

Geothermal District Heating System Under Variable Loads - Pump Station and Pipe System Design

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Abstract—This article proposes an optimal design methodology for designing a pump station and a geothermal water distribution network for a district heating system for various loads. A new approach to model based design and optimization using evolutionary algorithms, is presented. The approach makes use of functional and model based reasoning techniques, by applying elementary knowledge or information to optimize locally each element in a pump and a pipe system model. The global search methods for the pump arrangement, the topology and the pipe diameter design are adaptive genetic algorithms. The basic features of the presented approximations are illustrated by redesigning a district heating distribution system in use in Reykjavik under various loads, resulting in an improved design.

Keywords—geothermal, district heating system, pipelines, pump station, optimization

I. Introduction

In geothermal district heating systems, the water distribution networks are costly infrastructures in terms of construction and energy requirements. This paper describes a novel approach for the designing of a water distribution network under various loads that includes a pump station and a pipe system based on life cycle cost.

For district heating systems, the flow and pressure at each node varies over time of the year. Thus the pump control affects the operational cost. In this paper, the flow control is based on the variable speed and the on/off control on serial pumping or pressure controlled valves. In the pipe system design, the topology, or the pipe layout, and the pipe diameter is optimized using genetic algorithms. Elementary knowledge is used for optimizing the pipe thickness, supports, anchors and the thermal expansion loop locally. The interconnection between the pipe system and the pump station design is discussed. The objective is to minimize the total or life cycle cost (capital maintenance and operational cost), subject to ensuring demands or constraints at all points.

Optimization of water distribution networks has been the subject of many articles during the last decades, where thorough discussion on topology, route selection and pipe diameters can be found ([1] and [2]). Pipe system and pump station optimization problems usually give rise to complex objective functions that employ modeling analysis for fluid flow assessment.

A number of researchers have addressed the important problem of minimizing the number of evaluations of the objective function needed to reach an optimal solution ([3] and [4]). This is crucial due to the computational complexity of the objective functions. Both classical and mathematical methods which generally require some simplification, and meta-heuristics methods inspired by nature, have been developed and applied to the nonlinear and combinatorial engineering problem. [3].

Searching for the best solution is often limited by the narrow-mindedness of the human brain. With this in mind, the designer must tackle his or her project without missing the best solution through restraining the solution space. To expand the horizon the model based analysis of complete systems is used. The problem is formulated by developing an objective function where the optimization parameters define the pump arrangement, pipe system topology, and pipe diameters. The generality of the optimization problem is reduced by using common design layouts and thus we do not consider fundamental topological changes of junctions. The pump station and pipe system optimization consist of selecting components from a pre-defined set of elements and is implemented with discrete decision variables. Optimization of pipe elements consists of optimizing the diameter, after the topology has been defined, and is implemented with discrete variables. Flow distribution and pressure analysis is performed using EPANET[5]. Thicknesses, pressure classes, supports, expansion loops and anchors are not part of the optimization parameters, but are determined during the evaluation of the objective function. Each time the objective function is evaluated, the pipe system is designed in a sub-optimization according to given loads. The pressure head constraints are considered using penalty functions. The method is tested on a geothermal district heating system in Iceland.

The model based analysis is described in section II. In section III the adaptive model or objective function for designing the distribution network is given. The case study, where a pipe distribution network is designed, is presented in section IV. The paper concludes with a general discussion and a summary.

II. District Heating Systems

Designing a distribution network can be divided into a fluid flow analysis, the pump and pressure control arrangement, pipe route selection, pressure class design, and a mechanical and thermal stress analysis. The assumptions are: flow load, intake and outflow or demand, pressure head, placement of each junction and a map with all restrictions.

A. Pump System

The pump element is defined by the pump curve and the efficiency curve. The pump curve $H(Q,n)[m]$ gives the pressure height for different flow rates Q (m^3/h) and rotational speed (RPM). The efficiency is also flow dependent as shown in Fig. 1. For serially connected pumps the pump heights are added together but for pumps connected in parallel, the flow is added together. Other alternatives are flow control by using pressure guided valves and pumps with an on/off control. For the pump station, the design variables are the number and type of pumps, connection and flow control.

