INSTITUTE OF FLUID-FLOW MACHINERY
POLISH ACADEMY OF SCIENCES

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

109

Selected papers from the National Seminar
devoted to 60th birthday anniversary of
Professor Jarosław Mikielewicz,
Gdańsk, Poland, April 10th, 2001

WYDAWNICTWO
IMP PAN

GDAŃSK 2001

EDITORIAL AND PUBLISHING OFFICE

IFFM Publishers (Wydawnictwo IMP), Institute of Fluid Flow Machinery, Fiszera 14, 80-952 Gdańsk, Poland, Tel.: +48(58)3411271 ext. 141, Fax: +48(58)3416144, E-mail: esli@imp.gda.pl

Financial support of publication of this journal is provided by the State Committee for Scientific Research, Warsaw, Poland

Terms of subscription

Subscription order and payment should be directly sent to the Publishing Office

Warunki prenumeraty w Polsce

Wydawnictwo ukazuje się przeciętnie dwa lub trzy razy w roku. Cena numeru wynosi 20,- zł + 5,- zł koszty wysyłki. Zamówienia z określeniem okresu prenumeraty, nazwiskiem i adresem odbiorcy należy kierować bezpośrednio do Wydawcy (Wydawnictwo IMP, Instytut Maszyn Przepływowych PAN, ul. Gen. Fiszera 14, 80-952 Gdańsk). Osiągalne są również wydania poprzednie. Prenumerata jest również realizowana przez jednostki kolportażowe RUCH S.A. właściwe dla miejsca zamieszkania lub siedziby prenumeratora. W takim przypadku dostawa następuje w uzgodniony sposób.

ISSN 0079-3205

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

Appears since 1960

Aims and Scope

Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

EDITORIAL COMMITTEE

EDITORIAL BOARD

INTERNATIONAL ADVISORY BOARD

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY
No. 109, 2001, 45-57

WŁADYSŁAW NOWAK[1], ALEKSANDER A. STACHEL[1]

Modelling of thermal-hydraulic processes of geothermal energy extraction and utilization

In the work presented have been selected problems concerned with modelling of thermal-hydraulic systems of extraction and utilization of geothermal energy for the purpose of heating. With respect to temperature of extracted geothermal water and a value of return temperature of municipal water, independently from the system of geothermal energy extraction, there are two kinds of installation solutions in the geothermal power station on the geothermal water side used, namely heat exchangers co-operating with peak-load boilers and heat exchangers with absorption heat pump and peak-load boilers. The first solution is used for higher temperatures of geothermal waters and the second one is used in the case of lower temperatures of extracted water. The applied solution depends also on the temperature of feeding and return municipal water, which directly results from applied design of district heating network, i.e. kind and way of connection of heat receivers. The method of assessment of the possibility of extraction and utilization of geothermal energy in selected district heating networks, where qualitative regulation is used in a parallel combination of two groups of heat receivers and implementation of geothermal water heat exchangers has been also described. Presented methodology enables to conduct a comparative analysis of network designs with parallel connection of two different groups of heat receivers independently of applied systems of geothermal energy extraction. It can also be the basis for conducting economical analysis of comparable variants in both cases.

Nomenclature

$\dot{m}$ – mass flowrate, kg/s
$\dot{V}$ – volumetric flowrate, m^3/s
$\dot{Q}$ – heat flux, W
φ share of radiator-type heating,
Q – heat, J
T – temperature, ^oC
$\tau = \tau^*/\tau_0^*$ – reduced heating time

Subscripts

g – regards radiator-type heating or geothermal water,
p – regards floor-type heating or return temperature,
s – regards municipal water,
z – regards feeding temperature or external temperature,
w – regards the heat exchanger

---

[1] Technical University of Szczecin, Faculty of Mechanical Engineering, Department of Heat Engineering, 70-310 Szczecin, Al. Piastów 19

1. Introduction

Poland belongs to the countries, where resources of geothermal springs with temperatures in the range from approx. ~ 30 ^{o}C to ~ 120 ^{o}C are rich. Particularly good conditions for exploration of such waters exist in the Szczecin-Łódź region.

