ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

Fırat EKİNCİ

MSc THESIS

EXPERIMENTAL INVESTIGATION OF A WATER-AIR HEAT PUMP

DEPARTMENT OF MECHANICAL ENGINEERING

ADANA, 2001

ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Fırat EKİNCİ

EXPERIMENTAL INVESTIGATION OF A WATER-AIR HEAT PUMP

DEPARTMENT OF MECHANICAL ENGINEERING

ADANA, 2001

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

EXPERIMENTAL INVESTIGATION OF A WATER-AIR HEAT PUMP

Fırat EKİNCİ

YÜKSEK LİSANS TEZİ

MAKİNA MÜHENDİSLİĞİ ANABİLİM DALI

Bu Tez 29 / 01 / 2001 Tarihinde Aşağıdaki Jüri Üyeleri Tarafından Oybirliği İle Kabul Edilmiştir.

İmza:	İmza:	İmza:
Doç. Dr. Orhan BÜYÜKALACA	Prof. Dr. Beşir ŞAHİN	Doç. Dr. R. Tuğrul OĞULATA
DANIŞMAN	ÜYE	ÜYE

Bu Tez Enstitümüz Makina Mühendisliği Anabilim Dalında Hazırlanmıştır.

Kod No: 1791

Prof. Dr. Melih BORAL
Enstitü Müdürü

Bu çalışma Çukurova Üniversitesi Araştırma Fonu tarafından desteklenmiştir.
Proje No: FBE.2000.YL.57

ABSTRACT

MSc THESIS

EXPERIMENTAL INVESTIGATION OF A WATER-AIR HEAT PUMP

Fırat EKİNCİ

DEPARTMENT OF MECHANICAL ENGINEERING
INSTITUTE OF NATURAL AND APPLIED SCIENCES
UNIVERSITY OF ÇUKUROVA

Supervisor : Assoc. Prof. Dr. Orhan BÜYÜKALACA
Year: 2001, Pages: 82
Jury : Assoc. Prof. Dr. Orhan BÜYÜKALACA
: Prof. Dr. Beşir ŞAHİN
: Assoc. Prof. Dr. R. Tuğrul OĞULATA

In this study, the use of waters of Seyhan River and Dam Lake as heat source and sink in a heat pump for Adana was investigated experimentally. Temperature of the water in Seyhan River measured in different depths during one year. Using the experimental set-up built, both water and air experiments were performed for various heat source and sink temperatures in winter and summer. A room located in the laboratories of Mechanical Engineering Department of Çukurova University was heated in winter and cooled in summer. The experimental results obtained from the air and water source and sink experiments were compared.

Key Words : Heat Pump, Air Source Heat Pump, Water Source Heat Pump and Seyhan Lake/Dam Water

ÖZ

YÜKSEK LİSANS TEZİ

SU-HAVA KAYNAKLI BİR ISI POMPASININ DENEYSEL İNCELENMESİ

Fırat EKİNCİ

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ
MAKİNA MÜHENDİSLİĞİ ANABİLİM DALI

Danışman : Doç. Dr. Orhan BÜYÜKALACA
Yıl: 2001, Sayfa: 82
Jüri : Doç. Dr. Orhan BÜYÜKALACA
: Prof. Dr. Beşir ŞAHİN
: Doç. Dr. R. Tuğrul OĞULATA

Bu çalışmada, Adana şehir merkezi için Seyhan Nehri ve Seyhan Baraj Gölü suyunun ısıtma amaçlı bir ısı pompasında ısıl enerji kaynağı olarak kullanılması deneysel olarak araştırılmıştır. Bu amaçla, Çukurova Üniversitesi Makine Mühendisliği Laboratuarlarında hem havayı hem de suyu ısıl enerji kaynağı olarak kullanabilen bir ısı pompası imal edilmiştir. Seyhan Nehri/Göl suyu sıcaklığı bir yıl boyunca ölçülmüştür. Deney düzeneği kullanılarak, değişik kaynak sıcaklıklarında, hem hava hem de su kaynaklı deneyler yapılmış ve sonuçlar değerlendirilmiştir.

Anahtar Kelimeler: Isı Pompası, Su Kaynaklı Isı Pompası, Hava Kaynaklı Isı pompası, Seyhan Göl/Nehir Suyu

ACKNOWLEDGEMENTS

Firstly, I am grateful to my supervisor Assoc. Prof. Orhan BÜYÜKALACA for helping me patiently throughout the preparation of this thesis.

I would like to thank Prof.Dr.-Ing Tuncay YILMAZ for introducing me to the subject of the heat transfer.

I want to thank my friend research assistant H. BULUT, D. Ali BİRCAN, Hasan SERİN, Abdullah ÇINGI and Ramazan GÜLER. I also want to thank all staff of Mechanical Engineering Department and all of my friend research assistants.

And special thanks to my mother.

CONTENT Page

LIST OF TABLES

LIST OF FIGURES

LIST OF PICTURES

NOMENCLATURE

C_d	Flow coefficient	-
c_{tw}	Specific heat of the transport water	kJ / ^{0}C
COP	Coefficient of performance	-
COP_{Cool}	Coefficient of performance of cooling process	-
COP_{Heat}	Coefficient of performance of heating process	-
$COP_{Heat, CARNOT}$	Coefficient of performance of a heat pump in ideal Carnot cycle	-
$COP_{Cool, CARNOT}$	Coefficient of performance of a refrigerator in ideal Carnot cycle	-
g	Gravitational acceleration	m / s
Δh	Head differences	m
$\dot{m}_{tw}$	Mass flow rate of transport water	kg / s
$\dot{Q}_c$	Heat transfer rate in the condenser	Watt
$\dot{Q}_e$	Heat transfer rate in the evaporator	Watt
Δp	Pressure difference	Pa
$T_{tw,ci}$,	Temperature of transport water at condenser inlet	^{0}C
$T_{tw,ce}$	Temperature of transport water at condenser exit	^{0}C
$T_{tw,ei}$	Temperature of transport water at evaporator inlet	^{0}C
$T_{tw,ee}$	Temperature of transport water at evaporator exit	^{0}C
$\dot{W}_{comp}$	Power consumption of compressor	Watt
$\dot{W}_{fans}$	Power consumption of fans	Watt
$\dot{W}_{pumps}$	Power consumption of pumps	Watt
W_{tot}	Total power consumption of the set-up system	Watt
ρ	Density	kg/m^3

1. INTRODUCTION

The limited natural energy sources and increasing energy consumption will create vital energy problems in near future. Considering the limited energy sources, being more careful in the energy consumption has become an obligation. In recent years, the produced energy has not met the demand and as a result of this, interruption in electricity occurred in Turkey.

In 1996, Total Primary Energy Supply (TPES) of Turkey increased to 65.5 Mtoe with a growth of 5.3 % over 1995. GDP (Gross Domestic Product) growth was also rapid, at 7 % in 1996. Growth in energy production of 2.7 % was not as fast as energy consumption growth, so net energy imports increased by 5.7 % to 39.2 Mtoe (IEA report for Turkey, 1998).

Energy production and economic use of energy are now and will also be in the near future on the agenda of Turkey. Heat pump systems are regarded as energy-efficient devices for heating and cooling of buildings.

Heat pump is thermodynamically identical to refrigerator. The principal difference between the heat pump and the refrigerator is in the role they play as far as the user is concerned. Refrigerators and air conditioners provide useful cooling, whereas the heat pump provides useful heating.

The popularity of heat pumps is increasing rapidly in Adana. Majority of the houses built in Adana is in the form of flats in apartment blocks. A high percentage of the houses built in recent years do not have central heating or cooling systems. The heating and cooling are usually achieved by heat pump systems. Window-type heat pump units were popular before 1990. Since then the use of split-type heat pump units has been increasing rapidly, although window type heat pump units are still on the market. Not only houses, but also other small and middle-sized light commercial buildings use heat pump systems for heating and cooling.

Heat pumps are available in many shapes, sizes and types, of which those operating on the vapour compression cycle are the most common. Other types include absorption cycle units and thermoelectric devices. Heat pump sizes varies from a few watts to several Megawatts output, with a multiplicity of compressor drives available, ranging from electric motors to internal and external combustion engines of all types.

The technical and economic performance of a heat pump is affected by a large number of factors. Among these, the characteristics of heat source-sink play an important role. Commonly used heat sources and sinks are ambient air, exhaust air, ground water, lake water, river water, sea water, rock, ground, waste water and effluent.

Heat pumps for building heating and cooling are classified according to, (1) type of heat source and sink, (2) heating and cooling distribution fluid, (3) type of thermodynamic cycle, (4) type of building structure, and (5) size and configuration.

The four basic heat pump designs for space heating and cooling may be tabulated as follows:

Table 1.1. Four basic heat pump designs for space cooling and heating

Heat source/ sink	Heating and cooling medium
Air	Air
Air	Water
Water	Air
Water	Water

The air-to-air heat pump is the most common type in use today. It is particularly suitable for factory-built or unitary heat pumps and is widely used in residential and light commercial applications. The change from cooling to heating is usually accomplished by reversing refrigerant flow, although some other methods are available.

The water-to-air heat pumps use water as heat source and sink. They use air to move the hot to or from the conditioned space. Almost any water can be used the source: river water, lake water, ground or well water and waste water.

The air-to-water heat pumps are commonly used in large buildings where zone control is necessary, and also quite commonly used for the production of hot or cold water for industrial applications.

The water-to-water heat pumps use water as the heat source and sink for both cooling and heating operation.

The use of more than one heat source is also possible. Some heat pumps are utilized air as the primary heat source, but are changed over to extract heat from water (e.g. from a well or storage tank) during periods of peak load. The use of the solar energy requires another heat source during periods of insufficient solar radiation. Quite often, electric coils or gas-fired units are used for auxiliary heat source.

The major problem with air-source heat pumps is frosting, which occurs in humid climates when temperature falls below 2 to 5 ^{0}C. The frost accumulation on the evaporator coils is highly undesirable since it seriously disrupts the heat transfer. The coils can be defrosted, however, by reversing the heat pump cycle (running it as an air conditioner). This results in a reduction in the efficiency of the system (Y. Çengel and M.Boles, 1999).

Both the capacity and the efficiency of heat pump fall significantly at low temperatures. Therefore, most air-source heat pumps require a supplementary heating system such as electric resistance heaters or an oil or gas furnace. Since water temperature does not fluctuate much, supplementary heating may not be required for water-source systems. But the heat pump system must be large enough to meet the maximum heating load (Y.Çengel and M.Boles, 1999).

Water source heat pump systems have very attractive performance characteristics when properly designed and installed. They are now considered a viable alternative to conventional cooling and heating systems. The installation and design integrity currently available has transformed these units from novel alternatives into reliable, efficient, and well-packaged systems (Kavanagh, 1989).

Water source heat pumps offer many performance advantages over air source heat pumps due to outstanding heat transfer properties of water and the generally much more favourable temperatures of river or lake water (Kavanaugh, *et. al*, 1991).

Water-source heat pumps are designed in the form of open-loop or closed-loop. In open-loop applications, the water extracted from the lake or river is pumped through the heat pump and then discharged back to lake or river some distance from the location at which it was extracted. The pump is located submerged below the water level or slightly above it. In closed-loop applications, heat pump system is linked to a coil submerged in the lake or river. A heat transport medium circulating between the coil and the heat pump extracts heat from the water in heating mode and discharges heat to it in cooling mode. A pump is used for circulation of the heat transport medium. Advantages and disadvantages of these systems are discussed by several researches (Kavanaugh (1989), Pezent *et. al.* (1990) and Kavanaugh *et.al.* (1991)).

Almost all the heat pump systems (small or large) in operation in Turkey use ambient air as the heat source and sink. Although the country has rich water resources, the number of heat pump systems utilising water is only few and they are only in industrial applications. The use of other heat sources (and sinks) is very rare. Barriers still exist in Turkey regarding the use of water and the other alternative sources in heat pumps. Such sources are not very well known, and their reputation is sometimes that of a troublemaker. Another barrier is the lack of designers, contractors and operators who can properly design, install and operate these systems economically and reliable.

Using water as heat source (such as dam, lake, river, ground) may be economic when its temperature is higher than ambient air and also available. Seyhan River divides Adana City into two equal parts. Seyhan Dam Lake is located on the north of city. There are many offices and residences located on sides of Seyhan River and Dam Lake. Seyhan River/Dam water has not been used in heat pumps at all and it has not been investigated until now. The aim of this study is to investigate the possibility of using Seyhan River and Dam Lake water in heat pumps.

The thermal characteristics of Seyhan River have not been studied previously, although some discrete measurements of water temperature were made. Therefore, a study was initiated to monitor the temperature of Seyhan River. The measurements were taken from the River water downstream of the Dam in the city. The temperature of Seyhan River was monitored at three different depths (0.25 m, 0.5 m and 1 m from the surface). The data obtained was compared with the data for air. Using a laboratory-made heat pump system that was capable of utilizing both air and water as heat source or sink, two separate sets of experiments were performed. Heating experiments were carried out in the winter of 2000 (from January to March) and cooling experiments in the summer of 2000 (from May to August). Both air and water were utilised as heat source and sink in two sets.

2. PREVIOUS STUDIES

Kavanaugh (1989) investigated the operation of water-to-air heat pumps using lake water as the heat source and sink for southern lakes of the United States of America. Several open and closed-loop heat pump systems were monitored and as the result of these studies, some recommendations concerning heat pump selection, pumping systems, piping arrangements and lake size/depth characteristics were made. Kavanaugh (1989) stated that water source heat pump systems have very attractive performance characteristics when properly designed and installed. They are now considered a viable alternative to conventional cooling and heating systems. The installation and design integrity currently available has transformed these units from novel alternatives into reliable, efficient, and well-packaged systems.

Kavanaugh *et. al.* (1991) presented performance of two water-to-air heat pumps that were designed primarily for southern installations in the United States of America. They stated that water source heat pumps offer many performance advantages over air source heat pumps due to outstanding heat transfer properties of water and the generally much more favourable temperatures of river or lake water.

Water-source heat pumps were installed in two waste treatment buildings at Ft. Greely, AK in USA. These heat pumps use primary effluent as a source of heat. Intermediate loops circulating an ethylene glycol/water mixture are used to transfer heat from the effluent heat exchangers to the heat pump evaporators. In one case, heat exchange is accomplished via an embossed panel heat exchanger immersed directly in the effluent. In the other case, the effluent heat exchanger is a plate-and-frame unit. Detailed performance data were taken on both units during the 1985-86 and 1986-87 heating seasons. When fully operational, the unit archived an average Coefficient of Performance (COP) of 2.6 (Phetteplace and Uead, 1988).

A block of 34 new luxury apartments around Sydney Harbor were recently equipped with water source heat pump, using 120 meters coils piping at the bottom of the Harbor (Heat pump center newsletter, 1999).

In USA, the heat pump system of Great River Medical Center draws water from the 60.000 m^2 artificial lake that serves as a heat and cold source. The pumps distribute 0.32 m^3/s of water over 800 heat pumps for space conditioning in the hospital, two new medical buildings and two existing facilities. In total, the heat pump system heats and cools 66.000 m^2 of building space (Heat pump center newsletter, 1999).

American Refrigeration Institute (ARI) published different standards for rating and testing of water source heat pump systems:

-ARI Standard 325: Ground Water-Source Open -Loop Heat Pumps

-ARI Standard 330: Ground Water-Source Closed-Loop Heat Pumps

-ARI/ISO 13256-1 Standard covers those heating and cooling systems usually referred to as "Water Source Heat Pumps"(www. ari.org).

Rackliffe and Schabel (1988) presented results of a demonstration project to evaluate the performance of groundwater heat pumps in residential space conditioning applications. Fifteen groundwater heat pumps installed in single-family residences throughout New York State were monitored from the fall of 1982 to the spring 1984 using a microprocessor-based data acquisition system with remote accessing and data retrieval capability. Data were collected on a unit cycle basis and were summarized for each month in addition to each heating/cooling season. Performance data, homeowner economics, electrical demand characteristics, and factors influencing performance were evaluated.

The groundwater heat pump systems used at two high schools in USA were analyzed. One school is in the Northern California and the other is in Western Oregon. The California site, a 506 kW, 14 ^{0}C groundwater system in operation for two years, demonstrates the importance of verifying the groundwater resource prior to final mechanical design. The Oregon, 415 kW system employs a 12 ^{0}C, production well and injection well. It has been in operation for approximately eighth years. Experience with these two systems indicates that properly designed groundwater systems are efficient, low maintenance and cost effective (www.oit.osshe.edu).

Ground source heat pump systems have been shown to significantly reduce energy bills in commercial buildings. In recent work for ASHRAE, buildings with ground source heat pump systems had average annual total energy bills of 10.44 $\$/m^2$ compared to 12.59$\$/m^2$ for the same buildings with conventional systems (Caneta Research Inc, 1995).

In countries such as Australia, where temperatures are often extremes of hot and cold, constant temperatures not far below the surface of earth (or water) can be used. Australia currently has approximately 2.000 residences converted to geothermal heating. The efficiency of earth-coupled system was demonstrated by new ABC-CBN television building in Manila, which has an amazing, demonstrated COP of 7. The USA Department of Energy has declared it the most energy-efficient building in the world (Heat pump center newsletter, 1999).

ASHRAE RP-863 includes document case studies of the design and performance of a wide variety of commercial and institutional building ground source heat pump systems in North America. The aim of this study was to increase member awareness, and understanding of GSHP and confidence in this energy-efficient heating and cooling technology.

Although ground-source heat pump (GSHP) systems are an effective means of reducing building energy consumption and electric load peaks, mechanical design teams at large need more information about them before they will be confident enough to consider GSHP systems for their clients (Cane, 1996).

A recent trend is to combine heat pumps with thermal storage. At the offices of insurance company Anova Verzekering im Amersfoort, heating or cooling capacity was stored in two groundwater aquifers. In winter, groundwater from one aquifer-the warm well was used as the heat source for an electric heat pump. The groundwater, which was cooled to 8 ^{0}C, was transferred to a second aquifer-the cod well. By the end of heating season, sufficient cold groundwater has been stored to meet the building's cooling needs throughout the summer, without using heat-pumping equipment. During cooling, the groundwater was transferred to warm well at between 17 and 20 ^{0}C to provide a warm heat source (Heat pump center newsletter, 1999).

A comprehensive field-test to study the operating details of a representative Water-Loop Heat Pump (WLHP) system was carried out for three years in commercial office building in Stanford, Connecticut by Kush and Burner (1991). The large body of results showed that the WLHP system studied provides satisfactory comfort in all seasons and very reliable but that there are many areas in which energy efficiency and cost-effectiveness could be improved.

The experimental study of this thesis is based on the heat pump system originally designed and constructed by Özgören (1996) (see also Yılmaz and Özgören, 1997). They constructed an air-to-air heat pump in the Laboratories of Mechanical Engineering Department of Çukurova University. The heat pump was capable of producing hot water in addition to heating or cooling air. In this study, the heat pump was modified in order to perform water-source (sink) experiments.

3. MATERIAL and METHOD

3.1. Introduction to Heat Pump

A heat pump is thermodynamic device that operates in a cycle that requires work and accomplishes the objective of transferring heat from a low-temperature body to a high-temperature body. The heat pump cycle is identical to a refrigeration cycle in principle except that the primary purpose of the heat pump is to supply heat rather than remove it from an enclosed space.

Heat pumps are available in many shapes, sizes and types, of which those operating on the vapour compression cycle are the most common. Heat pump sizes varies from a few watts to several megawatts output, with a multiplicity of compressor drives available, ranging from electric motors to internal and external combustion engines of all types. The technical and economic performance of a heat pump is affected by a large number of factors. Among these, the characteristics of heat source-sink play an important role. Commonly used heat sources and sinks are ambient air, exhaust air, ground water, lake water, river water, sea water, rock, ground, waste water and effluent.

In the following sections various refrigeration cycles, heat sources (sinks), practically used heat pump systems and components of a typical heat pump are presented.

3.2. Refrigeration Cycles

A major application area of thermodynamics is refrigeration, which is the transfer of heat from lower temperature region to a higher temperature one. Devices that produce refrigeration are called refrigerators or heat pumps, and the cycles on which they operate are called refrigeration cycles. The most frequently used refrigeration cycle is the vapor-compression refrigeration cycle in which the refrigerant is vaporized and condensed alternately and is compressed in the vapor phase. Another well-known refrigeration cycle is the gas refrigeration cycle in which the refrigerant remains in the gaseous phase throughout. Other refrigeration cycles are cascade refrigeration, where more than one refrigeration cycle is used, absorption refrigeration, where the refrigerant is dissolved in a liquid before it is compressed; and thermoelectric refrigeration cycle, where refrigeration is produced by the passage of electric current through two dissimilar materials (Çengel and Boles, 1999). Brief information is given below for some refrigeration cycles.

3.2.1. Vapor Compression Refrigeration Cycle

Vapor compression cycle is the most frequently used refrigeration cycle. The most efficient refrigeration cycle is the reversible cycle processes. The best-known reversible refrigeration cycle is the "Reversed Carnot Cycle", first proposed in 1824 by a French engineer Sadi Carnot.

3.2.1.1. The Reversed Carnot Cycle

A refrigerator or heat pump, which operates on the reversed Carnot cycle, is called a Carnot refrigerator or Carnot heat pump. A reversed Carnot cycle executed within the saturation dome of refrigerant is shown in figure 3.1. The refrigerant absorbs heat isothermally from a low-temperature source at T_L in the amount of Q_L (process 1-2), is compressed isentropically to state 3 (temperature rises to T_H), rejects heat isothermally to a high-temperature sink at T_H in the amount of Q_H (process 3-4), and expands isentropically to state 1 (temperature drops to T_L). The refrigerant changes from a saturated vapor state to a saturated liquid state in the condenser during process 3-4. The coefficients of performance of Carnot refrigerators ($COP_{cool,CARNOT}$) and heat pumps ($COP_{Heat,CARNOT}$) can be expressed as:

$$COP_{cool,Carnot} = \frac{1}{T_H / T_L - 1} \tag{3.1}$$

$$COP_{Heat,Carnot} = \frac{1}{1 - T_L / T_H} \tag{3.2}$$

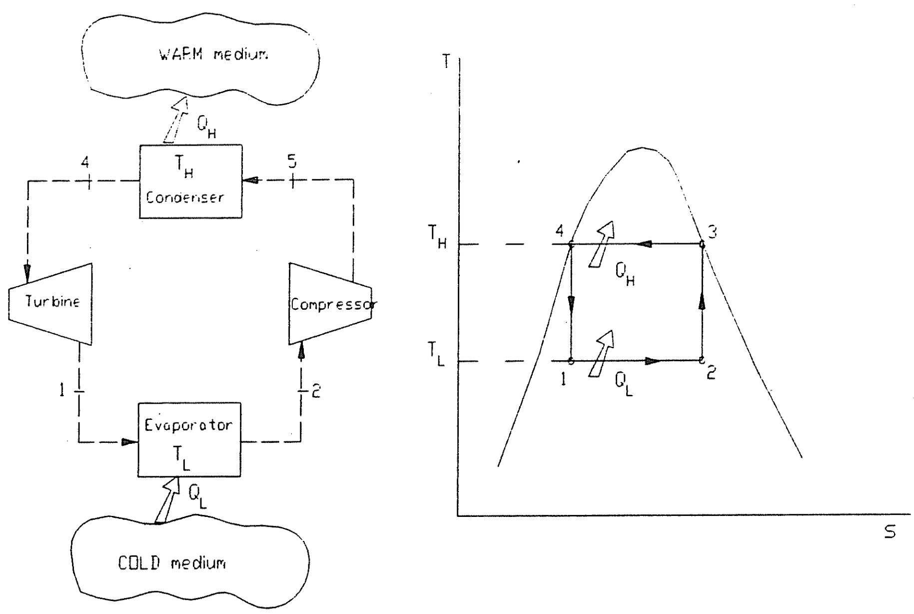


Figure 3.1. Schematic and T-s diagram for the Carnot refrigerator

3.2.1.2. The Ideal Vapor-Compression Refrigeration Cycle

Many of the impracticalities associated with the Carnot cycle can be eliminated by vaporizing the refrigerant completely before it is compressed and by replacing the turbine with a throttling device, such as an expansion valve or capillary tube. The cycle that results is called the ideal vapor-compression refrigeration cycle, and it is shown schematically on a T-s diagram in figure 3.2. The vapor-compression refrigeration cycle is the most widely used cycle for refrigerators, air conditioning systems, and heat pumps. It consists of four processes:

1-2	:	Isentropic compression in a compressor
2-3	:	Constant pressure heat rejection in a condenser
3-4	:	Throttling in an expansion device
4-1	:	Constant pressure heat absorption in an evaporator

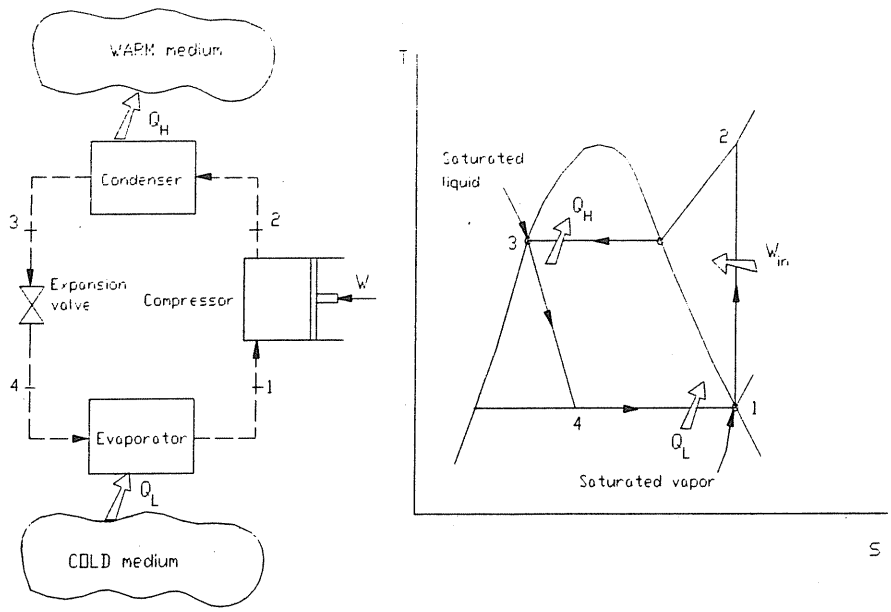


Figure 3.2. Schematic and T-s diagram for ideal vapor-compression refrigeration cycle

In an ideal vapor-compression refrigeration cycle, the refrigerant enters the compressor at state 1 as saturated vapor and is compressed isentropically to the condenser pressure. The temperature of the refrigerant increases during this isentropic compression process to well above the temperature of the surroundings medium. The refrigerant then enters the condenser as superheated vapor at state 2 and leaves as saturated liquid at state 3 as a result of the heat rejection to the surroundings. The temperature of the refrigerant at this state is still above the temperature of the surroundings.