B. Topology and Route Selection

Topology and route selection is a process of identifying constraints, avoiding undesirable areas, and maintaining the economic feasibility of the pipeline. For a landscape with no restriction, the shortest path is a straight line between two points but installation pipelines often follow roads. For the area in Fig. 1, the distances between junctions are shown in Table 1 for all available routes. The height of each area and the flow demand as a ratio of total flow is also shown in the table.

TABLE I. HEIGHT, FLOW AND DISTANCE TABLE.

Location	J1	J2	J3	J4	J5	J6
Height	43 m	67 m	88 m	75 m	96 m	110 m
Flow ratio	18%	20%	22%	16%	10%	14%
Distances	(m)	(m)	(m)	(m)	(m)	(m)
J1	0	6580	11020	8580	5320	10900
J2	6580	0	7300	5360	7800	8240
J3	11020	7300	0	4350	6530	7590
J4	8580	5360	4350	0	4600	3200
J5	5320	7800	6530	4600	0	3500
J6	10900	8240	7590	3200	3500	0

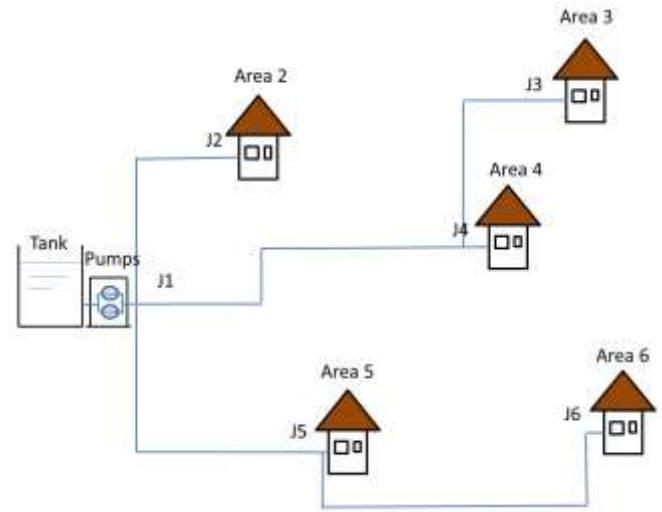


Figure 2. Topology and route selection.

C. Flow Analysis

The method used in EPANET [5] to solve the flow continuity and head loss equations at a given point in time is a hybrid node loop approach. The head loss relation in a pipe between nodes i and j is given by,

$$H_i - H_j = dH_f \tag{1}$$

where H is the nodal head (m), r is the resistance coefficient, Q is the flow rate (m^3/s), n is the flow exponent and m , is the minor loss coefficient. For the pipe element j the Darcy-Weisback equation gives the pressure drop or friction head,

$$dH_f = f V^2 L_e / (2 g D) \tag{2}$$

where f is the friction factor, V (m/s) is the velocity of fluid, L_e (m) is the equivalent length, g (m/s^2) is the gravity and D (m) is the inner diameter. Using the continuous and Darcy-Weisback equations, n pressure heads and m flow variables can be solved. The friction factor f for the turbulent flow, that is when the Reynolds number $Re \geq 2100$, is calculated according to the Colebrook-White equation,

$$f = 0.25 / (\log_{10}(k / (3.7 D) + 5.74 / Re^{0.9}))^2 \tag{3}$$

where k (m) is the roughness. For a Reynolds number that is lower, $Re < 2100$, the friction factor is $f = 64 / Re$.

The second set of equations that must be satisfied is flow continuity around all nodes,

$$\sum_j Q_{ij} - q_i = 0 \quad \text{for } i = 1, \dots, N \tag{4}$$

where q_i (m^3/s) is the flow demand at node i and by convention, flow into a node is positive.

Equations (1) and (4) are solved using gradient method.

