5. MODELLING OF HEAT DEMAND BY USING TIME SERIES ANALYSIS

The term *time series* refers to an ordered sequence of values of a variable at equally spaced time intervals. The usage of time series models is twofold:

- Obtain an understanding of the underlying forces and structure that produced the observed data;
- Fit a model and proceed to forecasting, monitoring or feedback and feedforward control.

In district heating systems the main goal of using this model is to estimate the heat load of the system according to weather forecasts, so that the heat demand of customers can be met at the right time.

In Figure 3, points 1 and 2 indicate the locations where the temperature, pressure and flow rate of city circulation water is measured hourly. By combining these system measurements with hourly outdoor temperature measurements, a data set suitable for the time series analysis can be obtained.

Heat demand behaviour of a system, is actually the reaction of the system to outside temperature changes. Therefore, it is important to determine the most obvious relationship between measured system parameters and outside temperature. In Figure 8, system heat load is plotted as a function of outside temperature by using 4500 hours continuous data of the 2001-2002 heating session. There is an obvious trend of the heat load according to changing outside temperature.

Time series analysis of this data is done by using ready functions in Matlab. First, a linear prediction model, auto-regressive with exogenous inputs (ARX) technique, is estimated using a recorded time series. Then, the residual error, which is the difference between the actual time measurement and the prediction from the previously estimated ARX model, is defined. The results are presented in Section 6.

![Heat load vs. outside temperature](image)

FIGURE 8: Outside temperature vs. system heat load
6. RESULTS

6.1 Distribution system

6.1.1 Results of the simulation

In the Pipelab district heating simulation program, the distribution system was modelled between the peak flow demand of 305 l/s total flow rate and minimum flow demand of 17 l/s. During modelling, necessary system information was provided by the Balçova district heating company. It is assumed that hot water is delivered to all buildings in a sufficient amount to meet their energy requirements. While modelling the system, it was divided into two parts, supply and return networks. In Figure 9, a combined head loss versus distance from the head source diagram, obtained from Pipelab, is shown for the supply and return networks.

As can be seen from Figure 9, the maximum head loss along the pipes of the distribution system is 43 m for the maximum flow rate. For the critical head loss path, heat exchanger and flow regulator pressure drop values were taken as 4 m.

The distribution system was simulated in Pipelab for the range of flow demands, and a system loss curve for the critical path was obtained (Figure 10). It should be stressed that this head loss diagram does not include the head losses in the pumping station.

The temperature decrease of the distribution system for the supply network is shown in Figure 11. As can be seen, node temperatures are in the range 85 to 80°C except for one branch.

FIGURE 9: Length from source vs. head loss diagram for the Balçova distribution system

FIGURE 10: Pressure loss curve for the critical path of city distribution loop
6.1.2 Distribution system problems

During peak demand, certain parts of the system cannot get sufficient heat. These buildings are shown by dots in Figure 12. Although heating problems seem to occur mostly in one region (I and II), it is wise to investigate these parts according to their branching structures. As shown in Figure 12, there are three main regions where heating problems occur. These three regions constitute 80% of the heating problems in the system. Among these three regions, region I contains most of the buildings with heating problems.
FIGURE 13: Presentation of regions with heating problem in the h-L diagram of supply network

In Figure 13 these three branches, which are highlighted and circled, are shown in the h vs. L diagram of the supply network. As can be seen, region I, which is the most problematic part of the system, has the highest pressure drop in the network. Also, as shown in Figure 14, the largest temperature drop in the network belongs to one of the branches of region I.

FIGURE 14: Presentation of regions with heating problem in T-L diagram of supply network

Although regions I and II are located close to each other, they belong to different branches of the system and unlike region I, region II is not one of the low-pressure zones in the system. While investigating this branch of the system, it should be noted that it has the greatest distance to the pumping station. In Figure 13, there is a steep pressure decrease for region III. It is due to the high speed of the water in that part of the network. High-speed flow generally occurs at undersized distribution branches.
6.1.3 Possible sources of the problems

Region I
Region I, which has the highest pressure drop on the head loss diagram, contains most of the buildings with a heating problem. If outside temperature gets close to 0°C, which is the design temperature for Izmir City, customers living in region I start to complain about the heating service. From temperature and head loss diagrams, it is seen that this region has the highest temperature and pressure drops in the system. Therefore, if there is a low-pressure problem in the system, region I will be affected by it first.

