BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LXII No. 3B/2010	126 - 134	Seria Tehnică

Experimental Research Regarding the Maximum Thermal Power that Can Be Extracted from Soil

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Abstract

A mathematical function to evaluate the time evolution of the thermal flow extracted from the soil is necessary within system design processes for extracting the heat from the soil. This paper presents the research conducted in the laboratory of renewable energy from the Petroleum - Gas University of Ploiesti, research which aims to reveal the mechanism of heat removal from the soil and determine the limits of this process.

Key words: *heat, soil, thermal power, decline*

Introduction

The renewable energy laboratory operates in the Petroleum - Gas University of Ploiesti. A department of this laboratory is engaged in studying surface geothermal energy that can be captured by using heat pumps.

The studies and the research are aimed at highlighting the mechanism of heat removal from the soil and determining the limits of this process. Some of the research results are presented in this paper.

Description of experimental installation

The renewable energy laboratory is equipped with a 5 kW heat pump connected to an experimental polygon (Figure 1.). This installation is used for the research made in the geothermal energy area. The heat pump is equipped with sensors and a real time data acquisition system which can cause all operating parameters.

The experimental shooting includes the following systems to extract heat from the ground (Figure 2.):

1. ground water wells - depth 15m, 4m hydrostatic level;
2. Vertical well equipped with a U-shaped loop, depth 40m;
3. spiral loop - the total length 200m, mounted at a depth of 2m in a ditch area of 24m * 3m = 72m^2;
4. Simple loop depth 64m, mounted at 1m.

Fig. 1. Heat pump

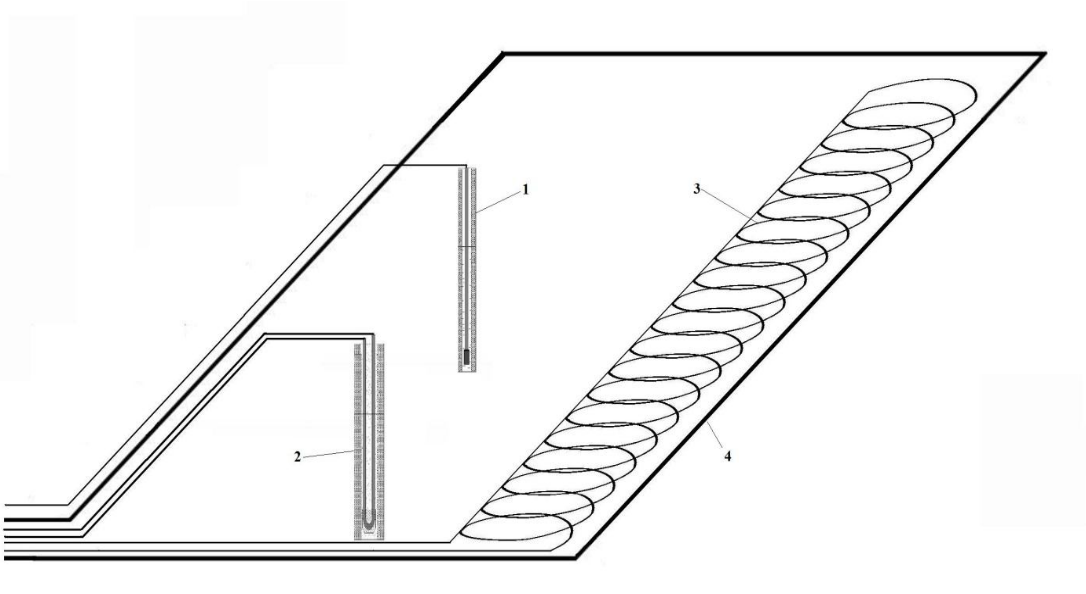


Fig. 2. Experimental polygon

All ground-mounted heat exchangers are made of polyethylene pipe with a diameter of 1 ″.

There are 40 temperature transducers mounted in the polygon. These transducers measure the thermal field around the heat exchangers.

