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Heating and Cooling with a Heat Pump

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Abstract: This thesis starts by giving the theoretical operational limits for a heat pump. The limits are found in the laws of thermodynamics. After the theoretical foundation has been laid, the thesis progresses to a general discussion on different types of heat pumps, and narrows down to the vapour-compression heat pump. The major components of a vapour-compression heat pump are examined after which the thesis examines possible heat sources and heat sinks. Next, the thesis examines the conditioned space. The thermal energy distribution systems are discussed and the heating and cooling loads are examined. In addition, advice on sizing and choosing an optimal heat pump system is offered.

All of the above is the foundation on which a case study is laid. The case study is of the heat pump system of the ABC service station in Viitasaari. The heat pump system includes: Carrier heat pump with a nominal cooling capacity of 310.0 kW, 7 500 m of pipe at the bottom of the Lake Keitele,two water tanks serving as thermal storages (warm and cold), a solar collector array, a connection to the local district heating network and an in-floor and ventilation heating and cooling distribution system.

When operating properly the heat pump system at the Viitasaari ABC service station produces a large amount of thermal energy. The estimated amount of upgraded thermal energy from the lake covers about 20% of the estimated yearly heating load of the service station. The Keitele Lake provides a relatively stable temperature heat source (sink) with monthly average temperatures varying from 0°C to 15 °C.

Suomenkielinen tiivistelmä: Alussa tutkitaan lämpöpumpun teoreettista taustaa ja raja-arvoja. Raja-arvot löytyvät termodynamiikan laeista. Teoreettisen pohjan luomisen jälkeen tarkastellaan yleisesti erilaisia lämpöpumppuja, jonka jälkeen siirrytään tutkimaan ainoastaan höyrykompressorilämpöpumppuja. Höyrykompressorilämpöpumpun tärkeimmät osat käydään läpi, jonka jälkeen siirrytään tarkastelemaan lämmönlähteitä ja -nieluja. Seuraava tarkastelun kohde on sisätilat. Sisätila osiossa tarkastellaan lämmön ja jäähdytyksen jakoa, sekä lämmön ja jäähdytyksen tarvetta. Tämän lisäksi tarjotaan tietoa optimaalisen lämpöpumppujärjestelmän mitoitukseen ja valintaan.

Kaikki edellä oleva on perustusta tapaustutkimukselle. Kyseessä oleva tapaustutkimus on Viitasaaren ABC liikennemyymälä lämpöpumppu järjestelmä. Tämä järjestelmä sisältää: Carrier lämpöpumpun, jonka nimellinen jäähdytysteho on 310.0 kW, 7 500 m keräysputkea Keitele-järven pohjalla, kaksi vesivaraajaa (kylmä ja lämmin), aurinkokeräin järjestelmän, yhteyden paikalliseen kaukolämpöverkkoon, sekä lattia ja ilmanvaihto lämmitys- ja jäähdytysjärjestelmät.

Toimiessaan Viitasaaren ABC liikennemyymälä lämpöpumppujärjestelmä tuottaa suuren määrän lämpöä. Arvioitu lämpöpumpun läpi ajettu järvestä otettu terminen energia kattaa noin 20% huoltoaseman arvioidusta vuotuisesta lämmöntarpeesta. Keitele toimii suhteellisen vakiolämpötilaisena lämmönlähteenä ja nieluna. Keskimääräinen kuukausittainen lämpötila pysyy 0°C ja 15 °C välissä.

Keywords: heat pump, heat source, heat sink, vapour-compression heat pump, conditioned space, heating load, cooling load, thermal storage

Avainsanat: lämpöpumppu, lämmönlähde, lämpönielu, lämmön tarve, jäähdytys tarve, termisen energian varastointi

Preface

I would like thank my advisors Prof. Jussi Maunuksela and Prof. Jouko Korppi-Tommola for their patience, time and advice. I would also like to thank PhD. researcher Viivi Aumanen who was one of the examiners of my thesis. I thank my friends and family who supported my during the writing of this thesis. And I thank God for getting me through the process.

Contents

1 Introduction

A heat pump is a device that takes heat from a low temperature heat source and releases it into a high temperature heat sink. Heat does not naturally flow in this direction so heat pumps need an energy input to complete the process.

The broad definition of a heat pump allows for many different kinds of technical applications to be called a heat pump. There are electricity driven vapour-compressor heat pumps, heat driven chemical heat pumps, heat/electricity driven thermoelectric heat pumps and many others.

The most familiar application of a heat pump is a fridge. A fridge is actually an electricity driven vapour-compression heat pump, that cools the inside of the fridge and releases heat into the room. Air-conditioners also work with the same principles. The difference between a heat pump and an air-conditioner is that the first is used to heat a conditioned space whereas the latter is used to cool the space. Modern heat pump systems are often built with the option to be used for both heating and cooling.

Heat pump heating competes with traditional heating systems such as oil and gas furnaces, fireplaces and electric resistors. The main advantages that heat pumps have over the traditional heating systems are found in the lack of local exhaust fumes, that are present with furnaces and fire places, a lower consumption of electricity, when compared with electric resistors, to provide the same amount of heating and the possibility to use the same system for cooling. In general the choice of the optimal heating system for a building depends on many factors and how well a heat pump compares with another heating option will depend on what factors are emphasized.

This thesis starts out with general discussion of heat pumps in chapters 2 to 7 and then it focuses on a specific case in chapter 8. Chapter 2 presents the theoretical background for the operation of a heat pump. In chapter 3 a few heat pump types are presented. The discussion in chapter 4 focuses on vapour-compression heat pumps. Chapter 5 is about heat sources and heat sinks. Chapter 6 focuses on thermal energy distribution systems and calculating the heating and cooling loads of a building. Chapter 7 is a general discussion about choosing a heat pump. Chapter 8 is a case study on a heat pump system installed at Viitasaari's ABC service station.

The reader of this thesis is expected to have basic knowledge in thermodynamics.

2 Physical Background

2.1 Heat Pump Basics

A heat pump is a device that takes heat from a low temperature source and transfers it to a high temperature sink. However, it is known that the natural direction in which heat flows is from a high temperature to a low temperature: A freshly baked cake is left on the table to cool not to be heated; A glass of cold water will not remain cold for long if it is left in room temperature. So, is it even possible for a device like a heat pump to exist? In this chapter, we will look at thermodynamic basics to see the theory behind the operation of a heat pump.

2.1.1 The First and Second Laws of Thermodynamics

We will start setting some ground rules for our theoretical analysis. For this particular case, we need two thermodynamic laws:

1. The law of energy conservation, which is also called the first law of thermodynamics; and

2. The law of entropy growth, which is one form of the second law of thermodynamics.

We apply these laws to a system that undergoes a process. A system is a quantity of matter or a region in space chosen for study and a process is a change that takes a system from one equilibrium state to another [1].

In this theoretical section, we choose a heat pump as our system. Our system, the heat pump, is a closed system that undergoes a cyclic process between a low temperature heat source and a high temperature heat sink. A system that does not have mass flowing across its boundaries is called a closed system. A closed system has heat and work transferred over its boundaries. A cycle is a process in which the initial and the final states are the same. [1][2]

For our chosen system the law of energy conservation takes on the following form

$$E_{in} - E_{out} = (Q_L - Q_H) + (W_{in} - W_{out}) = \Delta E = 0, \tag{2.1}$$

where for a system during a cycle E_{in} = energy gain, E_{out} = energy loss, Q_L = heat gain from low temperature, Q_H = heat loss into high temperature, W_{in} = work done on the system, W_{out} = work done by the system, and ΔE = energy change of the system. The second law of thermodynamics (for a reversible process) becomes

$$\Delta S = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \geq 0, \tag{2.2}$$

where Q_H and Q_L are the same as before, ΔS = change in system entropy, T_H = temperature of heat sink, and T_L = temperature of heat source. [1]

2.1.2 Heat from a Low Temperature Source to a High Temperature Sink

Let us consider any closed system undergoing a cyclic process into which heat would freely flow from the low temperature T_L heat source and out of which heat would flow to the high temperature T_H heat sink. Since this is a free process, no work is done on the system or by the system (W_{in}=W_{out}=0). Now from equation 2.1 we see that the amount of heat from the heat source must be equal to that from the heat sink (Q_L=Q_H). Equation 2.2 becomes

$$\Delta S = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = Q_H \left(\frac{1}{T_H} - \frac{1}{T_L} \right). \tag{2.3}$$

Because ($T_H > T_L$), we find that

$$\Delta S < 0. \tag{2.4}$$

Having a negative change in entropy is impossible and so we can conclude that heat cannot spontaneously flow from a low temperature to a high temperature.

Now lets take a heat pump as our closed system. A heat pump has a work input ($W_{in} \geq 0$). The energy conservation equation 2.1 becomes

$$Q_H = Q_L + W_{in} \tag{2.5}$$

and the change of entropy becomes

$$\Delta S = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = Q_H \left(\frac{1}{T_H} - \frac{1}{T_L} \right) + \frac{W_{in}}{T_L} \geq 0 \tag{2.6}$$

and it follows that

$$W_{in} \geq Q_H \left(\frac{T_H - T_L}{T_H} \right). \tag{2.7}$$

We find that

$$\frac{Q_H}{W_{in}} \leq \frac{T_H}{T_H - T_L} = \frac{1}{1 - \frac{T_L}{T_H}}. \tag{2.8}$$

The fraction Q_H/W_{in} is actually the efficiency of a heat pump *i.e.* the desired output divided by the required input [1]. This efficiency is called the *Coefficient of Performance* (COP). In the equation above, we seem to have found a boundary for the COP of a heat pump between the given temperatures. The same limit can also be found by studying the ideal Carnot cycle.

2.1.3 The Reversed Carnot Cycle

The Carnot cycle is an idealistic heat engine cycle that sets an upper limit for the efficiency of any real heat engine applications. The reversed Carnot cycle is an idealistic refrigeration or heat pump cycle that also sets the upper limit for real applications. [1]

The reversed Carnot cycle, seen in figure 2.1, consist of the following four reversible processes:

1. An Isothermal Expansion (1⟶2)

2. An Adiabatic Expansion (2⟶3)

3. An Isothermal Compression (3⟶4)

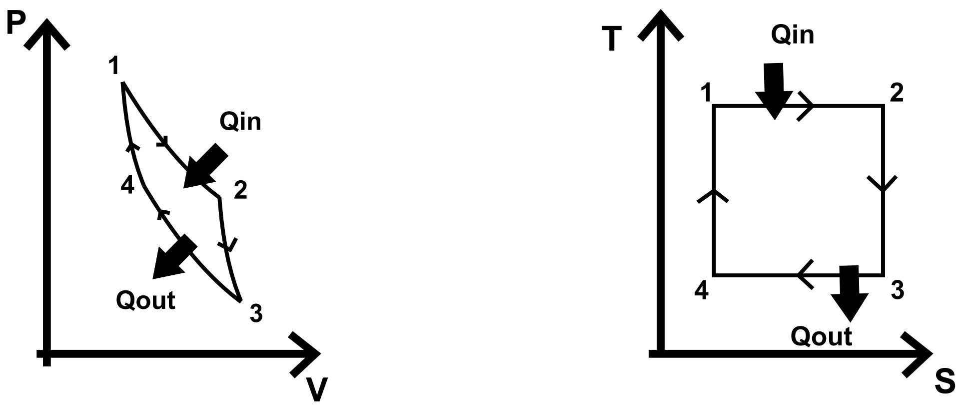

Figure 2.1: The Carnot Cycle

4. An Adiabatic Compression (4⟶1)

Please note that the Q_{in} and the Q_{out} in figure 2.1 are Q_L and Q_H respectively, in the following equations.

The COP of a heat pump is defined as

$$\mathrm{COP}_{HP} = \frac{Q_H}{W_{in}}. \tag{2.9}$$

The work input can be expressed as (equation 2.1)

$$W_{in} = Q_H - Q_L \tag{2.10}$$

and, thus

$$\mathrm{COP}_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}. \tag{2.11}$$

Now for a Carnot cycle, we can apply the Kelvin scale for absolute temperatures [1],

$$\left(\frac{Q_H}{Q_L}\right)_{rev} = \frac{T_H}{T_L}, \tag{2.12}$$

and we find that

$$\mathrm{COP}_{carnot,HP} = \frac{1}{1 - \frac{T_L}{T_H}}. \tag{2.13}$$

We received the same result previously in equation 2.8 and it sets an upper limit for the efficiency of a real heat pump with an irreversible cycle operating between two specific temperatures.

2.1.4 Efficiency Measurement Labels

We already found one efficiency measurement label *i.e.* COP. The general equation for COP is

$$\mathrm{COP} = \frac{desired\,output}{required\,input}. \tag{2.14}$$

The COP measurement can be used for both heat pumps and refrigerators.

The objective of a heat pump is to heat and the objective of a refrigerator is to cool a conditioned space. The different objectives can be seen in how the COP of each is calculated. The COP of a heat pump is

$$\mathrm{COP}_{HP} = \frac{Q_H}{W_{in}} \tag{2.15}$$

and for a refrigerator the COP is

$$\mathrm{COP}_{R} = \frac{Q_L}{W_{in}}. \tag{2.16}$$

Comparing equations 2.15 and 2.16 we notice that the two COP_{HP} and COP_R are related to one another as follows

$$\mathrm{COP}_{HP} = \mathrm{COP}_R + 1. \tag{2.17}$$

From this we see that $\mathrm{COP}_{HP} > 1$ as COP_R is always a positive number.

The COP is calculated using SI units. However, in the Unites States air conditioners are labelled using the *Energy Efficiency Rating* (EER). This is calculated using the *British thermal units* (Btu). The conversion between the two efficiency labels is EER = 3,412 COP_R.

It is important to note that the conversion is done between the refrigerant COP_R and EER. COP does not have a unit. The unit of EER is Btu/Wh.

2.2 Heat Transfer

We gained an understanding of how a heat pump operates through the study of thermodynamics. When we consider the heat sources, heat sinks, heat loads and cooling loads additional theory is needed. Here we will take a very brief look into the subject of heat transfer. Heat transfer deals with the actual interaction that takes place when thermal energy is transferred from one medium to another. This interaction takes time and it often causes a temperature gradient to form in the system before the system reaches equilibrium.

Heat is transferred in three basic modes: conduction, convection and radiation. Conduction takes place in solid materials and at surfaces where two substances are in a thermal contact. Convection is the type of heat transfer that takes place when heat is moved by the flowing of fluids. Radiation takes place without a thermal contact or a flow of fluid. Heat is transferred by electromagnetic waves. In table 2.1 the one-dimensional equations for each of these transfer modes are presented.

For further reading on the subject of heat transfer please refer to the books Lämmönsiirto by Walter Wagner [3] and Fundamentals of Heat and Mass Transfer by Frank P. Incropera and David P. DeWitt [4], which were used as sources for this section.

Table 2.1: The Basic Equations of Heat Transfer in One-Dimensional Cases

Mode	Heat Transfer Equation	Variable	Definition (Unit)
Conduction	$q^{''} = -k\frac{\Delta T}{L}$	$q^{''}$	heat flux (W/m^2)
(Fourier's law)		k	thermal conductivity (W/mK)
		Δ T	temperature difference
			between two surfaces (K or $^\circ C$)
		L	thickness of substance
			between two surfaces (m)
Convection	$q^{''} = h(T_s - T_\infty)$	$q^{''}$	heat flux (W/m^2)
		h	convection heat
			transfer coefficient (W/m^{2}K)
		T$_s$	surface temperature (K)
		T$_\infty$	fluid temperature (K)
Radiation	$q^{''} = \epsilon\sigma T_s^4 - \alpha G$	$q^{''}$	heat flux (W/m^2)
		ϵ	emissivity ($0 \leq \epsilon \leq 1$)
		σ	Stefan-Boatman constant
			5.67 $\times 10^{-8}$ W/m^{2}K^4
		T$_s$	surface temperature (K)
		α	absorptivity
		G	irradiation (W/m^2)

3 Types of Heat Pumps

3.1 Basics

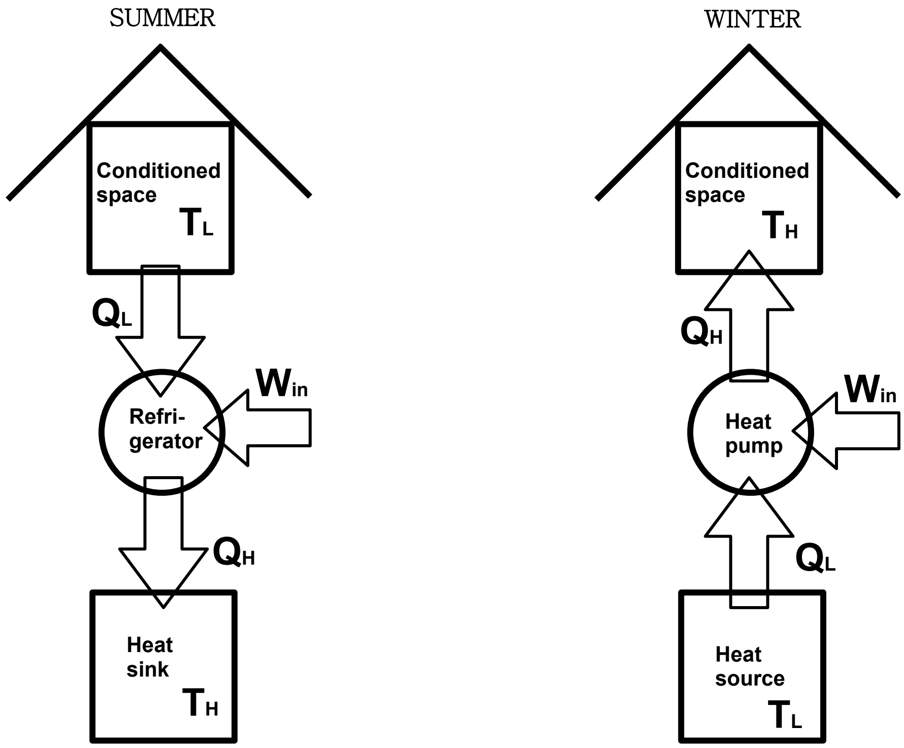

Figure 3.1: Heating with a heat pump and cooling with a refrigerator; $\mathbf{T}_H$ high temperature, $\mathbf{T}_L$ low temperature, $\mathbf{Q}_H$ heat released from heat pump/refrigerator, $\mathbf{Q}_L$ heat entering heat pump/refrigerator and $\mathbf{W}_{in}$ required work input

A heat pump operates just as an air conditioner turned backwards [1]. This means that heat pumps and air conditioners use the same machinery, the mode of application gives one the name heat pump and the other the name air conditioner. Thus, a heat pump can be used for both heating and cooling (see figure 3.1).

For reasons of clarity, we will call the machinery used for cooling a refrigerator not an air conditioner. The term air conditioner will be used when talking about any type of heat pump or refrigerator that is used to condition the air of a confined space.

In picture 3.1 the terms heat sink and heat source are applied only to the part of the heat pump system that is not the building. The building is referred to as the conditioned space. The conditioned space is the heat sink in the heating mode and the heat source in the cooling mode. However, to provide a distinction between the building and the external surrounds, we will use the terms heat source and heat sink only for the surrounds and the term conditioned space for the building.

Heat pumps can be grouped by the type of energy, *e.g.* mechanical energy or heat, they consume to up-grade heat from the heat source. They can also be grouped according to their cycles *i.e.* into open or closed cycles. Combining the two grouping methods we end up with four heat pump groups. In table 3.1, an example for each group is mentioned. In table 3.2 the main components of the four example heat pump types are listed.

Table 3.1: Heat Pump Grouping [5]

	Mechanical energy	Heat
Open System	Gas Expansion	Ejector
Closed System	Vapour-Compression	Absorption

Heat pumps that fall under the category of a closed cycle heat pump, have a closed refrigerant cycle *i.e.* the refrigerant remains within the heat pump throughout the process cycle and heat exchangers are used to transfer heat to and from the refrigerant. The refrigerant in an open cycle enters the heat pump and exits it before and after every cycle. The refrigerant of an open cycle is usually the medium that is being cooled or heated instead of a separate refrigerant.

Table 3.2: Four Different Heat Pump Types

Absorption	Ejector	Gas Expansion	Vapour-Compression
absorber, generator	ejector	compressor	compressor
expansion valve		turbine	expansion valve
condenser		condenser	condenser
evaporator			evaporator

3.2 Vapour-Compression Heat Pump

A vapour-compression heat pump is a closed cycle mechanical energy driven heat pump. It is the most used heat pump type and often the type that people refer to when using the general term heat pump. The next chapter 4 will focus entirely on this type of a heat pump. Here we will briefly discuss the vapour-compression cycle.