One of the most frequently occurring operational problems associated with water distribution systems is low or fluctuating pressure. While confirming that the problem exists is usually easy, discovering the cause and finding a good solution can be much more difficult. According to Walski et al., (2002), customer complaints, modelling studies, and field measurements obtained through routine checks can indicate that a portion of a system is experiencing low pressure. The pressure problem can be verified by connecting a pressure gage equipped with a data logging device or chart recorder to the system, continuously recording pressure. Occasionally, a customer may report a low-pressure problem when the pressure at the main is fine. In such cases, the low pressure may be due to restriction in the customer's plumbing, or a point-of-use/point-of-entry device that is causing considerable head loss. If measurements indicate that pressure in the main is low and a problem in the distribution system is suspected, the next step is to examine the temporal nature of the problem. Pressure drops that occur only during periods of high demand are usually due to insufficient pipe or pump capacity, or a closed valve.

As stated before, pressure measurements are done at two points in the city distribution loop. These locations are points 1 and 2, shown in Figure 3. The water pressure at point 1, should be sufficient to provide water circulation to point 2 (Figure 3). In Figure 15, variation of actual pressure differences between points 1 and 2 (Figure 3) is shown by dots. To compare the actual data with the simulation result, a system characteristic curve obtained from simulation (Figure 10) is given by a continuous curve in Figure 15. Values obtained from simulation are accepted as a minimum required head difference (between 1 and 2), to provide circulation in the system at any flow rate. Comparing actual measurements with the required head value obtained from simulation, the points under the curve indicate the existence of insufficient pressure difference in the system. The distribution of points under the curve is homogeneous, which means that the problem is not related to pump capacity. Possible sources of the problem are

- Lack of coordination between operation of expansion tank and circulation pumps;
- Flow regulators cannot create enough resistance to increase the pressure difference between 1 and 2 (Figure 3);
- Speed of operator response to system changes is slow.
To overcome this problem

- Operators should watch for the minimum head difference criterion between 1 and 2 (Figure 3);
- Circulation pumps should be operated according to future estimates of heating demand so that system pressure losses can be kept above the allowable level;
- Set points of the flow regulators should be revised.

By investigating region I and its branches in Figure 13, it can be seen that there is no steep pressure gradient for the pipes carrying water to region I. Therefore, undersized piping is not one of the sources of problems there.

In Figure 14, there is steep temperature decrease for region I. The reason for high temperature decrease is low speed of the water in this area. Decreasing the size of the piping can prevent the temperature drop. However, decreasing the size of the piping increases pressure loss in the system; since this region already has the highest pressure drop, decreasing the size of the piping is not a cost effective solution.

Once the cause of the pressure and temperature problems has been identified and confirmed, possible solutions are usually fairly straightforward, and include the following (Walski et al., 2002):

- Changing pump control settings;
- Locating and repairing any leaks;
- Implementing capital improvement projects such as constructing new mains;
- Installing pumps to set up a new pressure zone;
- Installing a storage tank.

Each of these options affects the system in different ways and has different benefits, so a comparison of the alternatives should be performed, based on a benefit/cost analysis as opposed to simply minimizing costs. The modelling for this evaluation can usually be performed with steady-state modelling.

Among these solutions, installation of a booster pump is usually the least costly method of correcting low-pressure problems from an initial capital cost standpoint. Booster pumps can, however, significantly increase operation and maintenance costs, and do not allow as much flexibility in terms of future expansion as other available options. Also, booster pumps can over-pressurize portions of the system and even cause water hammer, especially when there is no downstream storage or pressure relief. It should be remembered that pumping increases the pressure at the pump location but does not reduce the hydraulic gradient (Walski et al., 2002).

Adding storage at the fringe of the system tends to be a costly alternative, but provides the highest level of benefit. Storage increases the reliability of the system in the event of a pipe break or power outage, and helps to dampen transients.

The first option to focus on is the pump and expansion tank settings. Since the pumps have sufficient capacity to meet maximum required pressure at the system, system control strategy should be reconsidered under the light of simulation results. Although low-pressure problems can be overcome by changing pump and expansion tank settings, the low-temperature problem is not that easy to solve, since the problem is related to low velocity of water at that area. In Figure 16, an enlarged view of region I is given. From Figure 16, it is seen that the lowest pressure and the lowest temperature drops do not occur at the same branch of the system. The branch with the lowest temperature is circled in
Figure 16. Temperature drop of this branch from start to end is show in Figure 17. As can be seen from Figure 17, only the last 10 nodes have temperatures lower than 80°C. Low temperature at these 10 nodes affect the last 6 buildings connected to the system.