Experimental research on thermal power extracted from the soil

The heat extracted from the soil is used for the vaporization of the thermal agent in the heat pump. After this process, the water which leaves the heat pump evaporator has a temperature lower than that of the soil; this is inserted in the heat exchanger and circulated through the ground taking the heat from it.

Experimental results obtained

For each of the four systems the thermal power extracted from the soil in time is shown below.

a) a simple 60 m long polyethylene loop.

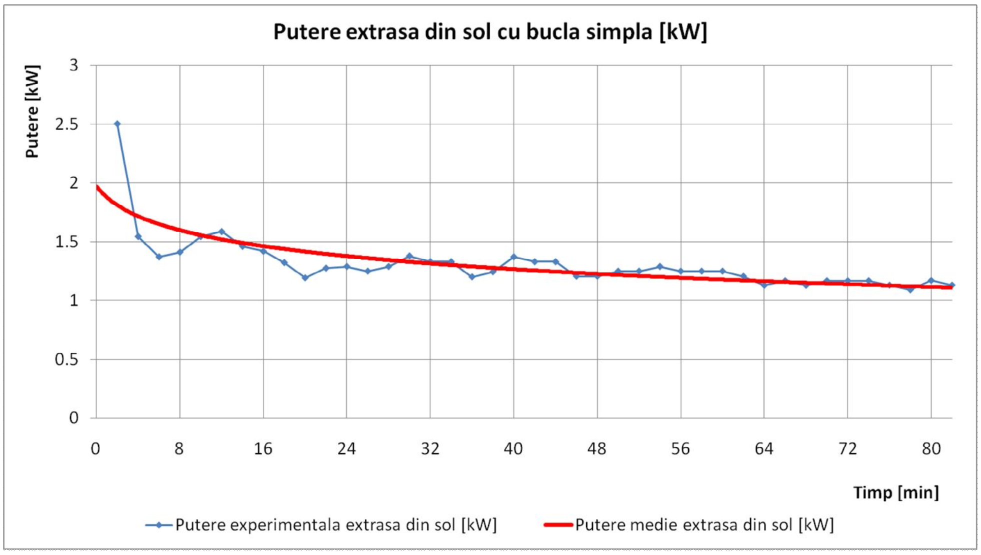


Fig. 3. Variation of the power extracted from the soil using a simple loop [kW]

Figure 3 presents the thermal power decrease per linear meter from 33.33 W/m to 20 W/m in about 80 minutes.

b) a polyethylene loop placed in a 40 m deep pit

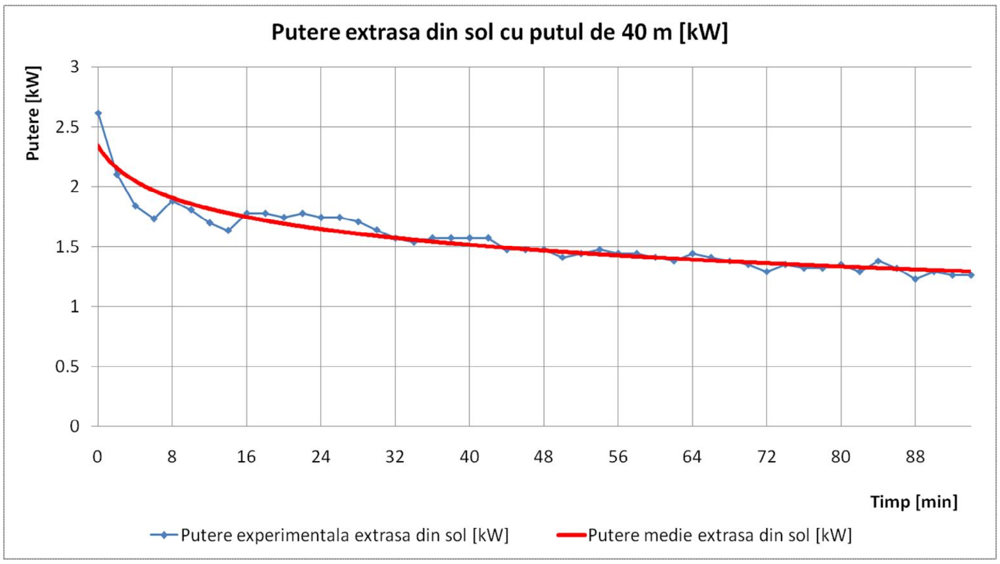


Fig. 4. Variation of the power extracted from the soil using the 40 m deep pit [kW]