The saturated liquid refrigerant at sate 3 is throttled to the evaporator pressure by passing it through an expansion valve or capillary tube. The temperature of the refrigerant drops below the temperature of the refrigerated space during this process. The refrigerant enters the evaporator at state 4 as a low quality saturated mixture, and it completely leaves the evaporator as saturated vapor and reenters the compressor, completing the cycle.

Another diagram frequently used in the analysis of vapor-compression refrigeration cycles is the P-h diagram, as shown in figure 3.3 On this diagram, three of the four processes appear as straight lines, and the heat transfer in the condenser and evaporator is proportional to the length of the corresponding process curves.

The COPs of refrigerators (COP_{cool}) and heat pumps (COP_{heat}) operating on the ideal vapor-compression refrigerant cycle can be expressed as:

$$COP_{Heat} = \frac{Q_H}{W_{net}} = \frac{Q_H}{Q_H - Q_L} \tag{3.3}$$

$$COP_{Cool} = \frac{Q_L}{Wnet} = \frac{Q_L}{Q_H - Q_L} \tag{3.4}$$

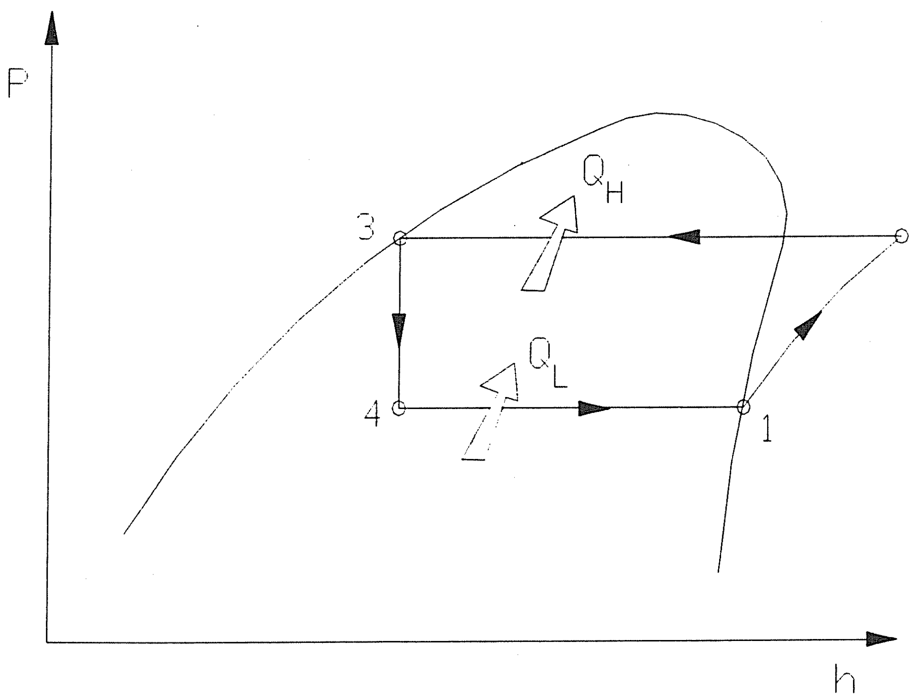


Figure 3.3. Log P-h diagram for ideal vapor-compression refrigeration cycle

3.2.1.3. Actual Vapor-Compression Refrigeration Cycle

An actual vapor-compression refrigeration cycle differs from the ideal one in several ways, owing mostly to the irreversibilities that occur in various components. Two common sources of irreversibilities are fluid friction (causes pressure drops) and heat transfer to or from the surrounding. The T-s diagram of an actual vapor-compression refrigeration cycle is shown in figure 3.4.

In ideal cycle, the refrigerant leaves the evaporator and enters the compressor as saturated vapor. This cannot be accomplished in practice, since it is not possible to control the state of refrigerant so precisely. Instead, the system is design so that the refrigerant slightly superheated at the compressor inlet. This slight overdesign ensures that the refrigerant is completely vaporized when it enters the compressor. Also, the refrigerant line connecting the evaporator to the compressor is usually very long, thus the pressure drop caused by fluid friction and heat transfer from surroundings to the refrigerant can be very significant. The result of superheating, heat gain in the connecting line, and pressure drops in the evaporator and the connecting line is an increase in the specific volume, thus an increase in the power input requirements to the compressor since steady-flow work is proportional to the specific volume.

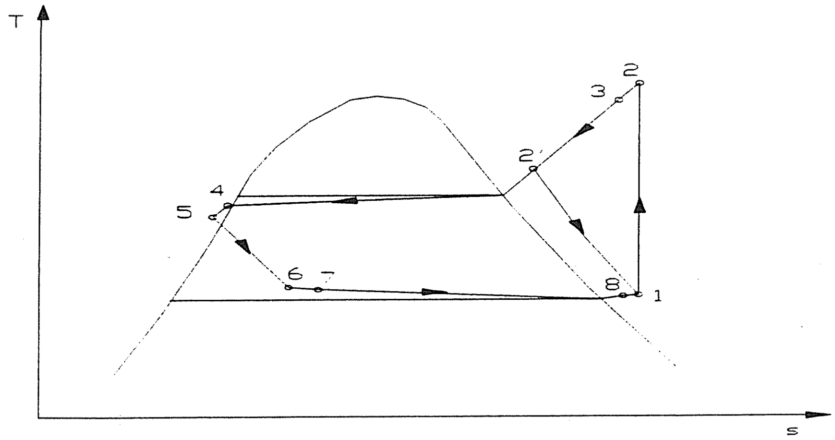


Figure 3.4. T-s diagram for actual vapor-compression refrigeration cycle

The compression process in the ideal cycle is internally reversible and adiabatic, thus isentropic (1-3). The actual compression process, however, will involve frictional effects, which increases the entropy, and heat transfer, which may increase or decrease of the entropy, depending on the direction. Therefore, the entropy of the refrigerant may increase (process 1-2) or decrease (process 1-2') during an actual compression process, depending on which effect dominant.

In the ideal case, the refrigerant is assumed to leave the condenser as saturated liquid at the compressor exit pressure. In actual situations, however, it is unavoidable to have some pressure drop in the condenser as well as in the refrigerant lines connecting the condenser to the compressor and to the throttling valve. Also, it is not easy to execute the condensation process with such precision that the refrigerant is a saturated liquid at the end, and it is undesirable to route the refrigerant to the throttling valve before the refrigerant is completely condensed. Therefore, the refrigerant is sub-cooled (process 4-5) somewhat before it enters the throttling valve (Çengel and Boles, 1999).

Cascade refrigeration cycle, multistage compression refrigeration cycle and multipurpose refrigeration cycle can be given as examples to the modified vapor compression refrigeration cycles.

3.2.2. Absorption Refrigeration Cycle

In vapor-compression cycle described above, the work of compression is comparable in magnitude with the other energy in the cycle. The compression work can be reduced considerably, however, if the vapor is dissolved in a suitable liquid before compression. After compression the vapor can be drawn off, and then throttled and evaporated in usual way. This is employed in absorption refrigerators.

An ammonia absorption refrigerator is shown schematically in figure 3.5. The process of condensation (2-3), throttling (3-4), and evaporation (4-1), occur in conventional components. After evaporation to state 1, the vapor is first passed into an absorber and dissolved in water. The water temperature is only a little above atmospheric, and at such a temperature the solubility of ammonia vapor is very high. The process of solution is accompanied by a rejection of heat Q_8 to the surroundings (just as the process of driving off the vapor from the solution requires heat absorption). The liquid solution is then compressed to the required pressure and heated, first in a heat exchanger, and then in the generator that is maintained at a temperature T_g. At the higher temperature the solubility of ammonia in water is appreciably smaller, and the heat received Q_g results in the removal of vapor from solution. The generator may be heated by steam coils, gas, or electricity. The ammonia vapor is passed to the condenser to complete the main cycle, while the remaining weak solution is returned to the absorber via a throttle valve. The heat exchanger is merely used to reduce the quantities of heat Q_8 and Q_g (Rogers and Mayhew, 1980).

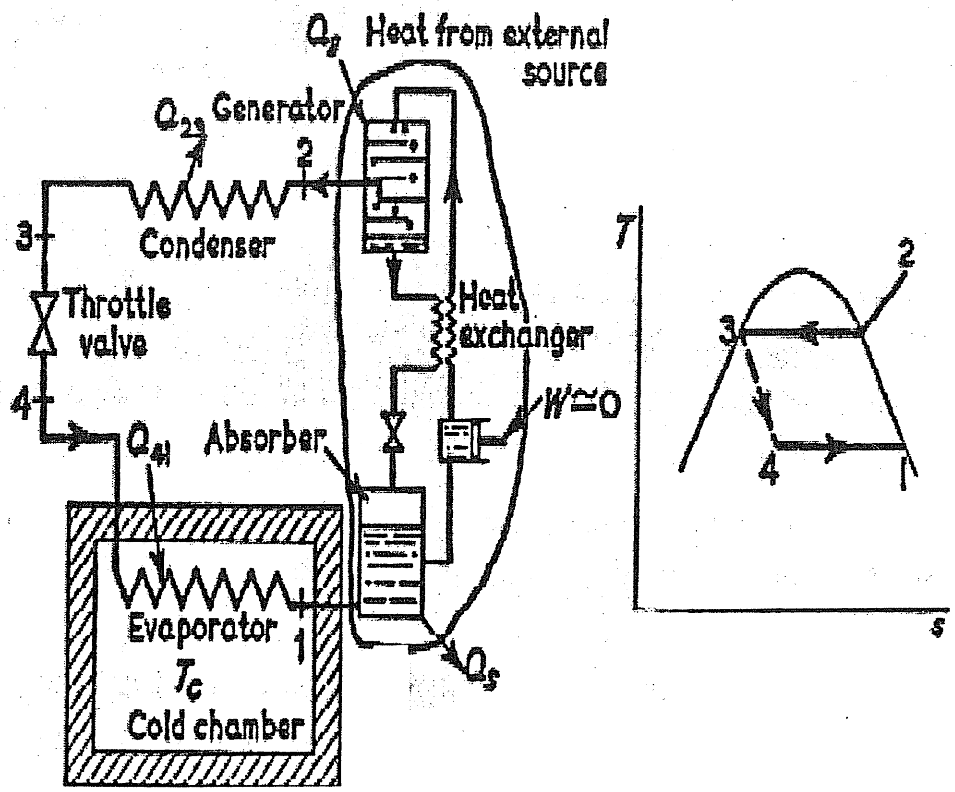


Figure 3.5. Absorption refrigeration cycle

The absorption refrigeration systems are much more expensive than the vapor-compression refrigeration systems. They are more complex and occupy more space, they are much less efficient thus requiring much larger cooling towers to reject the waste heat, and they are more difficult to service since they are less common. Therefore, absorption refrigeration systems should be considered only when the unit cost of thermal energy is low and is projected to remain low relative to electricity. Absorption refrigeration systems are primarily used in large commercial and industrial installations (Çengel and Boles, 1999).

3.2.3. Gas Refrigeration Cycle

It is possible to reverse some thermodynamic refrigerating effect cycles to obtain a similar effect. Among the many gas cycles that have been proposed as prototypes for practical engines, the reversed Brayton cycle has been used to produce refrigeration. The earliest mechanical refrigeration system used air as the refrigerant due to its availability and safety. However, due to its high operating costs and low coefficient of performance, it has largely become obsolete. However, with the introduction of high-speed aircraft and missiles, lightweight high-refrigeration-capacity systems are required to cause a minimum reduction in payload. The gas cycle refrigeration system using air as refrigerant has become generally used for this application due to the small size and weight of components, which is of prime importance. The power to operate the system is of secondary importance in this application. In additional, the power source used for the air cycle aircraft refrigeration system is the same as is used for pressurization of the cabin. Since pressurization is not needed at sea level but refrigeration is, and at high altitudes pressurization is required but less refrigeration is needed, it is found that the power requirement for the combined pressurization and cooling is approximately constant (Granet, 1990).

3.2.4. Vacuum Refrigeration Cycle

The low pressures (8-22 mbar) required to evaporate water as a refrigerant at 4-7 ^{0}C for air-conditioning duty can be obtained a with steam ejector. High-pressure steam at 10 bar is commonly used. The COP of this cycle is somewhat less than with the absorption system, so its use restricted to applications where large volumes of steam are available when required (large, steam-driven ships) or where water is to be removed along cooling, as in freeze drying and fruit juice concentration (Trott, 1989).

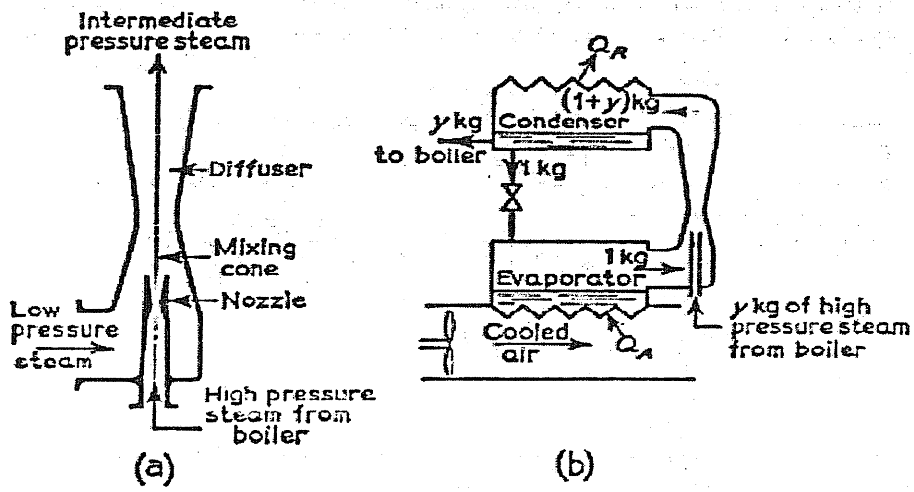


Figure 3.6. Vacuum refrigeration cycle

The ejector pump is shown in figure 3.6.(a). Steam is expanded in a nozzle to form a high jet at low pressure, which entrains the vapor to be extracted from the vacuum chamber. The combined stream from the mixing chamber is then diffused in the divergent part of the venturi until the required exhaust pressure is reached. Such a pump has no moving parts, but it has a very low efficiency.

Figure 3.6.(b) shows how the pump is used in the refrigeration plant. Water in the evaporator at low pressure vaporizes and is pumped, together with the motive steam, into the condenser. A portion of the condensate is throttled into the evaporator, and the remainder is pumped back to steam boiler. If waste steam is available from an existing boiler plant, the poor efficiency of the ejector pump is of

no consequence, and the refrigeration plant itself is cheap to construct and operate (Rogers and Mayhew, 1980).

3.2.5. Thermoelectric Refrigeration Cycle

A refrigeration effect can also be achieved without using any moving parts by simply passing a small current through a closed circuit made up of two dissimilar wires. This effect is called the Peltier effect, and a refrigerator that works on this principle is called a thermoelectric refrigerator (Figure 3.7). Heat is absorbed from the refrigerated space in amount of Q_L and rejected to the warmer environment in the amount of Q_H. The differences between these two quantities is net electrical work that needs to be supplied; that is, $W_e = Q_H - Q_L$. Thermoelectric refrigerators presently cannot compete with vapor-compression refrigeration systems because of their low coefficient of performance. They are available in the market, however, and are preferred in some applications because of their small size, simplicity, quietness, and reliability.

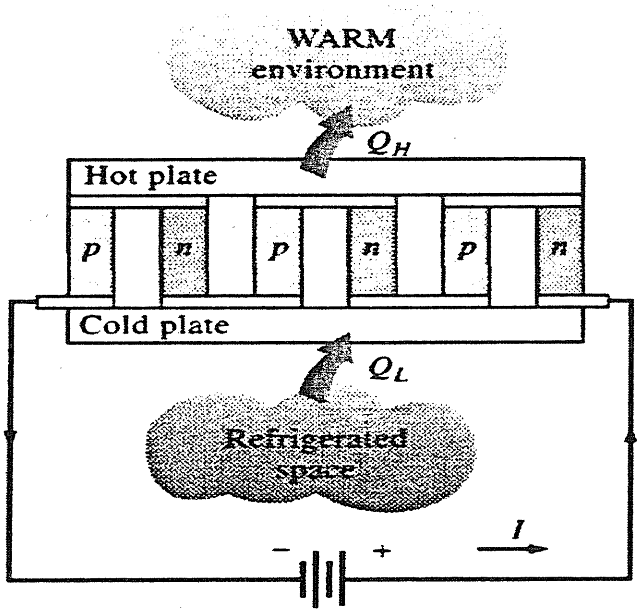


Figure 3.7. A thermoelectric refrigerator

3.3. Heat Sources and Sinks

The technical and economic performance of a heat pump is closely related to the characteristics of the heat source and sink. An ideal heat source for heat pumps in buildings has a high and stable temperature during the heating season, is abundantly available, is not corrosive or polluted, has favorable thermophysical properties, and its utilization requires low investment and operational costs. In most cases, however, the availability of the heat source is the key factor determining its use.

Ambient and exhaust air, soil and ground water are practical heat sources and sinks for small heat pump systems, while sea/lake/river water, rock (geothermal) and waste water are used for large heat pump systems. In the following sections, possible heat sources (sinks) are discussed briefly.

3.3.1. Ambient Air

Ambient air is free and widely available, and it is the most common heat source and sink for heat pumps. In mild and humid climates, frost will accumulate on the evaporator surface in the temperature range 0-6°C, leading to reduced capacity and performance of the heat pump system. Coil defrosting is achieved by reversing the heat pump cycle or by other, less energy-efficient means. Energy consumption increases and the overall coefficient of performance (COP) of the heat pump drops with increasing defrost frequency. Using demand defrost control rather than time control can significantly improve overall efficiencies.

3.3.2. Exhaust air

Exhaust (ventilation) air is a common heat source for heat pumps in residential and commercial buildings. The heat pump recovers heat from the ventilation air, and provides water and/or space heating. Continuous operation of the ventilation system is required during the heating season or throughout the year. Some units are also designed to utilize both exhaust air and ambient air. For large buildings, exhaust air heat pumps are often used in combination with air-to-air heat recovery units.

3.3.3. Water

Commonly used water sources (sinks) are city, geothermal, river or lake and sea water. Because of its heat capacity and good heat transfer properties, water is the best heat source and sink. City water is seldom used because of cost and municipal restrictions. Geothermal water is an innovative heat source in some areas. Well water is particularly attractive because of its relatively high and nearly constant temperature. Frequently, sufficient water is available from wells where the water is re-injected into aquifer. The water quality should be analyzed, and the possible effect of scale formation and corrosion should be minimized. In some instances, it may be necessary to separate the well fluid from the system equipment with an additional heat exchanger.

River and lake water is in principle a very good heat source because of a relatively high and constant temperature throughout a year. But, in some places river and lake water has the major disadvantage of low temperature in winter. River and lake water may be used, but under reduced winter temperatures, the temperature drops across the evaporator may need to be limited to prevent freeze up. Within the context of this study, the temperature of Seyhan River and Lake water was measured during a year. The result showed that (see later in figure 4.16 at section 4.1) Seyhan River and Lake water is suitable as the heat source and sink in heat pump systems. Although Turkey has no restrictions and rules for using river and lake water as heat source, many countries have rules and restrictions. Other parameters must be considered when river water is used in heat pumps. These are moss, clearness and flow rate.

Another water source that is sea water is an excellent heat source under certain conditions, and is mainly used for medium-sized and large heat pump installations. At a depth of 25-50 metres, the sea temperature is constant (5-8°C), and ice formation is generally no problem (freezing point -1°C to -2°C). Both direct expansion systems and brine systems can be used. It is important to use corrosion-resistant heat exchangers and pumps and to minimize organic fouling in sea water pipelines, heat exchangers and evaporators, etc.

3.3.4. Soil

Soil is a very suitable heat source and sink bearing in mind the constant temperature, range of the temperature, availability and storage capacity. Soil composition varies widely from wet clay to sandy soil and has a predominant effect on thermal properties and attendant overall performance. The heat transfer process in soil is primarily one of bulk temperature change with time. The moisture content has an influence, since energy in the ground may also be transported via moisture travel in the soil.

3.3.5. Solar

The use of solar energy as a heat source, either on primary basis or in combination with other sources, has attracted interest but has not emerged as an economical system. Air, surface water, shallow groundwater, and shallow ground-source systems all use solar energy indirectly. The principal advantage of using solar energy directly as a heat pump heat source is that, when available, it provides heat at a higher temperature level than other sources, resulting in an increase in coefficient of performance. The collector efficiency and capacity are increased because of the lower collector temperature required.

3.3.6. Waste Water and Effluent

Waste water and effluent are characterized by a relatively high and constant temperature throughout the year. Examples of possible heat sources in this category are effluent from sewers (treated and untreated sewage water), industrial effluent, cooling water from industrial processes or electricity generation, condenser heat from refrigeration plants. The major constraints for use in residential and commercial buildings are, in general, the distance to the user, and the variable availability of the waste heat flow. However, waste water and effluent serve as an ideal heat source for industrial heat pumps to achieve energy savings in industry.

3.4. Heat Pump Systems

In this section, heat pump systems that use different sources (sinks) are given.

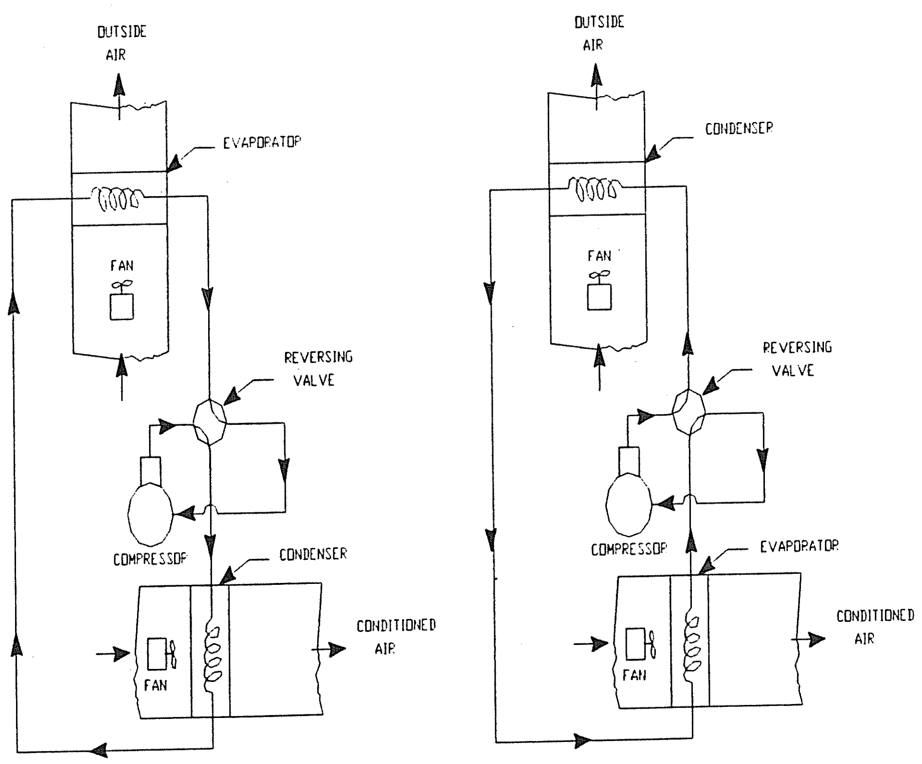
3.4.1. Air Source Heat Pumps

Outdoor air offers a universal heat source and heat sink medium for heat pumps. Extended-surface, forced-convection heat-transfer coils are normally employed to transfer the heat between the air and the refrigerant (Figure 3.8). Typically, these surfaces are 50-100% larger than the corresponding surface on the indoor side of heat pumps using air as the distributive medium. The volume of outdoor air handled is also usually greater in about the same proportions. The temperature difference during heating operation between the outdoor air and the evaporating refrigerant is generally in the range of 10-25 ^{0}C.