Geothermal waters can be utilized in district heating networks as a sole heat source or in combination with other sources of energy. The first solution is justified in the case when a sufficient amount of geothermal water is available with temperature exceeding 100^{o}C. In the case of using geothermal water with lower temperatures, the geothermal thermal power station should usually be enhanced by an additional heat source. In such case there can be used various combinations of systems, where the choice is dependent on several factors [1, 4].

In extraction of geothermal energy most often are used two basic systems, namely single and two-borehole systems. With respect to temperature of extracted geothermal water and a value of return temperature of municipal water, independently from the system of geothermal energy extraction, there are two kinds of installation solutions in the geothermal power station on the geothermal water side used, namely

- heat exchangers co-operating with peak-load boilers,
- heat exchangers with absorption heat pump and peak-load boilers.

The first solution is used for higher temperatures of geothermal waters and the second one is used in the case of lower temperatures of extracted water. The applied solution depends also on the temperature of feeding and return municipal water, which directly results from applied design of district heating network, i.e. kind and way of connection of heat receivers [1, 2, 4].

Thermal efficiency on the geothermal water side is influenced both by a volumetric efficiency of geothermal water as well as its temperature at extraction and feeding. Temperature of extracted water, in the case of classical single and two-borehole systems, can be determined based on simple relations, independently from values of feeding water. In the case of single-hole extraction-feeding systems the temperature of extracted geothermal water depends both on the rate of extracted geothermal water and its feeding temperature.

In the present work presented has been the method of assessment of the possibility of extraction and utilization of geothermal energy in selected district heating networks, where qualitative regulation is used in a parallel combination of two groups of heat receivers and implementation of geothermal water heat exchangers.

2. Systems converting geothermal energy

It has been assumed that the geothermal power station supplies heat to recipients equipped with two differentiated types of heating installations, namely radiator or floor-type ones. Required heat is produced in a central heat source. Geothermal water with temperature T_g and volumetric flowrate $\dot{V}_g$ is taken from the extraction hole and pumped through a geothermal water heat exchanger, where energy contained in geothermal water is transferred to municipal water. The heat produced in the heat source is distributed to recipients by means of the water main encompassing a system of water circuit together with pipelines of feeding and return municipal water. Municipal water is directed to the recipients of heat connected in a parallel way and analysed have been two different systems of combination of geothermal power station with recipients. In both cases there has been used a qualitative regulation of a rate of supplied heat.

First schematic of a geothermal power station has been presented in Fig. 1. In the system of a modified geothermal power station, consisting of a geothermal water heat exchanger and a peak-load boiler together with the existing network of high-temperature receivers, there is a possibility of additional modification by gradual incorporation of low-temperature receivers. A parallel inclusion of groups of low-temperature heat receivers increases the efficiency of operation of the entire system.

A characteristic feature of described system is that, with a preserved network, the feeding temperature of both groups of heat receivers is the same in both cases and corresponds to the temperature resulting from the regulation graph for the radiator-type heating. On the other hand, the municipal water temperature at the outlet from both groups of receivers is differentiated and independent from the external temperature, which occurs in both cases.

The second system of geothermal power station schematic has been presented in Fig. 2. This kind of installation, realized in real conditions, can be found predominantly in newly designed and newly developed district heating systems with different, separated feeding of particular groups of low and high-temperature heat receivers. Such solution enables utilization of available geothermal energy in a more effective way than in the case of the first system. In the presented system, municipal water with differentiated temperatures is directed to both kinds of heat recipients. Temperature of municipal water supplied to the radiator-type heating and floor-type heating results from regulation graphs corresponding to particular kind of heating.

Return municipal water from the floor-type heating is directed to the heat exchanger if the flowrate $\dot{m}_{sp}$ exceeds the flowrate $\dot{m}_s$, and then a part of municipal water $\dot{m}_{pu}$ is directed through a bypass, whereas in the case when the flowrate $\dot{m}_{sp}$ is lower then the flowrate $\dot{m}_s$, a missing amount of municipal water is supplemented by the stream of municipal water from the conventional heating $\dot{m}_{gu}$. Remaining flowrate of water from radiator heating $\dot{m}_{sg}$, is directed back to the pipeline feeding the radiator-type heat receivers.