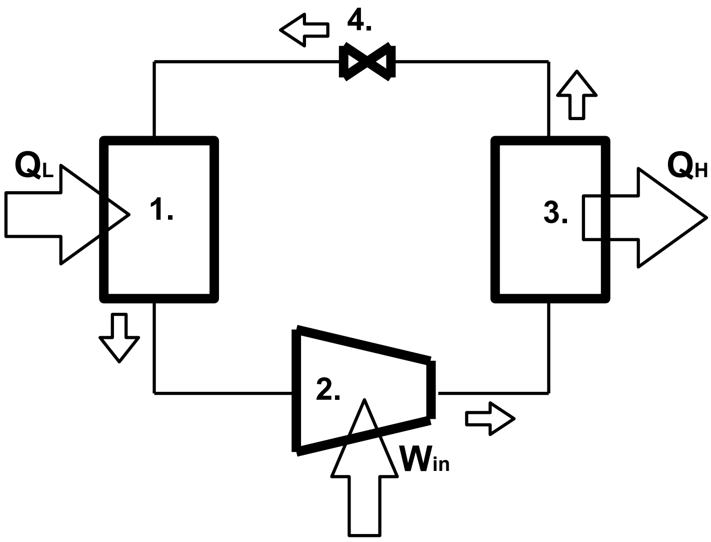

Figure 3.2: The refrigerant cycle of a vapour-compression heat pump: **1.** Evaporator, **2.** Compressor, **3.** Condenser, **4.** Expansion valve

The refrigerant cycle of a vapour-compression heat pump is shown in figure 3.2. Using the figure numbering the cycle is described in the following list:

1. The refrigerant enters the evaporator and is vaporized by the heat it receives from the heat source.

2. The pressure of the refrigerant vapour is raised in the compressor.

3. Pressurized and high temperature refrigerant vapour enters the condenser where it releases heat into the heat sink.

4. The refrigerant's pressure drops as it goes through the expansion device and becomes a vapour liquid mixture or a liquid.

Vapour-compression heat pumps are used in all kinds of applications. Even the very familiar household appliance, the fridge uses a vapour-compression refrigerant cycle. The COP of vapour-compression heat pump ranges between 1 to 4 [6], depending on the temperature difference between the heat source and heat sink.

3.3 Absorption Heat Pump

An absorption heat pump is a closed cycle heat driven heat pump. The cycle involves the absorption of the refrigerant by a transport medium. Lithium bromide/water and water/ammonia are two examples of the working agent pairs (transport medium/refrigerant) used in absorption heat pumps [7].

Figure 3.3 presents the refrigerant cycle of an absorption heat pump. Here the same is expressed in words. The refrigerant is evaporated in the evaporator (**1.**) by heat Q_L at temperature T_L. The refrigerant then enters the absorber (**2.**) and is absorbed into a solution containing the transport medium and the refrigerant. This process is an exothermic process and heat Q_{abs} is released at temperature T_{abs}. The solution in liquid phase, now with a strong concentration of refrigerant, is transported by a pump (**3.**) through the regenerator (**4.**), where it gains heat Q_{regen}, to the generator (**5**). In

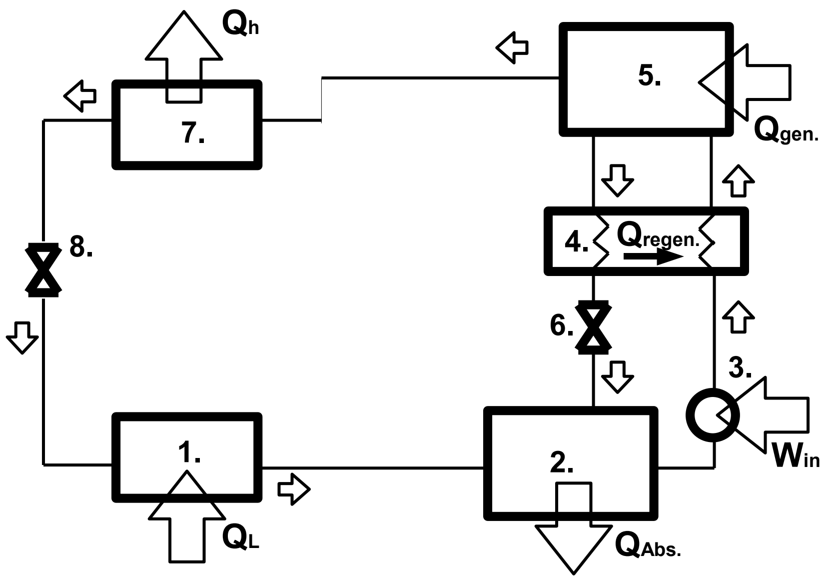

Figure 3.3: The refrigerant cycle of an absorption heat pump; **1.** evaporator, **2.** absorber, **3.** pump, **4.** regenerator, **5.** generator, **6.** & **8.** expansion valve, **7.** condenser, $\mathbf{Q}_h$ heat released from condenser, $\mathbf{Q}_L$ heat from heat source, $\mathbf{Q}_{gen}$ heat needed to evaporate refrigerant in generator, $\mathbf{Q}_{regen}$ regenerated heat, $\mathbf{Q}_{abs}$ heat released in absorber, $\mathbf{W}_{in}$ work input for pump.

the generator the endothermic process of evaporating the refrigerant from the solution is put into motion by heat Q_{gen}. The concentration of refrigerant in the solution drops and the pure refrigerant continues its way to the condenser. (**7.**). The solution with a weak concentration of refrigerant returns to the absorber (**2.**) via the regenerator (**4.**), where it releases heat Q_{regen}, and the expansion valve (**6.**). In the process starting from the absorber (**2.**) and ending at the generator (**5**), the pressure of the refrigerant is raised to the condenser pressure. In the condenser the pure refrigerant releases heat Q_h at temperature T_H. Then the pure refrigerant returns to the evaporator via the expansion valve (**8.**). [1] [8]

It is important to notice that an absorption heat pump is heat driven *i.e.* the up grading of heat Q_L to heat Q_h is done by heat Q_{gen}. In the cycle a lower quality heat Q_{abs} is also realised. Thus, the COP of an absorption heat pump is calculated as follows [1] [8]

$$\mathrm{COP}_{\mathrm{absorption},HP} = \frac{Q_h + Q_{abs}}{Q_{gen} + W_{in}}. \tag{3.1}$$

.

An absorption heat pump is best suited for applications where waste heat around the temperature of 200 ^{o}C is available [1]. An absorption heat pump can also be combined with a heat generator such as a solar collector array when waste heat is not available [9].

Compared with a vapour-compression heat pump an absorption heat pump has a more complex cycle and thus requires more space. The efficiency of an absorption heat pump typically is 1.2 to 1.4 in industrial applications [10].

3.4 Gas Expansion Heat Pump

The cycle of a gas expansion heat pump is based on the Brayton cycle. Here we will concentrate on the open Brayton cycle heat pump, which has three main components, a compressor, a turbine and a heat exchanger.[5]

The cycle has three steps. **1.**) The refrigerant is compressed in the compressor. **2.**) Heat is released from the refrigerant in the heat exchanger. **3.**) The refrigerant is depressurised in the turbine. The cycle is presented in figure 3.4.

The COP of a Brayton heat pump is calculated as follows

$$\mathrm{COP}_{\mathrm{Brayton},HP} = \frac{Q_H}{W_{net,in}}, \tag{3.2}$$

where $W_{net,in}$ = the network input. The COP values of a Brayton heat pump are typically between 1,5 and 2 [5]. In spite of their relatively low COP, Brayton heat pumps are used because of their simple and light components and the possibility for heat regeneration. *E.g.* Brayton cycle based heat pumps are used on airplanes for air conditioning because of their lightness [1].

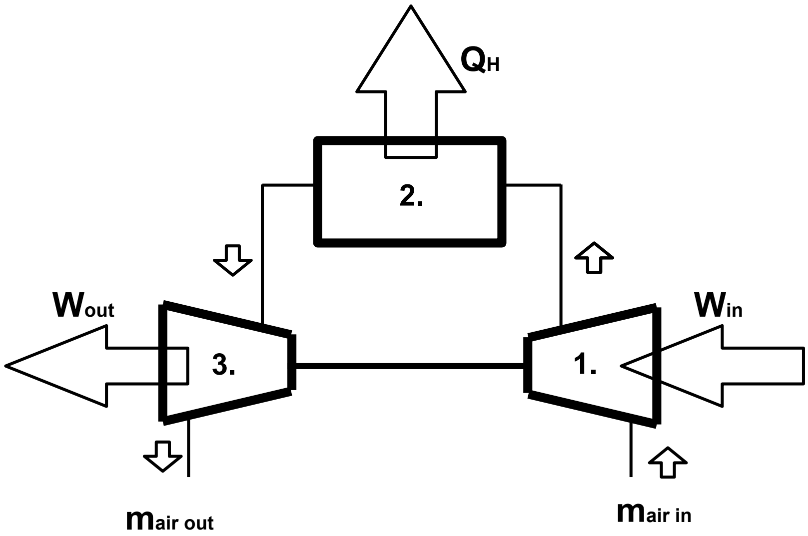

Figure 3.4: The open refrigerant cycle of a Brayton heat pump, **1.** compressor, **2.** heat exchanger, **3.** turbine, $\mathbf{Q}_H$ heat loss, $\mathbf{m}_{air\,out}$ cool air exiting the cycle, $\mathbf{m}_{air\,in}$ warm air entering the cycle, $\mathbf{W}_{in}$ work input and $\mathbf{W}_{out}$ work output.

3.5 Ejector Heat pump

An ejector heat pump is a thermo compressor that uses three stages to compress steam. Each stage takes place in its own chamber. In the first stage, high-pressure steam enters the ejectors first chamber. Here the steam expands and its kinetic energy increases. The next stage is the mixing stage. In the mixing chamber, the fast moving steam mixes completely with low-pressure steam. In the third and final stage, the steam mixture enters the diffuser losing speed, while it's pressure increases.

The COP of an ejector heat pump is typically between 1,1 and 1,5 and it can be calculated as follows

$$\mathrm{COP} = \frac{Q_{\mathrm{recieved}}}{Q_{\mathrm{used}}}. \tag{3.3}$$

The ejector heat pump is used in applications were high-pressure steam is available. [5]

3.6 Thermoelectric Heat Pump

There are other heat pump types that have not been discussed here. One of them is based on the Peltier effect. The Peltier effect was first discovered by Jean Charles Athanase in 1834. When a current is passed through a junction of dissimilar wires their junctions are cooled. The Peltier effect is the bases for thermoelectric refrigeration. Thermoelectric heat pumps are used mainly in research applications and in small portable appliances like fridges. [1] [11]

4 Vapour-Compression Heat Pump

4.1 Introduction

Vapour compression heat pumps have been around for a long time and the technology has been well tested. For the remainder of this thesis when talking about a heat pump we will be referring to the electric driven vapour-compression heat pump. In the previous chapter in section 3.2, we briefly discussed the closed cycle of a vapour-compression heat pump. Now we will take a closer look at the different components of a vapour-compression heat pump.

The major components of a vapour-compression heat pump are the compressor, two heat exchangers that function as an evaporator and a condenser, and an expansion device. The refrigerant can also be considered a major component. Minor components are the parts that are needed but do not have an active role in the cycle process. These components are the pipes, the oil, the oil separator etc. Here we will only discuss the major components. [12][13]

4.2 Compressor

The compressor is the active component of a heat pump and thus it is most vulnerable to breakage. A faulty or malfunctioning compressor will immediately affect the overall performance of the heat pump. In addition, the compression of the refrigerant is also the noisiest stage in the cycle. It is very important to choose a compressor that fits the specific needs as well as possible.

Compressors are devises that include a motor and moving parts. They can be divided into three main groups based on their type of casing *i.e.* hermetic, semi-hermetic and open compressors.

A hermetic compressor's casing is welded shut. The compressor and its motor are inside the casing in an environment that is impermeable to gas. The hermetic casing dampens the compressor noises and thus the operational noises of a heat pump. The refrigerant vapour is sucked into the casing, compressed and then let out through an opening at the other end. This type of casing provides a good protection from outside influences during compression and it prevents refrigerant leakage into the atmosphere. The welded casing is effective in keeping the refrigerant inside, but it also stores excess heat produced by the motor and prevents easy access to the compressor during maintenance. The motor of a hermitic compressor comes in direct contact with the refrigerant and must be able to withhold against the refrigerant's corrosive effect. Hermetic casings are usually combined with electric motors. [13] [14]

In an open compressor, the motor is outside the compressor's casing and the two are connected by a work transferring staff. The motor does not come into direct contact with the refrigerant and effective cooling is possible, making the environment of the motor friendlier than it was in the case of a hermetic compressor. Maintenance of an open compressor is relatively easy as the motor is not inside a casing. However, refrigerant is vulnerable to leakage and outside influences during the compression. Open compressors are used in situations were the motor of the compressor needs to be refuelled *e.g.* gas motors. [13][14]

A semi-hermetic compressor is like a hermitic compressor in that the motor is placed inside the casing. However the casing is bolted, not welded, shut. The bolted casing can be opened for maintenance reasons and when properly bolted the properties of a semi-hermitic compressor resemble that of a hermitic compressor. [13][14]

Compressors can also be divided into two groups based on the type of compression they perform on the refrigerant *i.e.* dynamic or positive displacement compressors. A positive displacement compressor causes the pressure of a fluid to increase by decreasing its volume. A dynamic compressor on the other hand compresses a fluid by giving it kinetic energy and the pressure rises in accordance with the Bernoulli principle as follows

$$p + \frac{1}{2}\rho c^2 - \Delta p_k = \text{constant}, \tag{4.1}$$

where p = pressure of the fluid, ρ = fluid density, c = absolute speed of the fluid and Δp_k = friction loses. [13]

The reciprocation compressor, a positive displacement compressor, has the longest history of all compressor technologies. It is made out of a piston, a compression chamber and pressure sensitive valves that allow the refrigerant to flow in and out of the compression chamber. The piston moves up and down changing the volume and the pressure of the compression chamber. The change in pressure opens and shuts the valves. Figure 4.1 presents the cyclic process of a reciprocation compressor. The reciprocation compressor has the advantage of being a simple and well-known technology with high efficiencies. It can operate at high-pressure ratios and is used in versatile applications. Its disadvantages are a sensitivity towards liquid slugging and dirt particles as well as the pulsation nature of the compression process and a large number of moving parts. [13][14]

A screw compressor is also a positive displacement compressor. It can have one or two screws. In a screw compressor, the refrigerant flows into the spiral canal on the side of the screw. As the refrigerant flows down the spiral canal, it is compressed. At the end of the screw canal the refrigerant exits the compressor. In a single screw compressor, there are rotors that compress the refrigerant as it moves down the spiral. In a twin-screw compressor the spiral edges of the screws run together compressing the fluid that is between them. [12][13][14]

The advantages of a screw compressor are a continuous flow of refrigerant into the compressor allowing a continuous compression, the same efficiency as good reciprocation compressors with a higher tolerance towards liquid slugging and few moving parts. A screw compressor does not need suction nor discharge valves. The disadvantages include the need for precise manufacturing of helical screws. [12][13]

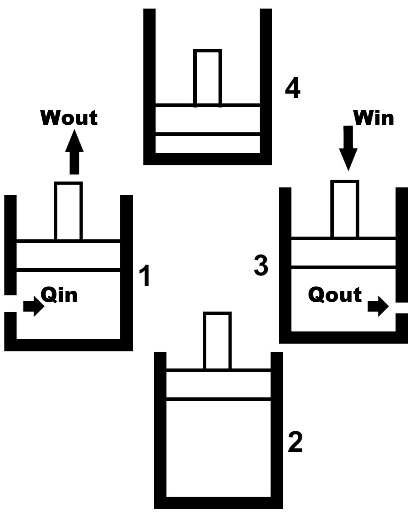

Figure 4.1: The Cycle of a Reciprocation Compressor, **1.** The piston moves up increasing the chamber volume, decreasing pressure. Work W_{out} is done on the environment. The suction valve opens and a flow of refrigerant vapour (heat Q_{in}) enters the chamber. **2.** The piston reaches its upper limit and the pressure with-in the chamber closes the inlet valve. **3.** Work W_{in} is done on the piston causing it to move down changing the volume of the chamber. The increased pressure opens the discharge valve and refrigerant (heat Q_{out}) exits at the desired pressure. **4.** The piston has moved to its lowest position and the cycle can start over again.

Scroll compressors are also positive displacement compressors. They are a fairly new development amongst the technologies of compressors. A scroll compressor has two spirals wound together. One of the spirals remains fixed while the other rotates compressing the refrigerant (see figure 4.2). Just like a screw compressor a scroll compressor achieves a continuous flow of refrigerant into the compressor. It also has a high efficiency and is reliable. The lack of suction and discharge valves enhances its reliability. The operation of a scroll compressor is generally quieter than that of a reciprocation compressor. However, the manufacturing prices of a scroll compressor are higher. Both the scroll compressor and the screw compressor are widely used in heat pump technologies. [12][13][14]

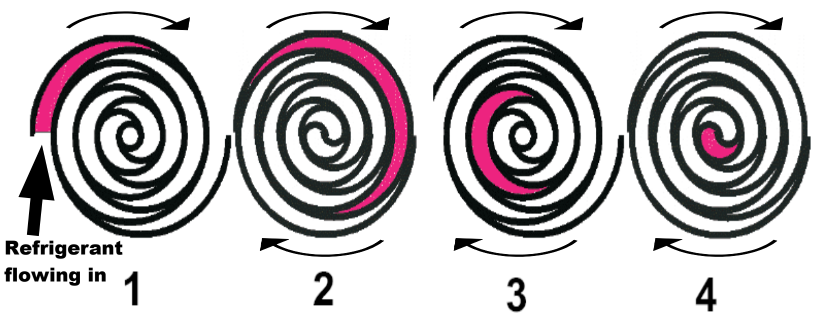

Figure 4.2: Scroll Compressor, Gas enters a scroll compressor in a continues flow. In this figure, we are observing a certain mass of gas as it makes its way through the compressor. **1.** Refrigerant is sucked into the scroll compressor. **2.** and **3.** The refrigerant travels through the scroll compressor and is compressed. **4.** The compressed refrigerant is discharged from the compressor.

A centrifugal compressor is a dynamic compressor. It compresses the refrigerant with centrifugal motion. The suction gas is accelerated by a rotating impeller. The accelerated gas is let into the diffuser that has a set of passages with increasing cross-sectional areas. In the diffuser, the velocity of the gas is changed into pressure as the gas decelerates. Centrifugal compressors need a steady and relatively large flow of refrigerant vapour and they have their highest efficiencies with small pressure ratios. Centrifugal compressors are used in large heat pumps. [13][14]

A compressor can be equipped with two-speed or variable speed motors allowing the compressor to have a variety of compression capacities and more precise temperature control with the heat pump unit can be achieved. Heat pumps can also have more than one compressor in their refrigerant cycle. In these cases there is the option of having the refrigerant compressed to higher pressures than would be possible with only one compressor.

4.3 Heat Exchanger

Heat exchangers are used in the heat pump cycle to transfer heat between the refrigerant and the heat sink/heat source, without allowing the two mediums to mix. In the heat pump cycle, one heat exchanger is used as a condenser and the other as an evaporator.

Heat exchangers are built out of materials with high thermal conductivity. The surface area of a heat exchanger is maximized to provide as much heat exchange surface as possible. Since heat exchangers come in direct contact with two fluids, the refrigerant and the medium of heat transfer from the heat source or to the heat sink, they need to withhold the corrosive effects of both fluids. [13]

Heat exchangers can be grouped based on the different phases of fluids between which they operate. There are liquid-to-liquid (*e.g.* plate heat exchangers) , gas-to-gas, liquid-to-gas (*e.g.* water radiators), gas-to-liquid heat exchangers. Here we will only consider the plate heat exchanger that can operate with liquids and gasses. It is often used in heat pump applications.[14]

Plate heat exchangers are staked plates that have appropriate pressed patterns on them. The heat-exchanging surface is increased by adding more plates to a stake. The edges of the plates can be welded together or they can be otherwise sealed (*e.g.* bolted together). The openings between the plates serve as channels for the fluids to move through. Every other channel is for the refrigerant and every other for the other fluid. In a counterflow plate heat exchanger, the refrigerant and the other fluid flow in opposite directions. In a parallel-flow plate heat exchanger, the refrigerant and the other fluid flow in the same direction (see figure 4.3). [4][13]

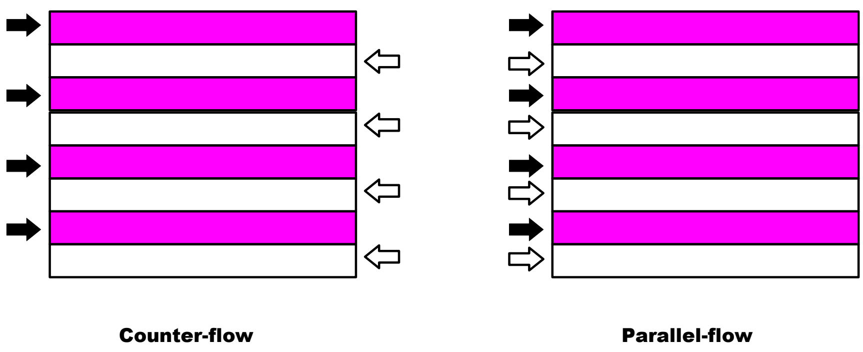

Figure 4.3: Counterflow and parallel-flow plate heat exchangers; In a plate heat exchanger every other channel is for the refrigerant every other for the other fluid. The direction of flow in each channel is shown by an arrow.