The thermal power per linear meter varies from 34.2 W/m to 19.3 W/m in about 90 minutes.

c) a 180 m long spiral polyethylene loop

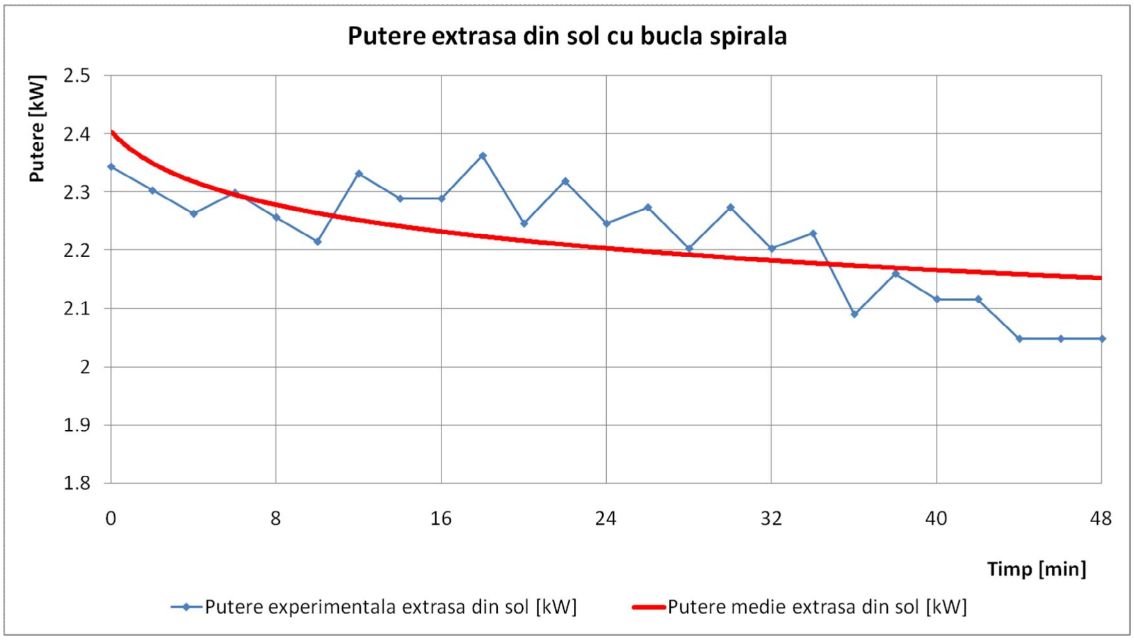


Fig. 5. Variation of the power extracted from the soil using the spiral loop

A decrease in thermal power per linear meter from 13.33 W/m to 11.95 W/m in about 48 minutes can be observed.