In the case, when temperature of municipal water beyond the heat exchanger is lower than required, which results from the regulation graph for a given kind of heating (i.e. radiator or floor-type one), then utilized is a peak-load boiler, where municipal water from the radiator-type heating or even floor-type heating attains the required temperature.

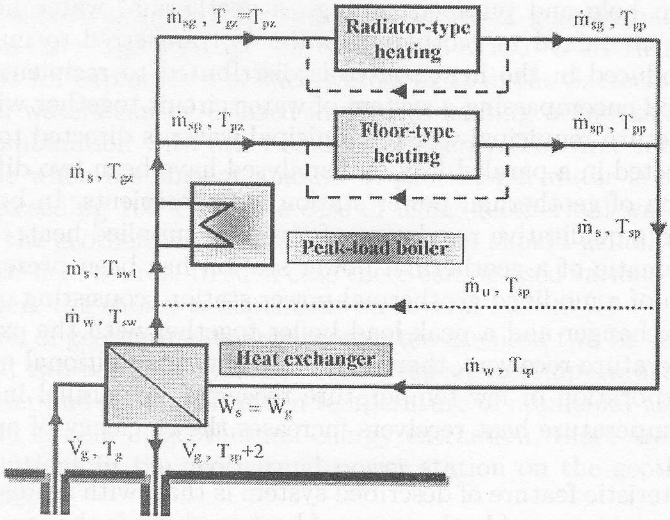

Fig. 1. Schematic of geothermal power plant – system I.

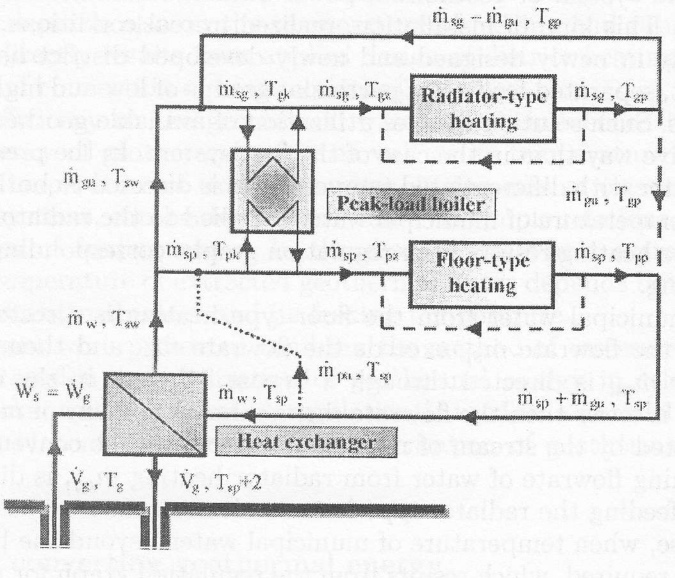

Fig. 2. Schematic of geothermal power plant – system II.

3. Assessment of the possibility of extraction of geothermal energy

Assessment of the possibility of extraction of geothermal energy can be conducted on the basis of a characteristics of the geothermal bed, which encompasses amongst the others, a maximum volumetric flowrate of geothermal water, maximum temperature, thickness and depth of location of geothermal bed, mineralisation of geothermal water and the bed exploitation time. Very often on such basis, in the case of assessment of the possibility of extraction of geothermal energy, there can be constructed graphs of acquired geothermal energy heat rates in function of volumetric flowrate of geothermal water, its temperature and feeding temperature, where the latter value is closely connected with a return temperature of municipal water [2, 3]. In the opinion of present authors such assessment of the possibility of geothermal energy acquisition for heating purposes, independently of the kind of utilized system design, can be conducted more precisely if apart from the geothermal bed characteristics considered will also be a characteristics of the district heating network encompassing also a regulation graph and district heating operation time.

