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IMPORTANCE OF LOAD BASED AUTOMATIC CONTROL IN GEOTHERMAL ENERGY SYSTEMS

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Abstract: Geothermal energy production is not possible without use of electricity, since electricity is needed to pump geothermal fluid from underground to consumption point. The biggest portion of the operating cost in geothermal district heating systems comes from pumping energy consumption. In this study Balçova-Narlıdere geothermal district heating system has been analysed and the optimum control strategies minimising the energy consumption in the system discussed. Then decisive factors in the efficient control and operation of geothermal heating systems have been studied. Finally fundamental automation requirements for efficient operation of geothermal district heating systems has been introduced.

Keywords: Geothermal energy, control, automation, operational optimisation.

1. INTRODUCTION

Turkey is one of the richest countries in geothermal potential which is mostly located at the western part of the country. Characteristics of the geothermal resources in Turkey are mostly suitable for heating. The use of medium temperature (30 to 150 °C) geothermal resources as a heat source in Turkish district heating systems and greenhouses has been accelerating since 1980's. Considering the geothermal district heating projects, which are in the phase of conceptual planning and construction, it is obvious that geothermal energy will be started to use widely for the heating purposes in the next decade.

In geothermal heating systems heat extracted from the underground is transferred to the buildings either directly or by using cascaded systems. Production and re-injection of geothermal energy and circulation of hot water in the system is achived by pumping. As can be seen from the operational data of Balçova-Narlıdere geothermal district heating system (GDHS), the production of geothermal energy can only be accomplished by significant amount of electricity consumption. In other words geothermal district heating systems are dependent on primary energy resources.

The main goal of this study is to analyse the relation between produced heat energy and electricity consumption with respect to the success of control in GDHSs. From the data sets of 2001 and 2002 heating seasons the amount of electricity consumption and heat production were found in Balçova-Narlıdere GDHS. Then operational control strategy of the system has been discussed and minimum possible electricity consumption of the system was calculated. Finally the results were compared and importance of automation for efficient use of geothermal energy was stressed.

Geothermal district heating systems usually have several production and re-injection wells to meet the peak heat demand. In general the characteristics of these wells (e.g. water level, drawdown, production capacity, temperature) and the pumps are different from each other. The operational strategy of the system should predict the heat demand, select the most efficient wells for production, adjust the operation point of the booster pumps to provide the minimum possible energy consumption in the system. In this perspective Balçova-Narlıdere geothermal district heating system has been analysed. As a result of this analysis two factors "*Conventional Energy Ratio* (CER)" and "*Conventional Energy Excess Ratio* (CEER)" have been defined. These factors provide the comparison of geothermal heating systems in terms of efficiency and define criterion for the success of the control.

Conventional Energy Ratio (CER) is defined as a ratio of produced heat to the consumed electricity. Conventional Excess Energy Ratio (CEER) is a ratio of the actual electricity consumption to the minimum possible electricity consumption that is used to meet the heat load of the system. If the system is operated according to the optimum operational control strategy, the CEER will be equal to 1.

However, geothermal district heating systems are huge systems and spread over large areas. It is imposibble to forecast and control system behaviour exactly. For instance, the dynamic behaviour of well characteristics and dynamic heat load of the system can not be forecasted exactly. Therefore, to meet the heat demand of the system without loosing thermal comfort conditions, excess heat energy is given to the system. It is for sure that CEER is bigger than 1 for all systems.

In this study CER and CEER values for Balçova-Narlıdere GDHS has been found as 68 (kWh_t/kWh_e) and 1.92 respectively by using the data set of 2001 and 2002. If certain improvements are done in the system the CER value may be increased to 131 (kWh_t/kWh_e) and the CEER value can be brought closer to the 1. As a result the lack of automation in Balçova-Narlıdere GDHS causes the doubling of operating cost in the system.

2. BALÇOVA-NARLIDERE GDHS

In Balçova-Narlıdere GDHS the energy of the geothermal fluid is transferred to tap water in the pumping stations, then clean tap water is circulated in the city distribution system.

2.1. Geothermal Pipeline System

Balçova-Narlıdere geothermal pipeline system transmits geothermal fluid from 8 production wells to 8 different heat exchanger stations. After transferring its energy at the heat exchanger stations, geothermal fluid is pumped to re-injection wells. In Table 1 maximum flows and wellhead fluid temperatures of these wells are given for the heating season of 2002-2003. Also facilities connected to geothermal pipeline system are shown in Table 2.

