Optimisation of Balçova-Narlıdere Geothermal District Heating System

By

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ABSTRACT

The main goal of this study is to determine optimum control strategy of Balçova-Narlıdere geothermal district heating system to minimise the energy consumption. First heat demand model of the system was constructed by using statistical method called time series analysis. This model provides the heat demand forecast of next day, by considering ambient temperature forecast of the next day. Then geothermal pipeline system and city distribution system have been modelled in the PIPELAB district heating simulation program. To model the system close to the actual case, database of Balçova geothermal company was used as an input, and the code of PIPELAB program was adapted to be used in geothermal pipeline system. Once the sysem was modelled in PIPELAB, it would be possible to obtain pressure and temperature distribution along the pipe networks in the system. To determine the optimum operation strategy of the wells according to the changing heat demand first the energy consumption of each well pump was defined as a function of their heat production rate. Then these functions were inserted into dynamic programming algorithm which selects the optimum well operation strategy among thousands of options. Also power consumption models of circulation pumps were built and calibrated with actual values. Finally optimum control strategy for the system was determined and the system model was operated by using optimum control strategy according to ambient temperature data of 2001 and 2002. The acual energy consumption values were compared with the optimum energy consumption values and decisive factors in efficient control and operation of the system have been defined.

ÖZ

Bu çalışmanın amacı Balçova-Narlıdere Jeotermal Bölge Isıtma Sisteminde enerji tüketimini minimize edecek optimum sistem kontrol stratejisinin belirlenmesidir. Çalışmaya, sistemin ısı yükünü önceden tahmin edebilen bir model oluşturulması ile başlanmıştır. Bu modelin oluşturulmasında istatistiksel bir yöntem olan zaman serisi analizi metodu kullanılmıştır. Bu model sayesinde sistemin bir gün sonraki ısı yükünü, aynı güne ait dış hava sıcaklığı tahminine bağlı olarak tahmin etmek mümkündür. Çalışmanın ikinci aşamasında jeotermal boru hattı ve şehir dağıtım şebekeleri PIPELAB bölge ısıtma sistemi simülasyon programında modellendi. Böylece sistemdeki bütün boru ağlarında basınç ve sıcaklık dağılımları bulundu. Sistemin modellenmesi işlemi sırasında Balçova Jeotermal Şirketi'nin veri tabanından yararlanıldı, böylece modelin gerçeğe yakın sonuçlar vermesi sağlandı. Değişen yüke bağlı olarak optimum kuyu çalıştırma stratejisinin bulunması için ilk olarak kuyu pompalarının enerji tüketimi, ürettikleri ısı enerjisinin fonksiyonu olarak tanımlandı. Daha sonra bu fonksiyonlar dinamik programlama yöntemleri kullanan bir programa veri olarak aktarıldı. Bu program sayesinde değişen yüke bağlı optimum kuyu çalıştırma stratejisine ulaşıldı. Daha sonra sistemdeki sirkülasyon pompalarının enerji tüketimi modellendi ve gerçek datalarla kalibre edildi. Son olarak tüm sistemin optimum kontrol stratejisi belirlendi, ve sistem 2001 ve 2002 yıllarının dış hava sıcaklığı verileri kullanılarak bilgisayar ortamında optimum kontrol stratejisi dahilinde işletildi. Optimum enerji tüketim değerleri ile gerçekleşmis değerler karşılaştırıldı. Sistem kontrolünün başarısını ve verimliliğini tanımlayan faktörler ortaya çıkarıldı.

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NOMENCLATURE

SCALARS

a, b, c	: Polynomial coefficients of pump curve	
C_p	: Specific heat of water	[kJ/kg.^{o}C]
D	: Pipe diameter	[m]
f	: Frequency	[Hertz]
e_P	: Pump efficiency	
h_P	: Pump head	[m]
h_0	: Shutoff head (Pump head at zero flow)	[m]
h_l	: Static lift	[m]
H	: Total head	[m]
g	: Accelaration due to gravity	[m/s^2]
K_P	: Pipe resistance coefficient	[s^z/m^{3z-1}]
K_M	: Minor loss coefficient	[s^2/m^5]
m, c	: Coefficients describing pump curve shape	
m_{well}	: Flow rate of well	[kg/s]
$\dot{m}$	: Flow rate of the city distribution network	[kg/s]
n	: Pump speed	[1/s]
N_s	: Synchronous speed	[rpm]
p	: Number of poles in the rotor	
P_P	: Required power to pump the fluid	[kW_e]
P_{total}	: Total power consumption of well pumps	[kW_e]
ΔP	: Power loss of geothermal fluid through pipe	[kW_t]
Q_{well}	: Heat extracted from geothermal well	[kW_t]
Q_{demand}	: Heat demand of the Balçova-Narlıdere GDHS	[kW_t]
$Q_{Forecast}$	: The heat load estimation of the next day	[kW_t]
Q_{Today}	: Actual heat load of today, measured from heat exchangers	[kW_t]
Q_P	: Pump discharge	[m/s^3]
Q_{pipe}	: Pipe discharge	[m/s^3]
Q_{BD2}	: Heat extracted from well BD2	[kW_t]

Q_{BD3}	: Heat extracted from well BD3	[kW_t]
Q_{BD4}	: Heat extracted from well BD4	[kW_t]
Q_{BD5}	: Heat extracted from well BD5	[kW_t]
Q_{BD7}	: Heat extracted from well BD7	[kW_t]
Q_{B4}	: Heat extracted from well B4	[kW_t]
Q_{B5}	: Heat extracted from well B5	[kW_t]
Q_{B10}	: Heat extracted from well B10	[kW_t]
$T_{outForecast}$	: Ambient temperature forecast of the next day	[^oC]
$T_{outToday}$	: Measured ambient temperature of today	[^oC]
$T_{outYesterday}$	: Measured ambient temperature of yesterday	[^oC]
$\Delta T_{hexCity}$	: Temperature difference between inlet and outlet of the heat exchanger for the city distribution network.	[^oC]
T_n	: Temperature of a n^{th} node	[^oC]
T_{well}	: Well head temperature of geothermal fluid	[^oC]
T_{return}	: Heat exchanger outlet temperature	[^oC]
$\eta_{overall}$	: Wire-to-water efficiency	
η_{Pump}	: Pump efficiency	
η_{Motor}	: Motor efficiency	
η_{VSD}	: Variable speed driver efficiency	
ρ	: Density of pumped fluid	[kg/m^3]
z	: Coefficient	

Vectors and Matrices

$\mathbf{A}$	: Flow elements connectivity matrix	
$\mathbf{A}_f$	: Flow connectivity matrix	
$\mathbf{A}_L$	: Cotree connectivity matrix	
$\mathbf{A}_q$	: Constant heat flow connectivity matrix	
$\mathbf{A}_T$	: Tree connectivity matrix	
$\mathbf{A}_t$	: Constant temperature connectivity matrix	
$\mathbf{A}_x$	: Heat exchanger connectivity matrix	
$\mathbf{D}$	: Cutset matrix	
$\mathbf{E}$	: Element flow origin matrix	
$\mathbf{I}_{hT}$	: Tree head source identity matrix	
$\mathbf{I}_{sT}$	: Tree storage tank identity matrix	
$\mathbf{I}_{rT}$	: Tree resistor identity matrix	
$\mathbf{I}_{pT}$	: Tree pipe identity matrix	
$\mathbf{i}$	: Index vector	
$\mathbf{m}$	: Flow vector	[kg/s]
$\mathbf{m}_{hT}$	: Tree head source flow vector	[kg/s]
$\mathbf{m}_{mL}$	: Link flow source flow vector	[kg/s]
$\mathbf{m}_{pL}$	: Link pipe flow vector	[kg/s]
$\mathbf{m}_{pT}$	: Tree pipe flow vector	[kg/s]
$\mathbf{m}_{rT}$	: Tree resistor flow vector	[kg/s]
$\mathbf{m}_{sT}$	: Tree storage tank flow vector	[kg/s]
$\mathbf{F}_{ij}$	: Submatrix of the cutset matrix	
$\mathbf{q}_f$	: Vector of heat flow in flow elements	[W]
$\mathbf{q}_q$	: Constant heat flow vector	[W]
$\mathbf{q}_t$	: Vector of heat flow in constant temperature elements	[W]
$\mathbf{q}_x$	: Heat exchanger duty vector	[W]
$\mathbf{T}_n$	: Node temperature vector	[°C]
$\mathbf{U}_{eq}$	: Heat exchanger transfer matrix	[W/°C]

Chapter 1

INTRODUCTION

1.1. Definitions

Geothermal energy, which is obtained from heat of the earth is an important source of alternative energy. Geo (Earth) thermal (heat) energy is an enormous, heat and power resource that is clean, reliable, and homegrown. The possible alternative uses of the earth's heat are as wide as the uses made of other heat sources. The particular range of methods for using the geothermal resource depends to a large degree on the temperature range of the resource. One of the most common uses of geothermal energy is district heating. Geothermal district heating systems (GDHS) provide clean and cheap heat to the cities. It is a fact that the districts where geothermal heating exists improve much faster than other parts of the city.

District heating can be defined as using boiler plant or any other source of heat to heat a number of dwellings or blocks of buildings. It has been found that the larger the consumer network in such case, the more economical boiler plant can be run. For this reason it is the practice in many countries today to heat entire sections of towns and cities, and in some cases even clusters of towns from a central heating plant. Among countries where extensive district heating systems have been built are the Russia, Former Soviet Republics, Germany, France, Austria, Holland, Belgium, Switzerland, Norway, Sweden, Denmark, United States of America and Iceland. [1]

Like other developing countries in the world, energy need of Turkey is increasing very rapidly. Since Turkey doesn't have significant conventional energy resources, use of alternative energy resources is vital. Turkey is one of the richest countries in geothermal potential which is mostly located at the western part of the country. Characteristics of the geothermal resources in Turkey are mostly suitable for heating. The use of medium temperature (30 to 150 ^{o}C) geothermal resources as a heat source in Turkish district heating systems and greenhouses has been accelerating since 1980's. Considering the geothermal district heating projects, which are in the phase of conceptual planning and construction, it is obvious that geothermal energy will be started to use widely for the heating purposes in the next decade. [2]

Balçova-Narlıdere GDHS is the biggest district heating system of Turkey. It is mainly composed of two subsystems, geothermal pipeline system and city distribution network. The geothermal pipeline system carries the geothermal fluid from wellheads to the pumping stations. In the pumping stations, the energy of the geothermal fluid is transferred to water, with the help of plate type heat exchangers. It is then circulated in the city distribution network. 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 and after transfering its energy; it is pumped into the injection wells from the geothermal pipeline system.

Although the system is usually called Balçova geothermal district heating system (GDHS), the geothermal pipeline system does not supply heat to only Balçova. Balçova GDHS constitutes the biggest portion of heat demand in the system. However there is also Narlıdere GDHS, which is much smaller then Balçova GDHS. Narlıdere GDHS and Balçova GDHS are connected to same geothermal pipeline system therefore although their distribution systems are different they are actually one system. Geothermal pipeline system is also connected to the several facilities (Pool, spa, hotels, hospitals, medical faculty), which take approximately 20% of the produced heat energy. The basic scheme of the geothermal pipeline system supply part is shown in Figure 1.1. Therefore the geothermal pipeline system can also be treated as distribution system supplying geothermal water to different stations. In this study the all of the heating system including Balçova GDHS, Narlıdere GDHS, and other facilities like hospitals, hotels, spa will be called as Balçova-Narlıdere geothermal district heating system. If there is a need to refer only one part of the system then Balçova GDHS or Narlıdere GDHS terms will be used.

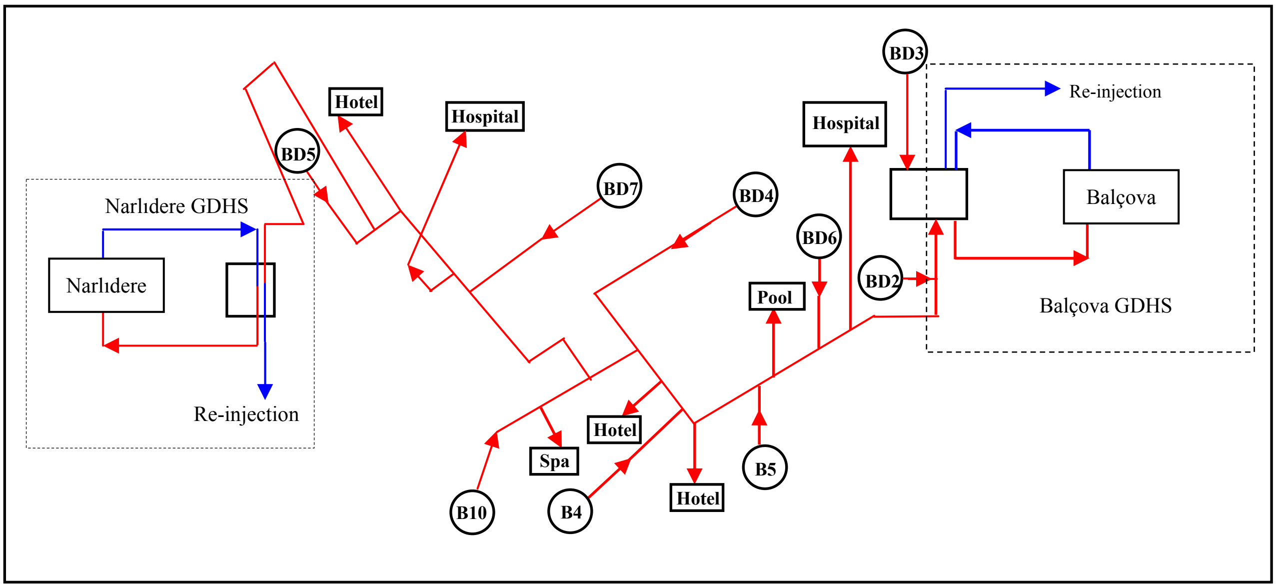

Figure 1.1: Basic Scheme of Balçova-Narlıdere GDHS

Balçova-Narlıdere city distribution networks deliver hot water to the buildings, which are 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 building heating system, the city circulation water returns to the pumping station.

The recorded peak heat production rate of Balçova-Narlıdere GDHS is about 50 MW_t, which is produced from 8 production wells. There are 8 heat exchanger stations connected to the geothermal pipeline system. Heat demand characteristics of these heat exhanger stations are different from each other. For proper operation of Balçova GDHS, control algorithm of the system should consider following points.

- *Thermodynamic balance of the system*: The heat demand of each facility connected to the system should be met according to changing outside temperature.
- *Hydraulic balance of the system*: Thermodynamic balance is not enough alone for proper operation of the system. In GDHSs the heat is carried by hot water which is pumped from underground to consumer point. Therefore the pressures in the pipeline system should satisfy the requirements for the proper circulation of hot water.

- *Minimising electricty consumption*: In geothermal district heating systems the biggest portion of the operation cost comes from pumping energy. While meeting the energy demand of the system the operation algoritm of the system should select the best option to minimise the electricity consumption.

These tasks can only be achieved if the system has automatic control. Since it has been constructed, Balçova-Narlıdere GDHS is operated manually. The control algorithm of the system is based on the past experiences of the operators and there is no pre-determined algorithm to operate the system according to changing outside temperature. Naturally it is almost impossible to reach optimum working conditions, with this kind of control. In this study optimum working conditions of the system is found for changing heat demand. Then certain improvements for proper operation of the system will be suggested, to reach these objective.

1.2. The Path of Study

The main objective of this study is to decrease the energy consumption in the system. To achieve this task route, which is shown in Figure 1.2 has been followed.

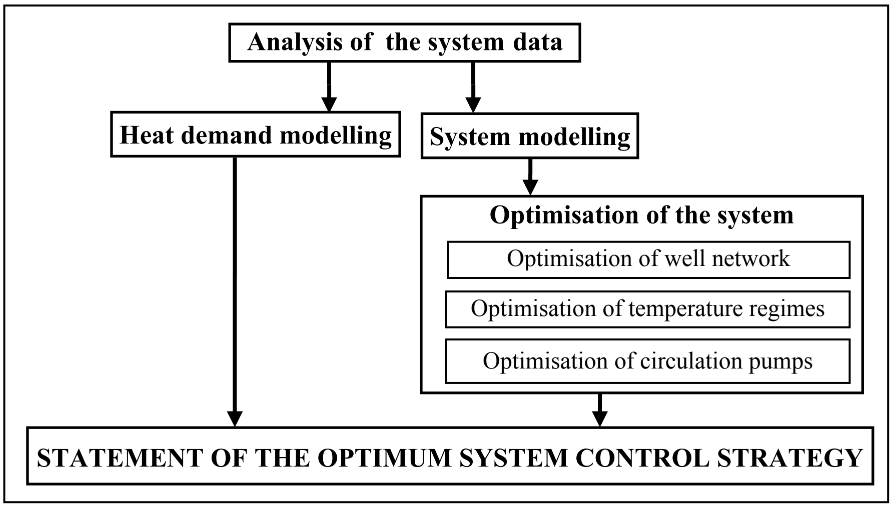

Figure 1.2: Flow chart of the study

These tasks were achieved with the help of the system data and use of advanced computer programs. Huge amount of data set were analysed to model and optimise system operations. The data sets were first investigated to fix the improper data then arranged to be used in the computer programs.

The term modelling refers to the process of reproducing the behaviour of one system through the functions of another. In this project, the term modelling will refer to the process of using mathematical representation of the real system. Modelling, 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 [3]. To find the total energy consumption of the system, all components of the system was modelled then optimum operation strategy minimising the energy consumption was determined on the model.

It should be stressed that the results obtained from mathematical model can rarely be applied to the real systems exactly. It is because of numbers of unforecastable factors that appear in the real life. Therefore, in this study the modelling has been performed in coordination with system operators and engineers. Practical efforts have been spent on the system for calibration of the mathematical model.

1.3. Methods

Modelling of the heat demand is achieved with the help of system data. Variation of the system heat demand with outside temperature has been modelled by using times series analysis methods. The data has been converted to be used in computer program which contains ready functions of time series analysis methods. Derivation of the model from program will be explained in detail in further chapters.

Since the characteristics and control strategies of geothermal systems are different from each other, it is not possible to use standard software in the optimisation of well pump operations. The problem of well network optimization is a staged process which requires decision at each stage (well). Therefore for the optimisation of well pump operations dynamic programming algorithm was created and user interface was developed for the future use of the program by operators. Moreover the program has been connected to the district heating simulation program called PIPELAB to analyse the distribution of pressure and temperature in the pipe network.

Simulation of both geothermal pipeline and city distribution network has been achieved in PIPELAB district heating simulation program. Algorithm of the PIPELAB has been improved to be used in Balçova-Narlıdere geothermal district heating system. PIPELAB algorithm uses graph theory for the flow and heat analysis of network systems. Although it is not the main goal of this study brief description of graph theory and its implementations are given in the report.

Modelling of pumps driven by frequency converters has been achieved by using turbomachinery principles and the the results were calibrated according to the actual power consumption data, that was read from frequency converters.

Great amount of time and effort had been spent to provide the matching of model with actual system. Especially, the power consumption model of pumps has been first derived from turbomachinery principles and then the results were compared with actual data sets. As a result the power consumption of each pump in the system can be simulated on the computer for varying flow rates very accurately.

Once the model of power consumption in the system has been derived, then optimum operation conditions for the system were found.

1.4. Results and Expectations

In this study optimum control algorithm of the system was found and certain improvements were suggested. Most of these improvements have been implemented on the system at the end of the study and significant amount of energy economy has been provided.

As a result of power consumption modelling studies, it was found that the power consumption of the system can be decreased approximately 50%. This amount of decrease in the power consumption can only be provided by automation.

This study can be seen as a first phase of automation efforts in the system. However, it should be stressed that some improvements suggested in this study can be applied without automation. Therefore operators should follow the optimum control algorithm as good as it is possible.

It is for sure that geothermal energy clean, cheap and sustainable energy source. However geothermal energy production depends on primary energy sources and efficient use of geothermal energy increases the advantages of it. At the end of this study it is expected that geothermal heating in Balçova-Narlıdere will become more efficient.

Chapter 2

GEOTHERMAL ENERGY

2.1. Introduction to Geothermal Energy

“Heat is a form of energy and *geothermal energy* is literally the heat contained within the Earth that generates geological phenomena on a planetary scale. "Geothermal energy" is often used nowadays, however, to indicate that part of the Earth's heat that can, or could, be recovered and exploited by man. [4]”

The natural heat of the earth has been utilized for centuries. According to historical records it has been used as a direct source of heat for centuries in many areas throughout the world. In the begining of 1900s in Italy, geothermal energy was used for the first time as a primary energy source for the generation of electricty. These two uses of the resource are commonly referred as “direct use” and “electricity generation.”

“Since the early 1970’s, dwindling reserves of oil and gas, continued price increase of oil on the world market and environmental concerns associated with coal and the nuclear energy have created a growing interest in the use of geothermal energy. Geothermal energy, clean and highly multi-purpose resource is now being used on a limited basis in a great number of diverse applications, e.g., space heating, vegetable dehydration, agriculture, aquaculture, light manufacturing and other applications requiring a reliable and economic source of heat. [5]”

2.2. Basic Terms of Geothermal Energy

The *geothermal gradient* expresses the increase in temperature with depth in the Earth's crust. Down to the depths of the earth, the average geothermal gradient is about 2.5-3 °C/100 m. Thermal energy is transmitted to the earth’s surface by conduction of heat through solid rock, by movement of molten rock (magma), or by movement of water. The vertical movement of thermal energy by conduction is called *heat flow*. [5]

In some geothermal areas, temperatures at some depths differ from the temperatures in nearby terrain. This temperature variation is called a *geothermal anomaly*. It may be limited to a small area and only a single hot spring may indicate the anomaly or the area may be a region of thousands of square kilometers. Becasue drilling, developing and maintaining wells that will produce warm or hot water is expensive, *geothermal exploration* involves locating positive geothermal anomalies with relatively high temperatures close to the surface. [5]

"Geothermal energy in the earth's crust is stored predominantly in rock and subordinately in water, steam or other fluids that fill pores or fractures within the rock. This diffuse energy must be collected from large volumes of rock and transported to a discharge point to make the energy available for practical uses. The water contained in nearly all rocks within the upper few kilometers of the earth's crust provides the mechanism for collecting and discharging the energy. [5]"

For the economical production of geothermal energy, the rocks through which the water moves must contain huge amounts of water and transmit it freely. S*torage coefficient* is the capacity of the rock to store water, and the ability of a rock to transmit water is termed the *hydraulic conductivity* or *permeability*.

"Energy from rock of porosity and permeability can be extracted from a confined circulation loop, which is two wells connected by a network of fractures induced by hydraulic or other means. Cold water is pumped down one well, heated by conduction as it flows through the induced fractures and extracted as hot water from second well. The rocks adjacent to the fractured volume must remain impermeable so that the fluid losses from the circulation loop are small. This procedure, commonly called "*hot dry rock technology*," is still experimental. Its widespread applicability and its economics have yet to be demonstrated. [5]"

2.3 Types of Geothermal Systems

Geothermal systems can be found in regions with a normal or slightly above normal geothermal gradient, and especially in regions around plate margins where the geothermal gradients may be significantly higher than the average value [4]. The classification of geothermal areas according to their thermal gradient is the most important criteria for the assessment of the viability of the resources. Accessibility through drilling is a necessary condition for any potential resource and, in areas with high thermal gradients, useful temperatures can be obtained through relatively shallow drilling. “However, a high thermal gradient alone is not a sufficient condition leading to exploitable resources. Geothermal energy is primarily stored in rocks, it is a diffuse form of energy and it must be collected and delivered to some central point before it can be made available for use. The mineral waters which are contained in porous rocks and in cracks, fractures and faults provide the necessary medium for the transfer of the heat from the rocks. Thus, the productivity of a thermal area is determined and often limited by the hydrology of the geological formations. Not all thermal areas have suitable hydrologies and this is a further restriction on the number and the extent of valuable geothermal resource areas. [6]”

Geothermal systems can be divided into five groups. These are: [5]

1. Hydrothermal convection systems related to young igneous intrusions,
2. Fault-controlled systems,
3. Radiogenic heat sources,
4. Geopressured geothermal reservoirs,
5. Deep regional aquifers.

Figures 2.1, 2.2 and 2.3 illustrate the most common geothermal systems.

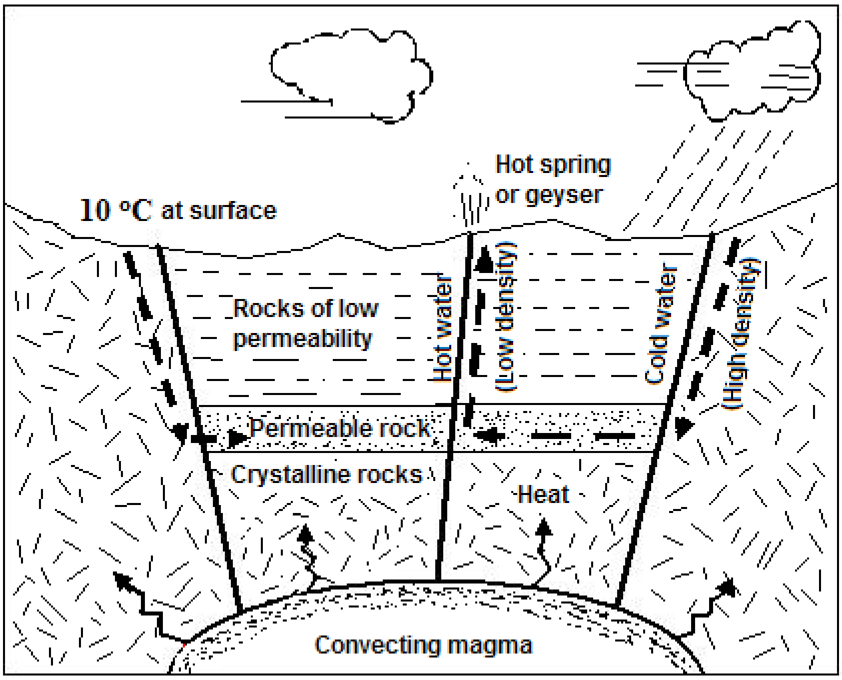

Figure 2.1: Schematic model of a hydrothermal convection system driven by an underlying young igneous intrusion [5]

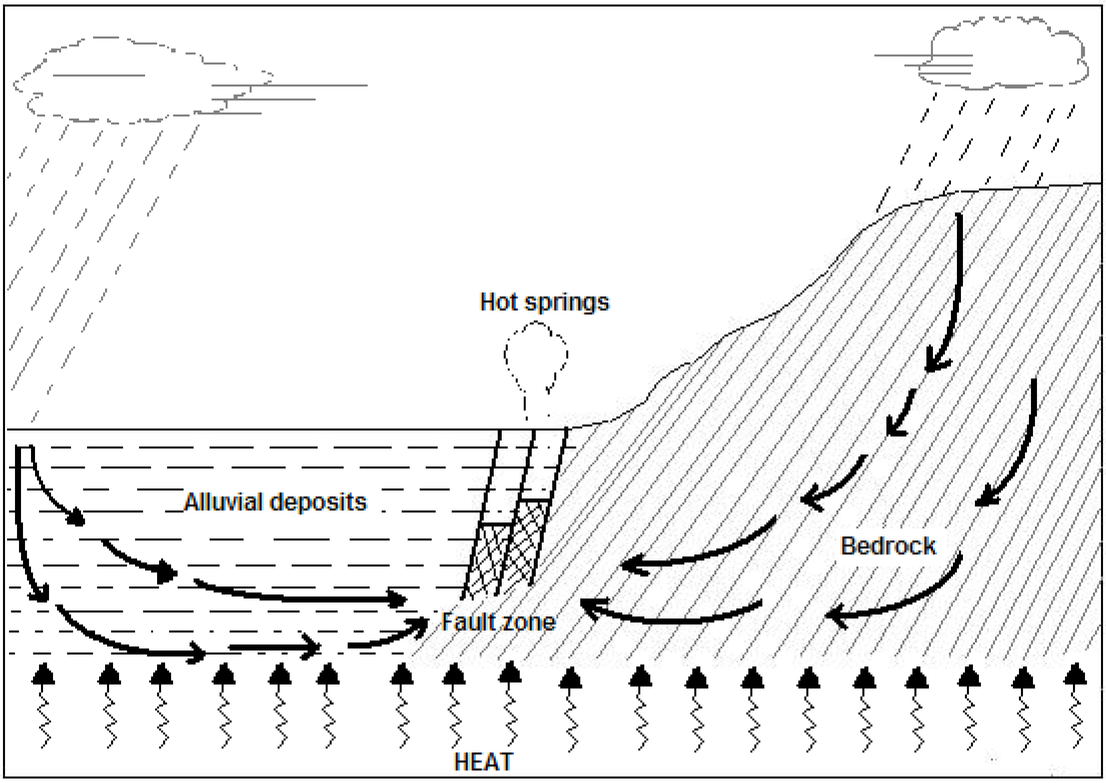

Figure 2.2: Schematic model of a hydrothermal convection system (fault-controlled) related to deep circulation of meteoric water without the influence of young igneous intrusions. [5]

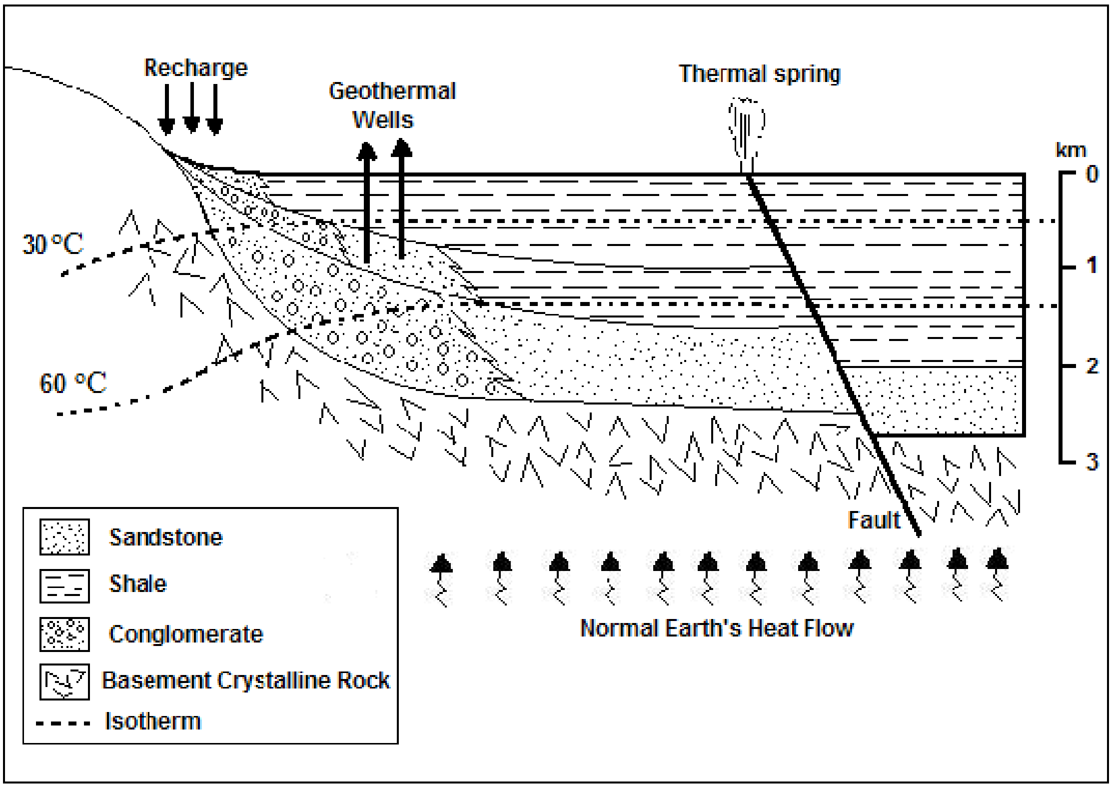

Figure 2.3: Schematic model of a geothermal reservoir in a deep regional aquifer [5]

2.4 Definition and Classification of Geothermal Energy Resources

One of the most common criterion for classifying geothermal resources is based on the enthalpy of the geothermal fluids that transports heat from the deep hot rocks to the surface. Enthalpy, which can be considered more or less proportional to temperature, is used to express the heat (thermal energy) content of the fluids, and gives a rough idea of their 'value'. The resources are divided into low, medium and high enthalpy (or temperature) resources, according to several criterion (Table 2.1). To avoid confusion and ambiguity the temperature values or ranges involved need specifying each time, since terms such as low, intermediate and high are meaningless at best, and frequently misleading. [4]

Table 2.1: Classification of geothermal resources according to several criterion [4]

	Muffler and Cataldi, 1978	Hochstein, 1990	Benderitter and Cormy, 1990	Nicholson, 1993
Low enthalpy resources	<90 ^{o}C	<125 ^{o}C	<100 ^{o}C	=150 ^{o}C
Intermediate enthalpy resources	90-150 ^{o}C	125-225 ^{o}C	100-200 ^{o}C	-
High enthalpy resources	>150 ^{o}C	>225 ^{o}C	>200 ^{o}C	>150 ^{o}C

Distinction is also made between water- or *liquid-dominated* geothermal systems and *vapour-dominated* geothermal systems. In waterdominated systems liquid water is the continuous, pressure-controlling fluid phase. These geothermal systems, whose temperatures may vary from < 125 to > 225°C, are the most common geothermal systems in the world. In vapour-dominated systems liquid water and vapour normally co-exist in the reservoir, with vapour as the continuous, pressure-controlling phase. [4]

Geothermal energy is generally defined as renewable and sustainable. Renewable describes a property of the energy source, whereas sustainable describes how the resource is utilized. [4]

Rate of energy recharge is the most critical aspect for the classification of geothermal energy as a renewable energy source. In the exploitation of natural geothermal systems, the recharge of energy takes place by advection of thermal water on the same time scale as production from the resource. This justifies classification of geothermal energy as a renewable energy resource. [4]

“The sustainability in consumption of a resource is dependent on its initial quantity, its rate of generation and its rate of consumption. Consumption can obviously be sustained over any time period in which a resource is being created faster than it is being consumed. The term sustainable development is used by the World Commission on Environment and Development to mean development that “..meets the needs of the present generation without compromising the needs of future generations.” In this context, sustainable development does not imply that any given energy resource needs to be used in a totally sustainable fashion, but merely that a replacement for the resource can be found that will allow future generations to provide for themselves despite the fact that the particular resource has been consumed. Thus, it may not be necessary that a specific geothermal field be exploited in sustainable fashion. Perhaps geothermal sustainability studies should be directed towards reaching and then sustaining a certain overall level of geothermal production at a national or regional level, both for electrical power generation and direct heat applications, for a certain period, say 300 years, by bringing new geothermal systems on line as others are depleted. [4]”

2.5 Geothermal Energy Resources in Turkey

Geologically, Turkey is composed of the Aegean and Anatolian plates which cover the western and central parts of the country. These plates are bordered in the north by the North Anatolian Fault Zone and in the south and east by the Ecemis Fault Zone, the Aegean Trench, and the Dead Sea-Eastern Anatolian Fault Zone. [7]

“Turkey lies on the active Alpine-Himalayan Orogenic Belt, an important geothermal energy zone which is the scene of geologically recent volcanic activities and is characterized by acidic volcanism. The area has more than 600 hot springs with temperatures ranging from 25 ºC to as high as 102 ºC, fumaroles, and numerous other hydrothermal alteration zones. Geothermal manifestations are widely spread in western Anatolia, extending to the Sea of Marmara. Temperatures are higher in western Anatolia than in the highlands of eastern Anatolia. [8]”

Turkey can be divided into four main geothermal regions [9]:

1. western Anatolia,
2. the north Anatolian fault zone,
3. eastern Anatolia, and
4. central Anatolia.