Plate heat exchangers require a relatively rapid flow to keep the fluid evenly distributed in the channels. The required flow depends on the amount of plates stacked together. A stack of many plates requires a faster flow than a stack of fewer plates. [13]

4.4 Expansion Device

Expansion devises are used to lessen the pressure of the refrigerant at the end of the process cycle. Lowering the pressure lowers the boiling point of the refrigerant allowing it to vaporize once heat is added. Here we will briefly discuss the operation of a capillary tube, a thermostatic expansion valve and an electronic expansion valve.

A very basic expansion device is a capillary tube. A capillary tube widens at the end, causing the refrigerant flowing through it to expand lowering its pressure and increasing its internal energy. [13]

The operation of a thermostatic expansion valve (see figure 4.4) is governed by the temperature of the refrigerant. When the temperature rises, the temperature sensor causes the expansion valve to open up more allowing for a more rapid flow of refrigerant. The temperature sensor is mechanically connected to the valve. [13]

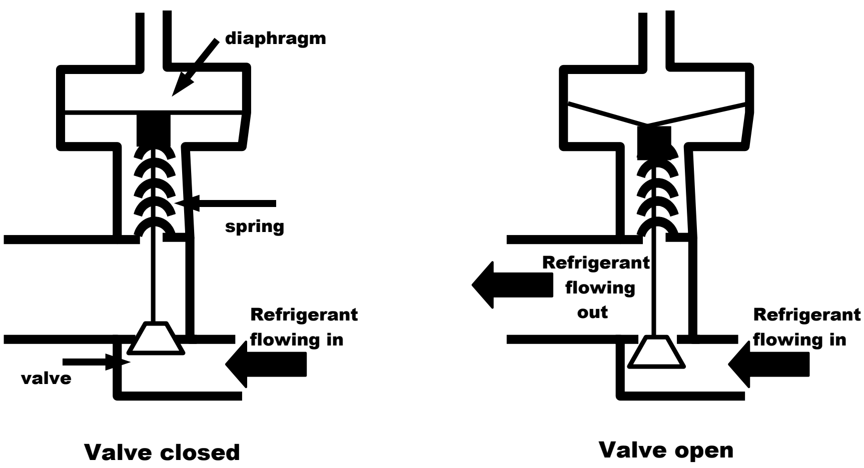

Figure 4.4: A thermostatic expansion valve, The pressure of the diaphragm is governed by a temperature sensor. When the pressure is high in the diaphragm the spring is pushed down and the valve opens for the refrigerant to pass.

An electronic expansion valve is also governed by the temperature of the refrigerant. However, it has at least two temperature sensors and the valve itself is operated electronically. [13]

4.5 Refrigerants

In a vapour-compression heat pump the refrigerant is the fluid that undergoes the cyclic process. The compression stage is the most demanding on the refrigerant. During all other steps, the refrigerant is confined within closed walls, but in the compressor, the refrigerant is in a more or less open environment. This is because the compressor is the component that introduces work into the heat pump cycle. The way work is introduced into the cycle can be a way for refrigerant to leak out of the closed cycle. Refrigerant leakage is undesirable as the lost refrigerant needs to be replaced and because of the generally toxic or harmful nature of the refrigerant. Compressors also require oil to operate properly and often the oil mixes with the refrigerant. The oil can cause the refrigerant to lose heat-transferring properties and it can accumulate on the walls of other parts of the heat pump cycle causing damage and/or loss of heat transferring properties. [12][13]

Here a few of the desirable properties for a refrigerant are listed. The refrigerant should be non-toxic, environmentally friendly (*e.g.* not harmful for the atmosphere), non-flammable, chemically stable, non-corrosive, detectable in case of leakages, and completely miscible or not miscible with the used machine oil and affordable. The refrigerant should have an appropriate saturation pressure-temperature relation, a high specific heat, a high vapour density and a low viscosity. [13][15]

The first six requirements deal with safety issues related to the usage of a refrigerant. If the refrigerant is toxic, environmentally unfriendly leakages will cause problems. A flammable refrigerant could not undergo the constant changes in temperature and pressure. A corrosive or chemically unstable refrigerant will significantly shorten the lifetime of the equipment.

The seventh requirement deals with the effect machine oil will have on the refrigerant. In the compressor, the refrigerant will be exposed to machine oil. To avoid lowered heat transfer properties the oil and the refrigerant should be able to be separated from one another. If the refrigerant is only partly miscible with the oil, the separation process will be difficult. On the other hand, if the oil and refrigerant were completely miscible then the two might not need to be separated at all. [13]

The six last requirements deal with heat transfer and technical issues. When determining the appropriate saturation-pressure temperature relation the following things should be considered: **1.** the pressure of the refrigerant should be greater than the surrounding pressure to prevent air leakage into the cycle and **2.** lower pressures are desirable from a design point of view. A high specific heat will allow the refrigerant to carry more heat. A high vapour density will keep the compressor capacity at a minimum and pipe diameters small. Low viscosity keeps the pressure losses low. [13]

It is impossible to find a refrigerant that fills all of the requirements perfectly and thus compromises must be made. A large number of refrigerant compounds exist and choosing the right refrigerant depends on the purpose of use. In the following paragraphs, a few refrigerants are presented.

Probably, the most famous refrigerants are ChloroFluoroCarbons (CFC), also called Freons. They were very popular in refrigerant technology applications for long time. However, they were found to be harmful to the ozone layer and now many of the CFC compounds are banned by law in almost all countries. R11, R12, R502 and R13B1 are examples of CFCs. [12]

Hydro-ChloroFluoroCarbons (HCFC) are similar to CFCs. Like CFCs, HCFCs are harmful to the ozone layer and are banned in new applications. R22 and R401A are examples of HCFCs. [12]

Hydro Fluorocarbons (HFC) and Halogen free refrigerants are used in place of CFCs and HCFCs. HFCs do not contain chlorine and they are harmless for the ozone layer. R134a and R404A are HFCs. Propane, butane, ammoniac and CO_2 are examples of

Halogen free refrigerants. [12]

It is also possible to mix refrigerants to achieve desired properties. These mixtures can be azeotropic or zeotropic mixtures. An azeotropic mixture behaves as a one component refrigerant *i.e.* it has a set evaporation and condention temperature at a certain pressure. Zeotropic mixtures evaporate and condense over a set temperature range. For example, R-407C is a zeotropic mixture of R32 (23%), R125 (25%) and R134a (52%). It's boiling point at atmospheric pressure is -43.81 °C with a temperature drift of 7°C. It can be used to replace R22. [12] [16]

4.6 Fitting the Major Components Together

If we were to build a heat pump, we would start by examining the temperature difference between the heat source and heat sink. Then we would choose a refrigerant that has a fitting saturation pressure-temperature relation. Our next steps would be to find out the pressures of the refrigerant in the condenser and in the evaporator. From these we could calculate the desired pressure ratio for the compressor. The pressure ratio of the compressor should match that of the condenser and the evaporator as closely as possible. The pressure ratio is calculated as follows

$$P_{\text{ratio}} = \frac{P_{\text{condenser}}}{P_{\text{evaporator}}}, \tag{4.2}$$

where P_{ratio} = pressure ratio, $P_{\text{condenser}}$ = pressure in condenser and $P_{\text{evaporator}}$ =pressure in evaporator. The pressure ratio is related to the volumetric efficiency of compressor. We would want to have a high volumetric efficiency. If it seems that the volumetric efficiency is low then the pressure ratio should be readjusted. [14]

4.7 Reversing Valve

The reversing valve is not a major component in a heat pump. However, it is an important component in heat pump systems that provide both heat and cooling. For this reason we will briefly mention some things about it.

The reversing valve is installed at the discharge side of the compressor. When the heat pump is in heating mode the reversing valve connects the compressor's discharging side to the condenser and the suction side to the evaporator. In the cooling mode, the reversal valve connects the compressor's discharging side to the evaporator and the suction side to the condenser. The same is presented in figure 4.5 (also see figure 3.1. [14]

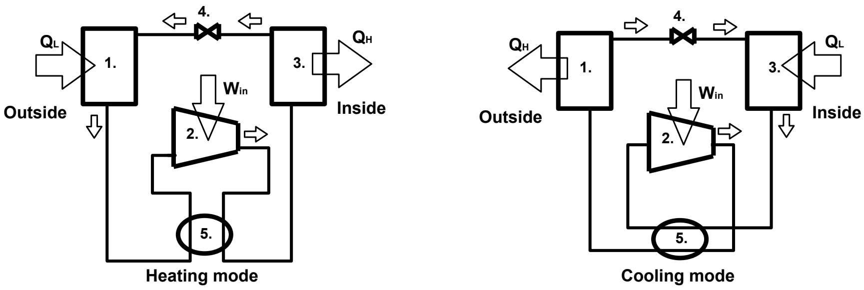

Figure 4.5: A vapour-compression heat pump with a reversal valve; **1.** evaporator, **2.**compressor, **3.** condenser, **4.** expansion device, **5.** reversal valve.

It is also possible to build a heat pump system in such a way that there is no need for a reversal valve with-in the heat pump itself. In Chapter 8 we will examine a real heat pump system that is an example of this.

5 Heat Sinks and Sources

In the previous chapter, we looked at the build of a vapour-compressor heat pump. We noticed that by choosing the appropriate parts and refrigerant one can optimise the operation of a heat pump. As mentioned in chapter 2, the COP of a heat pump is always limited by COP of the ideal Carnot cycle, which in turn depends on the temperatures T_H and T_L as seen in equation 2.13. The smaller the temperature difference the higher the COP. Since the temperature of conditioned space, *i.e.* the room temperature is kept constant at somewhere between 18 and 20°C, the temperature of the heat source (heat sink) determines the temperature difference. In this chapter, we will discuss some of the possible heat sources (heat sinks).

5.1 General Requirements

Air, exhausts, ground and surface water, soil, and bedrock are a few of many heat sources (heat sinks), which can be used. Each has advantages and disadvantages that need to be considered when trying to decide on the optimum heat source (heat sink) .

A good heat source (heat sink) should have a temperature close to that of the conditioned space and it should maintain a constant temperature independent of seasonal changes or heat loss (heat gain) caused by the heat pump system. As seen in the previous chapter a heat pump is designed for a specific pressure-ratio. Since the pressure of the refrigerant is dependent on its temperature, a heat source with an unstable temperature will cause the heat pump efficiency to drop.

In real situations, the temperature of a heat source (heat sink) is subject to seasonal temperature changes. For example, the change of seasons strongly affects the temperature of ambient air. Therefore, in areas where temperatures change dramatically during a year it is often beneficial to choose heat sources (heat sinks) that are not so strongly influenced by this change. For example, bedrock has a relatively constant temperature throughout the year [17].

Sometimes, the impact of the changing seasons can be evened out by storing (removing) thermal energy into the heat source (from the heat sink) during the warmer (cooler) periods [18]. A good thermal storage has a high specific heat. It must also be able to maintain the local temperature difference caused by storing (removing) thermal energy. For example, the ambient air does not make a good thermal storage at the scale of a heat pump system. The warmer (cooler) air will quickly drift off and be lost in the vastness of the ambient air. However, on the global scale the ambient air does work as a thermal storage.

The previous example brings us to another important factor that concerns a good heat source (heat sink). A heat source (heat sink) must have a large enough volume compared to the heating (cooling) loads it will provide for. A heat source (sink) that is too small will quickly under cool (overheat), causing the heat pump systems efficiency to drop.

The heat pump takes heat from (adds heat to) the heat source (heat sink). Local changes of temperature are unavoidable whenever heat is added or lost. A local temperature change will cause a temperature gradient in its immediate environment as heat flows from cooler areas to warmer areas to bring about a temperature equilibrium. In heat sources (heat sinks) with good heat transferring properties and a large volume the temperature gradient will quickly even out without leaving a noticeable trace. In heat sources (heat sinks) where the volume is small compared to the heating load (cooling load) or heat-transferring properties are poorer the temperature gradient may become an almost permanent feature of the heat source (heat sink) [18]. Later in this chapter we will discuss thermal storage in which the goal is to create a permanent temperature gradient within the heat source (heat sink).

The location and accessibility of the heat source (heat sink) with relation to the heat pump are aspects that will effect the heat pump system's operation and price. Using a heat source (heat sink) that is far from the heat pump and the conditioned spaces, will increase heat losses and the overall price of the system. On the other hand using a heat source (heat sink) that is close to the heat pump site, but hard to access will prove to be just as unprofitable.

In reality it is impossible to find an ideal heat source (heat sink). Therefore, a comparison between the different available heat sources (heat sinks) is needed. Many times the best solution is a combination of two or more heat sources (heat sinks). Next, we will take a short look at different heat sources (heat sinks).

5.2 Air

Air is a mixture of gasses, mainly nitrogen and oxygen. It fills up most of the vacant space on the surface of our planet. Using air as a heat source (heat sink) has its benefits. Air is readily available in large quantities, making it an easily accessible heat source (heat sink). Air is a gas mixture that transfers heat via convection. Thus, temperature differences in one place will cause an airflow that will even out temperature gradients rapidly. This minimizes the local effect that lost (added) heat has on the temperature of the heat source (heat sink).

On the downside ambient air is strongly influenced by the changing of seasons. In the winter when the need for heating is highest the temperature of the heat source is low and in the summer when the need for cooling is highest the temperature of the heat sink is high. Low temperatures in the heat source cause low refrigerant temperatures. The density of the refrigerant drops in low temperatures, causing the efficiency of the heat pump to drop. The COP of an air-source heat pump will be low in cold temperatures and at very low temperatures it is possible that the heat pump will not operate at all. [19] [20]

Air humidity also influences the operation of an air-sourced heat pump. High air humidity increases the heat transferring properties of an air-source heat pump. However, when air temperature is below 5°C an ice coating starts to form on the outer air-inlet of the heat pump. At first, the ice layer will enhance the heat transferring properties of the heat pump. As the layer thickens it will begin to prevent heat transfer and air flow. An air-sourced heat pump must be equipped with defrosting equipment to prevent ice build-up. This equipment lowers the overall efficiency of the heat pump system. [19][20][21]

Building exhaust air can provide a heat pump with a heat source at a more constant temperature. The difficulty in this option is the changing airflow of the exhaust air. In cold temperatures when the heat need is high ventilation systems are turned low and the exhaust airflow is small. For this reason when using exhaust air as a heat source (heat sink), it is important to be sure that the heat pump receives a sufficient airflow at all times. [22][23]

A simple air-source heat pump has a air-inlet (air-outlet) unit that is placed outdoors. The outdoor unit has a fan and possibly defrosting equipment. This unit is connected to the indoor unit via a pipe through which air may flow. The indoor contains the actual heat pump and a fan equipped air-outlet (air-inlet). Often the heat pump packages include temperature sensors that are used to control the heat pump operation. [2][14]

An air-source heat pump can be used for heating even in Finland. However, another heating system is required to top off the heating spikes that occur during colder days. In Finland, air sourced heat pumps are often used in combination with direct electric heating and/or a heat-storing fireplace. [6][14]

5.3 Water

Water is a good thermal storage and has also good heat transferring properties. In heat pump systems both groundwater and surface water for example lakes, rivers, and oceans can be used as heat sources (heat sinks). Here we will deal with groundwater and surface water heat sources (heat sinks) separately.

5.3.1 Groundwater

Groundwater can be used as a heat source in areas where it is available. It has the benefit of being only moderately impacted by the seasonal temperature changes in comparison to the ambient air. However, the available groundwater is often heavily regulated and groundwater heat pumps systems are not very popular in Finland. [14][24]

Groundwater heat pump systems circulate the groundwater itself through the heat pump evaporator. Care must be taken that the water is not contaminated. If the groundwater has high mineral or microbe contents it can cause scaling and biofouling within the evaporator. [14][24]

Groundwater can be used in a heat pump system for *free cooling*. Free cooling is cooling that is caused by the temperature difference between the heat sink and the conditioned space. The temperature of the heat sink is lower than that of the conditioned space and the conditioned space can be cooled without operating the heat pump. Only the pump circulating the groundwater needs to be operated. In cases were cooling needs are great, the possibility for free cooling is an advantage. Free cooling is also know as *passive cooling*. [20]

Groundwater heat pump systems have an open-looped connection with the groundwater. Ground water is pumped from a groundwater well into the heat pumps evaporator side. Then the groundwater is re-injected into the ground via an injection well (double well system) or into surface water (single well system). The double well and the single well systems are presented in figure 5.1. [6][14][18]

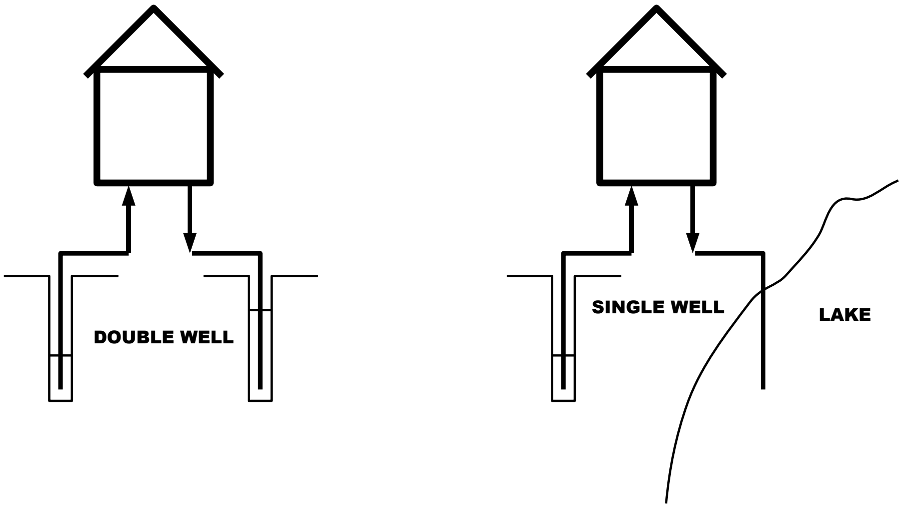

Figure 5.1: A single and a double well groundwater heat exchange systems

5.3.2 Surface water

Surface water is influenced by seasonal changes less than the ambient air but at times more than groundwater. Here we will consider the cases of lakes and rivers in Finland.

Water is most dense at 4°C. So in the spring and in the fall the water in a lake goes trough a cycle where the dense 4°C water sinks to the bottom of the lake and the colder or warmer water rises to the top. Because of this it can be roughly estimated that the water at the bottom of a lake is 4°C. [18][20]

However, the temperature of water in a lake is also dependent on other things such as the depth of the lake, winds, currents *etc.* In the summer the temperature at the surface of the lake can be 30°C. Even at the bottom of the lake the temperature can rise as high as 15°C. In fall time the lake water temperature begins to fall as the air temperature drops and heat is released from the lake. Winds increase the heat loss from the lake. The water temperature continues to decrease until an ice cover is formed over the lake. This ice cover serves as an insulation against the coldness of the ambient air. During the winter the temperature at the bottom of the lake can drop close to

0°C. Very shallow ponds can even freeze. [18][20]

In rivers, currents are often stronger than in lakes. The currents keep the water mixed and the kind of different temperature levels we see in lakes do not form as readily. In the winter it is possible for the temperature of a river to drop below zero before an ice cover is formed. [18][20][23]

The ecological effects of taking (adding) heat into surface water depends on the amount of heat transferred and the size of the water body. In cases where the heat gain (loss) is small in comparison to the size of the water body and thus the overall temperature change is small ecological effects are almost non-existing [18].