D. Pipe System Design

According to ANSI B31.3, the nominal pipe thickness t_n is larger or equal to the requisite pipe thickness t_m , according to the equation,

$$t_n \geq t_m = P D / (2 (S E + P y)) + A \tag{5}$$

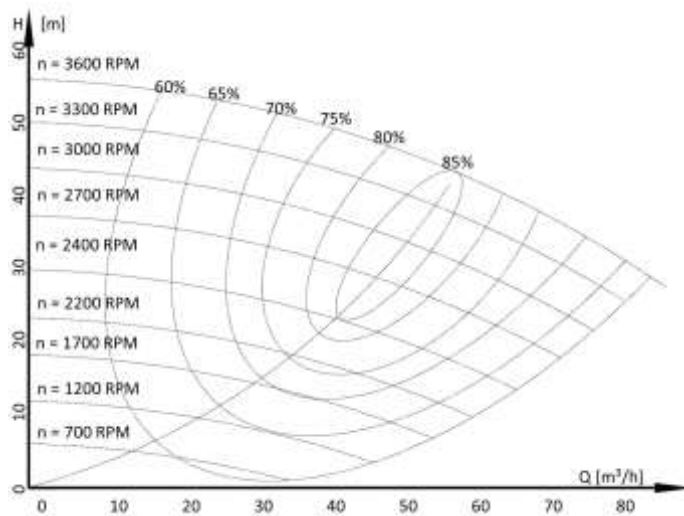


Figure 1. Pump performance curves for variable speed driven pumps.

where P (Pa) is the design pressure, D (m) is the outer diameter, S (Pa) is allowable stress, E is the welding factor, y is the temperature dependent coefficient and A (m) is additional thickness.

The criterion for stresses due to sustained load is given by the equation,

$$PD/(4 t_n) + (0,75 i_a) M_A/Z \leq 1,0 S_h \quad (6)$$

where M_A (Nm) is the bending moment, S_h (Pa) is allowable stress under operational conditions, i_a is the stress intensification factor according to the ANSI B31.3 standard and Z (m³) is the cross section modulus for the pipe.

The effects of pressure, weight, other sustained loads, and occasional loads, including earthquake, wind and snow weight must meet the requirements of the equation,

$$S_L = PD/(4 t_n) + (0,75 i_a) M_A/Z + (0,75 i_a) M_B/Z \leq k S_h \quad (7)$$

where $k = 1.15$ for occasional loads acting for less than 10% of the operating period and $k = 1.20$ for occasional loads acting for less than 1% of the operating period, M_B is bending moment loading on the cross section due to occasional loads.

The load is pipe weight q_p (N/m), fluid weight q_v (N/m), insulation weight q_e (N/m), snow weight q_s (N/m), wind load q_w (N/m) and seismic load q_j (N/m). Wind and seismic loads are according to the Icelandic standards IST 12 and IST 13 with reference to Eurocode 8. The distance supporting vertical movements is L_z (m) and the distance between supports for both vertical and horizontal movements is L_y (m). The maximum bending moments M_A and M_B used in the equation for sustained and occasional loads are according to the equation,

$$M_A = 1/8 \sqrt{[(q_p + q_e)^2 L_z^2]} \quad (8)$$

$$M_B = 1/8 \sqrt{[(q_v + q_s + 0,5 q_j)^2 L_z^2 + \min(q_w, q_j)^2 L_y^2]}$$

The expansion loop meets the following requirements with respect to thermal expansion,

$$DY/(L - U)^2 \leq 208.3 \quad (9)$$

where D (mm) is the nominal pipe diameter, Y (mm) is the resultant movement to be absorbed by the pipe loop, L (m) is the developed length of the line axis and U (m) is the length between anchors.

III. GA and Optimization Model

For the geothermal district heating system the decision variables are the pump station arrangement, pipe system topology or layout, and pipe diameters. Selection of topology, pump arrangement and pipe diameters from a set of available discrete alternatives for the least total cost is an NP hard problem. Figure 3 shows the representation of the objective function and the genetic optimization algorithm.

