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MODELLING OF BALÇOVA GEOTHERMAL DISTRICT HEATING SYSTEM, TURKEY

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ABSTRACT

In this study, the geothermal district heating system of Balçova has been simulated to determine the optimum working conditions of the system. The geothermal pipeline system and the city distribution system were modelled in the Pipelab district heating simulation program. To model the system as close as possible to the actual case, the database of Balçova geothermal company was used as an input, and the code of the Pipelab program was adapted to the system conditions. Moreover, to determine the optimum operation strategy of the 8 well pumps according to the changing heat demand, dynamic programming algorithm was created for selecting the best operation strategy. A time series analysis technique was used to model the time dependent behaviour of the heat demands of the system. Finally, the results were compared with the actual situation of the system, and potential improvements on the system are discussed.

1. INTRODUCTION

The term simulation refers to the process of reproducing the behaviour of one system through the functions of another. In this project, the term simulation will refer to the process of using a mathematical model to represent the real system. Network simulations, which replicate the behaviour of an existing or proposed system, are commonly performed when it is not practical for the real system to be directly subjected to experimentation (Walski et al., 2002).

This study had two goals: 1) Simulating the system, and 2) from the results of the simulation, to determine the optimum operation strategy for the system.

Balçova geothermal district heating system is composed of two main subsystems, the geothermal pipeline system and the city distribution loop. The geothermal pipeline system transfers the geothermal fluid from wellheads to the pumping stations. In the pumping stations, the energy of the geothermal fluid is transferred to clean water, with the help of plate type heat exchangers, and then circulated in the city distribution loop.

The geothermal pipeline system is connected to production and injection wells. Geothermal fluid produced from the production wells, is pumped into the geothermal pipeline system. After giving its energy, it is pumped into the injection wells from the geothermal pipeline system. Although the system is generally called Balçova district heating system, the geothermal pipeline system does not supply heat to only Balçova. It is also connected to several facilities (Pool, spa, hotels, hospitals), which take approximately 40% of the produced heat. Therefore, the geothermal pipeline system can also be treated as a distribution system supplying geothermal water to different stations.

The Balçova city distribution loop delivers hot water to the buildings connected to the system. Each building has its own heat exchanger in which energy of city distribution water is transferred to the building heating system. After giving its energy to the building heating system, the city circulation water returns to the pumping station.

There are two main criteria for properly working geothermal heating systems: the required heat should be supplied to the system (thermodynamic balance) and this energy should be transmitted to the location where it is required (hydraulic balance). Therefore as a first step, the geothermal pipeline system has been modelled thermodynamically and hydraulically, assuming that the system works properly. After modelling the system for various heat loads, the system was simulated and optimum working conditions for the system were determined.

During modelling, the actual system information taken from Balçova geothermal company was used to get the best possible results. For optimisation of well operations a dynamic programming algorithm was created in the Turbo Pascal language. Modelling of the network was done using the Pipelab district heating simulation program. The geothermal pipeline system and the city distribution loop were modelled separately. With the help of the programs, pressure and heat losses, flow directions, temperatures and nodal pressures of the system were determined for varying flow rates.

Finally, the results of the study were compared with the actual system data. Potential improvements and possible control strategies were investigated to reduce power consumption and provide proper operation of the system.

2. BALÇOVA GEOTHERMAL DISTRICT HEATING SYSTEM

2.1 Brief description and history of Balçova geothermal field

Balçova is one of the districts of İzmir City which is located at the western tip of Anatolia (Figure 1). The history of the Balçova geothermal field goes to ancient times. Balçova geothermal field or the so-called Agamemnon Spas were attractive places for settlers over the ages. Agamemnon Spas were known in antiquity for the therapeutic qualities of the water. According to legend, Agamemnon was advised by an oracle to bring soldiers who had been wounded during the campaign against Troy to the sulphur-rich waters of these natural hot springs. When the Ionians passed to the Aegean coasts, injured soldiers from Alexander the Great's

FIGURE 1: Map of Turkey

army were cured in these hot springs. The spas were used widely during that period. Today, the ancient ruins can not be seen in the area. Before 1763, historical information about the springs is only available from written sources. At that time, Agamemnon Spas was reconstructed by a Frenchman named Elfont Meil, who added the existing units (Gökçen, 1999).

In 1962 and 1963, reconnaissance and exploration studies started with resistivity, thermal probing, and self potential surveys in Balçova. It was the first time that the geothermal area received a systematic, scientific delineation in Turkey. There was a single manifestation of hot water, a spring, with temperature of 72˚C. At the begining three wells were drilled, including the first geothermal exploratory well in Turkey. The first well drilled produced a mixture of hot water and steam at 124˚C at a depth of 40 m. The survey revealed a fault zone delineated by low resistivity and huge temperature closures under 30-50 m thick alluvium. Because of high carbonate content and rapid scaling, geothermal utilization did not start until 1981-82. From 1981 to 1983, 16 wells, including 7 thermal gradient and 9 production wells (100-150 m) were drilled. Temperatures of 50-126˚C with a flow of 4-20 kg/s were encountered. Turkey's first downhole heat exchanger application was used to heat the health centre and a hotel. In 1983, geothermal heating for Dokuz Eylül University, Medical Facility Campus and Hospital Building (about 30,000 m^2) began operation (Battocletti, 1999). For the next 18 years, geothermal energy utilization was put into use for certain facilities like swimming pools, health centres, hospital buildings, and district heating systems. At present the total capacity of the geothermal complex is 50,000 kW_{th}.