Systematic geothermal exploration began in Turkey in 1961-1962 when the MTA Institute began an inventory of Turkey's hot springs. The inventory was followed by the development and implementation of geological and hydrogeological studies, magnetic maps, gravity studies, hydrochemical analysis, gradient drillings, and resistivity and seismic reflection methods. [8,10]

In western Anatolia, a study conducted by the Mineral Research and Exploration Institute (MTA Institute) identified 123 hot springs and 36 geothermal areas. The 37 hot springs along the 1500 km north Anatolian fault are mainly used by local people for balneological purposes. Widespread young volcanism and hydrothermal alteration is observed and 44 hot springs occur in central Anatolia. In eastern Anatolia, seven geothermal areas have been defined. [8,10]

Geothermal fluids encountered in Turkey can be classified chemically as 95% incrusting and two to three geothermal fields have highly corrosive geothermal fluids. Turkish geothermal operators claim to have virtually overcome the consequences of scaling and corrosion in both high and low temperature wells, and scientific research continues. [8]

The first geothermal exploration drilling took place in 1963 in the Izmir-Balçova field, but the 124ºC fluid was not utilized for almost 20 years due to rapid scaling. Currently, the country's geothermal resources are primarily being used for heating, which accounts for over 90% of total direct use, greenhouses, and balneology. Turkey has extensive geothermal resources. Estimated values are 4,000-4,500 MW_e of power generation potential and 32,000 MW_t of low enthalpy direct use resources, enough to heat approximately five million homes. [8]

Chapter 3

GEOTHERMAL ENERGY UTILIZATION

3.1. Introduction to Gethermal Energy Utilization

The methods by which heat is extracted from the geothermal fluid depend strongly upon the temperature of the fluid and upon the nature of the heating application. High temperature fluids are highly versatile and can be used for direct heating or electricty production. With lower fluid temperatures it becomes increasingly difficult to extract the heat. In these cases it is important to match the fluid with heating applications which require temperatures that are lower than the fluid temperature. With very low fluid temperatures heat pumps are required to match supply and demand temperatures. Approximate temperature requirements of geothermal fluids for various applications is shown in Figure 3.1.

3.2. Electricity Production From Geothermal Energy

Electricity production mainly takes place in conventional steam turbines and binary plants, depending on the characteristics of the geothermal resource.

3.2.1. Flash Steam Geothermal Power Plant

Conventional steam turbines require fluids at temperatures of at least 150°C and are available with either atmospheric (backpressure) or condensing exhausts. Atmospheric exhaust turbines are simpler and cheaper. The steam, direct from dry steam wells or, after separation, from wet wells, is passed through a turbine and exhausted to the atmosphere. With this type of unit, steam consumption (from the same inlet pressure) per kilowatt-hour produced is almost double that of a condensing unit. [4]

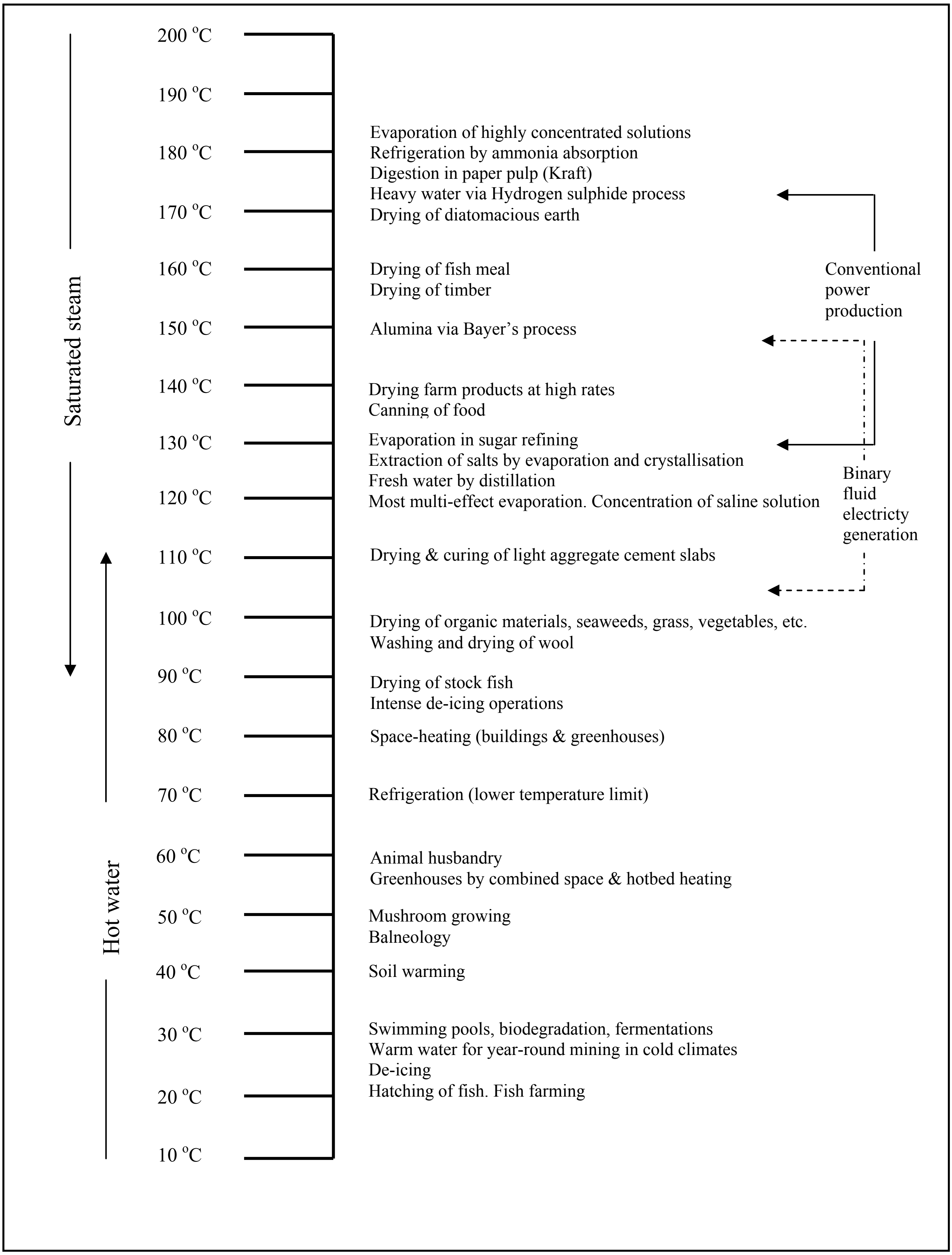

Figure 3.1: Approximate temperature requirements of geothermal fluids for various applications [11]

Turkey currently has only one operating geothermal power plant at Denizli-Kızıldere field where scaling has caused serious production problems. The plant has an installed capacity of 20.4 MWe. The plant also provides power to an enterprise which produces 120,000 tons of industrial food grade CO2 annually. In addition to Denizli-Kızıldere, other fields in Turkey which have high enthalpy resources suitable for electric power generation are:

- Aydın-Germencik,
- Çanakkale-Tuzla,
- İzmir-Seferihisar,
- Bitlis-Nemrut-Zilan-Süphan-Tendürek,
- Nevşehir-Acıgöl,
- Aydın-Salvatlı,
- Kütahya-Simav, and
- İzmir-Dikili-Bergama.

3.2.2. Binary Power Plants

The binary plants use a secondary working fluid, usually an organic fluid, that has a low boiling point and high vapour pressure at low temperatures when compared to steam. The secondary fluid is operated through a conventional Rankine cycle: the geothermal fluid transmits its heat to the secondary fluid through heat exchangers, in which this fluid is heated and vaporizes; the vapour produced drives a normal axial flow turbine, is then cooled and condensed, and the cycle begins again. By selecting suitable secondary fluids, binary systems can be designed to utilize geothermal fluids in the temperature range 85-175°C. The upper limit depends on the thermal stability of the organic binary fluid, and the lower limit on technical-economic factors: below this temperature the size of the heat exchangers required would render the project uneconomical. [4]

A new binary cycle system has been developed recently, called the *Kalina cycle*. The Kalina cycle uses an ammonia-water mixture as the working fluid and takes advantage of regenerative heating. The ammonia-water mixture has a low boiling point, so that the excess heat coming from the turbine’s exhaust can be used to vaporize a substantial portion of the working fluid. This plant is estimated to be up to 40% more efficient than existing geothermal binary power plants. [4]

3.3. Direct Use of Geothermal Energy

A geothermal direct use project utilizes heat of geothermal fluid, which is capable of providing heat and cooling to buildings, greenhouses, aquaculture ponds and industrial processes. Geothermal utilization projects require successful location and assesment of a resource, and concurently matching the varied needs of the user.

3.3.1. Space Cooling

Space cooling is a feasible option where absorption machines can be adapted to geothermal use. The technology of these machines is well known, and they are readily available on the market. The absorption cycle is a process that utilizes heat instead of electricity as the energy source. The refrigeration effect is obtained by utilizing two fluids: a refrigerant, which circulates, evaporates and condenses, and a secondary fluid or absorbent. Geothermal fluids provide the thermal energy to drive these machines, although their efficiency decreases with temperatures lower than 105°C. [4]

3.3.2. Space and District Heating

District heating involves the distribution of heat from a central pumping station, through a network of pipes to individual houses or blocks of buildings. The distinction between district heating and space heating systems, is that space heating usually involves one geothermal well per structure. [4]

An important consideration in district heating projects is the thermal load density, or the heat demand divided by the ground area of the district. A high thermal load density is required to make district heating economically feasible, because the distribution network that transports the hot water to the consumers is expensive.

Geothermal district heating systems are capital intensive. The principal costs are initial investment costs for production and injection wells, downhole and circulation pumps, heat exchangers, pipelines and distribution network, flowmeters, valves and control equipment. Operating expenses of the geothermal district heating systems consist of pumping power system maintenace, control, and management. Geothermal district heating systems will be focused in chapter 4 in detail.

The use of medium temperature (30 to 150 ^{o}C) geothermal resources as a heat source in Turkish district heating systems has been accelerating since 1980's. Considering the geothermal district heating projects, which are in the phase of conceptual planning and construction, it is obvious that geothermal energy will be started to use widely for the heating purposes in the next decade. Following cities are heated (partly or fully) with geothermal energy.

- Balçova-Narlıdere (İzmir)
- Simav (Kütahya)
- Kırşehir (Kırşehir)
- Kızılcahamam (Ankara)
- Kozaklı (Nevşehir)
- Afyon (Afyon)
- Sandıklı (Afyon)
- Ağrı (Diyadin)
- Gönen (Balıkesir)
- Salihli (İzmir)

In addition to these district heating systems, several district heating systems are in planning or construction phase. Moreover, constructed systems have been expanding each year with the addition of new facilities.

3.3.3. Geothermal Heating of Greenhouses

A number of commercial crops can be raised in greenhouses, making geothermal resources in cold climates particularly attractive. Crops include vegetables, flowers (potted and cut), house plants, and tree seedings.

Greenhouse heating can be accomplished by several methods: finned pipe, unit heaters, fan coil units, radiant floor, bare tubing, and a combination of these methods. The use of geothermal energy for heating can reduce operating costs and allow operation in colder climates where commercial greenhouses would not normally be economical.

Greenhouses are one of the fastest growing applications in the direct use industry. Many of the successful operations are aggressively expanding.

Utilisation of geothermal energy in greenhouses is one of the fastest growing applications in Turkey. Vegetables and flowers are raised in geothermal greenhouses in many places.

3.3.4. Aquaculture

Aquaculture involves the raising of freshwater or marine organisms in a controlled environment to enhance production rates. The principal species raises are aquatic animals such as catfish, bass, tilapia, sturgeon, shrimp, and tropical fish. The application temperature in fish farming depends on the species involved. The benefit of controlled rearing temperature in aquaculture operations can increase growth rates by 50 to 100%, and thus increase the number of harvests per year. [12]

3.3.5. Industrial Uses of Geothermal Energy

Drying and dehydration may be the two most important process uses of geothermal energy. A variety of vegetable and fruit products can be considered for dehydration at geothermal temperatures. Dehydration process involve either continuous belt conveyors or batch dryers, using low temperature air from 40 ^{o}C to 95 ^{o}C. Blowers and exhaust fans move the air over coils through which through which the geothermal fluid flows. The heated air then flows through the beds of vegetables or fruits on conveyors in trays, to evaporate the moisture. [12]

The use of geothermal energy in industry is limited in Turkey. The only significant use of geothermal energy in industry exists in Kızıldere-Denizli. 120,000 tons/year CO_2 is produced in Kızıldere geothermal field.

3.3.6 Spas and Pools

Use of geothermal energy in the swimming pools and spas is the earliest type of utilization in the civilization history. People have used geothermal water and mineral waters for bathing and their health for many thousand of years. *Balneology*, the practice of using natural mineral water for the treatment and cure of disease, also has a long history. Based on the archeological findings in Asia, mineral water has been used for bathing since the Bronze Age, about 5000 years ago. The Greeks, Turks and Romans were famous for their spa development and use from Persia to England. [13]

Today, especially in Europe and Japan, the use of medically supervised spas has long been accepted. They are used for both treatment and preventive therapy. The word "*spa*" is also used as a Latin abbreviation for: S = salud, P = per, A = aqua, or "Health through Water." [13]

Throughout its long history as a cradle of diverse civilisations, Turkey's many thermal springs have ministered to the infirm. Among the most famous thermal spas, where people have sought remedies since antiquity are at Agamemnon (Balçova) in İzmir, Sards in Manisa, Sultaniye in Muğla, Aesculapium in Bergama, Pamukkale in Denizli, Kurşunlu in Yalova, Ilgın in Konya, and at Çekirge in Bursa. The Ministry of Tourism has issued investment and operating licences for 34 thermal hotels, and when these are completed, licensed thermal beds will number 6878. So far Turkey uses only three percent of the country's potential in terms of mineral springs, but both the Tourism Ministry and entrepreneurs in the tourism industry are endeavouring to harness more of this potential, and put Turkey on the map of spa tourism. [14]

3.3.8 Geothermal Heat Pumps

Heat pumps are used where geothermal water or ground temperatures are only slightly above normal, generally 10 to 35 ^oC. Conventional geothermal heating (and cooling) systems are not economically efficient at these temperatures. Heat pumps, at these temperatures, can provide space heating, cooling and domestic hot water.

"The Ground source heat pump (GSHP) industry is rather young in Turkey. Residential case studies represent that GSHPs are widely used in two or three-storey houses having a floor area ranging from 230 m^2 to 1100 m^2. The primary barrier to marketing GSHP systems in Turkey is the incremental cost of installing ground heat exchangers, which makes the total investment higher. Well prepared pilot projects that will demonstrate the advantages of GSHPs and new financing projects are needed to promote investment in energy efficiency and renewable energy. [15]"

Chapter 4

GEOTHERMAL DISTRICT HEATING SYSTEMS

4.1. District Heating Systems

District heating can be defined as using boiler plant or any other source of heat to heat a number of dwellings or blocks of buildings. It has been found that the larger the consumer network in such case, the more economical boiler plant can be run [1]. Another economic appeal of district heating is that the facility can be concentrated in one location, thus requiring fewer technical specialists and supervisors. Obstacles to district heating are the cost of the distributing the heat, the loss of heat in distribution, the high cost of heating one-family houses and the high initial investment.[5]

An important economic factor for a heating district is the number of buildings in an area that can be supplied. An area that has a number of buildings concentrated in a small area can be served more efficiently by a heating district. The more consumers that can be served in a limited area reduces the cost because the distribution network to supply heat is expensive. For instance, a downtown area with many high rises or multi-storied buildings could be served economically by a district heating system.

Heat for the district may come from low or high temperature steam. Low temperature (below 120^{o}C) water in the main lines may permit direct connections at the consumer buildings. The direct connection provides better efficiency and allows the use of small pipes (thus, less circulating hot water), which reduces heat loss. The design of the system is simplified because recirculation is eliminated. In turn, internal pumps in space heating installations are also eliminated, leading to lower installation and operating costs.

High-temperature (above 150^{o}C) water systems usually require heat exchangers and recirculation pumps. These cause the distribution network to lose more heat than using low-temperature water. Among these three systems (low-temperature water, high-temperature water and steam), steam is the least efficient as it cannot be transported as far as the other two. [5]

A geothermal district-heating system will generally have the same basic components as those in a conventional heating system. The geothermal production field (which includes the wells, pumps and collection mains) replaces the boiler. All other components (piping, valves, controls and metering) would be like those in a conventional system. The most desirable network for distribution from an economical standpoint would be the single open-ended (only supply) system with heat exchangers installed in each building. The geothermal fluid would be disposed of at the end of the customer connection. This network would cost 30% less than a closed network (supply and return), which requires central heat exchanger, pumping and control equipment. If it is necessary to inject fluid into the reservoir, two-pipe system might be the most desirable. [5]

The biggest difference between conventional district heating systems and geothermal district heating systems is that the geothermal district heating systems distribute water rather than energy because all cost is directly related to water usage rather than energy usage [16]. Geothermal district heating systems are operated according to *constant temperature difference (ΔT) – variable flow rate* principle. Therefore in the design of direct use systems one of the major goals is capturing the most possible heat from each litre of fluid pumped. This arises from the fact that owning and operating costs for the systems are composed primarily of well pumping and well capitalisation components. Maximising system ΔT (minimising flow requirements) minimises well capital cost and pump operating cost [17].

4.2. Heat Demand in District Heating Systems

"The size of the connected heat load and the pattern of the variation of its power levels throughout the heating season are of basic importance in determining the energy and financial savings produced by the geothermal fluid in any particular application. Thus, the problem of analysing heat demand in the context of geothermal heating applications is, in general, more complex than that encountered in the more usual situation when conventional fossil fuel fired boilers are being used. [6]" In a conventional system, the main problem is that of the sizing of heat emitters and boilers to meet peak loads and, in this context, all that is really required is knowledge of the extreme demand conditions, which must be met. When designing a geothermal scheme such limited information is not adequate. More detailed information is required about the variations in demand levels throughout the heating season together with an understanding of the way in which these determine the temperatures and flows at the primary heat exchanger. This is information, which is usually not directly available from monitoring. Normally, heat demand levels are estimated using a model based upon the physics of the heating processes and upon those operational aspects which also affect thermal power levels. [6]

The analysis of space heating demands is in itself a substantial problem. At the individual level the nature of space heating demands can be difficult to define uniquely. This is because the interaction between diverse and variable human habits and attitudes and the complex physical influences due to weather introduce level of indeterminateness. This makes the problem difficult to analyse and model in all of its aspects. There are indeed many different cases; thus, the space heating of dwellings is different from the heating of shops, offices and public buildings. The pattern of use will be different, as will the temperatures, which are required. These factors will have large effects on the patterns of demands. [6]

In geothermal district heating schemes, it is normal for a collection of buildings to be connected together to form a large heat load. Because of this many random fluctuations due to individual user habits may be averaged out, or they may be excluded because the central heating system can not accommodate them. Thus, general heating trends change only gradually and the relationship between these and the heat demanded of the central supply facilities becomes better defined. [6]

Estimation of heat demand according to changing outside temperature is vital for proper operation of district heating systems. Geothermal district heating systems are huge systems, and their operational efficiency strongly depends on the correct estimation of the heat demand. Since certain amount of time is needed to deliver hot water from well head to consumer the reaction point, heat demand estimations will determine the operational decisions.

4.3. Components of Geothermal District Heating Systems

In a typical geothermal district heating system, the geothermal fluid is produced from the well by a lineshaft multistage centrifugal pump. (For free-flowing wells with adequate quantities of fluid, a pump is not required. However, most commercial operations require pumping to provide the necessary flow.) When the geothermal fluid reaches the surface, it is delivered to the application site through the transmission and distribution system.

In the system shown in Figure 4.1, the geothermal production and disposal system are closely coupled, and they are both separated from the contact with the equipment by a heat exchanger. This secondary loop is commonly used in larger systems to limit the exposure of geothermal fluid to a small portion of the system. Then the geothermal fluid is pumped directly back into the ground without loss to the surrounding surface.

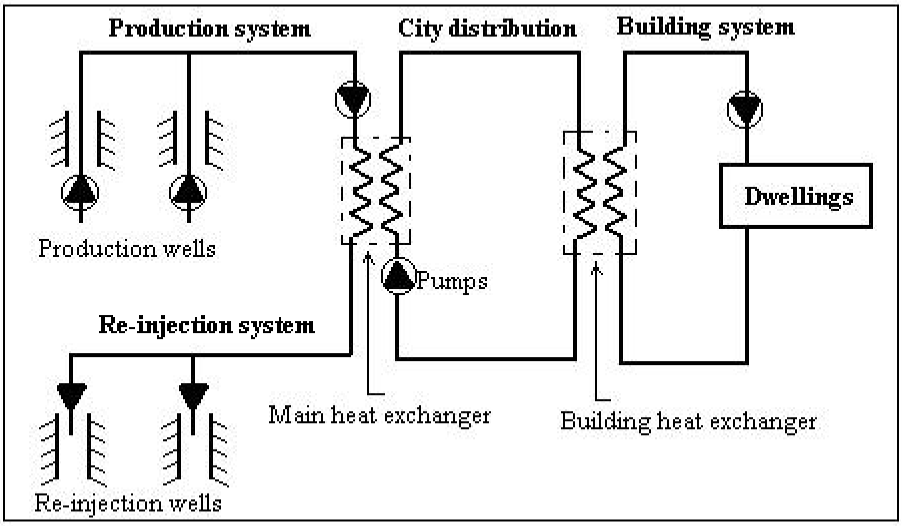

Figure 4.1: Basic schme of the typical geothermal district heating system

Direct Use systems can be divided into five sub-systems [17]:

1. The production system, including the producing wellbore and associated wellhead equipment.
2. The transmission and distribution system that transports the geothermal energy from the resource site to the user site and then distributes it to the individual user loads.
3. The user system.
4. The disposal system, which can be either surface disposal or injection back into a formation.
5. An optional peaking/backup system.

4.3.1. Geothermal Well Pumps

In geothermal direct use systems pumping is usually needed to bring geothermal fluid to the surface. For direct-use applications, there are primarily two types of production well pumps; 1.lineshaft turbine pumps and 2.submersible pumps.

The difference between these two types is the location of the driver. In a lineshaft pump, the driver, usually a vertical shaft electric motor is mounted above the wellhead and drives the pump. In a submersible pump, electric motor is usually located below the pump itself and drives the pump through a relatively short shaft with a seal section to protect the motor from the well fluid. In some installations, selection of a pump type is dictated by setting depth, well size, well deviation, or temperature. If not restricted by these, the engineer or developer should select a pump based on lowest life cycle costs, including important factors such as expected life, repair costs, availability of parts, and downtime costs. For most direct heat applications, the lineshaft pump has been the preferred selection [18]

The use of lineshaft pumps for geothermal direct use applications is common all around the world. There is no specific application of submersible pumps in Turkish geothermal district heating systems. Therefore lineshaft pumps will be focused in this study, and geothermal well pumps will refer to lineshaft pumps.

Figure 4.2 shows a typical lineshaft turbine pump with an enclosed oil-lubricated shaft. Enclosed shaft water lubricated pumps are also manufactured. A vertical turbine pump can be thought of as two concentric systems. The outer system consists of the column, impeller housings (bowls) and shaft enclosing tube. The inner system consists of the shaft and impellers. Forces resulting from dead weight, hydraulic thrust and thermal expansion result in different changes in length of these two systems. If not adequately allowed for in the design and operation of the pump, interference can occur resulting in damage to the pump. Thermal expansion is one of the most important points in the design and installation of lineshaft pumps. [18]

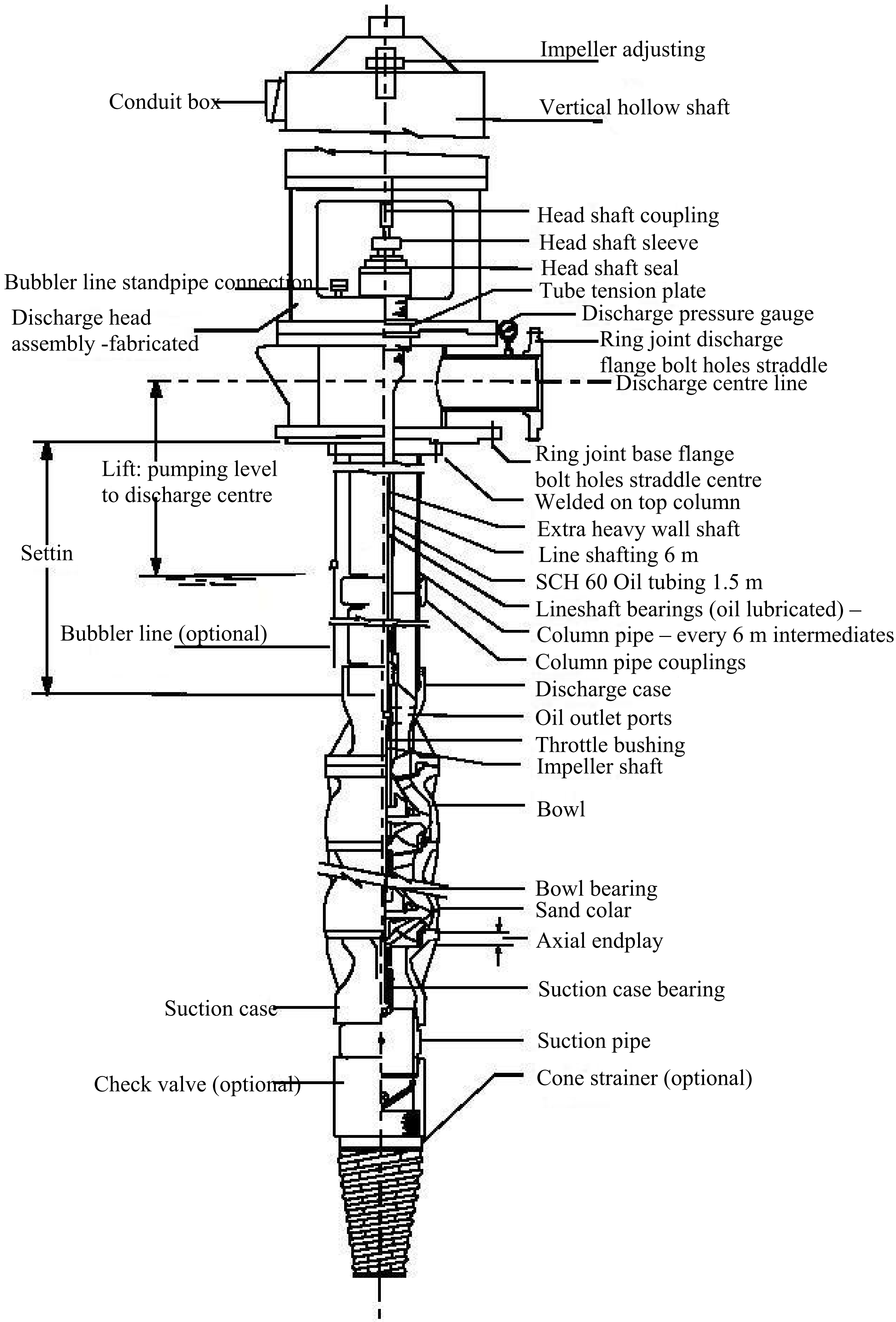

Figure 4.2: Typical lineshaft turbine pump with an enclosed oil-lubricated shaft [18]

4.3.2. Circulation and Booster Pumps

In geothermal district heating systems circulation pumps are used to deliver hot water to the customers and collect relatively cold water from the customers. Booster pumps are used to increase the pressure of the fluid, for instance the head of the well pumps may not be sufficient to transmit geothermal fluid until heat exchangers. Booster pumps are installed into the geothermal pipeline system to increase the pressure of the fluid. Also sometimes the circulation of hot water in the city distribution system can not be provided by the circulation pumps then booster pumps are installed into critical places where fluid pressure becomes insufficient. These pumps may be centrifugal or vertical turbine pumps. In both cases they are commonly used in industry.

Circulation pumps are generally operated in parallel combinations in district heating systems. The use of variable speed drives in control of pumps became common in recent applications. Variable speed drives provide efficient operation at partial loads.

Pump operating cost constitutes the biggest portion of the system operating cost. Efficient operation of pumps has great influence on the economics of the system. Selection, design and operation of all pumps in the system should be well understood by system engineers and operators. The detailed technical information about pump operations will be given in Chapter 6.

4.3.3. Piping in Geothermal Systems

In geothermal heating applications wells are located some distance away from the user. Transmission pipeline system is required to transport the geothermal fluid. Even in the absence of transmission line requirements, it is frequently advisable to employ other than standard piping materials. Geothermal fluid for direct use applications is usually transported in the liquid phase and has some of the same design considerations as water distribution systems. Several factors including pipe material, dissolved chemical components, size, installation method, head loss and pumping requirements, temperature, insulation, pipe expansion and service taps should be considered before final specification. [19]

There are many types of piping materials with great variation in cost and durability for geothermal heating systems. Some of these materials are: ductile iron (DI), slip-joint steel (STL-S), welded steel (STL-W), gasketed polyvinyl chloride (PVC-

G), solvent welded PVC (PVC-S), chlorinated polyvinyl chloride (CPVC), polyethylene (PE), cross-linked polyethylene (PEX), mechanical joint fibreglass reinforced plastic (FRP-M), FRP epoxy adhesive joint-military (FRP-EM), FRP epoxy adhesive joint (FRP-E), FRP gasketed joint (FRP-S), and threaded joint FRP (FRP-T). The temperature and chemical quality of the geothermal fluids, in addition to cost, usually determines the material used. Both metallic and non-metallic piping can be considered for geothermal applications. Carbon steel is the most widely used metallic pipe and has an acceptable service life if properly applied. Ductile iron has seen limited application. [19]

Since metallic pipes used in high temperatures compared to non-metallic pipes, they are commonly used in most of the geothermal applications. In addition, its properties and installation requirements are familiar to most installation crews. The advantage of non-metallic materials is that they are virtually impervious to most chemicals found in geothermal fluids. However, the installation procedures, particularly for fibreglass and polyethylene are, in many cases, outside the experience of typical labourers and local code officials. This is particularly true in rural areas. [19]

In Balçova-Narlıdere GDHS carbon steel pipes are used. Steel pipe is available in almost all areas and manufactured in wide range of sizes. Steel is the material most familiar to pipe fitters and installation crews. The joining method for small sizes (<50 mm) is usually threading, with welding used for sizes above this level. For underground installations, all joints are typically welded when unlined piping is used.

The most important disadvantage of steel piping is corrosion. In many geothermal fluids, there are various concentrations of dissolved chemicals or gases that can result in corrosion. If the potential exists for this type of attack, or if the fluid has been exposed to the air before entering the system, carbon steel should be the material of last resort. Steel piping is used primarily on the clean loop side of the isolation heat exchanger, although in a few cases it has been employed as the geothermal transmission line material. A distinct disadvantage in using steel pipe is that the buried pipe is also subject to external corrosion unless protected with a suitable wrapping or cathodic protection [19]. For instance, the distribution system at Balçova-Narlıdere GDHS consists of carbon steel pipe with polyurethane foam insulation wrapped with insulating coat (glass fibre) to provide a seal. The water seal degraded with time (approximately 5 years) and allowed ground water to contact the pipe. External corrosion resulted in a number of failures, which cause significant amount of leakage from the system.

4.3.4. Heat Exchangers

“Most geothermal fluids, because of their elevated temperature, contain a variety of dissolved chemicals. These chemicals are frequently corrosive toward standard materials of construction. As a result, it is advisable in most cases to isolate the geothermal fluid from the process to which heat is being transferred. [20]”

The task of heat transfer from the geothermal fluid to a closed process loop is most often handled by a plate heat exchanger. The two most common types used in geothermal applications are; bolted and brazed.