A. Objective Function and Representation

The objective function is assumed to be the cost function of the pump arrangement and the pipe system. The capital costs of pumps, valves, bends, junctions and the length of pipes as given in Table 2. Lengths depend on the route or the topology of the pipe system but the operational cost or the cost of pumping energy depends on the pipe diameter. The objective function or the total life cycle cost, becomes

$$f(P_a, R_{11}, \dots, R_{1N}, R_{21}, \dots, R_{2N-1}, D_1, \dots, D_N) = C_c + C_o + C_m$$

where the design variables are P_a discrete variable describing the pump arrangement, R_{11} number of the placement that the pipe no. 1 goes to and R_{21} is the number of placement that the pipe no. 2 goes from. Pipe no. 1 always goes from the pump station. The diameter D_i is an index to the diameter table (Table 2). The construction cost is C_c and the updated operational and maintenance costs are C_o and C_m . The pumping cost is associated with the electrical energy input to drive the pumps. The number of pumps and the rotational speed is optimized locally as an adaptive part of the GA where the head and flow constraints at each area are fulfilled.

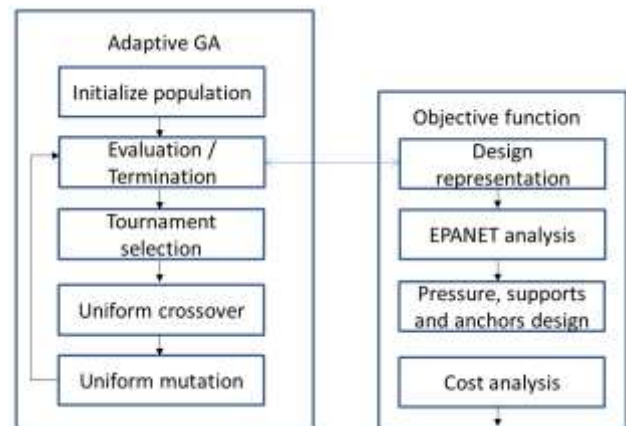


Figure 3. Adaptive Genetic Algorithm and objective function.

B. Genetic Algorithm

The main property of Genetic Algorithms (GA) is that each individual in a population is coded as a binary string of ones and zeros, corresponding to chromosomes in biology. A general GA goes as shown in Fig. 3. GA individuals store the design variables in a coded representation. Gray coding is the most common representation of the design variables, since single digit changes in the encoding translates into smooth variations of the decoded variables. A commonly used selection method for GA is the tournament selection. In this selection method, a number of n-individuals is chosen randomly from the population and the best individual from the group is copied to the intermediate population. This is repeated as often as the number of individuals in a generation. The size n is called the tournament size. Increasing the

tournament size results in a loss of diversity and increasing selection intensity. Genetic Algorithms implicitly maintain statistics about the search space through the population. It has been proposed to use this implicit statistics to explicitly enhance GA's performance. Inspired by this idea, a statistics based non-uniform crossover method has been proposed. In order to get a good coverage of the search space random bits in the resulting individuals from the crossover are mutated with a probability of p_m .

iv. Results

The case study described in this paper is a district heating system that was developed some years ago and is currently operating. The case was constructed for the purpose of verifying the method by comparing results with the best design.

For a geothermal district heating system, the hot water is pumped from the earth to a tank. From the tank the water is pumped to different areas as shown in Figure 1. Each area has a pump for the local network. In this case study, the distribution network from the tank to the local area pump stations is designed. The pressure at the intake of each area shall be equal or higher than 2 bars. Water temperature is 80°C and thermal expansion loops are used at each 160 m between anchors. Pipe material is S355 according to the EN 10025 standard and the welding factor is 0.9. The snow load factor is 1.7 and the maximum wind speed is 48 m/s as in the IST 12 standard. The seismic load factor is 0.24 according to Eurocode 8.

TABLE II. PRICE TABLE WITH REFERENCE PRICES (USD).

Nom. Diam.	Outer mm	Thick. mm	Pipe USD/m	Bend USD/p	Valve USD/p	Junc. USD/p
125	139.7	3.2	25	26	579	39
150	168.3	4.0	32	42	702	44
200	219.1	4.5	42	39	936	53
250	273.0	5.0	45	55	1112	70
300	323.9	5.6	57	59	1346	114
400	406.4	6.3	72	69	1434	132
500	508.0	6.3	95	86	1717	155
600	609.6	6.3	115	107	1913	217

The distances between locations or areas are shown in Table I, and the flow demand, is shown in Figure 4. The size of each area is different as shown in Fig. 4 and the flow at each intake is related to the area size given as a ratio of the total flow in Table I. The flow shown in Fig. 4 is the total demand (100%) from the pump station J1.