2.2 Presentation of existing geothermal utilization at Balçova

2.2.1 Geothermal pipeline system

Balçova geothermal pipeline system carries geothermal fluid from 8 production wells to 8 different heat exchanger stations. After giving its energy at the heat exchanger stations, geothermal fluid is pumped to 8 re-injection wells. In Tables 1 and 2 the maximum flows and wellhead temperatures of these wells are given. However, the number of wells and heat exchanger stations has been changing since the system was first established. The number of connections to and from the system change according to changing well characteristics, the addition of new wells and new customers. Data provided in Table s1 and 2 refer to the 2001-2002 heating session. In addition to the re-injection wells given in Table 2, geothermal water is used for curing purposes in the spa. Facilities which are connected to geothermal pipeline systems are given in Table 3.

TABLE 1: Production wells in Balçova (November 2001)

Well no.	Temperature (˚C)	Max flow (kg/s)
BD2	126	22.2
BD4	138	38.9
BD6	135	33.3
BD7	118	22.2
B4	86	13.9
B5	105	41.7
B10	92	30.5
B11	92	11.1

A schematic presentation of the geothermal pipeline system is given in Figure 2. However, the real system is much more complicated than the scheme, as heat exchanger stations and wells are not located in the same order in the field. The system is actually composed of two parallel pipeline systems. While the supply pipeline transmits the geothermal fluid to the stations, the return pipeline collects the geothermal fluid at the heat exchanger outlets and transmits it to the re-injection wells. The biggest portion of the energy produced by the wells is used by the Balçova district heating system.

TABLE 2: Re-injection wells in Balcova (November 2001)

Well no.	Flow (kg/s)
BD3	13.88
BD5	16.67
B2	10
B9	60
B12	30
ND1	5
N1	3.33
K1	13.88

TABLE 3: Heat exchanger stations directly connected to geothermal pipeline system (November 2001)

Facility	Max. heat demand (kW)	Heat demand (%)
Balcova geothermal DHS	50364	63%
Narlidere geothermal DHS	5800	7%
9 Eylul Hospital - 1	14000	17.5%
9 Eylul Hospital - 2	1700	2%
Pools	1275	1.5%
Spa	2200	3%
T. Hotel	1700	2%
P. Hotel	3200	4%
Total	80239	100

Each of the production wells has a down-hole pump. These pumps are controlled with the help of frequency converters. Therefore, the flow of each well can be controlled from zero to a maximum value. For practical reasons, a certain minimum flow exists for each well.

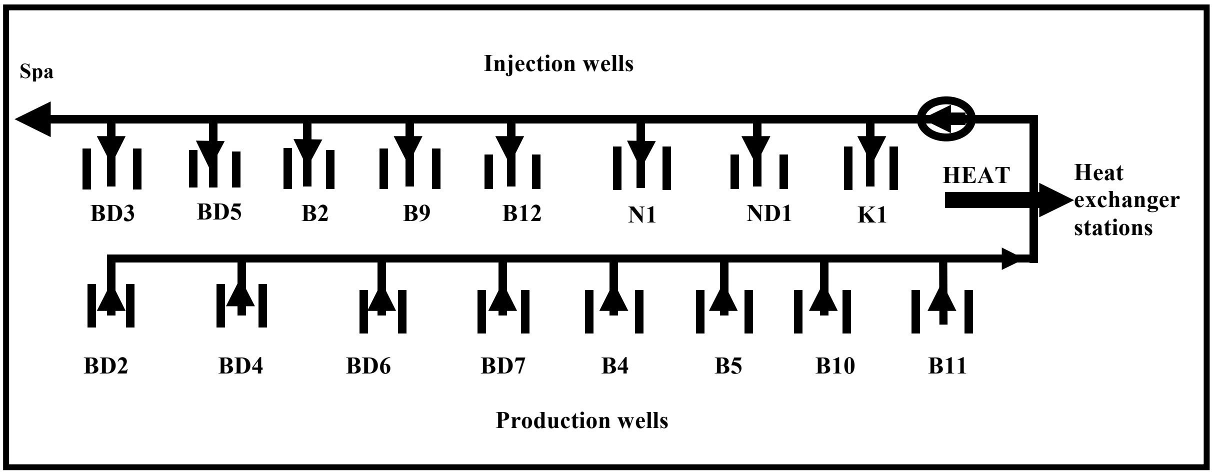

FIGURE 2: Basic scheme of geothermal pipeline system in Balçova

2.2.2 City distribution system

In Balçova, hot water at 85°C is delivered to customers using the city distribution loop. The city distribution loop is a 42 km long pipeline system, which distributes hot water and collects warm return water. Today approximately 850 buildings are connected to the system. Each building has its own heat exchanger on the first floor. Heat is transferred to the building heating systems with the help of these heat exchangers.

In Balçova, a 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 very variable. For instance, five floor buildings, mosque, schools, and single houses are all connected to the distribution system. Therefore, heat load demands of customers are variable. Diameters of building connection pipes, sizes of heat exchangers and flow controller elements are set according to heat demand.

The basic control scheme of the city distribution loop is shown in Figure 3. Water is heated in the main heat exchanger, and pumped to the supply network. The supply network branches at each building connection. Pipes diameters in the main network vary from 350 to 40 mm, while building connection pipes vary from 25 to 50 mm in diameter. The duty of flow regulators is vital for the system. As can be seen from Figure 3, flow regulator valves are installed to outlets of building heat exchangers (city distribution site). Flow regulators are used to keep heat exchanger outlet temperature of city circulation water at a constant value.