d) a groundwater well with a hydrostatic level at 4m

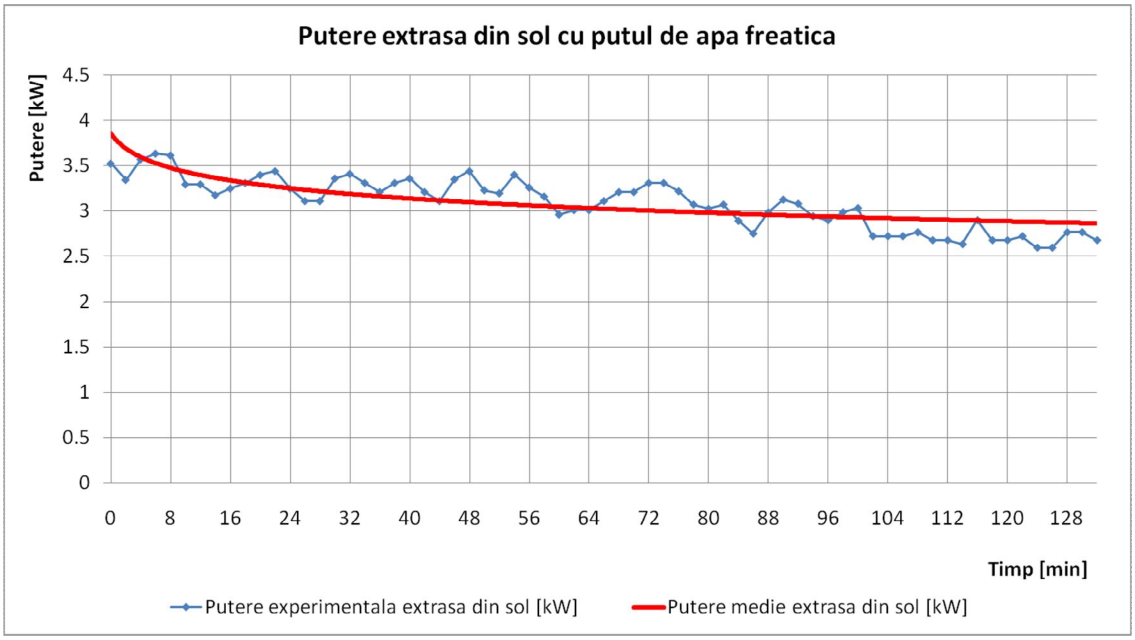


Fig. 6. Variation of the power extracted from the soil using the groundwater well

The thermal power varies from 3.6 kW to 2.8 kW in approximately 130 minutes.

The first part of the curve is influenced by local conditions (temperature) around the pipe at the beginning of heat pump running. Because the necessary groundwater flow is low (~ 0.2 l/s), the stabilization of the thermodynamic conditions around the pipe takes about 60 minutes. After this interval the thermal power extracted from groundwater remains constant throughout the duration of pump operation.

Defining the thermal decline curves

In the petroleum industry, the decline characterizes the decrease rhythm of production (flow) of an oil reservoir. Let us note with Q_0 – the initial flow and with Q – the flow at a certain moment in time, the production decline or the effective decline is defined as:

$$D_e = \frac{Q_0 - Q}{Q_0} \tag{1}$$

The nominal decline is defined using the equation

$$D = -\frac{1}{Q}\frac{dQ}{d\tau} \tag{2}$$

The nominal decline has a definition corresponding to the decrease process of the flow produced by the reservoir because it can be theoretically interpreted. Thus, the nominal decline represents the slope corresponding to graph $\ln Q$ in time, taken as a positive value:

$$D = -\frac{d}{d\tau(\ln Q)} \tag{3}$$

Arps (Trans AIME 1945), using empirical data, showed that the production decline graphs of the reservoirs can be characterized by three types of functions for the nominal decline, functions which characterize a constant, hyperbolic or harmonic decline.

It has been observed that, in practice, the variation of the decline D follows a rule such as:

$$D = \frac{1}{a + b\tau} \tag{4}$$

where a and b are constant and τ is the time.

By integrating the equation (3) with separable variables and introducing the equation (4), the following equation for flow is being obtained:

$$Q(\tau) = \frac{Q_0}{\left(1 + \frac{b}{a}\tau\right)^{\frac{1}{b}}} \tag{5}$$

Equation (5) expresses the hyperbolic dependence of the flow in time.

If in equation (5) the constant $b = 1$, it follows that:

$$Q(\tau) = \frac{Q_0}{1 + \frac{\tau}{a}} \tag{6}$$

This equation represents a harmonic law of flow variation.