Table 1. Production wells in Balçova-Narlıdere

Well	**Fluid Temperature (°C)**	**Max flow (kg/s)**
BD2	130	50
BD3	120	40
BD4	135	45
BD5	112	22
BD7	115	22
B4	100	14
B5	100	28
B10	90	30

Table 2: Facilities directly connected to geothermal pipeline system

Facility	**Max. Heat demand (kW)**
Balçova GDHS	50364
Narlıdere GDHS	5800
9 Eylül Hospital- 1	14000
9 Eylül Hospital-2	1700
Pools	1275
Spa	2200
T. Hotel	1700
P. Hotel	3200

Each of the production wells has downhole pumps. These pumps are controlled by variable frequency drivers. Therefore, flow of each well can be controlled from zero to maximum value. Due to practical reasons, a certain minimum flow does exist for each well.

2.2 City Distribution System

Balçova city distribution pipeline system distributes hot water at 90 °C to the buildings, which are connected to district heating system and collects relatively cold water at about 60 °C. It is a close loop system, and the domestic hot water needs of the customers met by building heating system. Today about 880 buildings are connected to the system. Each building has its own heat exchanger at the basement. Heat is transferred to the building heating systems with the help of these heat exchangers.

Like geothermal pipeline system, city distribution system is composed of two parallel pipeline systems which are called supply and return. In the heating season circulation of water in the pipeline system is provided by 4 identical centrifugal pumps, which are connected in parallel. Normally, 3 pumps work in parallel and one serves as a back up in the system.

In Balçova-Narlıdere, constant tariff is applied for the heating service. There is no flow meter at the customer end of the system. Moreover types and sizes of buildings are variable. Therefore heat load of the each connection is different from each other.

Diameters of building connection pipes, sizes of heat exchangers and flow controller elements are set according the heat demand.

3. OPTIMUM OPERATIONAL STRATEGIES FOR BALÇOVA-NARLIDERE GDHS

The operational goal of the district heating systems can be summarised as "*Meeting the heat demand of the customers while minimising operating cost of the system.*" Operational strategy for the geothermal district heating system should be determined during project & planning phase of the system. Once it is constructed, it is very difficult to change control strategy of the system, since it requires high investment costs. Although there are common points, every GDHS has different characteristics. For instance characteristic of geothermal resource, weather conditions, infrastructures of the buildings change for each region. In other words each geothermal project is unique.

3.1 Geothermal Fluid Production

In Balçova-Narlıdere, heat energy is produced from 8 production wells providing geothermal fluid in different temperatures and flow rates. In addition to properties that are shown in Table 1, other properties like drawdown and pump characteristics also change for each well. These differences mean that cost of producing heat energy is different for each well. The electricity consumption of four wells is shown as a function of their heat production in Figure 1.

Well pumps are controlled by frequency converters, which provide continuous flow control from zero to maximum flow rate for each well. Capability of controlling flow by using frequency converters allow the operator to decrease production of geothermal fluid, when it is not needed, therefore significant amount of pumping energy can be saved. This feature also brings the problem of, "*selecting the best well operating policy*" to meet the energy demand of customers (Sener 2003)

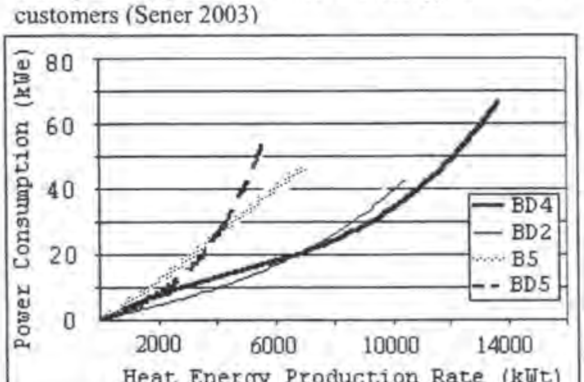

Figure 1. Heat Production vs. Power Consumption Relation for production wells

To provide the most economic operation of these wells there should be geothermal fluid production strategy targeting minimum cost of production according to changing heat demand of customers. Unfortunately today in Balçova-Narlıdere frequency converters are adjusted manually to control the pump operations and there is no production strategy for these 8 wells. Frequencies of the converters are adjusted according to the experience of the operators. Naturally, it is almost impossible to find optimum working conditions without any serious study on this system.

