspect

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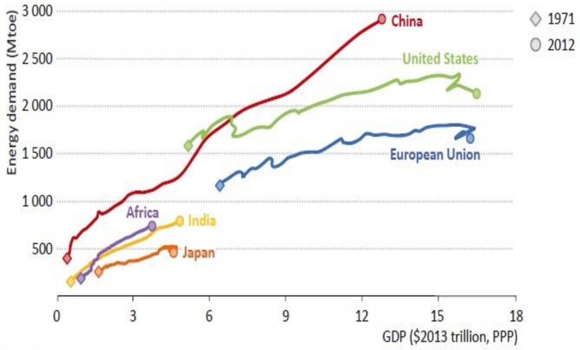
Abstract – The issues of sustainable development costs and thermal energy production and not, only push us towards renewable energy like shallow geothermal energy using groundwater extraction/injection wells (GSHP). This paper focuses on elaboration of an analytical method in order to evaluate the propagation time of injected water with modified temperature into groundwater. This is useful to analyze of eventually environmental and conflictual aspects between neighbors which use such systems.

The elaborated mathematical model presented in the paper highlights that shallow geothermal energy installations (GSHP), which use geothermal doublets, can affect the temperature field of neighboring owners and so can leads to conflictual aspects

Keywords: heat pump, heat exchanger, flow, geothermal doublets

1. INTRODUCERE

Romania has available a wide range of energy resources: oil, natural gas, coal and uranium, as well as important potential exploitable renewable resources. Stocks of hydrocarbon gas, coal, lignite, uranium are falling and limited in terms of shrinking domestic production and unidentified major potential fields. Taking into account the increasing demand for energy (fig. 1) and increasing the share of sustainable energy supply, it is obvious that in the future, emphasis should be putted on regenerative energy, thus reducing dependence on energy imports and while reinforcing domestic market.



Note: Mtoe = million tonnes of oil equivalent.

Fig. 1. Total primary energy demand and GDP in selected countries from 1971-2012 [9].

Using geothermal energy is economically, environmentally and geopolitically of particular importance because of decreasing fossil fuel deposits. According NAPRE from June 2010 the share of energy from renewable sources, in gross final energy consumption for 2005, were 17.8% and the gross final energy consumption 24% by 2020. According to the Department for Energy, the share of electricity produced from renewable sources in gross final consumption of electricity in the country, 2013, was 41%, above the target of 38% assumed by Romania in 2020, and over 35% indicated intermediate target for 2015. Romania has assumed to the European Commission that 24% of total energy consumption and be renewable by 2020. This target includes electricity, heat and fuels. The Energy Regulatory Authority (ANRE) has already announced that this target has already been reached on 1 January 2014 [7,8 and 10].

Seeing the clear potential of renewable energy it is correct to say that using any type of system could bring new problems that we were not aware of till now. For example, the use of groundwater source heat pumps (GSHP) can have as result the extraction of heat from neighboring land plots. If cooling is the main purpose of our system then the neighboring land will receive a heat input. Hence the purpose of this paper, which is focused on the effects of a groundwater source heat pump on the groundwater heat flow transport as well as.

2. SHALLOW GEOTHERMAL ENERGY

In order to understand GSHP first we must comprehend geothermal energy, which is the heat stored beneath the surface of solid earth ranging from the upper 100m to the hot rock found at thousands of meters. The energy of the earth, under 10-20 meters, (known as shallow geothermal energy) is resulting largely from scrap gravitational energy, initial heat when the earth formed and absorption of radiant energy that is released in the earth's crust when radioactive elements decay. Radioactive isotopes 238U, 235U, and 40K 232TH, that are found in all mineral layers in various concentrations, are highly mobile and therefore rich in the upper crust of the earth.

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High heat releasing elements are, for example granite (3.0 µW / m3), gneiss (2.4 µW / m3) or metamorphic schists (1.4 µW / m3).

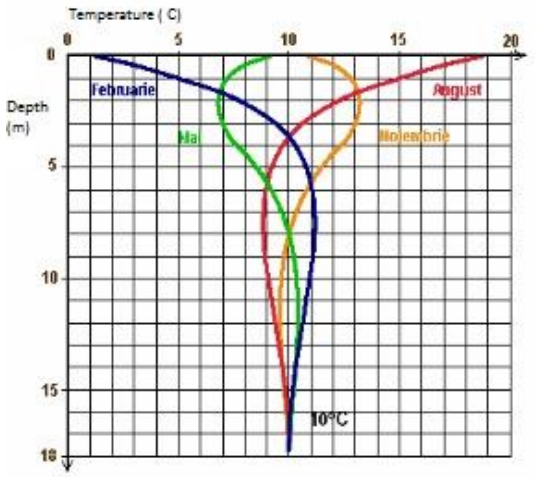

Fig. 2 Changes in soil temperature in the area of the surface crust [11]

Soil layers, up to about 20 meters, are influenced by air temperature and solar energy. After this depth the temperature remains approximately constant. It is known that heat flow is vertically oriented and this leads to a continuous climb of temperature, the thermal gradient has an average of 3,3K/100 m. However there are exceptions to the rule, especially in areas with volcanic/tectonic activity and high thermal conductivity.