If in equation (5) $b \to 0$, it follows that:

$$Q(\tau) = \frac{Q_0}{e^{\frac{\tau}{a}}} \tag{7}$$

equation that represents an exponential law of flow in time or a constant value $D = \frac{1}{a}$ of the decline.

The harmonic decline is a particular case of the hyperbolic decline corresponding to $b = 1$ and it has the following equation:

$$D = cQ \tag{8}$$

Due to the similarity between the flow equation of the oil through porous medium and the diffusion equation of the heat through the soil, similar measurements for the extracted geothermal flux will be defined.

1. The constant thermal decline, D_t = ct.

$$\dot{Q} = \frac{\dot{Q}_0}{e^{\frac{\tau}{a}}} \tag{9}$$

2. The hyperbolic thermal decline

$$\dot{Q} = \frac{\dot{Q}_0}{\left(1 + \frac{b}{a}\tau\right)^{\frac{1}{b}}} \tag{10}$$

3. The harmonic thermal decline

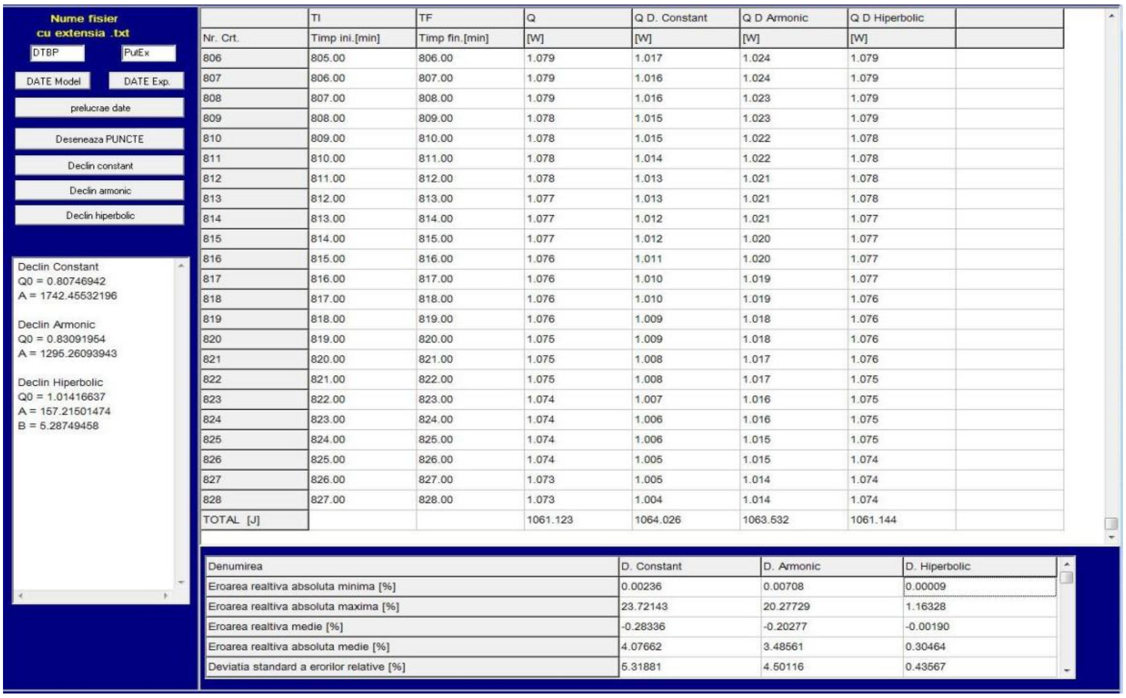
$$\dot{Q} = \frac{\dot{Q}_0}{1 + \frac{\tau}{a}} \tag{11}$$

$\dot{Q}_0$ - the initial thermal flux which is extracted from soil when the heat pump starts to function.

Taking the experimental data for the initial thermal flux, one can consider the value after 15…20 minutes from the starting procedure of the heat pump, time necessary to stabilize the functional parameters of the heat pump.