For assumed operation time of thermal installation (τ_0^*) with a qualitative regulation of network if the mass flowrate of municipal water ($\dot{m}_s$) is constant and flows in its entire volume through the geothermal water heat exchanger ($\dot{m}_w$), then the amount of available geothermal energy can be determined from the relation

$$Q_g = \dot{m}_s c_s \tau_0^* (T_{sz} - T_{sp}) = \dot{m}_w c_s \tau_0^* [(T_g - 2) - T_{sp}]. \tag{1}$$

Mass flowrate of municipal water flowing through the geothermal water heat exchanger can be determined based on a volumetric flowrate of geothermal water, with assumption of utilization of counter-current multi-plate heat exchangers and assuming equal rates of thermal capacities of both liquids

$$\dot{m}_w = \dot{V}_g \rho_g \frac{c_g}{c_s}. \tag{2}$$

From above relation and (1) results that the amount of available for extraction geothermal energy is a function of several variables

$$Q_g = f(\dot{V}_g, T_g, T_{sp}, \tau_0^*). \tag{3}$$

Sample graphs illustrating the influence of geothermal water parameters and return temperature of municipal water on the amount of available for extraction geothermal energy in the heating seasons have been presented in Figs. 4 and 5.

4. Thermal-hydraulic calculations of a system of extraction of geothermal energy

In further considerations it has been assumed that the demanded by recipients heat for heating purposes, which has been prepared in the central heat source, is distributed using a district heating network, where two groups of recipients connected in a parallel way have been included, presented in Figs. 1 and 2. Preparation of utility hot water takes place individually in dwellings, where gas or electric water heaters are installed. Such solution enables utilization of lower temperatures of feeding municipal water, particularly in the case presented in Fig. 2. In the present analysis it has been assumed that in the considered networks for both groups of heat receivers (radiator and floor-type ones) there is used a qualitative regulation, i.e. the amount of transferred in receivers heat is controlled by the feeding temperature of municipal water T_{sz} in function of external temperature T_z, according to relation

$$T_{sz} = a + bT_z. \tag{4}$$

On the other hand return water temperature T_{sp} and the flowrate of municipal water are constant quantities.

Demand for the thermal power can be determined based on a maximum heat flux for heating purposes, which can be obtained from the relation

$$\dot{Q}_{co} = \dot{Q}_{co\,\max}\frac{20 - T_z}{20 - T_{z\ min}} = \dot{Q}_{co\,\max}\frac{20 - T_z}{36}\,, \tag{5}$$

if minimum external temperature is $T_{z\ min} = -16^oC$, and temperature in dwellings is $T_p = 20^oC$, or based on parameters of municipal water from the relation

$$Q_{co} = \dot{m}_s c_s (T_{sz} - T_{sp}). \tag{6}$$

Substituting (6) into (5) the following relations describing coefficient a and b of the straight line (4) have been determined

$$a = T_{sp} + \frac{20}{36}(T_{sz\,\max} - T_{sp}), \tag{7}$$

$$b = -\frac{1}{36}(T_{sz\,\max} - T_{sp}). \tag{8}$$

Knowing the coefficients a and b in the equation of a straight line we can determine the change of feeding temperature of municipal water T_{sz} in function of external temperature T_z. Re-arranging expression (6) for a maximum feeding temperature of municipal water we can obtain a relation describing the mass flowrate of municipal water

$$\dot{m}_s = \frac{\dot{Q}_{co\,\max}}{c_{ps}(T_{sz\,\max} - T_{sp})} = \text{idem}. \tag{9}$$

Presented above considerations pertain both to radiator and floor-type heating. In the case of simultaneous implementation of radiator and floor-type heating we need to determine a mean temperature of return water. If a share of radiator-type heating is denoted by (φ), and the share of floor-type heating is denoted by $(1-\varphi)$, then mass flowrates of municipal water feeding the radiator and floor heating systems can be determined from (9), respectively

$$\dot{m}_{sg} = \frac{\varphi \dot{Q}_{co\,\max}}{c_{ps}(T_{gz\,\max} - T_{gp})}; \quad \dot{m}_{sp} = \frac{(1-\varphi)\dot{Q}_{co\,\max}}{c_{ps}(T_{pz\,\max} - T_{pp})}. \tag{10}$$

