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Exergy and Economic Analysis of Effectiveness of Geothermal Heat Supply Systems

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ABSTRACT

In the article an analysis method of geothermal heat supply systems is presented, that allows to identify factors of energy and economical system effectiveness. The given method can be applied for search of optional parameters and comparison of effectiveness of different system options of geothermal heat supply systems.

1. INTRODUCTION

Usefulness of geothermal energy usage for heat supply has to be technically and economically justified. Originally it is necessary to forecast stocks of geothermal resources and their energy potential, to determine construction sites of geothermal circulation systems, to take into account potential and prospect customers, necessity of combining with other energy sources, technical, ecological and other aspects.

One of the primary tasks under formation of geothermal heat supply systems is determining of constructional and technological parameters that provide optimal economic conditions of their construction and operation (Boguslavskiy, 1981; Boguslavskiy, 1984; DiPippo, 2008). Tasks of optimizing of rates and scales of including of geothermal power sources into supply-demand balance of a country, tasks of optimal design and control of geothermal heat supply systems are known. Complex solution of the given tasks is quite complicated.

The system of geothermal heat supply combines with complicated interaction of factors of natural, technogenic and economical character, that requires optimization of its parameters for support of effective operation.

Economic factors (reduced costs, production cost, payback period, earning power and others) are considered mostly as a general criterium in the tasks of optimization of geothermal heat supply systems (Boguslavskiy, 1981; Boguslavskiy, 1984). Under current conditions a geothermal heat supply system has to meet the requirements as per resource-saving (economy of power resources, lowest material consumption), energy (maximum efficiency factor) and economic effectiveness, environmental safety.

2. OBJECTIVE

From the presented analysis it follows, that the search task of optimal parameters of a geothermal heat supply system needs to be considered from the viewpoint of economical and energy effectiveness simultaneously. Therefore, there can be several target functions (at least two), that is the task of optimization is multi-criteria. Search of optimal constructional and technological parameters of a geothermal heat supply system is represented as parametric optimization – the definition procedure of internal parameters values of a designed object, under which the best combination of properties is achieved.

3. MAIN RESULTS

The simplest system of geothermal heat supply consists of a geothermal circulation system, a force pump, a heat exchanger for heat transfer from geothermal fluid to a heat carrier of a heat supply system, an ultimate customer of thermal power (for example heating systems, hot water supply). If required, a peak thermal energy source, operating on fuel or electric power, can be included into the system (Boguslavskiy, 1984; Gadzhyev et al., 1984; Bugai and Redko, 2013).

Therefore, various kinds of energy, such as geothermal, electrical, thermal, are involved into the system of geothermal heat supply. Usage of each kind of energy in the system determines its energy efficiency. Use of thermal efficiency factor is not rational for estimation of the given kind of effectiveness, because it does not indicate usage effectiveness of all kinds of energy in the system. That is why, using of exergy efficiency, indicating thermodynamic perfection of any technical system, is rational (DiPippo, 2008; Brodyanskiy, 1991; Redko and Bugai, 2009).

Annual exergy efficiency factor for a geothermal heat supply system with a peak reheater can be presented in the following formula:

$$\eta_e = \frac{E_{u.h}}{E_f + E_{p.r} + E_p^h + E_p^s}, \tag{1}$$

where $E_{u.h}$ – exergy of useful heat flow for heating and hot water supply for a year; E_f – exergy of geothermal fluid flow for a year; $E_{p.r}$ – exergy heat flow from a peak reheater (for example a gas boiler) for a year; E_p^h – exergy of electric power, that is used for pump work during a heating season of a year; E_p^s – exergy of electric power, that is used for pump work during a non-heating (summer) season of a year.

Production cost of heat energy, provided to a customer, is rational to apply as an economical objective function for search of optimal parameters of a geothermal heat supply system. The given economical parameter is rather complex to define, as it depends on a lot of factors. That is why, the following economical parameters such as unit capital and operating costs, can be used for simplification of optimization tasks.

The reason of choice of proposed economical parameters is as follows. It is commonly known that capital and operating costs determine production cost. Initial investments are accounted for building of wells in the systems of geothermal heat supply. A lot of factors influence over cost of well building, these are a category of strength rock, a drilling method, depth and others. One of the main parameter, determining cost of a well, is a diameter. 1 meter cost of a well from a diameter for definite drilling conditions can be presented in the formula:

$$C_w = f(C,d) \quad , \tag{2}$$

where C – cost of 1 meter of a well with a normal diameter of an operational pipe, for example 146 mm; d – a diameter of an operational pipe of a well, the cost of which is determining.