The plate heat exchanger is the most commonly used heat exchanger type in geothermal systems of recent design. A number of characteristics particularly attractive to geothermal applications are responsible for this. Among these are [20]:

1. Superior thermal performance: Overall heat transfer coefficients (U) for plate type exchangers are three to four times those of shell and tube units.
2. Availability of a wide variety of corrosion resistant alloys:
3. Ease of maintenance: The construction of the heat exchanger is such that, upon disassembly, all heat transfer areas are available for inspection and cleaning.
4. Expendability and multiplex capability: The nature of the plate heat exchanger construction permits expansion of the unit should heat transfer requirements increase after installation.
5. Compact design: The superior thermal performance of the plate heat exchanger and the space efficient design of the plate arrangement result in a very compact piece of equipment

As shown in Figure 4.3, the plate heat exchanger is composed of individual plates pressed between two heavy end covers. The entire assembly is held together by the tie bolts. Individual plates are hung from the top carrying bar and are guided by the bottom-carrying bar. For single-pass circuiting, hot and cold side fluid connections are usually located on the fixed end cover. Multi-pass circuiting results in fluid connections on both fixed and moveable end covers. [20]

The primary and secondary fluids flow in opposite directions on either side of the plates. Water flow and circuiting are controlled by the placement of the plate gaskets. By varying the position of the gasket, water can be channelled over a plate or past it. Gaskets are installed in such a way that a gasket failure cannot result in a mixing of the fluids. In addition, the outer circumference of all gaskets is exposed to the atmosphere. As a result, should a leak occur, a visual indication is provided. [20]

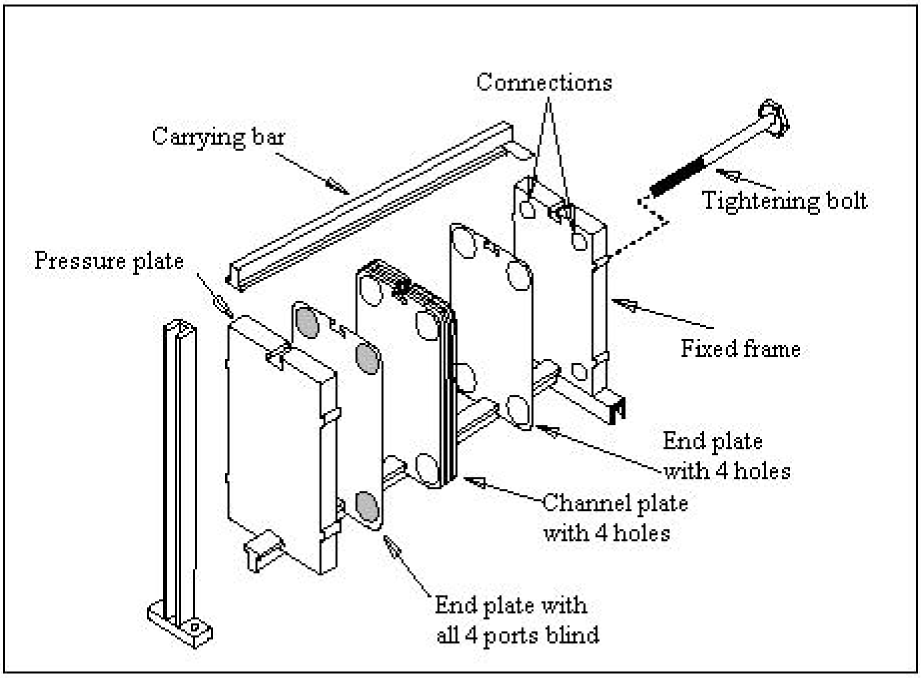

Figure 4.3: Plate type heat exchanger [20]

4.3.5. Controllers and Regulators

Controllers and regulators are useful tools for operators, which provide proper operation and control of the system. They might be connected to the automatic control system or controlled manually. They control and regulate the system according to their set points by considering feedback information. The ideal case is to control all of these elements from central control centre. However, because of cost considerations cheaper alternatives like manual control or self-actuating elements are used in Turkish geothermal district heating systems. There are numbers of controller and regulator alternatives depending on the type of the system design. Among these variable frequency drivers and self-operated regulators are the most common ones, which are used, in Turkish GDHSs as well as other GDHSs.

4.3.5.1. Variable Frequency Drivers

Pumping energy costs constitute a largest portion of expense for many geothermal systems. In district heating systems, there is a wide variation in flow requirements, because of a variation in heat load. As a result, an efficient means of controlling flow should be an integral part of these systems.

Variable frequency is mostly used variable speed drive technique in geothermal energy field. Use of frequency drivers increase both the operational efficiency and pump life compared to other techniques.

AC variable frequency control technology is based on induction motor operation. The speed of an induction motor is a function of the number of poles and the frequency of the applied power supply according to the following relationship [18]:

$$N_s = 120\ f/p \qquad (4.1)$$

In reality, there is a slight “slip” in the actual motor speed compared to synchronous speed. This slip amounts to 2 to 6% at full load, depending upon motor design.[18]

Equation 4.1 states that motor speed can be adjusted by controlling the frequency of the power supply. This frequency adjustment must be carried out at a constant relationship to voltage or at constant volts per Hz. This is necessary due to the method by which a motor produces torque. Torque is produced by a magnetic flux that is directly proportional to voltage applied, and inversely proportional to the frequency. Therefore, as motor speed is reduced by frequency adjustment, voltage must also be reduced to avoid unreasonable motor losses. [18]

Frequency and voltage adjustment are accomplished by drives referred to as inverters. Inverters include at least three basic components. The rectifier serves to convert the incoming AC power to DC. The DC is then fed to the inverter section for conversion back to variable frequency AC. The inverter accomplishes the conversion task using either transistors or thyristors. These electronic devices switch the DC input (from the rectifier) on and off to provide a controllable AC output. The third major component in the drive unit, the controls, regulates the activity of the inverter switching such that the motor operates at the speed required. [18]

Adjustable frequency drive efficiency is generally given by the manufacturers as 95%. This value applies only to the base frequency. Figure 4.4 shows efficiency at other operating points. The plot is based only on the efficiency of the frequency controller.

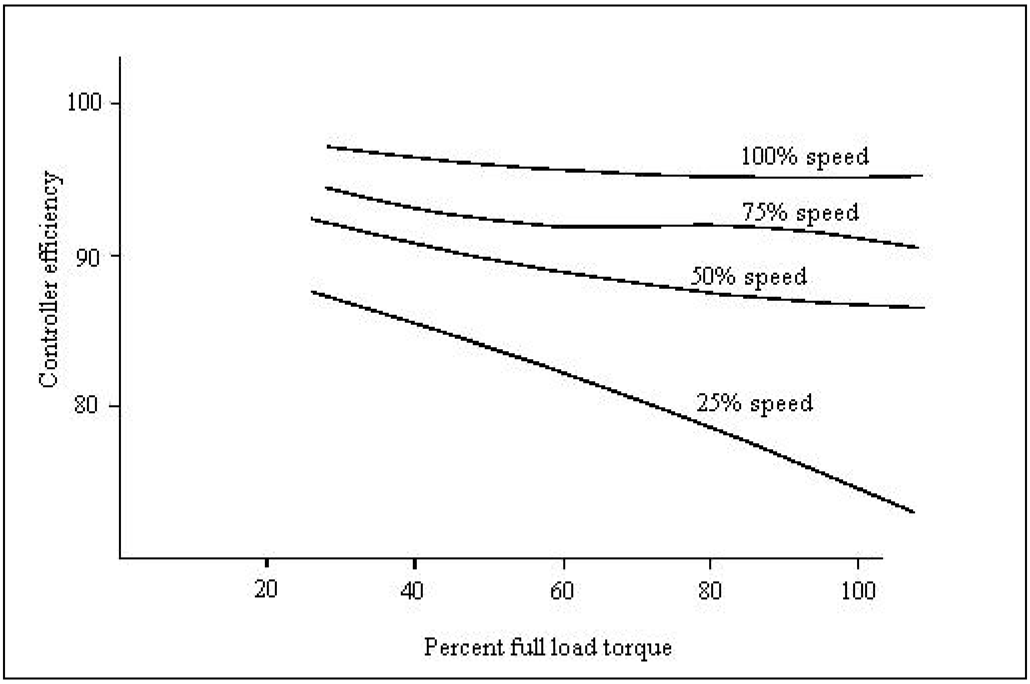

Figure 4.4: Adjustable frequency drive performance [18]

Maintenance requirements are low for the variable frequency drive. The controller itself is constructed primarily of solid state components that require virtually no attention. However, the controller units sometimes have maximum and minimum temperature limits. As a result, when they are used at well heads, they would have to be housed in some type of conditioned wellhead structure for protection. [18]

4.3.5.2. Self-Operated Regulators

The control of a flow according to heat exchanger outlet temperature requires three basic functional units (the measuring equipment, the controller, and the final controlling equipment). Usually, these control loop components are separate devices that must be supplied with auxiliary energy. For the control tasks of pressure, flow, differential pressure, or temperature, conventional instrumentation is often too complex and, from an economic point of view, too expensive. For these applications, self-operated regulators can be used.

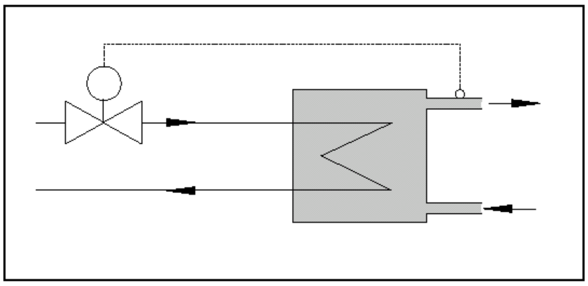

Figure 4.5: Control loop of a self-operator

Self-operated regulators take over all the tasks required in a control loop. They integrate measuring sensor, controller as well as control element all in one system (Fig. 4.5). Since self-operated regulators do not require auxiliary energy from external supply sources, the cost of installation is significantly lower than for conventional instrumentation.

Self-operated regulators are available for temperature, pressure, flow, and differential pressure control. They are suitable for all those applications where deviations of the controlled variable from the adjusted set point are acceptable and the set point remains constant over a long time. Self-operated flow and temperature regulator used in Balçova-Narlıdere GDHS is shown in Figure 4.7. The flow regulator consists of a control valve with throttle, seat and plug, the closing actuator with operating diaphragm and the thermostat with set point adjuster and a temperature sensor. The regulator is designed to maintain the flow and the temperature to a set point value. The valve closes when the controlled value increases.

Figure 4.6: Temperature and flow regulator

Chapter 5

BALÇOVA-NARLIDERE GEOTHERMAL DISTRICT HEATING SYSTEM

5.1. History of Geothermal Utilisation in Balçova-Narlıdere

Balçova Geothermal Field or so called Agamemnon Spas have been attractive place for settlers over the ages. Agamemnon Spas were known in antiquity for the therapeutic qualities of the water. According to a legend, Agamemnon was advised by an oracle to bring soldiers who had been wounded during campaign against Troy to the sulphur-rich waters of these natural hot springs. The periods that Ionians passed to Aegean Coasts, a part of Alexander the Great's army's injured soldiers were cured in these hot springs. It had a wide usage in that period, constructions were brought and progressed. Today, the ancient ruins are not seen in the area. Only information about the springs are available from the historical sources in 1763. After that period, Agamemnon Spas are reconstructed by a Frenchman called Elfont Meil with adding the staying units and they endured to our century. Today there is a modern spa complex with a total capacity of 1000 person/day providing hot spring pools and baths, therapy pool. [21]

The reconnaissance and exploration studies started in Balçova in 1963. The first well was 40 m deep and producing two phase fluid at 124°C. Then 3 exploration wells were drilled after the first evaluation of geological, geophysical and geochemical data. Because of high calcite precipitation problem, the field could not be developed until 1981. Turkey's first downhole heat exchanger application was conducted at the B-1 well in 1982. This well was 100 m deep with a bottom temperature of 115°C. The clean water temperature circulating in the loop was 50-95°C depending on flow velocity and outer effects. [8]

After the first application of downhole heat exchanger, 10 gradient wells were drilled. These were shallow wells at maximum 200m with the maximum temperature of 130°C. The reservoir temperature was calculated as approximately 200°C. BD-2 production well is located in the 1st zone which has the highest temperature. [21]

5.2 Development of Geothermal Utilisation in Balçova-Narlıdere

Geothermal utilisation in Balçova-Narlıdere have been continualy improving since 1963. Especially in the last ten years, geothermal utilisation has been accelarated with the help of local governments. The advantages and benefits of geothermal utilisation have been well understood in the region. There is strong public support behind the geothermal energy projects. The milestones of geothermal development in Balçova-Narlıdere have been given in Table 5.1.

Table 5.1: Chronogical improvement of geothermal utilisation in Balçova-Narlıdere [15, updated version]

Year	Improvement
1963	The first geothermal well was drilled in the field.
1983	Down hole heat exchanger (DHE) was used to heat Balçova thermal facilities.
1983	DHE was used to heat Dokuz Eylul University Medical Faculty (DEUMF).
1992	The use of plate type heat exchangers was started in (DEUMF).
1994	Geothermal heating of Princess Hotel was started.
1995	Adjudication of the first stage geothermal heating and cooling works with 2500 and 500 dwellings, respectively.
1996	Increasing the capacities from 2500 to 5000 dwellings for heating and from 500 to 1000 dwellings for cooling.
1996	Balçova GDHS was commissioned.
1996	Re-injection was started.
1997	The capacity was increased to 7680 dwellings.
1998	Narlıdere GDHS was commissioned for 1500 dwellings
2001	Modernisation and enlargement of DEUMF geothermal heating centre
2001	İzmir Economy University was connected to the Balçova GDHS
2001	Geothermal reservoir was modelled by ITÜ Petroleum and Natural Gas Eng. Dept.
2002	Energy economy and automation studies were started.
2002	Feasibility studies for the geothermal heating of 5000 dwellings were started.
2002	Re-injection to the shallow wells was stopped and re-injection to the deep wells was started. Geothermal fluid temperatures increased in the field.
2002	Complete modelling of pipe networks in the system was completed.
2003	Dokuz Eylul University Fine Arts Faculty has been connected to the system.
2003	Özdilek Hotel and shopping centre was connected to the system.

As can be seen from the table, number of facilities and dwellings connected to the system has been increasing. This increase is actually in parallel with the geothermal reservoir engineering studies done in the field. With the better understanding of Balçova-Narlıdere geothermal reservoir, the capacity of the Balçova-Narlıdere GDHS is being increased. New district heating project called Balçova GDHS-2 are being considered nowadays and feasibility studies have already been started.

5.3 Recent Situation in Balçova-Narlıdere Geothermal Field

Recorded maximum heat extraction from the Balçova-Narlıdere field is approximately 50 MW_t. In the years of 2001 and 2002 the old wells, which have no longer been used have been re-activated by Balçova Geothermal Company. The total production capacity has been increased from 620 m^3/h to 1250 m^3/h. Re-injection strategy has been changed in the year of 2002. It has been found that the re-injection to shallow wells causes decrease in the geothermal fluid temperature. As a result re-injection of geothermal fluid to the shallow wells has been stopped and especially in shallow production wells, increase in geothermal fluid temperatures have been observed.

Since October 2002 all re-injection has been routed to the BD-8, which is on the eastern side of the field. The effect of BD8 re-injection are still being observed and until now there is no disadvantage detected [22]. The heat extraction rates from the Balçova-Narlıdere geothermal field is given in Figure 5.1. As can be seen frıom Figure 5.1, there is increasing trend in the rate of heat extraction.

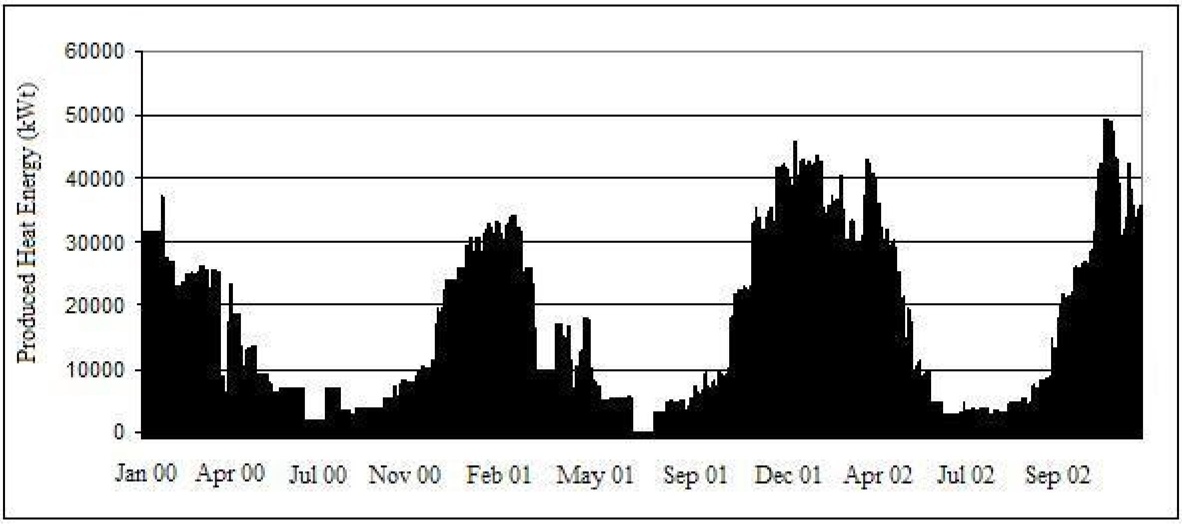

Figure 5.1: Produced heat energy rates in Balçova-Narlıdere GDHS

Recent situation of wells in Balçova-Narlıdere geothermal field is given in Table 5.1. The total heat extraction capacity of the existing wells is approximately 90 MWt. However, this capacity could not have been utilised until now, because of the economical and technical difficulties (re-injection problem). In 2002, the projects have been started to utilise this excess energy.

Table 5.2: Recent situation of wells in Balçova-Narlıdere (Updated from, [22])

Well	Date	Length (m)	Temperature (°C)	Flow Rate (m^3/h)	Position
BD-1	1994	200	110	50	Production
BD-2	1995	677	132	180	Production
BD-3	1996	750	120	85	Production
BD-4	1998	624	135	140	Production
BD-5	1999	1100	115	80	Production
BD-6	1999	605	135	100	Production
BD-7	1999	1100	125	60	Production
BD-8	2002	630		2500	Re-injection
B-1	1982	104	115	100	Production
B-2	1989	150	95	-	No production
B-3	1983	160	110	-	No production
B-4	1983	125	117	55	Production
B-5	1983	109	120	135	Production
B-6	1983	150	95	-	No production
B-7	1983	120	115	140	Production
B-8	1983	250	95	-	No production
B-9	1983	48	95	-	No production
B-10	1989	125	105	100	Production
B-11	1989	125	109	40	Production
B-12	1998	160	95	-	No production
ND-1	1996	800	115	-	No production
N-1	1997	150	95	-	No production
BTF-2				-	Closed
BTF-3			100	30	No production
BH-1			80	15	No production

5.4. Presentation of Balçova-Narlıdere Geothermal District Heating System

Balçova-Narlıdere GDHS consists of several sub-systems. Dokuz Eylül University Medical Faculty (Hospital), Balçova Thermal Facility, Spa, Swimming Pool, Princess Hotel, Balçova GDHS and Narlıdere GDHS have all different heating systems. All of these facilities are connected to the geothermal pipeline system. Among these facilities Balçova GDHS is the biggest consumer of the geothermal energy. About 75% of the extracted heat energy is consumed by Balçova GDHS.

Geothermal pipeline system, Balçova GDHS and Narlıdere GDHS are operated by Balçova Geothermal Company, while other facilities have separate heating systems and operators. There are flowmeters at the each connection point and these facilities pay for the geothermal energy according to their amount of use. In this study geothermal pipeline and Balçova GDHS will be investigated in detail since most of the heat demand and problems belong to these parts.

5.4.1. Balçova-Narlıdere Geothermal Pipeline System

Balçova-Narlıdere geothermal pipeline system transmits geothermal fluid from 8 production wells to 8 different heat exchanger stations. After transferring its energy at the heat exchanger station (pumping station), geothermal fluid is pumped to re-injection well(s). In Table 5.3 maximum flows and wellhead temperatures of production wells are given. However, number of wells and heat exchanger stations has been changing since the system was first established. Number of connections changing according to changing well characteristics, addition of new wells and new customers. Data provided at Table 5.3 and Table 5.4 refers to the 2002-2003 heating session. In the 2003-2004 heating season one more heat station, which has just been connected to the pipeline system will be taken into operation and one more hotel and more dwellings will be heated.

Table 5.3: Production wells in operation (2002-2003)

Well	Temperature (°C)	Max flow (m^3/h)
BD2	132	180
BD3	120	85
BD4	135	140
BD5	115	80
BD7	125	60
B4	117	55
B5	120	135
B10	105	100

Table 5.4: Facilities directly connected to geothermal pipeline system [23]

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

Recent situation of geothermal pipeline system is shown in Figure 5.1. Geothermal pipeline system consists of two parallel pipeline systems supply and return.

Supply part of the system transmits geothermal fluid from wells to heat exchangers, and return part transmits geothermal fluid from heat exchangers to re-injection wells. In Figure 5.1 only supply part of the system is shown.

Most of the pipes in the main geothermal pipeline system are 300 mm steel pipes, and smaller part of the system is made of 250 mm steel pipes. All pipes in the system have polyurethane foam insulation wrapped with insulating coat (glass fibre) to provide a seal.

Geothermal fluids pumped from different wells are mixed in the geothermal pipeline system. However, temperatures of the geothermal fluid vary for each well (Table 5.3). Therefore, the temperature of the geothermal fluid in the geothermal pipeline system is not constant and it changes according to well operation strategy.

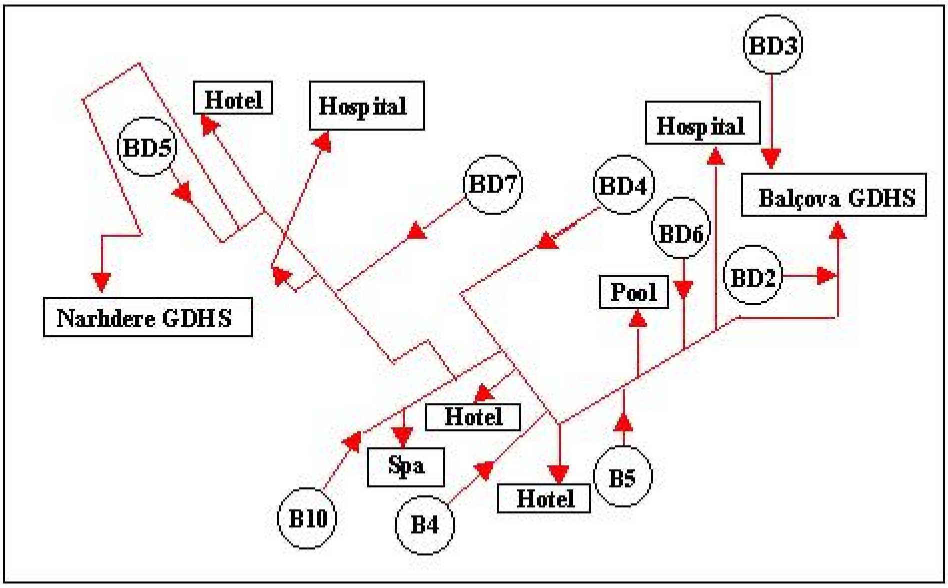

Figure 5.1: Balçova-Narlıdere geothermal pipeline system – supply part

As can be seen from the Figure 5.1 geothermal pipeline system is rather complex network with 8 production wells and 8 heat exchanger stations. It is important to monitor and control the temperatures and pressures along the geothermal pipeline system. Thermodynamic and hydraulic balance of the system carries great importance for the proper operation of the system.

Geothermal well pumps in the system are operated according to *constant wellhead pressure* strategy. In the system, wellhead pressures are kept constant with the help of valves. To provide the lubrication of the pump shafts, 3 bars pressure is kept constant at the wellheads. Pressure monitoring is available only at the wellheads.

Booster pumps have been installed into the system at the Balçova and Narlıdere heat exchanger stations. These pumps increase the pressure of the geothermal fluid at the heat exchanger inlet. The geothermal fluid pressure along the pipeline is about 1.5-2 bars. Geothermal pipeline system is treated as a big collector in practice, although it is not. There is no monitoring or controlling device for the geothermal pipeline pressure.

The temperature of the geothermal fluid changes according to well operation strategy. Heat exchanger inlet temperatures vary between 105 – 115^{o}C. Re-injection temperature is about 60^{o}C in the system.

Flowrates and directions are regulated with the help of valves, which were installed into critical points of the system. There is no automatic control in the system and all valves are controlled manually. Data acquisition and monitoring processes have also been done manually.

5.4.2. Balçova Geothermal District Heating System

Balçova GDHS is the distribution system, which delivers hot water to the district heating consumers. Consumers of the system have been enjoying from heating and domestic hot water services. City distribution network is approximately 40 kilometres long closed-loop pipeline system, which distributes hot water and collects warm return water. The design temperatures of the system are 0 ^{o}C for the outdoor and 22 ^{o}C for the indoor. System is operated below 18 ^{o}C outdoor temperatures. Today approximately 880 buildings are connected to the system. Each building has its own heat exchanger at the basement. Heat is transferred to the building heating systems with the help of these heat exchangers. In Balçova, constant tariff is applied for the heating service. There is no flow meter at the customer connections. Moreover types and sizes of buildings are variable. For instance, five storey buildings, mosque, schools, and single houses are connected to the distribution system. Therefore heat demands of the customers are variable. Diameters of building connection pipes, sizes of heat exchangers and self-operated regulators are set according to the heat demand.

Balçova GDHS city distribution network is shown in Figure 5.2. Distribution network is actually closed loop system. The circulation provided by three 160 kW centrifugal pumps. City distribution water (clean water) at 60^{o}C is pumped into the main heat exchanger and the heat is transferred from the geothermal fluid site of the heat exchanger. At the heat exchanger outlet, the temperature of the city distribution water reaches to 90^{o}C. Hot water at 90^{o}C is delivered to the customers.

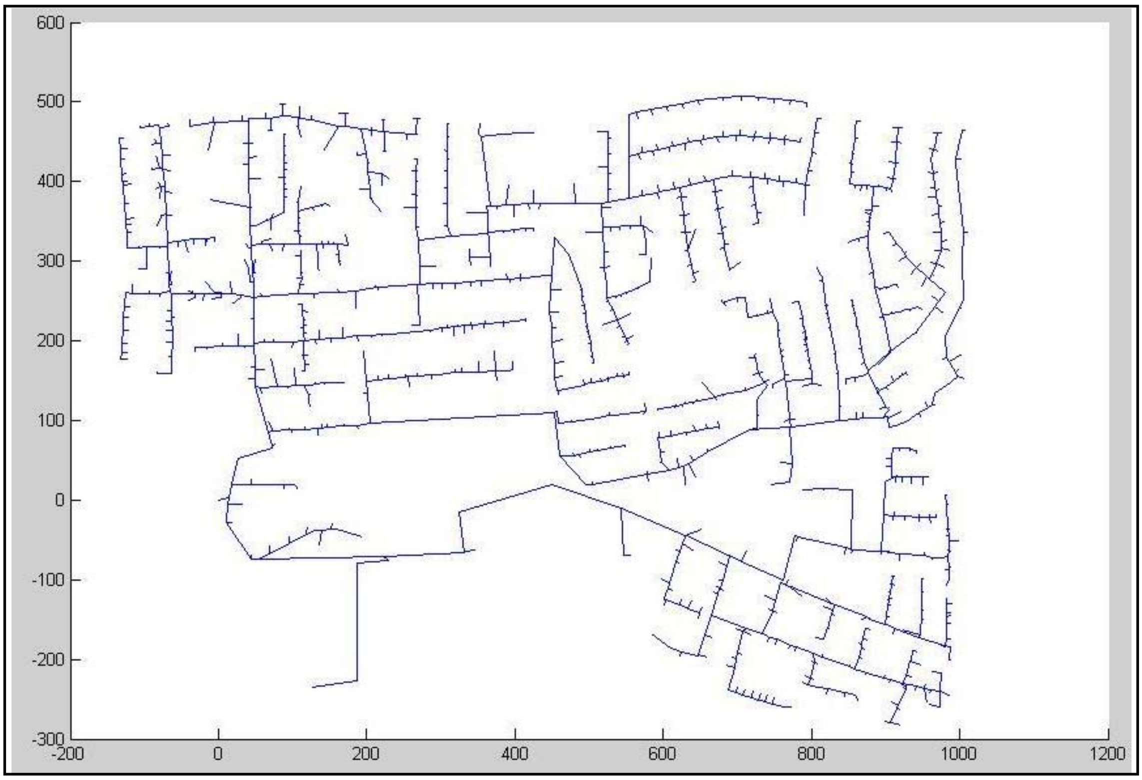

Figure 5.2: Balçova City Distribution System (All dimensions are in meters)

At the each building connection there are self-operated flow and temperature regulators. These regulators keep the heat exchanger outlet temperature at the required value, and limit the maximum flow rate of each connection. The proper operation of these regulators has a great influence on the system. Temperature and flow rate values of these regulators must be set correctly to provide proper operation of the system. As can be seen from the Figure 5.3, flow regulator valves are installed to outlet of building heat exchangers (city distribution site). They measure the temperature with the help of sensors and adjust the flow rate by changing the cross sectional area of flow.

When, heat demand of the building decreases (outside temperature increases), the return temperature of city circulation water, coming from building heat exchanger, increases. The temperature sensor of flow regulator measures this temperature change. Then cross sectional area of flow is decreased by the regulator. Also if heat demand increases, flow regulator increase the cross sectional area of flow. These pressure changes are continuously observed by system operators at points 1 and 2 in the Figure 5.3 and recorded at the pumping station where 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 the pumping cost by adjusting the flow rate of the hot water according to varying heat demand.

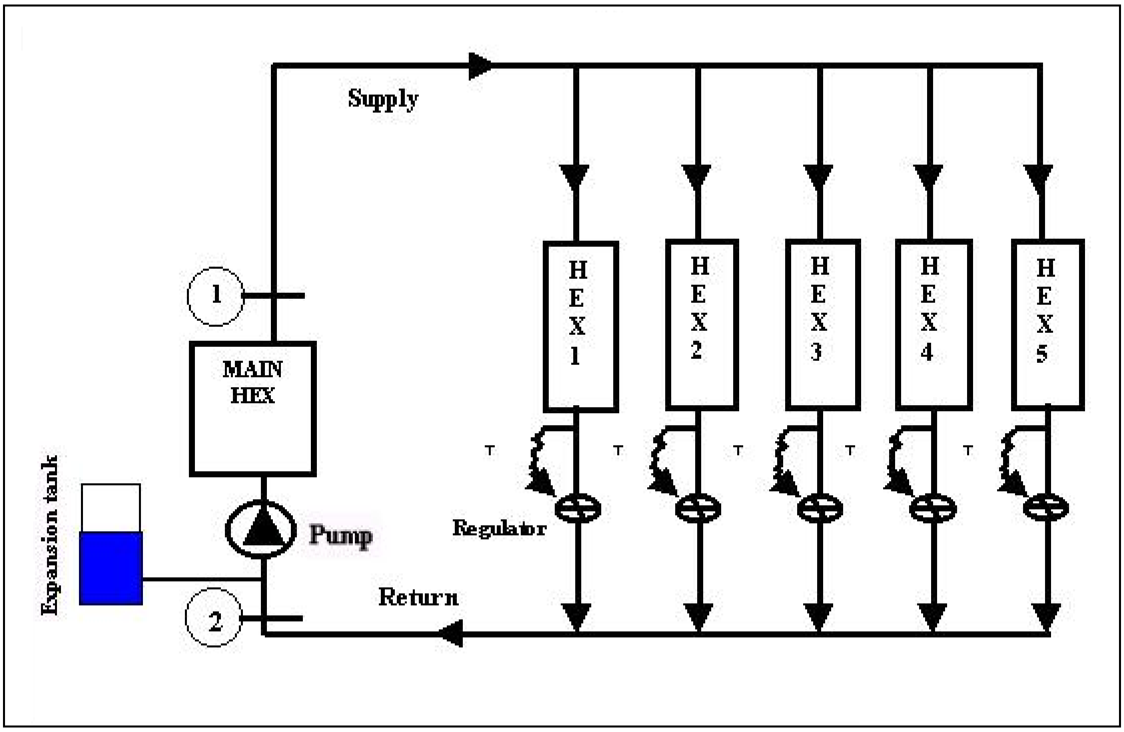

Figure 5.3: Basic Control Scheme of Balçova City Distribution System

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 expansion tank, minimum required pressure at point 2 is 20 m (2 bars).

Temperature regime, which is the most critical operational parameter for the geothermal district heating system is determined as 90 – 60 ^{o}C for the Balçova GDHS. Although system was first designed for 90 – 42^{o}C, experiences on the system show that the system works properly at 90 – 60^{o}C temperature regime. It should be stressed that the 90^{o}C refers to main heat exchanger outlet of the city distribution site and 60^{o}C refers to the main heat exchanger inlet of the same site. Geothermal site of the heat exchanger has been operated according to 115 – 65^{o}C temperature regime. Other temperature regimes are shown in Figure 5.4.

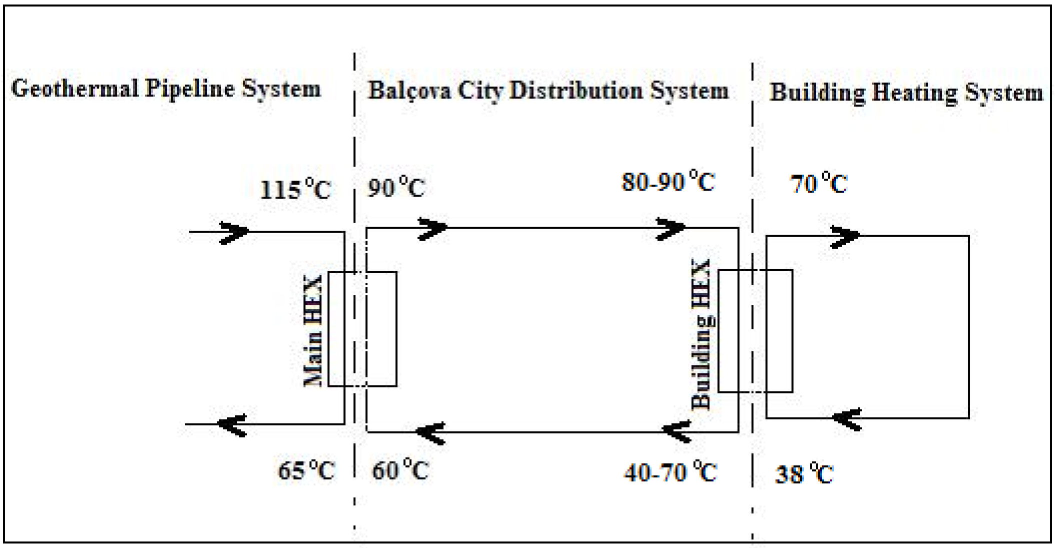

Figure 5.4: Temperature regimes in the Balçova GDHS

5.4.3. Narlıdere Geothermal District Heating System

Narlıdere GDHS provides heating and domestic hot water services to approximately 1500 dwellings. The operation principle of the system is same as Balçova GDHS's. Self-operated regulators are used to control the flow and temperature regimes at the each building connection. There is no variable frequency driver in Narlıdere GDHS. The system is operated at the constant flow rate all through the heating season, and it causes lack of energy economy in the system. In the heating season of 2003-2004 the installation of variable frequency drivers are being planned.