2.1 Use of geothermal energy

Geothermal energy requires special systems to raise the water temperature to acceptable levels. One of these systems is called ground source heat pump (GSHP) and work on the same principle as the refrigerating machines. The differences between these heat pumps are the type of heat extraction method. Our test is based on open loop systems also called a groundwater heat pump. In an open loop system the heat is extracted from water coming through the extraction well. After the heat transfer is done the water is injected into the ground by another well, called injection well. Open-loop systems have more potential problems than closed-loop geothermal systems because they bring outside water into the unit. This can lead to clogging, mineral deposits, and corrosion in the system.

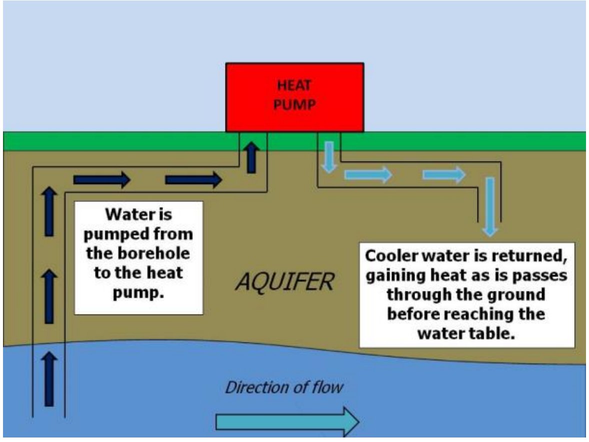

Fig.3 Example of open loop geothermal doublet extraction/injection wells [14]

3 ANALYTICAL SOLUTIONS FOR A GEOTHERMAL DOUBLET SYSTEM WITH A PRE-EXISTING UNIFORM GROUND WATER FLOW

We consider a practically relevant geothermal exploitation system with a groundwater flow generated by two wells, one well is a production well of thermal water (-Q) coupled with an injection well (re-pressing) cooled water with the same discharge (+Q). This coupled system is particularly useful in geothermal energy exploitation, both in shallow geothermal territory, the upper 100 m of the Earth, as well as in hot water and steam found in the rocks at a few thousand meters depth under the Earth's surface. For such a system we will analyze the influence of a pre-existing ground water flow with uniform Darcy-velocity V0 which makes with the OX axis an angle which is named α.

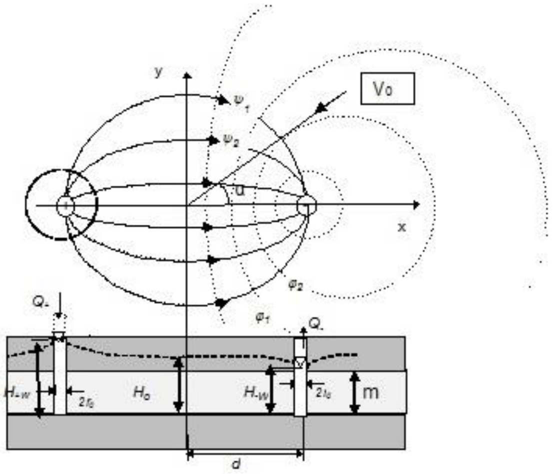

Fig. 4 Sketch of the flow for a geothermal doublet heat exploitation system in a pre-existing uniform groundwater flow [4]

The complex potential of the groundwater flow can be writing as a superposition of two coupled wells and the uniform parallel flow. With the assumption that the wells have the same discharge (i.e. Q+=-Q-=Q) the complex potential has the following form:

$$F(z) = -V_0 z e^{i\alpha} - \frac{Q}{2\pi} \ln\left(\frac{z-d}{z+d}\right) \tag{1}$$

The velocity V_0 will be expressed using the gradient I_0 of the pre-existing parallel groundwater flow:

$$V_0 = k_f I_0 \qquad (2)$$

z is the complex variable (i.e. $z = x + iy$) and k_f describes the conductivity coefficient of the groundwater layer.

