# Analysis of the Thermal Power Decline Extracted from a Vertical Shaft Equipped with a Simple Polyethylene U-shaped Loop

**SORIN NEACSU[1]*, MIHAI ALBULESCU[1], CRISTIAN EPARU[1], MARCELA PATARLAGEANU[1], FLORINEL DINU[1], ADRIANA CONT[2]**
Petroleum-Gas University of Ploieşti, 39 Bucureşti Blv., Ploieşti, Romania
[2] S.C. Ciocârlia S.A, 71 Postei, Str., Ploiesti, Romania

*This paper presents the research performed in the laboratory of Renewable Energy Sources within the Petroleum-Gas University of Ploieşti regarding the use of heat pumps for surface geothermal energy extraction. The paper also examines the decrease of thermal power extracted via heat exchangers mounted in the soil, due to the cooling of the surrounding soil. The results obtained for a simple U-shaped loop mounted in a vertical shaft are presented as well.*

*Keywords: thermal decline, Geoexchange, polyethylene, heat pump, numerical models*

Numerical models and experimental research [3, 5] have shown that in the case of heat pumps used for heating dwellings, the thermal power extracted from the soil through heat exchangers made of polyethylene pipe (Geoexchange system) mounted in different geometries, decreases with increasing the continuous run time of the unit.

Taking into account that the heat diffusion equation (1) is similar to the oil flow equation through porous medium (2) and that during the exploitation of crude oil reservoirs a decline in production occurs, this paper proposes a method of assessing the decline of thermal power extracted from soil similar to the methods used in the petroleum industry.

$$\nabla^2 T = \frac{\rho c_p}{\lambda}\frac{\partial T}{\partial \tau} \qquad (1)$$

$$\nabla^2 p = \frac{s}{k}\frac{\partial p}{\partial \tau} \qquad (2)$$

where:

$T$ is temperature;
$\rho$ - density;
$c_p$ - specific heat mass;
$\lambda$- coefficient of thermal conductivity;
$\rho c_p$ - characteristic of thermal storage heat capacity;
$p$ - pressure;
$s$ - storage coefficient;
$k$ - permeability environment;
$\tau$ - time.

**Defining the thermal decline curves**

The decline in oil industry characterizes the decrease production (flow) rate of an oil reservoir. Let us note $Q_0$ - initial flow and $Q$ - flow at a certain moment, the decline in production or the actual decline is thus defined [2]:

$$D_e = \frac{Q_0 - Q}{Q_0} \qquad (3)$$

The nominal decline is defined by the formula

$$D = -\frac{1}{Q}\frac{dQ}{d\tau} \qquad (4)$$

Thus, the nominal decline represents the gradient of ln $Q$ in time taken as positive value:

$$D = -\frac{d}{d\tau(lnQ)} \qquad (5)$$

Using empirical data, ARPS (Trans AIME 1945) has shown that the decline production graphs of the reservoirs can be characterized according to three types of functions for a nominal decline, functions that characterize a constant, hyperbolic or harmonic decline.

In practice it has been found that the variation of the decline $D$ follows a law such as:

$$D = \frac{1}{a + b\tau} \qquad (6)$$

where $a$ and $b$ are constant values and $\tau$ is the time.

By integrating equation (4) with separate variables and by inserting equation (6), the function below is being obtained:

$$Q(\tau) = \frac{Q_0}{\left(1 + \frac{b}{a}\tau\right)^{\frac{1}{b}}} \qquad (7)$$

Equation (7) expresses the hyperbolic dependence of flow over time.

If in equation (7) the constant value $b = 1$ is customized, this equation follows:

$$Q(\tau) = \frac{Q_0}{1 + \frac{\tau}{a}} \qquad (8)$$

This equation represents a harmonic law of flow variation.

If in equation (7) the term $b \rightarrow 0$, this equation becomes:

$$Q(\tau) = \frac{Q_0}{e^{\frac{\tau}{a}}} \qquad (9)$$

equation which is an exponential law of the flow in time or a constant value D = 1 / $\alpha$ of the decline.