To see the effect of changing piping size in system, the diameter of pipes which are circled in Figure 16 were decreased from 50 to 32 mm and 25 to 20 mm. A new temperature drop curve is presented in Figure 18. The figure shows that, although there is an increase at the end node of the branch, it is not significant. Resizing this branch is not a cost effective method to decrease the temperature drop problem.

To solve the problem of excess temperature drop, changing the settings of flow controllers at this branch was also considered. Flow capacities of the last 6 buildings in this branch were increased by 60%. Results of the simulation are given in Figure 19. By changing the flow capacities of these 6 buildings, temperature drop changed to acceptable levels.

In Figure 20, head loss results of increased-flow simulation were
presented; the head loss diagram changed drastically. Increased flow at this branch, which is circled in Figure 20, gave it the highest pressure drop in the system. There is about a 5 m increase in the supply network maximum head loss value, which is the required pumping head for the circulation pumps. Therefore, it is obvious that increasing the flow capacity of the branch is not a cost effective solution, as it increases pumping costs.

To overcome the problems in this region, the first item to focus on is pumping the necessary head required by the system. This will drastically decrease the number of buildings with a heating problem. Changing the pipes to better insulated ones can prevent excess heat loss of water in the pipes. Also, while changing the pipes in that branch, new pipe diameters should be selected, smaller than the existing ones.

It should be stressed that the simulation results change according to the roughness of the values and heat loss coefficients of the pipes. In Figure 21, variation of maximum temperature drop in the system is compared for good insulation and bad insulation. It is obvious that temperature drop changes significantly according to insulation quality. However, the temperature decrease trend does not change. Simulating the system by assuming pipes have good insulation, results in the highest temperature drop in the same branch as for the less insulated case. Therefore, if there is an excess temperature drop problem in the system, this branch is the first place affected. It should also be considered that customer complaints have been reported from buildings which are located at the end of the highest temperature drop branch. Close investigation of Figures 12, 16 and 17 shows the obvious existence of high temperature drop in this branch. Therefore, with the actual temperature measurements taken from the system, heat loss coefficients used in the model should be calibrated and possible solution methods discussed in this study should be reconsidered.

**Region II**

The most significant characteristic of region II is, its being farthest from the pump station. From the head loss diagram (Figure 13) of this region, it can be said that region II does not experience low-pressure problems. Even with the worst piping insulation, simulation results for maximum temperature drop in this region is only 5°C, which is sufficient for proper operation of heating systems. However, this region still contains buildings with a heating problem. Considering the distance between the pump station and region II, it can be said that this region may experience low flow during peak flow demands.

Low flow during peak demand times, is another common operational problem. Solving this problem in an existing system is different from designing pipes for new construction, in that the utility cannot pass the cost of improvements onto a new customer. Rather, the operator must find the weak link in the system and correct it. The possible reasons for poor flow during peak demand in an existing system are (Walski et al., 2002).

- Small mains;
- Long-term loss of carrying capacity due to tuberculation and scaling;
- Customers located far from the source;
- Inadequate pumps;
- Closed or partly closed valves;
- Improper setting of flow regulators in that branch;
- Some combination of above.
As stated before, in the Balçova district heating system, flow regulator valves play a very important role in the hydraulic balance of the system. Each flow regulator should be adjusted according to the heat demands of that specific customer. Changing the setting point in one regulator affects the entire system, as explained in Section 2.2.2. Therefore, while adjusting a new setting point for one building, other buildings in that branch should be considered, too.

In region II, this problem becomes obvious. Buildings which are connected to the system before region II get more hot water than necessary and buildings at the end point cannot get sufficient flow for heating. Also leakage detection efforts should be focused on this region, as there is a 5 l/s average leakage which has not been located yet.