During calculations of the demand for heat for heating purposes $Q_c = Q_{co}$ there has been utilized a universal reduced external temperature graph, constructed by Raiss [5] and approximated in function of a reduced time $\tau = \tau^*/\tau_0^*$ in the form

$$\frac{T_{zg} - T_z}{T_{zg} - T_{z\,min}} = \left[1 - \sqrt[3]{\tau} + \tau^2\left(1 - \sqrt{\tau}\right)\right]. \tag{11}$$

Then the total heat demand in the heating season can be determined from the expression

$$Q_{co} = \dot{m}_s c_s \tau_0^* \int_0^{\tau_0 = 1} (T_{sz} - T_{sp})d\tau. \tag{12}$$

Assuming, that the lowest reference temperature for external conditions for the considered climatic zone is $T_{z\,min} = -16^{o}$C and, that the lowest external temperature when the heating starts is $T_{zg} = 12^{o}$C, then after determination of external temperature from re-arranged relation (11), considering (4), (12), and integration and simple re-arrangements we can arrive at

$$Q_{co} = Q_c = \dot{m}_s c_s \tau_0^* \left(a + \frac{11}{3}b - T_{sp}\right). \tag{13}$$

The amount of extracted geothermal heat can be considered in a twofold manner. The first part of acquired geothermal heat is connected with heating of municipal water, which flows through the heat exchanger in the amount of $\dot{m}_w$, and its temperature changes from the return temperature T_{sp} to the temperature beyond the heat exchanger (i.e. $T_{sz}^* = T_g - 2$ K) and can be determined from presented below relation, where an assumption $\dot{m}_s = \dot{m}_w$ holds

$$Q_{g1} = \dot{m}_s c_s \tau_1^* (T_{sz}^* - T_{sp}). \tag{14}$$

The time $\tau_1^* = \tau_0^* \tau_1$ means that the period of full utilization of geothermal energy described by a relation describing the reduced time $\tau_1 = f(T_{zs}^*)$ according to a formula

$$T_{sz}^* = T_g - 2 = a + b\left[-16 + 28\left(\tau_1^{1/3} - \tau_1^2 + \tau_1^{5/2}\right)\right]. \tag{15}$$

The second part of acquired geothermal energy in the period from τ_1 to τ_0, due to the fact that the temperature of water beyond the heat exchanger is T_{sz}^* and is higher than the required feeding temperature of municipal water $T_{sz}^* > T_{sz}$, then it is equal to the amount of heat resulting from the regulation graph and is determined from relation

$$Q_{g2} = \dot{m}_s c_s \tau_0^* \int_{\tau_1}^{\tau_0} (T_{sz} - T_{sp}) d\tau. \tag{16}$$

In Fig. 3, which illustrates the ordered demand for heat for heating purposes there

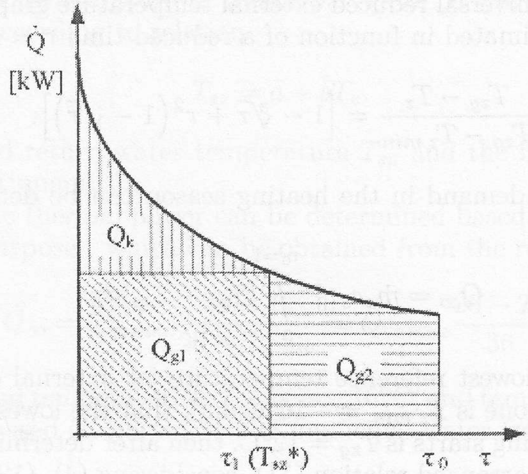

Fig. 3. Coverage of heat demand for heating purposes from geothermal resources Q_{g1} and Q_{g2} and a peak-load boiler Q_k.