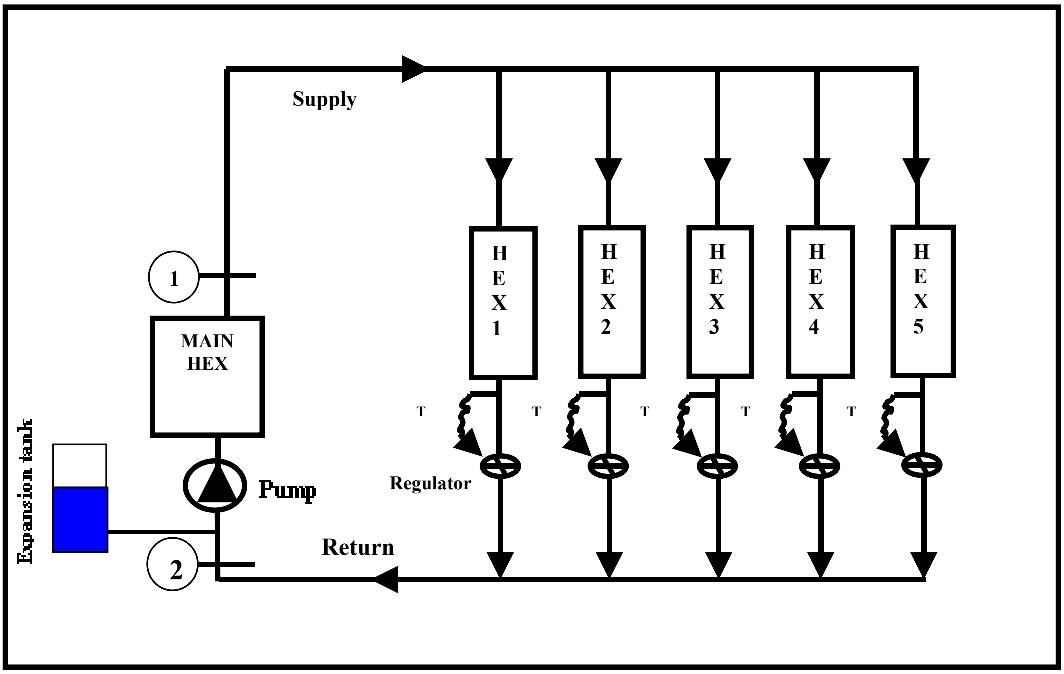

FIGURE 3: Basic control scheme of city distribution network

When heat demand of a building decreases (outside temperature increases), the return temperature of city circulation water, coming from the building heat exchanger, increases. The temperature sensor of the flow regulator measures this temperature change. The cross-sectional area of flow is decreased by the regulator. Also, if heat demand increases, the flow regulator increases the cross-sectional area of flow. These pressure changes are measured by system technicians at points 1 and 2 in Figure 3 and are recorded at the pumping station where the main heat exchanger and pumps are operated. According to pressure changes of the system, flow rates of the city circulation pumps are changed by frequency converters, which are adjusted manually. The main idea in using this kind of control is to decrease pumping cost by adjusting the flow rate of the hot water according to varying heat demand.

An expansion tank is used to compensate pressure fluctuations and supply stable suction head to the circulation pumps. It is also used to add water to the system, when there is leakage. For proper operation of the expansion tank, a minimum required pressure at point 2 is 20 m (2 bars).

3. MODELLING OF DISTRICT HEATING SYSTEMS

Models can be used to solve ongoing problems, analyse proposed operational changes, and prepare for unusual events. By comparing model results with field operations, the operator can formulate solutions that will work correctly the first time rather than resorting to trial-and-error changes in the actual system (Walski et al., 2002).

In this study, the Balçova geothermal pipeline system and the Balçova district heating system were modelled according to the graph theory approach. The use of graph theory in district heating system modelling is a rather new approach, giving fast convergence and reliable results at the end.

3.1 Theory behind the model

Treatment of the theoretical background in Section 3.1 is based on Valdimarsson (1995).

3.1.1 Graph theory

A suitable method for describing a district heating pipe system is to use concepts from network theory. A graph is commonly defined as a composite concept of

a. a set of nodes;
b. a set of branches; and
c. an incidence relation.

The connectivity relation relates each branch to a pair of nodes, the node where the branch originates and the node where it ends. A distribution system can be treated as a connected graph, where pipes correspond to branches and nodes to points where the pipes divide, are united, or convey the flow to the consumer. Here the word "pipe" is used in a general sense, that is a conduit carrying fluid or heat from one point in space to another, and can have many elements, pumps, valves, etc.

In network theory, a connectivity matrix must be defined in order to describe the above mentioned connectivity relation for a network with n_n nodes and n_f branches:

Matrix *A* is a $n_n \cdot n_f$ matrix, with entries a_{ij} where

a_{ij} = 1 if pipe *j* starts at node *i;*
a_{ij} = -1 if pipe j ends at node *i*;
a_{ij} = 0 otherwise.

The connectivity matrix, as defined above, has one column for each flow stream in the system, and one row for each node. Each column can only have two non-zero entries, -1 and 1, as the flow stream has to originate somewhere and end at some other location. Therefore, the column sums of the matrix will always be zero. The rows can have any number of non-zero entries greater than one, as many flow streams can be connected to a single node. A connectivity matrix for the pipes is normally not sufficient to describe a district heating system completely. There are inflow and outflow points in the system or in the part of the system to be studied. These points set boundary conditions for the system.