As the outdoor temperature goes down, the heating capacity of an air source heat pump decreases. Selecting the equipment for a given outdoor heating design temperature is therefore more critical than for a fuel-fired heating system. When the surface temperature of an outdoor air coil is 0 ^{0}C, frost may form, and if allowed to continue to form it will interfere with heat transfer. When temperature, time or demand controls mandate defrosting of the coil, a four-way valve temporarily reverses the heat pump cycle. During the reverse-cycle defrost period, heat is taken from inside the house (from air blown across the indoor coil) and is pumped outside to raise the temperature of the outdoor coil sufficiently to melt the accumulated frost.

In an attempt to compensate for this heat loss and to temper the resulting decrease in the temperature of the air supplied to the indoor space, conventional systems must energize supplemental resistance heating elements. However, even with substantial power flowing through the heating element, the indoor air temperature is temporarily lowered- resulting in what is commonly called "cold blow" a major concern of the heat pump manufacturers and consumers. The term "cold blow" in heat pump means the indoor supply air temperature by the heat pump is usually lower than our skin temperature that gives us a "cold blow" feeling.

The characteristics of the defrosting cycle described above (a) reduces occupant thermal comfort because of the cool blow effect (b) decreases system reliability because of the periodic cycle-reversing stress imposed on components such as the four -way valve, the compressor, and the resistance-heating elements.



a) Heating mode b) Cooling mode

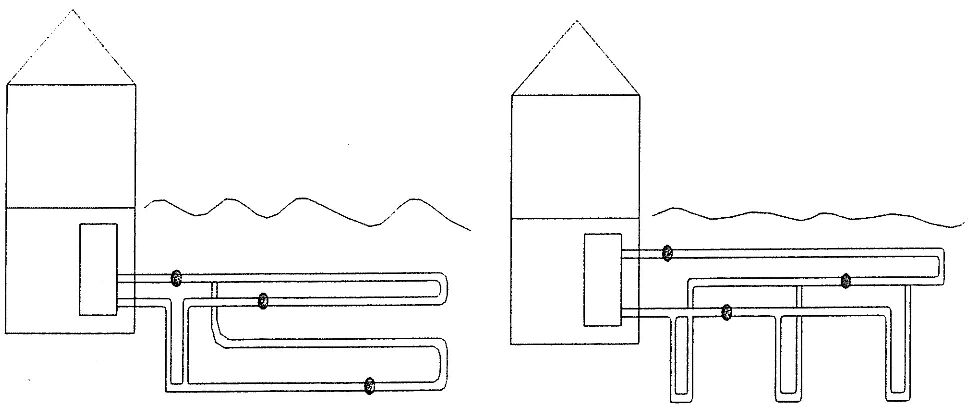
Figure 3.8. Air source heat pump

3.4.2. Ground Source Heat Pumps

Another type of heat pump now being used for residential space conditioning is the ground-source heat pump. These heat pumps tap the relatively stable temperature of the earth as heat source for heating operations. Performance is relatively independent of outside air temperature because the earth's subsurface ground temperature remains relatively uniform year around.

There are two types of ground source heat pumps: 1- a closed-loop system using an antifreeze solution that circulates through a ground coil (a buried loop of pipe) before passing through the heat pump and 2- an open-loop system using well water that is discharged after passing through the heat pump. The first type of system is called an "earth-coupled heat pump" and the second type is called a "groundwater heat pump". Both systems use heat pumps equipped with the refrigerant-to-liquid heat exchangers.

Earth-coupled heat pumps can be installed horizontally or vertically (figure 3.9) (Rackliffe and Schabel, 1983). Groundwater heat pump systems are presented in section 3.4.4 under the title of water source heat pump.



a) Horizontal b) Vertical

Figure 3.9. Earth-coupled heat pump system arrangements

3.4.3. Solar-Assisted Heat Pumps

The principal advantage of employing solar radiation as a heat pump heat source is that, when available, it provides heat at a higher temperature level than other sources, thus resulting in an increase in the COP. As compared to a solar heating system without a heat pump, the collector efficiency and capacity are materially increased due to the lower collector temperature.

Research and development in the solar-source heat pump field has been concerned with two basic types of systems, direct and indirect (figure 3.10). In the direct system, refrigerant evaporator tubes are embodied in solar collector, usually of the flat-plate type. Research has shown that when the collector has no glass cover plates, the same collector surface can also function to extract heat from the outdoor air. The same surface may than be employed as a condenser, using outdoor air as heat sink for cooling.

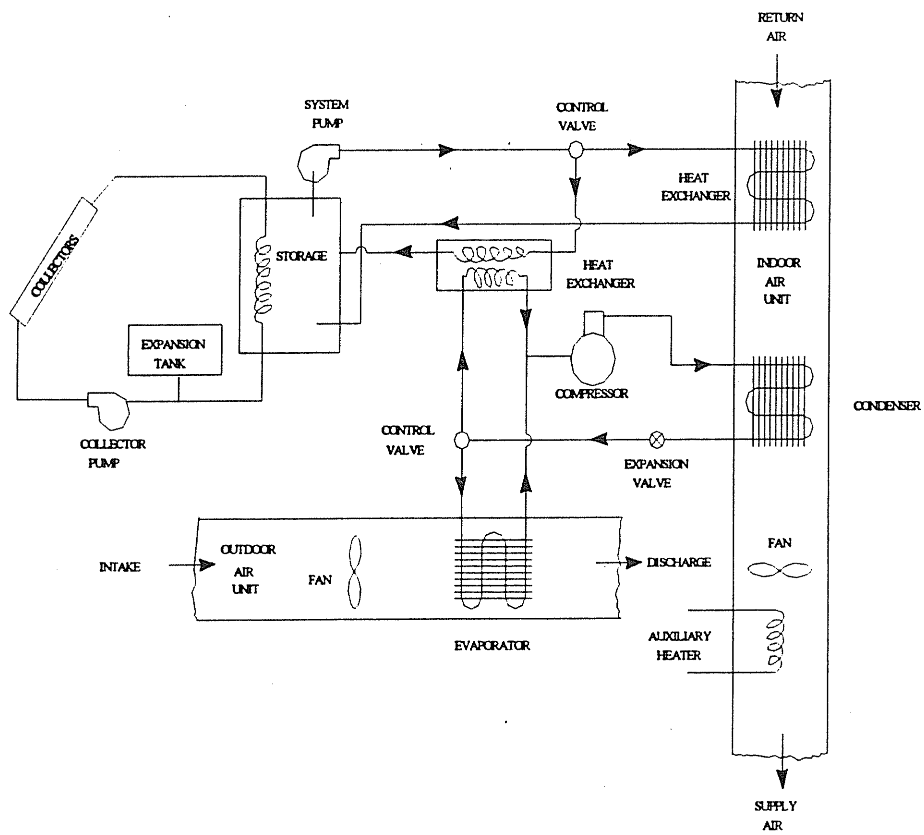


Figure 3.10. Solar assisted heat pump

An indirect system employs another fluid, either water or air, which is circulated through the solar collector. When air is used, the first system for air-to-air heat pump may be employed, the collector being added in such a way that the collector can serve as an outdoor-air preheater; the outdoor-air loop can be closed so that all source heat is derived from the sun; or the collector may be disconnected and the outdoor air used as the heat source or sink (Sauer and Howell, 1983).

3.4.4. Water Source Heat Pumps (WSHP)

Water may represent a satisfactory, and in many cases an ideal, heat source and sink for heat pumps. Well water is particularly attractive because of its relatively high and nearly constant temperature. Its temperature varies with location. Frequently, sufficient water may be available from wells, but the condition of the water often will either cause corrosion in the heat exchanger or induce scale formation. Some water-source heat pumps are single-package reverse-cycle heat pumps that use water as heat source when in the heating mode and as heat sink when in the cooling mode. The water supply may be a circulating closed loop, a well, a lake, or a stream. The main components of a WSHP are compressor, a refrigerant-to-water heat exchanger, a refrigerant-to-air heat exchanger, refrigerant expansion devices, and a refrigerant-reversing valve. Figure 3.11 shows schematic of a typical WSHP system. Water source heat pumps are used in variety of systems. They can be classified in different ways.

Surface water heat pump (SWHP) uses water from a nearby lake, stream, or canal. The adequacy of the total thermal capacity of the body of water must be considered. After passing through the heat pump heat exchanger, it is returned to the source or drain at a temperature level several degrees warmer or cooler, depending on the operating mode of the heat pump.

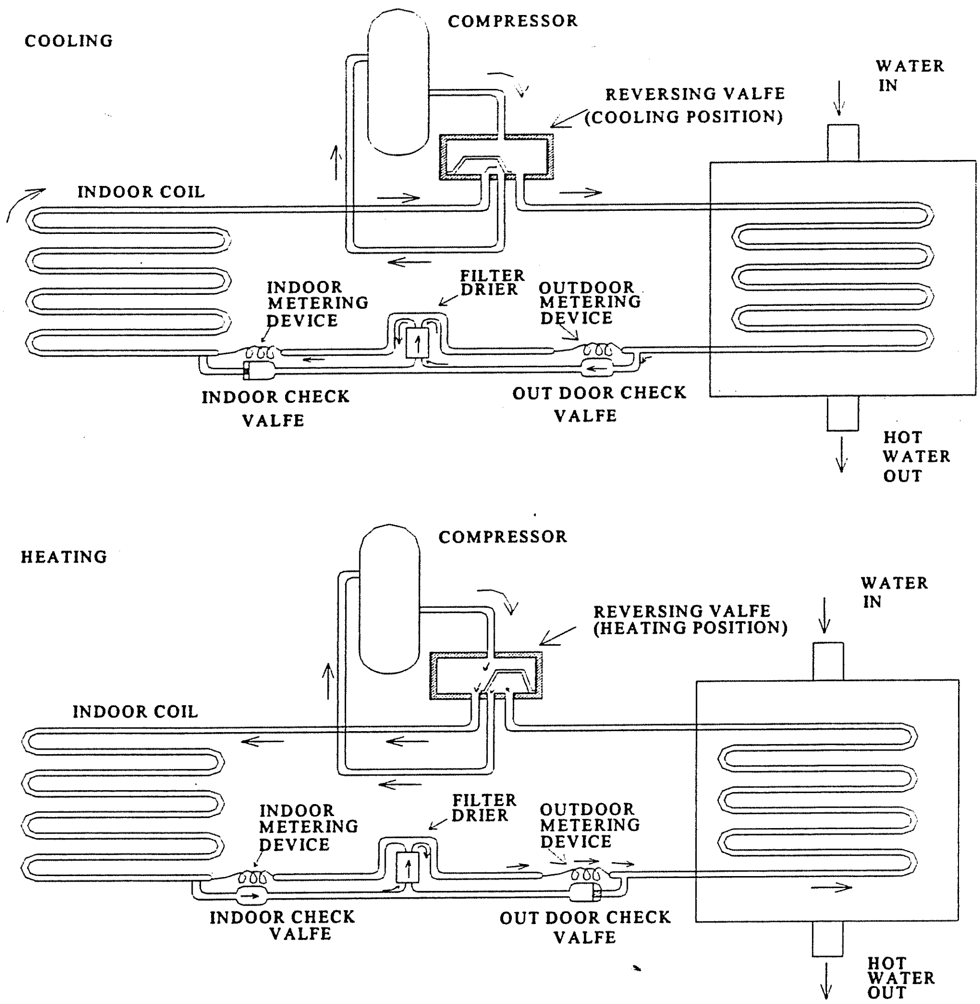


Figure 3.11. Working principle of water source heat pump

SWHP can be classified as open-loop and closed-loop. In this study, an open-loop SWHP was investigated experimentally. Working principle of open-loop SWHP is shown in figure 3.12.a.

Closed loop surface water heat pumps use closed water or brine loop that includes pipes or tubing located in the surface water (river, lake, or large pond) that serves as heat exchanger. Usually, a plastic piping is installed in either a shallow horizontal or deep vertical array to form the heat exchanger (figure 3.12, b).

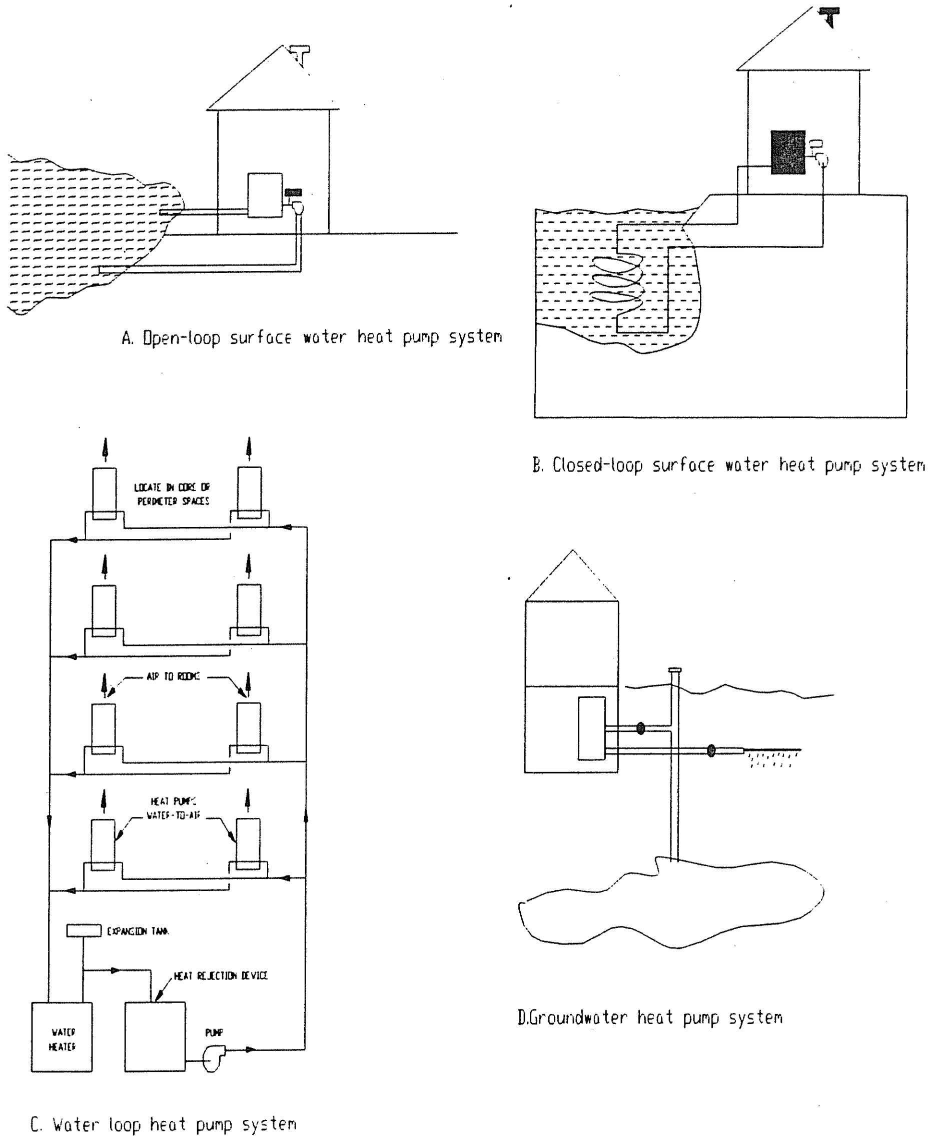


Figure 3.12. Water-source heat pump systems

Water-loop heat pumps use a circulating water loop as the heat source and the heat sink. When the loop water temperature exceeds a certain level due to heat added as the result of heat pump cooling, a cooling tower dissipates heat from the water loop to the atmosphere. When the loop water temperatures drop below a prescribed level due to heat being removed as a result of heat pump heating, heat is added to the circulating loop water, usually with a boiler (figure 3.12, c).

Ground water heat pump use groundwater from a nearby well and pass it through the heat pump's water-to-refrigerant heat exchanger where it is warmed or cooled, depending on the operating mode. It is then discharged to a drain, a stream, a lake, or returned to the ground through a re-injection well. Many state and local jurisdictions have enacted ordinances relating to use and discharge of groundwater. Since aquifers, the water table, and groundwater availability vary from region to region, these regulations cover a wide spectrum (figure 3.12,d) (ASHRAE, 1992).

In this study, the use of waters of Seyhan River and Dam Lake in heat pump systems as heat source and sink is considered. Therefore, the study focuses on the surface water heat pump systems. Kavanaugh (1991) illustrated several effective water loops used in lakewater systems (figure 3.13). The performance of the closed loop heat pump system is slightly reduced because the circulation fluid temperature degrades 2 to 7 ^{0}C when compared to the lake temperature. The second disadvantage of close loop system is the possibility of damage to coils located in public lakes. Thermally fused polyethylene or polybutlyne loops would be much more resistive to damage than copper, glued plastic, or tubing with band-clamped joints. The third possible disadvantage is fouling on the outside of the lake coil. This would be a possibility in murky lakes or in installations in which coils are located on near the lake bottom. Closed loop lakewater heat pump systems are preferred by heat pump manufactures because of the lack of water-to-refrigerant heat exchanger fouling. Properly designed systems require 50% to 75% less pumping power than open systems. The penalty is a slight decrease in capacity, but efficiency may be improved because of the smaller pump requirements (Kavanaugh, 1991).

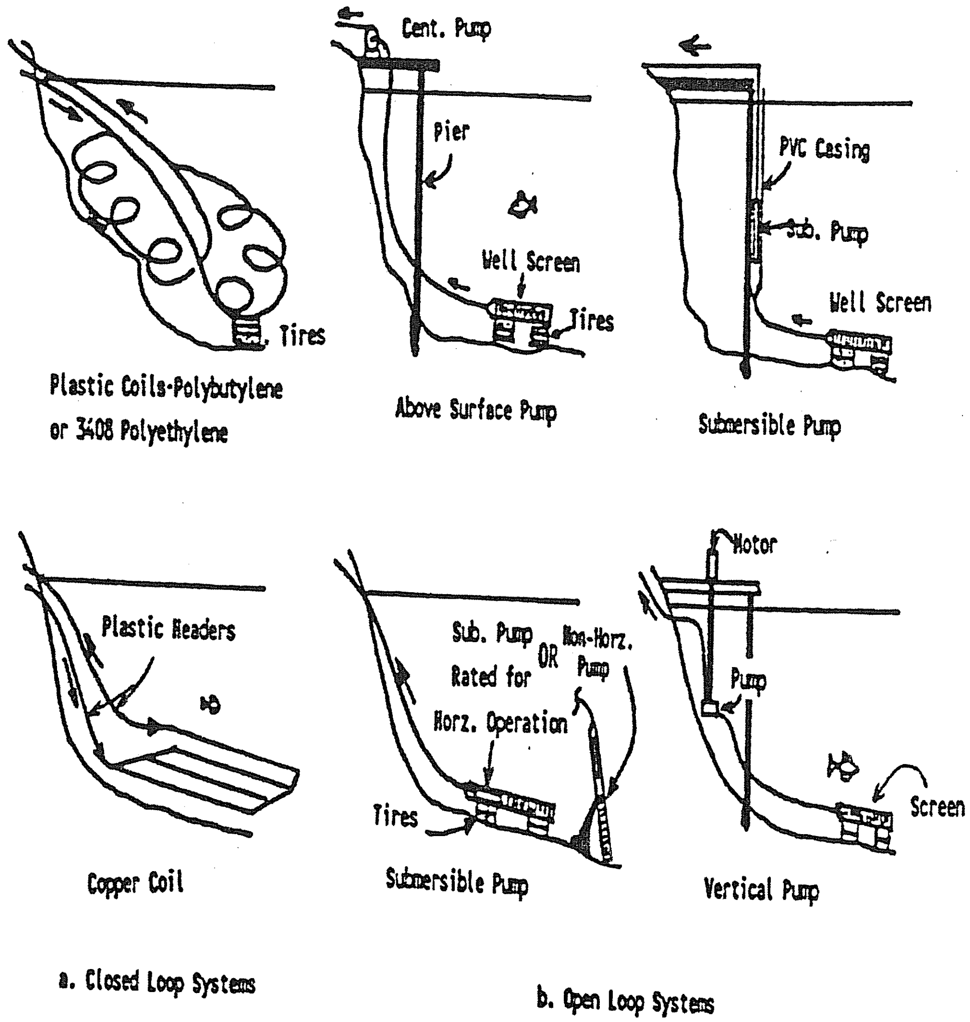


Figure 3.13. Possible coil and pump arrangements for lakewater heat pumps

Open-loop systems can utilize pumps located above, partially below, or fully submerged below the lake surface. Care must be taken to keep the pump inlet filter well off the lake bottom. Open systems are simple and less subject to damage, but fouling may result if water flow rates are too low or pump suctions are placed on muddy lake surfaces. Pumping power requirements are two to four times larger than closed systems. The performance of an open-loop coil can be more easily predicted, since the heat pump entering water temperature will be near the lake temperature. However, the unit efficiencies are typically reduced 15 % to 25% when pumping requirements are included. An important conclusion is the requirements of sufficient water flow. Successful installations require flow rate to be near 3.2 lpm/kW for both open- and closed-loop lake systems (Kavanaugh, 1991).

3.5. Heat Pump Components

The basic components of a vapor-compression heat pump are compressor, heat exchanger, and miscellaneous refrigerant components (reversing valves, expansion device, etc.). These components are given briefly below.

3.5.1. Compressors

The compressor is the heart of the refrigeration or heat pump system. The high operating temperatures and wide range of operating conditions likely to be met in space-heating heat pumps make greater demands on compressors than do air-conditioning applications, so that purpose-designed heat pump compressors are generally more reliable than units designed primarily for the smaller range of temperatures required in air-conditioning or cooling applications.

Reciprocating compressors are used more than any other type for systems in the general range of 1.75-350 kW, and larger. Reciprocating compressors are used in unitary heat pumps, and, in most cases, are either fully hermetic or accessible hermetic and should be designed and approved for this usage. The open compressor has no motor, base, or controls. The hermetic compressor has an integral motor with a separate control panel.

Centrifugal compressor characteristic essentially do not meet the needs of air-source heat pumps. High compression ratios or high lifts, associated in many instances with low gas volume resulting from low-load conditions, cause the centrifugal compressor to surge. Therefore, most centrifugal applications in heat pumps have been limited to heat-transfer systems, storage, and hydronically cascaded systems. With these applications, the centrifugal compressor enables the heat pumps to enter the large multistory buildings, and installations with double-bundle condensers up to 26.360 kW have been accomplished successfully. The transfer cycles permit low compression ratios, and many single-and two-stage units.

Rotary compressor has characteristics similar to a reciprocating compressor expect that it has low clearance and high volumetric efficiency. From this standpoint it is well suited to heat pump service, providing about 30% grater capacity than a medium clearance-reciprocating compressor. However, this characteristic also tends to increase the power demand at the maximum cooling load conditions.

Screw compressors offer high-pressure ratios at low capacities. Capacity control is usually provided by such means as variable porting or valving. Generally large oil separators are required, since currently available compressors use oil injection. They are less susceptible to damage from liquid spillover and have fewer parts than do reciprocating compressors.

3.5.2. Heat Transfer Component

A heat exchanger is a device that permits the transfer of heat from a warm fluid to a cooler fluid through an intermediate surface and without mixing of the fluids. The correct choose of heat exchangers and sizing is probably the most important factor in designing an efficient and economic heat pump. It is also in some ways the most difficult. The complex geometries of heat exchanger, together with wide variations in operating conditions, make precise calculation of sizes from basic physical principles impracticable, and various empirical factors have to be applied to heat-transfer relationships that themselves been determined by experiment. Many types of heat exchangers have been developed for use at such varies levels of technology sophistication and sizes. Heat exchanger can be considered: -the transfer process as direct and indirect contact, - compactness, - construction type as tubular plate, plate-fin, tube-fin and regenerative types, - flow arrangements as parallel, counter flow and multi-pass flow, - heat transfer mechanisms single-phase or free, forced, phase change, radiation or combined convection and radiation.

Plate exchangers are available in many configurations, materials, sizes, and flow patterns. Many are modular, and modules can be arranged to handle almost any air flow, effectiveness, and pressure drop requirement plates are formed with integral separators (ribs, dimples, ovals) or with external separators (supports, braces, corrugations) air stream separations are sealed by folding, multiple, gluing, cementing, and welding or any combination, depending on the application and manufacturer. Ease of access to examine and clean both heat transfer surfaces depends on the configurations. The experimental set-up of this study utilizes fixed plate heat exchanger as condenser and evaporator.