Region III
In Figure 13, region III has a high-pressure loss gradient. The main cause of a high-pressure gradient is high speed flow in this branch. This kind of problem occurs in undersized distribution networks. An undersized distribution network problem is not easy to identify in average-day conditions. If a pipe is too small, it may become a problem only during high flow conditions (Walski et al., 2002). Therefore, peak flow simulations are the best way to identify an undersized distribution network. Sizing new piping and rehabilitating existing pipes flattens out the slope of the hydraulic gradient for a given flow rate. By investigating head loss diagrams of the system, pipes needing repair or rehabilitation can be located.

To see the effect of diameter change on region III, pipes diameters, shown in Figure 22, were increased from 80 to 100 mm and 65 to 80 mm in the Pipelab simulation program. Results are shown in Figure 23. The head loss gradient for region III decreased significantly. Therefore, this part of network contains undersized pipes which should be changed for efficient operation of the system.
6.1.4 Pump control strategy for city circulation loop

The distribution system and characteristics of circulation pumps are explained in Sections 2.2.2 and 4.2. In this section, best pumping strategy for minimum energy consumption according to the results of the simulation will be determined.

To provide water circulation in a system, pumps must supply enough pressure to the water. In Figure 24, the basic pressure loss scheme of the system is shown. Required pumping head \( H_{\text{pump}} \) is shown in the figure. Since the pressure loss values of the distribution network have already been calculated by simulation, the only parameter to add to the simulation results is the main heat exchanger pressure loss in the pumping station.

Figure 25, pressure at the outlet of the heat exchanger in the pumping station is given as a function of the heat exchanger inlet pressure. Figure 25 shows hourly measurements of heat exchanger inlet and outlet pressures. As can be seen, heat exchanger outlet pressure values fluctuate between 4 and 6 bars with an average of 4.8 bars. Therefore, heat exchanger inlet pressure (pump head) has no effect on the heat exchanger outlet pressure of the system. One of the important reasons for fluctuations of heat exchanger outlet pressure is changing water temperatures in the heat exchanger. Since there is no effect of running pumps at pressures higher than 6 bars, pump analysis was done by keeping a constant pump head of 6 bars.

In Figure 26, power consumptions of 3 different combinations are given. As can be seen, until about 100 l/s flow, operation with one pump is the most economic solution; between 100 and 150 l/s, operation of two pumps gives the minimum power consumption. Finally, for flow rates higher than 150 l/s, operation of three pumps is the most economical option. It should be noted once more that Figure 26 is based on the assumption that pump head is kept constant at 6 bars. Since increase in the pump head is compensated by a heat exchanger, it is obvious that there is no need to operate pumps at higher heads. In Figure 27, heat exchanger pressure drop is given as a function of a pump head. Plotted by using actual data, compensation of excess pump head by a heat exchanger is clearly seen.
FIGURE 26: Power consumption of circulation pumps for different combinations

FIGURE 27: Heat exchanger pressure drop as a function of pump head

6.2 Geothermal pipeline system

The structure of a geothermal pipeline system and the problem of finding the minimum well pump operation policy were explained in Sections 2.2.1 and 4.1, respectively. The results are given in Table 4. According to requirements, program input parameters can be changed so that the best combination for other heat loads can be found. While choosing the best option from among the alternatives, continued operation of the same pump was considered.
TABLE 4: Well operation policy for different heat loads

<table>
<thead>
<tr>
<th>Power cons. (kWe)</th>
<th>Heat production (kWth)</th>
<th>Total flow (kg/s)</th>
<th>Flow (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>BD2</td>
</tr>
<tr>
<td>371</td>
<td>49043</td>
<td>210</td>
<td>22</td>
</tr>
<tr>
<td>309</td>
<td>44750</td>
<td>181</td>
<td>22</td>
</tr>
<tr>
<td>258</td>
<td>40239</td>
<td>168</td>
<td>17</td>
</tr>
<tr>
<td>213</td>
<td>35806</td>
<td>151</td>
<td>17</td>
</tr>
<tr>
<td>172</td>
<td>31371</td>
<td>122</td>
<td>17</td>
</tr>
<tr>
<td>138</td>
<td>26796</td>
<td>106</td>
<td>17</td>
</tr>
<tr>
<td>108</td>
<td>22350</td>
<td>88</td>
<td>17</td>
</tr>
<tr>
<td>82</td>
<td>18461</td>
<td>70</td>
<td>8</td>
</tr>
<tr>
<td>59</td>
<td>13701</td>
<td>55</td>
<td>8</td>
</tr>
<tr>
<td>40</td>
<td>9299</td>
<td>43</td>
<td>13</td>
</tr>
<tr>
<td>26</td>
<td>4637</td>
<td>18</td>
<td>13</td>
</tr>
</tbody>
</table>

In Figure 28, presentation of the geothermal pipeline system in Pipelab is shown.