The functions potential φ and flow line function ψ can be written as real part and imaginary part of the complex potential F(z):

$$\varphi = \mathrm{Re}\{F(z)\} = -kh + c =$$
$$= -v_0 r\cos(\theta+\alpha) - \frac{Q}{2\pi m}\ln\left(\frac{\sqrt{(x-d)^2+y^2}}{\sqrt{(x+d)^2+y^2}}\right) \qquad (3)$$

$$\psi = \mathrm{Jm}\{F(z)\} = -V_0\sin(\theta-\alpha) -$$
$$-\frac{Q}{2\pi m}\left[\arctan\frac{y}{x-d} - \arctan\frac{y}{x+d}\right] \qquad (4)$$

From the potential function (3) we can derive the Darcy groundwater flow velocity components, as follows:

$$V_x = \frac{\partial\varphi}{\partial x} = -V_0\cos\alpha +$$
$$+\frac{Q}{2\pi m}\left[\frac{x+d}{(x+d)^2+y^2} - \frac{x-d}{(x-d)^2+y^2}\right] \qquad (5)$$

$$V_y = \frac{\partial\varphi}{\partial y} = -V_0\sin\alpha +$$
$$+\frac{Q}{2\pi m}\left[\frac{y}{(x+d)^2+y^2} - \frac{y}{(x-d)^2+y^2}\right] \qquad (6)$$

From the potential function (3) we can deduce also the calculus formulas, using the reference piezometer heads in the wells H_{+W}, H_{-W} and the piezometer head H_0 between the wells at x = o:

$$Q = Q_{-W} = Q_{+W} = \frac{2\pi m k_f (H_0 - H_{-W} + I_0 d\cos\alpha)}{\ln\frac{2d}{r_0}}$$
$$= \frac{\pi m k_f (H_{+W} - H_{-W} + 2I_0 d\cos\alpha)}{\ln\frac{2d}{r_0}} \qquad (7)$$

From the assumption $Q_{-W}=Q_{+W}=Q$ the following relation between the piezometer heads in both wells is valid:

$$H_{+W} + H_{-W} = 2H_0 \qquad (8)$$

So for given discharge Q, we can calculate the piezometer heads in both production and repressing wells [3].

Remark: If $Q_{-W} \neq Q_{+W}$ then potential function (1) becomes:

$$\varphi = \mathrm{Re}\{F(z)\} = -kh + c = -v_0 r\cos(\theta+\alpha) -$$
$$-\frac{Q_{-W}}{2\pi m}\ln\sqrt{(x-d)^2+y^2} + \frac{Q_{+W}}{2\pi m}\ln\sqrt{(x+d)^2+y^2} \qquad (9)$$

With these mathematical relations it possible to analyze the influence of the groundwater flows on the heat flow. The main problem is to determine the influence of the existing groundwater flow on the neighboring land. This is especially due to the fact, when, or whether, the cooled/heated water from the injection well reaches the land plot limits

4. RESULTS AND ANALYSIS

For exemplification, using ASMWIN we modelled a land plot considering a doublet geothermal system was in use. The right and left blue lines are the land plot surface limits.

4.1 Case 1: The pre-existing groundwater flow is parallel to the line of the two wells (axis OX) toward the production well (α = 0). This is the most important practical case.

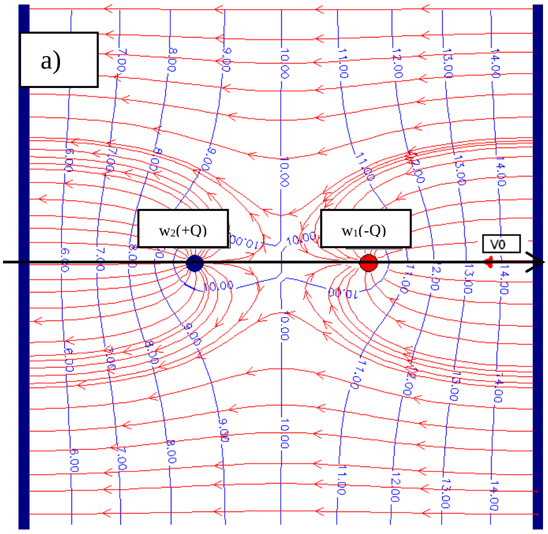

Fig. 5.a. Shapes of the potential network (potential lines and streamlines) for geothermal doublet system placed in a pre-existing groundwater (α = 0) [4]