3.5.3. Refrigerant Components

A reversing valve changes the system from cooling mode to heating mode or from heating mode to cooling mode. This changeover requires the use of a valve(s) in the refrigerant cycle, expect where the change occurs in the fluid cycle external to the refrigerant cycle. Reversing valves are usually pilot-operated by solenoid valves, which admit head and suction pressures to move the operating elements.

In this study heating-cooling changeover is achieved by changing the direction of heat transport water. Therefore no reversing valve was used in the refrigerant cycle.

Expansion devices for monitoring the refrigerant flow are normally thermostatic expansion valves. The control bulb must be located carefully. If the circuiting is arranged so that the refrigerant line on which the control bulb is placed can become the compressor discharge line, the resulting pressure developed in the valve power element may be excessive, requiring a special control charge or pressure -limiting element. When a thermostatic expansion valve is applied to an outdoor air coil, it is desirable to have a special cross-charge to limit the superheat at low temperatures for better use of the coil. When an expansion valve is attached to a coil operated as a condenser, a bypass with a check valve is normally provided.

A refrigerant receiver that is commonly used as a storage place for liquid refrigerant is particularly useful in a heat pump to take care of unequal refrigerant requirements of heating and cooling. The receiver is usually omitted on heat pumps used for heating only (ASHRAE, 1992).

3.6. Performance of Heat Pumps

The objective of a heat pump is to maintain a heated space at a high temperature or maintain a cooled space at a low temerpature. This is accomplished by absorbing heat from a low-temperature source (Çengel and Boles, 1999). COP is the ratio of heat energy output to electrical energy input when both are measured in consistent units. Heating COP of 2 means that the heat energy output of the water heater is twice the electrical energy input. For heating mode, the coefficient performance of COP is defined as;

$$COP_{Heat} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L / Q_H} \tag{3.5}$$

For Cooling mode, the COP is defined as

$$COP_{Cool} = \frac{Q_L}{Wnet} = \frac{Q_L}{Q_H - Q_L} \tag{3.6}$$

Where, Q_H, Q_L and W_{net} are the heat extracted from high-temperature source, the heat discharged to low-temperature source and net energy input, respectively.

The performance of heat pump is affected by a large number of factors. For heat pump applications in buildings, these include:

-The climate-annual heating and cooling demand and maximum peak loads

-The temperatures of the heat source/sink and heat distribution system

-The auxiliary energy consumption (pump, fans. etc.)

-The technical standard of the heat pump

-The heat pump control system

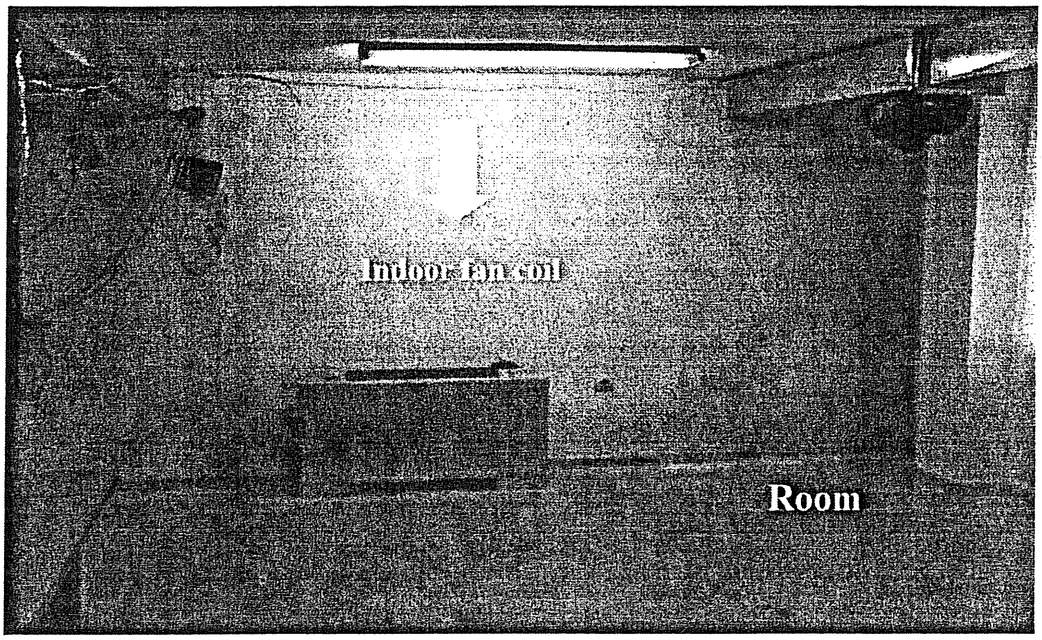
-The sizing of the heat pumps in relation to the heat demand and the operating characteristics of the heat pump (www.heatpumpcentre.org).

3.7. Experimental Study

In this experimental study, a room that is located in the Laboratories of Mechanical Engineering Department of Çukurova University was heated and cooled by a heat pump system that was capable of using both water and air as heat source and sink.

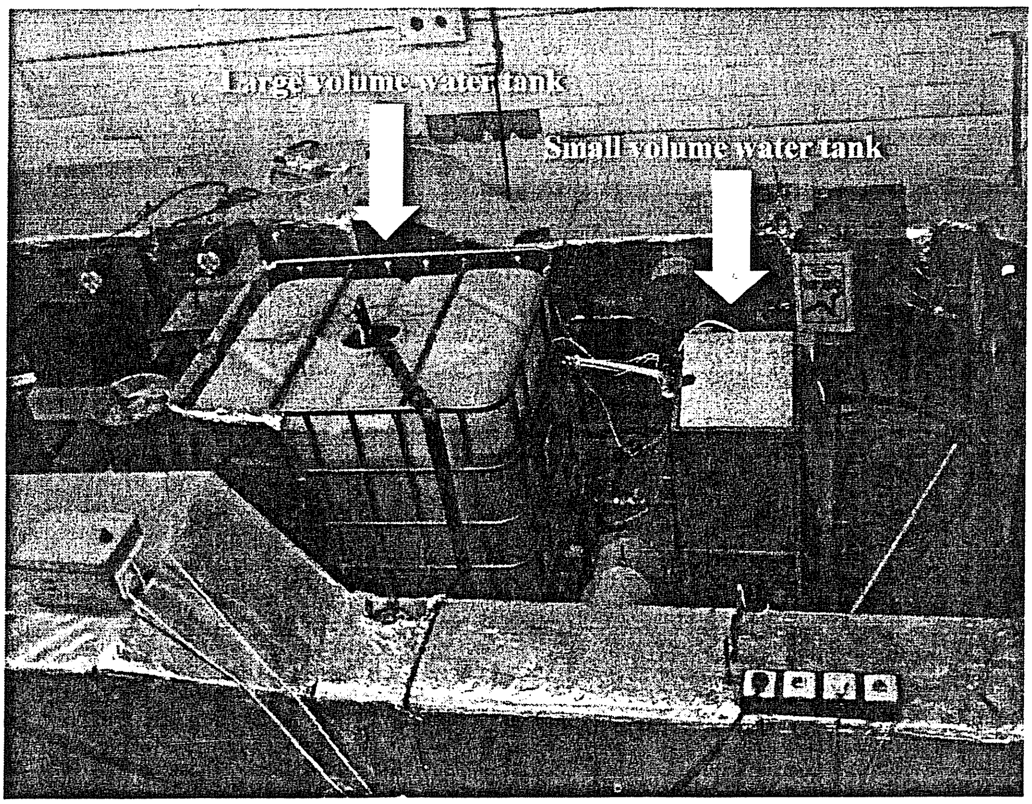
3.7.1. Experimental Set-up

Using the experimental set-up, a room (Picture 3.1) in the Laboratory was heated in winter and cooled in summer. The system mainly consists of a vapour-compression heat pump, fan-coils, circulation pumps, flow control valves, auxiliary heat pumps, electrical heaters, temperature controllers, sensors for various measurements and a data collection system.

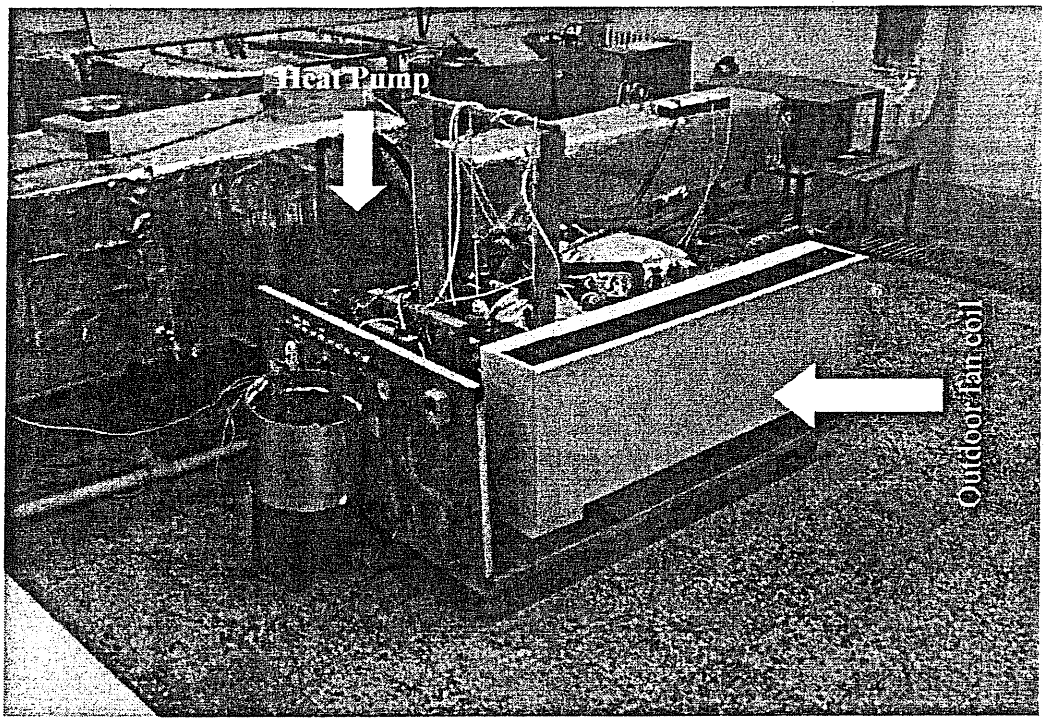


Picture 3.1. The room that is heated or cooled

The laboratory is located near the Seyhan Dam/River. However it is about 67 m above the water level. Therefore, it was not feasible to use lake water directly in the experiments. Instead of using the lake water directly, water tanks were used in the laboratory to model the lake water. One of the water tanks has a capacity of 1000 litres and serves as the main heat source and sink in the winter and summer experiments, respectively. In order to keep the temperature of the water returning to the condenser or the evaporator of the heat pump at a fixed desired value, a second water tank with 20 litre capacity was also used. An electric heater and an auxiliary air source heat pump, both controlled by PID temperature controllers were replaced into the second tank in order to make the fine adjustment of the water temperature. The temperature set values were adjusted daily so that the temperature of water returning to the system was constant and equal to that of Seyhan River. The experimental set-up is shown in Pictures 3.2 and 3.3 and also schematically in Figure 3.14.



Picture 3.2. The water tanks used in the experimental set-up



Picture 3.3. The heat pump used in the experimental study

The system has three different fluid loops, one for the refrigerant in the heat pump and two for the intermediate medium (which was water) used for the transport of energy from and to evaporator and condenser. Circulation of the transport water was provided by two separate circulation pumps. Experiments were performed in both winter and summer. Heating-cooling changeover is achieved by changing the direction of the transport medium by means of 4-way valves. Air and water were used as heat source and sink both in heating and cooling experiments. Three-way valves direct the energy transport water to the fan-coil located outdoors (air source-sink experiments) or to the water tank (water source-sink experiments).

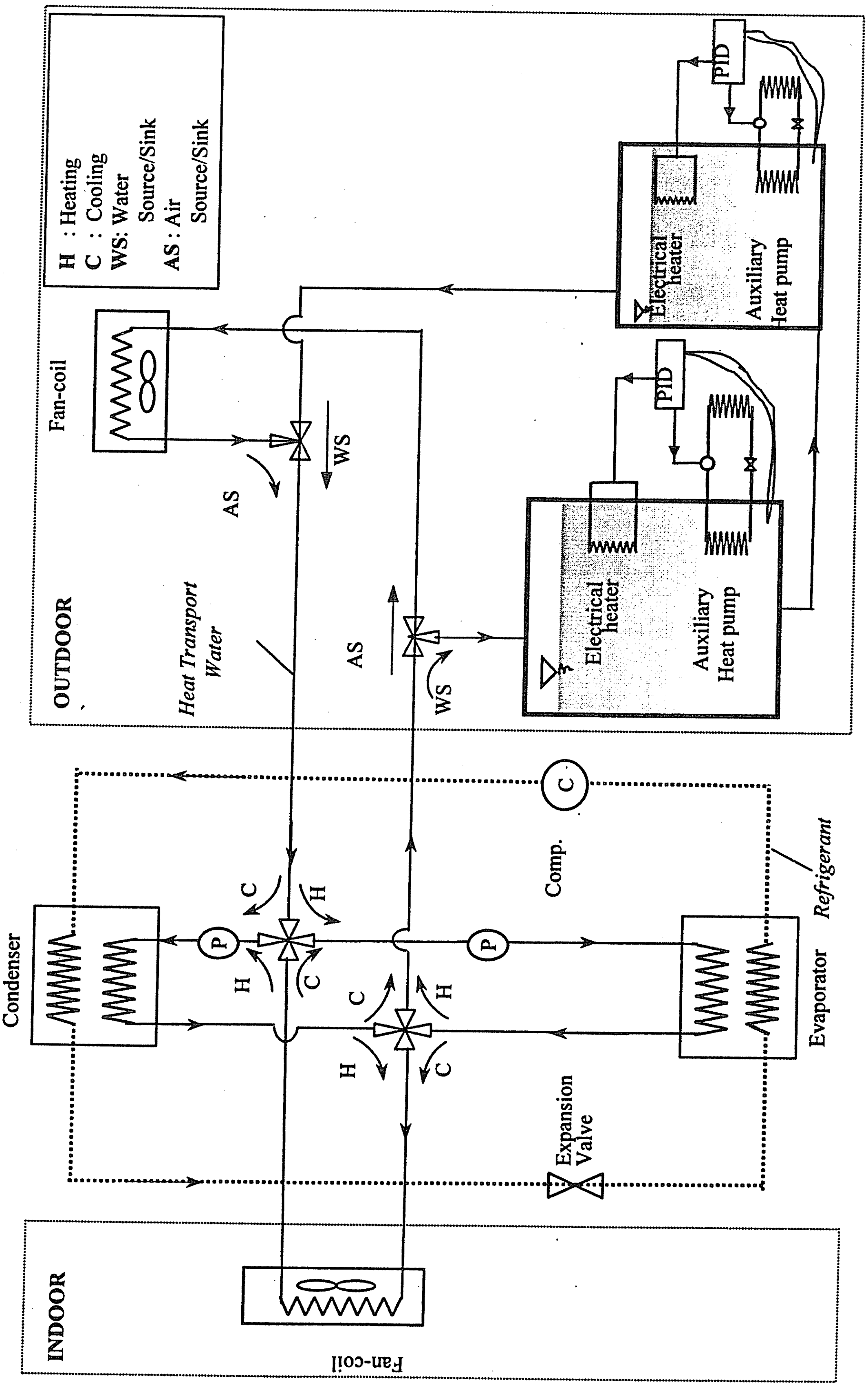


Figure 3.14. Schematic scheme of experimental set-up

The vapour compression heat pump system was designed and constructed originally by Özgören (1996) (see also Yılmaz and Özgören, (1997)) for space cooling and heating and also for hot water production. The theoretical design of the system was carried out by simulation program developed by University of Çukurova, Research and Application Center for Refrigeration and Air-Conditioning Technology. The system used by Yılmaz and Özgören (1997) was modified to carry out experiments in this study. The measurement system was also renewed, completely.

Refrigerant-22 was used as working fluid in the vapour compression heat pump. The compressor of the system has a nominal rating of 3.2 kW at conditions of 7.2 ^{0}C evaporating temperature and 54.5 ^{0}C condensing temperature. Both the condenser and the evaporator of the heat pump are plate type heat exchangers each having 0.088 m^2 heat transfer surface area. Figure 3.15 shows the details of the heat pump.

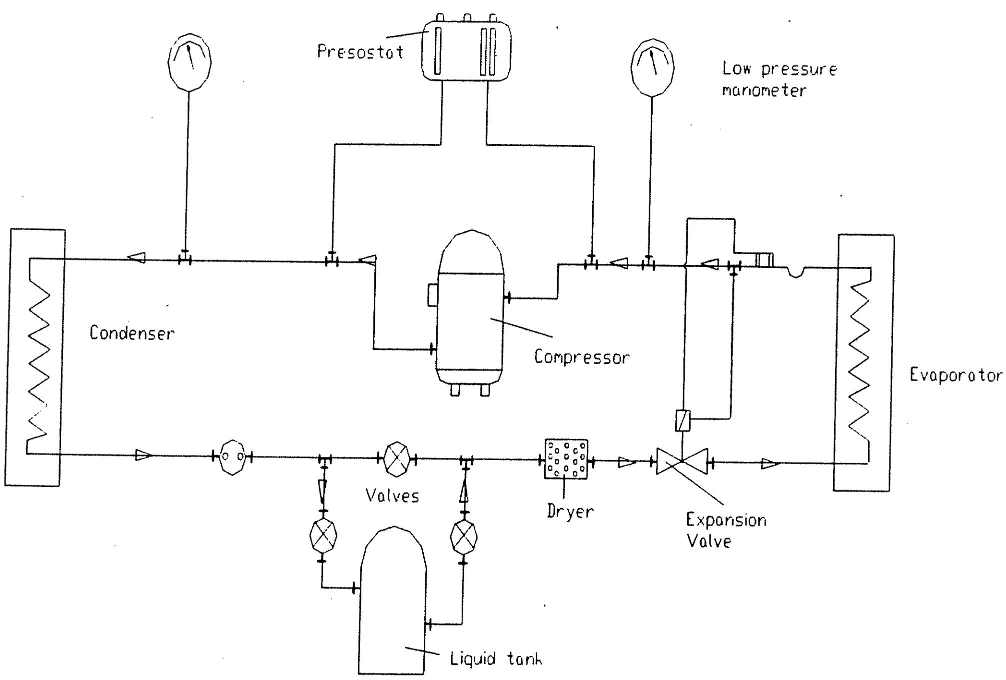


Figure 3.15. Details of the heat pump used in the experimental study

3.8. Measurement System

The amount of heat transferred in the evaporator and the condenser and the electric input were obtained to evaluate the performance of the heat pump. Total electric input to the system was evaluated from measurement of supply voltage and the current. For this purpose, electronic voltage and current transducers, which produce DC output signals proportional to voltage and current were employed.

Output capacity was determined from temperature and flow rate measurements of the energy transport water. Water temperature differences between the inlet and outlet of the condenser and the evaporator were measured using thermocouples inserted into the pipes. In addition, temperature of the water inside the water tanks, outdoor air temperature and the conditioned room temperature were also monitored with the help of thermocouples. An ice bath was employed as the reference junction for all the thermocouples used.

Two standard venturimeters (one at the inlet of the evaporator and one at the inlet of the condenser) were used for the flow rate measurement of the energy transport water. Figure 3.16 shows the measurement system

All the outputs of the measurement sensors were monitored continuously with a sampling rate of 10 readings/s, using a computer controlled data logging system. The system has a 16-bit analogue-to-digital conversion unit..

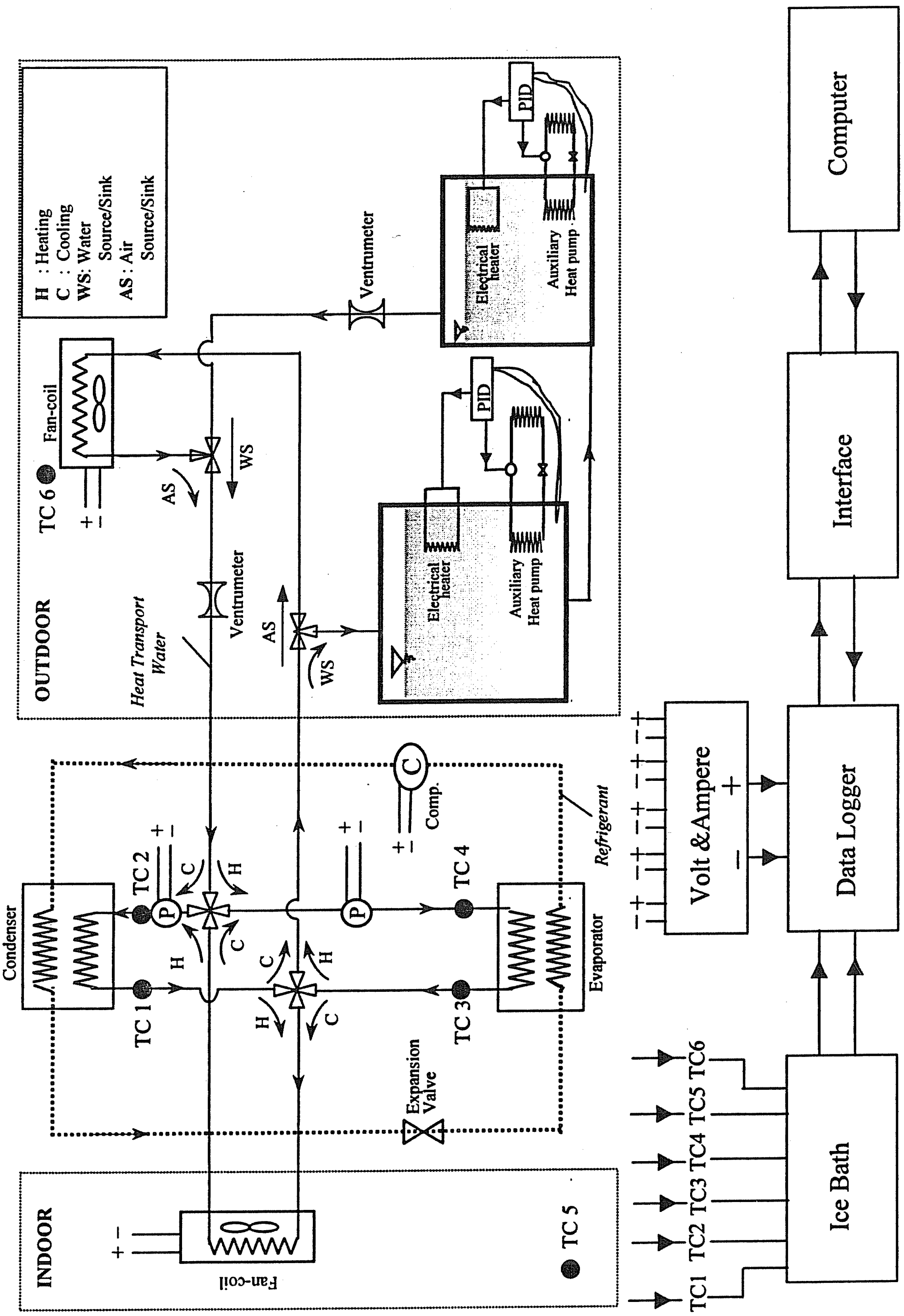


Figure 3.16. Measurement system on experimental set-up

3.8.1. Measurement of Temperatures

K type thermocouples (T/C) were used to measure the temperatures. Arrangement employed in the measurement is shown in figure 3.17.

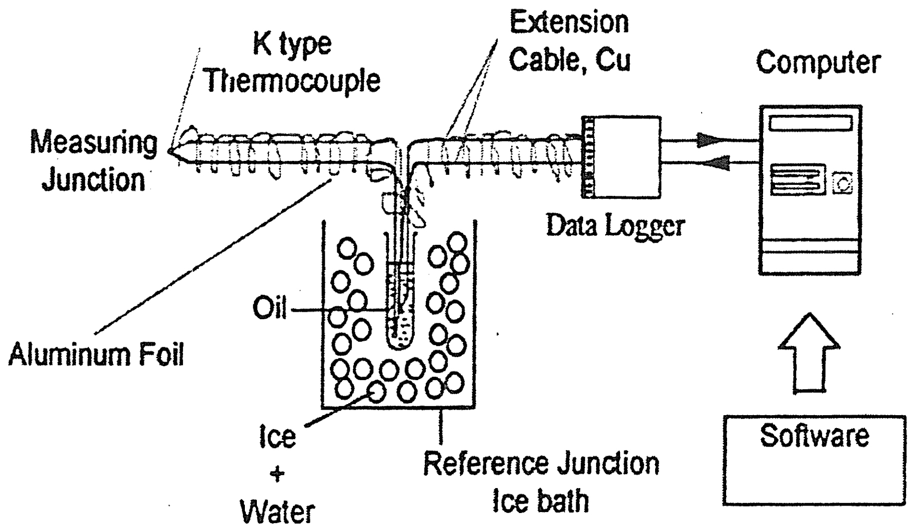


Figure 3.17. Schematic view of temperature measurement arrangement

Measuring junction (MJ) was placed into a measuring point to sense the temperature at that point. There are some desired properties from a measuring junction such as good electrical contact, low electrical resistance, and high mechanical strength. Welding, soldering, brazing, or twisting is some manufacturing processes for MJ. In this study, twisting method was used.