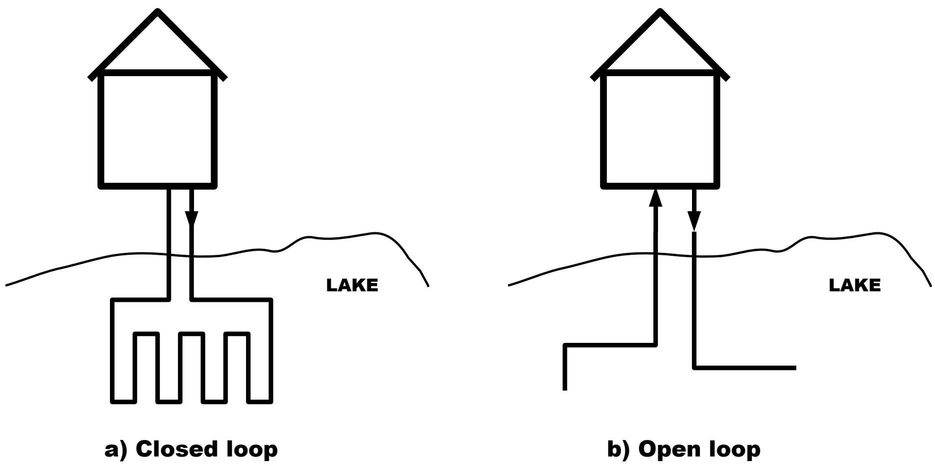

Figure 5.2: A closed and an open loop heat exchangers in a lake

There are two ways of using surface water as a heat source (heat sink). One way is to have an open loop connection with the surface water. In an open loop system, surface water is pumped to the evaporator of the heat pump, just as was the case with the groundwater heat pump system. The other way is to have a closed loop connection with the surface water. A closed pipe loop is placed on the floor of the surface water body. A water or water/antifreeze mixture is circulated between the water body and the heat pump. To prevent the pipes from being torn away in spring with the melting ice cover, the pipes need to be anchored to the bottom by weights. The two options are presented in figure 5.2. [6][18][14][24]

The closed loop connection is generally chosen in Finland. Pesonen states in his technical report [20] on heat pump usage that when using polyethylene (PE) pipes the received power density is 50 W/m . The power density is needed when designing the length of the closed-loop pipeline that will be placed in the water body. [6][18][14][24]

Surface water heat sinks offer the possibility for free cooling. Again it must be said that free cooling is a very desirable feature for buildings with high cooling loads.

Since surface water bodies vary, each case must be considered separately. In addition, using a surface water body as a heat source (heat sink) always requires permission from the owner of the water body. In the case of the closed-loop connection, underwater anchoring of boats must be forbidden to prevent damage to the piping. [6][23]

5.4 Ground

Ground-sourced heat pump systems can be connected to the earth in different ways. Here we will discuss the horizontal and vertical connections. The horizontal connection refers to pipes placed horizontally in trenches. The vertical connection refers to pipes placed vertically in boreholes. [17][25]

5.4.1 Horizontal

In Finland, the temperature of soil at 1 metre depth varies from -2°C to 12°C during a year [17] . The snow covering on the ground in the winter works as an insulation layer. This keeps the soil warmer than the air. In the summer the sun heats the ground and the temperature rises in the soil. [17]

It is important to know the type of soil and its latent heat of freezing, when considering a horizontal heat exchanger for a ground-sourced heat pump system. Soil's

Table 5.1: Latent heat of freezing (kWh/m^3) for different soils; maximum for wet soil, minimum for dry soil. [24]

Type	Maximum (kWh/m^3)	Minimum (kWh/m^3)
Clay	70	55
Dry Clay	45	30
Clay and Silt	55	45
Silt	55	25
Sand	45	10
Moraine	40	10
Peat	90	18

latent heat of freezing is strongly dependant on its moisture content. Table 5.1 is a list of seven typical Finnish soils and their latent heat of freezing. The numerical data presented in this table can be used when calculating the length of horizontal piping. [24][26]

In the ground, heat loss (heat gain) does not even out as rapidly as in cases of air or surface water. Because of this, heat loss can cause the frost line to move deeper than its original depth. This in turn will keep the ground frozen for a longer time into the spring causing less energy to be stored in the ground for the next heating season. As the ground remains frozen for a longer period of time early spring flora might suffer. To avoid this the horizontal pipes need to be placed within suitable distances from one another. [18][24][26]

5.4.2 Vertical

The temperatures in the bedrock, below seasonal impact depth but above 200 metres, range from 2°C to 8°C [17]. Bedrock provides a heat source (heat sink) with a more stable temperature than soil. On top of a more moderated temperature, vertical heat exchangers have the following advantages over the horizontal heat exchangers: a smaller surface area and the possibility for free cooling. [14][27]

In a standard vertical heat exchanger plastic (polyethylene or polypropylene) u-pipes are installed in boreholes. The remaining free space is grouted to provide a thermal contact between the pipe and the surrounding ground. The boreholes are typically 80 to 150 metres deep. [27][28]

In the ground surrounding the vertical heat exchanger, the loss (gain) of heat causes a temperature gradient. The taking (releasing) of heat from (into) the ground will cause the temperature in the ground surrounding the vertical heat exchanger to change. As was the case in the horizontal installation, the formed temperature gradient will not even out as quickly as it does in the air or in water. If boreholes are place too close to one another the surrounding ground may be overcooled (overheated) due to excessive amounts of heat loss (gain). This in turn will effect the overall performance of the heat pump system. The recommended space between boreholes is 15 m [24]. Even when the boreholes are not placed too close together the temperature of the ground will change. Eventually a new temperature equilibrium will be found. [14][18]

When designing a vertical heat exchanger the basic assumption is that the boreholes are dry. This assumption is done to simplify the modelling and the calculation process. The presence of groundwater increases the grounds heat transferring properties and moderates the temperature changes caused by heat loss (heat gain). [27]

5.5 Others

The heat sources (heat sinks) described above are the most common ones. However, heat pumps can be coupled with almost any heat source (heat sink) that is available.

One example is using the heat from city sewage as a heat source for a heat pump system. Because of the relatively high temperature of sewage, it is best suited for heating solutions, not cooling. The heat from the sewage is collected at the water treatment plant. The heat can then be used locally at the treatment plant or it can be

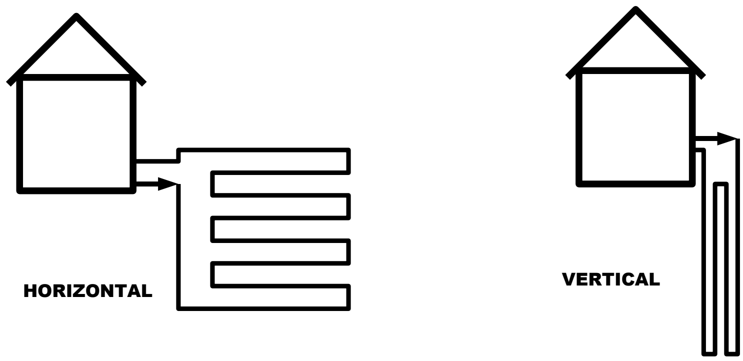

Figure 5.3: Horizontal and vertical ground heat exchangers

added into the district heating system. Sewage provides a rather constant temperature heat source. [29]

Another example is using the sediment in shore areas as a heat source. Mateva Oy decided to use the sediment as a heat source for the local district-heating scheme they designed for the Finnish Housing Fair in Vaasa 2008. Mateva Oy discovered that sea sediment at the shore of the Finnish Housing Fair in Vaasa had relatively high temperatures even in the winter. The temperature in the sediment at 5 metres of depth was as high as 8 °C [30]. They installed a horizontal heat exchanger in the sediment at a depth of 4 to 5 metres. This heat exchanger is the source and sink for a low temperature district heating system, which provides heating and cooling for 42 houses. Each house is connected to the system via their own heat pump. [31]

5.6 Storing Thermal Energy in a Heat Source, Removing It from a Heat Sink

It is an intriguing idea to improve the efficiency of a heat pump system by storing thermal energy in the heat source during the summer to be used in the winter and taking thermal energy out of the heat sink in the winter to increasing the cooling capacity for the summer. The idea in storing or removing thermal energy is to change the local temperature of the heat source (sink) and thus increasing its heating (cooling) capacity.

As mentioned previously, a good thermal storage has a high specific heat and it must also be able to maintain the local temperature difference caused by storing (removing) thermal energy. In their article H.-F. Zhang, X.-S. Ge and H. Ye [32] propose using a surface water pond as a thermal storage for a heat pump system. They propose an insulation soil layer to cover the pond in an attempt to decrease the amount of thermal energy transferred to and from the pond. In their proposal, thermal energy is stored in the pond during the cooling season and removed from the pond during the heating season. Their conclusions were that it is important to have an appropriate thickness of the insulation layer above the pond and a volume of water that corresponds to the heating and cooling loads. These conclusions confirm what has been said at the beginning of this chapter about the volume requirements of heat sources (sinks). In the case of thermal storage, a too large volume will decrease the storing efficiency. The volume of a thermal storage must correspond with the heating and cooling loads.

H.-F. Zhang, X.-S. Ge and H. Ye compared their model with models that had separate heat sources and heat sinks [32]. If a system that has a single element (*e.g.* a pond) that works as both the heat source and heat sink, seasonal temperature balancing that is presented in their article will happen automatically. Using seasonal balancing is a wise thing to do. However, their proposal of covering a pond with an insulation layer is a drawback on their scheme. Often if a pond exists or is built it does not make sense to cover it as the water element can add to the esthetics of the area where it lays.

A more convenient solution could be to store thermal energy underground. For example, heat exchangers placed under road surfaces and in the surrounding ground. During the summer, heat is taken from the road surface to the underground storage. In the winter, heat from the storage is used to de-ice the road surface. [28]

An example of thermal storage for a building is the Berlin Reichstagsgebäude, a large building, which is connected to an underground cool thermal storage at about 60 m belowground and a warm thermal storage at more than 300 m belowground. Excess heat and cool is moved to these storages. When needed, heat and cool is taken back into the building. [28]

It can be said that thermal storing is at its best when the storing can be done in a suitable storage with a high specific heat and an appropriate volume. The more it cost to add a thermal storage to a heat pump system the less profitable the scheme becomes.

6 Conditioned Space

In this chapter, we will focus on the conditioned space of a heat pump system (see figure 3.1). First, we will take a brief look at a few different heat distribution options. Second, we will see how the heating and cooling loads of a building can be calculated.

6.1 Thermal Energy Distribution in the Conditioned Space

The thermal energy produced by a central heating (cooling) system such as a heat pump needs to be distributed to all of the conditioned spaces. Water and/or air are typical distribution mediums. We will discuss their usage in ducted air, ventilation air, radiator and in-floor thermal energy distribution systems.

Different thermal energy distribution systems require different high-temperatures (low-temperatures) to effectively heat (cool) the conditioned space. A heat pump works most efficiently when the temperature difference between the heat source (heat sink) and conditioned space is small. Systems with a low high-temperature requirement (max. $\sim 50\ ^{o}$C) are best suited to be combined with a heat pump [6].

6.1.1 Ducted Air

A ducted air heating (cooling) system is central heating (cooling) system where the produced thermal heat (cool) is used to heat (cool) air. The heated (cooled) air is then distributed throughout the conditioned space via air ducts. A large portion of the air from the conditioned space is circulated to the heating (cooling) centre and then back to the conditioned space. The airflow of a ducted air heating (cooling) system is set in accordance with the heating (cooling) load. [33]

In a ducted air heat (cool) distribution system, there are no heat-storing elements that moderate the temperature changes in the room. This is another factor that contributes to the speed of room temperature change. A rapid change of temperature can be seen as a benefit as it adds to the flexibility of a heating (cooling) system. However, it can also be seen as a fault as room temperatures will drop (rise) relatively fast after the heating (cooling) system is turned off.

The building masses of the conditioned space can be used as heat and cool storage to moderate temperature changes after the system is turned off. In this type of a system duct air is driven through the building masses *i.e.* walls, floors and ceilings. The building masses are heated (cooled) by the air and then they slowly discharge their thermal energy into the conditioned space. This topic will be discussed further in connection with in-floor heating. [34].

It is important to note that ducted air distribution systems can be used effectively for heating, cooling and humidity control. The principles of the system are the same no matter which of the three functions it performs. In fact, one system can be used for all three functions. [33]

A ducted air system can be combined with a heat pump effectively as the air is typically heated or cooled to temperatures between 15 - 40 °C [33]. As the heated (cooled) air is distributed evenly throughout the room, high (low) temperatures are not required.

6.1.2 Ventilation Heating and Cooling

Ventilation air can be cooled and heated in an effort to provide heating and cooling for the conditioned space. This heating distribution system resembles that of duct air. One difference is that the airflow is not determined by the heating (cooling) load but by the ventilation load. Because of this, the ventilation heating system is best suited for energy saving buildings *i.e.* highly insulated buildings. From a construction-engineering point of view, a ventilation heating and cooling system combines two systems, ventilation and air conditioning reducing the required equipment. [33]

6.1.3 Radiators

Radiators are elements that are placed within the conditioned space generally under a window on the wall. They can be part of a central heating system with a fluid, typically water, flowing from the water heater to a network of radiators or they can be separate electric radiators containing electric resistors that produce heat. The later heating system is also known as direct electric heating and it is often used in residential buildings in Finland [33]. The system first mentioned can be combined with a heat pump.

Heat from the radiator needs to be transferred to the air of the conditioned space. To enhance the conduction of heat from within the radiator to its surface, radiators are built out of material with a high conductivity. To enhance the convection from the surface of the radiator, the ratio of the radiator's surface area to its volume can be increased by roughing, bent surfaces or even added fins. Often radiators require high temperatures to increase heat transfer. [33]

Unlike ducted air systems, radiators store heat and thus have a moderating effect on room temperature changes. However, their discharge time is relatively short and building masses are more effective temperature change moderators.

Radiators require a high temperature. They have a relatively small surface area compared to the volume of the space in which they are placed and therefore their temperature needs to be a lot higher than room temperature. Typically radiators are kept at a temperature of 70 °C [33]. A radiator heat distribution system, though suited for fuel burning heating systems, is not well suited for heat pump applications, because of it's high temperature requirement. The high temperature demand tends to have an negative impact on the COP of a heat pump.

In buildings, radiators are mainly used for heating, not cooling. There are systems that combine duct air or air-ventilation and radiators for cooling purposes. In these systems, radiators are placed in the entering-air vents of the conditioned space. These systems are closely related to the ducted air and ventilation systems and can be combined with heat pump system. [33]

6.1.4 In-Floor Heating

In-floor heating refers to a heat distribution system that has its heat transferring elements in the floor of the conditioned space. These elements can be electric resistors or pipes with either water or air flowing through them. [33]

Compared to the radiator heat distribution system in-floor heating has the advantages of having a large surface area and a lower high-temperature requirement. A in-floor heating system requires a high temperature of 50 ^{o}C [35], making it suitable to be coupled with a heat pump.

In this type of heat distribution, thermal energy is stored in the floor. The discharge time of the heat in the floor depends on the floor material and its properties. For example in a cement floor, heat is stored for a relatively long time.

In-floor heating can be used in combination with a variety of different floor materials. The important factor is that the chosen material can withhold the designed temperature levels of the in-floor heating system. [35]

In-floor heating systems are gaining popularity in Finland especially in residential house heating [33]. Floor heating provides a comfortable living temperature, without the space consuming radiators. It has the added comfort that warm floors have when compared to cold ones. An in-floor heating system is typically not used for cooling purposes.

The heat transferring elements mentioned here can also be placed within walls or ceilings. The principles are close to the same as with in-floor heating. [34].

6.2 Storing Thermal Energy in the Conditioned Space

In the previous chapter in section 5.6, we talked about storing thermal energy as it related to heat sources and heat sinks. Here we will discuss the same issue as it relates to the conditioned space. Thermal energy is usually stored in large masses. In the conditioned space concrete floors or walls, brick fireplaces, and water tanks are commonly used for thermal storage.

The thermal energy stored into the building structures and brick fireplaces is slowly released into the air of the conditioned space. These storages are passive storages. A passive storage discharges thermal energy over a period of time and the discharge is not controlled by any outside mechanism. It is simply controlled by the heat transferring properties of the storage and its surrounds.

A water tank can be considered an active thermal storage. Water from the tank is circulated through the thermal distribution system with the assistance of a circulation pump. The amount of thermal energy free to be discharged into the conditioned space is controlled by controlling the water flow rate. The water tank storage also has a uncontrolled thermal energy discharge, which is due to the finite nature of its insulation. [36]

The thermal energy released from water travelling through the heat distribution system can be stored in the building structural masses. In such cases, the active role of the water tank storage is combined with a passive storage. The passive storage has a moderating effect on the changes of room temperature. [34]

When a water tank is combined with a heat pump, the system is often called a water heating heat pump [14]. In such a system, the water tank works as a constant load for the heat pump, as it buffers the heat pump from the peaks in the heating and cooling loads. These peaks occur for example when warm service water is consumed in high quantities during a shower.

Water heating heat pump systems are easily combined with all of the distribution systems described earlier. It is also possible to build hybrid-heating (cooling) systems that combine different heating (cooling) systems. For example, a heat pump and solar collectors can be combined to the same water tank.

Large buildings often have simultaneous cooling and heating loads in different areas of the building. For such buildings, it is profitable to have an air conditioning system that can take heat from one area and release it in another. Using a water tank for heat and cool storage can help control such a system.

6.3 Heating and Cooling Loads of a Building

The objective in heating and cooling a building is to keep the room temperature at a constant level. The desired temperature varies between 18°C to 22°C. To maintain a constant temperature during the heating season all heat loses must be replaced and during the cooling season, all excess heat must be removed.

When trying to size a heating (cooling) system it is important to know the heating (cooling) load of the conditioned spaces. The heating load consists of all of the heat losses subtract the heat gains of the conditioned space. The cooling load consists of the excess heat subtract the heat losses.

To identify the heat losses and heat gains of a conditioned space, we will consider a thermodynamic system. Our thermodynamic system is a building and its walls are the system's boundary lines. Figure 6.3 presents a drawing of our system.

The system experiences all three forms of heat transfer, mentioned in the heat transfer section 2.2:

- Conduction through the insulated boundary lines (building envelop),
- Convection in the form of airflow to and from the system via ventilation and uncontrolled air infiltration (exfiltration); and
- Radiation of heat from and irradiation into the system.

The heat radiation from the system is minimal and will not be included in our discussion of calculating the heating and cooling loads presented in the following sections. The irradiation of the sun on the system's windows is a significant heat gain and it will be included in the discussion. Our examination assumes a one-dimensional heat transfer.

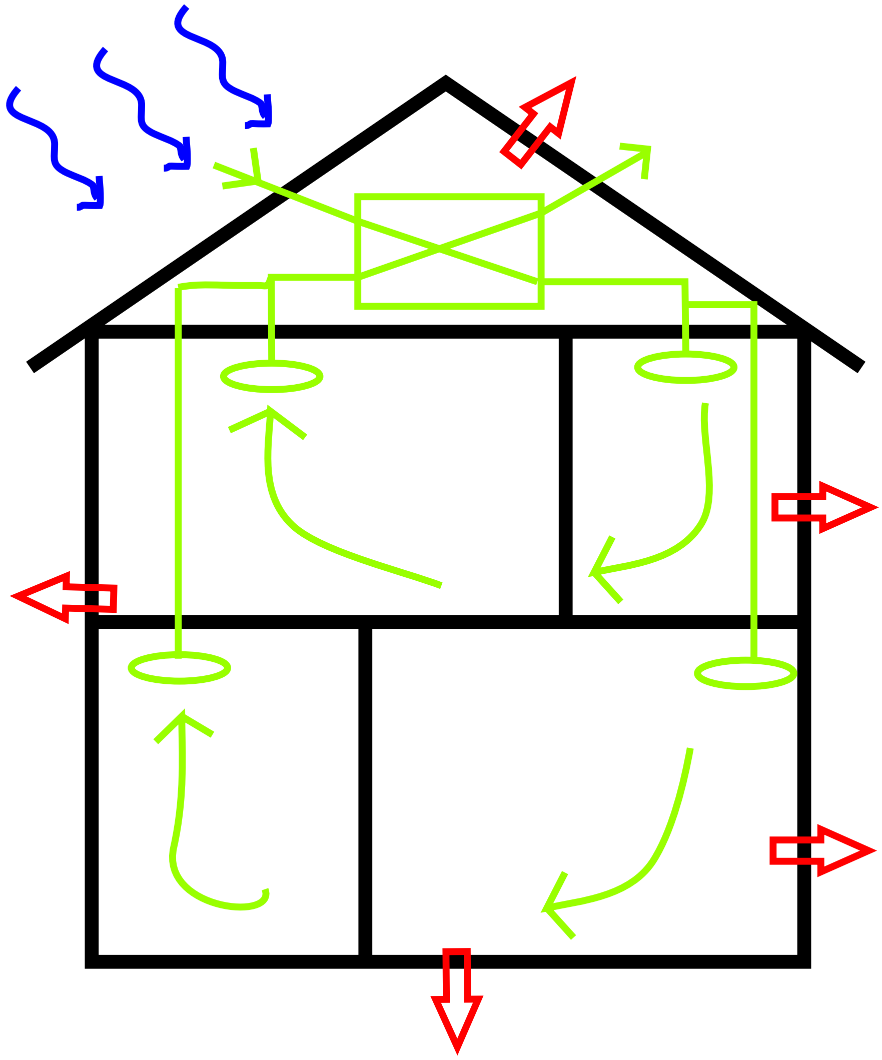

Figure 6.1: The three main heat transferring connections a building has with its surround. Thin arrows = convection via ventilation, Big arrows = conduction through walls, roof and floor, "Snake" arrows = irradiation from the sun.