Temperature regimes in Narlıdere GDHS are 110 – 50 ^{o}C for the geothermal site and 85 – 55^{o}C for the city distribution site. However, since there is no variable frequency driver in the system, the principle of constant ΔT – variable flow rate can not be applied in Narlıdere GDHS. Therefore temperature regimes can not be kept at constant values in the system.

The system was actually designed for 5000 dwellings capacity and enlargement of the system is being considered for the heating season of 2003-2004.

5.5. Problems Encountered in Balçova-Narlıdere GDHS

Balçova-Narlıdere GDHS provides cheap and environmentally friendly heat energy to the people of Balçova-Narlıdere. However, the problems of Balçova-Narlıdere GDHS have been increasing with the age of the system. The system has problems especially in the operational level.

There is neither automatic control nor control algorithm in the system. There has been no definite instructions manual for the proper operation since the construction of the system. The operator responses to varying heat demand of the system are arbitrary and based on operators experience. Until this study, there was no energy economy effort in the system. The advantages of variable frequency drive control have not been used.

Data acquisition and storage efforts are very limited and primitive. Temperature and pressure data are measured and recorded at the limited number of points. Pressure and temperature distributions along the pipeline neither measured nor modelled until now.

There is great amount of leakage from Balçova city distribution system (5-25 l/s). This leakage causes loss of heat energy and pumping energy. The capacity of water purification device is not enough to meet the demand. Therefore geothermal water and low quality water which contains particles of mud and sand is pumped in to the network.

There are problems in the use of self-operated regulators. The interference of the customers to the set points of the regulators has just been stopped with the use of special locks on the regulators. Poor quality of the city distribution water causes scaling and choking in the regulators. Although the system was designed for 90-42^{o}C temperature regime, the return water comes into the heat exchanger station at about 60^{o}C. It is an indication of existance of by-pass in the system. Currently high return water temperatures and unstable temperature regimes are the most important obstacles for the energy economy efforts.

Heating systems of some buildings in the system were not installed for the temperature regimes of geothermal district heating systems. These buildings experience insufficient heating in cold winter times.

One part of the system called "İş Bankası Houses" experience great problems especially below 7-8 ^{o}C outdoor temperatures. This branch of the system experience highest pressure drop in the system and the reason of this problem is insufficient pumping and incorrect adjustment of regulators at that branch.

From geothermal well to customer connection system has spread over a large area. Lack of automation limits the operator's intervention capability on the system.

Today, for district heating systems, operational optimisation based on simple models of the sub-systems is very attractive with an acceptable degree of accuracy. The operational costs can be minimised by use of these models. The modelling studies, and energy economy efforts were started 2 years ago and the results of these studies have been started to apply in the 2002-2003 heating season. Results show that the system can be operated much more efficiently than past years if optimum operational algorithm is applied.

Chapter 6

MODELLING OF BALÇOVA-NARLIDERE GEOTHERMAL DISTRICT HEATING SYSTEM

6.1. The Need for the Model

Models are needed to produce the behaviour of a system in a controlled environment, and manipulate it to reach optimal solution. Geothermal district heating systems are huge systems, and affected by numerous parameters. Their operation requires critical decisions at each step. Models calibrated with actual data have great benefits for GDHS, since they allow to operator test his decision before applying on the real system.

In this study Balçova GDHS was modelled to find the optimum working conditions in the system. During study, first mathematical models were constructed, then models were calibrated with actual data sets. It is a fact that successful modelling of is a key point for the optimisation of the system. While modelling Balçova-Narlıdere GDHS approach in Figure 6.1 was used.

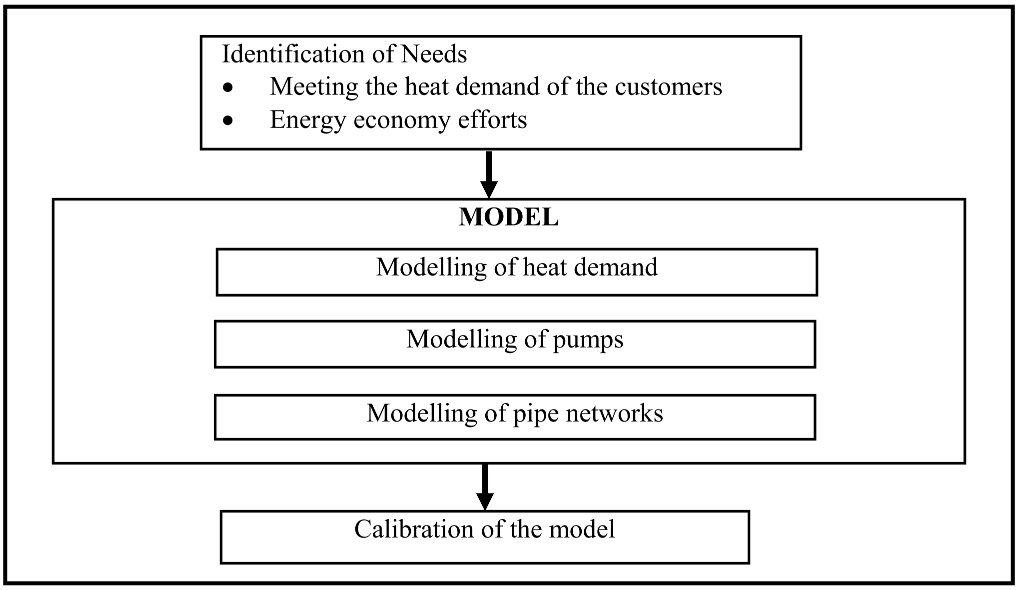

Figure 6.1: Modelling scheme of Balçova GDHS

6.2. Modelling of Heat Demand

Correct estimation of heat demand has a great importance for the proper operation of the district heating system. Static heat load calculations don't have any meaning for the district heating operators. Static heat load calculations do not take account of the heating and cooling effects which occur when temperature fluctuate. Thus it applies strictly only to steady-state conditions when temperatures are not varying.

The factors affecting the heat load can be classified into three separate groups: 1) behaviour of the district heating customers; 2) the physics of the network; and 3) weather conditions. The most important element of the district heat load prediction is ambient temperature. The heat load predictor cannot be any better than is the air temperature forecast. Approximately 70% of heat load can be attributed to air temperature. Other weather conditions, beside the air temperature, affecting the heat load are: radiation heat (especially in the spring); wind velocity and direction (coastal areas); the accumulation of heat in the network; and the thickness of the snow cover. [24]

The inclusion of a weather condition into the heat load model is not only dependent on the amount of training data (data used to construct the model) but also on how reliable the information about forthcoming conditions is. Typically, only forecasts of the ambient temperature are included in the heat load models. [24]

Like the other district heating systems Balçova-Narlıdere GDHS has cyclic behaviours caused by everyday human activities which consist of working hours; sleeping hours; weekends; common habits; holidays; mass events; and industrial cycles. The changes in the pipe network also have an effect on the heat load. These include the process dynamics as well as physical changes in the network topology. The dynamics of the whole network change with: water flow; the temperature of supply and return water; the accumulation of heat in the network; and changes in production units and in the network.

In this study the heat demand of the Balçova GDHS was modelled 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 even feedback and feedforward control. [26]

To construct the heat demand model of the system, 2001-2002 heating season data were used. Data set contains hourly measurements of heat exchanger inlet and outlet temperatures, flow rate and outdoor temperature for 188 days.

Time series analysis of this data is done by using ready functions in Matlab Software. First, a linear prediction model, Auto-Regressive with exogenous inputs (ARX) technique, is estimated using a time series recorded. Then, the residual error, which is the difference between the actual time measurement and the prediction from the previously estimated ARX model, is defined. By using this model, the heat demand of the next day can be estimated.