The harmonic decline is a special case of the hyperbolic decline corresponding to $b = 1$ and it has the expression:

$$D = cQ \qquad (10)$$

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

* email: iepy79@yahoo.com

1. The constant thermal decline, $D_t$ = ct.

$$\dot{Q} = \frac{\dot{Q}_0}{e^{\frac{\tau}{a}}} \quad (11)$$

2. The hyperbolic thermal decline

$$\dot{Q} = \frac{\dot{Q}_0}{\left(1 + \frac{b}{a}\tau\right)^{\frac{1}{b}}} \quad (12)$$

3. The harmonic decline

$$\dot{Q} = \frac{\dot{Q}_0}{1 + \frac{\tau}{a}} \quad (13)$$

where $Q_0$ is the initial thermal flow which is extracted from the soil at the beginning of the heat pump functioning. From the experimental data for initial thermal flow, the value after 15 ... 20 min of heat pump functioning can be considered, time that is required to stabilize the functional parameters of the heat pump.

**Analysis of the thermal flow decline using the numerical model**

The thermal flow, represented by the heat extracted from the soil via a section of the pipe, has been defined as equal to the conductive thermal flow taken by the pipe. By integrating the numerical model, the limit condition on the pipe is being determined out of the equality of convective thermal flow, taken by water and conductive thermal flow transferred to the soil. This thing allows determining the heat taken up by a segment of pipe only on conductive thermal flow [1, 3].

In a section of the pipe, the thermal flow is calculated according to the scheme in figure 1. Thus, the conductive thermal flow is calculated using the thermal gradient of the soil at the pipe wall. Using the notations in figure 1, the thermal flow is:

$$\dot{q} = -A\lambda \frac{T_2 - T_1}{x_2 - x_1}$$

where:

*A* is the lateral area of the pipe segment

λ-the coefficient of thermal conductivity of soil.

In order to determine the dynamics of the thermal flow and the curves that characterize it, the thermal flows have been calculated in the same section of pipe at various moments, then the results were processed with specialized programs to determine the coefficients of the decline curves. The numerical analysis presented in this paper was performed for the vertical shaft equipped with a simple U-shaped loop.

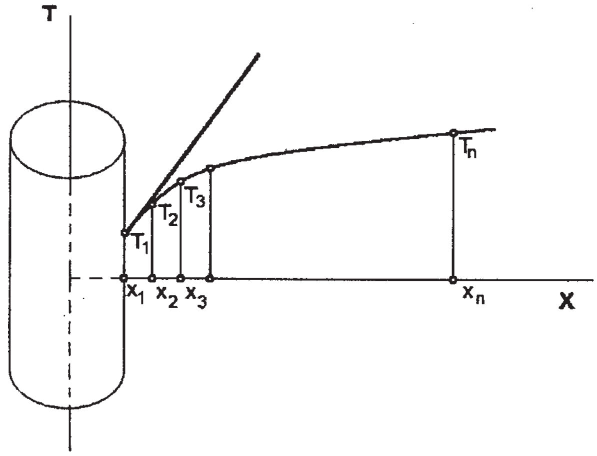


Fig. 1.

**Results and discussions**

*Numerical results for the vertical shaft*

Figure 2 shows a table with the final results of calculations, in which the bottom presents the errors between the actual thermal flow and the thermal flows calculated using decline curves and heat flow effectively.

Values ***A*** and ***B*** of the decline coefficients with initial thermal flow $Q_0$ are shown in the left box. The graphical analysis presented in figures 3, 4, 5 and 6 is more suggestive. Each figure presents the points which represent the actual thermal flow and a thermal flow curve that is resulted based on the decline variation.

The graphs show that the best decline curve, which approximates the lowest errors for the thermal decline flow, is the hyperbolic decline curve.