has been shown, in the form of relevant fields, the amounts of acquired geothermal heat Q_{g1} and Q_{g2} as well as the amount of heat supplied by a peak-load boiler Q_k. In calculations of the total geothermal heat $Q_g = Q_{g1} + Q_{g2}$ it is convenient to utilize the total heat demand in the heating season Q_c determined from relation (13). A simple relation can be written, that

$$Q_c = Q_k + Q_{gl} + Q_{g2} = Q_{c1} + Q_{g2}. \tag{17}$$

The amount of heat for heating purposes Q_{c1} in the period of time from $\tau^* = 0$ to $\tau^* = \tau_1^*$ can be determined from a simple relation

$$\begin{aligned} Q_{c1} &= \dot{m}_c c_s \tau_0^* \int_0^{\tau_1} (T_{sz} - T_{sp}) d\tau = \\ &= \dot{m}_s c_s \tau_0^* \Big[a + b\Big(-16\tau_1 + 21\tau_1^{4/3} - \frac{28}{3}\tau_1^3 + 8\tau_1^{7/2} \Big) - T_{sp}\tau_1 \Big]. \end{aligned} \tag{18}$$

Then the total amount of acquired geothermal heat can be determined from a formula

$$Q_g = Q_{g1} + Q_{g2} = Q_c - Q_{c1} + Q_{g1}. \tag{19}$$

where particular components Q_c, Q_{c1} and Q_{g1} can be determined from corresponding relations (13), (18) and (14).

Presented above relations enabled to conduct calculations, which are indispensable in construction of relevant graphs presented in Section 5.

5. Results of calculations and concluding remarks

In calculations a maximum heat flux for heating purposes in the amount of $\dot{Q}_{co\,\max} = 8000$ kW has been assumed. Maximum feeding temperature of municipal water corresponding to a minimum reference external temperature $T_z = -16^oC$, are respectively: for radiator-type heating $T_{sz\,\max} = T_{gz\,\max} = 90^oC$, for floor-type heating: $T_{sz\,\max} = T_{pz\,\max} = 60^oC$. On the other hand mean temperatures of return water are constant and in the case of various variants of calculations these have been assumed as follows: for radiator-type heating: $T_{sp} = T_{gp} = 35$, 40^oC, for floor-type heating: $T_{sp} = T_{pp} = 20, 25, 35, 40^oC$. Assumed has also been the length of the heating season, which is equal to 182 days (4368 h). Temperature of extracted geothermal water is constant and in the case of different variants it has been assumed the following values $T_g = 45, 55, 65, 75$ or 85^oC. Volumetric rate of geothermal water can vary in the limits as follows: $\dot{V}_g = 50 \div 150$ [m^3/h].

In order to assess the influence of the share of particular groups of heat receivers on the rate of utilization of geothermal energy for both systems of installations, considered have been five variants with different shares of radiator and floor-type heating, presented in Tab. 1.

Table 1. Share of the kind of heating in particular installation variants

Share of	Variant number				
	1	2	3	4	5
radiator heating (φ)	1	0.75	0.5	0.25	0.0
floor heating ($1-\varphi$)	0.0	0.25	0.5	0.75	1.0

From conducted calculations and constructed graphs for particular variants of both systems, for different values of geothermal water and return temperature of municipal water, presented below will only be selected graphs, which have a significant influence on the assessment and comparison of both considered systems.

In Figs. 4 and 5 presented are graphs, which characterize the geothermal source. It results from Fig. 4 that the amount of acquired geothermal energy increases linearly with the increase of temperature of geothermal water or with

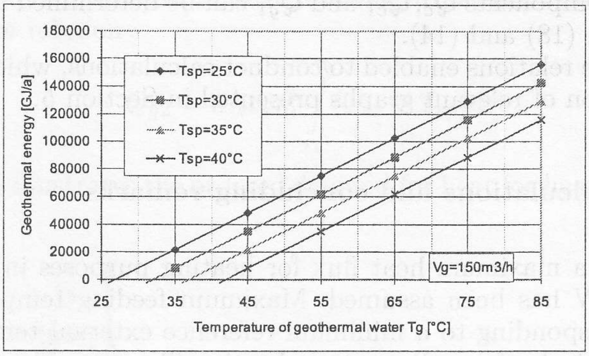

Fig. 4. Potential possibilities of acquisition of geothermal energy in geothermal power plant in function of temperatures: extracted geothermal water (T_g) and return municipal water (T_{sp}).