The original program output for the time series analysis of Balçova GDHS data is shown in Figure 6.2.

```
Discrete-time IDPOLY model: A(q) y(t) = B(q)u(t) + e(t)
A(q) = 1 - 0.8125 (+-0.03696) q^-1

B1(q) = -197.3 (+-46.34) - 148.9 (+-59.85) q^-1 + 71.84 (+-52.32) q^-2

B2(q) = 6714 (+-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 6.2: Original program output for time series analysis of Balçova GDHS data [25]

The fitted model for the heat demand of the Balçova GDHS can be simplified as:

$$Q_{Forecast} = A \cdot Q_{Today} + B \cdot T_{outForecast} + C \cdot T_{outToday} + D \cdot T_{outYesterday} + E \qquad (6.1)$$

where,

A = 0.8125±0.03696 (-)

B = -197.3±46.34 ($kW_t/{}^{o}C$)

C = -148.9±59.85 ($kW_t/{}^{o}C$)

D = 71.84±52.32 (kW_t/ ^oC)

E = 6714±1274 (kW_t).

Q_{Today} can be found from,

$$Q_{Today} = \dot{m} \cdot C_p \cdot \Delta T_{hexCity} \quad (6.2)$$

The values of flow rate, outside temperature of today and yesterday and heat exchange temperature differences are measured and recorded in the Balçova heat exchanger station. Weather forecast for the next day can be found from the web site of the state meteorology office.

The model has been checked on different data sets and the results are presented in Section 8.1.

6.3. Modelling of Pump Performance

In district heating systems energy needs to be added to a hydraulic system to overcome elevation differences, frictional losses, and minor losses. A pump is a device to which mechanical energy is applied and transferred to the water as total head.The head added is called pump head, and is a function of the flow rate through the pump. The pump performance is described by the following four parameters, which are plotted versus discharge. [3]

- Head: Total dynamic head added by pump in units of length.
- Efficiency: Overall pump efficiency (wire-to-water efficiency) in units of percent.
- Brake horsepower: Power needed to turn pump (in power units)
- Net positive suction head (NPSH) required: Head above vacuum required to prevent cavitation. (In units of length)

There are two types of pumps have been used in Balçova-Narlıdere GDHS. Lineshaft pumps and centrifugal pumps. Lineshaft pumps are used to pump geothermal fluid from geothermal reservoir to surface. Centrifugal pumps are used to transmit and circulate the geothermal fluid and water in the pipeline systems. The basic principles of performance calculations for both types are same. Pumps and their motor capacities installed in the system are given in Table 6.1.

Table 6.1: Pumps and their motor capacities in Balçova-Narlıdere GDHS

Function	Number	Power (kWe)
BD2 Well Pump	1	75
BD3 Well Pump	1	110
BD4 Well Pump	1	110
BD5 Well Pump	1	55
BD7 Well Pump	1	55
B4 Well Pump	1	55
B5 Well Pump	1	75
B10 Well Pump	1	45
Balçova city circulation pumps (Parallel)	4	160
Geothermal booster pump (Balçova)	1	200
Narlıdere city circulation pumps (Parallel)	3	15
Balçova city circ. Pumps (summer)	2	11
Balçova mixing tank pump	1	30
Hydrofor pumps	2	11
Hydrofor pumps	3	4
Geothermal booster pump (Narlıdere)	1	22

6.3.1. Pump Head vs. Flow Rate Relationship

The relationship between pump head and pump discharge is given in the form of a head versus flow rate curve. This curve also called *pump head characteristic* curve. Sample pump head characteristic curve is shown in Figure 6.3. This curve defines the relationship between the head that the pump adds and the amount of flow that the pump passes. The pump head versus flow rate relationship is nonlinear, and as it is expected, the more water the pump passes, the less head it can add. The head that is plotted in the pump head characteristic curve is the head difference between inlet and outlet of the pump, called the *total dynamic head* (TDH). [3]

This curve must be described as a mathematical function to be used in a hydraulic modelling. Some models fit a polynomial curve to selected data points, but a more common approach is to describe the curve using a power function in the following form.

$$h_P = h_0 - c \cdot Q_P^m \tag{6.3}$$

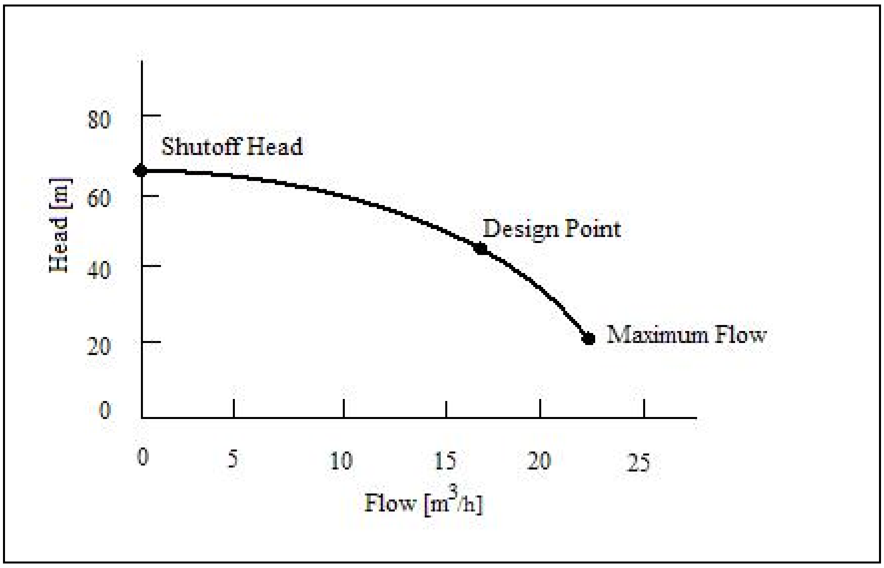

Figure 6.3: Pump head characteristic curve

A centrifugal pump's characteristic curve is fixed for a given motor speed and impeller diameter, but can be determined for any speed and any diameter by applying relationships called the affinity laws. For variable-speed pumps, these affinity laws are presented as:

$$\frac{Q_{P1}}{Q_{P2}} = \frac{n_1}{n_2} \tag{6.4}$$

$$\frac{h_{P1}}{h_{P2}} = \left(\frac{n_1}{n_2}\right)^2 \tag{6.5}$$

Thus, pump discharge rate is directly proportional to pump speed, and pump discharge head is is proportional to the square of the speed. Using this relationship, once the pump curve at any one speed is known, then the curve another speed can be predicted. Figure 6.4 illustrates the affinity laws for variable speed drive pumps where the line through the pump head characteristic curves represents the locus of best efficiency points. [3]

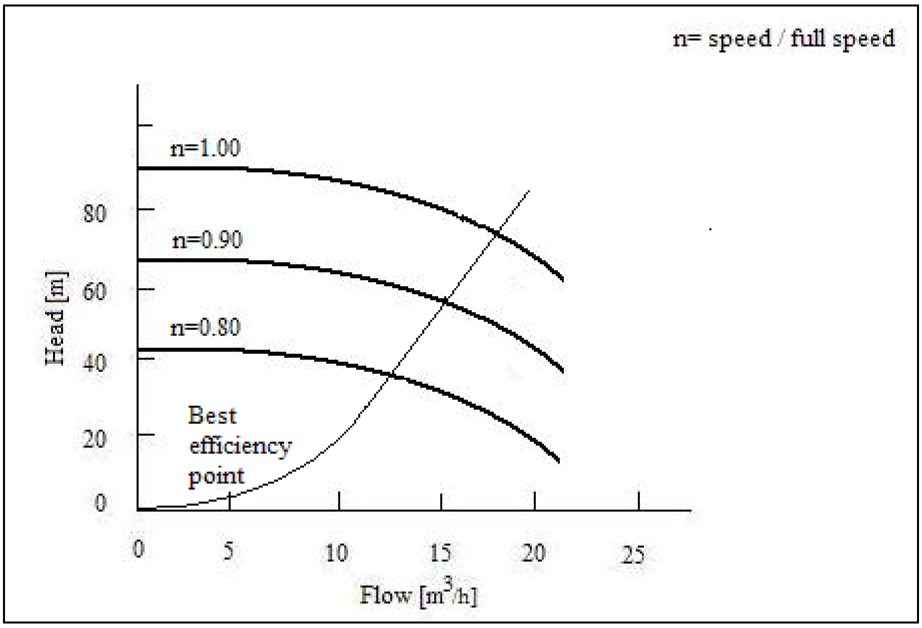

Figure 6.4: Relative speed factors for variable speed pumps

6.3.2. System Head Curve

The purpose of a pump is to overcome elevation differences and head losses due to pipe friction and fittings. The amount of head the pump must add to overcome elevation differences is dependent on system characteristics and topology (and independent of the pump discharge rate), and is referred to as static head or static lift. Friction and minor losses, however, are highly dependent on the rate of discharge through the pump. When these losses are added to the static head for a series of discharge rates, the resulting plot is called a *system head curve*.

The pump characteristic curve is a function of the pump and independent of the system, while the system head curve is dependent on the system and independent of the pump. For the case of a single pipeline between two points, the system head curve can be described in equation form as: [3]

$$H = h_1 + \sum K_P \cdot Q_{pipe}^{\ z} + \sum K_M \cdot Q_{pipe}^{\ 2} \qquad (6.6)$$

Thus, the head losses and minor losses associated with each segment of pipe are summed along the total length of the pipeline. When the system is more complex, the interdependencies of the hydraulic network make it impossible to write a single equation to desribe a point on the system curve. In these cases, hydraulic analysis using a hydraulic model may be needed. Detailed information about hydraulic modelling of complex networks will be given in Section 6.3.

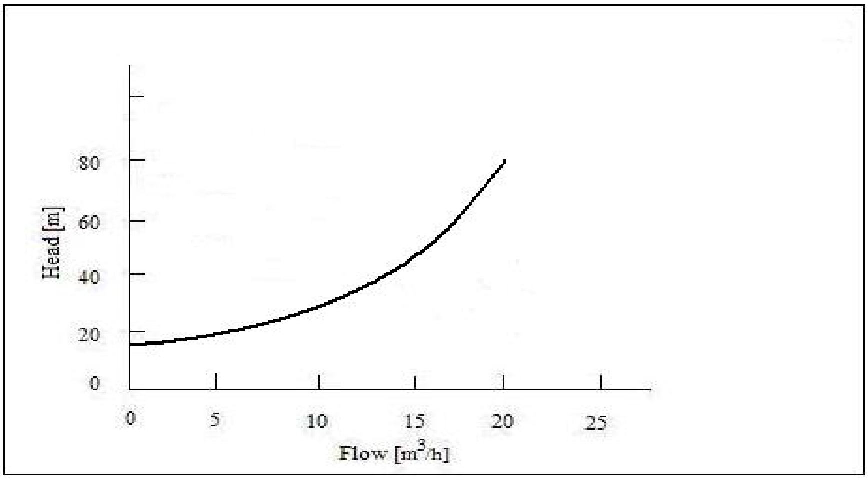

Figure 6.5: System head curve

6.2.3. Pump Operating Point

When the pump head discharge curve and the system head curve are plotted on the same axes, there is only one point that lies on both the pump characteristics curve and the system head curve. This intersection defines the pump operating point, which represents the discharge that will pass through the pump and the head that the pump will add. This head is equal to the head needed to overcome the static head and other losses in the system. Figure 6.6 illustrates the pump operating point.

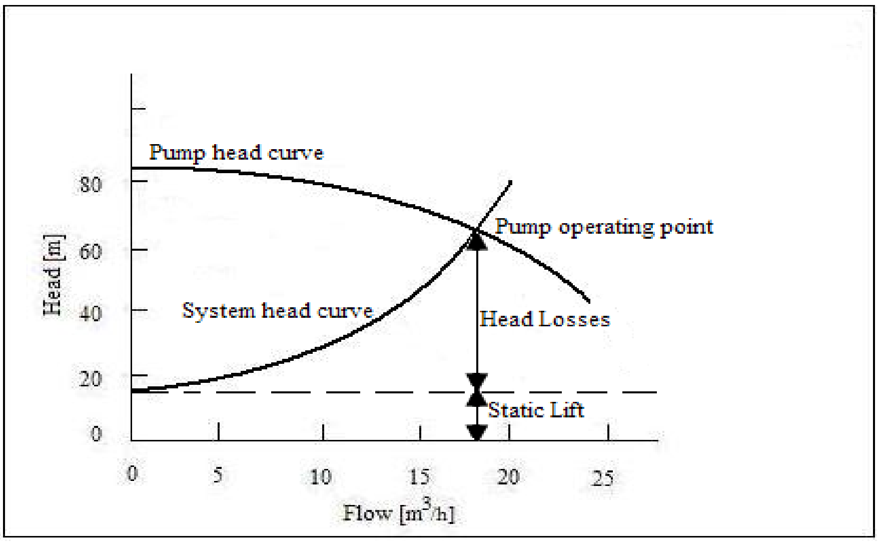

Figure 6.6: Pump operating point

6.3.4. Pump Power and Efficiency

The term power may have one of several meanings when dealing with a pump. These possible meanings are listed below [3]:

- Input power: The amount of power that is delivered to the motor, usually in electric form.
- Brake power: The amount of power that is delivered to the pump from the motor.
- Water power: The amount of power that is delivered to the water from the pump.

There are losses as energy is converted from one form to another, and every transfer has an efficiency associated with it. The efficiencies associated with these transfers may be expressed either as percentages or as decimal values (1.00 is perfectly efficient), and are typically defined as follows:

- Motor efficiency: The ratio of brake power to input power.
- Pump efficiency: The ratio of water power to brake power.
- Wire-to-water (overall) efficiency: The ratio of water power to input power.

Pump efficiency tends to vary significantly with flow, while motor efficiency remains relatively constant over the range of loads imposed by most pumps. Note that there may also be an additional efficiency associated with a variable speed drive. (See 4.3.5.1.).

A curve representing the relationship between pump discharge (Q_P) and pump efficiency (e_P) can usually be described by the equation for an inverted parabola as shown in equation 6.7.

$$e_P = a \cdot Q^2 + b \cdot Q + c \tag{6.7}$$

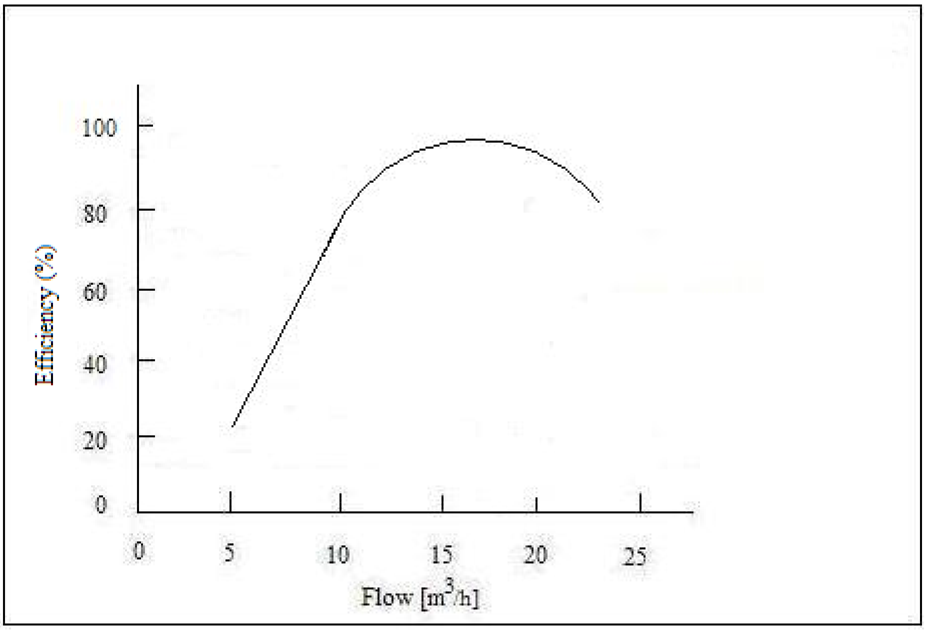

Figure 6.7: Flow vs. efficiency relation

Variable speed pumps do not run efficiently over a wide range of flows, as shown in Figure 6.8. District heating operators should be aware of the fact that, installation of variable speed drive into the system does not guarantee the efficient operation. Efficiencies and power consumptions must be calculated for each flow rate and optimum combination of pumps and speed should be selected to increase the efficiency in the system.

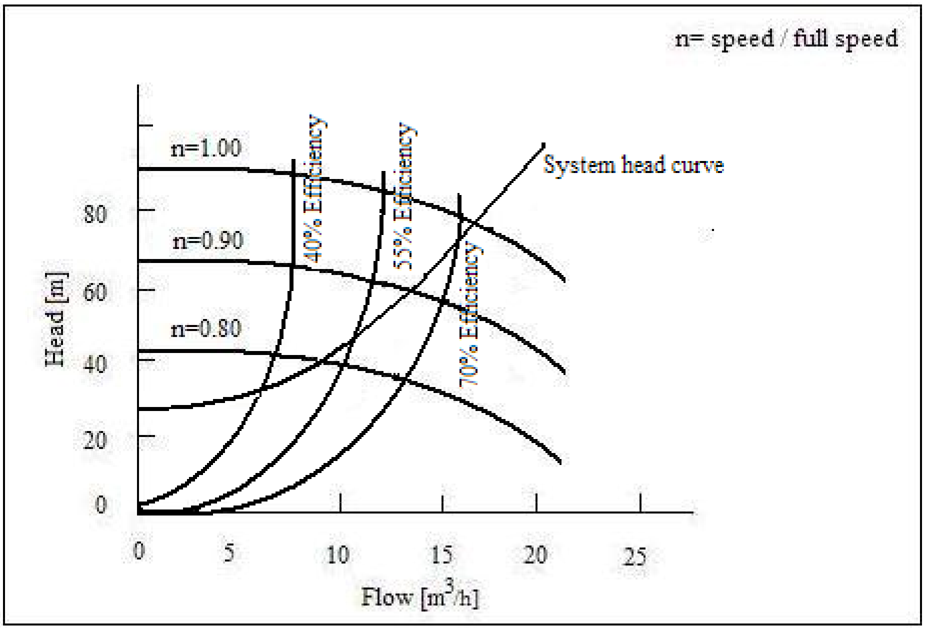

Figure 6.8: Pump operating points for variable speed pumps

Power consumption of the pump is given as:

$$P_P = \frac{\rho \cdot g \cdot Q_P \cdot h_P}{\eta_{overall}} \tag{6.8}$$

Overall efficiency can be calculated from:

$$\eta_{overall} = \eta_{Pump} \cdot \eta_{Motor} \cdot \eta_{VSD} \tag{6.9}$$

6.3.5. Parallel Pumps

In general, pump stations should at a minimum be capable of meeting average load when the largest pump is out of service. In smaller pump stations there are usually two pumps either of which can independently meet demands. In larger stations, it is common to provide additional reliability and flexibility by having more than two pumps. 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 the other pumps. [3]

A major factor affecting pump efficiency is the capacity of the piping system upstream and downstream of the pump station. This capacity is reflected in the system head curve.

The simplest way to evaluate pumps in parallel is modelling the system for each different combination of pumps. Power consumption models of circulation pumps in Balçova GDHS has been modelled and the results are presented in Section 7.2. System characteristics of the two identical pumps in parallel is given in Figure 6.9.

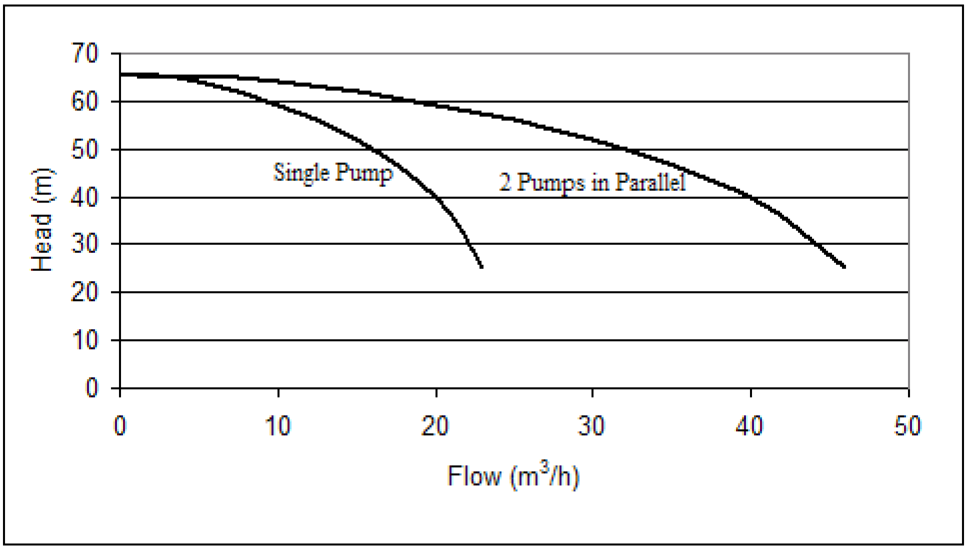

Figure 6.9: Two identical pumps in parallel

6.3.6. Geothermal Well Pumping

Well pumping is similar to most of the other types of pumping. An important difference is that the pump suction head will vary due to the drawdown of the water in the vicinity of the well as water is pumped from it. In very porous aquifers, the amount of water table will drop during pumping may be negligible, and the well can be represented by the reservoir alone. In most cases, however, the water level in the well will experience significant drawdown due to pumping, and this drawdown is relatively linear with respect to flow rate. [3]

The main goal of geothermal well pumping is to extract heat energy of geothermal fluid in a most efficient way. Therefore, the temperature of the geothermal fluid is one of the important decisive factors in geothermal well pumping. Like water level, geothermal fluid temperature may also decrease during production. This fall in the temperature decreases the efficiency of geothermal well pumping. Therefore, flow rate versus power consumption rate relationship is not enough for geothermal well pumps. The produced heat energy rate versus power consumption rate graphs should be plotted for each geothermal well. The produced heat energy rate versus power consumption rate plot of two production wells in Balçova-Narlıdere geothermal field is shown in Figure 6.10. These figures give very clear idea about the efficiency of geothermal fluid production and provides the comparison of geothermal wells.

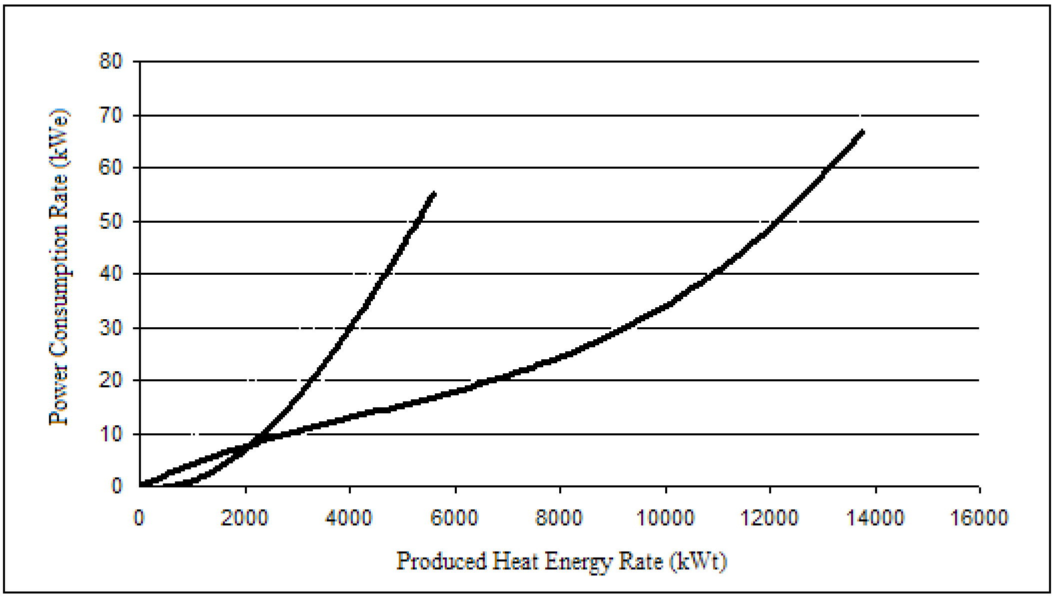

Figure 6.10: Power consumption versus heat production relationship for geothermal wells

6.3.7. Acquisition and Analysis of Pump Data

Ideally district heating operators will have pump operating curves on file for every pump in the system. These are provided by pump manufacturers. To perform energy cost calculations, pump efficiency curves should be obtained. It should be noted that the various power and efficiency definitions can be confusing, and it is important to distinguish which terms are being referred to in any particular document.

Every pump differs slightly from its catalog model, and normal wear and tear will cause a pump's performance to change over time. Thus pumps should be monitored continuously to verify that the characteristic curves on record are in agreement with field performance. If an operating point does not agree with a characteristic curve, new curve can be developed to reflect the actual behaviour. [3]

In Balçova-Narlıdere geothermal district heating system, variable frequency drivers (VFD) are used to control the speed of pumps. These drivers are sophisticated devices and it is possible to obtain data regarding to pump operation from these devices. Power consumption of each pump can be read from the display of the variable frequency driver. During this study, data acquisition and storage from VFDs were started. It should also be noted that, there is flowmeter at each pump outlet. Once having these data it is possible to calculate actual power consumption rate and efficiency of each pump.

In this study pump characteristics were modelled theoretically and from actual data sets. Then results were presented in Sections 7.2 and 8.2.

6.4. Pipe Network Modelling

Model of district heating network 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 determine the causes of formulate solutions that will work correctly the first time rather than a resorting to trial-anderror changes in the actual system. [3]

In this study Balçova GDHS distribution system and geothermal pipeline system were modelled by using *PIPELAB District Heating Simulation Software.* The software algorithm uses graph theory to solve network problems. This approach was first introduced by Valdimarsson in 1993. Especially in the modelling of geothermal pipeline system PIPELAB program was improved by inserting new sub-programs into the software. Graph theoretical approach to the network analysis will be introduced in the following sections. ***The treatment of the theoretical background is based on P. Valdimarsson*** who first applied graph theoretical solution to district heating networks. [16]

6.4.1. Theory Behind the Model

Following is a definition of some graph terms used in graph theory solution of networks:

- *Tree:* A subgraph $\mathbf{G_s}$ of the connected graph $\mathbf{G_n}$ is a tree if it is connected and $\mathbf{G_s}$ have no loops.
- *Spanning tree:* A subgraph $\mathbf{G_s}$ of the connected graph $\mathbf{G_n}$ is a spanning tree if it is connected, $\mathbf{G_s}$ contains all nodes of $\mathbf{G_n}$ and $\mathbf{G_s}$ 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 $\mathbf{G_n}$ (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 named cotree L with respect to the tree T.

A graph is commonly defined as a composite concept of:

a. a set of nodes
b. a set of branches
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 or are united or convey the flow to the consumer. Here the word "pipe" is used in a general sense, which 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 an incidence (or 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 an $n_n \cdot n_f$ 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 j,

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 the 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.

The connectivity matrix **A** can be rearranged with respect to a spanning tree containing n_T branches by splitting it into two submatrices $\mathbf{A_T}$ and $\mathbf{A_L}$ in the following manner:

$$\mathbf{A} = [\mathbf{A_T} \mid \mathbf{A_L}] \tag{6.10}$$

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

Continuity for the mass in a pipe network can be defined by reference to the current law of Kirchhoff: The sum of the mass flows at any node equals 0 at any time. The connectivity matrix has a row for every node in the system. In each row all entries of 1 represent an outgoing flow stream from that node, and entries of -1 an incoming flow stream. The system flow can conveniently be stated by means of a column vector with n_f entries, each stating the flow in the corresponding flow stream. A positive flow indicates flow in the same direction as defined in the connectivity matrix, a minus signs an opposite flow direction. By using the connectivity matrix this becomes:

$$\mathbf{A\ m} = \mathbf{0} \tag{6.11}$$

The connectivity matrix **A** is time-independent since the district heating system structure does not change with time. Equation (6.11) can be thus differentiated with respect to time:

A loop matrix is a matrix with one row for each loop in the network, and one column for each branch. The entries of the loop matrix are as follows:

b_{ij} = 1 denotes that branch *j* is a member of the loop *i* with same direction

b_{ij} = -1 that branch *j* is a member with opposite direction

b_{ij} = 0 that branch *j* is not a member of loop *i*.

It follows from the definition of a spanning tree, that every link is a member of one and only one loop together with some tree branches, but no other links. Such loops are called fundamental loops with respect to the cotree *L*. The fundamental loop matrix **B** is an $n_L \cdot n_f$ matrix, partitioned as follows:

$$\mathbf{B} = [\mathbf{B_T} | \mathbf{I}] \tag{6.12}$$

As the links are members of one and only one fundamental loop, the link part of the matrix is the identity matrix. The submatrix $\mathbf{B_T}$ reflects the membership of the tree branches in every fundamental loop.

A cutset matrix is a matrix with one row for a cutset in the network, and one column for every branch. The entries of the cutset matrix are as follows:

d_{ij} = 1 denotes that branch *j* is a member of the cutset *i* with same direction

d_{ij} = -1 that branch *j* is a member with opposite direction

d_{ij} = 0 that branch *j* is not member of cutset *i*.

It follows from the definition of a spanning tree, that every tree branch is member of one and only one cutset, together with some (or no) links, but no other tree branches. Such cutsets are called fundamental cutsets with respect to the spanning tree *T*. The fundamental cutset matrix **D** is an $n_T \cdot n_f$ matrix, partitioned as follows:

$$\mathbf{D} = [\mathbf{I} | \mathbf{D_L}] \tag{6.13}$$

As the tree branches are members of and only one fundamental cutset, the tree part of the matrix is the identity matrix. The submatrix $\mathbf{D_L}$ reflects the membership of the links in every fundamental cutset. It follows from the definition of the cutset matrix that:

$$\mathbf{D} \cdot \mathbf{m} = \mathbf{0} \tag{6.14}$$

$$\left[\mathbf{I} \middle| \mathbf{D_L}\right] \cdot \left[\frac{\mathbf{m_T}}{\mathbf{m_L}}\right] = \mathbf{0} \tag{6.15}$$

$$\mathbf{m_T} = -\mathbf{D_L} \cdot \mathbf{m_L} \tag{6.16}$$

Substituting (6.16) into (6.11):

$$-\mathbf{A_T} \cdot \mathbf{D_L} \cdot \mathbf{m_L} + \mathbf{A_L} \cdot \mathbf{m_L} = \mathbf{0} \tag{6.17}$$

$$\mathbf{A_T} \cdot \mathbf{D_L} = \mathbf{A_L} \tag{6.18}$$

$$\mathbf{D_L} = \mathbf{A_T^{-1}} \cdot \mathbf{A_L} \tag{6.19}$$

$$\mathbf{D} = \mathbf{A_T^{-1}} \cdot \mathbf{A} \tag{6.20}$$

Both the **B** and **D** matrices have one column for every branch in the graph. If both matrices are arranged in the same column order, the following relationship holds:

$$\mathbf{D} \cdot \mathbf{B^T} = \mathbf{0} \tag{6.21}$$

By inserting Equations (6.12) and (6.13) into Equation (6.21), the following expression is obtained:

$$\mathbf{B_T} = -\mathbf{D_L^T} \tag{6.22}$$

Then all the necessary system matrices have been constructed. This concludes the basic graph theory treatment based on Chua and Lin (1975).

6.4.2. Flow Solution

In networks of interconnected hydraulic elements, every element is influenced by each of its neighboors; the entire system is interrelated in such a way that the condition of one element must be consistent with the condition of all other elements. 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 sources

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:

$$\mathbf{m} = \begin{bmatrix} \mathbf{m}_{\mathbf{hT}} \\ \mathbf{m}_{\mathbf{sT}} \\ \mathbf{m}_{\mathbf{rT}} \\ \mathbf{m}_{\mathbf{pT}} \\ \mathbf{m}_{\mathbf{mL}} \\ \mathbf{m}_{\mathbf{pL}} \end{bmatrix} \tag{6.23}$$

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.

$$\mathbf{Dm} = \left[\begin{array}{cccc|cc} \mathbf{I}_{hT} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{F}_{11} & \mathbf{F}_{12} \\ \mathbf{0} & \mathbf{I}_{sT} & \mathbf{0} & \mathbf{0} & \mathbf{F}_{21} & \mathbf{F}_{22} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_{rT} & \mathbf{0} & \mathbf{F}_{31} & \mathbf{F}_{32} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_{pT} & \mathbf{F}_{41} & \mathbf{F}_{42} \end{array}\right] \cdot \left[\begin{array}{c} \mathbf{m}_{hT} \\ \mathbf{m}_{sT} \\ \mathbf{m}_{rT} \\ \mathbf{m}_{pT} \\ \hline \mathbf{m}_{mL} \\ \mathbf{m}_{pL} \end{array}\right] = \mathbf{0} \tag{6.24}$$