On top of the heat transfer between the system and its surround, the system is effected by internal heat generation. Internal heat is generated by electronic devises (*e.g.* computers, TVs), lighting, food storage facilities (fridges, freezers) and people. These internal heat sources can be significant and need to be taken into consideration [37]. For example computers are known to produce a lot of excess heat, so if a large amount of computers are to be placed in the same space, in a computer room, effective cooling needs to be provided.

Another part of a buildings heating load is the heating of the required warm service water. If heating the warm service water is part of the main heating system then it must be included in the heating load calculations. This part of the load can be significant especially in residential housing, hotels and spas.

In the following sections, we will take brief look at how heating and cooling loads are calculated. We will refer to Code D5 - Calculation of power and energy needs for the heating of buildings, of the National Building Codes of Finland as a bases for our discussion [37]. Code D5 is available only in Finnish and Swedish, the two official languages of Finland. English readers will find a brief presentation of Code D5 in the following sections. This type of a calculation is often done for buildings not yet built and it is presented here to help us understand what the heating load consists of. For buildings, all ready in use the heating and cooling loads can be calculated directly from the recorded energy consumption [37].

In the following calculations, the period of calculation plays an important role. The period of calculation can be a year, a month, a day or even shorter. The shorter the period of calculation the longer and more tedious the calculation, and the more precise details are required [36].

6.3.1 Heat Loss

A building looses heat mainly through the exterior surfaces of the building, through ventilation and through air infiltration (exfiltration). We will consider each loss separately.

To prevent heat loss via conduction walls, floors, and roofs are insulated. Insulation increases the thickness of the boundary lines and decreases the heat transferred via conduction as seen in the conduction equation presented in table 2.1. However, it is unrealistic to build a building with zero heat loss through its exterior surfaces.

The heat loss by conduction through the exterior surfaces of a building during the calculation period according to D5 [37] is calculated as follows:

$$\begin{aligned} Q_{\text{conduction}} = \quad & (U_{\text{exteriorwall}} A_{\text{exteriorwall}} + U_{\text{roof}} A_{\text{roof}} + U_{\text{base}} A_{\text{base}} \\ & + U_{\text{window}} A_{\text{window}} + U_{\text{door}} A_{\text{door}})(T_{in} - T_{amb})\Delta t / 1000, \end{aligned} \tag{6.1}$$

where $Q_{\text{conduction}}$ = the heat loss through the exterior surfaces (kWh), $U_{\text{exteriorwall}}$ = the conduction constant for the exterior walls (W/m^2 K), $A_{\text{exteriorwall}}$ = the surface area of the exterior walls (m^2), U_{base} = the conduction constant for the base of the building (W/m^2 K), A_{base} = the surface area of the base (m^2), U_{window} = the convection constant for the building windows (W/m^2 K), A_{window} = the window surface area (m^2), U_{door} = the convection constant of the building doors (W/m^2 K), A_{door} = the door surface area (m^2), Δt = calculation period (h), T_{in} = the temperature inside the building (°C) and T_{amb} = the outside ambient temperature during the calculation period (°C). The divider 1000 corrects the units. [37] It can be shown that equation 6.1 is another form of the conductivity equation presented in table 2.1.

Our next step is to consider the convection losses. Just as it is unrealistic to build a building with zero heat loss through its exterior surfaces, building an airtight house is unrealistic. The goal is to minimize uncontrolled air infiltration (exfiltration) and thus minimize uncontrolled heat loss.

The heat loss caused by air infiltration (exfiltration) can be calculated as follows

$$Q_{\text{infiltration}} = \rho_{\text{air}}\, c_{\text{p,air}}\, q_{\text{infiltration}}\, (T_{in} - T_{amb})\Delta t / 1000, \tag{6.2}$$

where $Q_{\text{infiltration}}$ = heat loss caused by air infiltration and exfiltration (kWh), ρ_{air} = density of air (1.2 kg/m^3), $c_{\text{p,air}}$ = specific heat of constant pressured air (1000

Ws/kgK), $q_{\text{infiltration}}$ = flow rate of infiltration air (m^3/s) and the rest are the same as in the previous equation. [37] Equation 6.2 is another form of the basic equation of convection found in table 2.1.

To keep the breathing air within a building clean and to prevent excess moisture build-up, which causes mold and mildew on building structures, the building needs to be properly ventilated [38]. The ventilation of a building can be gravity driven or an automated mechanical system. In newer buildings, the ventilation systems tend to be automated so that the airflow can be set and changed when needed. This type of a ventilation can be combined with the heat distribution as described earlier in this chapter.

Ventilation causes heat loss. However, a part of the heat lost through the ventilation system can be and is recovered by cooling the exhaust air. The heat loss through the ventilation system is calculated as follows

$$Q_{\text{vent}} = \sum \rho_{\text{air}}\, c_{\text{p,air}}\, q_{\text{exhaust}}\, t_d\, r\, t_w\, (1 - \eta_y)(T_{in} - T_{amb})/1000, \tag{6.3}$$

where Q_{vent} = heat loss through the ventilation system (kWh), q_{exhaust} = flow rate of exhaust air (m^3/s), t_d = average time of usage of the ventilation system per day (h/24h), r = reduction factor that takes into account the daily usage of the ventilation system (-), t_w = average usage of the ventilation system per week (day/7days), η_y = efficiency of heat recovery during the period of calculation (-) and the rest are the same as in the previous equation. [37]

The heating system itself is not ideal and heat losses take place in the system. These losses are calculated as follows

$$\begin{aligned} Q_{\text{spaceheatinglosses}} = \; & Q_{\text{heatgenerationlosses}} + Q_{\text{heatdistributionlosses}} + Q_{\text{heattransferlosses}} \\ & + Q_{\text{heatcontrollosses}} + Q_{\text{heatstoragelosses}}, \end{aligned} \tag{6.4}$$

where $Q_{\text{spaceheatinglosses}}$ = heat losses in the heating system, $Q_{\text{heatgenerationlosses}}$ = heat losses in the heat generation phase, $Q_{\text{heatdistributionlosses}}$ = heat losses in the heat distribution network, $Q_{\text{heattransferlosses}}$ = heat losses in the heat transferring processes and equipment, $Q_{\text{heatcontrollosses}}$ = heat losses caused by the network controlling system and $Q_{\text{heatstoragelosses}}$ = heat losses in the heat accumulating water tank. All have the unit kWh. [37]

6.3.2 Warm Service Water

The heating of the warm service water needed in a building can be done by a separate heating system or as a part of the main heating system. When it is part of the main heating system, it needs to be included in the calculation of the heating load as a "heat loss".

The heat needed for heating the warm service water is calculated as follows

$$Q_{\text{wsw,net}} = \rho_w \, c_{p,w} \, V_{wsw} \, (T_{wsw} - T_{csw})/3600, \tag{6.5}$$

where $Q_{\text{wsw,net}}$ = (net) heat required in heating the warm service water (kWh), ρ_w = density of water (1000 kg/m^3), $c_{p,w}$ = specific heat of constant pressured water (4.2 kJ/kgK), V_{wsw} = required amount of warm service water (m^3), T_{wsw} = temperature of warm service water (°C) and T_{csw} = temperature of cold service water (°C). The divider 3600 corrects the units. [37]

6.3.3 Heat Gain

A building experiences both internal and external heat gains. Internal heat gains come from internal heat generation sources such as lighting. The main external heat gain is solar irradiation incident on the windows (Q_{sun}). Others are the heat gain from occupants Q_{people}, from electronic devises Q_{elec} and heat losses from the warm service water system $Q_{\text{wsw,load}}$ and from the space heating system $Q_{\text{spaceheatingload}}$.

6.3.4 Heating Load

The total heating load is calculated as a summation of the heat losses and the heat gains as follows

$$\begin{aligned} Q_{\text{totalheatingneed}} = {} & Q_{\text{convection}} + Q_{\text{infiltration}} + Q_{\text{vent}} + Q_{\text{wsw}} \\ & -\eta_{\text{heat}} \left(Q_{\text{people}} + Q_{\text{spaceheatingload}} + Q_{\text{elec}} + Q_{\text{sun}} + Q_{\text{wsw,load}}\right), \end{aligned} \tag{6.6}$$

where η_{heat} = the monthly amount of the heat gain that is reclaimed and the rest of the variables are as defined in previous equations. The result is in kWh per month. [37]

6.3.5 Cooling Load

The cooling load consists of all heat gains that tend to raise the building temperature above that desired temperature. The cooling load is calculated as follows

$$\begin{aligned} Q_{\text{cool}} = {} & (1 - \eta_{\text{heat}}) \left(Q_{\text{people}} + Q_{\text{spaceheatingload}} + Q_{\text{elec}} + Q_{\text{sun}} + Q_{\text{wsw,load}}\right) \\ & - \frac{(T_{\text{cal,avg,in}} - T_{in})^{1.1}}{(T_{in} - T_{amb})} \left(Q_{\text{convection}} + Q_{\text{infiltration}} + Q_{\text{vent}} + Q_{\text{wsw}}\right), \end{aligned} \tag{6.7}$$

where Q_{cool} = the cooling load (kWh), $T_{\text{cal,avg,in}}$ = the calculated monthly average of the indoor temperature *i.e.* the set cooling temperature (°C) and the rest are the same as in the previous equations.

6.4 Instantaneous Heating Load

The calculations presented in the previous section *i.e.* equations 6.1 - 6.7 are used to calculate the heating (cooling) load for a given period of calculation. The results are in kWh. Now we will take a brief look at the calculation of the instantaneous heating load of a building. We will only consider the calculation of the instantaneous load for heating not for cooling.

The instantaneous heat load is needed when sizing the actual heat pump equipment and it can vary greatly from one moment to another *e.g.* the instantaneous heating load is great during a shower. The presence of a heat storage such as a water tank moderates the actual load seen by the heat pump. Only in cases where no heat storage is used is the required heat pump capacity equal to the instantaneous heating load. [37]

The instantaneous heating load is often calculated per room or heating zone. The total instantaneous heating load of a building can be calculated as a sum over all the rooms and heating zones. [37]

The instantaneous heating load is calculated as follows

$$\begin{aligned} \phi_{\text{heating}} = & \frac{\phi_{\text{convection}} + \phi_{\text{airinfiltration}} + \phi_{\text{vent}} - \phi_{\text{airinletheater}}}{\eta_{\text{roomheating}}} \\ & + \frac{\phi_{\text{airinletheater}}}{\eta_{\text{airinlet}}} + \frac{\phi_{\text{wsw}}}{\eta_{\text{wsw}}}, \end{aligned} \tag{6.8}$$

where ϕ_{heating} = the instantaneous heating load (W), $\phi_{\text{convection}}$ = the convection caused instantaneous heating load (W), $\phi_{\text{airinfiltration}}$ = the air infiltration caused instantaneous heating load (W) ϕ_{vent} = the air vent caused instantaneous heating load (W), $\phi_{\text{airinletheater}}$ = the entering air heater instantaneous heating load (W), $\eta_{\text{roomheating}}$ = the efficiency of room heating under the design conditions (-), η_{airinlet} = the efficiency of the entering air heating system under the design conditions (-), ϕ_{wsw} = the instantaneous heating load of warm service water (W) and η_{wsw} = the efficiency of the warm service water heating system (-). [37]

6.5 Sizing a Heat Pump System

6.5.1 Sizing a Heat Pump

The sizing of a heat pump takes into consideration the instantaneous heating (cooling) load, the possible heat storage within the conditioned space *e.g.* a water tank, the heat source (sink) and the intentioned type of heating (cooling to be provided) *i.e.* seasonal, baseline, complete or supplemental heating (cooling).

If a heat pump is designed to provide for the total amount of the heating (cooling) then the heat pump must have a heating (cooling) capacity equal to the instantaneous load. Often a heat pump is designed to cover baseline heating (cooling) *i.e.* it provides heat for up to a certain preset value. In this case, supplemental heating (cooling) must be provided to top off the heating (cooling) peaks. If the heat pump is connected to a heat (cool) storage the heating (cooling) capacity is more complex to calculate.

The heat source (sink) temperature will effect the efficiency of the heat pump. This also needs to be taken into consideration so that the size of the heat pump is in line with the size of the heat source (sink). For an air sourced heat pump the source temperature changes dramatically with the changing of seasons. For ground and surface water sourced heat pumps, the change is not as dramatic. However, in these cases the heat pump is coupled with a heat collection loop(s). This loop(s) needs to be sized as well.

6.5.2 Sizing the Heat Collection Loop

A thumb rule that can be used for sizing a heat collection loop for both ground and surface water coupled heat pump systems is

$$L = \frac{rQ_{total}}{q}, \tag{6.9}$$

where Q = total heating load per year (kWh/a), r = heating load reduction factor, q = energy from heat source per metre of piping (kWh/m). The total heating load per year is calculated in equation 6.6. The heating load reduction factor r reduces the total heating load to the heating load that needs to be covered by the ground loop. A part of the heating load is covered by the electric energy that operates the heat pump. For example if the COP = 2 then r = 0.5, if COP = 3 then r = 0.67 and if COP = 4 then r = 0.75. [24]

Using a thumb rule gives an rough estimate for the length of the heat collection loop. A more detailed calculation must be done during the actual planning of the heat pump system. For larger systems, test measurements of the temperature of the heat source (sink) can be done and computer modelling can be used to estimate the temperature changes that will occur in the heat source (sink) over the lifetime of the system. [14]

With accurate design calculations, the actual length of the heat collection loop is reduced and thus the initial investment is reduced. However, accurate calculations and temperature testing can be expensive. It is important to find the balance between the required accuracy of calculation and the costs of acquiring the required data for the calculation.

Here is an example of a more detailed way to calculate the length of a borehole collection loop

$$L = \frac{q_h R_b + q_y R_{20y} + q_m R_{1m} + q_h R_{6h}}{T_m - (T_g + T_p)}, \tag{6.10}$$

where L = depth of bore hole (m), q_h = peak hourly load (kW), q_y = the yearly average ground load (kW), q_m = highest monthly ground load (kW), R_b = effective borehole thermal resistance (mK/W), R_{20y} = effective thermal resistance for a 20 year thermal pulse (mK/W), R_{1m} = effective ground thermal resistance for a one month thermal pulse (mK/W), R_{6h} = effective ground thermal resistance for a six hour thermal pulse (mK/W), T_m = mean fluid temperature (°C) $(T_{in,HP} + T_{out,HP}/2)$, T_g = undisturbed ground temperature (°C), and T_p = temperature penalty (°C) [39].

Comparing the equation 6.9 with equation 6.10 we see that the later equation considers the thermal changes that take place in the ground surrounding the collection loop. This type of a calculation also helps to see the long term effect that the drawing (inserting) of thermal energy over a period of time will have on the ground.

7 Choosing a Heat Pump

The statements made in this chapter will be in relation to the current situation in Finland and not all of the statements will be directly applicable to other countries.

7.1 Choosing a Heating and Cooling System

7.1.1 General

Keeping the temperature inside a building at a comfortable level is a task that consumes a lot of energy. In fact regulating building temperatures is the greatest energy consuming process in residential buildings [33]. With this in mind, it is easy to see the importance of carefully considering different heating (cooling) options before choosing the most suitable one for a specific building. An improper choice of a heating and/or cooling system can cause loss of comfort, when the room temperatures rise too high or fall too low, and loss of money either in the form of too high initial costs or too high operational cost or in the worst case in the form of both of the before. A poorly sized heating (cooling) system will have a shortened useful life as it will be operating out side of the designed ranges. In addition, the chosen system will play a large part in impact the building has on the environment.

The process of choosing a heating (cooling) system starts with an evaluation of the heating (cooling) loads, a comparison of competing technologies and the economics of each option, the possible heat (cool) storage, the heat distribution options, the ecological effects of the system as well as the level of comfort or easy operation required from the system. In the previous chapter, we already looked into the details of calculating the heating (cooling) load (see section 6.3) and we discussed different heat distribution options (see section 6.1). The concept of heat storage was discussed both for heat storage within the conditioned space (see section 6.2) and for the heat source (sink) of a heat pump (see section 5.6). Therefore, we have yet to deal with the topics of competing technologies, economic evaluations, ecological effects and the required level of comfort.

7.1.2 Competing Technologies

Traditionally cooling and heating systems are separate units and in heating dominated areas such as Finland, cooling systems have been mainly used in non-residential buildings. For this reason we will discuss heating and cooling systems separately and start with heating systems.

The heating systems competing on the market today include different kinds of furnaces (oil, gas or wood fuelled), direct electric heating systems, heat pumps (ground, water, air or exhaust source), fireplaces, solar collectors, and district heating. Some of these, such as district heating, can provide enough heat to satisfy the full heating load of a building. Others are better suited to be used for baseline, supplemental, or seasonal heating. *E.g.*, solar collectors provide seasonal baseline heating. [33]

When choosing the appropriate heating system it is important to know the limitations of each competing option. Choosing a heating system that is best suited to provide supplemental heating as the main heating equipment can lead to problems. *E.g.* One could cover their roof with solar collectors thinking that it would be enough to keep the building warm all year around, but when winter comes and there is no sunshine that building will get very cold.

Many times the optimal heating system is a combination of different types of heating technologies, a hybrid heating system. One hybrid heating system that is gaining popularity combines an oil fuelled furnace for central heating, solar collectors and a water tank heat storage. This combination uses oil to provide heat in the winter and solar energy to provide heat during the summer. Both the furnace and the solar collectors are connected to the water tank. While solar heat is available, it is used to provide baseline heating. Space heating requires the temperature in the water tank to be a minimum of 35°C, for warm service water the temperature must be above 55°C [40]. The maximum temperature of the water tank should be set at 90°C , at which point both heat sources should be switched off [40]. The oil fuelled furnace is used to provide supplemental heat during the solar heating season, so that the minimum temperature levels are obtained. When solar heat is not available, the furnace covers the total heating load.

Cooling systems are generally based on the same technology as the vapour-compression heat pump (see section 3.1). Another cooling option is free cooling (see section 5.3).

Cooling systems that are based on the vapour-compression refrigerant cycle usually use air as their heat sink. This makes their efficiency dependant on the temperature swings in the ambient are as discussed in connection with air-sourced heat pumps in section 5.2. Different cooling capacities are achieved by having a varying amount of compressors in the refrigerant cycle.

7.1.3 Economics

A decisive part in choosing on a heating (cooling) system is the price tag that the system carries. The price of a heating (cooling) system can be divided into two parts, the initials costs and operational costs. The initial costs include all equipment and installation cost. These costs come at the beginning of a heating (cooling) system project and they do not reoccur. The operational costs include fuel costs, maintenance and all other costs that are required to keep the system running properly. These costs continue throughout the useful life of the heating (cooling) system and they are strongly influenced by changes in fuel prices.

It is easy to look at the initial cost and claim that this heating (cooling) system is cheaper than that one. However to get a better picture of what the system will cost in the long run it is important to estimate the operational costs as well.

A comparison between different options can be made by calculating the Net Present

Value (NPV) of each of the system. The NPV is calculated as follows

$$\sum_{j=0}^{n} \frac{B_j - C_j}{(1+i)}, \tag{7.1}$$

where B_j = benefits during period j, C_j = costs during period j, i = interest rate, n = useful life of the system, and j = period of time (*e.g.* one year). [41]

The NPV gives an overall estimation of the price of the system, taking into consideration both the initial investment and operational cost. The limitations of the NPV method are its sensitivity to changes in the interest rate (discount rate) and the fact that it focuses solemnly on the net flow of cash [42].

Another way to compare different options is to calculate the Simple Payback Period (SPB). The SPB is calculated as follows

$$\sum_{n} \Delta C_n \leq \sum_{n} \Delta B_n. \tag{7.2}$$

In this model the payback period is the time in which the cost are covered by the benefits or the savings. In the case of a heating (cooling) system the benefits are savings compared to another heating or cooling system. It is important to notice that the SPB does not included the time value of money. [42]

The acceptable length for the payback period depends on the usage of the building as well as the motivations of the building owner. *E.g.* For residential buildings a payback period of 15 years or more may be acceptable. For non-residential and commercial buildings the acceptable payback period is often short somewhere between 2-5 years.