In Figure 29, results of the simulation for 49,043 kWth heat production (Table 4) is given. Thick lines in the Figure 29 are main pipelines. Other lines are connections to production and consumption points. As can be seen, the distribution of geothermal water temperature is sufficient for the operation of heat exchanger stations in the system.

In Figure 30, pressure distribution of the pipeline system from well heads to heat exchangers is shown for maximum heat production (Table 4). The largest pressure needed to pump the water into the system is for BD4. Operation of well head pressures should proceed according to the head loss diagram of the pipeline system.
6.3 Estimation of heat demand

As stated in Section 5, a time series analysis of hourly measurements taken from the pumping station was done to fit an estimation model for the heat load of the system. Data used in this analysis are:

- Daily average of flow of circulation water;
- Daily average of outside temperature;
- Daily average of water temperature at the pumping station inlet;
- Daily average of water temperature at the pumping station outlet.

Data covers 188 days of the 2001-2002 heating session. Original outputs of the program, which used the ARX function from Matlab’s System Identification Toolbox to create a prediction model, are given in Figure 31. Figure 31 can be rewritten as the equation:

\[
q_{\text{tomorrow}} = A q_{\text{today}} + B T_{\text{outside}} + C T_{\text{outside}}^2 + D T_{\text{outside}}^3 + E
\]

where

\[
\begin{align*}
A &= 0.8125 \pm 0.03696 \\
B &= -197.3 \pm 46.34 \\
C &= -148.9 \pm 59.85 \\
D &= 71.84 \pm 52.32 \\
E &= 6714 \pm 1274
\end{align*}
\]

Discrete-time IDPOLY model: \( A(q) y(t) = B(q) u(t) + e(t) \)

\[
A(q) = 1 - 0.8125 (\pm 0.03696) q^{-1}
\]

\[
B(q) = -197.3 (\pm 46.34) - 148.9 (\pm 59.85) q^{-1} + 71.84 (\pm 52.32) q^{-2}
\]

\[
B2(q) = 6714 (\pm 1274)
\]

Estimated using ARX
Loss function 1.64798e+006 and FPE 1.73804e+006
Sampling interval: 1
Created: 07-Oct-2002 23:57:05
Last modified: 07-Oct-2002 23:57:05

FIGURE 31: Original program output for time series analysis
Success of the model was tested on two separate data sets. The first data set belongs to the 2001-2002 heating season. In Figure 32, estimated heat loads are shown by dots while variation of real load is given by a continuous curve. Only data from the 2001-2002 heating session were used. Therefore, success of the model can be checked by using another data set and comparing the actual values with the model. In Figure 33, 2000-2001 heating season measurements were used. Estimated heat load is shown by dots, and real heat load is shown by a continuous curve. As can be seen, results of the prediction model and actual heat load variation fit each other. Comparison of the results shows that using a prediction model to predict the head load demand for next day can give rather close estimation of the actual value.

FIGURE 32: Comparison of real heat load with estimations (2001-2002 session)

FIGURE 33: Comparison of real heat load with estimations (2000-2001 session)
7. CONCLUSION

The main goal of this study was to simulate the Balçova geothermal distribution system, and by considering simulation results, determine the operation strategy for the system. Simulations of city circulation and geothermal distribution networks were achieved by using the Pipelab district heating simulation program. During the modelling phase, system data taken from the Balçova geothermal company was used. However roughness values and heat loss coefficients of pipes were estimated by considering the catalogues of district heating pipes on the market, since there is no actual existing data.

The primary objective of a simulation is to reproduce the behaviour of a real system in a useful way. To achieve this aim, data are supplied that depict the physical characteristics of the system, the loads placed on the system, and the boundary conditions in effect. Even if all the data gathered describe a model that matches the real system exactly, it is unlikely that the pressures and flows computed by the simulation model will absolutely agree with observed pressures and flows. Modelling is essentially a balance between reality, a simulated reality, and the effort necessary to make the two agree (Walski et al., 2002).