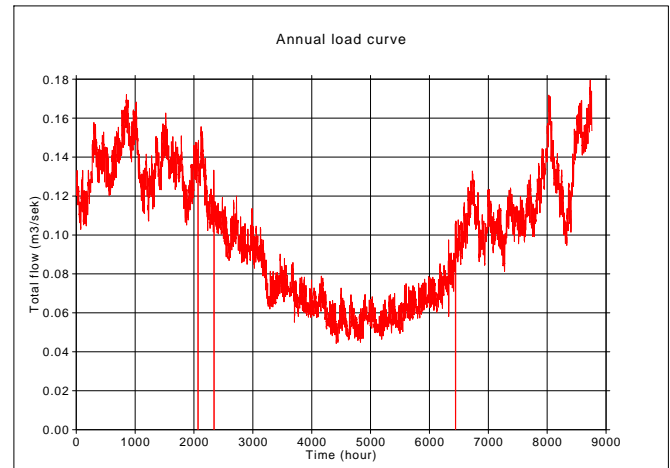


Figure 4. Total flow rate at the pump station.

The prices for ten different pumps and the power are shown in Table III. For each pump, the pump curves as shown in Figure 1 are used and the rotational speed is adapted to the head and flow rate. The prices for the pipes with supports and anchors, pipe bends and junctions are shown in TABLE II.

TABLE III. PUMP TYPES AND PRICES.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Price \$	1.3	1.4	1.5	1.63	1.67	1.8	1.9	2.1	2.4	2.7
P (kW)	20	30	35	40	45	50	55	60	70	80

The distribution network was optimized and the best solution is shown in Fig. 5 and listed in Table III. The total cost is 921 000 USD, thus reduced by 17% compared to the life cycle cost of the system that is designed similar to the one currently operating.

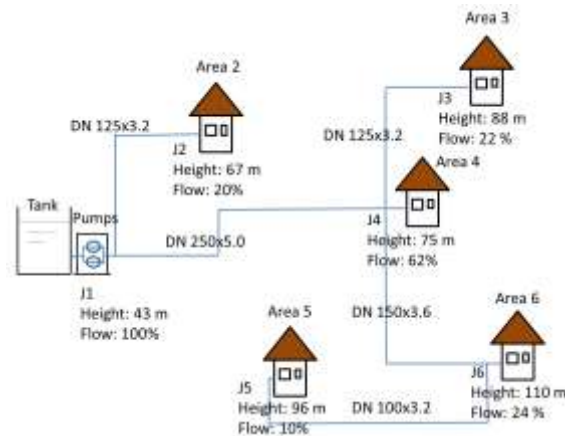


Figure 5. District heating system with the lowest life cycle cost.

TABLE IV. RESULTS

Pump station	Pump type	Pump size	Pump cost	Pressure control
1	P4	40 kW	1630 \$	Variable
2	P4	40 kW	1630 \$	Variable

Pipe system	Pipe size	Thickness	Length	Expansion loop	Length b supports
J1 – J2	125	3.2 mm	6580 m	16 m	12 m
J1 – J4	250	5.0 mm	8580 m	19 m	14 m
J4 – J3	125	3.2 mm	4350 m	16 m	12 m
J4 – J6	150	3.6 mm	3200 m	18 m	13 m
J6 – J5	100	3.2 mm	3500 m	14 m	10 m

v. Conclusion

This paper describes a novel approach for designing a distribution network for geothermal district heating systems. The design of a distribution network is a multitask problem, and this paper shows the importance of coordinating the design of the pump station and the pipe system design. The objective function was developed by using a model based reasoning. An algorithm solving both the fluid flow demand and the pump station arrangement using EPANET for different pipe system topologies was developed. A number of realizations of the proposed objective function were tried and a GA algorithm was able to find good solutions. This indicates that a GA algorithm is well suited for solving the proposed problem. The algorithm was successfully tested by designing a distribution network with one pump station and five outtake stations. The model and GA can be improved further by the operational part of the pumping station.

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