Numerical results obtained for the vertical shaft

Figure 7 presents a table with the final part of the results. One can observe in the second half of the table the errors between the real thermal flux and the thermal fluxes calculated with the help of the decline curves and the effective thermal decline.



Declin Constant
Q0 = 0.80746942
A = 1742.45532196

Declin Armonic
Q0 = 0.83091954
A = 1295.26093943

Declin Hiperbolic
Q0 = 1.01416637
A = 157.21501474
B = 5.28749458

	TI	TF	Q	Q D. Constant	Q D Armonic	Q D Hiperbolic
Nr. Crt.	Timp ini.[min]	Timp fin.[min]	[W]	[W]	[W]	[W]
806	805.00	806.00	1.079	1.017	1.024	1.079
807	806.00	807.00	1.079	1.016	1.024	1.079
808	807.00	808.00	1.079	1.016	1.023	1.079
809	808.00	809.00	1.078	1.015	1.023	1.079
810	809.00	810.00	1.078	1.015	1.022	1.078
811	810.00	811.00	1.078	1.014	1.022	1.078
812	811.00	812.00	1.078	1.013	1.021	1.078
813	812.00	813.00	1.077	1.013	1.021	1.078
814	813.00	814.00	1.077	1.012	1.021	1.077
815	814.00	815.00	1.077	1.012	1.020	1.077
816	815.00	816.00	1.076	1.011	1.020	1.077
817	816.00	817.00	1.076	1.010	1.019	1.077
818	817.00	818.00	1.076	1.010	1.019	1.076
819	818.00	819.00	1.076	1.009	1.018	1.076
820	819.00	820.00	1.075	1.009	1.018	1.076
821	820.00	821.00	1.075	1.008	1.017	1.076
822	821.00	822.00	1.075	1.008	1.017	1.075
823	822.00	823.00	1.074	1.007	1.016	1.075
824	823.00	824.00	1.074	1.006	1.016	1.075
825	824.00	825.00	1.074	1.006	1.015	1.075
826	825.00	826.00	1.074	1.005	1.015	1.074
827	826.00	827.00	1.073	1.005	1.014	1.074
828	827.00	828.00	1.073	1.004	1.014	1.074
TOTAL [J]			1061.123	1064.026	1063.532	1061.144

Denumirea	D. Constant	D. Armonic	D. Hiperbolic
Eroarea realtiva absoluta minima [%]	0.00236	0.00708	0.00009
Eroarea realtiva absoluta maxima [%]	23.72143	20.27729	1.16328
Eroarea realtiva medie [%]	-0.28336	-0.20277	-0.00190
Eroarea realtiva absoluta medie [%]	4.07662	3.48561	0.30464
Deviatia standard a erorilor relative [%]	5.31881	4.50116	0.43567

Fig. 7. Example of numerical results obtained

Values **A** and **B** of the decline coefficients together with the initial thermal flux Q_0 are presented in the panel on the left. The graphical analysis presented in figure 8 is more suggestive. This figure presents the points which represent the effective thermal flux and a curve which represents the thermal flux calculated taking into account the decline.

The graphical presentation of the results shows that the best decline curve is the hyperbolic decline curve, as it approximated the decline of the thermal flux with the lowest errors.