The other end of the thermocouple is replaced into a small oil-filled tube, which is placed into ice-water mixture to supply 0 ^{0}C reference junction (RJ). Copper wires were used to connect to measurement instrument.

The electromotor-force (emf) produced by the thermocouples is in the level of mV and measured by a data logger. The data stored in the computer in the form of mV was later converted to degree Celsius using the calibration curve shown in figure 3.18.

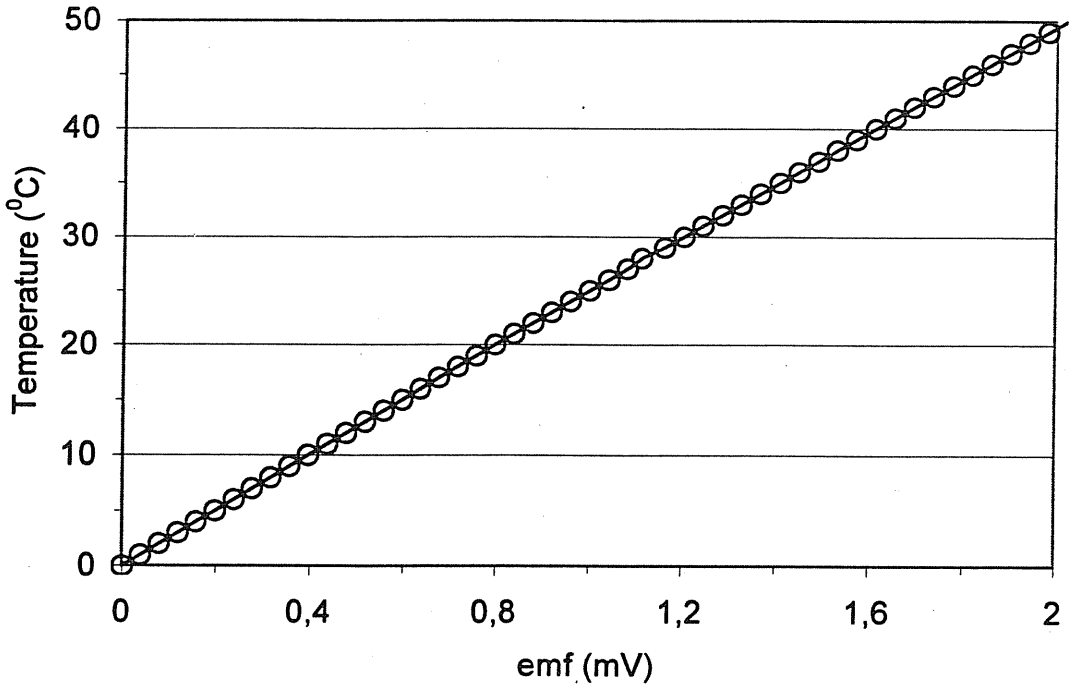


Figure 3.18. Calibration curve for T/C'used

3.8.2. Measurement of Water Flow Rate

A venturimeter (figure 3.19) was used to measure water flow rate in the condenser and evaporator water lines. The pressure difference occurred on the venturimeter was measured using a monometer. Using the pressure difference measured, the volumetric flow rate can be obtained using the equation below:

$$Q_{act} = C_d \cdot Q_{teo}$$

$$Q_{teo} = \frac{\pi . d^2}{4} \cdot \sqrt{\frac{2.\Delta P}{\left(1-\beta^4\right)}} \tag{3.7}$$

$$\Delta P = \rho . g . \Delta h$$

$$Q_{teo} = \frac{\pi . d^2}{4} \cdot \sqrt{\frac{2.g.\Delta h}{\left(1-\beta^4\right)}} \tag{3.8}$$

where Δp is the pressure difference between throat and tube diameter. ρ is fluid viscosity, g is gravitational acceleration and Δh is head differences. C_d is flow coefficient and it was taken 0.95 according to ASME.

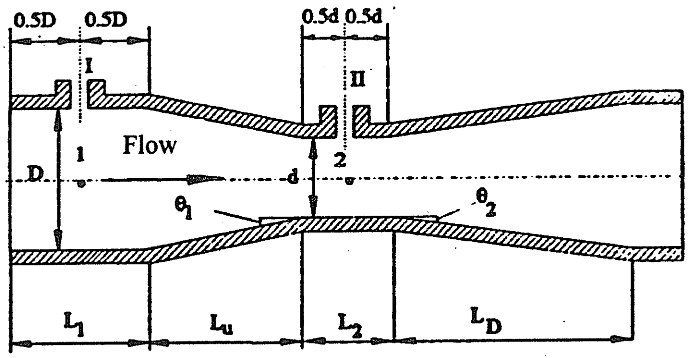


Figure 3.19 Venturimeter

3.8.3. Measurement of Electricity Consumption

A voltage and a current transducer were utilized in order to obtain electrical power consumption of the heat pump system. The transducers produce DC voltage output signals both for voltage and current inputs. The data logger used in the study accepts differential voltage between 0 and 5 VDC. Therefore, adjustment of the transducer was made so that 250 VAC input signal produces 5 VDC output and 25 A input signal produces 5 VDC output.

The calibration of the transducers was made using a standard digital multimeter. Figures 3.20, and 3.21 show the calibration curves for current and voltage inputs, respectively.

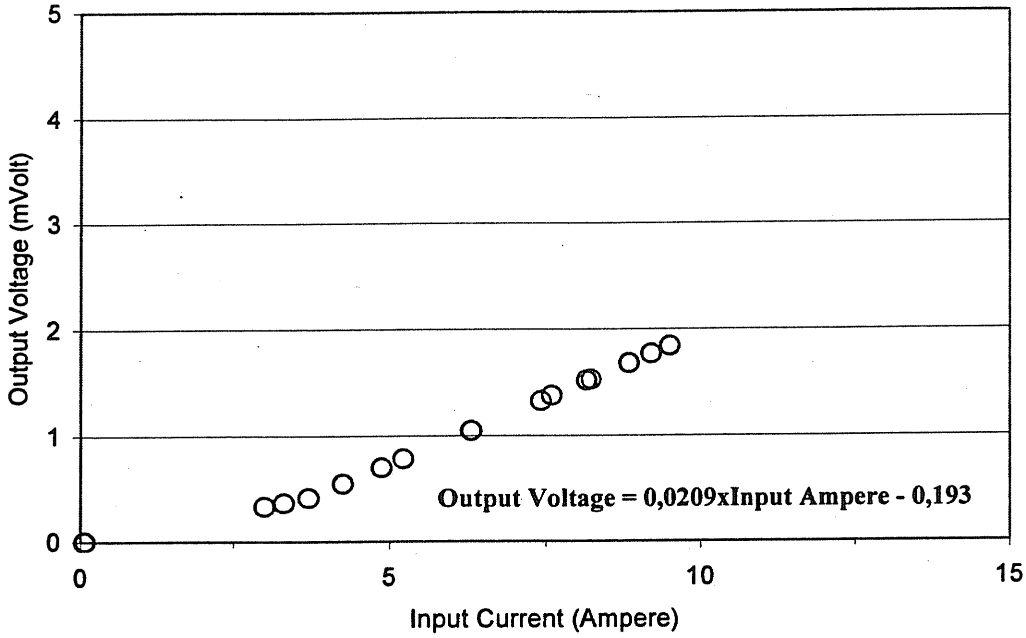


Figure 3.20. Calibration of the transducer for current input

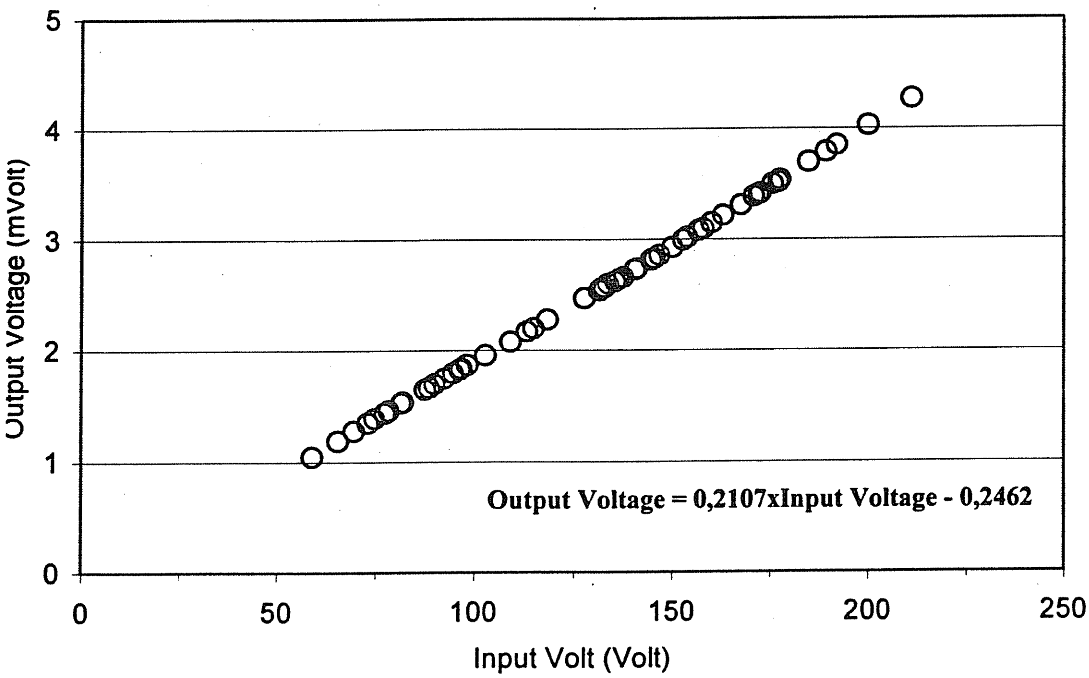
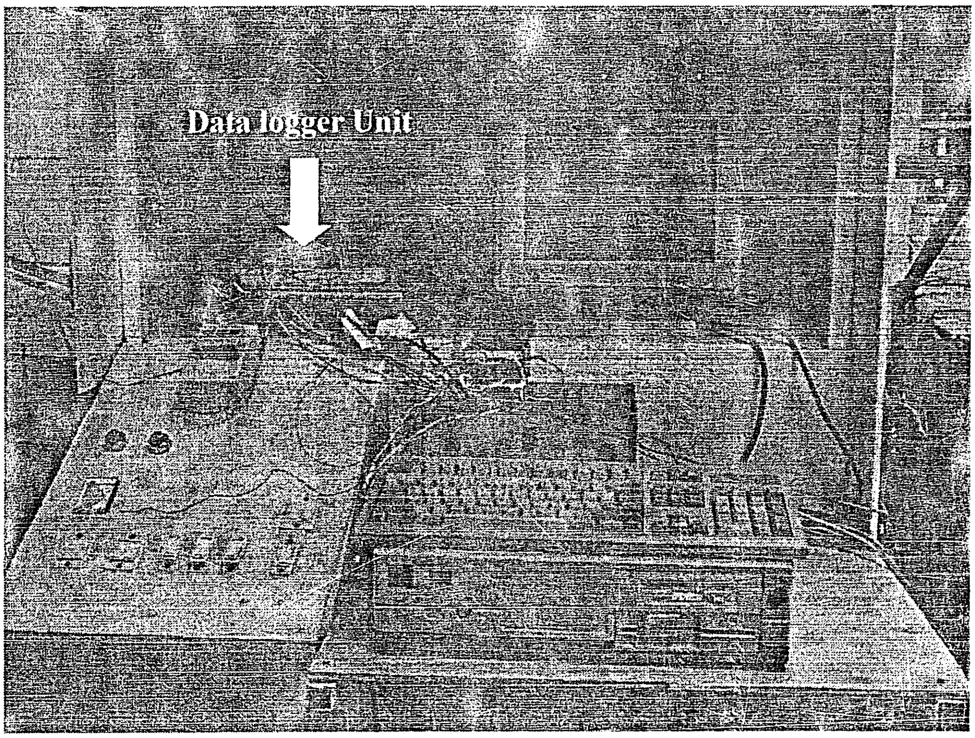


Figure 3.21. Calibration of the transducer for voltage input

3.8.4. Data Logger System

Various reading on the system were performed using a data logger (P.A. Hilton Ltd). The measured parameters are outputs of the thermocouples and voltage and current transducers. The data logger's interface is a multi channel analog and digital unit with both input and output capability. Command and data are transfer via 5 wire RS 232 serial link using ASCII character string sent and receive by a controlling computer (Picture 3.4).



Picture 3.4. Data logger unit and the computer

3.9. Evaluation of COP

The heating and the cooling performance of the heat pump were calculated, respectively, from;

$$COP_{heat}=\frac{\dot{Q}_c}{\dot{W}_{tot}}=\frac{\dot{m}_{tw}\,c_{tw}\left(T_{tw,ce}-T_{tw,ci}\right)}{\dot{W}_{comp}+\dot{W}_{pumps}+\dot{W}_{fans}+\dot{W}_{other}} \tag{3.9}$$

$$COP_{cool}=\frac{\dot{Q}_e}{\dot{W}_{tot}}=\frac{\dot{m}_{tw}\,c_{tw}\left(T_{tw,ei}-T_{tw,ee}\right)}{\dot{W}_{comp}+\dot{W}_{pumps}+\dot{W}_{fans}+\dot{W}_{other}} \tag{3.10}$$

Where $\dot{Q}_c$ and $\dot{Q}_e$ are, respectively, the amount of the heat subtracted from the condenser and added to the evaporator by the energy transport water, W_{tot} is the total power consumption of the system. $\dot{m}_{tw}$ and c_{tw} show, respectively, mass flow rate and specific heat of the transport water. $T_{tw,ci}$, $T_{tw,ce}$, $T_{tw,ei}$, $T_{tw,ee}$ are, respectively, temperature of the transport water at the condenser inlet and exit and at the evaporator inlet and exit.

It should be noted that, in equations (3.9) and (3.10), W_{tot} includes the power to the pumps ($\dot{W}_{pumps}$) used for circulation of the heat transport water and to the fans ($\dot{W}_{fans}$) of the indoor fan-coil unit and the outdoor fan-coil unit (used only in air-source experiments) and power to the control valves (three- and four-way solenoid valves), in addition to the power consumption of the compressor ($\dot{W}_{comp}$) of the heat pump. However, it does not include the energy consumption of the heaters, the auxiliary heat pump and the temperature controllers used for keeping the temperature of the water constant in the water tanks. In water source-sink experiments, the outdoor fan-coil unit is not used and, therefore, the fan power of the outdoor unit was taken zero.

4. RESULT AND DISCUSSION

4.1. Characteristics of Seyhan River and Adana

Situated in the middle of the Çukurova Plain, Adana is the fifth largest city of Turkey and located in the Eastern Mediterranean Region. It is situated 30 km inland from the north-eastern corner of the Mediterranean Sea. With a city population of over 1 million, it is the commercial centre of a thriving industrial and rich agricultural region.

Adana has a mild climate with moderate temperatures in winter and relatively high temperatures in summer. Heating degree-days for 18 ^{0}C base temperature and cooling degree-days for 22 ^{0}C base temperature are shown in Table 4.1 (Büyükalaca, *et. al.*, 2000). Heating and cooling seasons extend from mid-November to mid-April and mid-May to mid-October, respectively.

Table 4.1. Heating (18 ^{0}C base temperature) and cooling (22 ^{0}C base temperature) degree- days for Adana

Month	Heating degree-days	Cooling degree-days
January	235	0
February	197	0
March	131	1
April	33	17
May	4	80
June	0	174
July	0	264
August	0	281
September	0	220
October	4	94
November	79	5
December	191	0
Yearly	874	1136

The popularity of heat pumps is increasing rapidly in Adana. Majority of the houses built in Adana is in the form of flats in apartment blocks. A high percentage of the houses built in recent years do not have central heating or cooling systems.

The heating and cooling are usually achieved by heat pump systems. Window-type heat pump units were popular before 1990. Since then the use of split-type heat pump units has been increasing rapidly, although window type heat pump units are still on the market. Not only houses, but also other small and middle-sized light commercial buildings use heat pump systems for heating and cooling.

Air is the only heat source-sink in these systems. Although Adana has a mild climate and heating degree days are not very high (Table 4.1), the air temperature drops well below the critical temperature of 6 ^{0}C, and in some years below 0 ^{0}C. Figure 4.1 shows the variation of daily minimum air temperature during a year in Adana. In this figure, the data measured by the State Meteorological Affairs (DMİ) for the years between 1981 and 1996 (16 years) is shown. As can be seen from the figure that, there is a possibility of having air temperatures below 0 ^{0}C from December to February, even in March. In addition to this, relative humidity is quite high in the periods of the day during which the air temperature is low. This can be seen from Figure 4.2 that shows the variation of relative humidity for the years between 1981 and 1996 (16 years) at three different hours of the day (7, 14 and 21 o'clock). The relative humidity is usually higher than 60% at 7 o'clock and 21 o'clock during the whole heating season. Combination of low air temperature and high relative humidity in Adana leads to accumulation of frost on the evaporator surface of the air source heat pump units at certain hours of the day. This, in turn, leads to reduced heating capacity and performance of the heat pump systems. Since the heat pump units are usually not backed by a supplementary heating system, frost accumulation causes dissatisfactory comfort conditions are not leading to significant number of consumer complains.

Seyhan River originates from several springs in Taurus Mountains, which lie north of Çukurova Plain. The artificial lake of Seyhan Dam just north of the city centre is fed by Seyhan River. Although the amount of water in the Dam Lake varies with seasons it is around 1.2×10^9 m^3. The waters of the Seyhan River leaving the dam flow in north-south direction dividing Adana city centre into almost two equal parts (Picture 4.1).

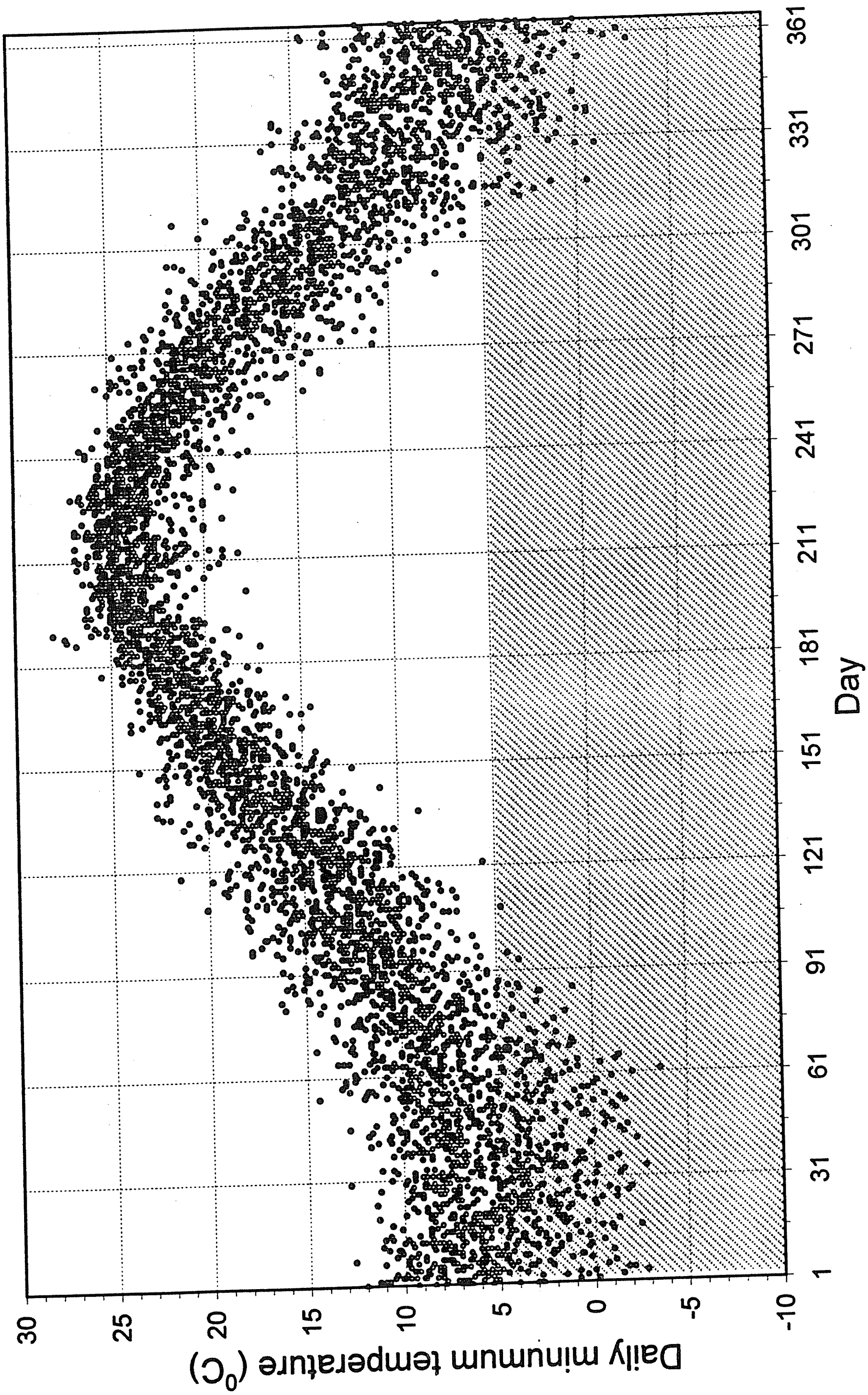


Figure 4.1 Daily minimum air temperature for Adana

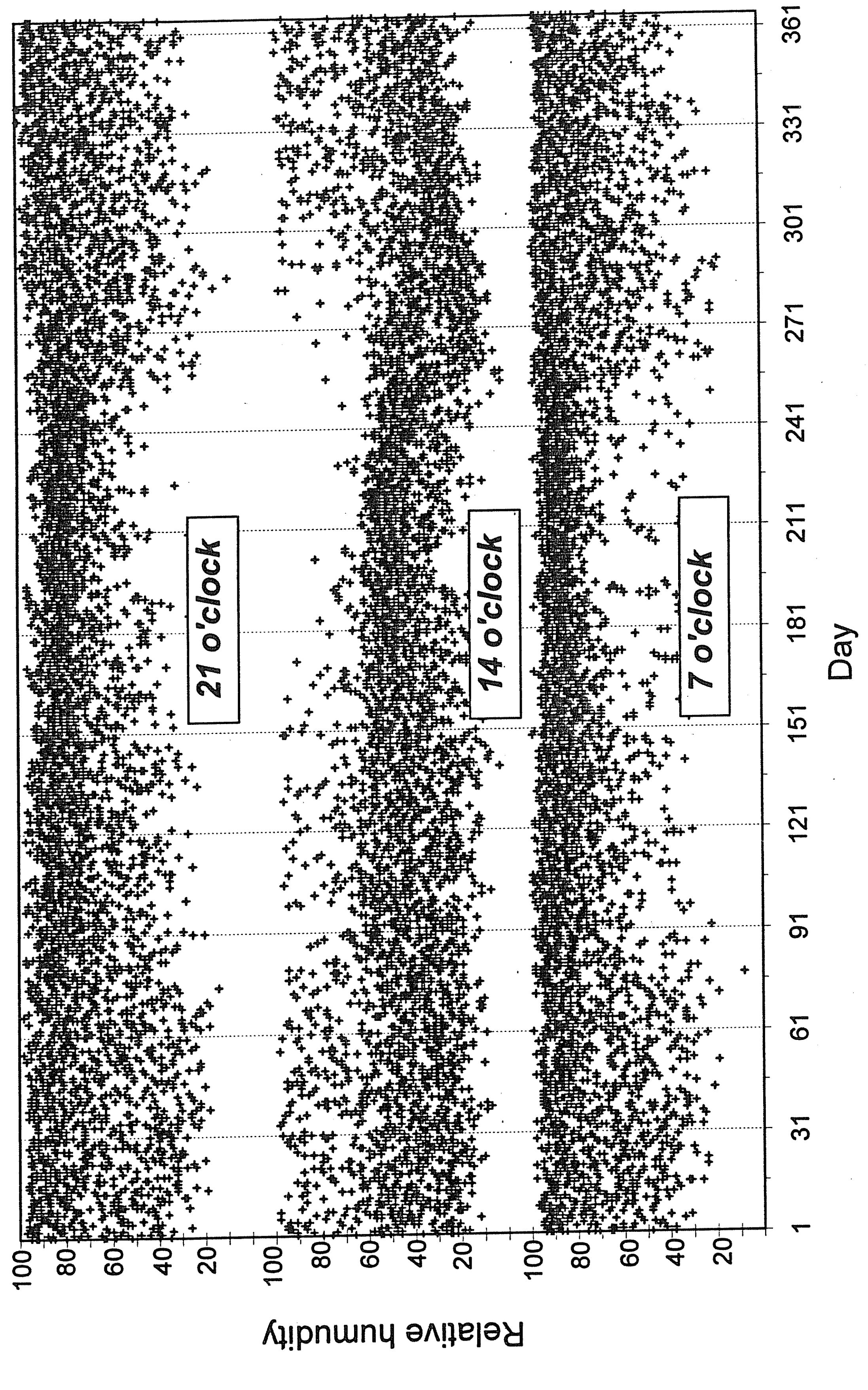
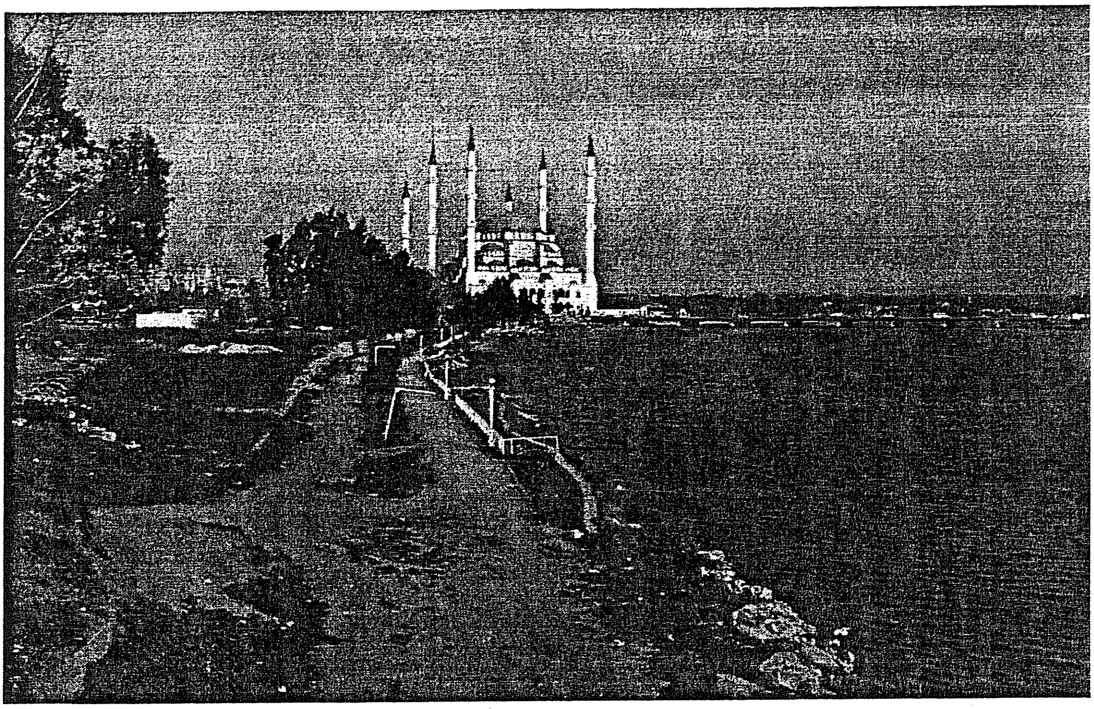