Even though the economical evaluation of a system is important there are some benefits that cannot be quantified in cash. Over emphasizing the costs might lead to choosing a heating (cooling) system that is too small, unsuitable or hard to operate.

7.1.4 Ecological effects

The ecological effects of a heating (cooling) system can be very complex. To see the total ecological effect of the system we would need to follow the full life cycle of the system. A life cycle analysis starts could start at the mining of the required raw material and end at the final recycling and disposal of the system. This type of an analysis is time consuming.

One point that might be easier to consider on an individual level when deciding on a heating (cooling) system is the ecological effect a system will have during its operational life.

7.1.5 Level of Comfort

The level of comfort refers to the idea of number and difficulty of operational tasks, temperature stability, aesthetics, room requirement and noisiness of a heating (cooling) system. How much time and effort can the heating (cooling) system demand before the user feels that it is too burdensome. Does the system overheat (under cool) rooms? How much space does the system require? Can it be thought as part of the interior decor of a room? How noisily does the system run?

A wood burning fireplace will serve as an example. Using a fireplace requires one to buy logs fit to burn, to light a fire, keep it going, to clean ashes, have the chimney swept etc. It requires a lot of work and can easily over heat a room. On the other hand a fireplace has a particular charm to it. A family can gather around a fireplace on a cold evening to enjoy the crackling of the wood and the warmth. A fireplace can also be designed as part of the interior design.

7.1.6 Why Choose a Heat Pump

How does a heat pump compare to other heating options in the mentioned categories? Firstly, vapour-compression heat pumps come in various sizes. There are small capacity heat pumps for small loads and for very large loads it is possible to combine heat pumps to build very large heating systems. Heat pumps can be used to provide both heating and cooling eliminating the need for a separate heating and cooling system. In large buildings the heat pump system can be used to transport heat from one zone to another.

A vapour-compression heat pump runs on electricity and thus its operational cost and operational environmental effect depend on the systems efficiency and the way electricity is produced.

Heat pump systems are generally automated and controlled with a control panel, making the operation of a heat pump fairly simple. Maintenance requirements are also minimal. A properly sized system provides a comfortable room temperature at all times.

8 ABC Service Station in Viitasaari

8.1 The Service Station

On the surface Viitasaari's service station resembles other ABC service stations found in Finland. It has a ground area of 1550 m^2 [43] on which the service station has gas dispensers, a small convenient store, a restaurant/cafe that can seat up to 250 costumers inside and 150 outside on the terrace, sanitation facilities, a conference room, showers for travellers, and a resting place for buss drivers and group leaders. The service station is open 24/7 all year round. [44]

Despite it's outward similarity to other ABC service stations, the Viitasaari ABC service station differs in its use of energy or more precisely in the type of energy it consumes. The Viitasaari ABC service station depends largely on renewable energy. Part of the electricity for the service station is provided by a 10 kW horizontal-axis wind turbine, a smaller 108 W vertical-axis wind turbine and a 100 m^2 PV-array (6 kW) all located at the service station. The service station's heating load is fully covered by a lake source heat pump (310 kW), solar collectors and the local district-heating network, which uses woodchips to produce heat. [43] [45]

Since this thesis is dealing with heat pumps, we will focus on the operation of the lake source heat pump in the following sections.

8.2 Description of the Heating and Cooling System

The heating and cooling system of the Viitasaari ABC service station is built around a heat pump with a nominal cooling capacity of 310.0 kW. Extra heating is provided by the local district heating network and, starting from early spring until late fall, by solar collectors installed on top of the canopy covering the fuel pumps. In addition, the other refrigerating machines (freezers, fridges *etc.*) and the ventilation heat recovery are connected to the system. Excess heat from the refrigerating machines is released into the heating system. The thermal energy is distributed in the conditioned space via ventilation heating and cooling, and in-floor heating. The system includes the heating of warm service water.

8.2.1 Thermal Storage

The heating and cooling system has two water tanks that are used as thermal storages. The larger tank (3000 dm^3) is used for heating, the smaller tank (1000 dm^3) is used for cooling. The solar collectors and the district heating are connected to the larger tank via heat exchangers. The other refrigerating machines, the service station's cool distribution system and ventilation heat recovery are connected to the smaller tank for super cooling.

8.2.2 Heating and Cooling Modes

The heating and cooling system has three modes of operation, which are heating, passive (free) cooling and active cooling. In the following paragraphs, a brief description of the operation of each of these modes is presented. The schema and description of operation of the heating and cooling system is included in appendix A.

During the heating mode, the fluid, Thermera, entering the heating system from the lake pipes, is directed to the smaller water tank. There the excess heat from the other refrigerating machines is added to the Thermera fluid. From the smaller thermal storage, the Thermera fluid is circulated to the evaporator side of the heat pump where it is cooled and then directed back to the lake pipes. The heating mode of the heat pump system uses heat collected from the lake, from cooling the service station, from ventilation heat recovery and from the other refrigerating machines. On the condenser side of the heat pump, water from the larger water tank is circulated to the condenser heat exchanger, where it is heated and then is sent back to the water tank.

In the passive cooling mode, the Thermera fluid is directed in the same path as in the heating mode, the difference is that the heat pump is not on. Therefore, the excess heat from the service station is removed by the Thermera fluid and transferred to the lake.

In the active cooling mode, the Thermera fluid is directed from the lake to the condenser side of the heat pump and then back to the lake. Via a heat exchanger, the Thermera fluid removes heat, upgraded by the heat pump, from the system.

8.2.3 Heat Pump

The installed heat pump is a Carrier 30RW300 Water-Cooled Liquid Chiller (no hydronic module), with a nominal cooling capacity of 310.0 kW. The 30RW300 model has two refrigerant circuits with two hermetic scroll compressors for each circuit that is four compressors in total. The condenser is a welded plate heat exchanger with a water volume of 46.6 dm^3. The evaporator is a welded direct-expansion plate heat exchanger with the same water volume as the condenser. The used refrigerant is R-407C. [46]

8.2.4 Heat Source and Sink

The main heat source and heat sink for the ABC service station is the Keitele Lake (493 km^2 [47]). For the heating and cooling system of Viitasaari ABC, 7 500 m of pipe length (25 loops each 300 m long) is placed at the bottom of the Keitele Lake at a depth ranging from 2 to 7 m. The place where the pipes are place is off-limits for anchoring. [45]

The circulation fluid in the lake pipes is Thermera -35, a non-toxic water and Betaine solution. [48].

8.3 Data analysis

8.3.1 Measuring Process and Equipment

The performance of the heat pump system is followed by measuring the temperature of the Thermera fluid at the point where it leaves (T_{lake2}) and the point were it re-enters (T_{lake1}) the lake pipes, and measuring the Thermera's volume flow with a flow meter. This data is used to calculate the amount of thermal energy taken from the lake. In addition, the temperature of the warm thermal storage is measured at two points: the top and the bottom of the water tank. The measuring system is made out of RESOL measuring devises and the free software RESOLServiceCenter all by *RESOL-Elektronische Regelungen GmbH* (/www.resol.de/index/index/sprache/en). The data is saved in a MySQL database.

The outdoor temperature is measured by a Vantage Pro Plus -weather station combined with a DAVIS 6510c (http://www.davisnet.com/) data collection unit and a Weatherlink program. This data is also stored in a MySQL database.

To monitor the heat pumps mode (heating or active cooling) a small resistor based measuring devise was made. This devise is connected to the RESOL measuring system.

8.3.2 Malfunctions and Other Problems

In the following paragraphs, we will be analysing data collected by the measuring equipment. During the operation time of the heat pump and the RESOL measuring system problems have occurred. These problems will be taken into consideration when analysing the gathered data. The problems are stated in the table 8.1 for easier referencing.

8.3.3 Thermal Storage Temperatures

We will start by analysing the data from the warm thermal storage (see figure 8.1). The temperature in the thermal storage ranges roughly between 50°C and 20°C. The temperatures at the top and at the bottom of the water tank fluctuate in a similar pattern, though the temperatures at the bottom of the water tank are slightly lower than at the top.

The maximum temperature at the top and at the bottom of the tank have a high peak in the middle of the summer around the time of peak solar heating and they are probably caused by the solar collectors. The maximum temperature hits a low point every year around September-November. This low in the maximum temperature could be caused by the fluctuation of the outside temperatures that takes place in the fall. The fluctuation of the outside temperatures causes fluctuation in the heat pump operation and thus the temperature in the water tank drops. A similar fluctuation should be seen in the spring , but it does not show up in figure 8.1 as radically as in the fall. The amount thermal energy collected by the solar collectors increases in the spring, evening out the temperature in the water tank. In the fall, the amount of thermal energy collected by the solar collectors decreases emphasizing the fluctuation of the temperature of the warm thermal storage. The heating season, *i.e.* winter, shows up as a constant temperature in the water tank. The minimum and average temperatures show the same pattern as the maximum temperatures.

8.3.4 Thermera Temperatures

Here we will be analysing figures 8.2, 8.3 and 8.4.

Figure 8.2 shows the monthly average of the ambient temperature and the Thermera fluid. As would be expected, the Thermera temperature follows the fluctuation of the ambient temperature. However, the temperature of the Thermera fluid in the winter remains close to zero even when the ambient temperature drops close to -15°C. The overall fluctuation of the average temperature of the heat source (sink) temperature remains with-in the range of 0°C and 15°C. In January 2009 the average Thermera temperature takes a sudden plunge and drops close to the -5°C. This can be explained by problems P5 and P6 (see table 8.1).

Figure 8.3 shows the minimum and maximum temperatures of the Thermera fluid and of the ambient temperature. This figure is of interest as we verify the limits defined by the average temperature. Comparing the minimum and maximum temperatures of the ambient air with those of the Thermera fluid we can see that the Keitele provides a heat source (sink) with a more stable temperature fluctuation than the ambient air. However, one cannot help but notice that the maximum temperature $T_{lake2max}$ is very high in September 2005. This peak could be related to problem P2 (see table 8.1). It could be, that while the heat pump was off, the circulation pumps were also off, enabling the Thermera temperatures to rise very high. The same explanation could work for the peak of $T_{lake1max}$ in August 2005. The peak in $T_{lake1max}$ in July 2008 could be at least partially explained by the active cooling mode starting up. Figures 8.5 and 8.6 show that the heat pump system was in active cooling mode in July 2008. As $T_{lake1max}$ is the temperature of the Thermera fluid as it exits the heat pump system, in the cooling mode its temperature should be higher than temperature $T_{lake2max}$.

The final figure on Thermera temperatures is figure 8.4. Its purpose it to magnify the seasonal temperature change, which takes place in the spring and in the fall. In the summer temperature T_{lake2} is lower than temperature T_{lake1} . Heat is being removed from the building and it is released into the lake. In the winter, the sitution is exactly the opposite. Thus during the fall and the spring the temperatures T_{lake1} and T_{lake2} must cross one another.

8.3.5 Heat Pump's Mode of Operation

Figure 8.5 shows the monthly average of the operational mode. During the winters, the heat pump operates in the heating mode only. During the summers 2006 and

2007, the heat pump operated in the heating and passive cooling modes. During the summers 2008 and 2009, the heat pump operated in the heating, passive cooling and active cooling modes.

In figure 8.6 we have the daily average operational mode of the heat pump during the month of July in 2008. On days when the outside temperature was low (average temperature bellow 14°C) the heat pump system operated in the heating mode. On days when the outside temperature was high (average temperature above 16°C) the heat pump system operated in the active cooling mode. The passive cooling mode took place on days when the temperature was moderate (average temperature a between 14°C and 16°C). The heat pump system operates in the passive cooling mode on days when neither the heating nor the active cooling mode is operating.

8.3.6 Thermal Energy from the Lake

The amount of thermal energy extracted from the lake is shown in figure 8.7. The figure has gaps in the parts where there were problems with the heat pump system.

8.3.7 COP

Calculating the COP of the heat pump has proven to be a difficult task. As shown in equation 2.14 the COP is calculated from the desired output and the required input. We do not have either of these values.

The Carrier Website offers software that can be used to find a proper sized Carrier heat pump for specific evaporator/condenser flow rates and temperatures [49]. This software can be downloaded free of charge. At first, I hoped to use this tool to estimate the COP of the ABC heat pump. However, it became apparent that the software was not applicable. The software did not allow for the temperature difference between the fluid entering and leaving the evaporator to be less than 2.8°C. The measured temperature difference was below this (see figures 8.4 and 8.2). Also, the software offered three fluid options: water, Ethylene Glycol and Propylene Glycol and depending on the temperature, the properties of Thermera differ significantly from the three [48].

One purpose of this thesis is to give suggestions on how to improve the measuring system. Here seems to be a point of development. There are at least two possible ways to go about measuring the COP. The first way would be to measure the thermal energy output of the heat pump as well as the electric input. Then the COP of the heat pump could be calculated using the equation 2.14. The second and more favorable way would be to measure the thermal energy output and input of the heat pump. With this information one could use table 8.2 to define the COP of the heat pump.

The second option is more favorable for two reasons. The first reason is because the new measuring points could be done using similar measuring devices as used so far. This would facilitate adding the new measuring devices to the RESOL measuring system. The other reason is that now the actual thermal energy input to the heat pump is not being measured. The thermal energy from the lake is being measured but the thermal energy added to the system by the other refrigerating devices and ventilation heat recovery is not measured. In the next section, we will see that this part of the thermal energy could be a significant amount. The measurement of the thermal energy extracted from the lake gives valuable information that should continued to be recorded, so that the different energy sources can be distinguished from one another.

8.3.8 Heating Load

Estimating the heating load of the ABC service station was not an easy task. The calculation method presented in chapter 6 requires a lot of information not available to the writer of this thesis. A direct calculation of the heating load cannot be done as the COP of the heat pump is unknown as is the thermal energy input to the heat pump. So, alternative heating load estimations have been made.

The first estimation of the heating load is shown in figure 8.8. This estimation was calculated from the energy consumption on the months when the heat pump was not operational but data from the solar collectors and the district heating where available. There have been four such months: July 2007, August 2006, September 2006 and November 2007.

The energy consumption of those four months was divided by the amount of days in each month to get the unit kWh/day. Then these values where set in a graph with the y-axis as thermal energy per day and the x-axis as the temperature difference of the ambient and inside temperatures. The inside temperature was fixed as 20°C. A linear regression was performed on the data. This is presented in figure 8.9. It can be seen from the heating load calculations presented in chapter 6, that the heating load is directly comparative to the temperature difference of the ambient and inside temperatures, making the use a linear regression acceptable. The polynomial from the linear regression was used to create the estimated heating load per month using the ambient temperature data gathered by the Davis weather station. The result is seen in figure 8.8.

The estimation assumes that both the thermal energy from the district heating and the solar collectors is fed into the system in accordance with the demand. However, solar collectors, unlike district heating or heat pumps, do not produce thermal energy according the demand. Solar collectors produce thermal energy when the sun is shining. So including the thermal energy produced by the solar collectors gives us a high estimation for the overall heating load. This estimation gives the result of 750 000 kWh/a in the 2006.

Another estimation of the service stations heating load could be calculated from the length of the lake pipes using equation 6.9. This calculation assumes that the thermal energy from the lake pipes was designed to cover the whole heating load and that the heat pump's COP is 3. The values for the equation would be L = 7500 m, r = 0.67 (for COP value 3) and q = 70 kWh/m (for water [24]). Here is the calculation

$$Q_{total} = \frac{7500\mathrm{m} \cdot 70\mathrm{kWh/m}}{0.67} \approx 784000\mathrm{kWh/a}.$$

A third estimation, can be calculated from the know amounts of thermal energy produced; *i.e.* the thermal energy from the solar collectors, the lake (the thermal energy upgraded by the heat pump, assuming the value of COP to be 3) and the district heating in the year 2006. A summation of these values comes to about 500 000 kWh/a.

The first two estimations are close to one another. The third estimation differs by 250 000 kWh/a. This could be accounted for as the thermal energy from the other refrigerating devices and the ventilation heat recovery that is not being measured. A significant amount of thermal energy.

Assuming the heat pump's COP is 3, we can calculate the share of the upgraded thermal energy from the lake heat for each estimation. The amount of thermal energy extracted from the lake during the year 2006 was about 114 000 kWh/a. Upgrading through a heat pump with a COP of 3, we get about 170 000 kWh/a. For estimation 1, we find that share of the upgraded thermal energy from the lake is 22.7%. For estimation 2 the share is 21.7% and for estimation 3 the share is 34%. This information and the same information for the years 2007 and 2008 is shown is also shown in table 8.3.

The third heating load estimation in the year 2008 is much smaller than the other two estimations. This has to do with problem P5 (see table 8.1), an error in the measuring recordings. The problem also affects the recorded number of heat taken from the lake, making the energy share of the upgraded thermal energy from the lake smaller in the other two estimations as well for the year 2008. From table 8.3 it seems that the thermal heat from the lake makes up about 20% of the heating load.

Table 8.1: Malfunctions and Other Problems with the Heat Pump System

Date	Description	Reference number
15 Apr 05	The measuring with RESOL equipment is commenced	P1
Aug 05	Heat pump turned off	P2
Sep 06	Compressor broken in the ventilation system.	P3
Nov - Dec 07	Wrong default value settings in the heat pump control	P4
Nov- Dec 08, Jan. 09	Error in measurement recordings	P5
Feb -Apr 09	Lake pipes partially surfaced.	P6
Aug - Sep 09	Lake pipes damaged and repaired.	P7

Figure 8.1: The monthly average, maximum and minimum temperatures of the warm thermal storage at the top and at the bottom of the water tank. The count is the number of recorded measurements.

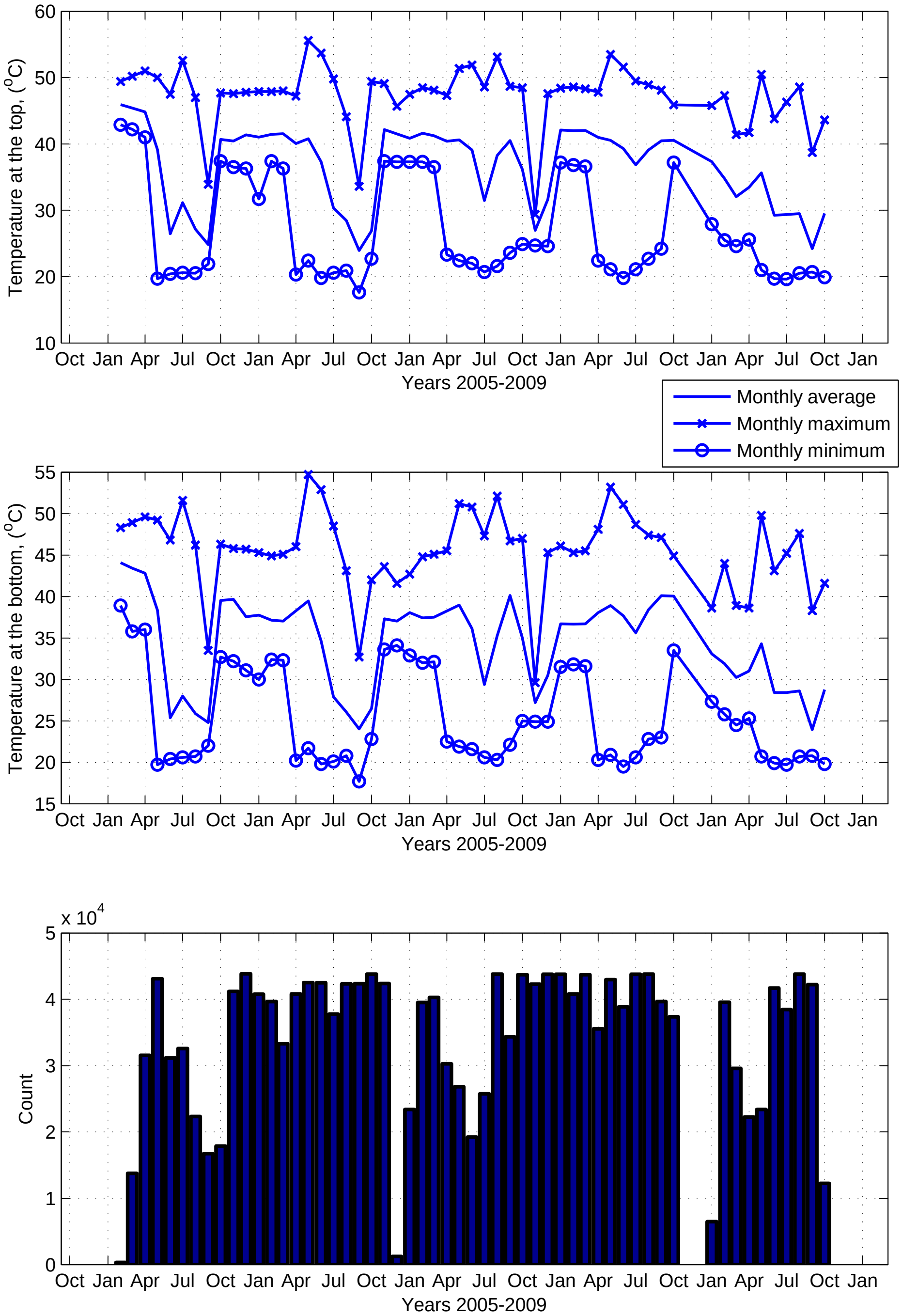

Figure 8.2: The monthly average of the ambient and Thermera temperatures; T_{lake1} = monthly average temperature of Thermera re-entering the lake pipes, T_{lake2} = monthly average temperature of Thermera leaving the lake pipes, T_{out} = monthly average temperature of ambient air, Count= number of recorded measurements.