Oil extraction from well and thermal flow extraction present similarities expressed mathematically by the similarity of the equations describing the two phenomena, but also differences. Thus, in the case of oil flow to the well, more than often the porous medium around the well is uneven, the production layer can be tilted, the water or the gas from the reservoir influence the flow process, etc. In the case of thermal flow transfer to the extraction well,

| | TI | TF | Q | Q Constant D. | Q Harmonic D. | Q Hyperbolic D. |
|---|---|---|---|---|---|---|
| No | Ini. time [min] | End time [min] | [W] | [W] | [W] | [W] |
| 19 | 19.00 | 20.00 | 1.984 | 1.791 | 1.814 | 2.017 |
| 20 | 20.00 | 21.00 | 1.983 | 1.790 | 1.813 | 2.015 |
| 21 | 21.00 | 22.00 | 1.982 | 1.790 | 1.813 | 2.013 |
| 22 | 22.00 | 23.00 | 1.981 | 1.790 | 1.813 | 2.011 |
| 23 | 23.00 | 24.00 | 1.980 | 1.790 | 1.812 | 2.009 |
| 24 | 24.00 | 25.00 | 1.978 | 1.790 | 1.812 | 2.008 |
| 25 | 25.00 | 26.00 | 1.977 | 1.789 | 1.812 | 2.006 |

| Name | Constant D. | Harmonic D. | Hyperbolic D. |
|---|---|---|---|
| Minimum absolute relative error [%] | 0.00148 | 0.00048 | 0.00021 |
| Maximum absolute relative error [%] | 11.42177 | 9.96566 | 2.56597 |
| Average relative error [%] | -0.13938 | -0.11237 | -0.01035 |
| Average absolute relative error [%] | 3.17056 | 2.87081 | 0.86299 |
| Standard deviation of relative error [%] | 3.73147 | 3.35094 | 1.01747 |

Fig.2.

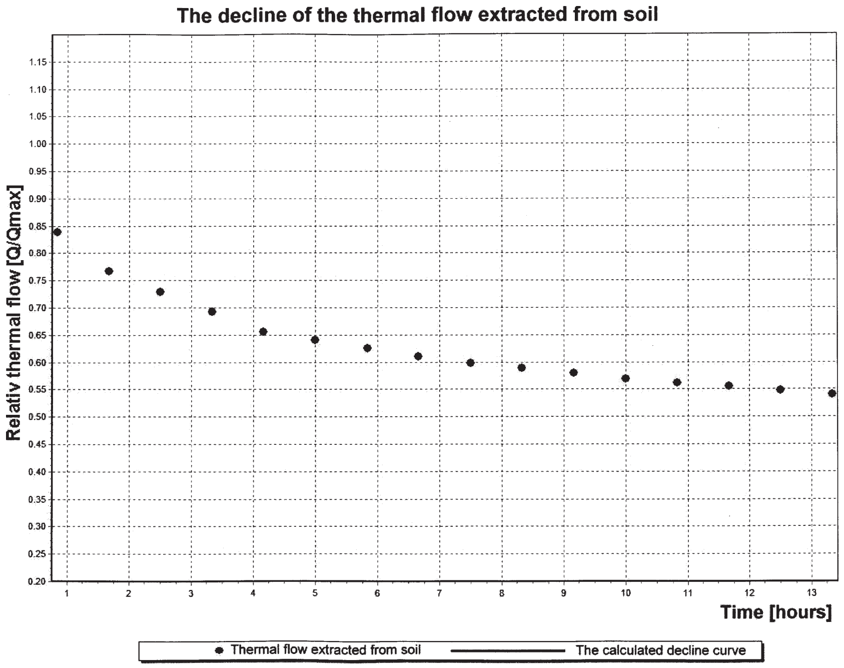


Fig.3.