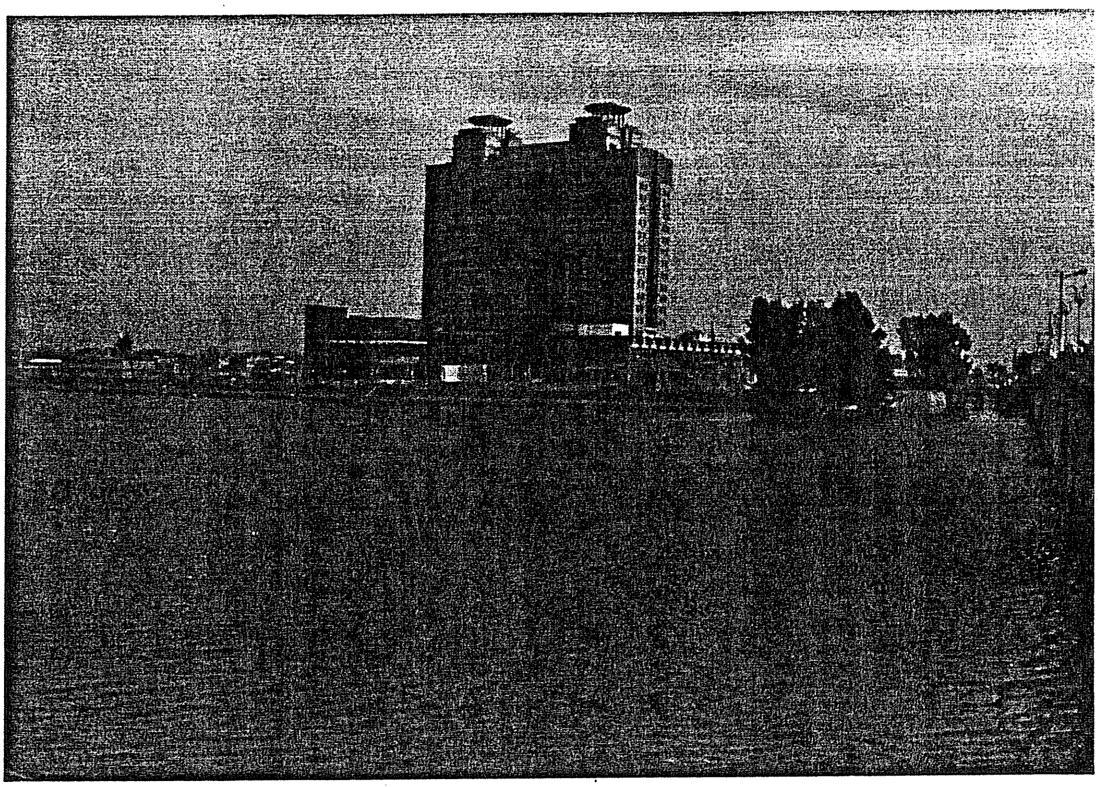
Figure 4.2 Relative humidity of air for Adana

Picture 4.1. A view of Seyhan River in city center

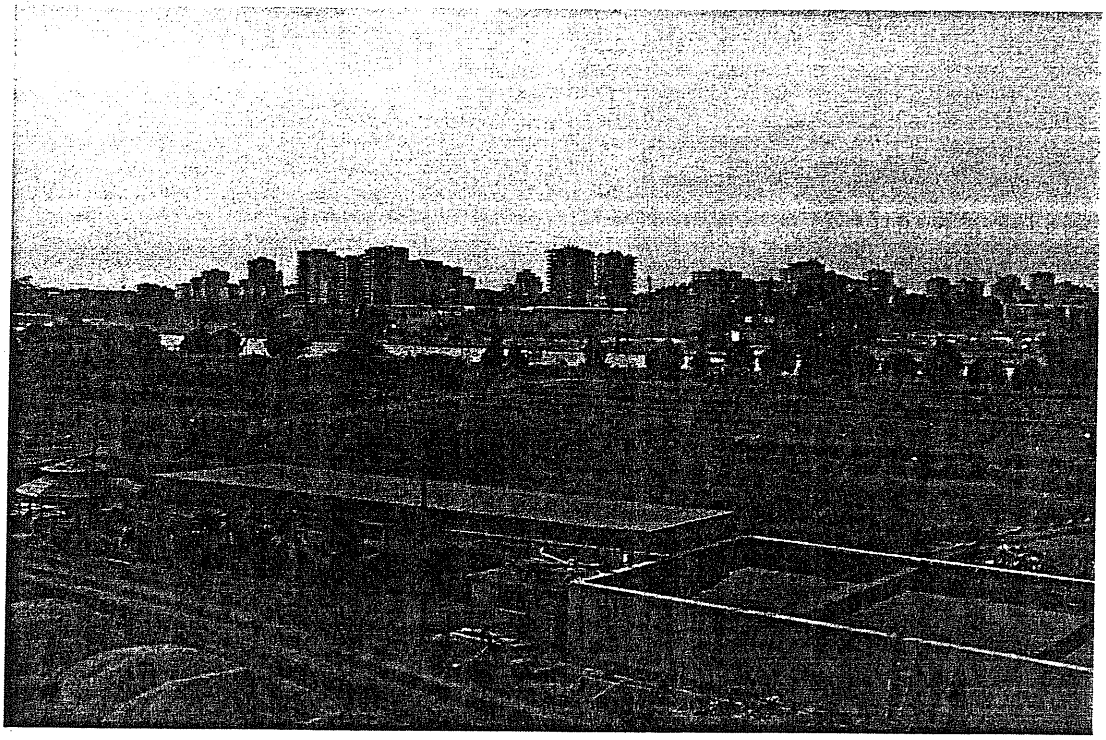
There are many buildings located on the banks of Seyhan River and the Dam Lake. These include houses (apartment blocks and duplex and triplex houses), restaurants, cafes, offices, shops, small and middle-sized industrial establishments, a 40000 m^2 shopping centre (Galeria), a big mosque (covered area for 7200 prayers) (Adana Merkez Cami), a 5-star hotel (40000 m^2)(HiltonSa Adana), 3 hospitals (total of 835 beds)(Devlet, Askeri and Numune) and a university campus (Çukurova University) of about 20000 students. Pictures 4.2, 4.3, 4.4 and 4.5 show some views of Adana Merkez cami, Hilton SA hotel, Galeria and Seyhan River, respectively.



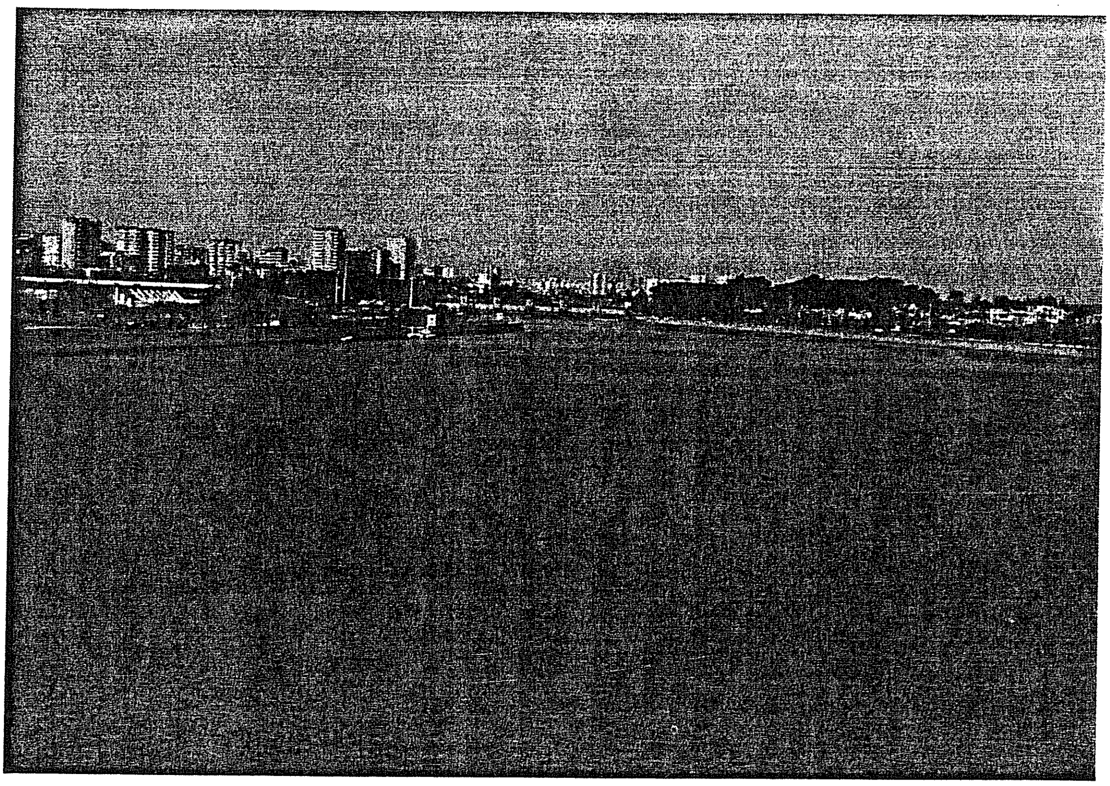
Picture 4.2. A view of Seyhan River near Central Sabancı Mosque



Picture 4.3. A view of Seyhan River near Hilton SA hotel



Picture 4.4. A view of Seyhan River near Galeria



Picture 4.5. A view of Seyhan River around Eskibaraj

In this study, possibility of using the waters of Seyhan River and Seyhan Dam Lake as heat source and sink is considered. There are many buildings near the water source (the river or the dam lake) and the distances (vertical and horizontal) between the buildings and the water are in a range that is suitable for using as heat source and sink in heat pumps for many buildings.

Thermal behaviour of water bodies should be understood before design stage is started (Kavanaugh, 1989). However, the thermal characteristics of Seyhan River have not been studied previously, although some discrete measurements of water temperature were made. However, these measurements that have not been published, are not regular and are recorded for certain days of the year. Therefore, a study was initiated to monitor the temperature of Seyhan River. The measurements were taken from the river water downstream of the dam which runs through the city. Initially, the temperature of the River Seyhan was monitored during a whole day at three different depths (0.25 m, 0.5 m and 1 m from the surface), and it was seen that the temperature does not fluctuate considerably during the day. Therefore, it was decided to measure the temperature daily. Influence of the measurement depth is also very slight in the range covered. The temperature difference between the minimum and the maximum measurement depths is usually less then 0.4 ^{0}C.

Figure 4.3 shows the depth-averaged water temperature obtained from the measurements performed between November-1999 and November-2000. Also shown on this figure are the daily minimum, daily maximum and daily average air temperatures. The air data were obtained by averaging the measured data for the years between 1981 and 1996 (16 years). A constant temperature difference of about 10 ^{0}C between the daily maximum and the daily minimum air temperatures is evident from the figure.

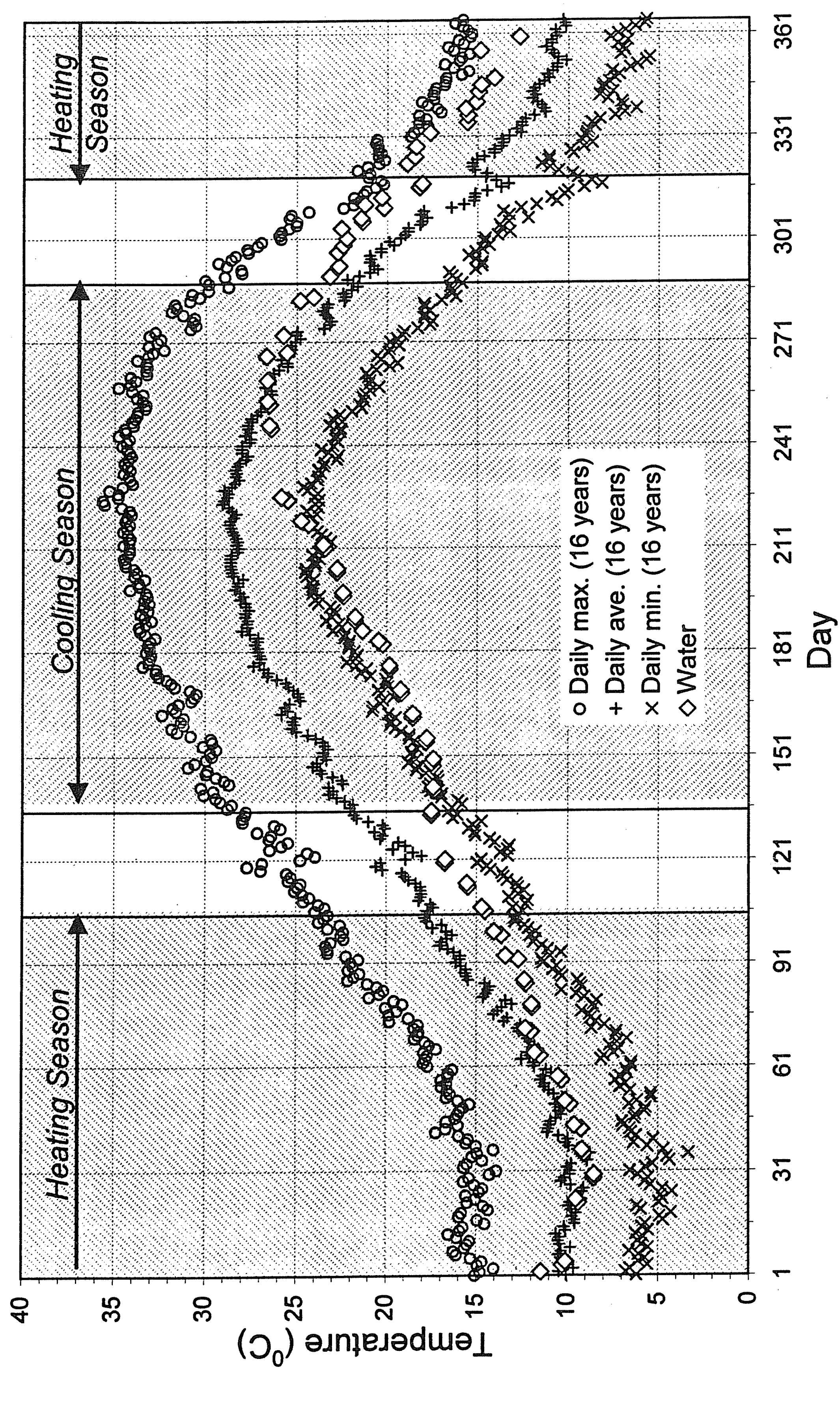


Figure 4.3 Daily minimum, daily average and daily maximum air temperature for Adana and temperature of Seyhan River

The temperature of Seyhan River is almost equal to daily average air temperature from January to mid-March. With the beginning of heavy rains in mid-March (towards the end of heating season), the water temperature drops below the daily average air temperature, however, still being higher than the daily minimum air temperature. The water temperature is about 2-3 ^{0}C higher than even the daily average air temperature from mid-November (the beginning of heating season) to December. It is close to the daily maximum air temperature. This behaviour can be explained in terms of thermal inertia of the Lake water. The water temperature starts to decrease and approaches the daily average air temperature at the end of December. It can be concluded in the light of foregoing analysis that the water temperature is always greater than the daily minimum air temperature and it is around or higher than the daily average air temperature during the whole heating season. This makes Seyhan River a good heat source alternative to air for heating with heat pumps in Adana city-centre.

When the cooling is considered, the use of Seyhan River is again favourable. The water temperature is always less than the daily maximum air temperature during the whole cooling season. It is even smaller than the daily minimum air temperature from the beginning of the cooling season (mid-May) to the beginning of August. The decrease in water temperature in May is due to melting of snow in Taurus Mountains from which Seyhan River originates. In the second half of the cooling season, the water temperature continues to increase while the daily maximum air temperature is still constant at a maximum level and, the daily minimum and the daily average air temperatures start decreasing. The water temperature becomes equal to the daily average air temperature at the end of the cooling season. It is obvious that, the water temperature is at least 5 ^{0}C lower than the maximum air temperature and the difference between the two is as high as 10 ^{0}C in a significant portion of the cooling season (from mid-May to beginning of August).

Cooling performance and capacity of the heat pump systems that utilise lake or river water as heat sink are accepted as outstanding when entering water temperature is between 13 ^{0}C and 24 ^{0}C. Performance is good for the entering water temperatures below 29 ^{0}C, and acceptable between 29 ^{0}C to 35 ^{0}C. If the water temperature is below 13 ^{0}C, direct cooling should be considered (Kavanaugh and Pezent, 1990). The temperature of Seyhan River is between 17 ^{0}C and 24 ^{0}C from a period of mid-May to beginning of August which is half of the cooling season. In the remaining period it is always less than 27 ^{0}C. Therefore, the use of Seyhan River as heat sink could be very advantageous.

The water of Seyhan River and the Dam Lake is very clean since discharge of pollutants into the river and the dam lake is limited. Because another dam (Çatalan Dam) is located about 40 km upstream of Seyhan Dam, there is no uncontrolled flow of river water (flooding) to Seyhan Dam and to the city centre. Although the water level in the Dam Lake changes with seasons, the change does not exceed 17 m. The flow rate of the water in the city centre also varies, however, due to electricity production at the Dam, it has a minimum value (288000 m^3/h) that is high enough for heat pump applications. These factors enable use of both open and closed-loop heat pump systems.

The temperature comparisons are shown in figure 4.3, the location of the river and the dam lake with respect to buildings and other parameters considered above make Seyhan River and the dam lake suitable heat source and sink for heat pump applications. However, water has not been used for this purpose at all. In this study the operation of a water-to-air heat pump using the waters of Seyhan River and the dam lake as heat source and sink was investigated experimentally. The air was also used as heat source and sink for comparison purposes.

4.2 Discussion of the Experiments

Two separate sets of experiments were performed. Heating experiments were carried out in the winter of 2000 (from January to March) and cooling experiments in the summer of 2000 (from May to August). Both air and water were utilised as heat source and sink in two sets. Tables 4.2 and 4.3 show the experiments performed in winter and tables 4.4 and 4.5 show the experiments performed in summer.

Table 4.2. Air source heating experiments

No	Date of Experiment	No	Date of Experiment
1	5 January 2000	16	7 March 2000***
2	17 January 2000	17	8 March 2000
3	18 January 2000	18	8 March 2000*
4	20 January 2000	19	8 March 2000**
5	22 February 2000	20	8 March 2000***
6	23 February 2000	21	8 March 2000****
7	24 February 2000	22	8 March 2000*****
8	25 February 2000	23	9 March 2000
9	1 March 2000	24	9 March 2000*
10	1 March 2000*	25	9 March 2000**
11	2 March 2000	26	9 March 2000***
12	2 March 2000*	27	10 March 2000
13	7 March 2000	28	10 March 2000*
14	7 March 2000*	29	10 March 2000**
15	7 March 2000**	30	10 March 2000***

* Indicates the number of the experiments carried out in a day.

Table 4.3. Water source heating experiments

No	Date of Experiment	No	Date of Experiment
1	18 January 2000	15	24 March 2000
2	21 January 2000	16	24 March 2000*
3	16 February 2000	17	24 March 2000**
4	18 February	18	18 April 2000
5	23 February 2000	19	18 April 2000*
6	23 February 2000*	20	19 April 2000
7	3 March 2000	21	20 April 2000
8	6 March 2000	22	21 April 2000
9	20 March 2000	23	24 April 2000
10	20 March 2000*	24	25 April 2000
11	21 March 2000	25	25 April 2000*
12	21 March 2000*	26	26 April 2000
13	22 March 2000	27	26 April 2000*
14	23 March 2000		

* Indicates the number of the experiments carried out in a day.

Table 4.4. Air sink cooling experiments

No	Date of Experiment
1	17 May 2000
2	17 July 2000
3	10 July 2000
4	30 May 2000
5	30 May 2000*
6	29 May 2000
7	29 May 2000*
8	26 May 2000
9	26 May 2000*
10	6 June 2000
11	13 June 2000
12	13 June 2000*
13	9 June 2000
14	19 June 2000
15	26 June 2000
16	26 June 2000*
17	27 June 2000*
18	8 June 2000
19	16 May 2000

Table 4.5. Water sink cooling experiments

No	Date of Experiment
1	3 June 2000
2	3 June 2000*
3	4 June 2000
4	4 June 2000*
5	14 July 2000
6	5 July 2000
7	31 May 2000
8	1 June 2000
9	11 July 2000
10	5 June 2000

* Indicates the number of the experiments carried out in a day.

4.2.1. Discussion of the Heating Experiments

Temperature of the Seyhan River (Figure 4.3) varies between 8 ^{0}C and 20 ^{0}C during the heating season. Therefore, the water-source heating experiments were carried out for source temperatures of between 8 ^{0}C and 20 ^{0}C.

Although it was possible to adjust the entering water temperature at any desired value, there was no control for the entering air temperature in the case of air-source experiments. The outdoor temperature varies with time during a day and it may also exhibit fluctuations. Therefore, after obtaining variation of values with time during the air experiments, mean values were calculated and used in the analysis. The air-source heating experiments were carried out for the mean air temperatures of between 6 ^{0}C and 20 ^{0}C. On the figures, given in the following sections, variation of water transport medium with time during the experiments is shown. It is clear from those figures that, the temperature of the transport water at the evaporator inlet is constant and does not exhibit considerable fluctuations. This proves that the temperature control system of the water tanks operate properly. The temperatures obtained in the case of air-source experiments exhibit fluctuations and the variations are not as smooth as seen in the water source experiments. This is due to variation and fluctuation of outdoor air temperature. The room thermostat was set to 22 ^{0}C during all heating experiments. COP_{heat} was used for both air and water source experiments.

4.2.1.1. Air Source Heating Experiments

25 air source heating experiments were performed between 6 ^{0}C and 20 ^{0}C. As an example to the air source heating experiments, the results of the experiment carried out on 1 March 2000 are given in Figures 4.4, 4.5 and 4.6 in detail. Figure 4.4 shows the values of the temperature at various measurement locations during the experiment. The heat pump system reaches to steady state after approximately 2200 seconds. The temperature of the heat transport water at the evaporator exit and at the inlet fluctuate. Also fluctuations occur at the condenser inlet and exit. The temperature of the heat transport water at the condenser outlet increases steadily to a value of 39 ^{0}C, and remains almost constant at this value. The temperature difference between the inlet and exit of the condenser is about 5 ^{0}C. The temperatures of the heat transport water at the evaporator inlet and outlet are 12 ^{0}C and 8 ^{0}C, respectively. The difference between them is about 4 ^{0}C.