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 $\mathbf{m_{pL}}$.

$$\begin{bmatrix} \mathbf{m}_{hT} \\ \mathbf{m}_{sT} \\ \mathbf{m}_{rT} \\ \mathbf{m}_{pT} \end{bmatrix} = -\begin{bmatrix} \mathbf{F}_{11} & \mathbf{F}_{12} \\ \mathbf{F}_{21} & \mathbf{F}_{22} \\ \mathbf{F}_{31} & \mathbf{F}_{32} \\ \mathbf{F}_{41} & \mathbf{F}_{42} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{m}_{mL} \\ \mathbf{m}_{pL} \end{bmatrix} \tag{6.25}$$

If the network does not contain pipes in the cotree, the flow can then be calculated by Equation (6.25), as the vector $\mathbf{m_{pL}}$ is empty and the vector $\mathbf{m_{mL}}$ is a boundary condition vector of known values.

The head loss in an element is a non-linear function of the flow. The head loss function can be linearised in order to obtain a steady state flow solution for the network. A well-suited iteration method is proposed by Wood and Charles. The head loss in all the network pipes and the associated linearisation can be written on matrix form as:

$$\begin{bmatrix} \mathbf{h_{rT}} \\ \mathbf{h_{pT}} \\ \mathbf{h_{pL}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{r_{rT}(m_{rT})} \\ \boldsymbol{r_{pT}(m_{pT})} \\ \boldsymbol{r_{pL}(m_{pL})} \end{bmatrix} \approx \begin{bmatrix} \boldsymbol{R_{rT}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{R_{pT}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{R_{pL}} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{m_{rT}} \\ \boldsymbol{m_{pT}} \\ \boldsymbol{m_{pL}} \end{bmatrix} \tag{6.26}$$

The steady state flow solution derived from these equations is according to Valdimarsson:

$$\mathbf{m_{pL}} = [\mathbf{F_{42}^T R_{pT} F_{42}} + \mathbf{F_{32}^T R_{rT} F_{32}} + \mathbf{R_{pL}}]^{-1}.[\mathbf{F_{22}^T h_{sT}} + \mathbf{F_{12}^T h_{hT}} - [\mathbf{F_{42}^T R_{pT} F_{41}} + \mathbf{F_{32}^T R_{rT} F_{31}}]\mathbf{m_{mL}}] \tag{6.27}$$

The remaining flows are then calculated by Equation (6.25).

6.4.3. 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 **m**. The time dependent flow connectivity matrix $\mathbf{A_f}$ describes the real connectivity of the flow but not only the connectivity of the flow element. This matrix does then change if any flowstream in the network does change direction. The flow connectivity matrix is defined by:

$$\mathbf{A_f} = \mathbf{A} \cdot diag(sign(\mathbf{m})) \tag{6.28}$$

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

$$\mathbf{E} = \frac{1}{2}\left(\mathbf{A_f} + |\mathbf{A_f}|\right) \tag{6.29}$$

The entries of the matrix are e_{ij} = 1 if the flow stream j does originate 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:

$$q_j = c_p \cdot m_j \cdot T_{origin} \tag{6.30}$$

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

$$\mathbf{T}_{origin} = \mathbf{E}^T \cdot \mathbf{T}_n \tag{6.31}$$

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

$$\mathbf{q}_f = diag\left(c_p \cdot \mathbf{m}\right) \cdot \mathbf{E}^T \cdot \mathbf{T}_n \tag{6.32}$$

The heat flow through a heat exchanger is a function f four temperatures; the two fluid inlet temperatures, and the heat transfer coefficient for the heat exchanger. The counterflow heat exchanger element is shown on Figure 6.11.

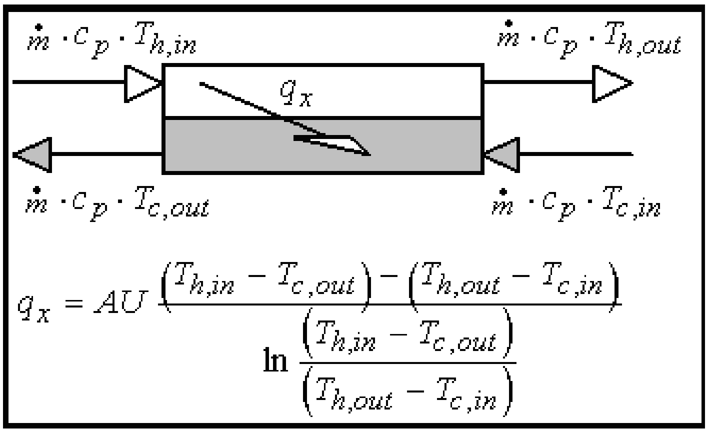

Figure 6.11: Heat exchanger schematic [27]

No exchange of mass is between the hot and cold fluid, 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 is shown on Figure 6.12.

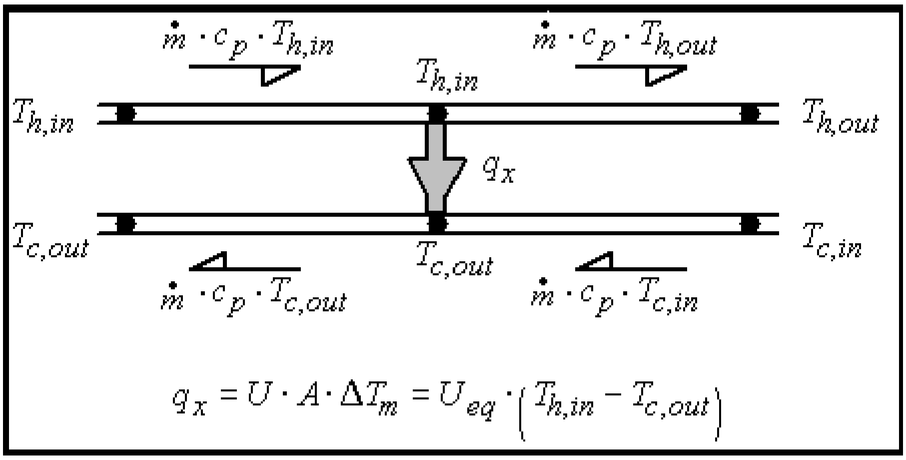

Figure 6.12: Graph representation of a heat exchanger [27]

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:

$$q_x = U_{eq} \cdot \left(T_{h,in} - T_{c,out}\right) \tag{6.33}$$

Each heat exchanger elements 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:

$$\mathbf{q}_x = \mathbf{U}_{eq} \cdot \mathbf{A}_x^T \cdot \mathbf{T}_n \tag{6.34}$$

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 $n_n \cdot n_t$ connectivity matrix $\mathbf{A}_t$.

The matrix notation for the current law of Kirchhoff 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:

$$\begin{bmatrix} \mathbf{A} & \mathbf{A}_x & \mathbf{A}_t & \mathbf{A}_q \end{bmatrix} \cdot \begin{bmatrix} \mathbf{q}_f \\ \mathbf{q}_x \\ \mathbf{q}_t \\ \mathbf{q}_q \end{bmatrix} = \mathbf{0} \tag{6.35}$$

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

$$\begin{bmatrix} \mathbf{A} & \mathbf{A}_x & \mathbf{A}_t \end{bmatrix} \cdot \begin{bmatrix} \mathbf{q}_f \\ \mathbf{q}_x \\ \mathbf{q}_t \end{bmatrix} = -\mathbf{A}_q \cdot \mathbf{q}_q \tag{6.36}$$

The heat flow vector $\mathbf{q}_f$ for the flow elements is substituted from Equation (6.32), and the heat flow vector $\mathbf{q}_x$ for the heat exchangers from Equation (6.34):

$$\begin{bmatrix} \mathbf{q}_f \\ \mathbf{q}_x \end{bmatrix} = \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq} \end{array}\right] \cdot \begin{bmatrix} \mathbf{E} & \mathbf{A}_x \end{bmatrix}^T \mathbf{T}_n \tag{6.37}$$

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

$$\begin{bmatrix} \mathbf{A} & \mathbf{A}_x & \mathbf{A}_t \end{bmatrix} \cdot \begin{bmatrix} \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq} \end{array}\right] \begin{bmatrix} \mathbf{E} & \mathbf{A}_x \end{bmatrix}^T \mathbf{T}_n \\ \mathbf{q}_t \end{bmatrix} = -\mathbf{A}_q \cdot \mathbf{q}_q \tag{6.38}$$

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

$$\begin{bmatrix} \mathbf{A} & \mathbf{A}_x & \mathbf{A}_t \end{bmatrix} \cdot \left[\begin{array}{c|c} \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq} \end{array}\right] \begin{bmatrix} \mathbf{E} & \mathbf{A}_x \end{bmatrix}^T & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{I}_t \end{array}\right] \begin{bmatrix} \mathbf{T}_n \\ \mathbf{q}_t \end{bmatrix} = -\mathbf{A}_q \cdot \mathbf{q}_q \tag{6.39}$$

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 to the desired numerical value T_t, according to the Modified Nodal approach.

$$\left[\begin{array}{c|c} \begin{bmatrix} \mathbf{A} & \mathbf{A}_x \end{bmatrix} \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq} \end{array}\right] \begin{bmatrix} \mathbf{E} & \mathbf{A}_x \end{bmatrix}^T & \mathbf{A}_t \\ \hline \mathbf{A}_t^T & \mathbf{0} \end{array}\right] \begin{bmatrix} \mathbf{T}_n \\ \mathbf{q}_t \end{bmatrix} = \begin{bmatrix} -\mathbf{A}_q \cdot \mathbf{q}_q \\ \mathbf{T}_t \end{bmatrix} \tag{6.40}$$

The final solution is obtained by matrix inversion, and gives the nodal temperature and the heat flow in the constant temperature elements as result. [16]

$$\begin{bmatrix} \mathbf{T}_n \\ \mathbf{q}_t \end{bmatrix} = \left[\begin{array}{c|c} \begin{bmatrix} \mathbf{A} & \mathbf{A}_x \end{bmatrix} \left[\begin{array}{c|c} diag(c_p \cdot \mathbf{m}) & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{U}_{eq} \end{array}\right] \begin{bmatrix} \mathbf{E} & \mathbf{A}_x \end{bmatrix}^T & \mathbf{A}_t \\ \hline \mathbf{A}_t^T & \mathbf{0} \end{array}\right]^{-1} \begin{bmatrix} -\mathbf{A}_q \cdot \mathbf{q}_q \\ \mathbf{T}_t \end{bmatrix} \tag{6.41}$$

6.4.4. PIPELAB District Heating Simulation Program

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

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.m).
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 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 6.13 shows the presentation of the Balcova city distribution system in the PIPELAB user interface screen.

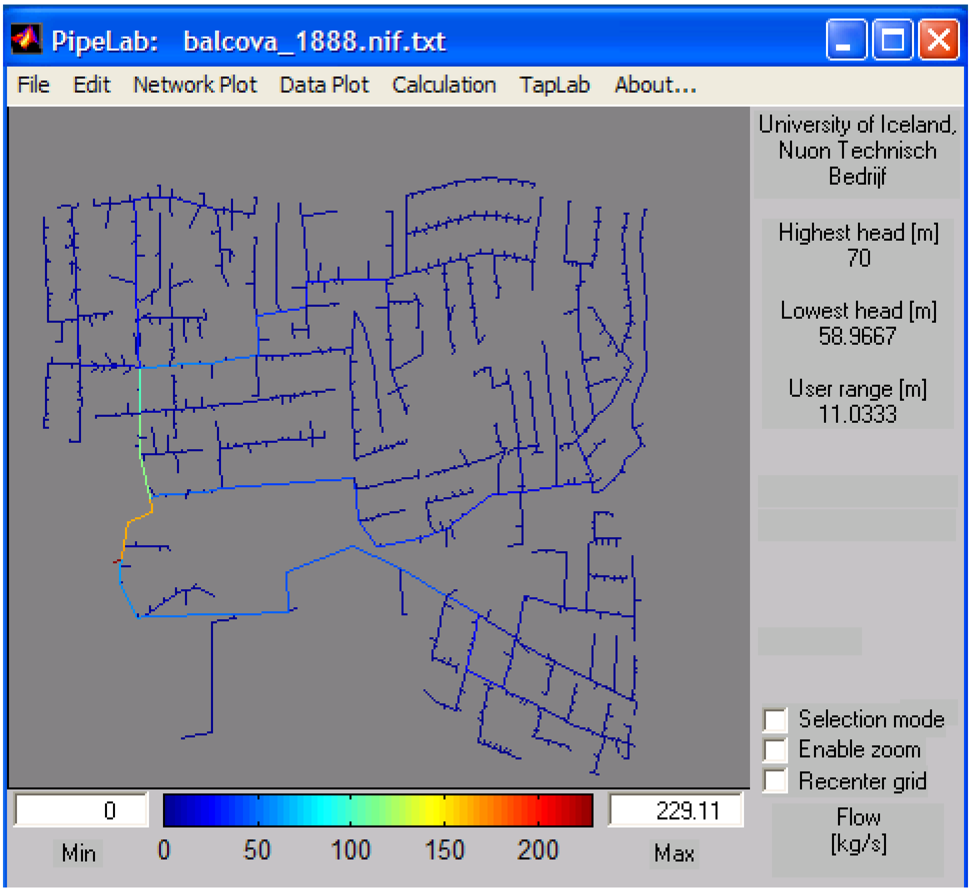

Figure 6.13: PIPELAB user interface screen

6.4.4.1. Calculation of Head and Flow in PIPELAB

The calculation of head and flow in a net is the single most important activity of PIPELAB. It is the reason that this program was written, these procedures are the core of the program.

A calculation of head and flow always compromises two steps:

1. Sorting the net. The net may contain loops which will disturb any calculations when left unchecked. By making an tree, loops are prevented by selecting and removing specific pipes. When no loops exist, all nodes are connected to the reference by one and only one route. This net is called the .tree. The removed pipes are called cotree.
2. Calculation. After the net is sorted (tree and cotree), an iteration is performed to match the flow through a pipe, the headloss over a pipe and the heads on each node. In each iteration a match is made for the tree and the cotree respectively. The iteration ends when the flows in two successive iterations are the same (barring a small difference epsilon).

The calculation requires a convergent iteration. When an iteration doesn't converge, this may indicate an unusual configuration in the net. Experiences show that this usually implies an erroneous network.

The first activity in the iteration is the calculation of resistances. the headloss over a resistor is determined from the velocity of the water:

$$\left.\begin{array}{r} A = \dfrac{\pi \cdot D^2}{4} \\ v = \dfrac{m}{A \cdot \rho} \end{array}\right\} h_1 = \frac{1}{2g} \cdot c \cdot v^2 \qquad (6.42)$$

The headloss over a pipe is determined from the velocity:

$$\left.\begin{array}{r} A = \dfrac{1}{4} \cdot \pi \cdot D^2 \\ v = \dfrac{m}{A \cdot \rho} \\ Re = v \cdot \dfrac{D}{n_y} \end{array}\right\} f = \frac{1.325}{\left[\log\left(\dfrac{3.7 \cdot k}{D} + Re^{-0.9}\right)\right]^2} \qquad (6.43)$$

$$h_l = \frac{1}{2g} \cdot f \cdot \frac{L}{D} \cdot v \cdot |v| \tag{6.44}$$

Then the resistance can be calculated by dividing the head loss by the flow.

$$R = \frac{h_l}{m} \tag{6.45}$$

6.4.4.2. Calculation of Temperatures and Heat Flow in PIPELAB

The temperature in a net is not uniformly distributed. It is dependent on the flow throughout the net, the laying of the pipes and the points where water with a given temperature is fed into the net.

When a pipe, through which hot water flows, lays in the ground, a powerloss occurs as temperature flows from the water to the environment. The powerloss of a pipe depends on the length of the pipe and the temperature of the water in it. The powerloss results in a loss of temperature.

$$\Delta P = \xi(D,T) \cdot L \tag{6.46}$$

$$\Delta T = \frac{\Delta P}{c_p \cdot \dot{m}} \tag{6.47}$$

$$T_{n+1}=T_n-\Delta T \tag{6.48}$$

The factor ξ is dependent on the diameter of the pipe and the (average) temperature of the water in the pipe. In essence, the temperature of a node in the net can be calculated from the temperature of the .previous. node and the temperature-loss over the connecting pipe.

$$T_{end} = T_{begin} - \Delta T_{pipe} \tag{6.49}$$

Equations (6.45), (6.46) and (6.47) applies to every pipe, equation (6.48) applies to every node. Obviously, there needs to be a starting-point to the calculation. This starting-point needs to be a point that has a fixed temperature, hence the source of flow is used. There is however a disadvantage of this method. The method cannot calculate the temperature when the flow is zero, as this implies indefinite temperature-loss. In reality, when the flow is zero, the temperature on the end-node. would equal the environment-temperature.

It should be noted that wherever multiple flows come together in a node, a mixture of temperature occurs as the water with different temperature mixes. It is necessary to recalculate the temperature in these points using a balance of energy.

6.4.4.3. Other Features of PIPELAB

PIPELAB is a program which calculates the steady state solution of head and flow as well as the temperature in a district heating net. It is introduced because it is one of the first programs that is able to calculate in a net containing loops. It can also be used for calculations in a net for hot domestic water. PIPELAB is a rather extensive program, its code is separated in more than a hundred textfiles (procedures), totalling over 600 kB of information.

In this study the latest version of the program PIPELAB version 3.18 has been used with the kind permission of the Prof. Pall Valdimarsson who is the author of the program.

Chapter 7

OPTIMUM CONTROL OF BALÇOVA-NARLIDERE GDHS

7.1. Motivation for Studying Optimisation

There exist numerous variety of activities in the Balçova-Narlıdere GDHS which can usefully be described as systems, such as geothermal pipeline system, circulation pumps, well pumps etc. The efficient operation of these systems often requires an attempt at the optimisation of various indices which measure the performance of the system. Sometimes these indices are quantified and represented as algebraic values. Then values for these variables must be found which maximise the profit of the system and minimise loss. The variables are assumed to be dependent upon a number of factors. Some of these factors are often under the control, or partial control, of the analyst responsible for the performance of the system.

"The process of attempting to manage the limited resources of a system can usually be divided into six phases: 1) mathematical analysis of the system 2) construction of a mathematical model which reflects the important aspects of the system 3) Validation of the model 4) Manipulation of the model to produce an optimal solution to the model 5) Implementation of the optimum solution 6) the introduction of a strategy which monitors the performance of the system after implementation. It is with the fourth phase, the manipulation of the model, that the theory of optimisation is concerned. [28]" The first three phases of this management strategy were concluded in Chapter 6. Optimum operation of pumps and factors which measure the performance of the system will be defined in this chapter.

7.2. Optimisation of Well Pump Operations

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

In Balçova-Narlıdere GDHS, heat energy is produced from different production wells providing geothermal fluid in different temperatures and flow rates. In addition to geothermal fluid temperature and flow rate other properties such as drawdown, pump characteristics also vary for each well. These differences mean that cost of producing heat energy is different for each well.

In Balçova-Narlıdere well pumps are controlled by variable frequency drivers, which provide continuous control of flow. Capability of controlling flow by using frequency converters allow the operator to decrease production of geothermal fluid, when it is not needed, therefore significant amount of pumping energy can be saved. This feature also brings the problem of finding "the optimum well operating policy" to meet the energy demand of customers.

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

However, finding the optimum production policy providing minimum electricity consumption is not enough, since effects of the pump operations on the hydraulics of the geothermal pipeline system remain as an unanswered question. Therefore after obtaining the optimum policy, the result should be simulated in PIPELAB, and 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 well operating policy of the system, all possible combinations are calculated, then the best option is selected. Since there is no general solution for this kind of problem, program algorithm selecting the best possible option for the minimum power consumption was created in this study. Program uses dynamic programming approach to find the optimum solution. This program is connected to PIPELAB, therefore the best possible production option simulated, and effects of pumps on geothermal pipeline system were tested.

7.2.1. Dynamic Programming

The following definition of dynamic programming is based on Helmke (1994)

Dynamic programming is a method of optimisation that is applicable 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 finitestep approach of dynamic programming is an approximation of the calculus-of-variations method.

Dynamic programming can be applied if the problem has four features [30].

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.

Considering these four steps, the solution of well operation optimisation problem can be based on dynamic programming.

1. There is actually one problem, which is minimisation of power consumption while meeting heat demand. The problem can be divided into stages, i.e. each well constitutes a stage. These stages have different characteristics from each other.
2. Each well has finite number of flow options. For instance the flowrate of well ,whose maximum flow is 40 l/s, can range between 0 to 40 l/s with optional increments.
3. The amount of heat production from other wells have to be considered while deciding heat production rate of a well.
4. Optimal production strategy may not include the optimal production condition for each individual well. For instance maximum efficiency of well pump may be 70%, however at optimal production the well pump may work at 60% efficiency.

As can be seen from the definition of dynammic programming the operation of well pumps in Balçova-Narlıdere GDHS can be achieved with the help of dynamic programming.

7.2.2. Formulation of the Problem

By using frequency converters, it is possible get continuous flow between minimum to maximum flow for each well. Therefore, the amount of heat extracted from each well can be adjusted by operator. Heat energy obtained from well can be written as:

$$Q_{well} = m_{well} \cdot c_p \cdot (T_{well} - T_{return}) \tag{7.1}$$

In Balçova, 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:

$$P_{pump} = \frac{m_{well} \cdot g \cdot h_{pump}}{\eta_{pump} \cdot \eta_{motor} \cdot \eta_{VSD}} \quad (7.2)$$

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

$$P_{pump} = f(Q_{well}) \quad (7.3)$$

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

$$P_{total} = f_{BD2}(Q_{BD2}) + f_{BD3}(Q_{BD3}) + f_{BD4}(Q_{BD4}) + f_{BD5}(Q_{BD5}) + f_{BD7}(Q_{BD7}) + f_{B4}(Q_{B4}) + f_{B5}(Q_{B5}) + f_{10}(Q_{10}) \quad (7.4)$$

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

$$Q_{BD2} + Q_{BD3} + Q_{BD4} + Q_{BD5} + Q_{BD7} + Q_{B4} + Q_{B5} + Q_{B10} \geq Q_{demand} \quad (7.5)$$

The performance criterion, which is to be minimised, is

$$P_{total} = \min\left[\sum (f_{BD2}(Q_{BD2}) + f_{BD4}(Q_{BD4}) + f_{BD6}(Q_{BD6}) + f_{BD7}(Q_{BD7}) + f_{B4}(Q_{B4}) + f_{B5}(Q_{B5}) + f_{B10}(Q_{B10}) + f_{B11}(Q_{B11})\right] \quad (7.6)$$

Then the programme should satisfy (7.5) according to the criterion stated in the (7.6).

7.2.3. WELLOPT Program

For the operational optimisation of geothermal fluid production in Balçova-Narlıdere GDHS, the program called WELLOPT was designed. Earlier version of this program which was written in Turbo Pascal language was not user friendly. The latest version WELLOPT 1.0 was created by using Delphi compiler and it is much more user friendly. It has user interface, and it can be easily used by an operators. It is also possible to connect the program to the supervisory control and data acquisition (SCADA) system.

In addition to the operational optimisation of geothermal fluid production, WELLOPT also forecasts the heat load of the next day by using heat demand model of Balçova GDHS.

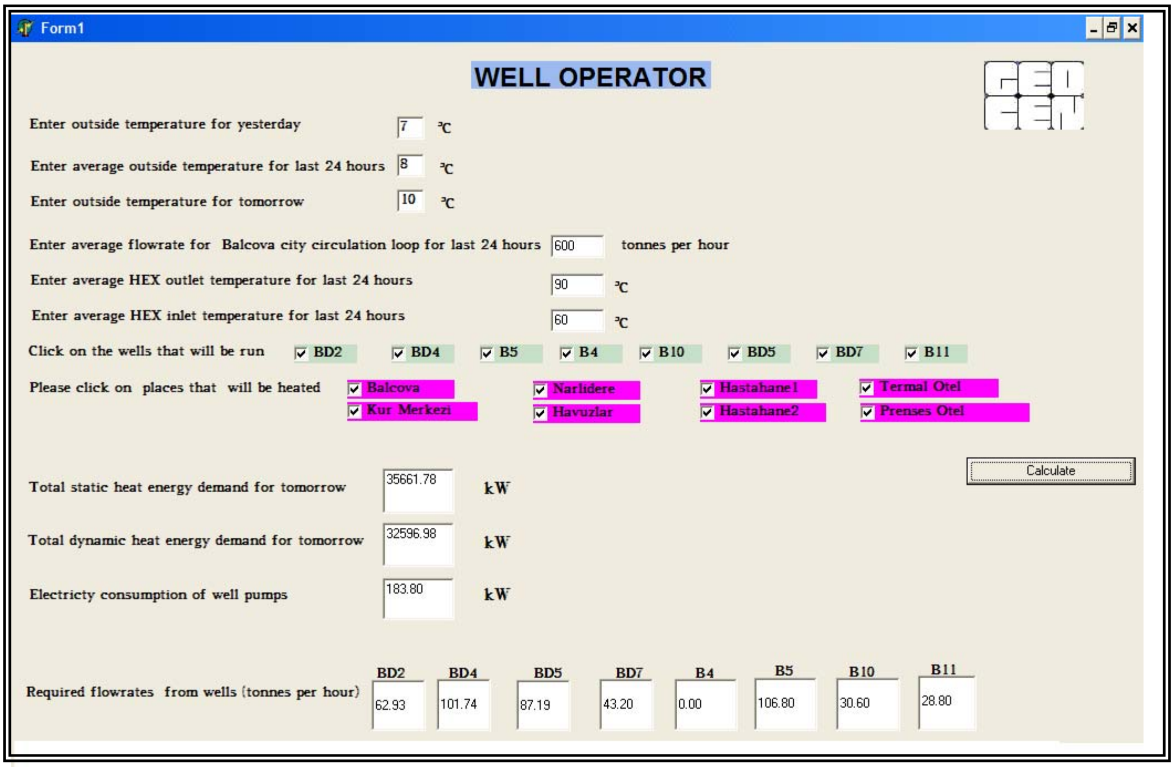

Figure 7.1: User interface screen of WELLOPT 1.0

7.3. Optimisation of Circulation Pump Operations

Circulation pumps are used to distribute hot water to the building heat exchangers and collect relatively cold water. In Balçova GDHS four parallel 160 kW centrifugal pumps are used to circulate water. Since these pumps are run all through the heating season, they constitute one of the biggest portions of the electricty consumptions in the system. Also in Narlıdere GDHS three parallel 15 kW centrifugal pumps exist to provide circulation.

Power consumptions of these circulation pumps were both calculated from actual data sets. Power consumptions for single pump, two pumps in parallel and three pumps in parallel were calculated. Since the fourth pump does't have variable speed control it has not been included in the calculations. Single pump is not enough for most of the times during heating season. However, capacity of two parallel pumps is enough for most of the times during heating season. As can be seen from Figure 7.2 operating three parallel pumps in parallel is more efficient than 2 parallel pumps.

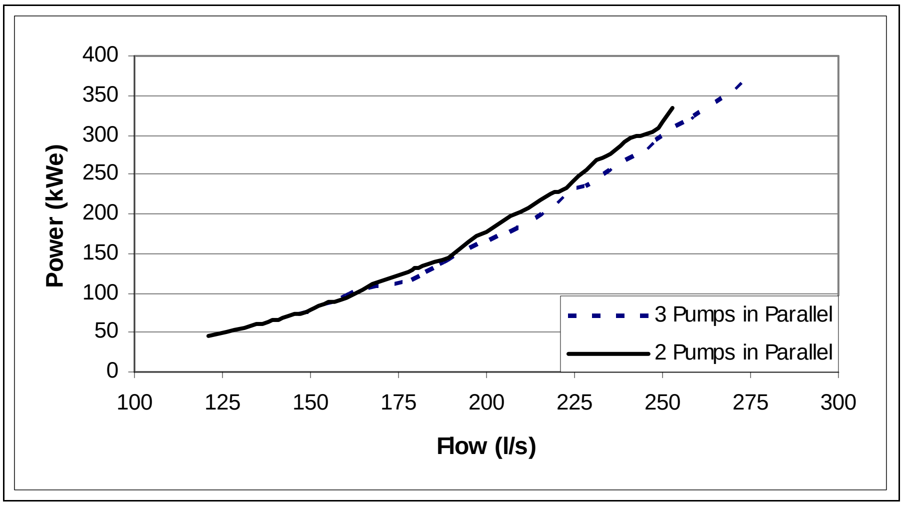

Figure 7.2: Comparison of Power Consumptions For the Circulation Pumps in Balçova GDHS

During summer time, 160 kW pumps are stopped and two 11 kW centrifugal pumps (Summer pumps) are operated in Balçova GDHS. For approximately 4 months these two pumps are operated continuously. Summer pumps don't have variable speed drives, therefore it is not possible to apply constant ΔT-variable flow rate principle. This situation causes excess power consumption in the system. For the efficient operation of the system summer pumps should be controlled with variable frequency drivers.

In Narlıdere GDHS three parallel pumps one of which serves as a back up are operated to provide the circulation of the hot water in the system. There is no variable frequency in Narlıdere GDHS. Installation of variable frequency drivers into the system can save significant amount of energy. Power consumption of Narlıdere GDHS was modelled by assuming that the pumps are controlled by variable frequency drivers and the results are presented in section 8.5.