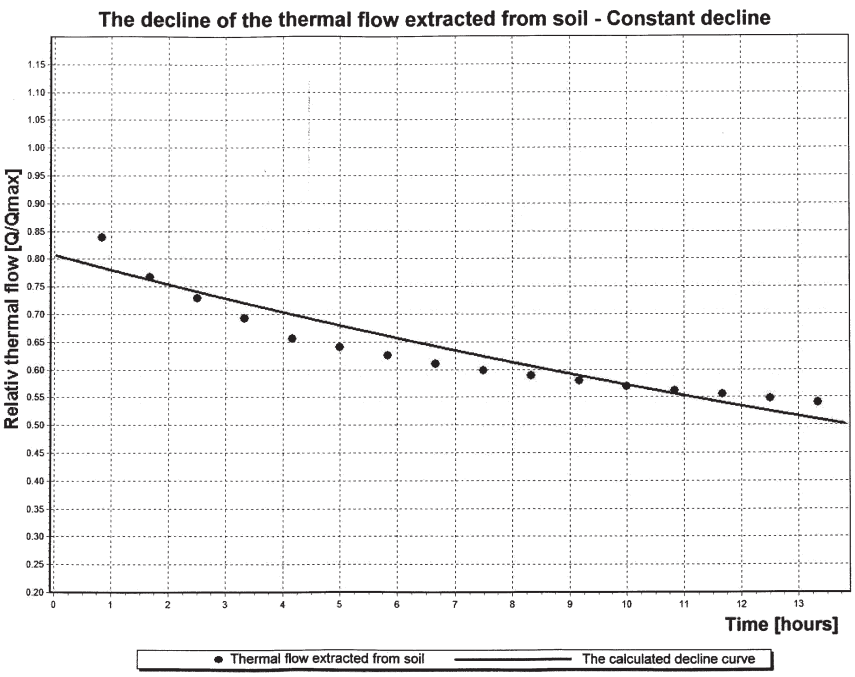


Fig.4.

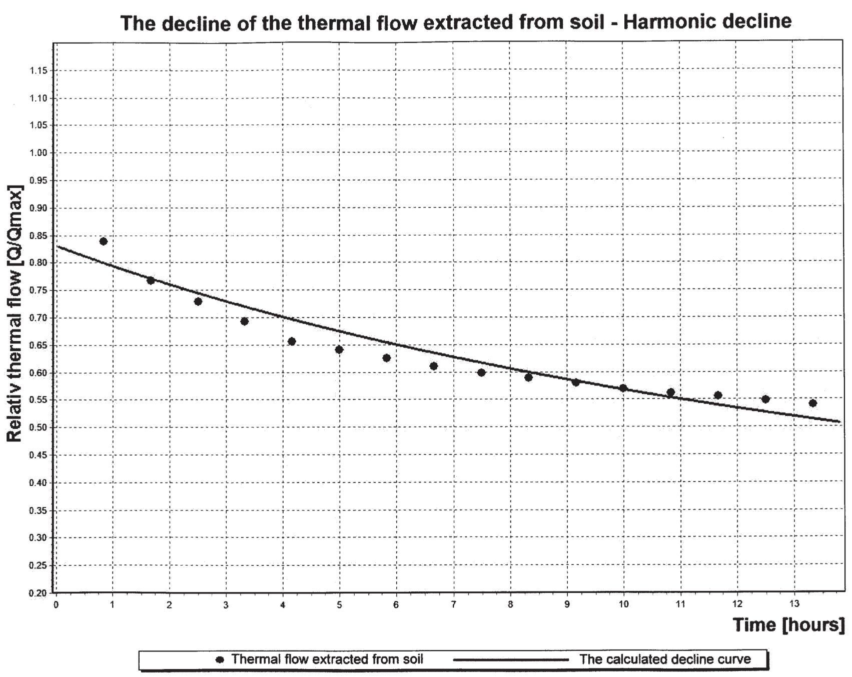


Fig.5.