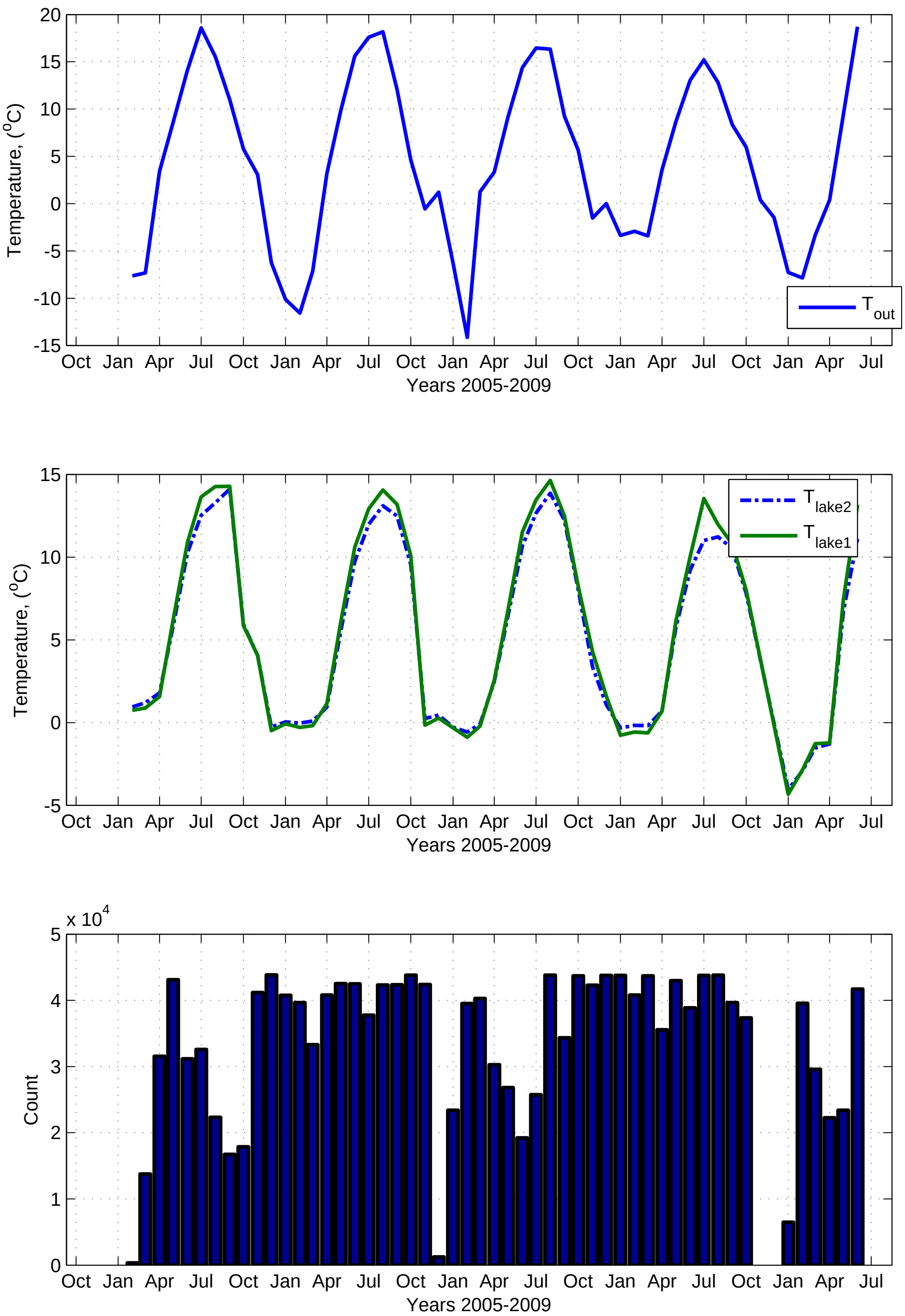

Figure 8.3: The monthly maximum and minimum ambient and Thermera temperatures; T_{lake1} = temperature of Thermera re-entering the lake pipes, T_{lake1} = temperature of Thermera leaving the lake pipes, Count= number of recorded measurements.

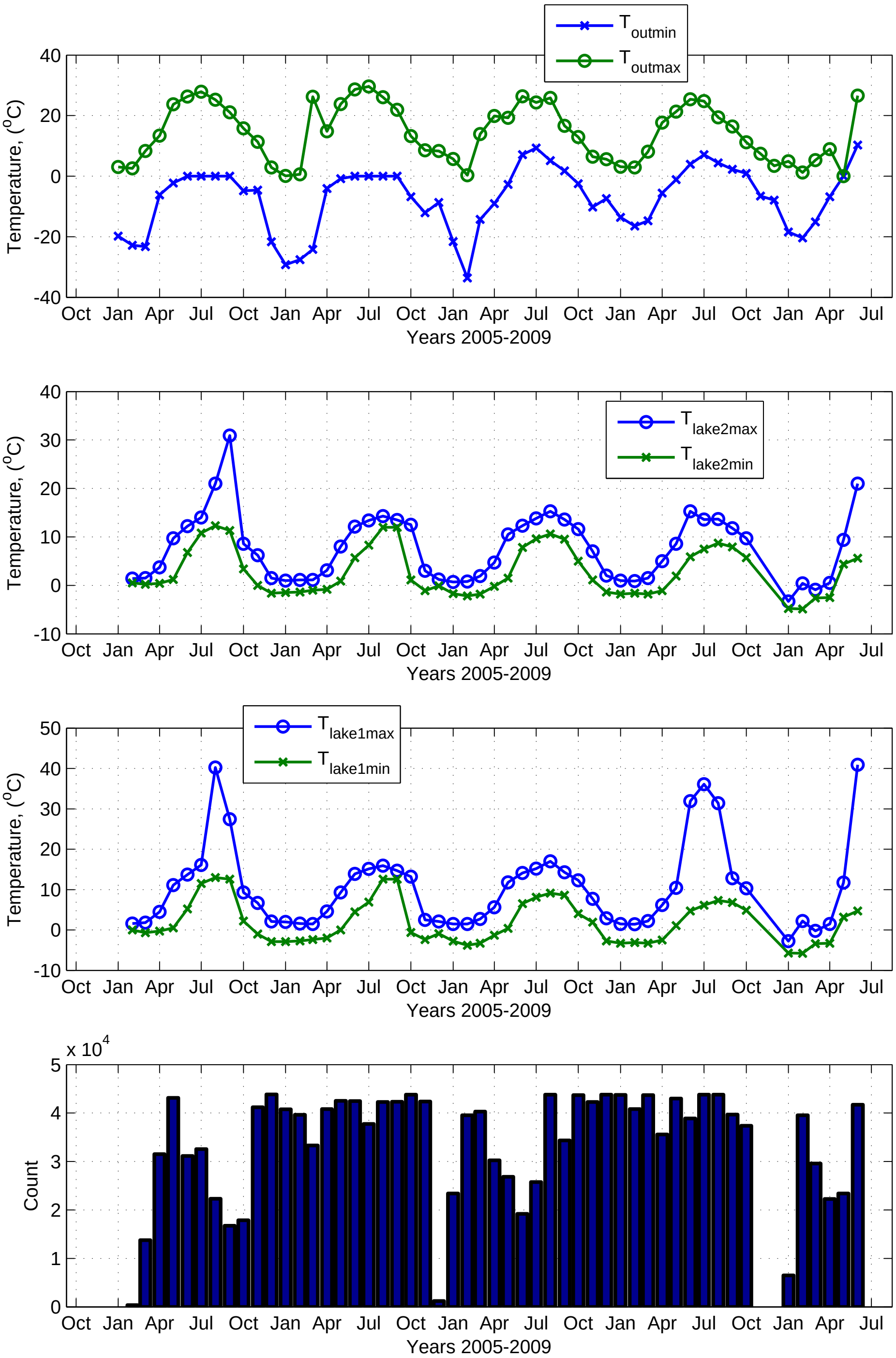

Figure 8.4: The daily average temperature of Thermera in the lake pipe system for the months of October-November 2006, T_{lake1} = daily average temperature of Thermera re-entering the lake pipes, T_{lake2} = daily average temperature of Thermera leaving the lake pipes, T_{out} = daily average temperature of ambient air, Count= number of recorded measurements.

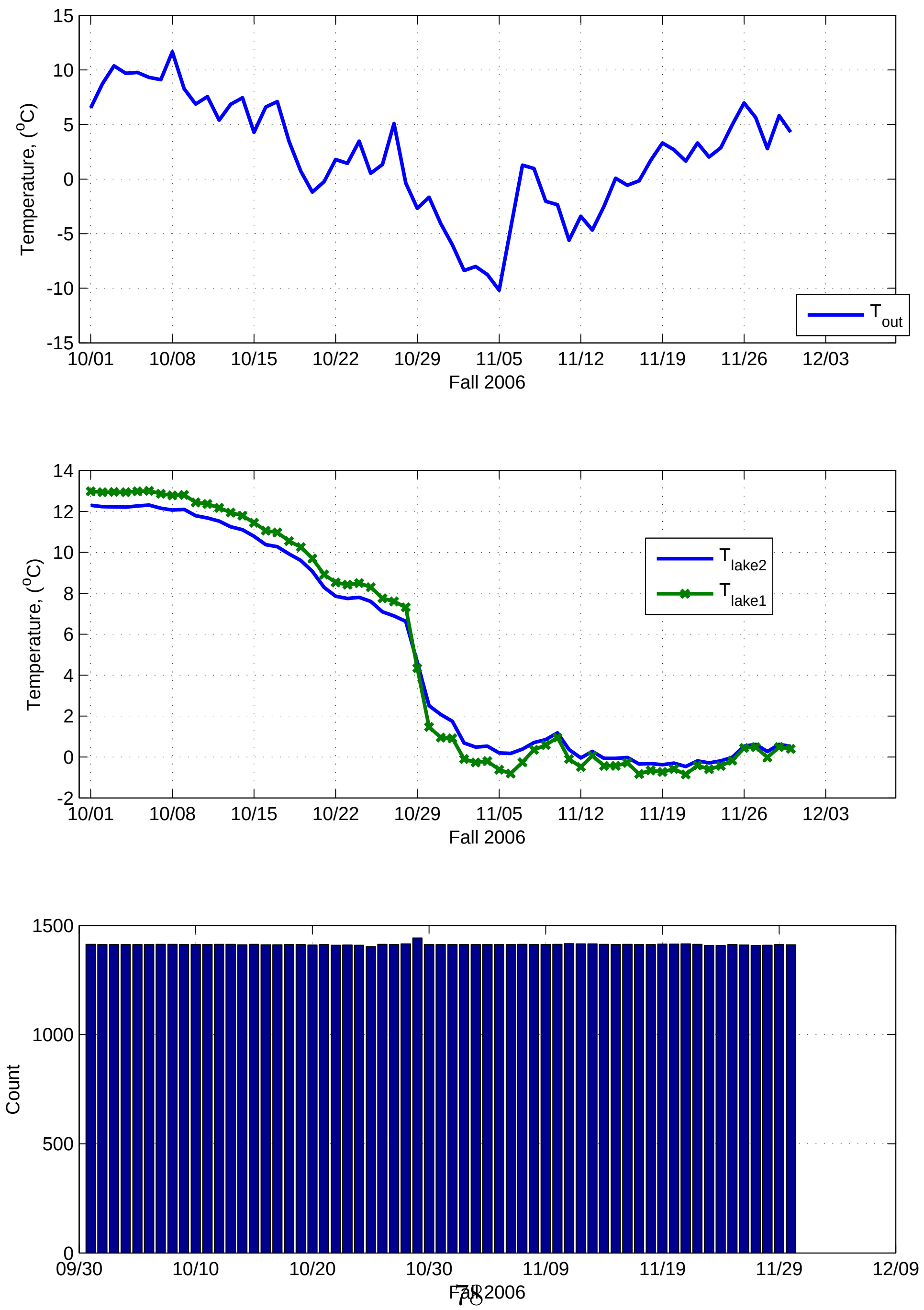

Figure 8.5: The monthly average mode of operation; The mode is "off" when T = 0°C and "on" when T = 100°C, T_{out} = monthly average ambient temperature, Count= number of recorded measurements.

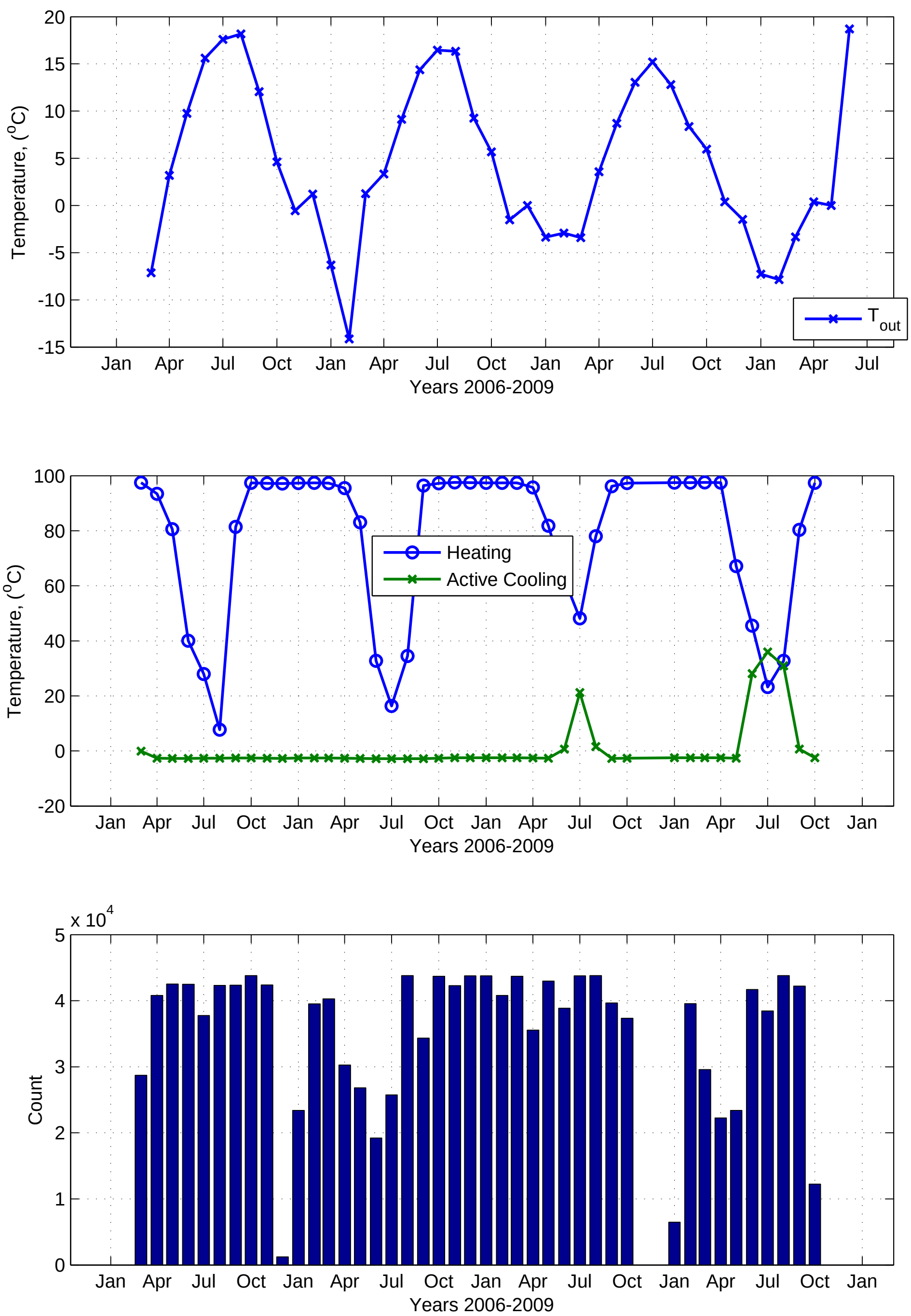

Figure 8.6: The daily average mode of operation for July 2008; The mode is "off" when T = 0°C and "on" when T = 100°C, T_{out} = daily average ambient temperature, Count= number of recorded measurements.

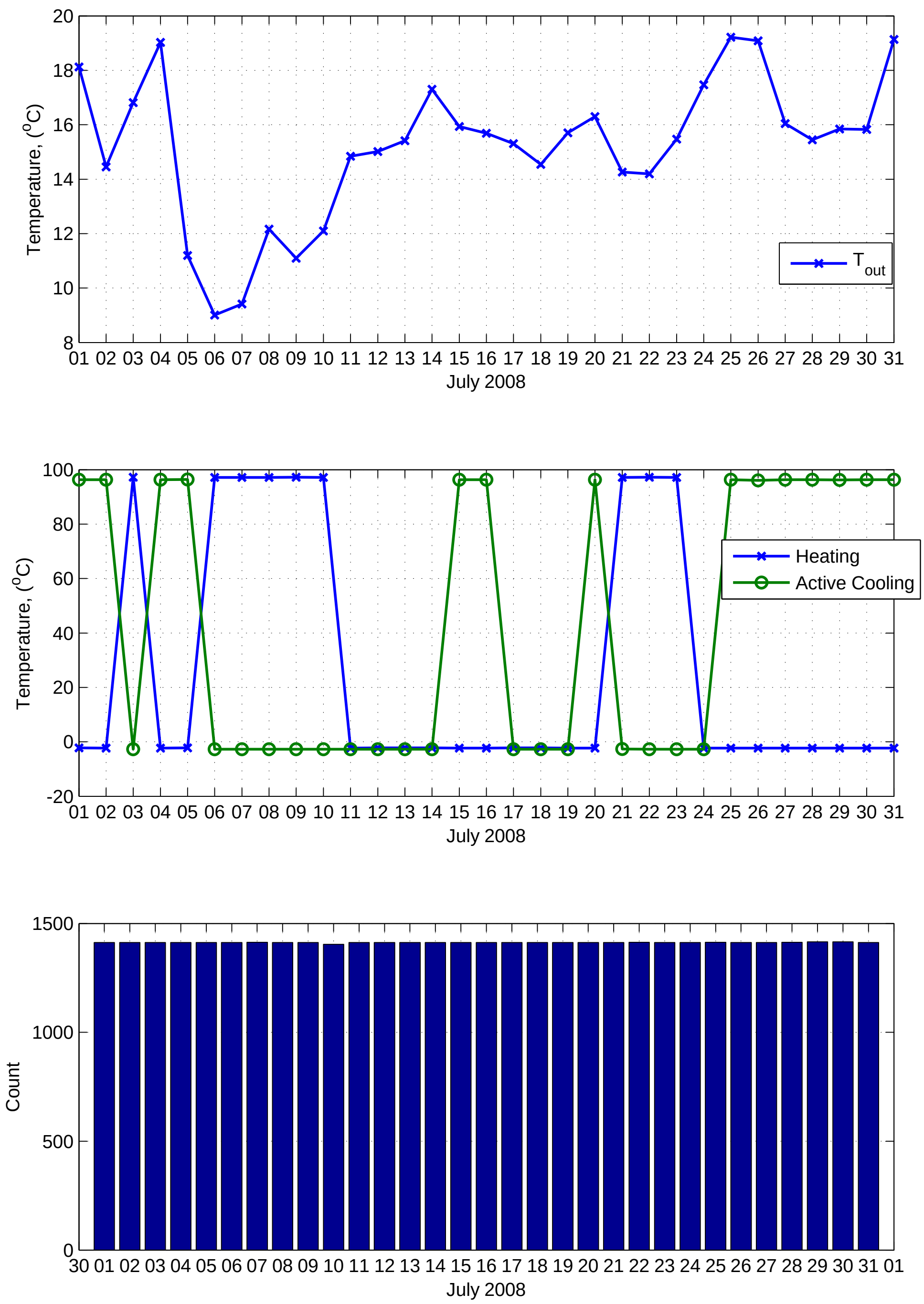

Figure 8.7: The amount of thermal energy extracted from the lake; T_{out} = monthly average temperature.