It is convenient to define the boundary conditions at physical system boundaries in a similar manner to that used in electrical circuit theory. A datum ("ground") point can be defined, where the driving potential is zero. It is not included in the **A** matrix, as the matrix will then become linearly dependent. A boundary element can then be defined, connecting the physical boundary point and the datum point. Following is a definition of some graph terms used in graph theory solution of networks:

Tree: A subgraph G_s of the connected graph G_n is a tree if it is connected and G_s has no loops.

Spanning tree: A subgraph G_s of the connected graph G_n is a spanning tree if it is connected, G_s contains all nodes of G_n and G_s has no loops.

Tree branch: The branches belonging to a tree T are called tree branches.

Cutset: A set of branches of a connected graph G_n (not their endpoints) is a cutset if the removal of these branches results in a graph that is not connected, and the restoration of any one of these branches results in the graph being connected again. The cutset can be seen as a border going through the graph. Associated with the cutset is a direction specified by the direction of a given datum branch in the cutset. The separate graphs obtained by removing the branches of the cutset are called components of the graph with respect to the cutset. The net flow over the cutset must be zero in order to conserve the mass in each of the components.

Link: The branches not belonging to a tree T are called links.

Cotree: The set of links in a network with a tree T is called cotree L with respect to tree T.
The connectivity matrix **A** can be rearranged with respect to a spanning tree T containing n_T branches by splitting it into two submatrices $\mathbf{A_T}$ and $\mathbf{A_L}$ in the following manner:

$$\mathbf{A} = [\mathbf{A_T} \mid \mathbf{A_L}] \tag{1}$$

The submatrix $\mathbf{A_T}$ is the $n_n \cdot n_T$ connectivity matrix for the branches of the spanning tree, and the matrix $\mathbf{A_L}$ is $n_n \cdot n_T$ connectivity matrix for the links, where n_L denotes the number of links. The sum of n_T and n_L is n_f, the total number of branches in network. As the datum point is not included in the connectivity matrix, and submatrix A_T is based on a spanning tree, $n_n = n_T$. Therefore, $\mathbf{A_T}$ is a square invertible matrix.

The system elements consist of the following groups:
- h = Head sources;
- s = Storage tanks;
- r = Non-linear resistances;
- p = Pipes;
- m = Flow sources;
- x = Heat exchangers;
- q = Heat sources;
- t = Temperature;
- h = Sources.

These group characters are used as indices in the following text, in addition to the tree and cotree letters T and L.

3.1.2 Flow solution

The flow in the network is treated as a vector, where the entries are sub-vectors for each flow transmitting element group, both in the tree and the cotree:

$$m = \begin{bmatrix} m_{hT} \\ m_{sT} \\ m_{rT} \\ m_{pT} \\ m_{mL} \\ m_{pL} \end{bmatrix} \tag{2}$$

The cutset matrix is calculated from the connectivity matrix by:

$$\mathbf{D} = \mathbf{A}_T^{-1}\mathbf{A} \tag{3}$$

As the flow sum for any cutset equals zero, the cutset matrix multiplied by the flow vector will equal the zero vector. The cutset matrix is then also portioned into submatrices according to the element groups.

$$\mathbf{Dm} = \left[\begin{array}{cccc|cc} \mathbf{I}_{hT} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{F}_{11} & \mathbf{F}_{12} \\ \mathbf{0} & \mathbf{I}_{sT} & \mathbf{0} & \mathbf{0} & \mathbf{F}_{21} & \mathbf{F}_{22} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_{rT} & \mathbf{0} & \mathbf{F}_{31} & \mathbf{F}_{32} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_{pT} & \mathbf{F}_{41} & \mathbf{F}_{42} \end{array}\right] \left[\begin{array}{c} \mathbf{m}_{hT} \\ \mathbf{m}_{sT} \\ \mathbf{m}_{rT} \\ \mathbf{m}_{pT} \\ \hline \mathbf{m}_{mL} \\ \mathbf{m}_{pL} \end{array}\right] = \mathbf{0} \tag{4}$$

This allows all system flows to be calculated in terms of the flows in the flow source branches and the flow in the branches in the cotree. The flow source flows are known, so a flow solution is obtained by finding the flow in the cotree branches $\mathbf{m}_{pL}$.

$$\begin{bmatrix} \mathbf{m}_{hT} \\ \mathbf{m}_{sT} \\ \mathbf{m}_{rT} \\ \mathbf{m}_{pT} \end{bmatrix} = -\begin{bmatrix} \mathbf{F}_{11} & \mathbf{F}_{12} \\ \mathbf{F}_{21} & \mathbf{F}_{22} \\ \mathbf{F}_{31} & \mathbf{F}_{32} \\ \mathbf{F}_{41} & \mathbf{F}_{42} \end{bmatrix} \begin{bmatrix} \mathbf{m}_{mL} \\ \mathbf{m}_{pL} \end{bmatrix} = -\mathbf{D}_L \begin{bmatrix} \mathbf{m}_{mL} \\ \mathbf{m}_{pL} \end{bmatrix} \tag{5}$$

If the network does not contain pipes in the cotree, the flow can be calculated by Equation 5, as the vector $\mathbf{m}_{pL}$ is empty and the vector $\mathbf{m}_{mL}$ is a boundary condition vector of known values.