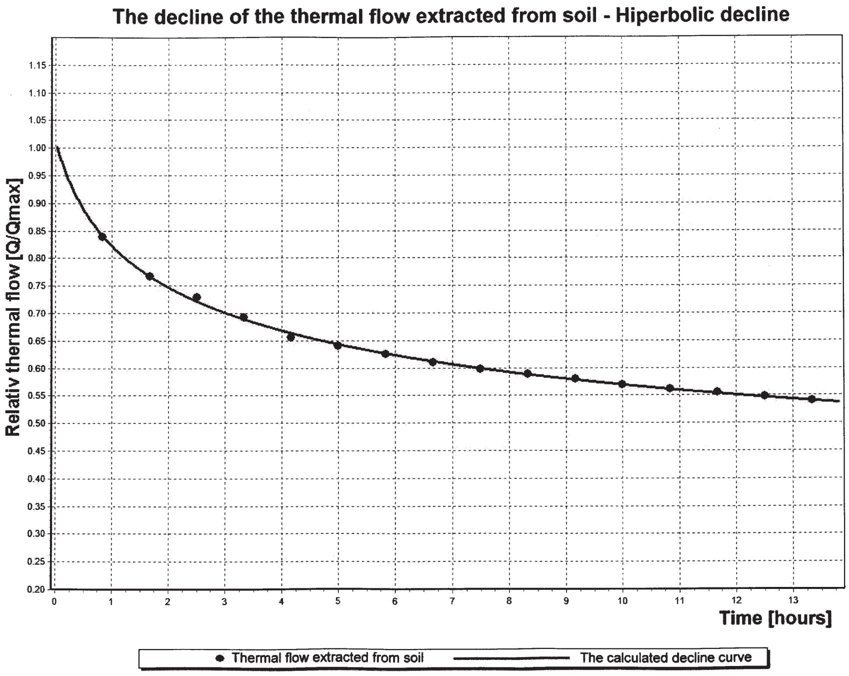


Fig.6.

| | TI | TF | Q | Q Constant D. | Q Harmonic D. | Q Hyperbolic D. |
|---|---|---|---|---|---|---|
| No | Ini. time [min] | End time [min] | [W] | [W] | [W] | [W] |
| 44 | 43.00 | 44.00 | 1.032 | 0.970 | 0.976 | 1.012 |
| 45 | 44.00 | 45.00 | 0.985 | 0.958 | 0.966 | 1.006 |
| 46 | 45.00 | 46.00 | 1.055 | 0.947 | 0.957 | 1.001 |
| 47 | 46.00 | 47.00 | 1.008 | 0.936 | 0.948 | 0.995 |
| 48 | 47.00 | 48.00 | 0.938 | 0.924 | 0.939 | 0.990 |
| TOTAL [J] | | | 59.290 | 59.644 | 59.611 | 59.517 |

| Name | Constant D. | Harmonic D. | Hyperbolic D. |
|---|---|---|---|
| Minimum absolute relative error [%] | 0.21885 | 0.11546 | 0.02922 |
| Maximum absolute relative error [%] | 27.60509 | 24.68069 | 20.28034 |
| Average relative error [%] | -0.56122 | -0.45343 | -0.30621 |
| Average absolute relative error [%] | 5.22139 | 4.55635 | 3.65847 |
| Standard deviation of relative error [%] | 7.54946 | 6.78951 | 5.58359 |

Fig.7.