Main operational costs, except various kinds of payments, are accounted for electric energy, necessary for work of pumps. Electric energy consumption of a force pump of a geothermal circulating system for a heating season will comprise, kW·h:

$$N_h = \frac{P_h \cdot m_h \cdot \tau \cdot 10^{-3}}{\rho \cdot \eta_p \cdot \eta_m}, \tag{3}$$

and for a non-heating season:

$$N_s = \frac{P_s \cdot m_s \cdot (\tau_y - \tau) \cdot 10^{-3}}{\rho \cdot \eta_p \cdot \eta_m}, \tag{4}$$

where P_h and P_s – average pressure, produced by a force pump, for heating and non-heating seasons of a year correspondingly, Pa; m_h and m_s – average consumption of geothermal fluid for heating and non-heating seasons of a year correspondingly, kg/s; τ_y – duration of an operating period of the system for a year, h; τ – duration of a heating season, h; ρ – density of geothermal fluid, kg/m^3; η_p – efficiency of a pump; η_m – efficiency of a pump motor.

Cost of consumed electric energy for a year:

$$C_{el.} = T \cdot \left(N_h + N_s\right), \tag{5}$$

where T – electric rate, money units/(kW·h).

Economical objective functions are unit capital and operating costs, with account for mentioned above tolerances, can be represented in the formulae:

$$C_c^U = \frac{\sum_{i=1}^{n} C_{wi} \cdot h_i}{\left(Q_h^g + Q_{h.w}^g\right) \cdot 10^{-3}}, \text{ money units/MW} \tag{6}$$

where C_{wi} – cost of 1 m of i-th well, included in a geothermal circulating system; h_i – depth of i-th well, included in a geothermal circulating system; Q_h^g – heat power of a heating system, provided by geothermal energy, kW; $Q_{h.w}^g$ – heat power of a hot water supply system, provided by geothermal energy, kW;

$$C_{op.}^U = \frac{T \cdot \left(N_h + N_s\right)}{Q_y^g}, \text{ money units/ GJ} \tag{7}$$

where Q_y^g – annual consumption of geothermal energy for heat supply, GJ.

Exergy and economical objective functions, expressed by formulae (1), (6-7), can be presented in functional form from the following technological and constructional parameters of a geothermal heat supply system such as ratio of heat power of a hot water supply system $Q_{h.w}^g$ to heat power of a heating system Q_h^g, provided by geothermal energy, number of production wells of a geothermal circulating system n, a diameter of production wells $d_{pr.}$, a diameter of an injection well $d_{in.}$. With a purpose of search of optimal parameters of a geothermal heat supply system, that provide its energy and economic efficiency, it is necessary to solve an optimization task, which is as follows:

$$\eta_e(Q_h^g, Q_{h.w}^g, n, d_{pr.}, d_{in.}) \rightarrow \max; \qquad (8)$$

$$C_c^U(Q_h^g, Q_{h.w}^g, n, d_{pr.}, d_{in.}) \rightarrow \min; \qquad (9)$$

$$C_{op.}^U(Q_h^g, Q_{h.w}^g, n, d_{pr.}, d_{in.}) \rightarrow \min\ . \qquad (10)$$

Thus, an optimization task of a geothermal heat supply system reduces to definition of optimal parameters of the system, providing maximum or near to maximum value of exergy efficiency under minimum capital and operating costs.

A genetic algorithm can be used for solution of the given multi-criteria optimization task (Poloni et al., 1997; Poloni et al., 2000). A lot of effective solutions are usually found to be nonequivalent solutions on the content (a set of initial parameters) in the multi-criteria task. That is why more complete information about preferences is necessary for a reasonable choice.

Using of a genetic algorithm, an optimization task of a geothermal heat supply system with power 2 MW on the base of the Northern Sivash deposit, AR Crimea in Ukraine, was solved. A lot of initial solutions with a set of initial constructional and technological parameters of the system are presented in Fig. 1. A lot of effective solutions after performance of optimization by the method of a genetic algorithm are presented in Fig. 2.