3.1.3 Heat solution

The system heat flow is found after the water flow has been found. A flow solution for this network does exist, and is stored in the $n_f \cdot 1$ column vector $\mathbf{m}$. The time dependent flow connectivity matrix $\mathbf{A_f}$ describes the real connectivity of the flow not only the connectivity of the flow element. This matrix changes if any flowstream in the network changes direction. The flow connectivity matrix is defined by:

$$\mathbf{A_f} = \mathbf{A} \times diag\,(sign\,(\mathbf{m})) \tag{6}$$

The element flow origin matrix $\mathbf{E}$ is defined in terms of the $\mathbf{A_f}$ matrix, by:

$$\mathbf{E} = \tfrac{1}{2}\,(\mathbf{A_f} + |\mathbf{A_f}|) \tag{7}$$

The entries of the matrix are $e_{ij} = 1$ if the flow stream j originates at node i, else $e_{ij} = 0$. The fluid temperature does not change when the fluid goes through an insulated pipe element. The heat transmitted through the element is only a function of the temperature at the input end of the element, the heat capacity of the fluid, and the flow itself. The condition at the downstream end of the element has no influence on the heat flow. The electrical analogy of voltage difference between element ends, as a driving potential for the current, does not apply at all for heat flow in pipe networks.

The heat transported with the flow in a pipe element is calculated by:

$$q_j = c_p \times m_j \times T_{origin} \tag{8}$$

The origin temperatures for each element can be found from the nodal temperatures by:

$$\mathbf{T}_{origin} = \mathbf{E}^T \times \mathbf{T}_n \tag{9}$$

The heat flow for the flow elements is then calculated by:

$$\mathbf{q}_f = diag\,(c_p \times \mathbf{m}) \times \mathbf{E}^T \times \mathbf{T}_n \tag{10}$$

The heat flow through a heat exchanger is a function of four temperatures, the two fluid inlet temperatures, and the heat transfer coefficient for the exchanger. The counterflow heat exchanger element is shown in Figure 4.

No exchange of mass occurs between the hot and cold fluids, so this element does not appear at all in the flow calculation model. The heat exchanger element is presented here as a linear resistance to heat flow between its connection nodes. The heat flow in a heat exchanger element and the elements connected to it are shown in Figure 5.

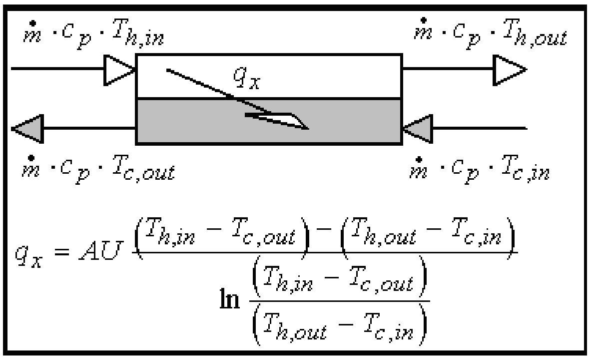

FIGURE 7: Heat exchanger schematic (Valdimarsson, 1995)

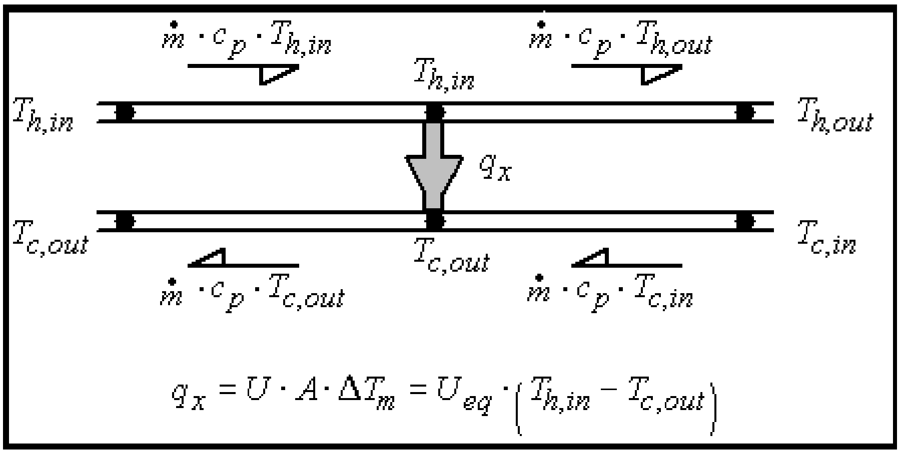

FIGURE 8: Graph representation of a heat exchanger (Valdimarsson, 1995)

The heat flow in the heat exchanger element is, thus, only based on the temperatures at the hot fluid inflow end. The heat flow in each of the heat exchanger elements is calculated by:

$$q_x = U_{eq} \times (T_{h,\,in} - T_{c,\,out}) \tag{11}$$

Each heat exchanger element is connected to two nodes in the network, and this connectivity is described by the $n_n \cdot n_x$. heat exchanger connectivity matrix $\mathbf{A}_x$. The equivalent heat transfer coefficients are stored in the $n_x \cdot n_x$ diagonal matrix $\mathbf{U}_{eq}$ in the same element order as the connectivity matrix. The heat flow for the heat exchanger elements in the system is then calculated by:

$$\mathbf{q}_x = \mathbf{U}_{eq} \times \mathbf{A}_x^T \times \mathbf{T}_n \tag{12}$$

The connection of the heat flow elements into the network is described by the $n_n \cdot n_q$ connectivity matrix $\mathbf{A}_q$. The heat flow q_q for these elements is known, and the connectivity matrix defines at which nodes the heat is input.

The temperature element has a heat flow sufficient to maintain the desired temperature at the connection node. This heat flow, q_t, in the temperature element is unknown. The temperature element is usually connected to the datum node. All boundary nodes for the flow have to have known temperature. The connection of the temperature elements into the network is described by the $n_n \cdot n_n$ connectivity matrix $\mathbf{A}_t$.