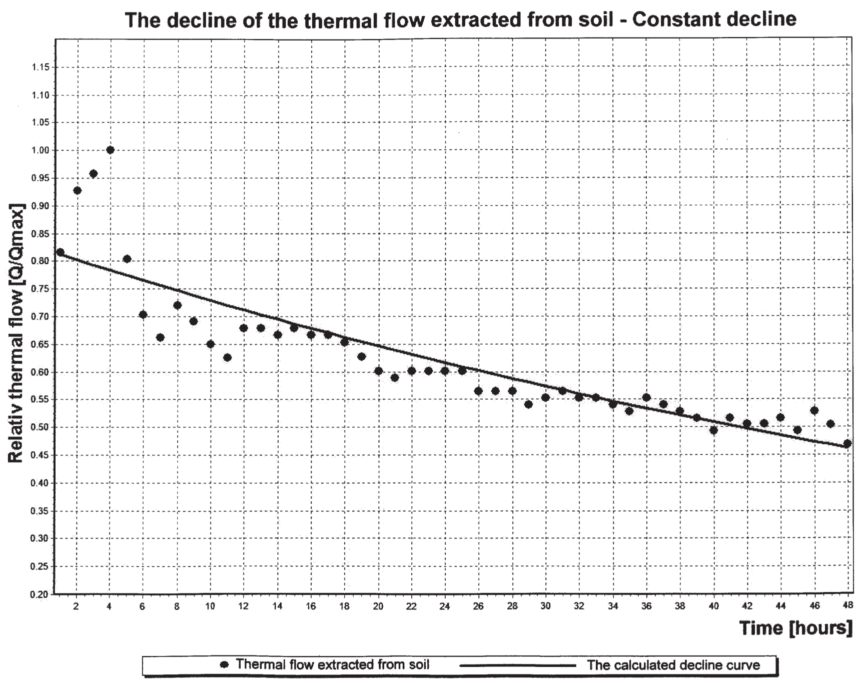


Fig. 8.