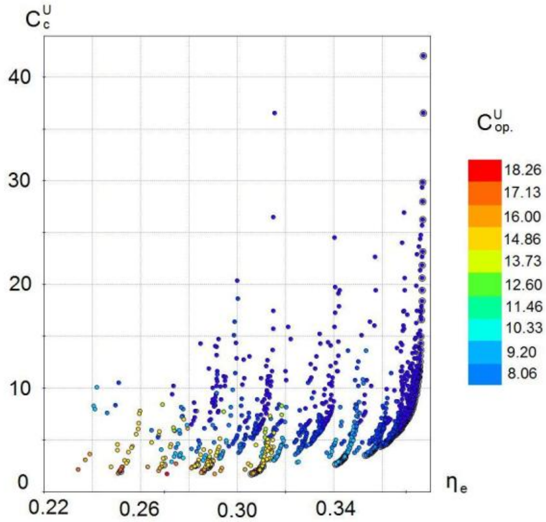

Figure 1: Initial variety of solutions of a geothermal heat supply system with power 2,0 MW

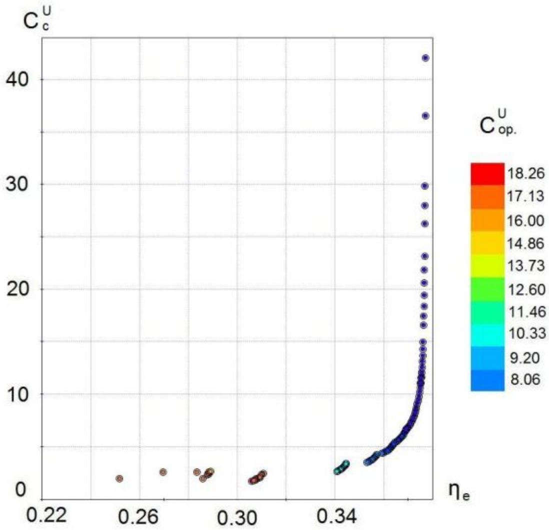

Figure 2: Variety of effective as per Pareto solutions of a geothermal heat supply system with power 2,0 MW

Each circle in the diagram (Fig. 1 and 2) presents one of the solution of a geothermal heat supply system, which a definite set of constructional and technological parameters of the system conforms to. Values of exergy efficiency are shown on the axis of abscissa, unit capital costs are shown on the axis of ordinates, the colour of the circle conforms to the value of unit operating costs.

Analyzing the diagrams, it can be defined that minimum values of operating costs and maximum values of unit capital costs are character for variants of geothermal heat supply systems with maximum values of exergy efficiency.

A lot of effective as per Pareto solutions of the system is much less, than initial number of variants. According to approach to optimization conditions, a solution area in the fracture zone in Fig. 2 should be emphasized: exergy efficiency of the given variants of the system aims to maximum, operating and capital costs – to minimum. The analysis of specified variants of the system as per constructional and technological parameters allows to define that variant, which complies with specified requirements in the best way.

In the given task, an optimal alternative is implementation of a geothermal circulation heat supply system, that consists of two (maximum three) production wells, with a diameter 114 mm and one injection well, with a diameter 179 mm under primary provision of heat duty for hot water supply by means of geothermal energy.

Further economical assessment of the chosen variant of a geothermal heat supply system should be performed as per the value of discounted free cash flow. The given method corresponds to modern approach regarding to the assessment of economical effectiveness of investment projects (McConnell et al., 1999).

For calculations of cash flow as per an investment project of geothermal heat supply the following parameters are calculated:

a) a profitable side of a project, consisting of gross revenue from sales of heat energy, calculated on the basis of volume of heat energy;

b) an expenditure side of a project consists of the following parameters:

1) value added tax;

2) capital investments, required for project realization (building of wells, heating networks, electric power lines, pumps, heat exchangers, separators, filters and others);

3) operating costs: labour costs; social security contributions; costs for electric power; fee for subsoil use; costs for current maintenance and scheduled repairs; cost of general maintenance; capital depreciation; expenses for energy carriers for peak reheaters.

Value of discounted free cash flow as an increment total allows to determine a payback period as per a project of a geothermal heat supply system.

4. CONCLUSIONS

Investigated methods of analysis and optimization of a geothermal heat supply system as per energetic and economic criteria simultaneously allow to determine optimal constructional and technological parameters at the stages of design and technical and economic assessment. The genetic algorithm can be used as an optimization method. Discounted free cash flow should be determined for a final economical assessment of projects of a geothermal heat supply system.

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