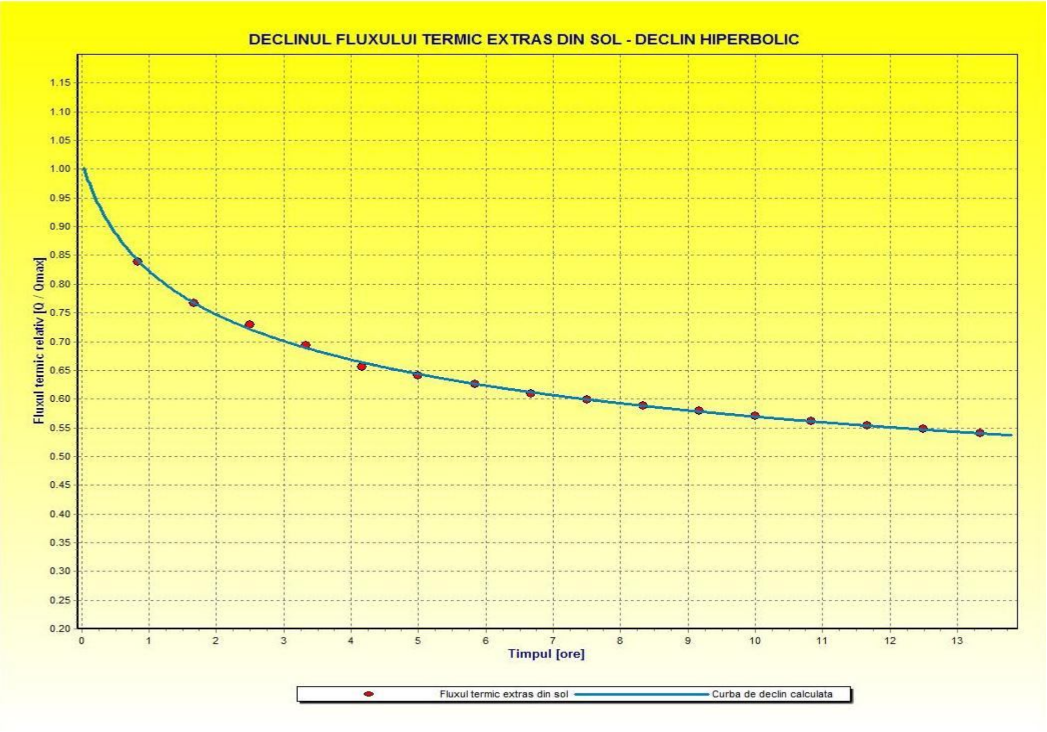


Fig. 8. The hyperbolic decline curve

There are both similarities and dissimilarities expressed mathematically by the equations that describe the two phenomena between the oil extraction and the thermal flux extraction from a well. Thus, in the case of oil flow to the well, more than often the porous medium is uneven, the production layer can be tilted, the water or gas in the reservoir influence the flow process, etc. In the case of the thermal flux transfer to the extraction well, the soil around the well is even in what the thermodynamic properties are concerned (conductivity, specific heat, density, etc) on large areas, so that the medium can be considered homogenous and isotropic [3]. These things can explain the fact that, during the oil production analysis, there are situations when the constant or harmonic decline can be used with minimal errors. In the case of thermal wells, only the hyperbolic decline approximates best the decrease of the thermal flux in time.

Conclusions

The experimental measurements made in the Renewable source energy laboratory from the Petroleum-Gas University of Ploiesti have shown that in the case of heat exchangers mounted in the soil, used for the extraction of the thermal energy using the heat pump, the thermal power extracted decreases in time [4, 6].

A mathematical function that allows the evaluation of the evolution in time of the thermal flux extracted from the soil is useful within the design processes of these systems.

A thermal decline was defined using the analogy with the production decline in the case of oil wells. Different decline curves were calculated for the extracted thermal power.

By comparing the decline curves with the data obtained both numerically and experimentally, it has been discovered that the decline curve method can be successfully used to estimate the evolution of the thermal power extracted from the soil.

In all cases analyzed, the curve that best approximates the decline of the extracted thermal power is the hyperbolic decline curve.

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Cercetări experimentale privind determinarea puterii termice maxime ce poate fi extrasă din sol

Rezumat

În cadrul proceselor de proiectare a sistemelor de extracţie a căldurii dinsol este utilă o funcţie matematică care să permită evaluarea evoluţiei în timp a fluxului termic extras din sol. Lucrarea de faţă prezintă cercetările întreprinse în cadrul laboratorului de surse regenerabile de energie din Universitatea Petrol – Gaze din Ploieşti ce au drept scop evidenţierea mecanismului de extragere a căldurii din sol precum şi determinarea limitelor acestui proces.