Fluctuations in the outdoor air temperature caused large fluctuations in the amount of the heat transferred from condenser and to evaporator (figure 4.5). Figure 4.5 shows the amount of the heat transferred in the condenser, and in the evaporator and, the total electric consumption. Their mean values are 2.5 kW, 1.3 kW and 1.2 kW, respectively.

Figure 4.6 shows variation of COP_{heat} of the system with time which was calculated using Eq.3.9. It is clear from this figure that, the mean value of the COP_{heat} is around 2.8.

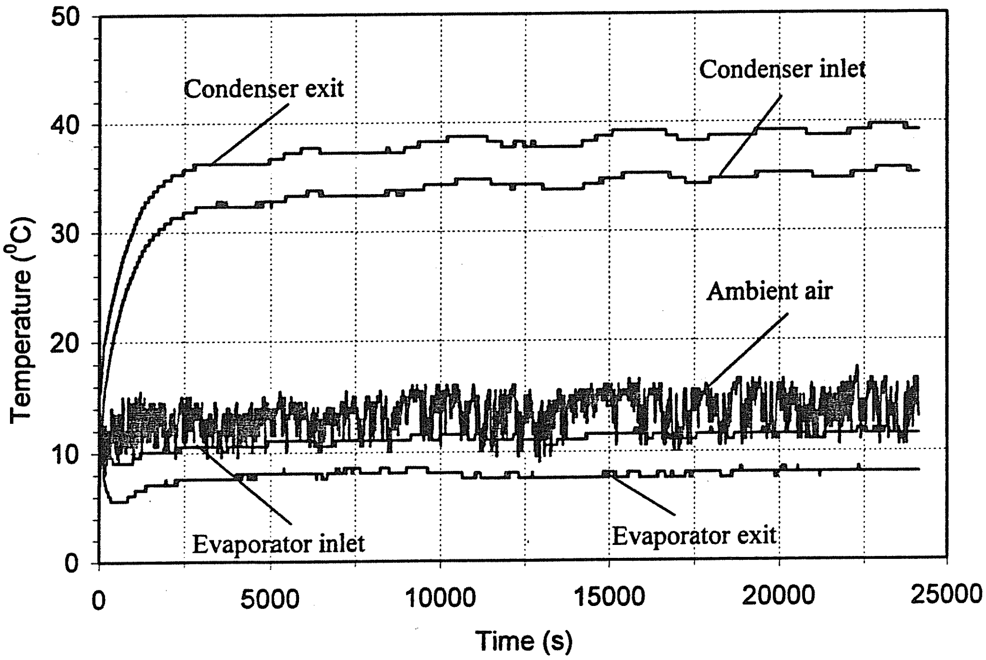


Figure 4.4. Temperature of the transport water in a typical heating experiment with air as heat source

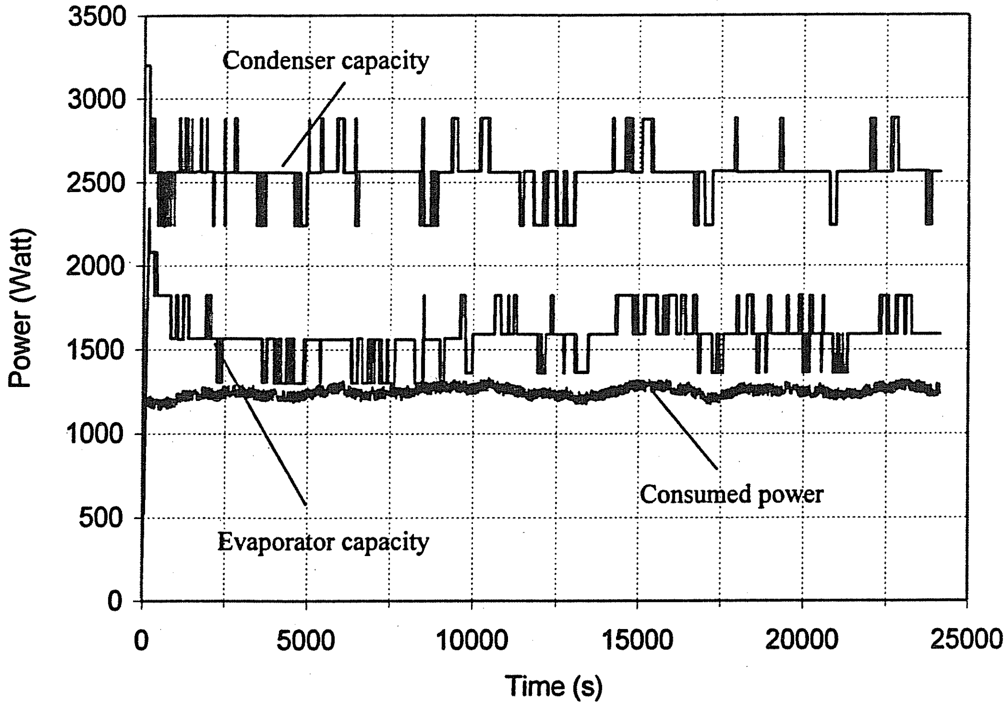


Figure 4.5. Variation power values with time during an air source heating experiment

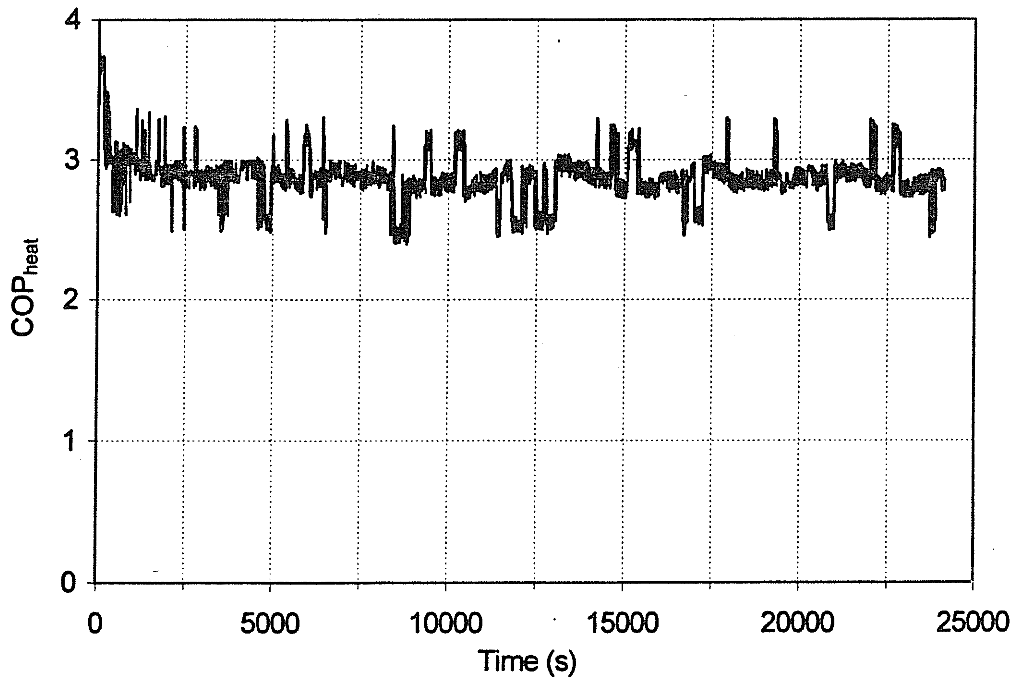


Figure 4.6. Variation of COP_{heat} with time

4.2.1.2. Water Source Heating Experiments

23 water source heating experiments were performed between 8 ^{0}C and 20 ^{0}C. As an example to the water source heating experiments, the results of the experiment performed on 6 March 2000 are given in Figures 4.7, 4.8 and 4.9. The heat pump system reaches to steady state balance after 2000 seconds.

In figure 4.7 the temperature at the condenser outlet is 47 ^{0}C and the temperature difference between the inlet and the exit is approximately 5.43 ^{0}C after steady state. During the experiment, the evaporator inlet temperature was kept at 20 ±0,2 ^{0}C. In figure 4.8, the heat transfer in the condenser and evaporator, and the electric consumption are about 3.2 kW, 1.8 kW and 1.4 kW respectively. In figure 4.9, variation of COP_{heat} with time is shown. COP_{heat} is around 3.2 in steady-state region.

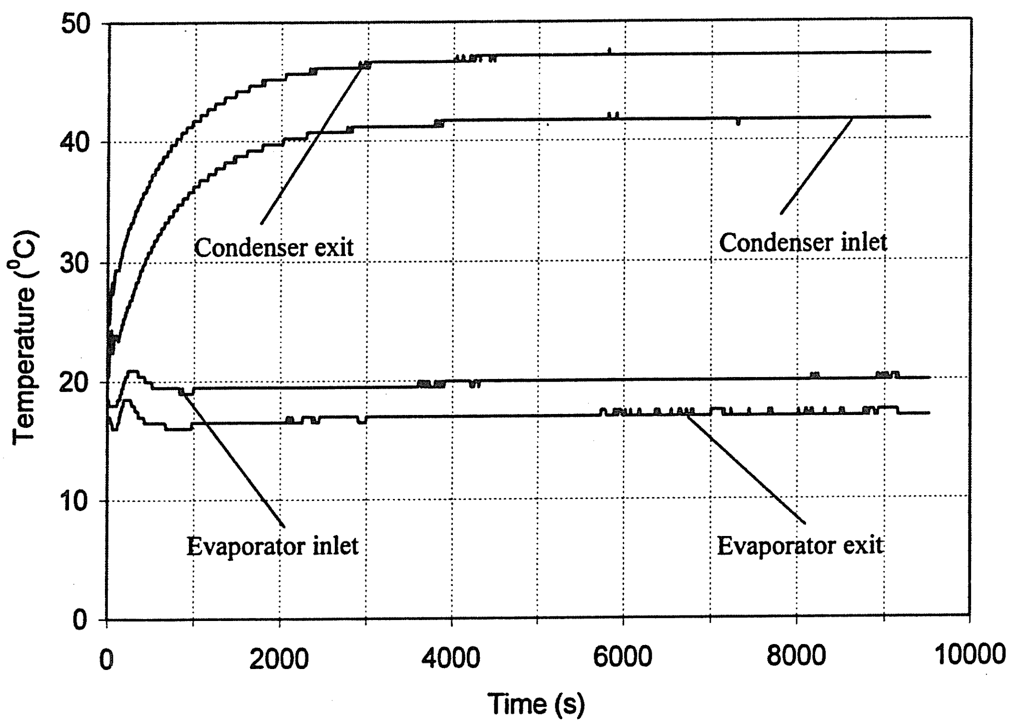


Figure 4.7. Temperature of the transport water in a typical heating experiment with water as heat source

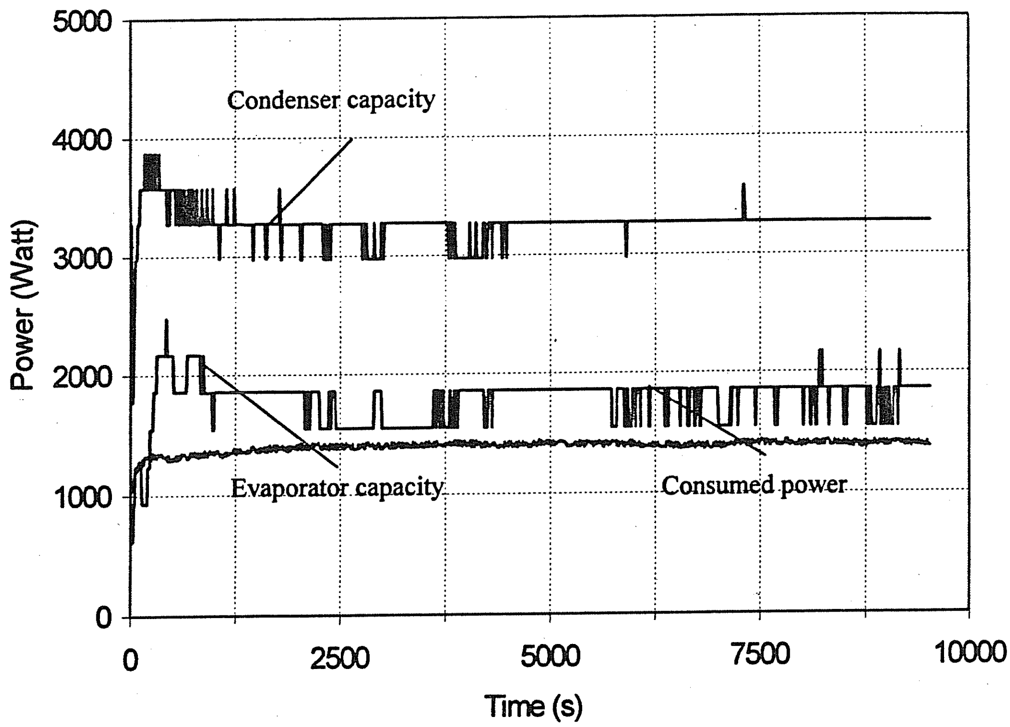


Figure 4.8. Power values versus time during experiment

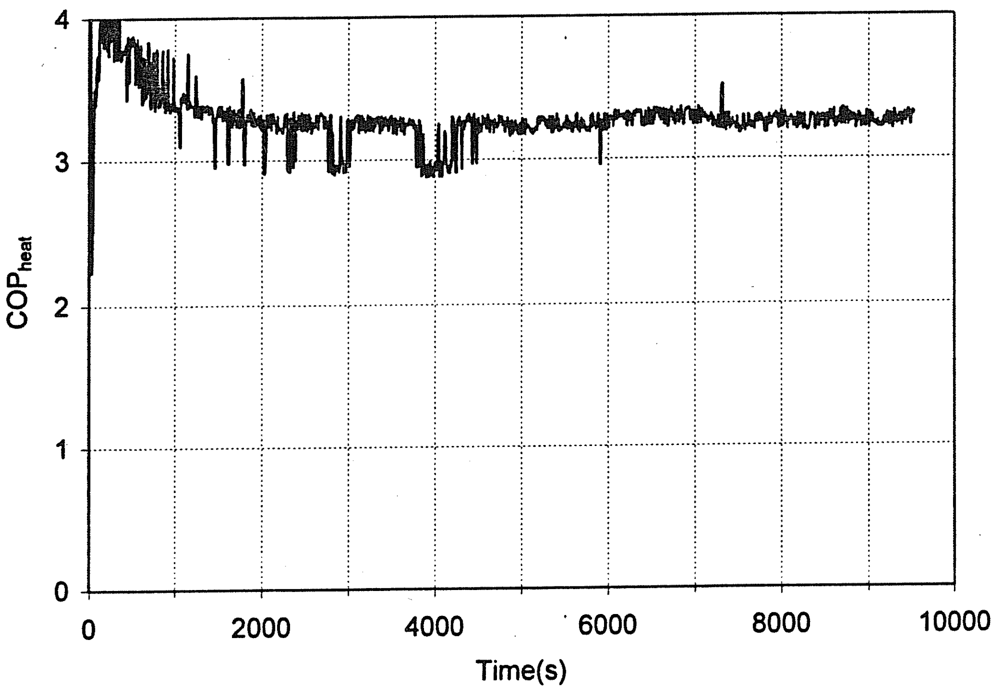


Figure 4.9. Variation of COP_{heat} with time

Figure 4.10 presents the mean *COP* values obtained from the heating experiments performed with various water and air temperatures. COP_{heat} was calculated from Equation (3.9). As expected, with the increase of source temperature, COP_{heat} increases for both sources.

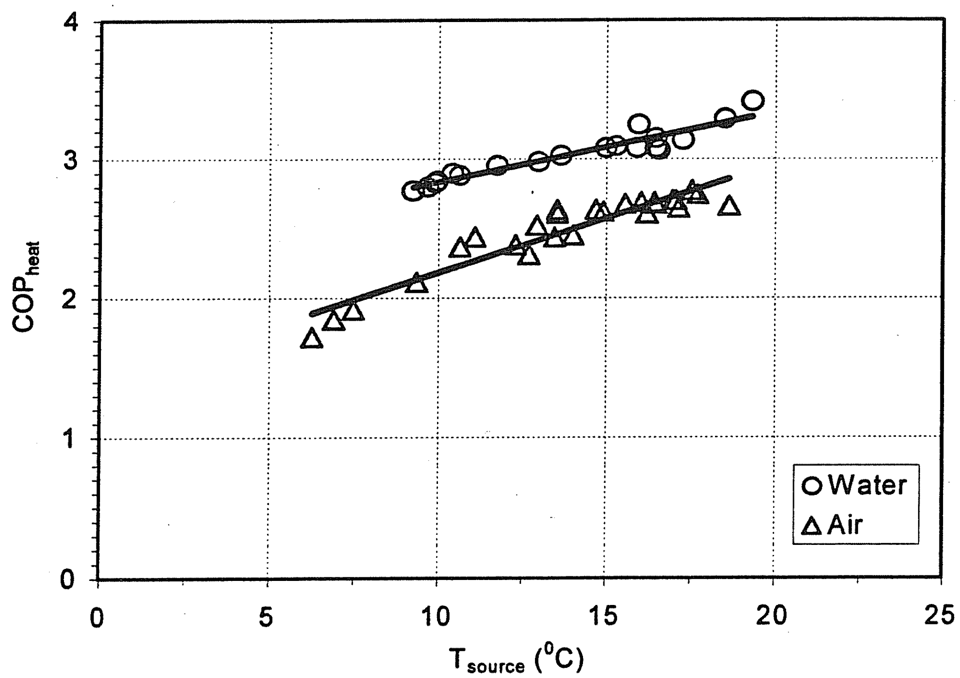


Figure 4.10. COP_{heat} for the heating experiments with water and air as heat source

A least-square, linear curve fit to the data points yields the following equations:

$$COP_{heat} = 2.33 + 0.050 x T_{source} \qquad \text{(For water-source)} \qquad (4.1)$$

$$COP_{heat} = 1.40 + 0.078 x T_{source} \qquad \text{(For air-source)} \qquad (4.2)$$

where T_{source} is in ^0C.

It is evident from Figure 4.10 that, COP_{heat} in the water-source experiments is about 15%-40% higher than that of the air source experiments for the same source-temperature. This is mainly due to absence of power consumption of the outdoor fan-coil unit (not used) and direct heat exchange between the source (the water within the tanks) and the refrigerant in the evaporator in the case of water-source experiments. In the water-source experiments, the water taken from the water tanks is circulated through the liquid-side of the evaporator. However, in the air-source experiments, the outdoor unit operates (the fan consumes energy) and the heat transfer between the source (ambient air) and the refrigerant in the evaporator is achieved by means of the heat transport water that circulates between the liquid-side of the evaporator and the outdoor fan-coil unit. This results in a less effective heat transfer and COP_{heat} is reduced. However, in real water source-sink applications, there will be a pump to circulate the water between the water source (lake, river, etc.) and heat pump system and the COP will decrease proportionally to the power consumption of the pump. This is valid for both heating and cooling modes. On the other hand, the power consumption of the pump is proportional to the distance and the elevation between the water source and the system. Therefore, feasibility of utilising water as heat source-sink in heat pump systems depends on the distance and the elevation between the water source and the building. Suitability of using water as heat source-sink in heat pump systems should be decided separately for each building. However, as a rough guide, the performance of the water source-sink heat pump units is reduced 15% to 25% in order to take into account of pumping power (Kavanaugh and Pezent). If this approach is applied to the water source results obtained in this study, equation (4.1) will produce COP_{heat} values close to that of equation (4.2) which was obtained from the air-source data.

Figure 4.11 shows COP_{heat} values calculated using Equation (4.2), which was obtained from the air-source data considering the whole heating season. Equation (4.2), instead of Equation (4.1), was also used for the water in order to take into account of power consumption of the pumps in real applications. The daily minimum, the daily average and the daily maximum air temperatures were used as the source temperature in the case of air source.

As discussed above, the temperature of Seyhan River is always greater than the daily minimum air temperature and it is around or higher than the daily average air temperature during the whole heating season (Figure 4.3). Reflection of this trend can be seen in terms of COP_{heat} (Figure 4.11). COP_{heat} of water source is around or higher than COP_{heat} calculated using daily average air temperature except at the end of the heating season (from mid-March to end of April). However even in this period, COP_{heat} of water is better if the daily minimum air temperature is considered. Use of water as heat source is very beneficial especially at the beginning of the heating season (from mid-November to beginning of January) during which COP_{heat} of water approaches to that of daily maximum air temperature. However, the pumping power requirement of a particular application should also be considered. It is clear that use of water will eliminate defrosting and its negative consequences such as reduced capacity, performance and comfort conditions.

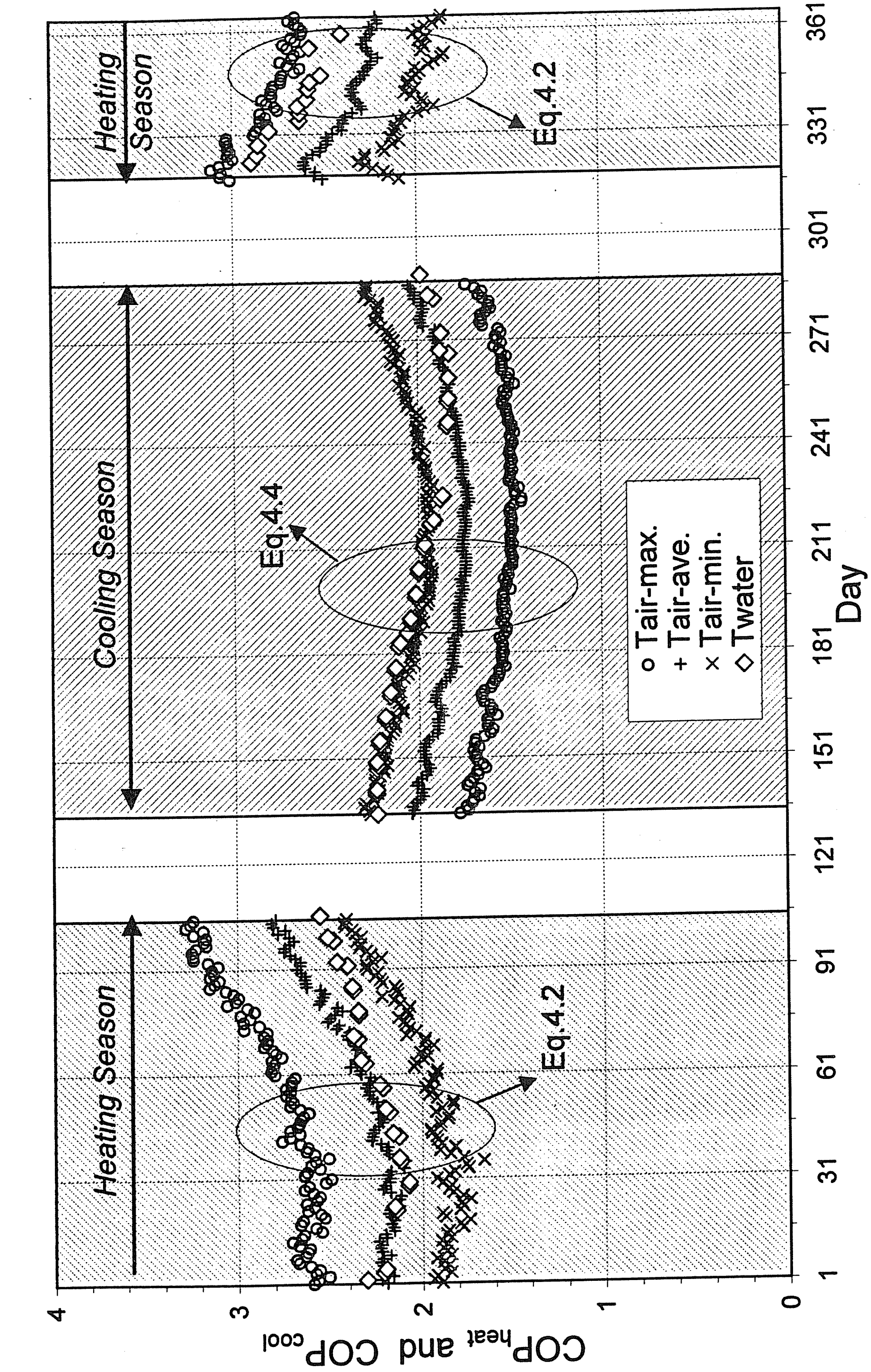


Figure 4.11 COP$_{heat}$ and COP$_{cool}$ values calculated using Eqs. (4.2) and (4.4)

4.2.2. Discussion of the Cooling Experiments

Cooling experiments were performed for sink temperatures between 20 ^{0}C and 40 ^{0}C for water and between 22 ^{0}C and 40 ^{0}C for air. COP_{cool} was calculated from Equation (3.10).

During the water source cooling experiments, the heat pump system was operated with an auxiliary heat pump to keep the water temperature in set value. Compressor of the auxiliary heat pump was controlled by PID controller device in cooling experiments.