By looking at Figure 15 where the actual system pressure loss is compared with simulation results, it can be said that simulation results follow the trend of actual system behaviour. It should also be noted the most problematical buildings, according to company record, experience high pressure or temperature drops in the simulation. This is also an indication of successful simulation.

Roughness values used in the simulation are for new pipes. However, the system is 5 years old. Therefore, it is certain that actual roughness values are bigger than those used in simulation. In Figure 34, variation of maximum head loss of a supply network with roughness values is given. According to Walski et al., (2002) two pipes of the same size, material, and age can have different effective diameters and roughness based on the quality of the water historically flowing through pipe. Although results of the simulation give quite reasonable results, further study of the calibration of roughness values in the model will improve the accuracy of results obtained from the system. Roughness values change over time. Also, scale formation in the pipes is highly possible since water in the circulation loop contains high amounts of calcite. Scaling, which occurs over time after the pipe has been installed, creates the difference between actual and nominal diameters. Reduction of diameters in the system creates higher pressure losses in the system. Since allowable pump head to provide circulation in the system is at a very critical level, the effect of these two factors (roughness and scaling) on the system should be investigated to provide efficient pumping operations.

Leakage is also a problem in the Balçova district heating system. The amount of leakage changes according to system operation conditions. During peak demand, leakage reaches up to 5 l/s. Although this amount is small compared to the total flow of the system, the effect of leakage can be much bigger than its value, depending on where it is placed. It is the general approach to distribute leakage homogeneously in the system during simulation, when the location of leakage is unknown. Simulation results should be investigated and compared with actual measurements taken from the system. Simulation can be used as a very efficient tool in locating leakages.

By investigating system head loss diagrams and available heads supplied from pumps to circulate in the city, it can be seen that available head is at a very critical level. Since the region having highest head loss in the system has continuous problems of insufficient heating, it is certain that there is a sufficiency problem in the system. Since the available head supplied from the pump station cannot be increased, other...
solution techniques (6.1.2) should be considered. However, it should also be taken into account that there is leakage in the system, and leakage detection efforts should be focussed on this region.

Results in finding an optimum well pump operation strategy were given in Section 6.2, determining the right combination of wells that should be operated for minimum power consumption while meeting system heat demands. The results were then used as an input parameter for the Pipelab simulation program and the interaction of the wells to each other checked. From the results of the geothermal pipeline simulation, it can be said that the most important parameter for a control system is well head pressure valves, since the requirement of head to pump geothermal fluid into the system is different for each well. Therefore, pressure between pipeline and well should be under control to provide sufficient head to the system.

The ARX prediction model provides the heat load estimation for the following day. As can be seen, in comparing model results with actual measurements, the model gives very accurate estimations of next day heat load. Therefore, the model results should be considered while determining the pumping strategy for the next day. In Figure 35, the suggested control diagram of the system is shown. By using next day estimated heat load, a system operation strategy (heat exchanger temperatures, pump settings, valve arrangements) can be determined.

It should always be remembered that simulation programs cannot reproduce actual operation conditions exactly. Using them for this kind of system is a continuous process of calibration. Simulation accuracy can only be increased with more data. Since it is impossible to place measuring devices at every point of the system to provide the necessary data to the program, mobile measuring devices should be used.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr. Ingvar Fridleifsson for giving me the opportunity to participate in the UNU Geothermal Training Programme in Iceland. I am very grateful to Mr. Lúdvík S. Georgsson and Gudrún Bjarnadóttir for kind and patient help during the last six months. Their great organizational skills made life easier for me.

Thanks to my professors in İzmir Institute of Technology Geothermal Energy Centre: Dr. Macit Toksoy introduced the area of geothermal energy and offered this project to me. Dr. Zafer İlken, Director of the Geothermal Energy Centre, gave me the necessary permission to come to Iceland. Dr. Gülden Gökçen, supervisor of my M.Sc. project, held very valuable lectures for me during the last two years. Great appreciation should be expressed to Balçova Geothermal Company, and chief engineer Cihan Çanakçı for his tireless efforts to create a system database and permission to use unpublished system data.