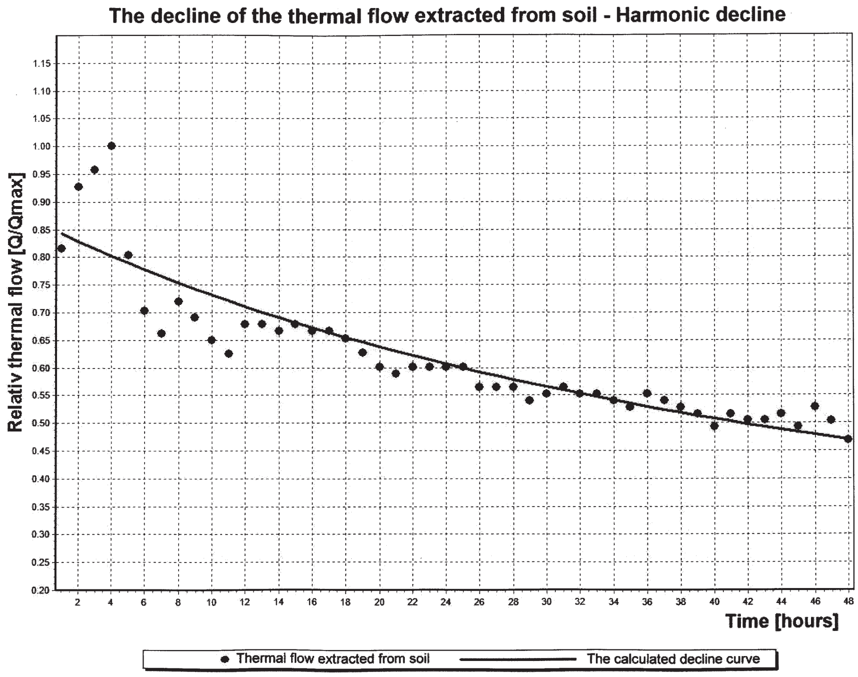


Fig. 9

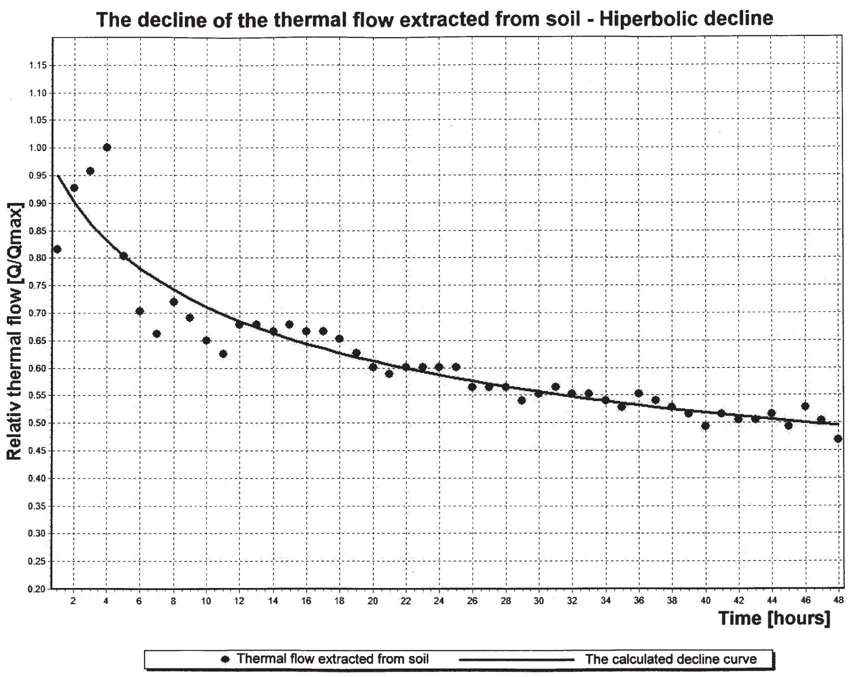


Fig. 10..

the soil around it is uniform in terms of thermodynamic properties (conductivity, specific heat, density, etc.) on large portions, so that the environment can be considered homogeneous and isotropic [6]. This may explain that during the analysis of oil production wells, there are situations in which constant or harmonic decline can be used with minimal errors, and in the case of thermal wells, only the hyperbolic approximates best the decrease of thermal flow in time.

*Experimental results for vertical shaft equipped with a simple polyethylene U-shaped loop*

For experimental determinations, in this case, water was circulated through the loop mounted vertically in the shaft for 48 min.

Time was short because the temperature of the water circulated through the loop decreased rapidly from 16 to 5°C which led to a vaporization temperature of freon in the heat pump evaporator -2°C.

The result of processing experimental data is shown in figure 7. One can notice that the above tendency is maintained, the smallest errors occurring in the case of the hyperbolic decline.

## Conclusions

The experimental measurements carried out in the Renewable Energy Laboratory polygon of the Petroleum-Gas University of Ploieşti showed that when mounted in soil, the polyethylene heat exchangers used to extract thermal energy using heat pumps, the extracted thermal power decreases in time [4, 6].

A mathematical function is useful to assess the evolution over time of the thermal flow extracted from the soil during the process of designing this type of systems.

A thermal decline has been defined using the analogy with the production decline in oil wells and various decline curves for the extracted thermal power have been calculated starting from this value.

Comparing the decline curves with the obtained data, both numerically and experimentally, shows that the decline curve method is a method that can be successfully used to estimate the evolution of thermal power extracted from the soil. In all cases considered the curve that best approximates the extracted thermal power decline is the hyperbolic decline curve.

## References


1.CONŢ, A., Cercetări privind creşterea capacităţii de valorificare a energiei geotermice prin utilizarea pompelor de căldură, PhD Thesis, Ploieşti, 2009

2.CREŢU, I**.,** Hidraulica zăcămintelor de hidrocarburi, vol. I, II, Editura tehnică, Bucureşti, 1987

3.EPARU, C., NEACŞU, S., RĂDULESCU, R., ALBULESCU, M., Experimental Determination of heat Losses for a Buried Transport Pipeline in Non-Isothermal State, Proceedings of the Internationally Attended National Conference on Technical Thermodynamics, Braşov, 2009

4.NEACŞU, S., EPARU, C., RĂDULESCU, R., AVRAMESCU, G., Experimental Analysis of Soil Heat Extraction Systems, Proceedings of the Internationally Attended National Conference on Technical Thermodynamics, Braşov, 2009

5.NEACŞU, S., EPARU, C., COSMA, M., Theoretical and Experimental Research Regarding the Soil Thermal Response, Conferinţa internaţională "Science and Technology in the Context of Sustainable Development", Ploieşti, 2008

6.NEACŞU, S., TRIFAN, C., ALBULESCU, M., RĂDULESCU, R., Rev. Chim.(Bucharest), **58**, nr. 10, 2007, p. 992


Manuscript received: 1.02.2010