4.2.2.1. Air Sink Cooling Experiments

18 air sink cooling experiments were performed between 22 ^{0}C and 40 ^{0}C. Figures 4.12, 4.13 and 4.14 show the results of a typical air sink cooling experiment carried out on 17 July 2000.

Figure 4.12 shows the temperatures at different locations of the experimental set-up. The temperature of the heat transport water at the condenser outlet and inlet is about 47 ^{0}C and 42 ^{0}C in steady-state region, respectively. The temperature difference between inlet and exit is about 5 ^{0}C. The mean temperature at the evaporator inlet and the outlet is about 15 ^{0}C and 13 ^{0}C, respectively. The temperature difference is about 2 ^{0}C.

The amount of the heat transferred in the condenser and in the evaporator, and the electric consumption of the system are 3.3 kW, 1.8 kW and 1.5 kW, respectively (figure 4.13).

The COP_{cool} varies with time between 1.58 and 1.72 (figure 4.14).

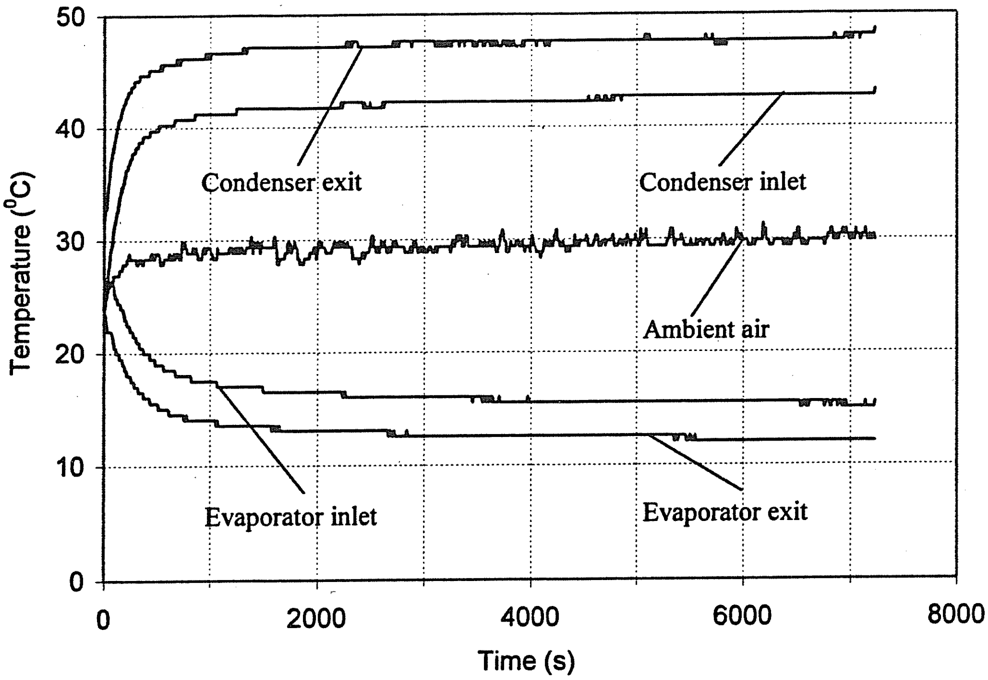


Figure 4.12. Temperature of the transport water in a typical cooling experiment with air as heat sink

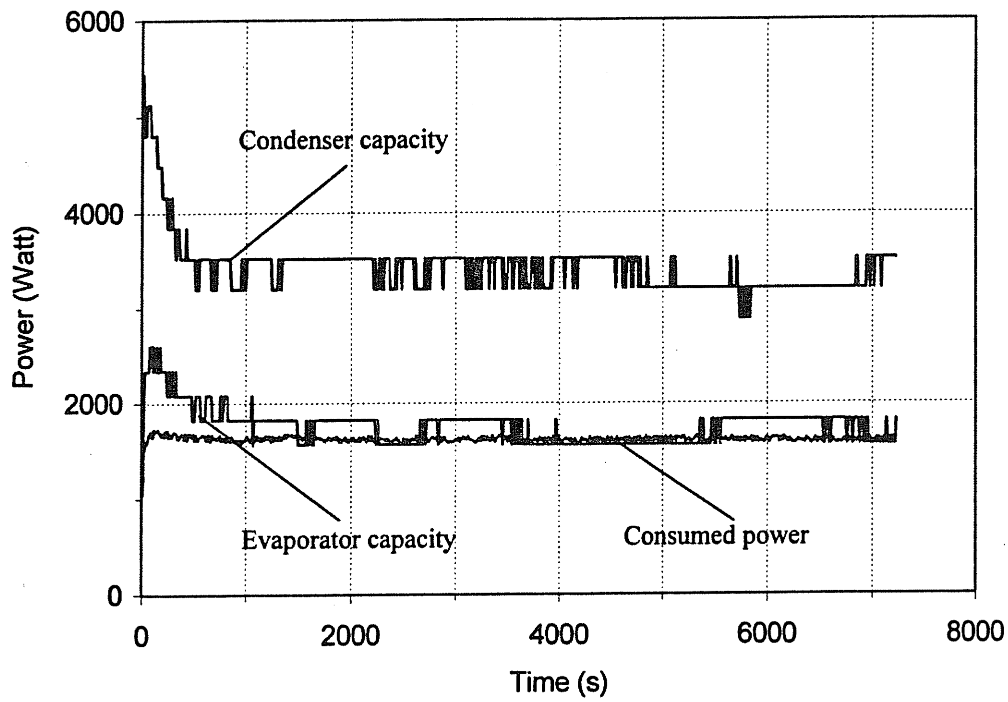


Figure 4.13. Power values versus time during experiment

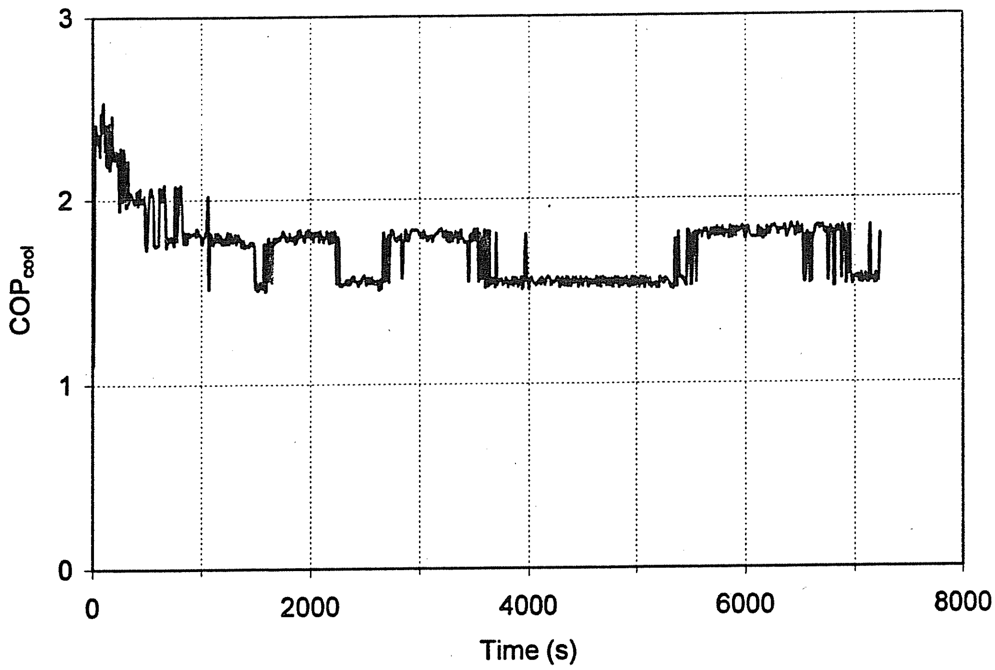


Figure 4.14. Variation of COP$_{cool}$ with time

4.2.2.2. Water Sink Cooling Experiments

10 water sink cooling experiments were performed between 20 ^{0}C and 40 ^{0}C. As an example to water source experiments, the results of the experiment performed on 1 June 2000 are given in Figures 4.15, 4.16 and 4.17.

Figure 4.15 shows the value of the temperatures at various measurement locations during experiment. The temperature of the heat transport water at the condenser inlet was kept at 26±0.3 ^{0}C by the auxiliary heat pump. The difference between the inlet and exit is about 3.45 ^{0}C. The evaporator inlet and outlet temperatures are 9 ^{0}C and 5 ^{0}C, respectively.

The amount of the heat transferred in the condenser and in the evaporator, and the electric consumption of the system are 2.5 kW, 1.45 kW and 1.15 kW, respectively (figure 4.16).

Figure 4.17 shows the variation of COP$_{cool}$ with time. The mean value of COP$_{cool}$ is around 2.08.

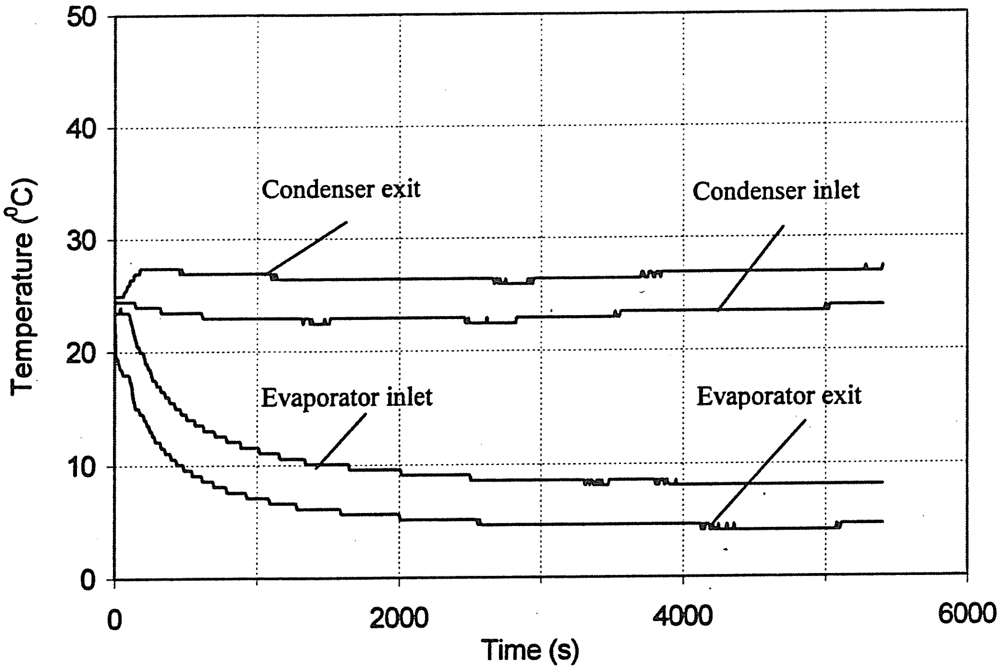


Figure 4.15.Temperature of the transport water in a typical cooling experiment with water as heat sink

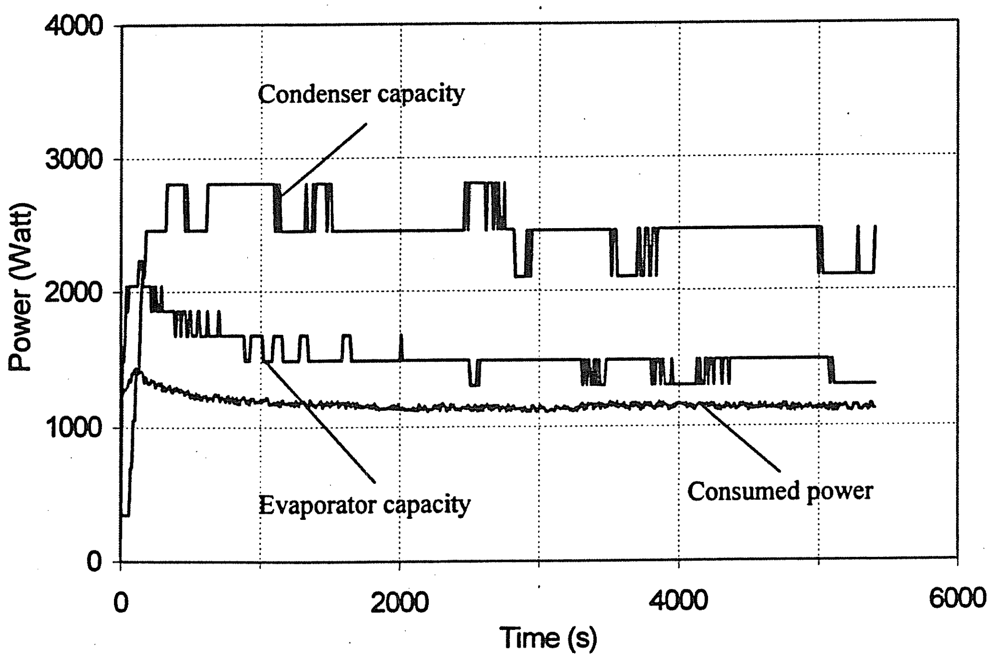


Figure 4.16. Power values versus time during experiment

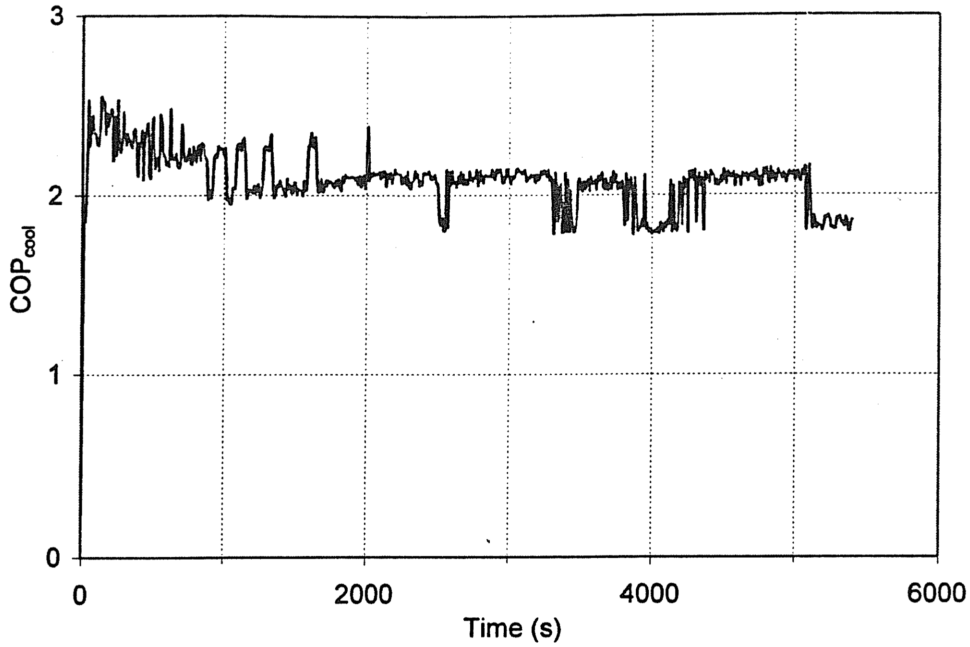


Figure 4.17. Variation of COP_{cool} with time

The COP values of the cooling experiments are given in the figure 4.18. As can be seen from figure, COP_{cool} decreases with the increase of sink temperature for both cases. A least-square, linear curve fit to the data points yield the following equations

$$COP_{cool} = 3.96 - 0.056xT_{sink} \quad \text{(for water-sink)} \tag{4.3}$$

$$COP_{cool} = 3.00 - 0.044xT_{sink} \quad \text{(for air-sink)} \tag{4.4}$$

where T_{sink} is in ^{0}C.

Similar to the results of the heating experiments, the water-sink experiments yield about 35 to 40% higher COP_{cool} values than that of the air-sink experiments for the same sink temperature in the figure 4.18.

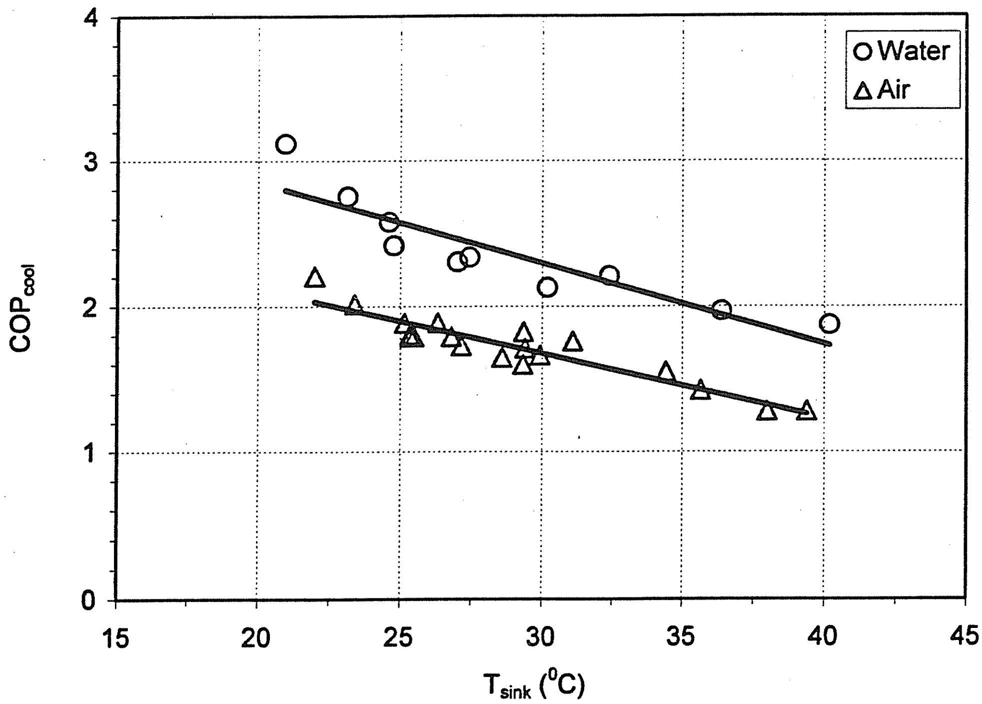


Figure 4.18. COP_{cool} for the cooling experiments with water and air as heat sink

Figure 4.11 shows COP_{cool} values calculated using Equation (4.4), which was obtained from the air-sink data considering the whole cooling season. Equation (4.4), instead of Equation (4.3), was also used for the water in order to take into account of power consumption of the pumps in real applications. The daily minimum, the daily average and the daily maximum air temperatures were used as the sink temperature in the case of air.

In the first half of the cooling season (from mid-May to beginning of August), Seyhan River temperature is lower than the daily minimum air temperature and it is lower or around the daily average air temperature in the remaining part (Figure 4.3). Therefore, the use of water instead of air as heat sink could be advantageous especially in the first half of the cooling season during which COP_{cool} of water is very close to that of the daily minimum air temperature (Figure 4.11). Even in the second half of the cooling season, COP_{cool} of water is better than that of the daily average air temperature. The pumping power requirement of a particular application should be considered again when deciding suitable sink.

If daily average temperature is considered as the temperature of the source and sink for air in heat pump systems, it can be concluded that, use of Seyhan River instead of outdoor air could be favourable during whole heating and cooling seasons except at the end of heating season (from mid-March to end of April).

Water is very attractive especially at the beginning of the heating and cooling seasons. It is possible to design heat pump systems that use more than one heat source-sink (Sauer and Howell, 1983). These systems can utilise water as the primary heat source-sink, but is changed over to extract-discharge heat from-to air. They should be supported by an intelligent control system that first decides which source-sink is more economic, evaluating the data (measured or default) for temperature of the source-sink and for energy consumption of the auxiliary units such as fans and pumps. After this stage, the intelligent control system produces control signals for automatically controlled units such as dampers and solenoid valves for source-sink change over. Main disadvantage of the heat pump systems that can utilise more than one heat source-sink is their higher initial cost compared with simple heat pumps.

5.CONCLUSION

Energy consumption in Turkey has been increasing steadily parallel to the development of the country. Therefore, either more energy must be produced or energy consumption must be decreased. Utilizing the existing energy carefully seems more tangible than decreasing the energy consumption. For this reason, new alternative solutions must be developed in order to utilize the energy effectively.

Considering the large amount of the energy consumed for heating and cooling, the use of heat pump systems should be encouraged. As heat source (sink) in heat pumps water, instead of air that is almost the only source in Turkey should be considered where it is available and suitable.

The air data for Adana, between the years 1981 to 1996, which were obtained from the State Meteorological Affairs General Directorate (DMİ) were analysed to obtain daily minimum, daily average and daily maximum temperatures and heating and cooling degree days, for Adana. Temperature of the Seyhan River was measured from November-1999 to November-2000 at three different depths. The suitability of using Seyhan River as heat source-sink for heat pump systems was discussed by comparing the air and water data and by considering other parameters. Analysis of the results of the experimental study that was carried out using a heat pump system which was capable of utilising both air and water as heat source-sink revealed that use of Seyhan River instead of outdoor air could be advantageous during whole heating and cooling seasons except at the end of heating season (from mid-March to end of April). Water is very attractive especially at the beginning of the heating and cooling seasons. Considering the rapid growth of Turkey's energy consumption and imports in recent years, use of heat pump systems for heating and cooling and use of water resources in these systems where it is more economic than air (as it is the case for Adana city centre) should be encouraged.

REFERENCES

ASHRAE Systems and Equipment Handbook (SI), Chapter 47, 1992.

ASHRAE Systems and Equipment Handbook (SI), Chapter 51, 1992.

BÜYÜKALACA, O., BULUT, H. and YILMAZ, T., (2000). Degree-days for Certain Cities of Turkey, Proceedings of 12th Turkish National Congress on Thermal Science and Technologies with international participation, Vol. 1, p. 107-112.

CANE, D., MORRISON, A. and CLEMES, B., (1996). Experiences With Commercial Ground-Source Heat Pumps, ASHRAE journal.

Caneta Resarch Inc.,(1995). Operating experiences with commercial ground-source heat pumps (RP-863). Prepared for ASHRAE, Technical Commitie6.8, Final Report.

ÇENGEL, Y.A. and BOLES, M.A., (1998). Thermodynamics, An Engineering Approach, Mc Graw Hill Inc.

ELLIS, D., (1999). An Overview of ARI/ISO Standards 13256-1 for Water-Source Heat Pumps, www.ari.org

GRANET, I., (1990). Thermodynamics and Heat Power, Prentıce Hall Inc.

KAVANAUGH, S.P., (1989). Design Considerations for Ground and Water source Heat Pumps in Southern Climates, ASHRAE Transactions, 95(1) p:1139-1149.

KAVANAUGH, S.P., WOODHPUSE, JG. and CARTER, JR., (1991). Test Results of Water-to-Air Heat Pumps with High Cooling Efficiency for Ground-Coupled Applications, ASHRAE Transactions, p: 895-901.

KAVANAUGH, S.P. and PEZENT, MC., (1990). Lakewater Applications of Water-to-Air Heat Pumps, ASHRAE Transactions, p: 813-820.

PHETTPLACE, G.E. and UEDA, H.T., (1988). Primary Effluent as a Heat Source For Heat Pumps, ASHRAE Transactions, 1989, 141-146.

RACKLIFFE, G.B. and SCHABEL, K.B., (1989). Groundwater Heat Pump Demonstration Results For Residential Applications in New York State, ASHRAE Transactions,3-9.

ROGERS, G.F.C., and MAYHEW, Y.R., (1980). Engineering Thermodynamics Work&Heat Transfer, Longman Inc.

ÖZGÖREN, M., (1996). Isıtma ve Soğutma Amaçlı Isı Pompası sisteminin Modellenmesi, Yüksek lisans Tezi, Çukurova Üniversitesi, ADANA.

SAUER, H., and HOWELL, R., (1983). Heat Pump Systems, John Wıley&Sons.

STEADMAN, M., (1994). Industrial heat Pump Application, An International Overview, Vol.12, No.4, IEA Heat Pump Centre Newsletter

STUIJ, B., (1999). Heat pumps in commercial Buildings, IEA Heat Pump Centre Newsletter.

TROTT, A.R., (1989). Refrigeration and Air-Conditioing, Butterworths Inc.

Turkey 1997 Review, (1997), Energy Policies of IEA Countries, www.iea.org

VEN DE VAN H., (1999). Residental Heat Pumps, IEA Heat Pump Centre Newsletter.

YILMAZ, T., and ÖZGÖREN., (1997). Hava-Hava ve Hava-Su ısı Pompası Uygulaması, 1. Makina Mühendisliği Kongresi Sonuç Bildirgesi kitapçığı, 86-93.

Frostless Heat Pump,(1999), www.ornl.gov

Heat sources and sinks and Heat Pumps types, www.heatpumpcenter.org

www.oit.osshe.edu

www.epri.com

CURRICILUM VITAE

Fırat EKİNCİ was born in Adana, 1973. After being graduated from Adana Borsa high school, he enrolled in Mechanical Engineering Department of Cukurova University. He graduated from Çukurova University as a Mechanical Engineer in September 1998. He started his master of science education in the same department in 1998. He has been working as a research assistant in the same department since 1998.