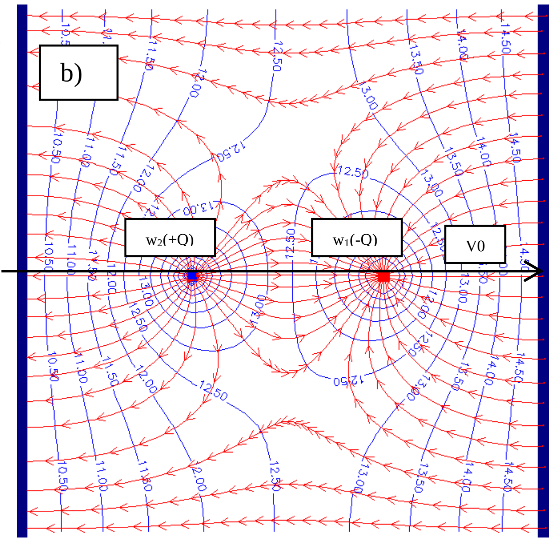

Fig. 5.b. Shapes of the potential network (potential lines and streamlines) for geothermal doublet system placed in a pre-existing groundwater (α = 0) [4]

The situations presented in Fig.5 appear when the flow satisfies certain conditions:

Fig. 5 a), when (V(x = 0) =0) i.e.

$$V_0 \geq \frac{Q}{\pi m d} \qquad (10)$$

In this case the production well (W_1) intercepts the parallel hot water flow, the cooled water from reinjection well (W_2) flows toward downstream without affecting the production well, hence the reinjection well recovery from the heat flux plus the clear direction of the cooled/heated groundwater toward neighboring land.

Fig.5 b), when and ($V(x = d\text{-}r_w) \leq 0$) i.e.

$$V_0 \leq \frac{Q}{2\pi m r_w} \qquad (11)$$

In this case can the injected cooled water reached the production well altering the GSHP performance and still influencing the neighboring land plot thermal regime. Velocity distribution along x-axis can be calculated as:

$$V_x = -V_0 - \frac{Q}{\pi m}\frac{d}{x^2 - d^2} \qquad (12)$$

When $x = d + L_\infty$

Knowing the velocity distribution gives us the possibility to calculate the travel time from the injection well to the land limits or neighboring land plot surface. In the equation of the propagation of water fronts, the pore velocity and retardation factor (1) are considered.

$$T_{L_\infty(v_0)} = \int_{x_1}^{x_2} \frac{dx}{V_x} =$$

$$= n_e R \int_{x_1}^{x_2} \frac{dx}{V_0 + \frac{Q}{\pi m}\frac{d}{x^2 - d^2}} \qquad (13)$$

Finally from (13) we can obtain a simple analytical formula:

$$T_{L_\infty} = \frac{n_e}{v_0}\left(L_\infty - d\right) - \frac{Qdn_eR}{\pi m v_0^2}\frac{1}{\lambda}\operatorname{arctg}\left[\frac{\lambda\left(L_\infty - d\right)}{\lambda^2 + L_\infty}\right] \qquad (14)$$

With $\lambda = \sqrt{\frac{Q \cdot d}{\pi m v_0}}$

An approach using the average velocity leads to:

$$T_{L_\infty} = \frac{n_e\left(L_\infty - d\right)}{v_m} \qquad (15)$$

Were v_m is the numeric average velocity.

Thus we are able to calculate the time in which the cooled/heated groundwater reaches the adjacent land plot. Using several parameters:

Table 1 Parameter values

K	0,0001	Hydraulic conductivity
I	2‰	Slope (%)
V_0	0,0000002	Velocity (m/s)
Q	0,00042	Discharge (m^3/s
n	0,25	Porosity
r_p	0,15	Diameter (m)
d	5	Length (m)

Using equations (14 and 15) we calculated the time it took the water from the injection well to reach the adjacent land. The results show that 31 days are needed for the water to reach and affect the neighboring groundwater land. The retardation factor is negligible but if we use higher values (1,5 or 2) the calculated time is higher.

5. CONCLUSIONS

The mathematical model and the analytical solutions provide a useful tool for experts who need rapid estimation of these GSHP effects on the groundwater and adjacent land plots. From the analysis we conclude that in both cases (fig 5 a, and b) the cooled/heated groundwater reaches other land plots and influences its thermal regime. This is especially true when groundwater flow velocity is high. As a result the neighbors are limited or cannot use their land with geothermal systems. In this regard this action can be considered as “a theft of heat or cold”. Also we found that using an average velocity does not give accurate results compared to the analytical solution. This comparison is subject of new paper.

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