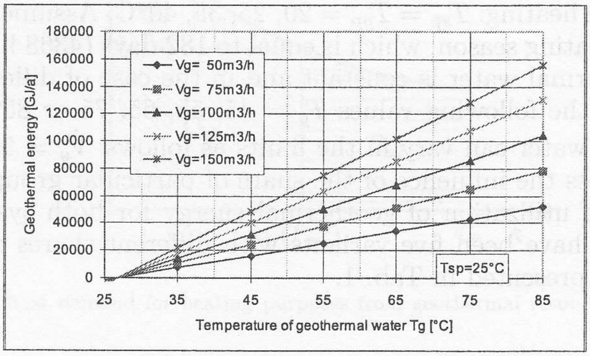

Fig. 5. Potential possibilities of acquisition of geothermal energy in geothermal power plant in function of geothermal water temperature (T_g) and a volumetric flowrate of geothermal water (V_g).

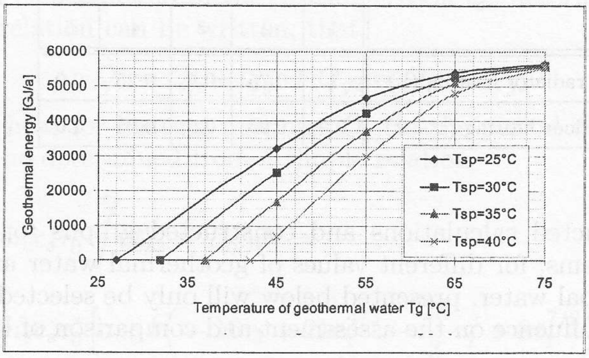

Fig. 6. Amount of geothermal energy possible for utilization in a geothermal power plant, (system I – variant 1 and 5; system II – variant 1) in function of extracted geothermal water temperature (T_g) and return municipal water temperature (T_{sp}).

decrease of return municipal water. Somewhat different trends can be observed in Figs. 6 and 7, where the possibility of utilization of geothermal energy is presented, as that depends also on the characteristics of heat receivers in the district heating network. For that reason the amount of utilized geothermal energy increases with the increase of geothermal water temperature, at the first stage linearly, and then beyond some limiting value of temperature the increases are correspondingly lower. With an increase of temperature of geothermal water gradually observed is a reduction of the influence of decrease of return water temperature on the amount of utilized geothermal energy. A value of the limiting temperature of geothermal water is determined by the characteristics of geothermal source and receivers, as well as district heating network. From the graphs it results that the increase of utilized geothermal energy obtained by reduction of the municipal water temperature is justified only up to some values of geothermal water temperature ($T_g <\sim 65^oC$). In the case of system I, due to assumption that the temperature of feeding municipal water is determined from the regulation graph of radiator-type heating, the Fig. 6 pertains to variant 1 (only radiator-type heating) and variant 5 (only floor-type heating). Therefore, the amount of utilized geothermal energy, for a given temperature of geothermal water, in the case of variants 2÷4 depends only on the temperature of return municipal water.

In the case of the system II, on the other hand, for variant 1 there is valid a graph presented in Fig. 6 (radiator-type heating), and in the case of variant 5 there is valid a graph presented in Fig. 7 (floor-type heating). It results from the fact that temperatures of feeding municipal water are different in the case of radiator and floor-type heating. Due to that fact, the amount of utilized geothermal energy in the case of variants 2÷4, for a given temperature of geothermal water, depends on the temperature of feeding and return municipal water. From the comparison of graphs presented in Figs. 6 and 7 there results a very beneficial influence of reduction of the temperature of feeding municipal water in the case of the floor-type heating on the amount of utilized geothermal energy. For example, for both systems at selected temperature of geothermal water, in Figs. 8 and 9 presented has been the influence of implementation of variants 2÷4 and temperature of return municipal water on the amount of utilized geothermal energy. Quite clear is the influence of increase of the share of floor-type heating as well as the influence of reduction of return temperature of municipal water on the increase of utilization of geothermal energy. For the same variants and same return temperature of municipal water the system II is more advantageous than the system I due to a favourable influence of reduced feeding temperature of municipal water. Presented in the work graphs describing the characteristics of extraction and utilization of geothermal energy are very useful in assessment of the degree of utilization of geothermal energy.