The matrix notation for Kirchhoff's current law has one row for each node in the network. A flow vector multiplied by its connectivity matrix will contribute the correct flow to each node. The current law for the heat flow is:

$$\begin{bmatrix}\mathbf{A} & \mathbf{A}_x & \mathbf{A}_t & \mathbf{A}_q\end{bmatrix} \cdot \begin{bmatrix}\mathbf{q}_f \\ \mathbf{q}_x \\ \mathbf{q}_t \\ \mathbf{q}_q\end{bmatrix} = \mathbf{0} \tag{13}$$

The heat flow in the heat source is known, so the known factors are separated from the unknown:

$$\begin{bmatrix}\mathbf{A} & \mathbf{A}_x & \mathbf{A}_t\end{bmatrix} \cdot \begin{bmatrix}\mathbf{q}_f \\ \mathbf{q}_x \\ \mathbf{q}_t\end{bmatrix} = -\mathbf{A}_q \cdot \mathbf{q}_q \tag{14}$$

The heat flow vector $\mathbf{q}_f$ for flow elements is substituted from Equation 10, and the heat flow vector $\mathbf{q}_x$ for heat exchangers from Equation 12

$$\begin{bmatrix}\mathbf{q}_f \\ \mathbf{q}_x\end{bmatrix} = \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq}\end{array}\right] \cdot \begin{bmatrix}\mathbf{E} & \mathbf{A}_x\end{bmatrix}^T \mathbf{T}_n \tag{15}$$

After this substitution, Kirchhoff's current law is written as

$$\begin{bmatrix}\mathbf{A} & \mathbf{A}_x & \mathbf{A}_t\end{bmatrix} \cdot \begin{bmatrix} \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq}\end{array}\right] \begin{bmatrix}\mathbf{E} & \mathbf{A}_x\end{bmatrix}^T \mathbf{T}_n \\ \mathbf{q}_t \end{bmatrix} = -\mathbf{A}_q \cdot \mathbf{q}_q \tag{16}$$

The heat flow in the constant temperature elements is unknown, and has to be made a part of the vector to be solved for

$$\begin{bmatrix}\mathbf{A} & \mathbf{A}_x & \mathbf{A}_t\end{bmatrix} \cdot \left[\begin{array}{c|c} \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq}\end{array}\right] \begin{bmatrix}\mathbf{E} & \mathbf{A}_x\end{bmatrix}^T & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{I}_t \end{array}\right] \begin{bmatrix}\mathbf{T}_n \\ \mathbf{q}_t\end{bmatrix} = -\mathbf{A}_q \cdot \mathbf{q}_q \tag{17}$$

In order to get the correct temperature difference for the temperature elements, one line is added to the set of equations for every temperature element. This new equation equates the temperature difference between the element ends of the constant temperature elements to the desired numerical value T_t.

$$\left[\begin{array}{c|c} \begin{bmatrix}\mathbf{A} & \mathbf{A}_x\end{bmatrix} \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq}\end{array}\right] \begin{bmatrix}\mathbf{E} & \mathbf{A}_x\end{bmatrix}^T & \mathbf{A}_t \\ \hline \mathbf{A}_t^T & \mathbf{0} \end{array}\right] \begin{bmatrix}\mathbf{T}_n \\ \mathbf{q}_t\end{bmatrix} = \begin{bmatrix}-\mathbf{A}_q \cdot \mathbf{q}_q \\ \mathbf{T}_t\end{bmatrix} \tag{18}$$

The final solution is obtained by matrix inversion, and gives the nodal temperature and the heat flow in the constant temperature elements as a result (Valdimarsson, 1995).

$$\begin{bmatrix} \mathbf{T}_n \\ \mathbf{q}_t \end{bmatrix} = \left[\begin{array}{c|c} [\mathbf{A} \quad \mathbf{A}_x] \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq} \end{array} \right] [\mathbf{E} \quad \mathbf{A}_x]^T & \mathbf{A}_t \\ \hline \mathbf{A}_t^T & \mathbf{0} \end{array} \right]^{-1} \begin{bmatrix} -\mathbf{A}_q \cdot \mathbf{q}_q \\ \mathbf{T}_t \end{bmatrix} \tag{19}$$

3.2 Pipelab district heating simulation program

Pipelab is a district heating simulation software which uses graph theory to solve network flow and heat distribution problems. It is used both during the design phase, and while analysing the networks. Necessary data to model the system in Pipelab include:

1. Nodal coordinates of the system;
2. Start and end nodes of the network elements;
3. Roughness values of pipes (m);
4. Heat loss coefficients of pipes (W/˚C);
5. Amount of head supply (m);
6. Required load (flow or heat) at the end points of the system (kg/s or W).

Once the necessary data has been entered, it is possible to determine the nodal heads, nodal temperatures, and head and heat loss gradients on the screen as well as in the stored files. Figure 6 shows the presentation of the Balcova city distribution system in the Pipelab user interface screen.