7.4. Optimum Temperature Regimes

Geothermal district heating systems are operated according to constant temperature, variable flow regime. This is because of the fact that, geothermal district heating systems distribute water rather than energy since all cost is directly related to water usage rather than energy usage .One of the most important decisions for the effective operation of GDHSs is the selection of operating temperature differences in the system. Temperature of geothermal fluid changes for each geothermal area. Therefore sizes of the radiators in buildings differ for each geothermal district heating system. In districts where old buildings exist, it is almost impossible to fix standard temperature regime for all buildings, since in most of the buildings heating systems were designed for conventional heat sources. This problem has been partly overcome by using temperature regulating valves in each building. The ideal solution for this problem is to change the heating systems of all buildings according to geothermal heating standards.

Balçova-Narlıdere GDHS has been both connected to old part of the town and newer part of the town. The problem of unstable temperature regime does exist in Balçova geothermal district heating system. As a result of this problem customer satisfaction decreases while operating cost of the system increases. The temperature regulating valves are not as effective as expected in the control of temperature regimes in Balçova-Narlıdere GDHS. According to the experiences in Balçova-Narlıdere GDHS the temperature regime of the Balçova GDHS is 115 C – 65 ^{o}C for the geothermal site and 90 – 60 ^{o}C for the city distribution site of the heat exchanger. Although system was first designed for 90 – 42 ^{o}C temperature regime for the city distribution network, it has never been realized. 90 – 60 ^{o}C temperature regime (ΔT=30) is actually very inefficient temperature regime for the geothermal district heating systems. However, if return temperature decreases below 60 ^{o}C, customer complaints begin.

Figure 7.2 shows the variation of the temperature difference between inlet and outlet of the heat exchanger (city distribution site) for the year of 2002. It can be seen from the graph, although the system should be operated with constant ΔT, it has not been. The data set is interrupted between the 170th and 194th days. However, the graph definetely shows the improper operation of the system. The operational ΔT during summer time decreases down to 5-10 ^{o}C, which causes poor energy economy. The main reason of this low ΔT is that the summer pumps don't have variable frequency drive control.

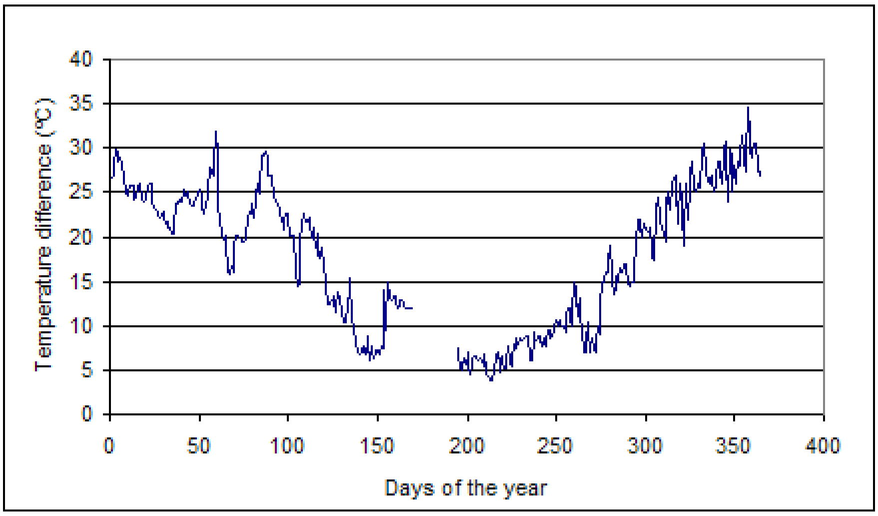

Figure 7.3: Variation of temperature of difference between inlet and outlet of the heat exchanger – city distribution

The main reason of ΔT variation is the unbalanced hyrdraulics of the pipeline. Especially during summer times, the heat demand is limited with the domestic hot water needs of the customers. However, because of the leakages in the system the amount of water that should be pumped into the system is more than the need of the customers. Also, one of the reasons of this variation is unconsciousness of the operator.

The improvement studies on the system have been started on December 2002 and nowadays operators are aware of the problem. As a result of these studies the most suitable temperature regime for the Balçova GDHS have been determined as 90 – 60 ^{o}C. It should be stressed here that the system was first designed according to 90 – 42 ^{o}C temperature regime. This big deviation between design value and operation value is one of the main obstacles in the front of energy economy efforts.

The problem of ΔT variation can be prevented during design phase of the systems. In the design phase of geothermal district heating systems, the old heating systems of the buildings in the area should be investigated in detail. Although it means additional cost, the heating systems of the buildings should be modified before connecting to geothermal district heating system.

7.5. Decisive Factors

As a result of power consumption analysis in the system two factors "*Conventional Energy Ratio* (CER)" and "*Conventional Energy Excess Ratio* (CEER)" have been defined. These factors provide the comparison of geothermal heating systems in terms of performance and define criterion for the success of the control.

Conventional Energy Ratio (CER) is defined as a ratio of produced heat to the consumed electricty. Conventional Excess Energy Ratio (CEER) is a ratio of the actual electricty consumption to the minimum possible electricity consumption that is used to meet the heat load of the system. If the system is operated according to the optimum operational control strategy, the CEER will be equal to 1. However, geothermal district heating systems are huge systems and spread over large areas. It is imposibble to forecast and control system behaviour exactly. For instance, the dynamic behaviour of well characteristics and dynamic heat load of the system can not be forecasted exactly. Therefore, to meet the heat demand of the system without loosing thermal comfort conditions excess heat energy is given to the system. It is for sure that CEER will be bigger than 1 for all systems.

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

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

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

$$\text{CEER} = \frac{\text{Actual electricity consumtion}}{\text{Optimum electricity consumption}} \tag{7.7}$$

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

$$\text{CER} = \frac{\text{Produced heat energy}}{\text{Consumed electricity}} \quad (\text{kW}_t/\text{kW}_e) \tag{7.8}$$

The CER and CEER factors has been calculated, from the hourly data of 2001 and 2002 years. Results are presented in the section 8.6.

Chapter 8

RESULTS AND DISCUSSION

8.1 Heat Demand Forecasting For Balçova GDHS

In the modelling studies of heat demand, 2001-2002 heating season data sets were used as training data. The relation between ambient temperature and heat given to the system was used in the time series analysis of heat demand. Figure 8.1 shows the hourly data of heat given to the Balçova GDHS versus ambient temperature relation for the heating season of 2001-2002. Heat given to the system was calculated from flow rate and inlet and outlet temperature difference of heat exchangers.

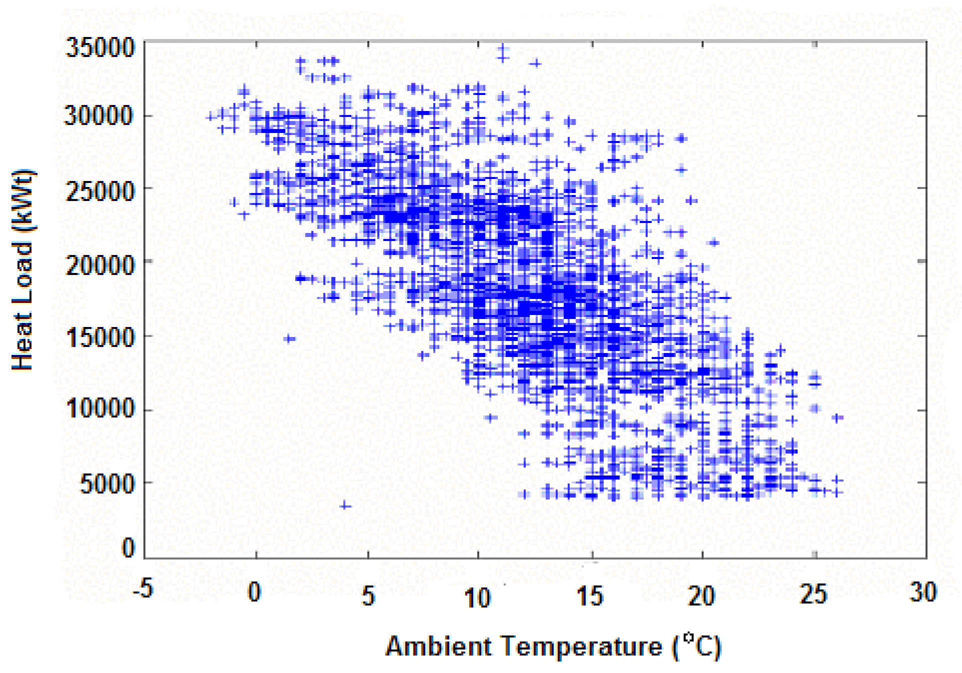

Figure 8.1: Heat Load vs. Ambient Temperature Relation in Balçova GDHS for the Heating Season of 2001-2002 [26]

Model has been tested on two separate data sets. The first data set belongs to heating season of 2001-2002, from which model has been derived. In Figure 8.2, estimated heat loads are shown by dots while variation of real load is given by continuous curve. It should be noted that, while deriving model, only the data of 2001-2002 heating session is used. Therefore, success of model can be checked by using another data set and comparing the actual values with the model results. In Figure 8.3, measurements of 2000-2001 heating season were used. Estimated heat load is shown by dots and real heat load is shown by continuous curve in Figure 8.3. As can bee seen from the figure, results of the prediction model and actual heat load variation fit each other. Comparison of results shows that use of a prediction model to predict the head load demand of next day can give rather close estimation of the actual value.

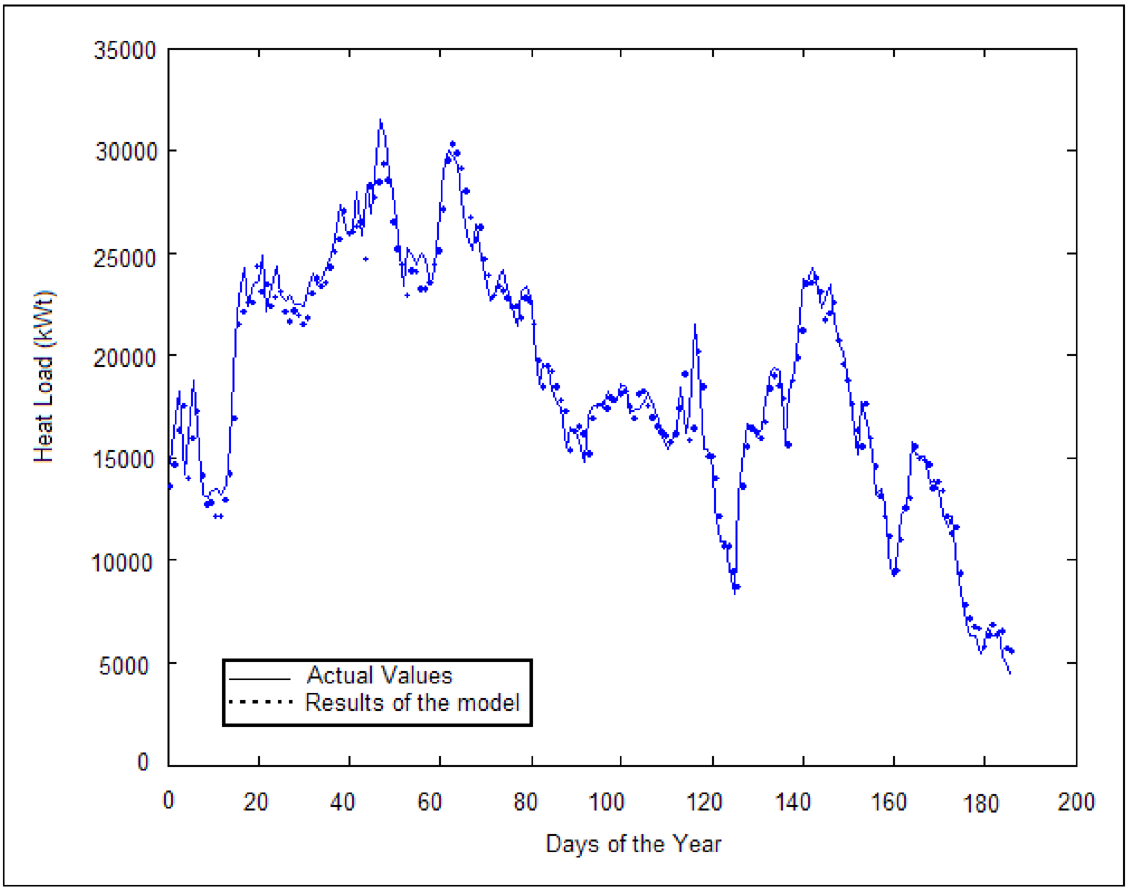

Figure 8.2: Comparison of Actual Heat Load with Forecasts (2001- 2002 Heating Season) [26]

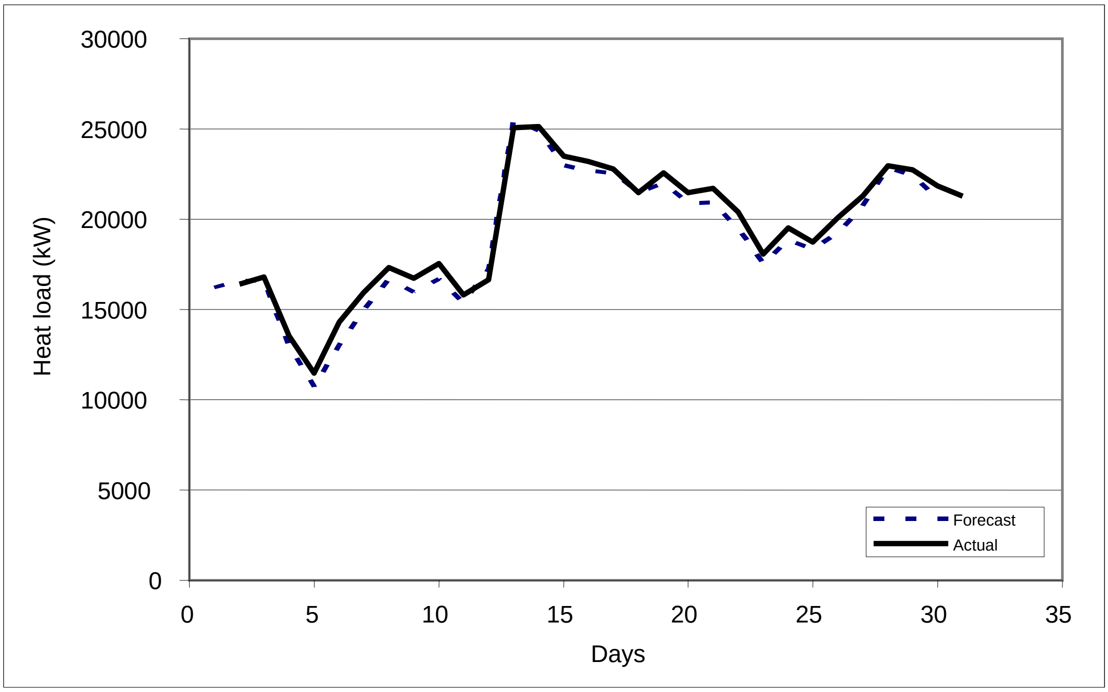

Figure 8.3: Comparison of Actual Heat Load with Forecast (2000-2001 Heating Season) [26]

Figures 8.2 and 8.3 derived from the data sets; however in 2002-2003 heating season Balçova GDHS has been operated by considering heat load estimation model. From the 28th of February to 20th of March flow rate of the Balçova city distribution network has been adjusted according to heat demand forecast. Ambient temperature forecasts have been taken from the web site of Office of Meteorology. During this period one of the circulation pumps broke down. This unexpected malfunction disturbed the forecast process slightly. The results are shown in Figure 8.4. It should be noted that the model was updated everyday with actual values.

During this period, the flow rate of the city distribution network has been decreased to below predicted values to check the operational limits of the system. It was detected that the customer complaints increase in significant amount, if flow rate decreased more than the predicted value. Therefore it can be said that during this period system was operated at the operational limits.

As a result close prediction of heat load for the next day and operation according to this prediction have been achieved in Balçova GDHS.

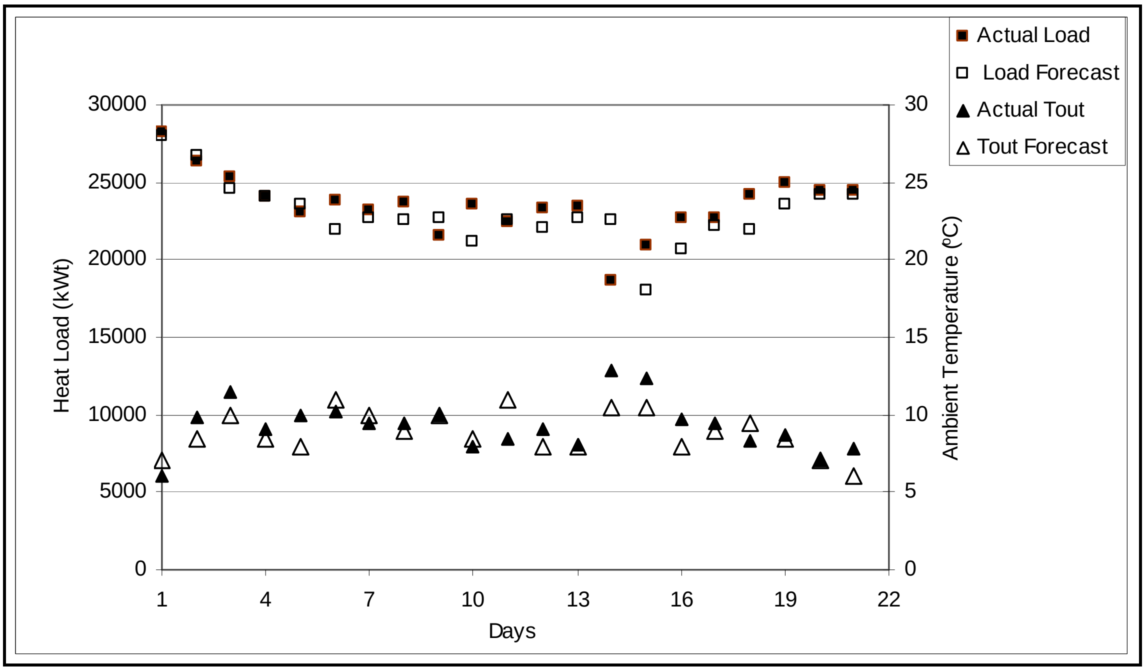

Figure 8.4: Heat Load Model Based Operation in Balçova GDHS

8.2 Power Consumption of Well Pumps in the System

Different from other pumping operations in geothermal well pumping the amount of heat extracted is more important than the amount of fluid pumped from the well. Since the temperature of the geothermal fluid change for each well, flow rate versus power consumption relation does not provide complete information about the efficiency of wells. Therefore, while modelling geothermal well pumps, it is reasonable to state the relation between heat production and energy consumption of wells.

Frequency drivers and flow meters were used to find the actual pumping power. It is possible to read power consumption of pumps from the display of the frequency driver. If the geothermal fluid flow, temperature, and power consumption of each pump are known it will be possible to derive actual power consumption models for each well pump. Pumping power model of each well can also be derived theoretically if pump and system characteristics are known. In Figures 8.5, 8.6 and 8.7 actual and theoretical power consumption versus heat production relations for BD4, B5 and BD7 are shown. In this study optimisation of geothermal fluid production is based on actual relation between power consumption and heat production. However, the flow meter of BD5 and frequency driver of B10 has not been working properly and theoretical values have been considered in coordination with the actual values only for these two wells.

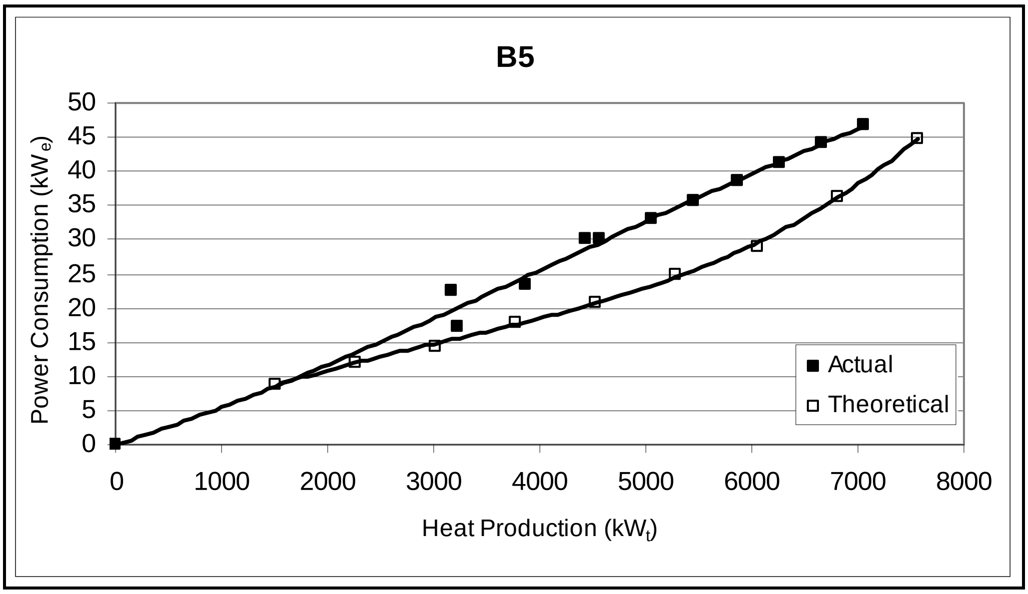

Figure 8.5: Power consumption vs. heat production relation for well B5

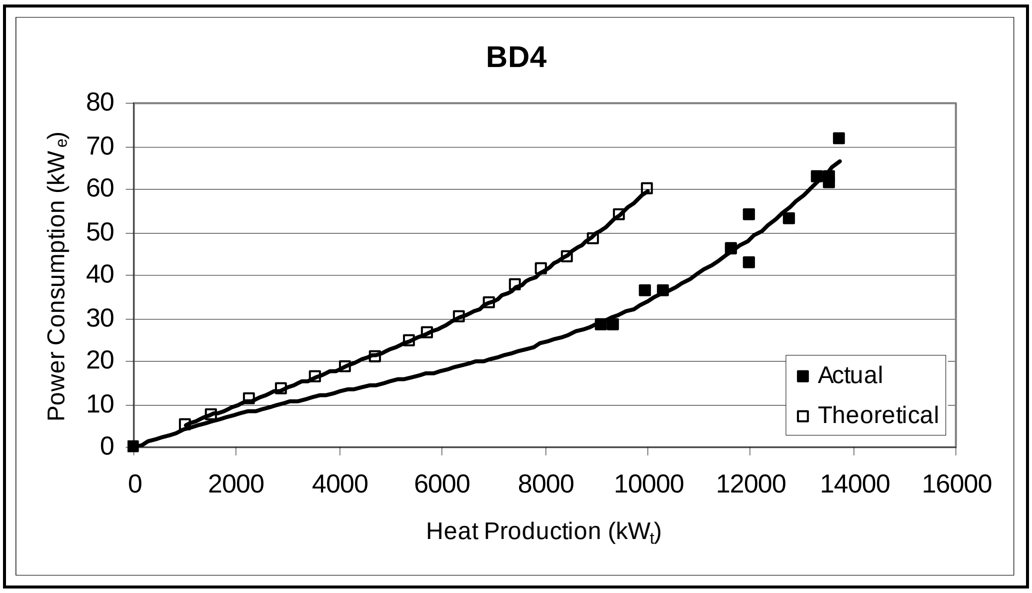

Figure 8.6: Power consumption vs. heat production relation for well BD4

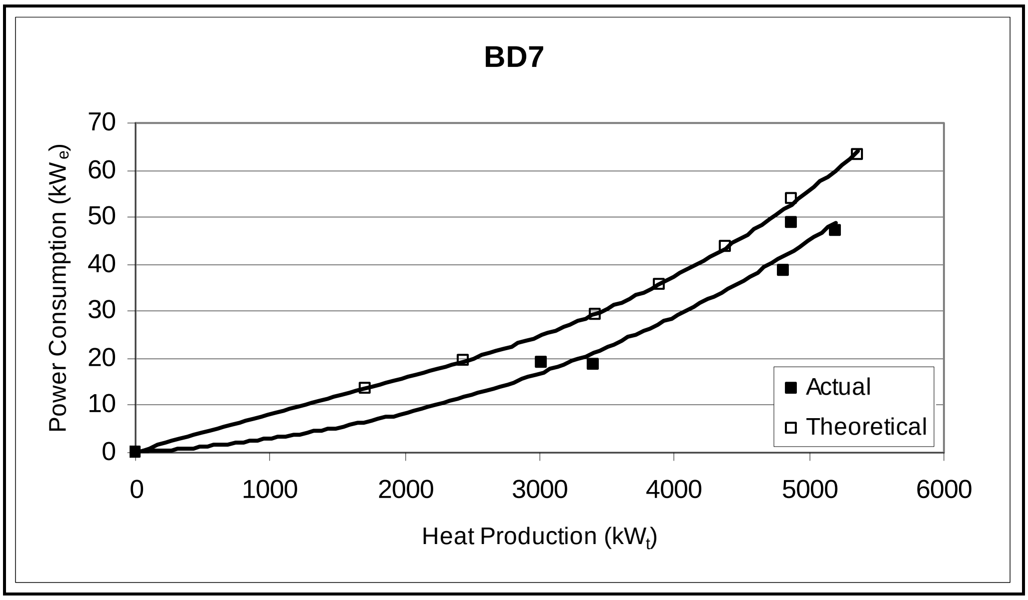

Figure 8.7: Power consumption vs. heat production relation for well BD7

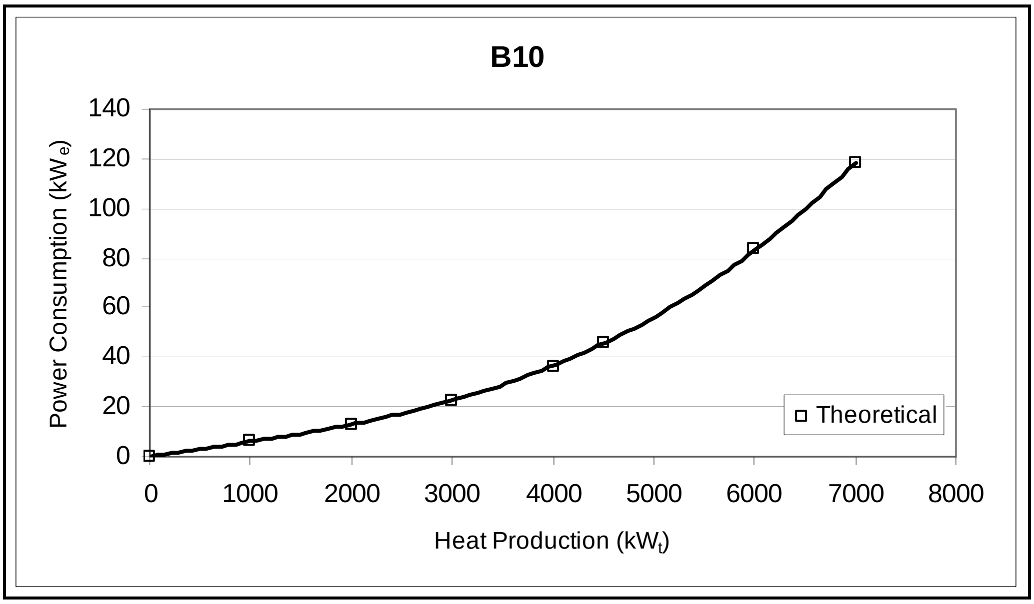

Figure 8.8: Power consumption vs. heat production relation for well B10

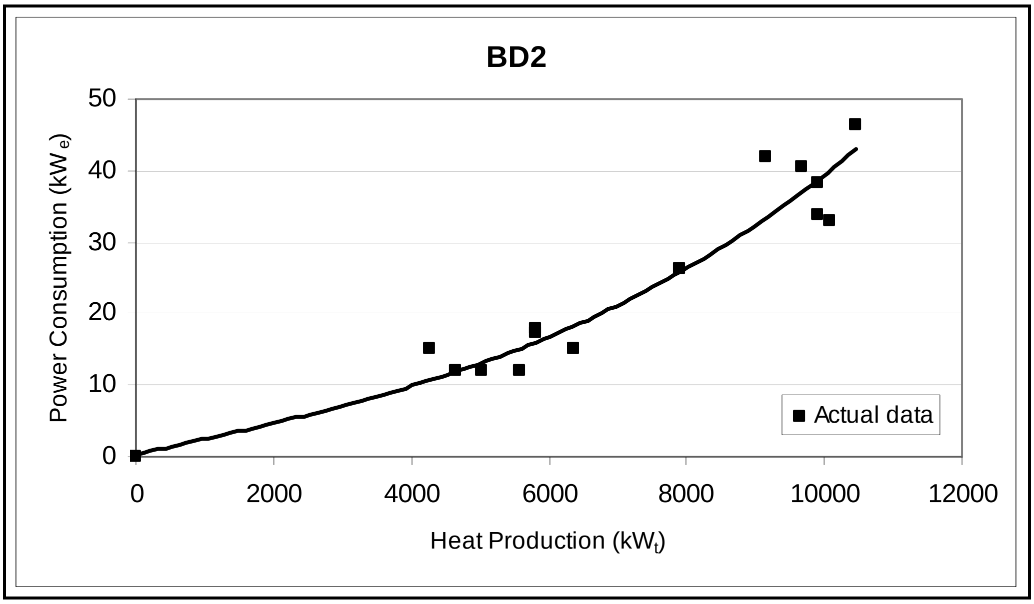

Figure 8.9: Power consumption vs. heat production relation for well BD2

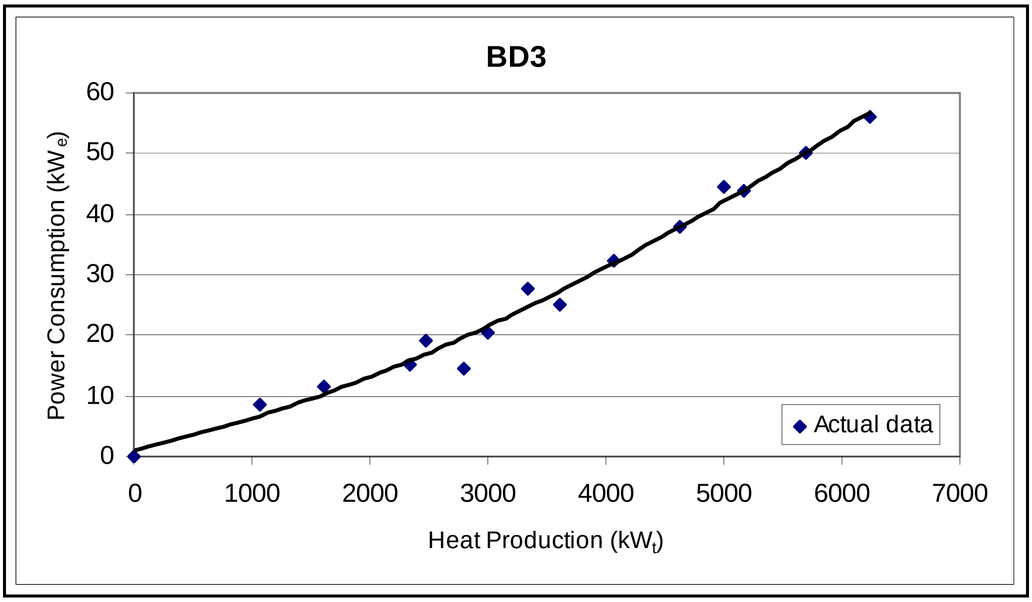

Figure 8.10: Power consumption vs. heat production relation for well BD3

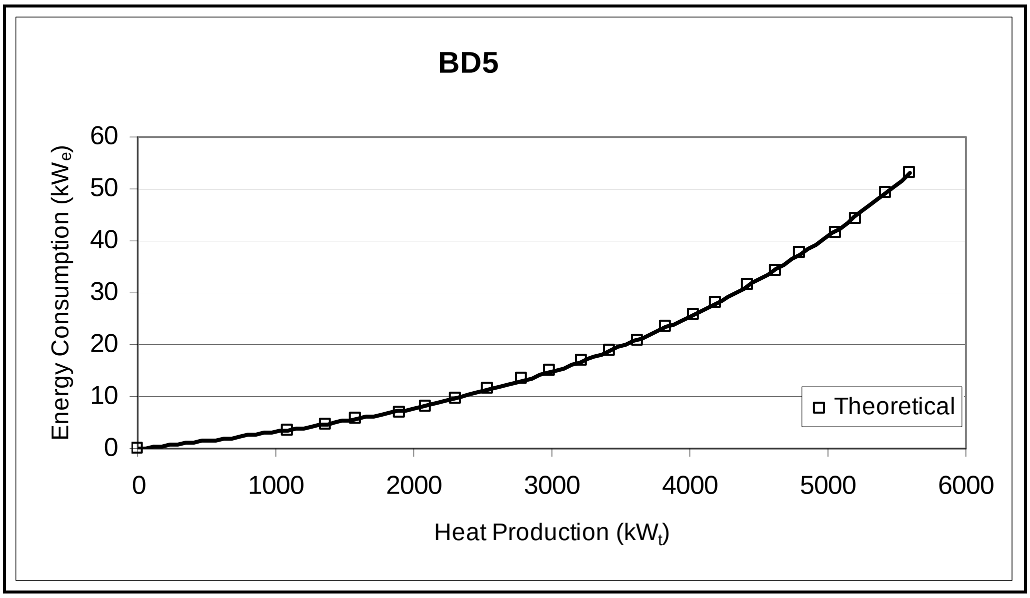

Figure 8.11: Power consumption vs. heat production relation for well BD5

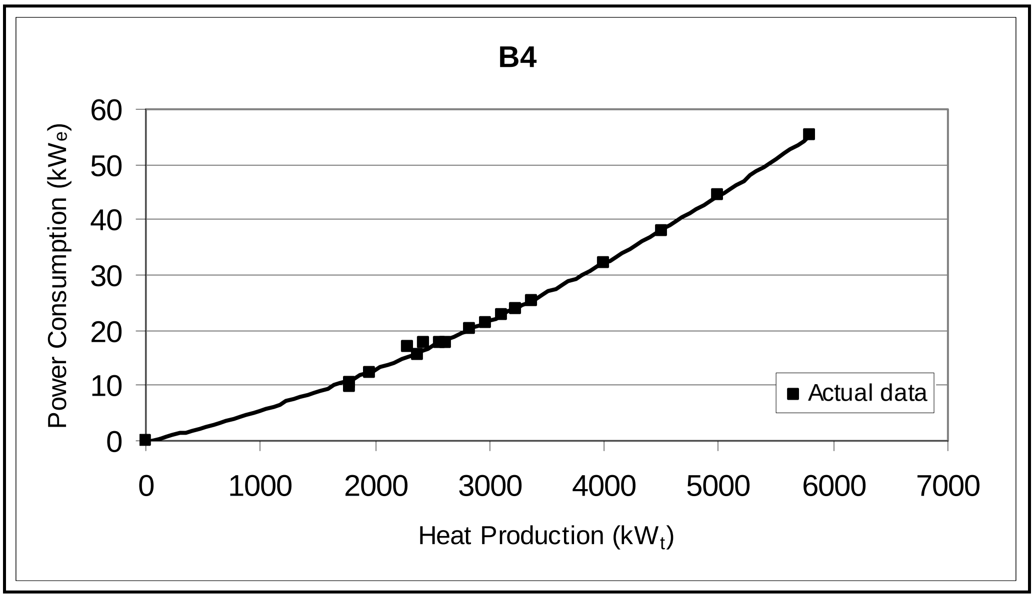

Figure 8.12: Power consumption vs. heat production relation for well B4

8.3 Optimum Operation of Wells in Balçova-Narlıdere GDHS

In these section results of the WELLOPT program is presented. The energy consumption rates in Table 8.1 are the minimum values to meet corresponding heat demands. Therefore Table 8.1 shows the best geothermal fluid production policy for different heat loads. Although there are always numbers of unforeseen reasons (motor, frequency converter or pump failures; repairs in the system) which prevents the selection of the optimum operational policy. The table bellow gives the very clear idea to the operator to run the system in a most efficient way.

Table 8.1: Well operation policy for different heat loads

Power cons. (kWe)	Heat production (kWth)	Total flow (kg/s)	Flow (kg/s)							
			BD2	BD3	BD4	BD5	BD7	B4	B5	B10
317	50,000	210	36.0	29.0	45.0	16.7	17.0	14.0	28.0	23.0
261	45,000	181	36.0	18.7	45.0	16.7	12.0	7.7	28.0	22.8
209	40,000	168	36.0	18.7	32.3	16.7	12.0	7.7	28.0	15.7
164	35,000	151	36.0	8.0	32.3	11.3	12.0	7.7	20.3	15.7
130	30,000	122	36.0	8.0	32.3	11.3	7.0	4.5	12.7	0
98	25,000	106	22.0	0	32.3	11.3	12.0	4.5	12.67	0
71	20,000	88	22.0	0	32.3	0	7.0	4.5	5.0	0
47	15,000	70	22.0	0	19.7	0	7.0	4.5	0	0
31	10,000	55	8.0	0	19.7	0	7.0	0	0	0

Among thousands of options the program selects the best option and ranks other options according to the their energy consumption rates. Each option suggests different operational policy to meet the heat demand. As stated before sometimes selection of the best policy may not be suitable. Then operator should select second policy. Table 8.2 shows power consumption of certain operational options to meet the heat demand of 40,000 kW_t.

Table 8.2: Power consumptions for different operational options to meet the heat demand of 40,000 kW_t

Power Consumption rank	Power consumption (kW_e)	Heat production (kW_t)
1	209	40221
5	212	40129
10	214	40758
15	215	40475
40	218	40037
75	221	40229
100	222	40471

The data taken from actual well operations was compared with the results of the WELLOPT program in Table 8.3. Comparison shows that significant amount of energy can be saved, if the system are operated according to the results of the program. The implementation of this program is only possible, if all wells and well pumps are monitored and controlled from one command centre. Since the input parameters of the program should be updated continuously and the results should be applied to the system immediately.

Table 8.3: Comparison of energy consumptions for actual and optimum well production policies

Date	**Heat production (kWh_t)**	**Actual power consumption of well pumps (kWh_e)**	**Optimum power consumption of well pumps (kWh_e)**	**Possible energy economy (kWh_e)**
03.11.2002	492739.20	2671.20	1737.60	933.60
16.11.2002	491025.60	2748.00	1699.20	1048.80
10.01.2003	658641.60	3475.20	2724.00	751.20
15.01.2003	829867.20	4824.00	3861.60	962.40
01.02.2003	822290.40	4380.00	3844.80	535.20

8.4 Modelling of Distribution Network in Balçova GDHS

In the PIPELAB district heating simulation program, Balçova GDHS distribution network has been modelled. During modelling, necessary information of the system was provided by the Balçova Geothermal Company. It is assumed that the hot water is delivered to all buildings in a sufficient amount, to meet their energy requirements. While modelling the system, it is divided into two parts, as supply and return networks. In Figure 8.13, combined head loss versus distance from the head source diagram, which is obtained from PIPELAB for a flow rate of 300 l/s is shown for the supply and return network. The approximate capacity of flow for three circulation pumps is about 300 l/s. As can be seen from the Figure 8.13 at the end of the critical path where the maximum pressure drop occurs, there is 5 m pressure difference between supply and return. Reason of this difference is the pressure drop at the heat exchanger and flow regulator.

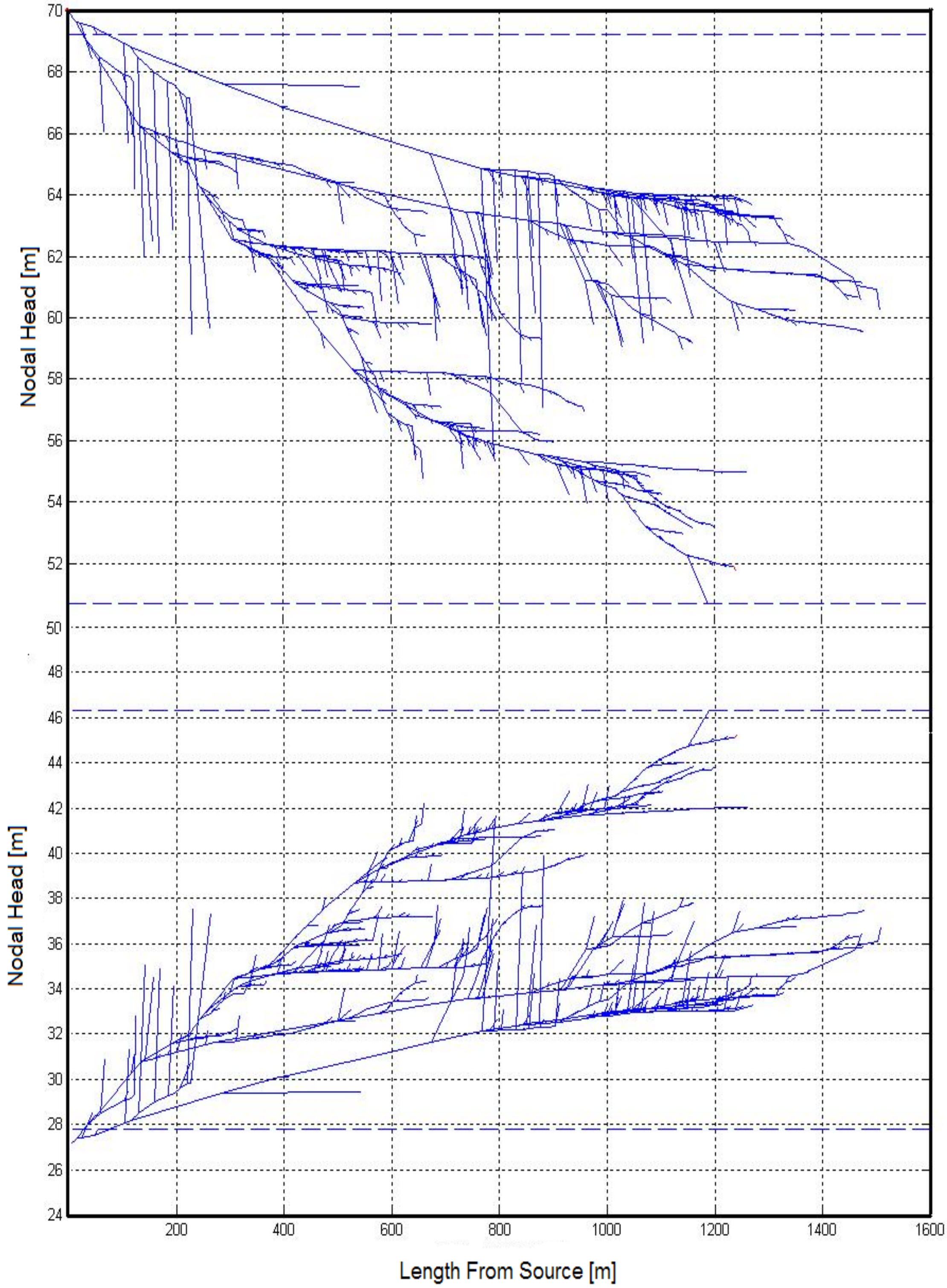

Figure 8.13: Head Loss Diagram for the Balçova GDHS Distribution Network

The maximum head loss along the pipes of the distribution system is 43 m for the maximum flow rate (Fig.8.13). The distribution system has been simulated in PIPELAB for the wide range of flow demands and, system loss curve for the critical path has been obtained. It should be stressed that, these head loss diagram does not include the head losses in the pumping station, only the pressure losses in the distribution system have been included. In other words, only the pressure loss of the distribution system has been found from the program. Figure 8.14 is head loss characteristic curve for the critical path of the Balçova GDHS city distribution network.

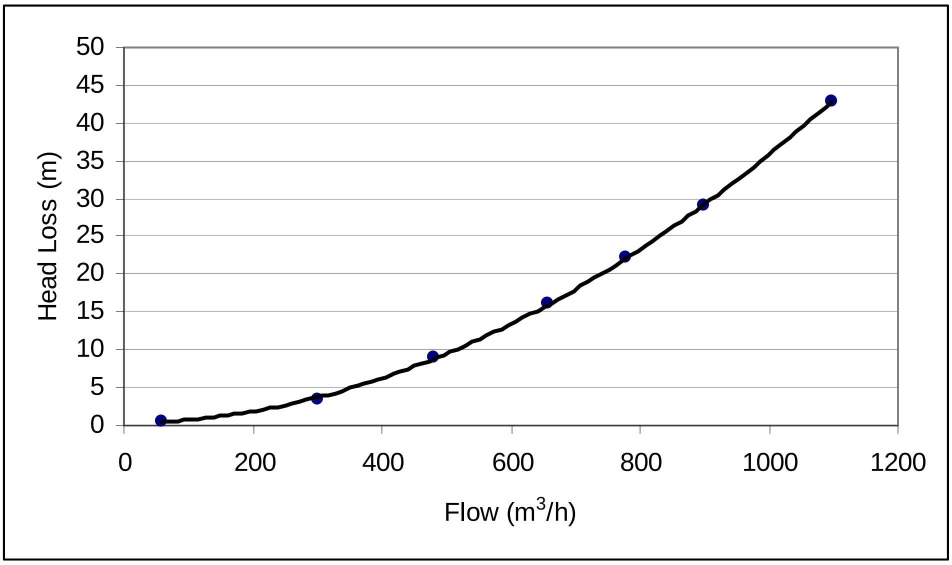

Figure 8.14: Head Loss Characteristic Curve for the Critical Path of Balçova GDHS (Pumping station losses are not included)

Figure 8.14 contains one of the most critical informations for the proper operation of the system. It shows the minimum amount of head to circulate the water in the system. In Figure 8.15 basic scheme of Balçova GDHS is shown. To provide the circulation at any flow rate in the network, minimum head at the point 1, shown in the Figure 8.15 should be equal to corresponding head loss shown in the Figure 8.14. The pressure at point 1 (Fig. 8.15) is called “operating pressure” by operators in Balçova GDHS and it is one of the most important inputs for the operation of the system.

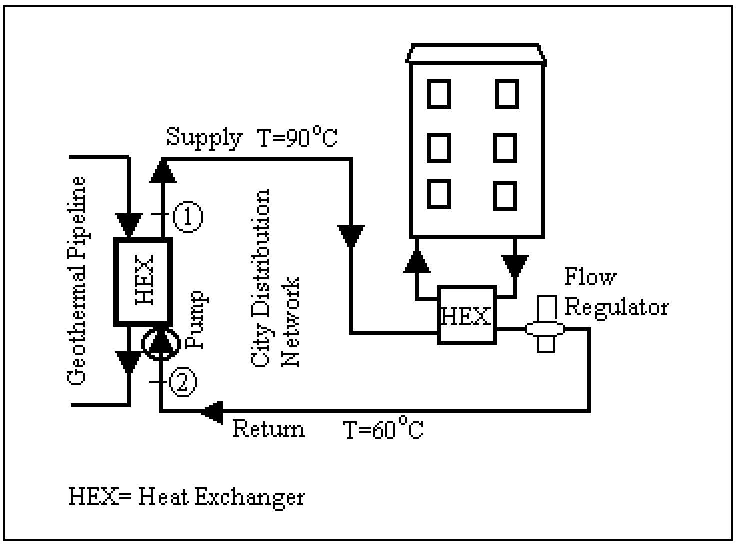

Figure 8.15: Basic Scheme of Balçova GDHS

As stated before, pressure measurements are done at points 1 and 2 in the city distribution loop. These locations are points 1 and 2, which are shown on Figure 8.15. It is possible to find variation of pressure difference with flow rate between 1 and 2 (In Figure 8.15) by using pressure data sets. In Figure 8.16 actual pressure differences for the heating season of 2001-2002 is shown by dots, and to compare the actual data, with the simulation results, system characteristic curve obtained from simulation (Figure 8.14), is given by continuous curve in Figure 8.16. It can be seen from the Figure that the results of the PIPELAB program fits the actual data set. The water pressure at point 1 (Figure 8.15), should be at sufficient amount to provide the circulation of water until point 2 (Figure 8.15).

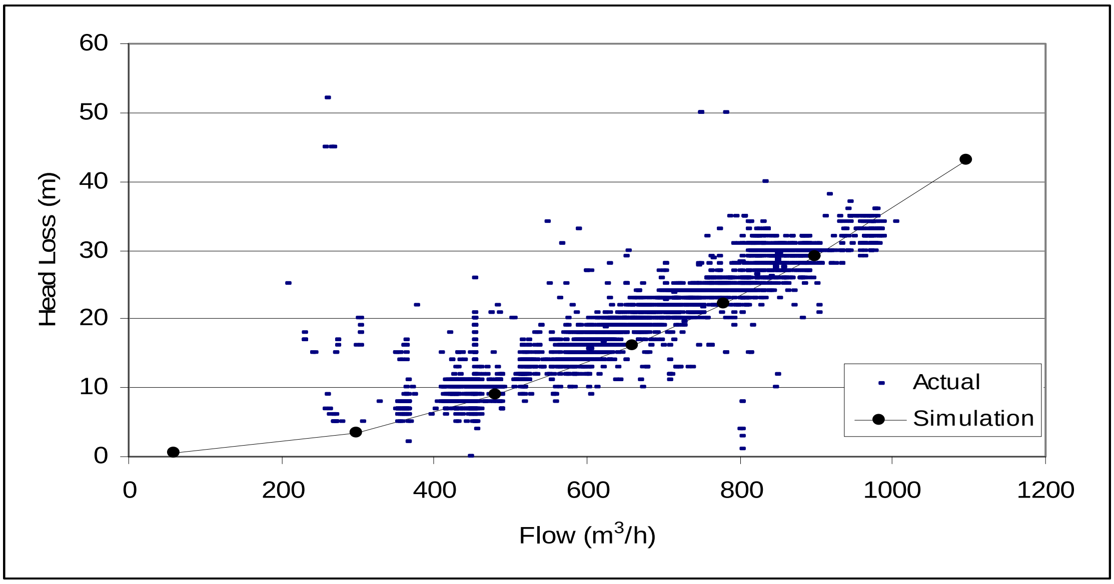

Figure 8.16: Comparison of Actual Pressure Difference with Simulation Results

Figure 8.14 shows only the distribution network pressure loss, however Figure 8.17 shows the entire pressure loss of the system. It includes pumping station losses (heat exchager, pump suction and collectors). It is derived by considering results of the PIPELAB program and then calibrated by using the pressure and flow rate data sets.

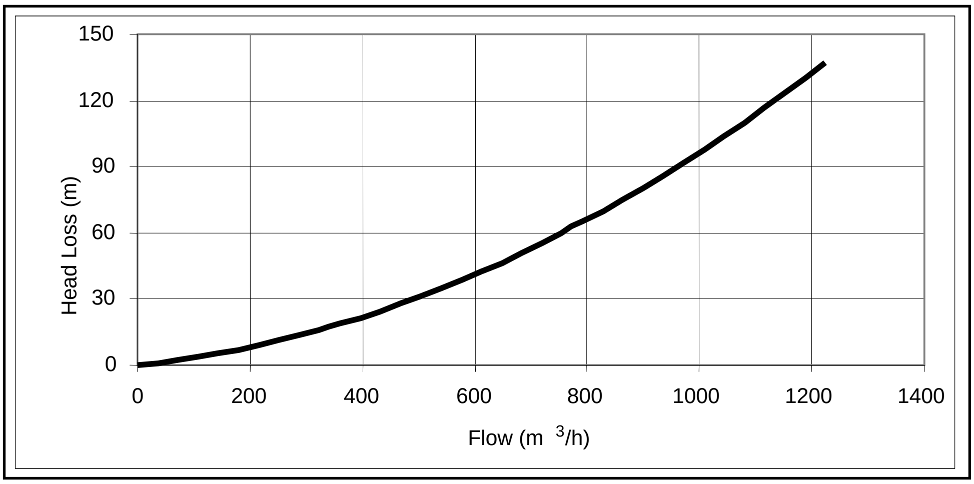

Figure 8.17: Pressure Loss Curve for Balçova GDSH Distribution Network (All losses are included)

Temperature distribution along the supply part of distribution network is shown in Figure 8.18. It is almost impossible to get exact heat transfer coefficient values for all pipes in the network since, the system is 8 years old and external corrosion damaged the pipe insulations. In this study, heat transfer coefficients of pipes in the system are based on catalog values of the steel pipes. The heat transfer coefficients then calibrated by considering measurements done on the system. Figure 8.18 should not be considered as an exact temperature distribution along the pipeline. It is useful tool to see temperature decrease trends along the pipeline.

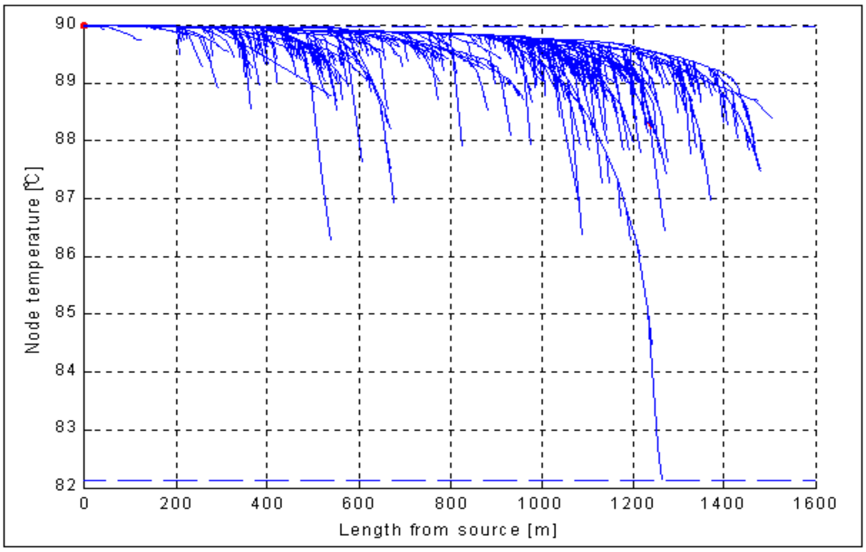

Figure 8.18: Temperature Distribution Along the Supply Network in Balçova GDHS

8.4.1 Problems of Distribution Network

During peak demand times certain parts of the system cannot get sufficient heat. These buildings are shown by dots in the Figure 8.19. Although heating problems seem to occur mostly in one region (I and II), it will be wise to investigate these parts according to their branching structures.

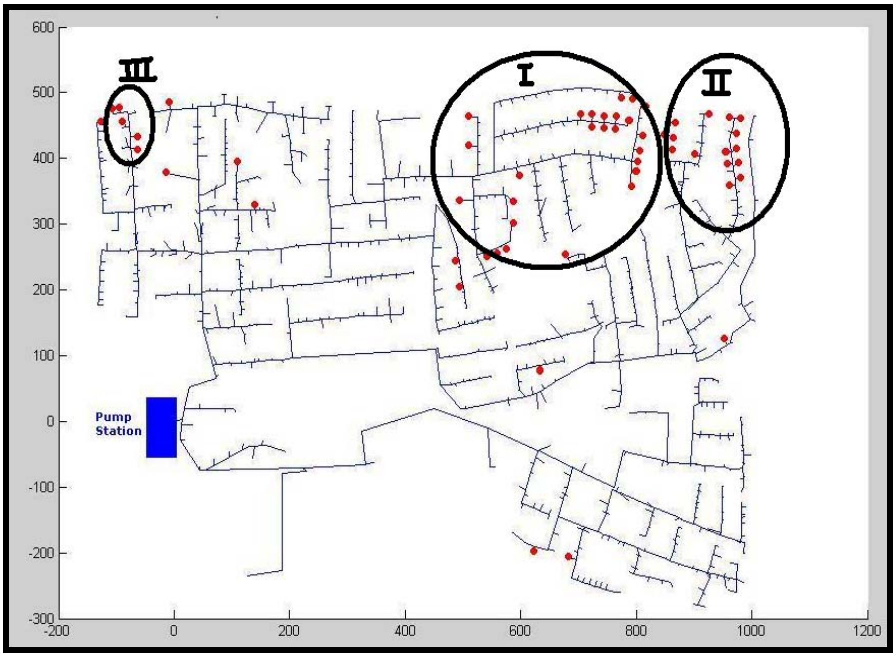

Figure 8.19: Buildings with Heating Problem

As shown on Figure 8.19, there are three main regions where the heating problems occur. These three regions constitute the 80% of the heating problems in the system. Among these three regions, region I (İş Bankası Houses) contains most of the buildings with a heating problem.

In Figure 8.20 these three branches, which are highlighted and taken into circle, are shown in the H vs. L diagram of supply network. As can be seen from the diagram region I, which is the most problematic part of the system, has the highest pressure drop in the network. Also, as shown in Figure 8.21, the largest temperature drop in the network belongs to one of the branches of region 1.

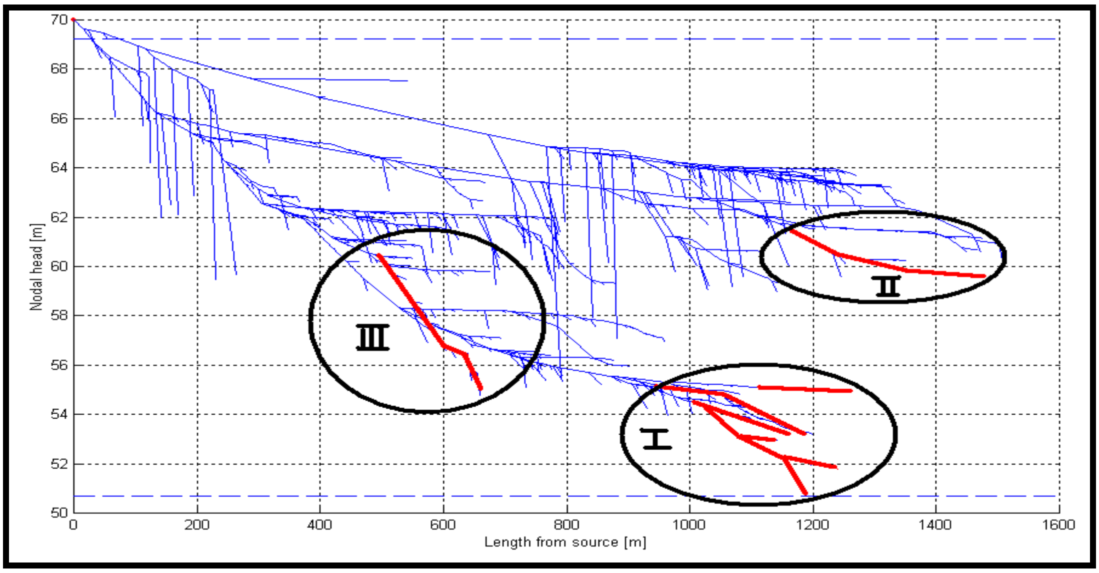

Figure 8.20: Presentation of regions with heating problem in h-l diagram of supply network

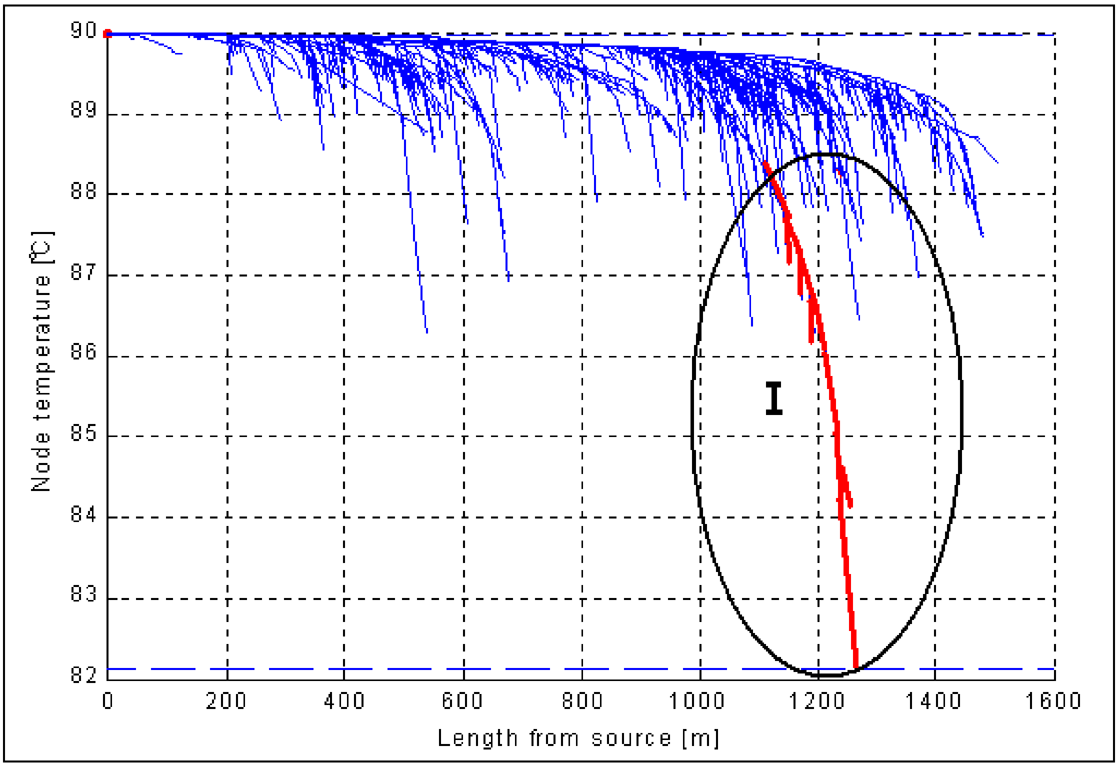

Figure: 8.21: Presentation of regions with heating problem in T-l diagram of supply network

Although region I and region II are located close to each other, they belong to different branches of the system and different from 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 highest distance to the pumping station

In Figure 8.20 there is steep pressure decrease for the region III. It is because of high speed of water at that part of the network. High-speed flow generally occurs at undersized distribution branches.

8.4.2 Possible Sources of the Problems