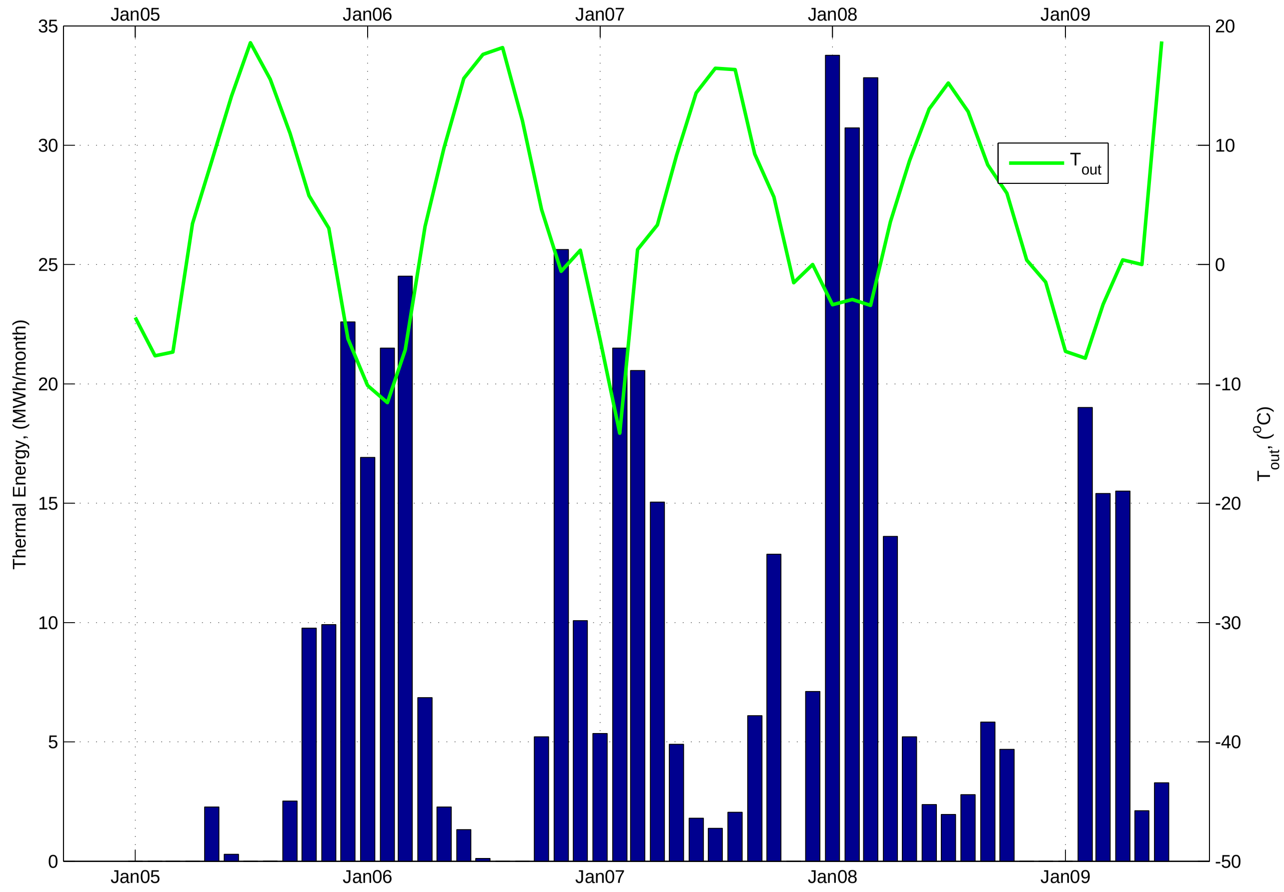

Table 8.2: How the COP of a heat pump affects the energy shares[24]

COP	Electric Energy Input	Thermal Energy Input
4.0	25 %	75 %
3.9	26 %	74 %
3.8	26 %	74 %
3.7	27 %	73 %
3.6	28 %	72 %
3.5	29 %	71 %
3.4	29 %	71 %
3.3	30 %	70 %
3.2	31 %	69 %
3.1	32 %	68 %
3.0	33 %	67 %
2.9	34 %	66 %
2.8	36 %	64 %
2.7	37 %	63 %
2.6	38 %	62 %
2.5	40 %	60 %
2.4	42 %	58 %
2.3	43 %	57 %
2.2	45 %	55 %
2.1	48 %	52 %
2.0	50 %	50 %

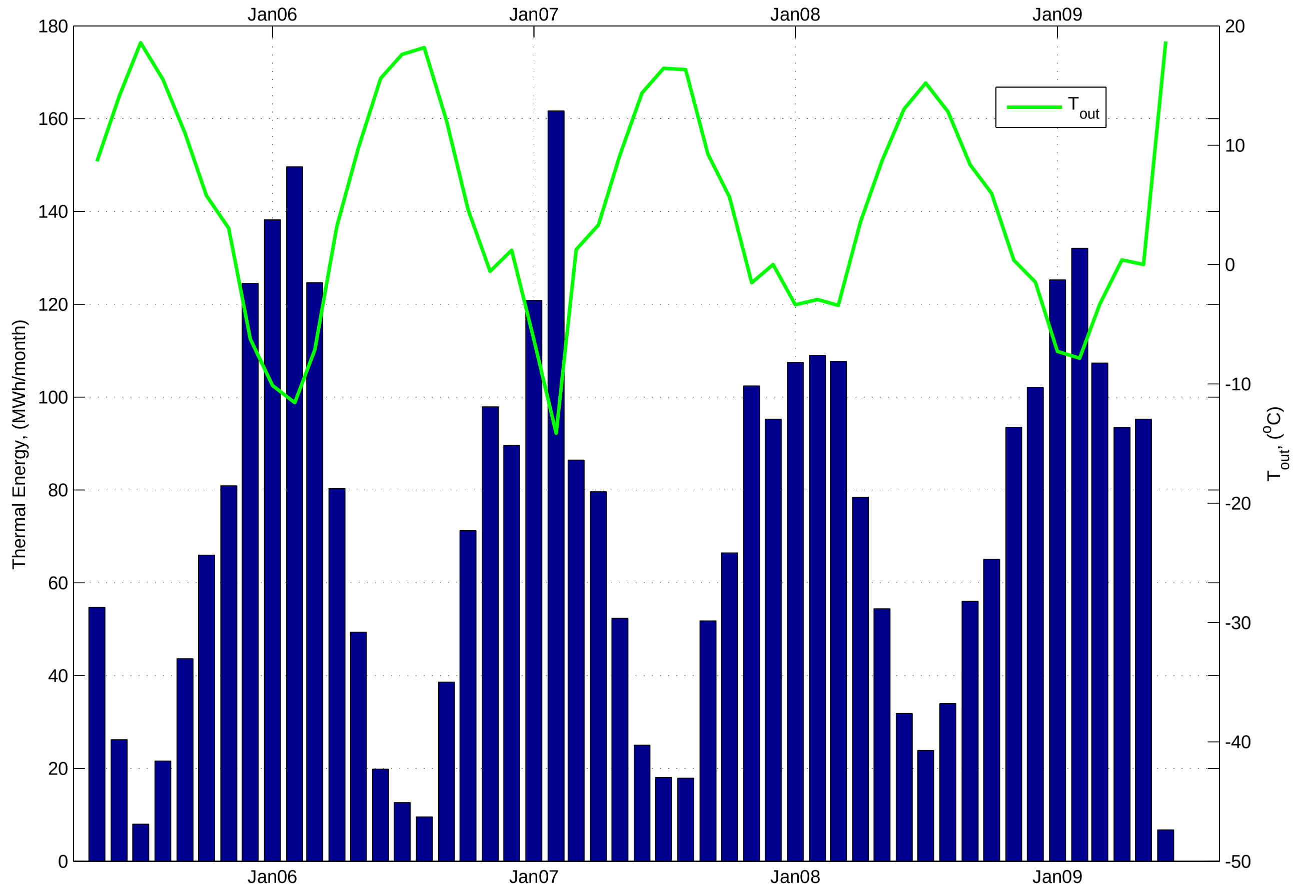

Figure 8.8: The first estimation of the service station's total heating load, T_{out} = monthly average temperature

Figure 8.9: The linear regression of data points from the months July 2007, August 2006, September 2006 and November 2007.

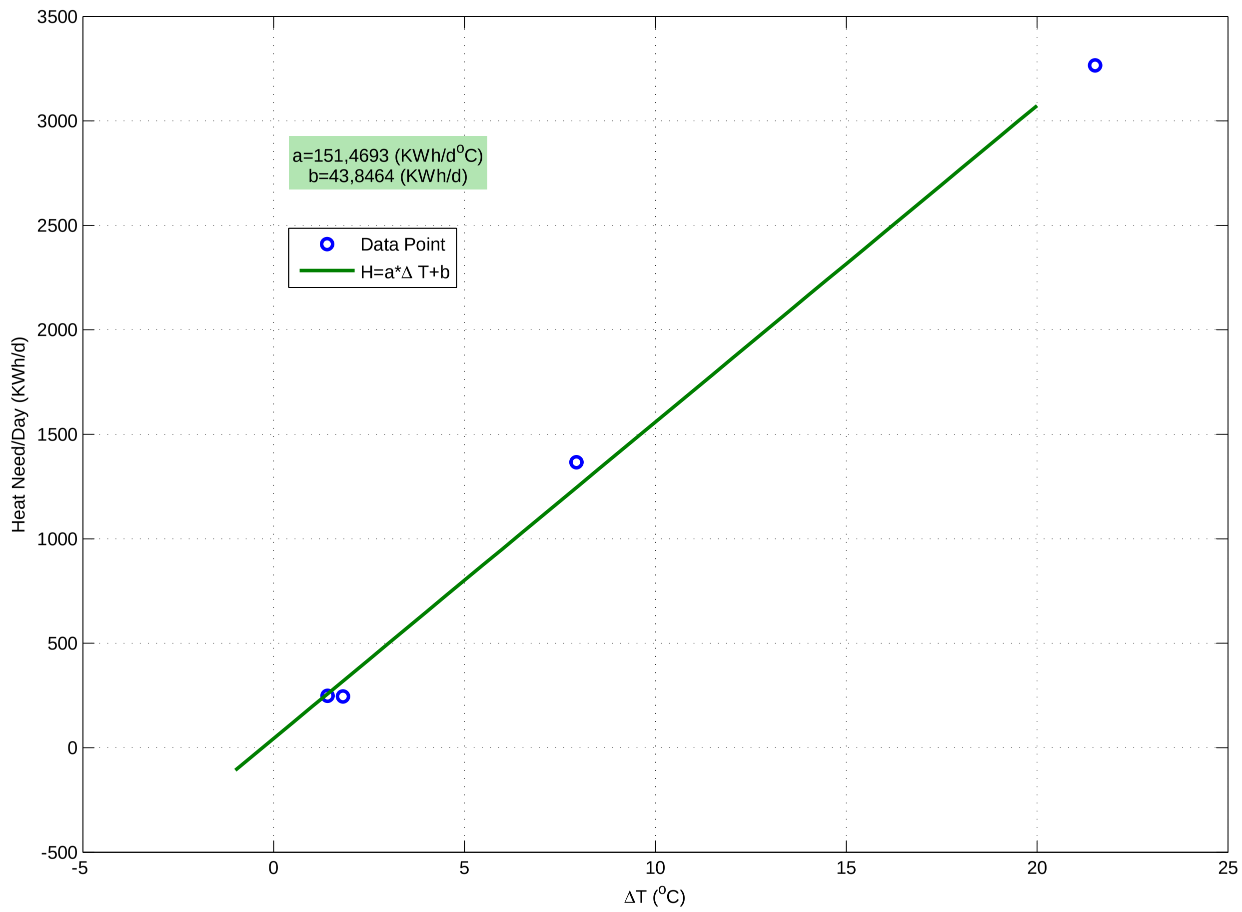

Table 8.3: Comparing the upgraded thermal energy extracted from the lake to the three heating load estimations for the years 2006-2008

Year	Estimation number	Estimated heating load (kWh/a)	Upgraded thermal energy from the lake (kWh/a)	Energy share
2006	1	750 000	170 000	22.7%
	2	784 000	170 000	21.7%
	3	500 000	170 000	34%
2007	1	745 000	148 000	19.9%
	2	784 000	148 000	18%
	3	338 000	148 000	43%
2008	1	845 000	199 700	23.6%
	2	784 000	199 700	25.5%
	3	256 000	199 700	74%

9 Conclusions

The definition of a heat pump is broad and many technically different devices can be called a heat pump. However, the operation of a heat pump is always founded in the laws of thermal dynamics and its efficiency is limited by the Carnot efficiency. The different technologies used to make a heat pump add to the variety of possible heat pump applications. *E.g.* absorption heat pumps work well in sites where a source of high temperature thermal energy is available.

The most used heat pump is the vapour-compression heat pump. A vapour-compression heat pump is composed of four main parts: two heat exchangers (evaporator and condenser) , a compressor and an expansion device. Electricity is the driving energy for a vapour-compression heat pump.

Vapour-compression heat pumps can use many elements as their heat source (sink). The most commonly used are air, ground and water. Each has their advantages and disadvantages. Sometimes it is profitable to increase (decrease) the thermal energy in a heat source (sink) by storing (removing) thermal energy. Using the seasonal temperature changes can help in storing (removing) excess heat in (from) a thermal storage.

The size of a heat pump and of an appropriate heat source (heat sink) is determined by the heating (cooling) loads of the conditioned space to which the heat pump will be connected. It is also important to choose a fitting heat distribution system for the conditioned space to optimise the whole heat pump system. On a whole, choosing a heating (cooling) system is a broad subject, which includes many variables.

Our case study was of the heat pump system of the Viitasaari ABC service station. The heat pump system includes: a Carrier heat pump with a nominal cooling capacity of 310.0 kW, 7 500 m of pipe at the floor of the Keitele Lake, two water tanks serving as thermal storages (warm and cool), a solar collector array, a connection to the local district heating network and an in-floor and ventilation heating and cooling distribution system.

When operating properly the heat pump system at the Viitasaari ABC service station produces a large amount of thermal energy. The estimated amount of upgraded thermal energy from the lake covers about 20% of the estimated yearly heating load of the service station. The Keitele Lake provides a relatively stable temperature heat source (sink) with monthly average temperatures varying from 0°C to 15 °C.

The current measuring system for the ABC heat pump does not provide enough information on the operation of the heat pump. The measuring system should be improved to provide sufficient information so the COP of the system could be calculated and so that the total thermal energy input into the heat pump would be known.

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A Appendix - The Schema of the ABC Heat Pump

Description of Operations

1. Controlling and Locking

   The control system directs the system to the heating, passive cooling or active cooling mode. The heat pump JK7 cannot operate unless pumps P7.1 and P7.2 are operating.

2. Heating Mode

   The heat pump will switch to the heating mode when the outside temperature drops below the limit value.

   Both pumps P7.1 and P7.2 are on. Pump P7.3 is off. Vent TV7.21 is open. Vents TV7.22 and TV7.23 are shut. JK7 is operating in the heating mode. Pump JK7.2 is operating with a constant revolution in accordance with the consumption (pseudopoint).

   The temperature of the fluid returning to JK7, at point TE7.11, is kept at a default value by controlling the vent TV7.1 and the revolution of pump P7.1 in series.

   The internal controls of JK7 control the operation of the compressors cooling the lake water (default + 0°C). The temperature of the condenser side limits the output of JK7, so that the temperature of the water exiting JK7 is the default value (—°C).

3. Passive Cooling Mode

   The passive cooling mode is activated when the outside temperature rises above the limit value (*e.g.* + 12°C) and the temperature of the lake water at point

TE7.24 is below the limit value (*e.g.* + 10°C).

JK7 is turned off and after a 5 minute delay pump P7.1 switches off and vent TV7.1 closes.

Vents TV7.21 ...23 remain in the same position they where in during the heating mode.

Pump P7.2 operates in accordance with the consumption (pseudopoint).

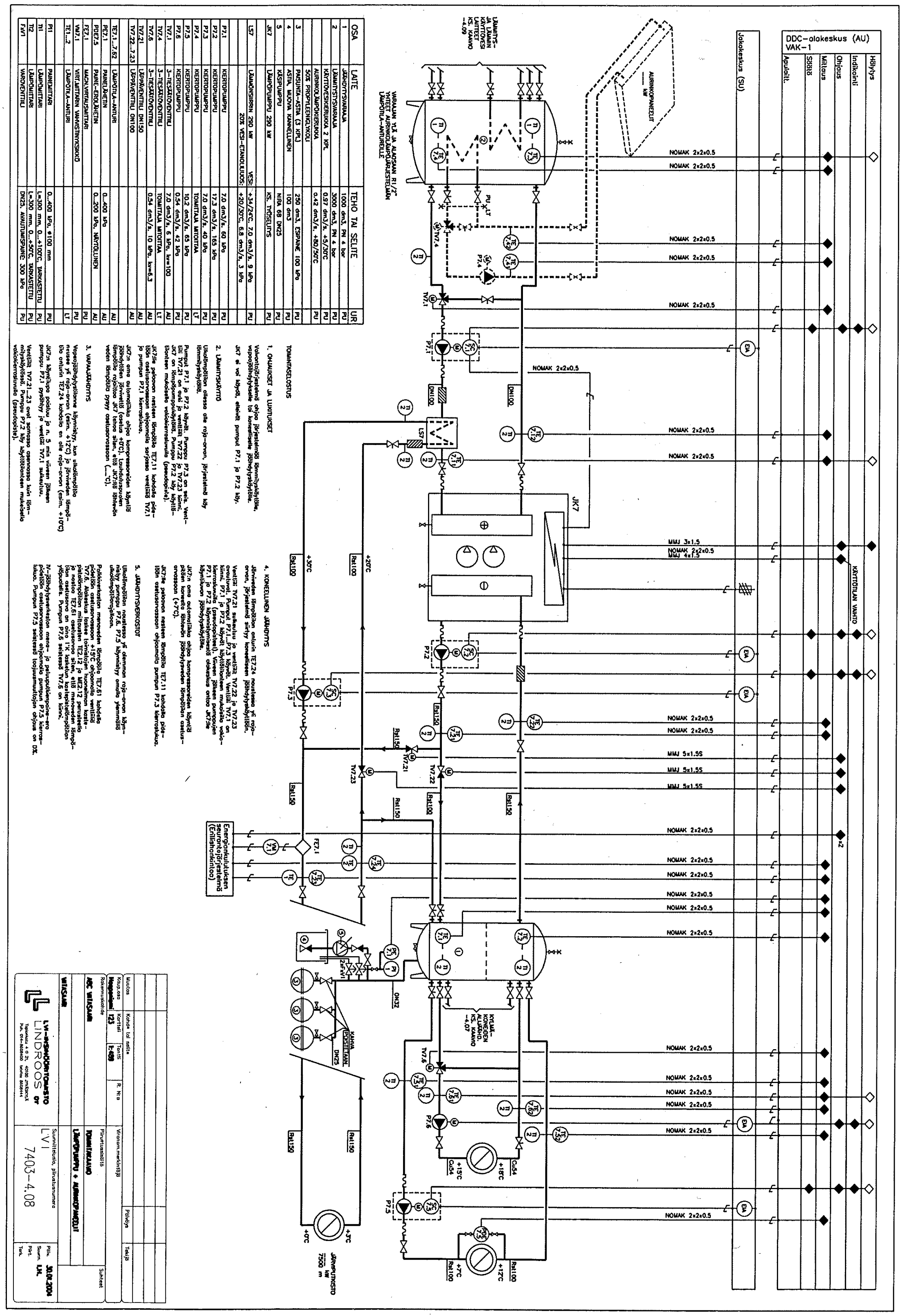
4. Active Cooling Mode

   When the temperature of the lake water at point TE7.4 rises above the limit temperature the active cooling mode begins.

   Vent TV7.21 closes and vents TV7.22 and TV7.23 open. Pumps P7.1 ...P7.3 are operating. Vent TV7.1 is closed. P7.1 and P7.2 operate in accordance with consumption. After a delay the control centre notifies JK7 about the operation of P7.1 and P7.2 . JK7 starts in the cooling mode.

   The internal controls of JK7 control the operation of the compressors keeping the exiting cooling water at the default value (+ 7°C).

   The temperature of the fluid returning to JK7, at point TE7.11, is kept at a default value by controlling the revolution of pump P7.3.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