Special and final thanks go to a great teacher and my advisor, Páll Valdimarsson, for his guidance and patience during the last six months. His enormous enthusiasm to teach motivated me every morning.
NOMENCLATURE

Scalars

\( A \) = Heat exchanger area \( [m^2] \)
\( a_{ij} \) = Connectivity matrix entry \([-]\)
\( a, b, c \) = Pump efficiency curve coefficients \([-]\)
\( c_p \) = Water heat capacity \([J/(kg \cdot ^\circ C)]\)
\( G_s \) = Subgraph
\( G_n \) = Graph
\( g \) = Acceleration due to gravity \([m/s^2]\)
\( h_{\text{pump}} \) = Pump head \([m]\)
\( T \) = Tree
\( L \) = Cotree (the set of links)
\( m \) = Water flow \([kg/s]\)
\( m_{h} \) = Flow of hot fluid \([kg/s]\)
\( m_{\text{well}} \) = Well flow \([kg/s]\)
\( N \) = Pump rotational speed \([rpm]\)
\( n_L \) = Number of links \([-]\)
\( n_n \) = Number of nodes \([-]\)
\( n_q \) = Number of constant heat flow elements \([-]\)
\( n_T \) = Number of tree branches \([-]\)
\( n_i \) = Number of constant temperature elements \([-]\)
\( P_{\text{pump}} \) = Pump power consumption \([W]\)
\( P_{\text{total}} \) = Total pump power consumption \([W]\)
\( Q_{\text{well}} \) = Heat produced from well \([W]\)
\( q \) = Heat flow \([W]\)
\( q'_q \) = Constant heat flow \([W]\)
\( q_t \) = Heat flow in constant temperature element \([W]\)
\( q_x \) = Heat exchanger duty \([W]\)
\( T \) = Temperature \( [^\circ C]\)
\( T_{c,\text{in}} \) = Cold fluid inlet temperature \( [^\circ C]\)
\( T_{c,\text{out}} \) = Cold fluid outlet temperature \( [^\circ C]\)
\( T_{h,\text{in}} \) = Hot fluid inlet temperature \( [^\circ C]\)
\( T_{h,\text{out}} \) = Hot fluid outlet temperature \( [^\circ C]\)
\( T_{\text{well}} \) = Geothermal fluid temperature at well head \( [^\circ C]\)
\( T_{\text{return}} \) = Geothermal fluid temperature at heat exchanger outlet \( [^\circ C]\)
\( U \) = Heat transfer coefficient \([W/(m^2 \cdot ^\circ C)]\)
\( U_{eq} \) = Equivalent heat transfer coefficient \([W/^\circ C]\)
\( V \) = Volumetric flow rate \([l/s]\)

Greek symbols

\( \Delta T_{m} \) = Logarithmic mean temperature difference \( [^\circ C]\)
\( \eta_{\text{pump}} \) = Pump efficiency
\( \eta_{\text{motor}} \) = Motor efficiency

Vectors and Matrices

\( \mathbf{A} \) = Flow elements connectivity matrix \([-]\)
\( \mathbf{A}_{f} \) = Flow connectivity matrix \([-]\)
\( A_L = \) Cotree connectivity matrix 
\( A_q = \) Constant heat flow connectivity matrix 
\( A_T = \) Tree connectivity matrix 
\( A_r = \) Constant temperature connectivity matrix 
\( A_x = \) Heat exchanger connectivity matrix 
\( D = \) Cutset matrix 
\( E = \) Element flow origin matrix 
\( I_{hT} = \) Tree head source identity matrix 
\( I_{sT} = \) Tree storage tank identity matrix 
\( I_{rT} = \) Tree resistor identity matrix 
\( I_{pT} = \) Tree pipe identity matrix 
\( I = \) Index vector 
\( m = \) Flow vector 
\( m_{hT} = \) Tree head source flow vector 
\( m_{mL} = \) Link flow source flow vector 
\( m_{pL} = \) Link pipe flow vector 
\( m_{pT} = \) Tree pipe flow vector 
\( m_{rT} = \) Tree resistor flow vector 
\( m_{sT} = \) Tree storage tank flow vector 
\( F_{ij} = \) Submatrix of the cutset matrix 
\( q_f = \) Vector of heat flow in flow elements 
\( q_q = \) Constant heat flow vector 
\( q_t = \) Vector of heat flow in constant temperature elements 
\( q_x = \) Heat exchanger duty vector 
\( T_p = \) Node temperature vector 
\( U_{eq} = \) Heat exchanger transfer matrix 

**REFERENCES**