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 closer to the 0 °C which is the design temperature for Izmir City, customers living in the region I start to complain about heating service.

From temperature and head loss diagrams, it is seen that this region has the highest temperature and pressure drop in the system. Therefore, if there is low-pressure problem in the system, region I will be affected by it at the first place.

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 (2002), customer complaints, modelling studies, and field measurements obtained through routine checks can indicate that a portion of the system is experiencing low pressure. The pressure problem can be verified by connecting a pressure gage equipped with data logging device or chart recorder to a system continuously record pressure. Occasionally, a customer may report a low-pressure problem, but 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 flow regulators in Balçova GDHS have not been functioning properly. Flow regulators are very sensitive to quality of water. Because of a scaling, flow regulators are locked and can not respond to temperature and pressure changes in the system. If the flow regulator is locked while it is closed, heating problem occurs only at that connection.This problem is easy to overcome since the problem can easily be determined and fixed. However, flow regulator can also be locked while it is open. If flow regulator is locked while it is open, it will not respond any temperature and pressure changes and excess flow through the regulator will pass. If excess flow is experienced at the buildings where pumping station is closer, at the end points of the network system the buildings will experience insufficient flow. This problem is one of the characteristic problems of Balçova-Narlıdere GDHS and it can be best seen in regions I and II.

Huge amount of leakage from the distribution network is also one of the causes of unbalanced hydraulics in the system. It is very hard to determine the leakage points, since the leaking water can only be seen at the insulation joints, and the actual crack may be tens of meters away from the insulation joint.

Leakage also affects the operating pressure of the network. As stated before, to provide the circulation the pressure at point 1 (Fig. 8.15) must be above the critical value. However, because of the leakage it is not possible to keep constant pressure without help of hydrafor in the system. Until 2002-2003 heating season the operating pressure was 50 meters in the system which was not enough, in 2002-2003 the results of this study was considered and the operating pressure was increased to 55 meters with the help of hydrafor. This adjustment solved the part of the problems and the customer complaints decreased. However, it should be noted that the usage of hydrafor pumps increases the electricity consumption in the system.

Steep temperature decrease in the system is the indication of insufficient flow rate (slow speed of fluid). Leakage and insufficient flow rate are also the sources of this problem. Note that the region I where the highest temperature drop is observed is one of the end points of the system.

It should be stressed that**,** the results of simulation changes according to roughness values and heat loss coefficients of pipes. In Figure 8.22, variation of maximum temperature drop in the system compared for the good insulation and bad insulation. It is obvious that temperature drop changes significantly according to insulation quality. However, the trend of temperature decrease 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 excess temperature drop problem in the system region I is at the first place to be affected by this problem. It should also be considered that customer complaints have been reported from buildings, which are located at the end of highest temperature drop branch. Also close investigation of Figures 8.20, 8.21 will give the result of obvious existence of high temperature drop in this branch. Therefore, with the actual temperature measurements taken from system, heat loss coefficients used in the model should be calibrated and the possible solution methods discussed in this study should be reconsidered.

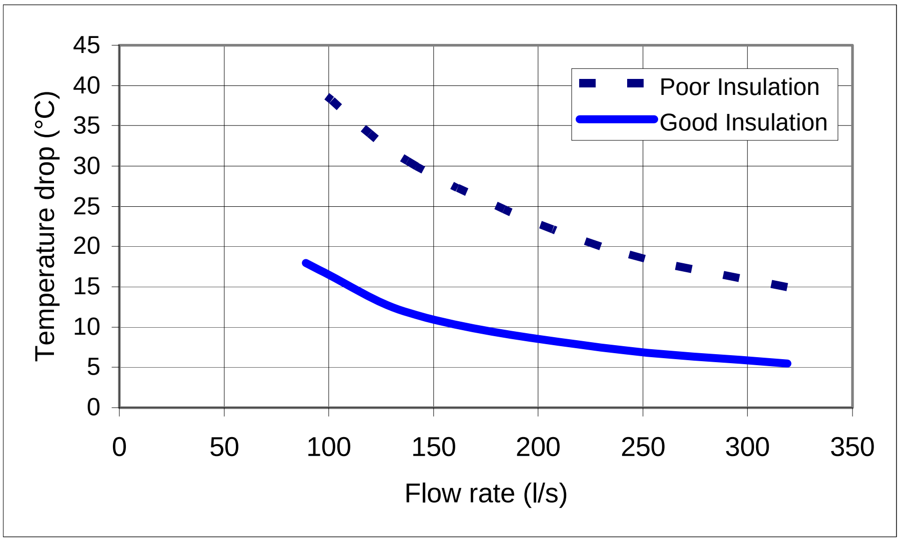

Figure 8.22: Variation of Maximum Temperature Drop with Flow

In Figure 8.20, region III has high-pressure loss gradient. Main reason of high-pressure gradient is high speed of flow in this branch. This kind of problems occurs at undersized distribution networks.

An undersized distribution network problem is not easy to identify during 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

To see the effect of diameter change on region III, diameters of pipes, which are shown in the Figure 8.23, has been increased 80 mm to 100 mm and 65 mm to 80 mm in the Pipelab simulation programme. Result is shown in the Figure 8.23. Head loss gradient for the region III has decreased significantly. Therefore, it is for sure this part of network contains undersized pipes, which should be changed for efficient operation of the system.

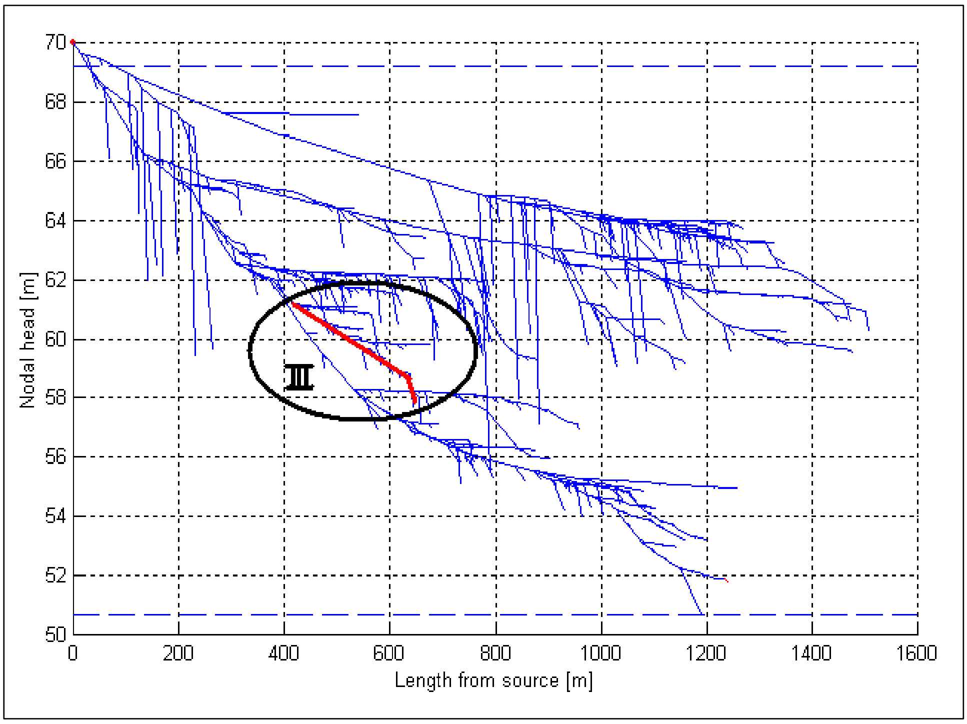

Figure 8.23: Resized Pipes in Region III

To overcome these problems in Balçova GDHS following approaches can be considered.

- 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
- Preventing flow regulator problems

Each of these options affects the system in different ways and has different benefits, so the comparison of alternatives should be performed based on a benefit/cost analysis as opposed to simply minimizing costs.

In 2001-2002 heating season booster pump installed to critical path. However it could not been operated efficiently. It disturbed the hydraulic balance of the network and operation of flow regulators.

In 2002-2003 heating season pump settings were changed and problems sourcing from low pressure have been partly overcome. However, there is still flow regulator and leakage problems.

Among these solution options, construction of new pipeline system is the best solution for Balçova-Narlıdere GDHS. Although it is much more expensive than other options. Because of external corrosion leakage increases every year, it is obvious that the system will require new pipes soon. It would be best to plan new pipeline system under the light of experiences and apply this plan. The plan can be spread over years, and start from the most critical parts of the system.

8.5 Modelling of Balçova-Narlıdere Geothermal Pipeline System

Pressure and temperature distribution along the geothermal pipeline system was modelled for each production policy. WELLOPT is connected to PIPELAB simulation program so that the optimum results can be tested in PIPELAB easily. Figure 8.24 shows the geothermal pipeline system in PIPELAB screen. Also from the Figure 8.24 the flow inside each pipe can be seen. In Figure 8.24 it is assumed that the all wells are in operation with their maximum capacities.

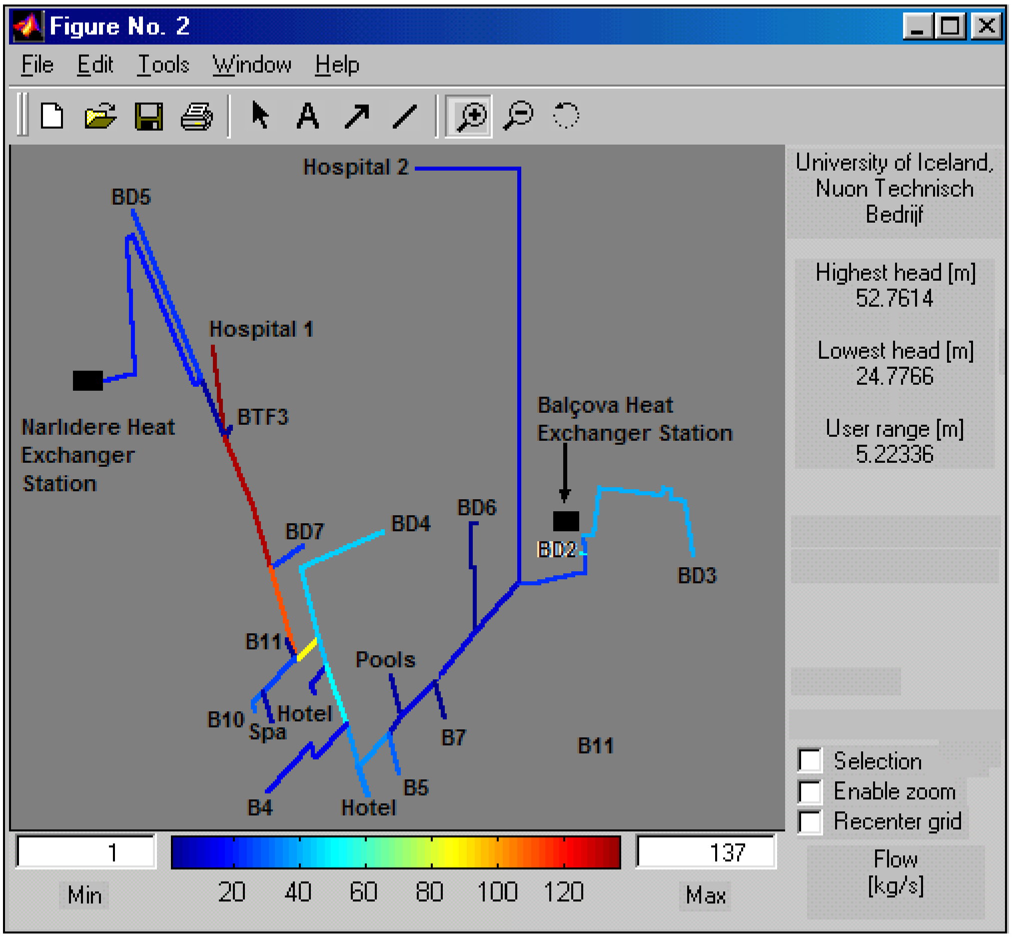

Figure 8.24: Flow Model of Balçova-Narlıdere Pipeline System

Pressure distribution along the geothermal pipeline system for the maximum production capacity is given in Figure 8.25.

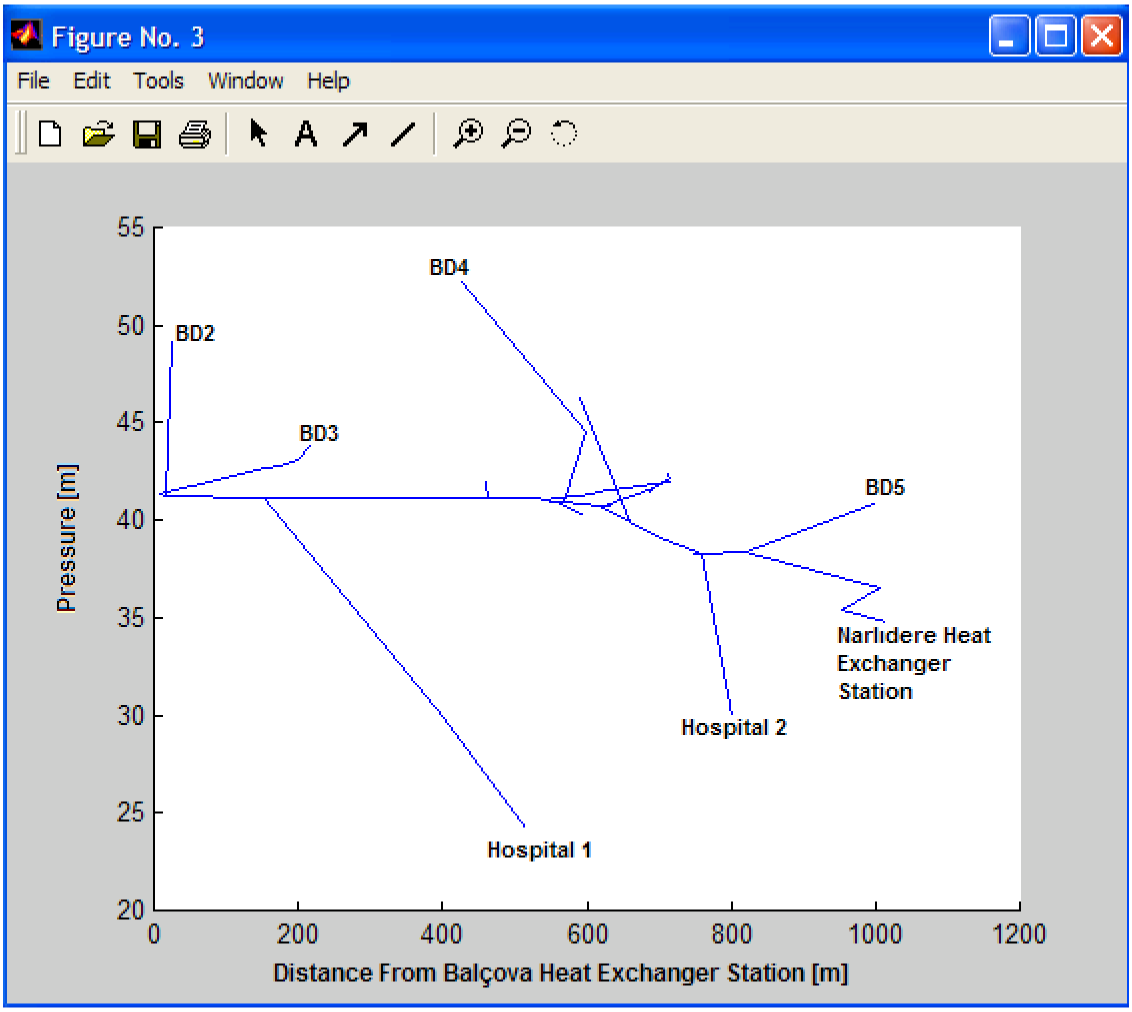

Figure 8.25: Pressure Distribution Along the Geothermal Pipeline

Temperature distribution along the geothermal pipeline system for the maximum production capacity is given in Figure 8.26. Considering production wells and heat exchangers connected to the geothermal pipeline system, there are thousands of production options. Besides every year new facilities are connected to the geothermal pipeline system. These models are very useful determine new connection points and production strategies. It should be noted that the model should be improved with the actual measurements. However, there is no pressure nor temperature measurement point on the geothermal pipeline system. Therefore, these models are the only way to determine temperature and pressure distribution along the geothermal pipeline.

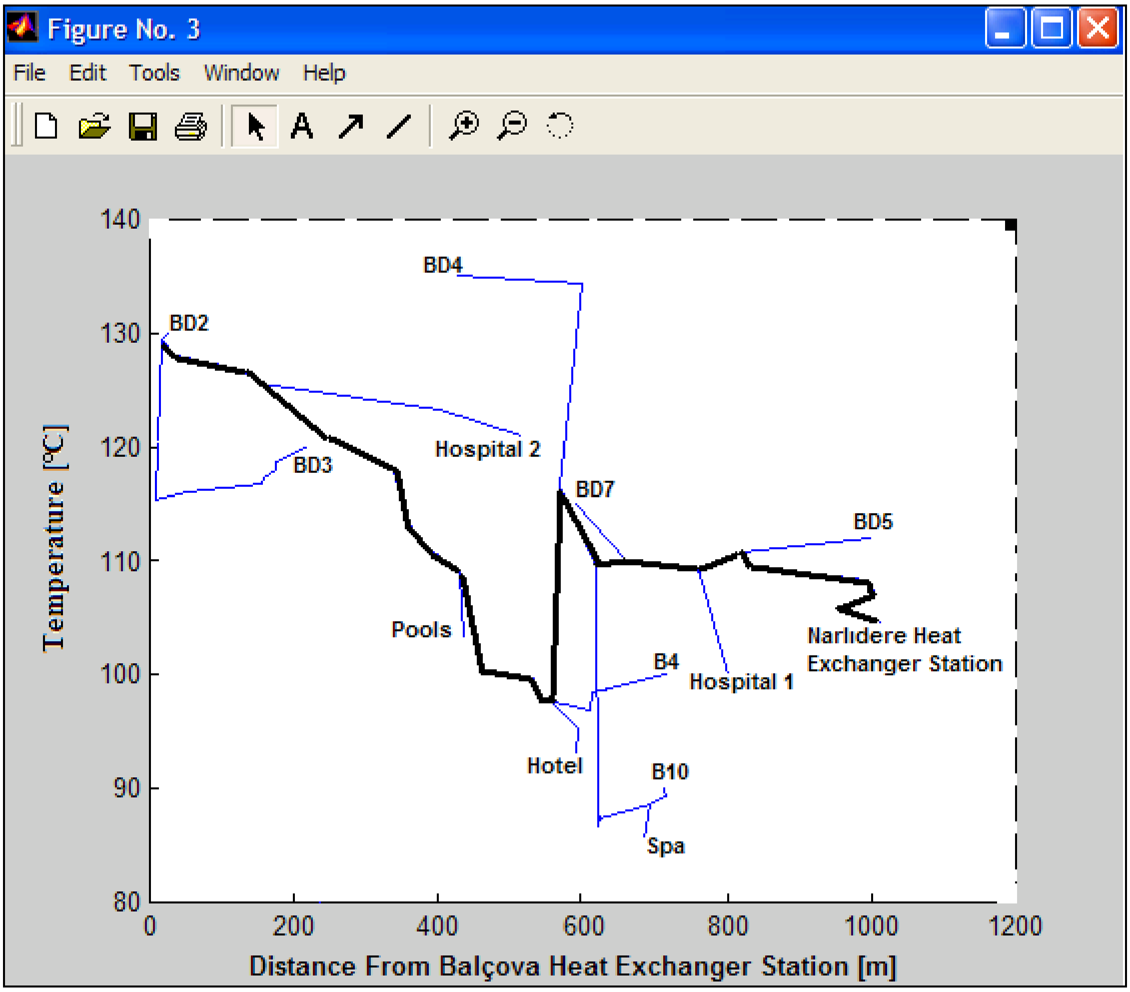

Figure 8.26: Temperature Distribution Along the Geothermal Pipeline

8.6 Comparison of Actual and Optimum Power Consumptions

The *Conventional Energy Ratio (CER)* and *Conventional Excess Energy Ratio (CEER)* have been defined in Section 7.4. From the data sets of 2000-2001 and 2001-2002 heating seasons, the actual and optimum power consumption of Balçova-Narlıdere GDHS have been found. Actual power consumption of the system was found from the electricty bills of the Balçova Geothermal Company. To find the optimum power consumption of the system following route has been followed.

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

The results are presented in Tables 8.4 and 8.5.

Table 8.4: Actual and optimum power consumption values for the 2000-2001 heating season

Months	Heat Demand (kWh_t)	Actual enery consumption (kWh_e)	Optimised energy consumption (kWh_e)	Actual CER	Opt. CER	CEER
1	18,586,848	362,814	164,502	51.2	113.0	2.2
2	18,356,232	217,488	161,594	84.4	113.6	1.3
3	12,195,168	136,886	75,883	89.1	160.7	1.8
4	9,395,520	85,772	56,638	109.5	165.9	1.5
5	7,464,600	42,178	36,773	177.0	203.0	1.1
6	3,743,160	86,358	20,720	43.3	180.7	4.2
7	760,296	121,820	6,717	6.2	113.2	18.1
8	3,050,616	128,532	19,231	23.7	158.6	6.7
9	3,941,880	127,720	21,150	30.9	186.4	6.0
10	7,530,816	136,006	40,530	55.4	185.8	3.4
11	18,541,464	264,111	146,428	70.2	126.6	1.8
12	27,852,096	401,158	281,837	69.4	98.8	1.4
Overall	**131,418,696**	**2,110,843**	**1,032,004**	**62.3**	**127.3**	**2.0**

Table 8.5: Actual and optimum power consumption values for the 2001-2002 heating season

Months	Heat Demand (kWh_t)	Actual enery consumption (kWh_e)	Optimised energy consumption (kWh_e)	Actual CER	Opt. CER	CEER
1	30,066,000	463,048	294,259	64.9	102.2	1.6
2	24,729,984	332,198	168,058	74.4	147.2	2.0
3	24,319,680	352,819	180,856	68.9	134.5	2.0
4	23,563,776	285,453	151,751	82.5	155.3	1.9
5	10,412,592	163,202	45,991	63.8	226.4	3.5
6	3,398,784	60,293	18,752	56.4	181.2	3.2
7	2,354,448	46,433	16,042	50.7	146.8	2.9
8	2,369,976	57,154	15,973	41.5	148.4	3.6
9	2,999,952	29,377	18,071	102.1	166.0	1.6
10	7,085,184	83,239	32,359	85.1	219.0	2.6
11	16,172,400	199,412	89,539	81.1	180.6	2.2
12	29,192,040	302,690	286,092	96.4	102.0	1.1
Overall	**176,664,816**	**2,375,317**	**1,317,744**	**74.4**	**134.1**	**1.8**

Figures 8.27, 8.28 and 8.29 are the graph forms of the Tables 8.4 and 8.5. As can be seen from Table 8.4, CEER value is 18.1, which is much higher than the average value. In 2001 June, the system was completely stopped and heat exchangers and pipes was taken into service for approximately 3 weeks. However, the well pumps and other

equipments have been operated for testing purposes. This CEER value (18.1) is not shown on the 8.29, to investigate the variation of CEER close.

In Figure 8.27, power consumption of the system changes according to seasons. Power consumption is highly related to variation of ambient temperature. However, for CER and CEER there is no such relation. It is normal, because the operational efficiency of the system is independent of heat demand. CEER value gets closer to the 1, when the system is operated in full capacity. Also optimum and actual CER values become closer to each other at full capacity. Because there are not too many operational options to meet the heat demand in winter times. Therefore the most critical time in energy economy is spring and autumn, because partial loads (loads higher than the design load) occur at these times.

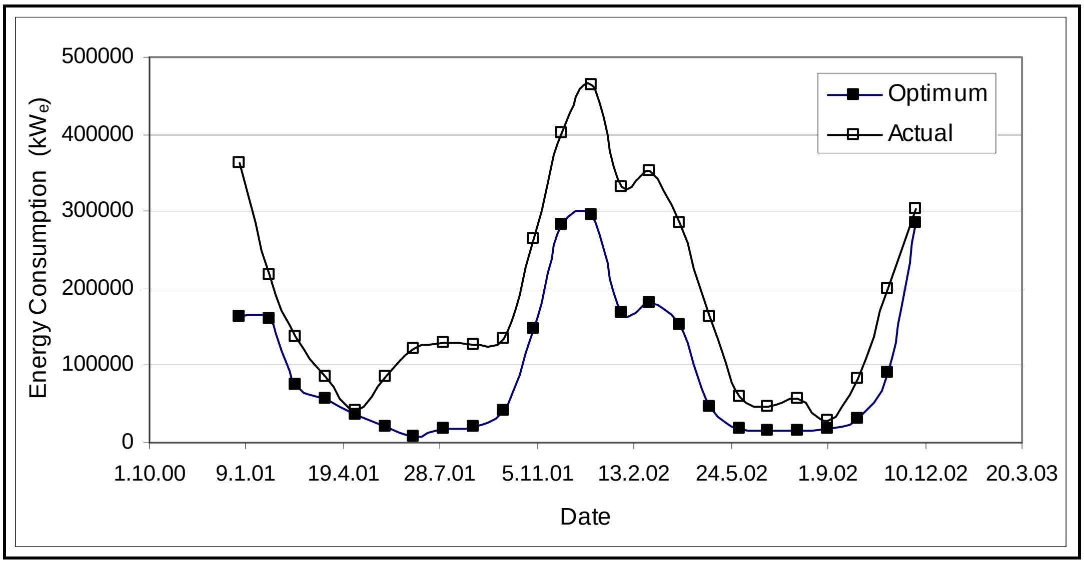

Figure 8.27: Variation of Actual and Optimum Power Consumptions

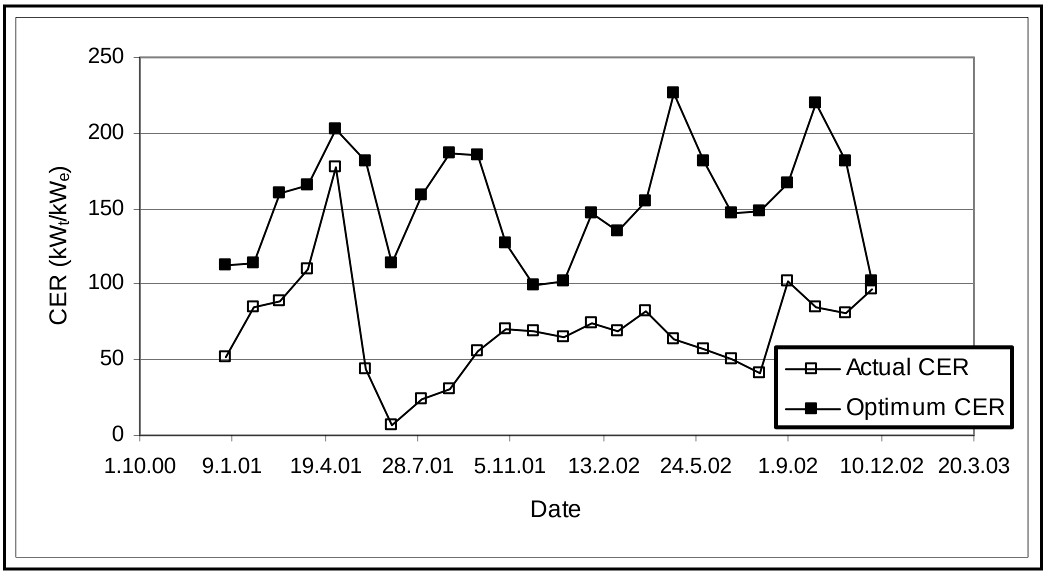

Figure 8.28: Variation of Actual and Optimum CER Values

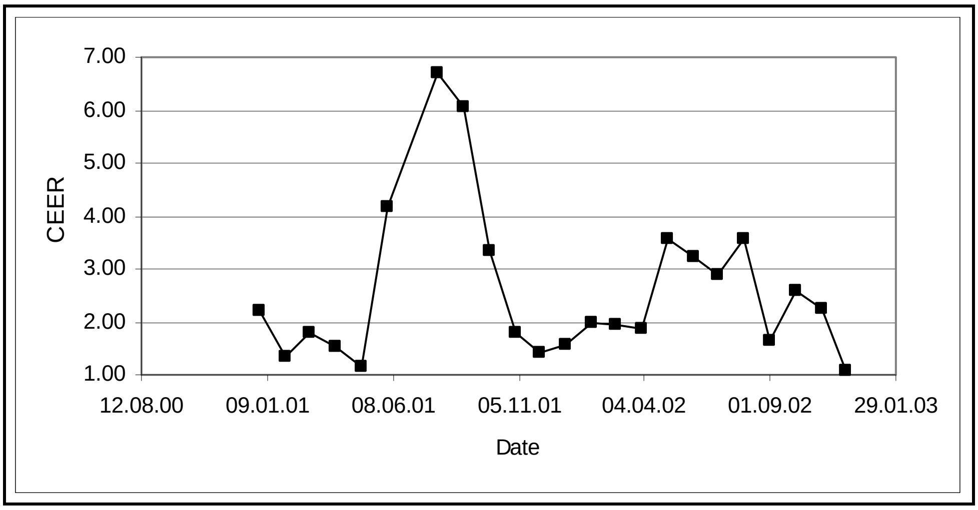

Figure 8.29: Variation of CEER Values

Table 8.6 illustrates the variation of CER and CEER factors with respect to seasons. The highest CEER value occurs in the summer, there are two main reasons for this poor efficiency. There is no variable frequency control in summer pumps and the temperature difference between inlet and outlet of the heat exchangers decreases down to 5-10^{o}C. Therefore the most inefficient operation of the system occurs in a summer time.

The optimum CER value is about 160 (kW_t/kW_e) for spring, autumn and summer, however for winter CER value is 110 (kW_t/kW_e). In winter the system is operated in full capacity and there are no too many operational options to meet the heat demand. Most of the pumps are operated at full capacity, which is far away from their best efficiency points. Therefore, the low optimum CER compared to other seasons is expected for the winter times in the system.

Comparing CEER and CER values the winter seems to have good actual CER and CEER values. Actually, the high CEER value is not the result of the good operation. It is the result of the limited operational options in winter. It is also obvious that the improvement of operational efficiency is more important in winter, if the possible energy economy is considered.

Table 8.6: Variation of Operational Efficiency Factors with Seasons

	Spring	**Winter**	**Autumn**	**Summer**
CEER	1.90	1.53	2.41	5.14
Optimum CER	159.43	109.69	161.66	160.90
Actual CER	81.92	71.55	67.00	31.32
Possible Energy Economy (kWh_e)	518,418	723,053	491,788	403,153

8.7 Optimimum Operation of Balçova-Narlıdere GDHS

Optimum operation of the system is possible if the route in Figure 8.30 is followed during operation.

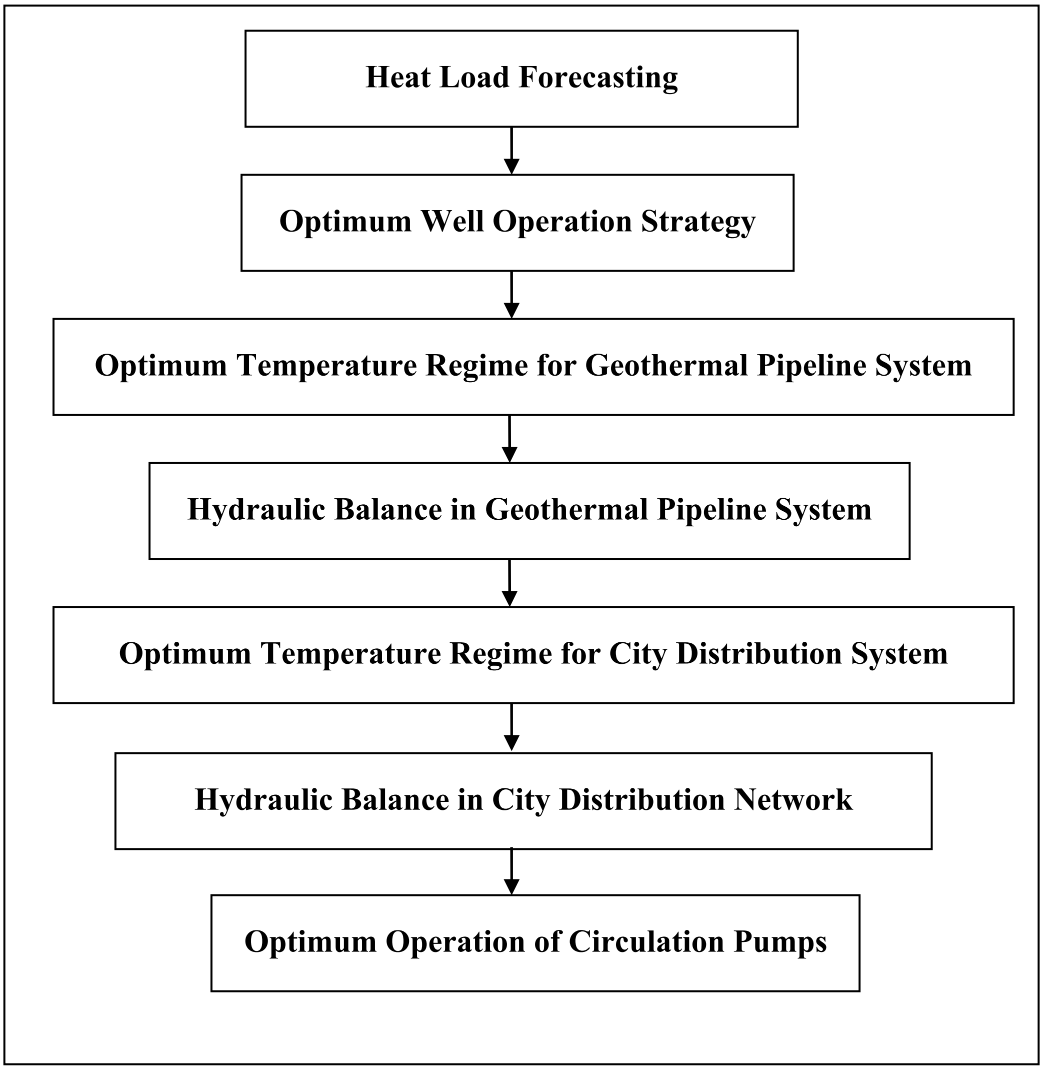

Figure 8.30: Operational Optimisation Diagram of the System

Without automation optimum control of the system is not possible since each of the tasks in Figure 8.30 should be done in coordination with each other. Besides, huge amount of feedback information is required for each of these tasks. It is not possible without use of supervisory control and data acquisition system.

8.8 Implementation of the Study on the System

Between the dates of 19.02.2003 and 19.03.2003, the system has been operated according to the optimum control strategy determined in this study. Because of the malfunction of some well pumps in the system, optimum well operation policy has been partly followed by the operators. However temperature regimes and the circulation pumps have strictly controlled according to the optimum control strategy and heat demand of the next day was forecasted.

Energy consumption and energy production analysis of Balçova GDHS is given in Table 8.7. Increase in the temperature difference and application of load based control have definite influence on energy economy. Note that the data in Table 8.7 belongs to only Balçova GDHS.

Table 8.7: Comparison of 2002 and 2003 March Control Strategies in Balçova Heat Exchanger Station

	Heat Load (kW_t)	**Power Consumption (kW_e)**	**Average Ambient Temperature (^oC)**	**Average Temperature Difference (^oC)**	**Average Flow (m^3/h)**	**(kWt)/(kW_e)**
2002 March	**10,187,883**	**263,002**	**13.7**	**22.0**	**614**	**38.7**
2003 March	**16,715,317**	**295,000**	**7.4**	**28.6**	**771**	**56.7**

Chapter 9

CONCLUSION

9.1 Interpretation of the Results

The main goal of this study was to find optimum control strategy of the system to decrease the energy consumption. Study began with investigation of successful geothermal district heating applications. Although there are common principles in the design and operation of all geothermal district heating systems, operation and design characteristics of each system are strongly dependent on resource characteristics, weather conditions and heating infrastructure of the country. Therefore each geothermal district heating project is unique and strongly dependent on local factors. This uniqueness requires the development of original solutions.

While operating district heating system, first thing to know is the heat demand. There are numerous studies and methods in the estimation of district heating heat demand. Since the 1999-2000 heating season huge amount of data were collected from the system. Considering these data, statistical methods are the most suitable selection for the estimation of heat demand. While performing time series analysis of Balçova-Narlıdere GDHS, ready functions in MATLAB were used. As can be seen from the results, rather satisfactory estimations were obtained for the heat demand of next day. Considering the situation of the system (leakage, regulator problems etc.), accuracy of this model is sufficient to be considered during operation.

Optimisation of well operations (geothermal fluid production) was one of the most critical and interesting problem in this study. The problem was overcome by creating dynamic programming algorithm. The author is not aware of prior application of such analysis. The results are satisfactory and give the optimum operational strategy for the geothermal wells. Results show that significant amount of energy can be saved if the results of the program is applied. To make the program user friendly, user interface screen was created and the heat load predictor model added to the algorithm. Program algorithm is so flexible that it can easily be adapted to other geothermal district heating systems. Program called WELLOPT can easily be used by district heating operators and it is rather guiding tool for them.

Operation of circulation pumps have also been investigated in this study. It was seen that there isn't enough variable speed drive control in the system. Circulation pumps of Narlıdere GDHS, and summer pumps of Balçova GDHS don't have variable speed drivers, which causes significant increase in the energy consumption. It has also been detected that the advantages of existing variable frequency drivers have not been utilised. According varying weather conditions, the number of pumps in operation have been changed (2 pumps in parallel or 3 pumps in parallel) in Balçova GDHS. However, it has been calculated that the operation with three parallel pumps is always more efficient than other alternatives.

Temperature regimes in the system is one of the major problems in the system. The reasons of this unstability can be summarised as:

1. Leakage
2. Improper operation of self operated valves
3. Insufficient heating systems of customers
4. Scaling in the heat exchangers
5. Lack of automatic control (Operator faults)

Parallel to geothermal reservoir studies, in 2002-2003 heating season the temperatures in the field have increased and the supply temperature of Balçova city distribution water has been increased to 90^{o}C , which has solved most of the problems. However the return water temperature is about 60^{o}C, which is rather high temperature for a return water. It shoud be stressed here that the design value for return water is 42^{o}C. Calculations show that the 40% of the circulation pump power can be saved if return water temperature is decreased to 42^{o}C. However, the stability of temperature regimes in the system can only be provided by revision of system, which requires installation of new pipes and regulators. It is a management decision rather than operational issue.

Pipe network problems were anaylsed by using PIPELAB district heating simulation program. This was the first district heating pipe network modelling study in Balçova-Narlıdere GDHS. Simulation results have indicated largest pressure drop at İş Bankası Houses branch (in Balçova), which is the most problematic part of the system.

Circulation pump control settings were re-considered and and operating pressure (pressure of supply part) was increased to 5.5 bars from 5 bars. The amount of customer complaints coming from this part has obviously decreased during 2002-2003 heating season.

The study has been completed in the 2002-2003 heating season. The results of the study were started to apply in 2002-2003 heating season. Comparing the last four months of years 2001 and 2002. The CER value 62 for 2001 and 90 for 2002. It is obvious that significant amount of energy economy was provided during this period.

9.2 Applicability of the Optimum Operational Conditions on the System

Geothermal district heating systems spread over large areas from geothermal field to customer the magnitude of the system can be measured with kilometres. Moreover the control of geothermal district heating systems requires numbers of specialists. Geothermal reservoir management and control of district heating system are two separate tasks, which must be done, in full coordination with each other. For this reason optimum control of geothermal district heating system has never been easy job.

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

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

The capability of optimum system control highly depends on level of automation. Naturally, the level of automation affects the selection of operational strategy. It is very fact that the financial sources of the investor may not be sufficient to install high level of automation at the beginning of the project. However, the optimum level of automation should be investigated in detail and the step by step improvements should be considered in automation.

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