Formulation of the optimisation problem can be summarised as (Şener 2003):

Heat energy obtained from well can be written as:

$$Q_{well} = m_{well} \cdot c_p \cdot (T_{well} - T_{return}) \qquad (1)$$

Where Q= Produced heat energy (kWt), m= mass flow rate (kg/s) and T= geothermal fluid temperature (°C). In Balçova-Narlıdere, average geothermal fluid temperature at heat exchanger outlets is 60 °C; therefore this value can be kept constant in calculations.

Energy consumed by well pumps for each well can be found from:

$$P_{pump} = \frac{m_{well} \cdot g \cdot h_{pump}}{\eta_{overall}} \qquad (2)$$

Where P= Pump power consumption (kWe), h= Pump head (m), η=Wire to water efficiency, g= Gravitational acceleration.

By substituting equation 1 into 2, pump power for each well pump can be obtained as a function of produced heat from well.

$$P_{pump} = f(Q_{well}) \qquad (3)$$

Where f gives pump power consumption as a function of heat production.

At any time to meet the heat demand of the system, total heat production from wells must be equal or bigger than heat demand of the customers.

$$Q_{Well1} + Q_{Well2} + ... + Q_{Welln} \geq Q_{demand} \qquad (4)$$

Where, n= Number of wells. The performance criterion, which is to be minimised, is

$$P_{Total} = \min[f_1(Q_{Well1}) + f_2(Q_{Well2}) + ... + f_n(Q_{Welln})] \qquad (5)$$

Then the program should satisfy (4) according to the criterion stated in the (5).

In order to find the optimum operation strategy of the system, computer program should check all possible combinations and then select the best option. Since there is no general solution for this kind of problem, program algorithm selecting the best possible option for the minimum power consumption was created for Balçova-Narlıdere GDHS.

Among thousands of options the program selects the best option and ranks other options according to their energy consumption rates. Each option suggests different operational strategy to meet the heat demand. Sometimes selection of the best option may not be suitable. Then operator should select second option. Table 3 shows power consumption of certain operational options to meet the heat demand of 40,000 kWt.

Table 3. Rank of operational options

Option rank	Power consumption (kW_e)
1	209
5	212
10	214
15	215
40	218
75	221
100	222

The energy consumption rates in Table 4 are the minimum values to meet corresponding heat demands in Table 4. Therefore Table 4 shows the best geothermal fluid production strategy for different heat loads. Although there are always numbers of unforeseen reasons (motor, frequency converter or pump failures; repairs in the system) which prevents the selection of the best operational policy. Table 4 gives a very clear idea to the operator to run the system in a most efficient way.

Actual well pump power consumptions were compared with the results of the well operation optimisation program in Table 5. Comparison shows that significant amount of energy can be saved, if system are operated according to the results of the program. The implementation of this program is only possible, if all wells and well pumps are monitored and controlled from one control centre. Because, the input parameters of the program should be updated continuously and the results should be applied to the system immediately.

Table 4: Well Operation Policy For Different Loads

Power (kWe)	Heat (kWt)	Flow (kg/s)							
		BD2	BD3	BD4	BD5	BD7	B4	B5	B10
317	50,000	36.0	29.0	45.0	16.7	17.0	14.0	28.0	23.0
261	45,000	36.0	18.7	45.0	16.7	12.0	7.7	28.0	22.8
209	40,000	36.0	18.7	32.3	16.7	12.0	7.7	28.0	15.7
164	35,000	36.0	8.0	32.3	11.3	12.0	7.7	20.3	15.7
130	30,000	36.0	8.0	32.3	11.3	7.0	4.5	12.7	0
98	25,000	22.0	0	32.3	11.3	12.0	4.5	12.6	0
71	20,000	22.0	0	32.3	0	7.0	4.5	5.0	0
47	15,000	22.0	0	19.7	0	7.0	4.5	0	0
31	10,000	8.0	0	19.7	0	7.0	0	0	0

Table 5. Comparison of energy consumptions for actual and optimum well production strategies

Date	Heat production (kWh_t)	Actual power consumption (kWh_e)	Optimum power consumption (kWh_e)
03.11.2002	492,739	2671	1738
16.11.2002	491,026	2748	1699
10.01.2003	658,642	3475	2724
15.01.2003	829,867	4824	3862
01.02.2003	822,290	4380	3845

3.2 Distribution Network and Building Control

The first condition of proper operation in district heating systems is the correct estimation of the heat demand. Especially in the old towns where the buildings has been constructed years before geothermal energy use, the heat demand of the buildings vary in a wide range. Considering dynamic heat loads, and hundreds of different buildings connected to the system it is almost impossible to predict heat demand of the system exactly. For instance there are about 880 buildings connected to the Balçova city distribution pipeline system and among these buildings there are schools, mosques, houses, appartments and university buildings. With the help of fast computers, improved weather forecast methods and huge amount of system data it is possible to obtain closer results from heat load forecasts.