Presented methodology enables to conduct a comparative analysis of network designs with parallel connection of two different groups of heat receivers independently of applied systems of geothermal energy extraction.

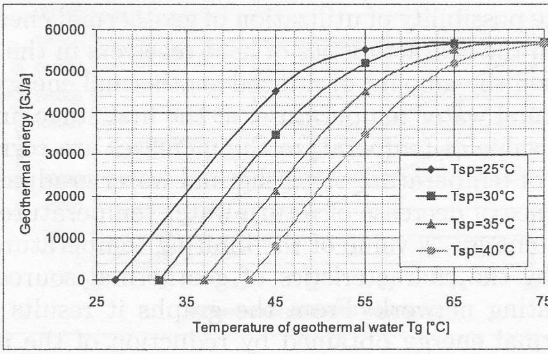

Fig. 7. Amount of geothermal energy possible for utilization in a geothermal power plant, (system II – variant 1) in function of extracted geothermal water temperature (T_g) and return municipal water temperature (T_{sp}).

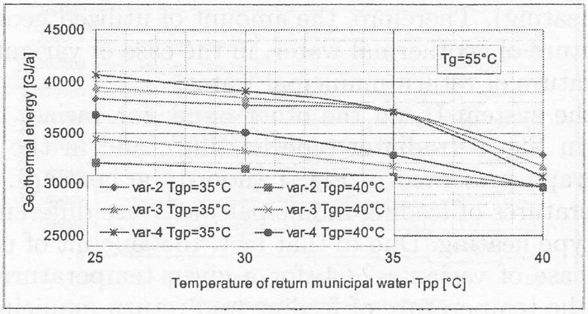

Fig. 8. Influence of return temperature of municipal water of radiator-type heating (T_{gp}) and floor heating (T_{pp}) on the amount of utilized geothermal energy for the case of system I of geothermal plant – variant 2, 3 and 4.

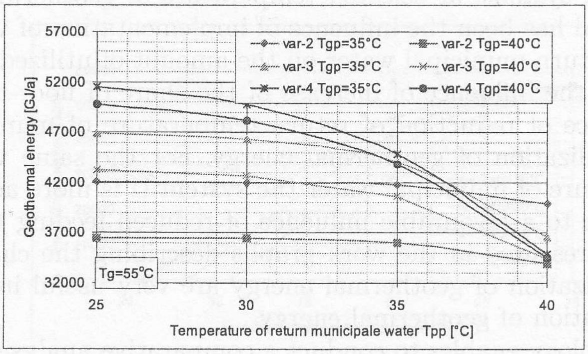

Fig. 9. Influence of return temperature of municipal water of radiator-type heating (T_{gp}) and floor heating (T_{pp}) on the amount of utilized geothermal energy for the case of system II of geothermal plant – variant 2, 3 and 4.

It can also be the basis for conducting economical analysis of comparable variants in both cases.

Received 15 June 2001

References

[1] Nowak W., Sobański R., Kabat M., Kujawa T.: *Systems of acquisition and extraction of geothermal energy*, Wyd. Politechniki Szczecińskiej, Szczecin 2000 (in Polish).

[2] Nowak W, Stachel A.: *Influence of parameters of geothermal water on utilisation of the water in small heating systems*, Acta Mechanica Slovaka, **3**(1999), 187-192.

[3] Nowak W, Stachel A.: *Ecological estimation of work of a geothermal heating plant*, Proc. of the ASME-ZSITS Int. Thermal Science Seminar, Bled–Slovenia, 11-14.06.2000, 522-528.

[4] Sobański R., Kabat M., Nowak W.: *How to acquire the heat from the Earth*, COIB, Warszawa 2000 (in Polish).

[5] Szargut J., Ziębik A.: *Fundamentals of thermal power engineering*, (in Polish), PWN, Warszawa 1998 (in Polish).