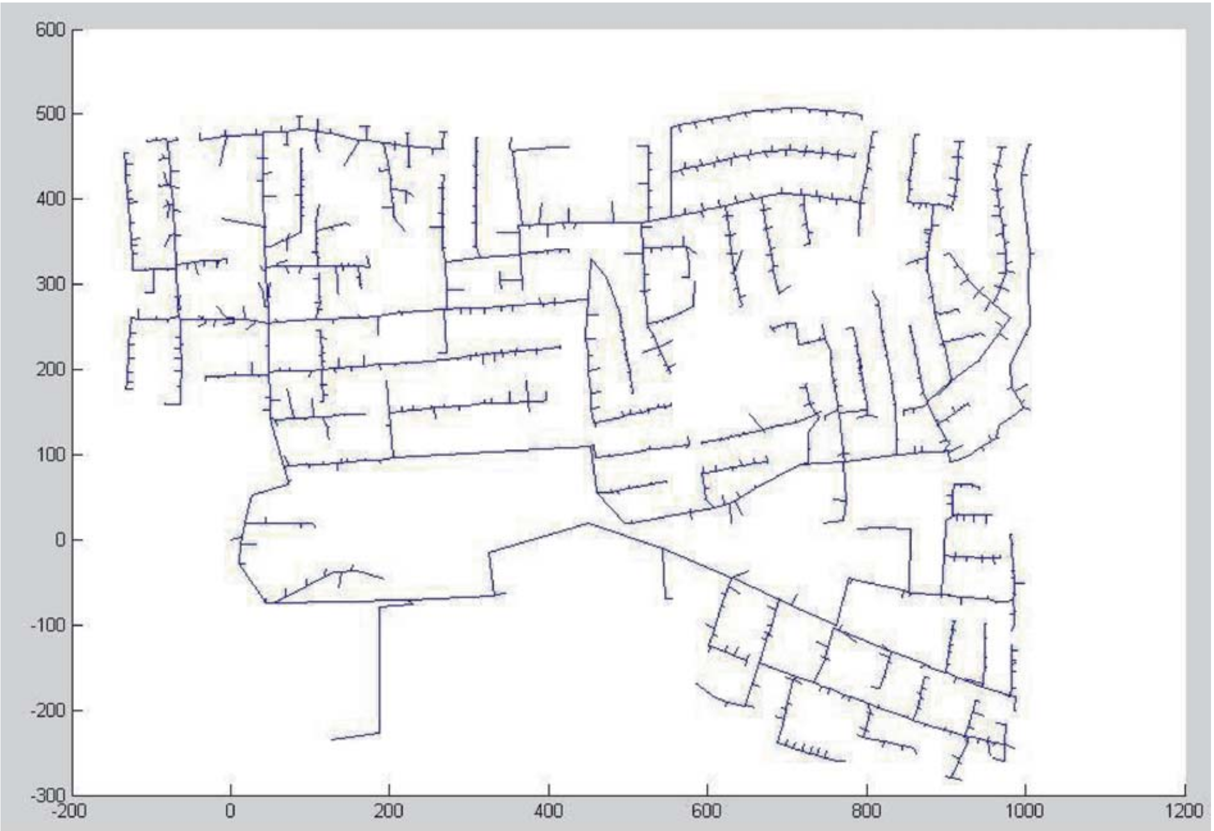

FIGURE 6: Presentation of Balcova city distribution system in the Pipelab screen, all dimensions in m

4. OPTIMISATION OF PUMP OPERATIONS

4.1 Well pumps

4.1.1 Statement of the problem

The geothermal district heating systems distribute water rather than energy because all cost is directly related to water usage rather than energy usage (Valdimarsson, 1993). Therefore, optimum usage of pumping power is very important for economic usage of geothermal energy.

In Balçova, heat is produced from 8 production wells providing geothermal fluid in different temperatures and flow rates. In addition to the properties shown in Table 1, other properties such as drawdown, and pump characteristics vary from well to well. These differences mean that the cost of producing heat is different for each well.

As stated before, the well pumps are controlled by frequency converters, which provide continuous control of flow from 0 to maximum flow rate for each well. Controlling flow by using frequency converters allows the operator to decrease production of a geothermal fluid when it is not needed, therefore saving a significant amount of pumping energy. This feature also brings up the problem of "selecting the best well operating policy" to meet the energy demands of customers.

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

However, finding the best production strategy for providing minimum electricity consumption is not enough; effects of the pump operations on the hydraulics of the geothermal pipeline system remain an unanswered question. Therefore, after obtaining the best production strategy, the result should be simulated in Pipelab, and the hydraulics of the geothermal pipeline system should be investigated.

Each well and its pump have characteristics independent of each other. In order to find the optimum operation strategy for the system computer program, all possible combinations are calculated, and the best option is then selected. Since there is no general solution for this kind of problem, a program algorithm selecting the best possible option for minimum power consumption was created in this study. This program was connected to Pipelab, the best possible production option was found and effects of pumps on geothermal pipeline system were tested.

4.1.2 Dynamic programming

The following definition of dynamic programming is based on Helmke and Moore (1994). Dynamic programming is a method of optimisation that is applicable for either staged processes or to continuous functions that can be approximated by staged processes. The word "dynamic" has no connection with the frequent use of the word in engineering technology, where dynamic implies changes with respect to time. As a method of optimisation, dynamic programming is not usually interchangeable with such other forms of optimisation as Lagrange multipliers and linear and non-linear programming. Instead, it is related to the calculus of variations, whose result is an optimal *function* rather than an optimal *state point*. An optimisation problem that can be subjected to dynamic programming or the calculus of variations is usually different from those suitable for treatment by Lagrange multipliers and linear and non-linear programming. The calculus of variations is used, for example, to determine the trajectory (thus, a function in spatial coordinates) that results in minimum fuel cost of spacecraft. Dynamic programming can attack this same problem by dividing the total path into a number of segments and considering the continuous function as a series of steps or stages. In such an application, the finite-step approach of dynamic programming is an approximation of the calculus-of-variations method. Dynamic programming can be applied if the problem has four features (Manoutchehr et al., 1971):

1. The problem must be one which can be divided into stages, with a decision required at each stage.
2. Each stage of the problem must have a finite number of states associated with it. The states describe the possible conditions in which the system might find itself at any stage of the problem.
3. The effect of a decision at each stage of the problem is to transform the current state of the system into a state associated with the next stage.
4. For a given current state and stage of the problem, the optimal sequence of decisions is independent of the decision made in previous stages. A policy is a set of decisions which contains one decision for each state variable for each stage. A policy may also be called a decision trajectory. The set of states, which results from the application of a policy, is called a state trajectory or simply trajectory. An optimal policy is the set of decisions that optimises the objective function, which is a measure of effectiveness.