In Balçova geothermal district heating system data are measured and stored by operators. The data collection and storage process has been started three years ago, although system is in operation for eight years. Investigations on these data showed that there are great amount of inaccurate and interrupted data series. It is sure that continuity and accuracy of these huge amount of data can only be provided by automation.

Even the exact prediction of heat demand does not guarantee that the demand will be met. After predicting the heat demand, flow regimes should be adjusted to meet the heat demand of the customers in time. Distribution network is operated according to *constant temperature-variable flow* principle. In this method the heat demand of the customers has been met by adjusting the flow rate of the hot water whose temperature is kept constant. This is achieved by using *variable frequency drivers*. In Balçova GDHS, frequency converters are used to change the rotational speeds of the pumps. Frequency converters are sophisticated devices and they can be easily adopted to automation.

Figure 3 shows the basic control scheme of the Balçova GDHS. Water is heated in the main heat exchanger, and pumped to supply network. Heat exchanger outlet temperature for city distribution system is about 90 °C. Energy of hot tap water is transferred to the building heating system in the building heat exchangers. Regulating valves are connected to the outlet of building heat exchangers. Duty of regulators is vital for the system, since they are the only controlling element of the city distribution system at the building connections. According to heat demand of the building, the return temperature of city circulation water changes. The temperature sensor of flow regulator measures this temperature change. Then the regulator adjusts cross sectional area of flow. Temperature and pressure changes are measured by system operators at points 1 and 2 (Figure 3) and recorded at the pumping station where main heat exchanger and pumps are operated. According to pressure and temperature changes of the system, flow rates of the city circulation pumps are changed by frequency converters, which are adjusted manually.

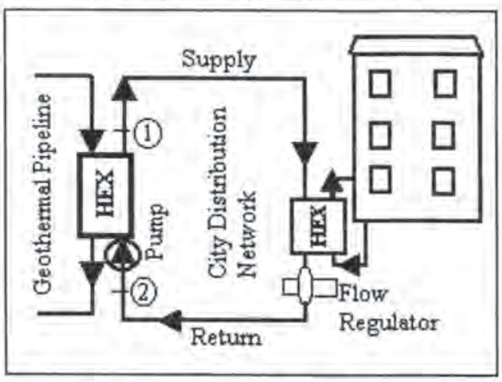

Figure 2. Basic Scheme of the Balçova GDHS (HEX= Heat Exchanger)

By using regulators flow rate of the city circulation water for each building can be limited and return temperature of the building heat exchanger can be controlled. For the control tasks of pressure, flow, differential pressure, or temperature, conventional instrumentation is often too complex and, from an economic point of view, too expensive. For these applications, self-operated regulators can be used. Self-operated regulators take over all the tasks required in a control loop. They integrate measuring sensor, controller as well as control element all in one system.

Finally the most important points for proper system operation and energy economy can be summarised as:

- Temperature difference between inlet and outlet of the heat exchangers should be close to the maximum available value.
- According to the changing outside temperature pump speeds should be adjusted and pumps should be operated in a most efficient combination.
- Operational pressure limits should be monitored.

4. DECISIVE FACTORS IN EFFICIENCY OF GEOTHERMAL HEATING SYSTEMS

If heat demand of the system is known, it is possible to calculate minimum possible electricty consumption of the system. During calculation of minimum possible energy consumption following steps has been followed.

1. According to the heat demand the most efficient wells has been chosen for geothermal fluid production.
2. Heat exchangers are operated at maximum possible temperature difference for both sides.
3. Pumps are operated at maximum available efficiency point by frequency converters.
4. For each production strategy hydraulic balance of the system is checked.

From the data of 2001 and 2002 heating seasons it is possible to calculate minimum possible electricity consumption of the system and compare it with the actual consumed electricity amount. In this study ratio of actual electricty consumption to the minimum posible electricity consumption is defined as *Conventional Energy Excess Ratio* (CEER). For an ideallly controlled geothermal district heating system CEER equals to 1. CEER is one of the most significant parameters, which shows the success of the control in the system.

$$CEER = \frac{\text{Actual electricity consumtion}}{\text{Minimum possible electricity consumption}} \qquad (6)$$

The second parameter, showing the efficiency of the system defined in this study is *Conventional Energy Ratio* (CER). CER is the ratio of produced heat energy to the consumed electricity. CER provides the comparison two different geothermal district heating systems. It is both influenced by operational strategy and geothermal resource characteristics.

$$CER = \frac{\text{Produced heat energy}}{\text{Consumed electricity}} \quad (kW_t/kW_e) \qquad (7)$$

The CER and CEER factors has been calculated, from the hourly data of 2001 and 2002 years. Results are presented in a tabular form in figures 4 and 5.

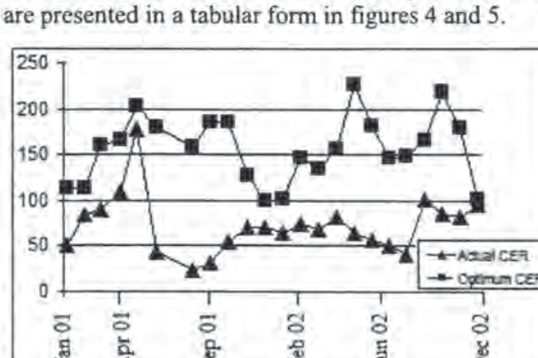

Figure 3. Actual and Optimum CER Values for Balçova-Narlıdere GDHS

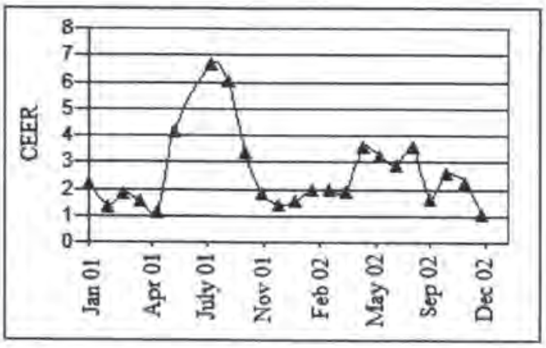

Figure 4. Variation of CEER for Balçova-Narlıdere GDHS

5. CONCLUSION

It is unquestionable fact that automation is the only way of efficient data acquisition and system operation. However, the cost of high-level automation means increase in initial investment cost of geothermal energy projects. In developing countries like Turkey, geothermal energy projects are mostly financed by municipalities or local governments whose financial sources are very limited. For this reason automation of district heating systems is frequently neglected at the beginning of projects. Moreover in developing countries cost of automatic control equipment compared to labour cost is so high that district heating companies prefer employing extra manpower rather than installing automatic control. Although, this investment strategy decreases initial investment cost of the projects, it definitely raises the operating cost of the system.

Economic level of automation changes for each country. Economic feasibility of automation must be investigated carefully at the beginning of each geothermal project. At the initial step of the project there may not be enough money to invest on automatic control, but at later stages, investment on automatic control might be economically possible. At the construction phase of the system infrastructure of the automatic control equipment should be prepared by considering future improvements of the system.

Experiences in Balçova-Narlıdere GDHS show that following features should exist in all GDHSs as minimum automation requirements.

- All pumps in the system should be controlled and monitored from one command centre.
- Temperature, pressure, drawdown and flow rate data of each well should be monitored and stored at the command centre.
- Temperature and pressure data at the inlet and outlet of each heat exchanger should be monitored and stored at the command centre.
- The level of expansion tank in the city distribution system should be monitored at the command centre.
- The temperature and pressure data of distribution system should be monitored and stored.

In this study the energy consumption of Balçova-Narlıdere geothermal district heating system was modelled by assuming that the system is operated according to the optimum operational control strategy. It would be realistic to state that, it is almost impossible to achive optimum operation in the system. Since geothermal district heating systems are huge and the behaviour of the system can not be forecasted exactly.

The actual CER value for the year of 2001 is 62.3. In the year of 2002 this value has been increased to 74.4. The increase of CER is because of the improvements done in the operational control of the system. Although there is no automation in the system yet, the efficiency of the system has been increasing. Because the operators have started to spend effort to control the system more efficiently. Even in the lack of automation pre-determined operation strategy has a great value, because it guides the operators to run the system in an optimum way. On the other hand improvements that can be done on the efficiency of the system without automation are limited. Although certain increase in the efficiency has been achieved in Balçova-Narlıdere GDHS, the system still consumes much more energy then optimum consumption level.

The CER and CEER values are important at this point to calculate the economical feasibility of the improvements during project phase and measure the success of the improvements during operation phase.

The automation efforts has just started on the system under the light of this study, and in the year of 2003, the significant increase in the efficiency of the system is expected with the help of automation.

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