4.1.3 Formulation of the problem

By using frequency converters, it is possible get continuous flow between minimum and maximum flow for each well.

$$m_{welli} = m_o,\ m_1,\ m_2, \ldots.., m_n \tag{20}$$

Heat obtained from a well can be written as:

$$Q_{well} = m_{well} \times c_p\ (T_{well} - T_{return}) \tag{21}$$

In Balçova, the 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 can be found from

$$P_{pump} = \frac{m_{well}\ g\, h_{pump}}{\eta_{pump}\ \eta_{motor}} \tag{22}$$

By substituting Equation 21 into 22, pump power can be obtained as a function of produced heat from a well.

$$P_{pump} = f\,(Q_{well}) \tag{23}$$

For all systems, total pump power can be written as;

$$P_{pump} = f_{BD2}(Q_{BD2}) + f_{BD4}(Q_{BD4}) + f_{BD6}(Q_{BD6}) + f_{BD7}(Q_{BD7}) + f_{B4}(Q_{B4}) + f_{B5}(Q_{B5}) + f_{B10}(Q_{B10}) + f_{B11}(Q_{B11}) \tag{24}$$

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

$$Q_{BD2} + Q_{BD4} + Q_{BD6} + Q_{BD7} + Q_{B4} + Q_{B5} + Q_{B10} + Q_{B11} \geq Q_{demand} \tag{25}$$

The performance criterion, which is to be minimised, is

$$P_{total} = \min\left[f_{BD2}(Q_{BD2}) + f_{BD4}(Q_{BD4}) + f_{BD6}(Q_{BD6}) + f_{BD7}(Q_{BD7}) + f_{B4}(Q_{B4}) + f_{B5}(Q_{B5}) + f_{B10}(Q_{B10}) + f_{B11}(Q_{B11})\right] \quad (26)$$

The program should satisfy Equation 25 according to the criterion stated in the Equation 26. The results of the program are given in Section 5 of the report.

4.2 Circulation pumps

In the Balçova city distribution system, circulation of water is provided by 4 identical centrifugal pumps which are in the main pumping station. These pumps are connected in parallel. In heating sessions, 3 pumps work and one serves as a back-up in the system. In Figure 7, the performance curve of a single pump used in the system is given for a pump test speed of 1450 rpm. The pump performance curve shown in Figure 7 is valid only if the pump is run at 1450 rpm. Pump performance curves for different speeds can easily be derived from affinity laws, given below:

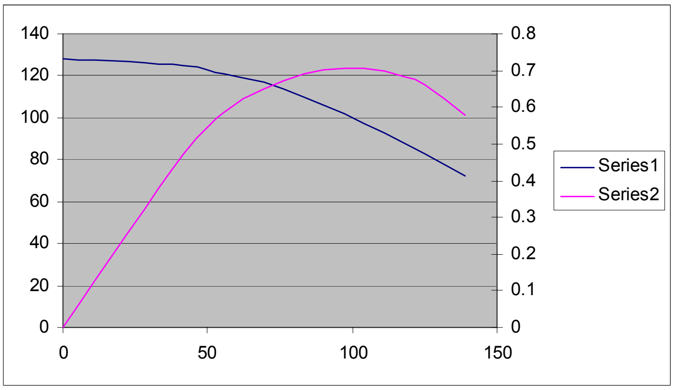

FIGURE 7: Performance curve of circulation pump at 1450 rpm

$$\frac{V_{p1}}{V_{p2}} = \frac{N_1}{N_2} \quad (27)$$

$$\frac{h_{p1}}{h_{p2}} = \left(\frac{N_1}{N_2}\right)^2 \quad (28)$$

Frequency converters can drive the pumps over a wide range of flows, however variable-speed pumps do not run efficiently over a wide range of flows. Therefore, to minimise power consumption of circulation pumps, it is important to know the efficiency characteristics of pumps for varying flows. The efficiency curve of a pump at test speed is usually given by a third degree polynomial

$$\eta_{pump\ test} = aV^3 + bV^2 + cV \quad (29)$$

If the speed of a pump is changed,

$$n = (pump\ speed)/(pump\ test\ speed) \quad (30)$$

then the new pump efficiency can be found from (Walski et al., 2002):

$$\eta_{pump} = a(V/n)^3 + b(V/n)^2 + c(V/n) \quad (31)$$

If the pump station is to be operated such that different combinations of pumps will be run under different demand conditions, it is important that the pumps be selected to work efficiently when operating both alone and in parallel with other pumps. Therefore, while developing a pump operation strategy the operator should consider the different combinations of pumps, as well as varying flows. In this study, all possible combinations of pump operations in Balçova were investigated, and efficiency characteristics of different combinations at different speeds were compared. Finally, the best combination of parallel pumps was determined over a range of flow for minimum power consumption.